Tropical Atlantic Observing System (TAOS)

REVIEW REPORT

Full Report

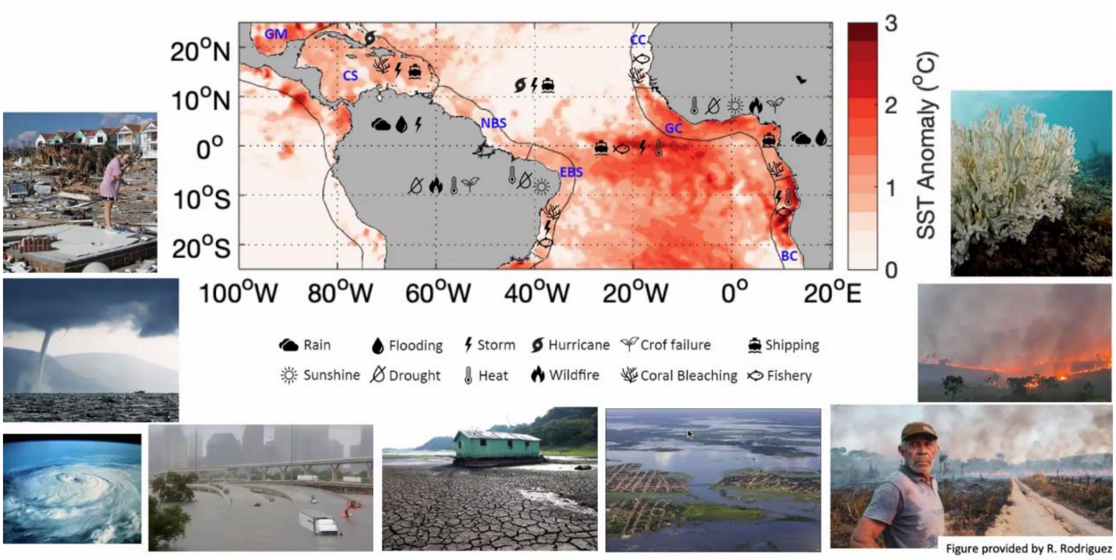

Figure provided by R. Rodriguez

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Preface

Rationale and Motivation for the TAOS Review

The tropical Atlantic observing system was last reviewed in 2006 by CLIVAR (Climate and Ocean: Variability, Predictability and Change) and GCOS-GOOS-WCRP through the OOPC (Ocean Observations Panel for Climate), with a primary focus on PIRATA (Prediction and Research Moored Array in the Tropical Atlantic). Since then, the CLIVAR Tropical Atlantic Climate Experiment (TACE) and the EU program Enhancing Prediction of Tropical Atlantic Climate and its Impacts (PREFACE) have been completed. Scientific priorities and observational technologies have evolved since 2006 and in parallel the observing system has evolved. For example, Argo is now fully developed and has been operating successfully for more than ten years. PIRATA has also expanded to new sites and has enhanced its measurement suite with higher vertical resolution in the mixed layer, and new CO_2 and O_2 measurements. It is therefore timely to systematically review the requirements for sustained observations in the tropical Atlantic, to critically review the design of the sustained observing system in order to take advantage of what has been learned to date, to collectively identify new opportunities to build on past accomplishments, and to explore the possibility for expanded interdisciplinary initiatives with other communities, e.g. in biogeochemistry.

To that end, a Tropical Atlantic Observing System (TAOS) review was proposed by the CLIVAR Atlantic Region Panel (ARP) and has been organized by the CLIVAR ARP in close cooperation with the PIRATA consortium. The review is intended to evaluate scientific progress since the last review and recommend actions to advance sustained observing efforts in the tropical Atlantic.

Implementation of the TAOS Review

The TAOS review was conducted by a Review Committee composed of members of the tropical Atlantic observing community and representatives from GOOS/GCOS, with oversight by the CLIVAR ARP, several of whose members also served in the committee. Bill Johns (U. Miami) and Sabrina Speich (LMD/ENS, ARP and GOOS/GCOS member) served as co-chairs of the review committee. The full review committee is listed in the **List of authors and Contributors**. Terms of reference (TORs) for the review were developed by the ARP in consultation with the review committee and are listed in Appendix 3.

Two workshops were held in association with this review:

1. A "kickoff" workshop held on February 8 and 9, 2018, adjacent to the 2018 Ocean Sciences Meeting in Portland, Oregon. A total of 30 participants attended the workshop. The main goals of this first workshop were to define the requirements for the Tropical Atlantic Observing System and to review the present status of the TAOS observing networks. A full report of the workshop is available at http://www.clivar.org/sites/default/files/documents/1st%20TAOS%20Review%20Workshop%20Report_final.pdf and the workshop agenda and presentations can be viewed at http://www.clivar.org/events/tropical-atlantic-observing-system-review-workshop.

2. A 2nd TAOS Review workshop was held in Marseille, France October 2018 immediately following the annual PIRATA meeting that was attended by over 50 participants. The main goals of this workshop were to finalize recommendations for the future TAOS and to make recommendations for the future governance of the TAOS. The agenda and presentations from the 2nd workshop are available at http://www.clivar.org/2nd-tropical-atlantic-observing-system-taos-review-workshop.

This report summarizes the outcomes from the two workshops and subsequent discussions among the review committee, including inputs from other members of the tropical Atlantic observing and modeling communities.

The structure of the report is organized with an executive summary that introduces the main societal drivers and provides a summary of the recommendations and where in the report these are more thoroughly discussed. The core text of the report then proceeds in the following order: (1) a concise review of TAOS societal, scientific and operational drivers; (2) a summary of the current TAOS observing network; (3) recommendations on the evolution of the TAOS; (4) information on the actual TAOS data flow and products and recommendations for their evolution; and (5) recommendations on the future governance of the TAOS. More detailed information on the scientific and operational drivers are provided in the Appendices as well as a rationalization of all observing requirements in terms of Essential Ocean and Climate Variables.

1. Executive Summary

1.1 Societal importance of the tropical Atlantic (TA)

The tropical Atlantic is the smallest of Earth's tropical ocean basins, one half the width, west to east, of the tropical Indian Ocean and less than one fifth that of the tropical Pacific. Thus, the tropical Atlantic interacts intimately with its bordering lands, strongly influencing their weather and climates, and it is readily accessible by the region's inhabitants (Fig. 1.1). At the same time, the tropical Atlantic plays an outsized role in the global climate system. Through the Atlantic Meridional Overturning Circulation (AMOC), it delivers nearly half a petawatt of energy from the Southern to the Northern Hemisphere, and it has marked, if still not fully understood, impacts on globally significant variations in the tropical Indian and Pacific Oceans.

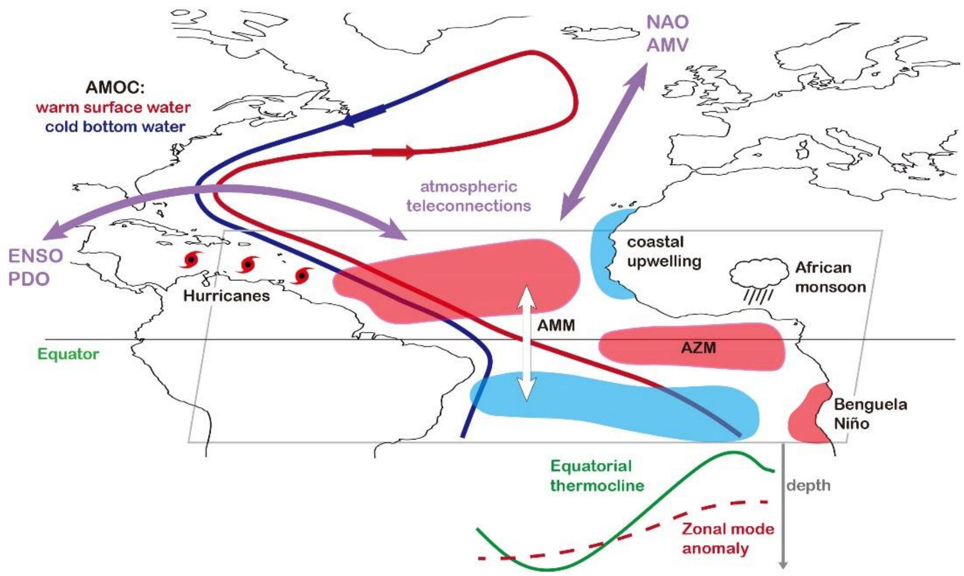

Figure 1.1: Important processes and modes of interannual variability in the tropical Atlantic. AMM: Atlantic Meridional Mode; AZM: Atlantic Zonal Mode (or Atlantic Niño); AMOC: Atlantic Meridional Overturning Circulation; ENSO: El-Niño/Southern Oscillation; PDO: Pacific Decadal Oscillation; NAO: North Atlantic Oscillation; AMV: Atlantic Multidecadal Variability.

All countries bordering the tropical Atlantic experience important societal challenges driven by regional ocean processes and air-sea-land interactions. These are exacerbated by climate change, which induces new emerging threats (Fig. 1.2). Examples include floods and droughts in South America and West Africa (Giannini et al., 2005; Berntell et al., 2018, Brito-Morales et al., 2018), more intense storms and hurricanes, and continuing sea-level rise that increases flooding risks and episodes of coastal erosion (Balaguru et al., 2018). Other regional emerging extreme events such as ocean heat-waves and episodes of anoxia and acidification amplify the vulnerabilities of regional marine ecosystems – systems already stressed by overfishing and pollution - and jeopardize local economies and food sources (Stramma and Schmidko 2019; Holbrook et al. 2019; Froelicher et al., 2018; Sen Gupta et al., 2020). Moreover, recent studies show that the tropical Atlantic has two-way connections with the Pacific (Cai et al., 2019; Patricola et al., 2017) and appears to play a driver role in mid- and high-latitude climatic events including the occurrence of impactful mid-latitude extremes throughout the year (Ole Wulff et al., 2017).

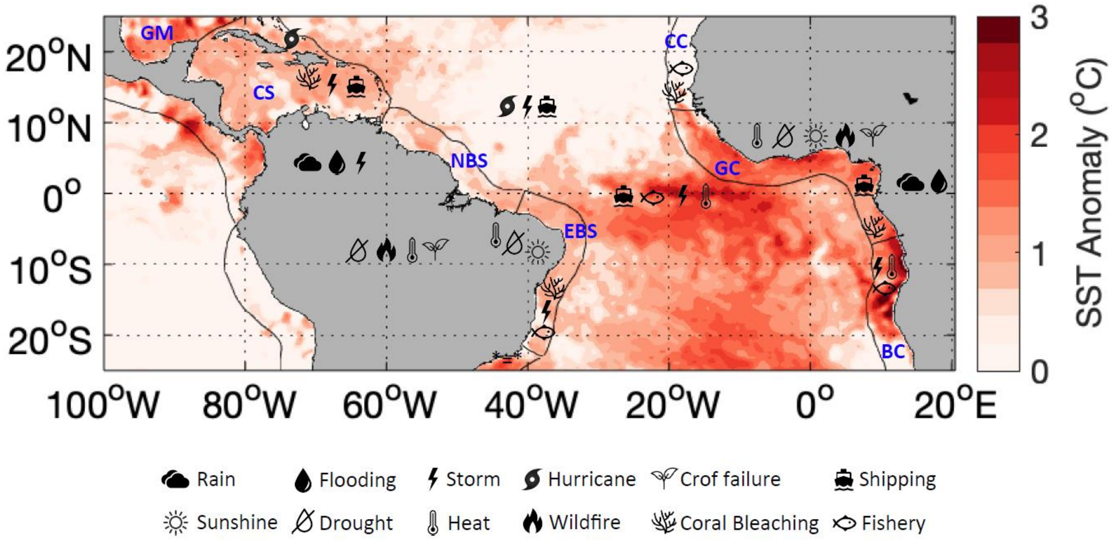

Figure 1.2: Main impacts of tropical Atlantic variability and changes on adjacent continents expressed as symbols. In the background, in red color, Sea Surface Temperature anomalies (SSTA) for 13 Jan 2020, with most of the tropical Atlantic experiencing a marine heatwave event (defined where SSTA > 1°C), using Hobday et al. (2016) methodology. SBS: South-Brazil Shelf; EBS: East-Brazil Shelf; NBS: North-Brazil Shelf; CS: Caribbean Sea; GM: Gulf of Mexico; CC: Canary Current; GC: Guinea Current; BC: Benguela Current (Figure provided by R. Rodrigues).

To address this large spectrum of interconnected phenomena, a diverse network of ocean observations and forecasts has developed, building on the PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) network (Bourles et al., 2019; Foltz et al., 2019). This network has evolved naturally over its 20 years of existence to address regularly the most important outstanding scientific questions and to improve predictions of severe weather in the tropical Atlantic and of global climate variability and change.

Tropical Atlantic Ocean observing and forecasting are, first and foremost, essential for countries bordering this sector of the world ocean, providing key information to mitigate such environmental risks as storms, hurricanes, floods, droughts, coastal erosion, sea-level rise, heat-waves, and anoxia events, and to better manage marine ecosystems, fisheries and aquaculture. Moreover, they are critical to underpinning any ocean-related activity, from science to the blue economy and from management to ocean-human interactions.

Despite the critical importance of the tropical Atlantic Ocean to society and the enhancement of the regional observing system that has occurred in the last 20 years, there are still fundamental gaps that limit significant progress in the understanding of societally-relevant phenomena and their prediction. These gaps cannot be filled by individual nations. This Tropical Atlantic Observing System (TAOS) review report has been conceived to assess the current status of the observing system with respect to societal requirements, and to provide recommendations on the most relevant gaps in observations and prediction capabilities that need to be addressed in a the near future and that can be sustained in the long term under international coordination.

The overall aim of the report is to build towards a TAOS that is a user-focused, truly interdisciplinary, and responsive international ocean observing and forecasting system; one that delivers the essential information needed for human wellbeing and safety, sustainable development, and the blue economy in a changing world.

This effort to build a fit-for-purpose TAOS comes at a time of novel and active international pan-Atlantic cooperation on ocean science centered on ocean observations and forecasting. This reflects the growing recognition of the key role oceans play in developing national and regional economies, including efforts to reach Sustainable Development goals and, in particular, to address climate change. TAOS contributes to both the Galway Statement signed by the European Union, Canada and the United States on 24 May 2013, which recognizes “the value of our ongoing cooperation on ocean science and observation in the Atlantic Ocean” and the Belém Statement, signed between the European Union, South Africa and Brazil on 13 July 2017, which notes “the mutual benefit that would accrue from linking research activities in the South Atlantic and Southern Ocean with those in the North Atlantic”.

1.2 Value of TAOS

The emergence of a tropical Atlantic observing system can be dated to 1997, with the deployment of the first elements of the PIRATA array. Drawing on these observations, the subsequent decades have witnessed an explosion in our knowledge of the tropical Atlantic Ocean: its modes of variability and the processes that govern these modes, its interactions with the atmosphere, its contributions - realized and potential - to improved weather and climate forecasts, its physical and biogeochemical roles in the global climate system, and its importance for fisheries that are vital to the livelihoods of millions of people on its shores.

Scientific priorities and observational technologies have evolved since the last tropical Atlantic observing system review in 2006, and the observing system has evolved, as well. Argo is now fully developed and has been operating successfully for more than ten years. PIRATA has also expanded to new sites and has enhanced its measurement suite, with higher vertical resolution in the mixed layer and with new CO_2 and O_2 measurements. Figure 1.3 gives an overview of the actual TAOS.

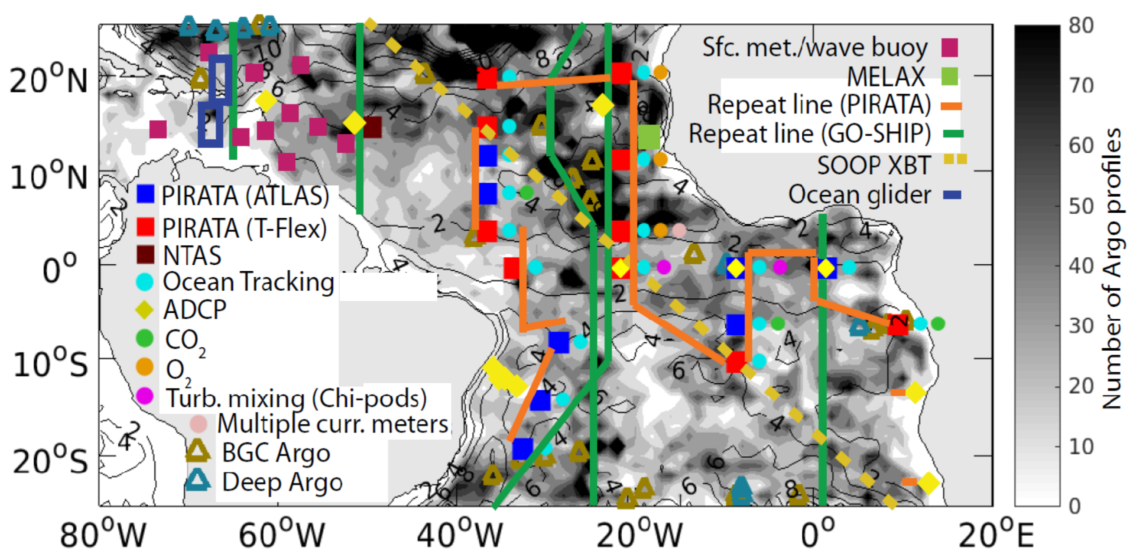

Figure 1.3: Key elements of the tropical Atlantic in situ observing system. Gray shading represents the number of Argo profiles made in each 1° box between 2008 and 2017. Contours show the average number of hourly surface drifter observations made in each 1° box per month during 2008-2017. (Figure provided by G. Foltz).

In addition to PIRATA, several time-limited international projects have been undertaken in the region, including the Tropical Atlantic Climate Experiment, the European projects PREFACE and AtlantOS, and new European projects (e.g., H2020 projects TRIATLAS, iAtlantic, AtlantEco, and EuroSea) funded under the All-Atlantic Ocean research framework, which includes partners across the Atlantic, have just started.

Over the nearly quarter century that a coordinated tropical Atlantic observing system has been in place, there have been enormous advances in tropical Atlantic science and great strides made in coordinating this science among nations and stakeholders. Among these are an improved understanding of mixed layer heat and freshwater budgets, equatorial and tropical circulations, influence of the tropical Atlantic in precipitation and drought extremes in western Africa and Brazil, and the prediction of tropical Atlantic hurricanes. The tropical Atlantic observing system has also contributed to an improved understanding of the ocean's regional influence on the carbon budget, minimum oxygen zone dynamics and changes, fisheries variability and evolution, as well as how the tropical Atlantic influences the tropical Pacific and Indian interannual modes of variability and North Atlantic and European extreme precipitation events. Moreover, TAOS observations have been proven necessary in satellite validation and for the generation, calibration, and validation of various satellite and/or in situ data products. TAOS buoy and cruise data are used extensively for model validation. TAOS ocean subsurface temperature and salinity real time data are used in operational prediction centers (for example ECMWF, MetOffice, MercatorOcean) in addition to classical meteorological data (provided regionally also by TAOS).

Despite these advances, recent studies - together with evidence contained within this TAOS review - consistently show that the existing Tropical Atlantic Observing system is minimal to ensure skillful predictions across timescales from weather to climate change, and to meet demands of adaptation and resource management. Moreover, the present observing system has important gaps, both regional and temporal, that impede improvements in prediction and in the monitoring of biogeochemical and marine ecosystems needed to support the sustainable management of fisheries and to provide vital information about the regional and global carbon system.

Organizationally, the increased international activity focused on ocean observing and forecasting has instigated the emergence of a pan-tropical Atlantic community among scientists and stakeholders. Increased dialogue on common objectives has fostered cooperation and the sharing of technologies, best practices and co-construction of scientific activities across the Atlantic generally, and in the tropical Atlantic in particular. During this TAOS review process, two workshops were organized; these garnered an unprecedented level of participation from a large panel of scientists and stakeholders drawn from countries bordering the basin.

TAOS is one mechanism to follow up on the recommendations of the OceanObs'19 conference. It supports the Atlantic Basin implementation of GOOS, and it contributes to the UN Decade of Ocean Science for Sustainable Development (2021-2030). TAOS is strategically situated in the All-Atlantic Ocean Research Alliance initiated through the Galway and the Belém statements and the G7 Future of the Seas and Oceans Working Group.

Over the past decade, Atlantic countries have been building collaborations to integrate, aggregate, and optimize national oceanographic investments for shared benefits. The Tropical Atlantic has been at the forefront of such efforts for more than 20 years. With its mature know-how in ocean observing and data services, TAOS represents a cornerstone of the Atlantic Observing System (AtlantOS) currently being developed (see http://www.atlantos-ocean.org).

1.3 Key recommendations

Consistent with the importance of the tropical Atlantic and the great returns in scientific understanding that have emerged from the existing TAOS, it is anticipated that enhancements to the system will lead to great benefits to society and to continued scientific discovery (Section 2). Here we briefly summarize the recommended expansions/enhancements to the TAOS and how these enhancements will support desired outcomes: improved prediction and projection of weather and climate over a range of time scales; better characterization of how the tropical Atlantic participates in anthropogenic climate change; and supporting efforts for sustainable management of tropical Atlantic ecosystems and fisheries, which provide a vital source of food and income for millions of people. A complete list of recommendations resulting from this TAOS Review is given in Section 5 of the report, including platform-specific enhancements to the current TAOS.

A key driver for an enhanced TAOS is the expectation that observing system enhancements will lead to improved tropical and extra-tropical Atlantic weather and climate forecasts and projections, over a broad range of timescales (Sections 2.1 & 2.3). Increasingly, weather and climate forecasting are carried out seamlessly, in the sense that common or unified models are used across timescales, and improved skill of a forecast for phenomena at a shorter lead time often implies that forecasts or simulations of slower phenomena are likewise enhanced. In general, the longer the timescale of the phenomenon in question, the deeper into the ocean that observations are relevant. Thus, at the short-time extreme, forecasts of tropical Atlantic hurricanes will benefit from improved observations of atmospheric conditions and upper-ocean heat content, while at century timescales, accurate projections of climate change to determine appropriate adaptation measures depend on heat storage in the deep ocean, which involves the Atlantic meridional overturning circulation, as well as the processes that control atmospheric convection changes and concentration of carbon dioxide.

Weather forecasts require that key essential variables be sampled at sub-daily frequencies in the atmosphere and at least daily in the upper ocean (Appendix 2: Numerical Weather Prediction & Extremes), and be reported in near real time. Thus moored platforms (Section 5.2.1), drifters (Section 5.2.2), satellite observations (Section 5.2.5), and upper-layer subsurface temperature and salinity from Argo (Section 5.2.3) are the observing systems most relevant to weather phenomena, while monthly sampling of ocean heat storage (Appendix 2: Heat Storage), is sufficient for interannual and longer climate forecasts (Appendix 2: Operational prediction and monitoring of tropical Atlantic climate on seasonal-to-decadal timescales). Climate projections will be improved by observations of physical and biogeochemical properties at the annual frequency offered by cruises (Section 5.2.4), and also supported by enhanced Argo observations (Section 5.2.3**).** While a range of these observations are already available in the actual TAOS network of observations, this report shows that they are not sufficient in terms of essential variable spatio-temporal coverage requirements.

The successful execution of a forecast depends on an accurate initial condition. Especially for timescales longer than weather, the initial state of the ocean is important, and this calls for the development of improved data assimilation systems (Section 5.2.8), which, in turn, requires the planning and execution of observing system simulation experiments (OSSEs) and observing system experiments (OSEs). These experiments are also essential for designing an enhanced observing system that is optimal for its uses, given the available resources.

Improved forecasts will also come from improved models. Perhaps the greatest challenges for models are in their representations of the exchanges of energy, moisture, and momentum between the ocean and the atmosphere. Better characterization of these fluxes is needed to develop, improve, and test flux parameterizations. This requires continual monitoring of key quantities at high temporal resolution from continuously deployed platforms (Appendix 2: Air-sea fluxes of energy and Vertical momentum transport in the equatorial Atlantic troposphere), as well as measurements at sufficiently high resolution to capture the atmospheric turbulence and the ocean sub-mesoscale that can be accomplished from autonomous vehicles, such as Saildrones and marine gliders (Section 5.2.6). Targeted process studies using new or existing technologies are also vital for improving models and to continually improve the efficiency and effectiveness of the deployed observing system (Section 5.2.7).

Important anthropogenically driven changes in the tropical Atlantic that must be better characterized and understood include its contributions to the uptake of anthropogenic carbon dioxide (Section 3.4) and to sea level rise through ocean heat storage (Section 3.7). While the temporal scales of these changes are long, they involve processes that require monthly or weekly observation to be understood (Appendix 2: Heat storage), and, again, call for enhancements of in situ and remote systems measuring ocean temperatures over a range of depths and temporal scales. To understand the changes in the carbon system occurring in the tropical Atlantic and their role in global CO_2 (Appendix 2: Anthropogenic carbon storage), enhanced observations of the surface pCO_2 and water column measurements of dissolved inorganic carbon (DIC), total alkalinity and pH are needed.

To address the future and the sustainable management of the tropical Atlantic fishery (Section 3.6), fishery data must be collected, collated and made freely available (Appendix 2: Fish stock assessment) along with observations of physical and biogeochemical parameters in the coastal regions where fishing is most active.

The maturity of tropical Atlantic science and the complexity of the TAOS, with major contributions from many nations around the Atlantic basin, argue for a governance structure that will ensure a high level of coordination among various observing system components, provide guidance for future evolution of the observing system, and advocate for resources to help to sustain the observing system over time (Section 7.2). Such a structure will consolidate progress in the individual components of TAOS by establishing a framework that encourages their co-evolution. The establishment of a "TAOS forum" is recommended, that will foster close coordination among observing system elements, provide a vehicle to share information on implementation strategies, challenges, and best practices, help to define new observing system initiatives, and advocate for resources necessary to sustain the TAOS effort. The Forum would be populated by scientists, agency representatives, and end users.

1.4 Summary

All countries surrounding the tropical Atlantic Ocean face societal challenges linked to ocean and ocean-atmosphere phenomena that are increasing in significance and consequences with climate change. These processes have a profound influence on the regional population's health and resources. At the same time, the tropical Atlantic exerts global influences on the climate on timescales from months to centuries.

The present TAOS review comes at an inflexion point for the tropical Atlantic, where scientific progress, demands on its resources, and environmental changes resulting from local and global stressors simultaneously are accelerating. At this juncture, there are great rewards to be reaped from an enhanced and invigorated TAOS, rationally planned and responsibly governed and coordinated. This report offers the rationale and the strategy for achieving a TAOS that will be well suited to serve the societal and scientific needs of the Atlantic basin and the globe over the coming decades. The recommended enhancements to the observing system across the range of platforms, with their associated sampling timescales, variables measured, and ranges of depths is expected lead to improved forecasts and projections of phenomena ranging from daily weather, fisheries and coastal managements, to anthropogenic climate change over multiple decades.

2. Societal Relevance of the Tropical Atlantic Observing System

The tropical Atlantic has an enormous impact on people who live around the ocean and even those who reside at great distances from it. For example, African and South American countries that border the South Atlantic depend strongly on the ocean for societal development, fisheries and tourism (Reyer et al., 2017; Serdeczny, et al., 2017). The tropical Atlantic also has strong influences in the Northern Hemisphere, e.g. in the USA, the Caribbean and Mexico, most notably because of the enormous impact of hurricanes. In the USA alone, hurricanes account for about half of the deaths and economic impact from weather and climate disasters (www.ncdc.noaa.gov/billions). Additionally, the tropical Atlantic plays an important role in modulating global climate, having been, for instance, a key driver of the recent hiatus in global warming (e.g., Li et al., 2016b). All aspects of the ocean – physical, biogeochemical and biological – have an impact on society.

Here we review the benefits derived from the existing observing system and how future developments in ocean observing could lead to enhanced societal benefits. In addition to advancing scientific understanding, the purpose of TAOS is to meet the broad socioeconomic and scientific needs of society. The design of the TAOS must recognize the needs of users so that the system is 'fit-for-purpose', providing the information that is needed and is relevant. While these benefits could be primarily of regional significance, particularly for operational services such as hurricane forecasting, others could be either basin-scale or global in their scope, for instance the needs related climate variability and change or ocean health. Different supporters of the system and different countries might see or expect different benefits. Among various examples - beyond operational and storm forecasting - we can cite regional fisheries that are impacted by marine heat waves and anoxia events, while the coastlines of the tropical Atlantic Ocean and Caribbean Sea have been plagued by extraordinary accumulations of Sargassum since 2011 that are becoming a large economic and environmental threat. Other examples concern precipitation and water availability in Western Africa and extreme floods and droughts in Brazil. To ensure that societal needs are met, the observing system should evolve and improve to address the widening range of stakeholders' needs.

The relevance of the Tropical Atlantic Observing System to society can be expressed in terms of four main overarching themes:

- **Operational Services** (Weather and Ocean Forecasting, Hazards and Extremes) – Operations at sea typically require updated information on the present and future states of the ocean in order to secure safe operations, optimization of time, and energy consumption. One aspect of operational services concerns ocean hazards, since ocean forecasts and early warning systems can help manage risk and improve business efficiency, e.g. for fishing fleets or transportation operations. Improved predictions of hurricanes and other catastrophic storm events are among the most important societal interests related to the tropical Atlantic Ocean. Climate services provided by operational centers are also becoming increasingly important to a broad spectrum of users, for both seasonal and longer-term climate forecasts.

- **Ocean Health and Fisheries -** Ocean ecosystems are coming under increasing pressure from anthropogenic influences, both through climate change that is causing warming, ocean acidification and changing oxygen distributions, as well as through direct human impacts, e.g. overfishing and pollution. Better monitoring and knowledge of the ocean will help sustain livelihoods and ecosystem services in the ocean. The most obvious direct benefit from TAOS related to a healthy ocean will be to fisheries management as countries around the tropical Atlantic derive enormous economic and social benefits from fishing.
- **Climate Variability and Change -** The ocean is a key component of the climate system and influences its evolution and variability through the energy, water, and carbon cycles. Enhanced monitoring and knowledge will inform both mitigation and adaptation to climate change as well as improve climate services. The TAOS will help to inform us about how changes in ocean-atmosphere conditions will influence weather patterns, e.g. changes in rainfall in the African Sahel and the Brazilian Northeast.
- **Research and Discovery -** It is necessary to continue to build our understanding of key oceanic and atmospheric processes and to improve our approach to making ocean observations. Linking research to ocean observation programs enables a synergy that benefits both activities. New research has led to the development of new technology such as ocean gliders for making observations in the path of hurricanes. New understanding of the ocean circulation has also highlighted links between the deep ocean and climate. Improved numerical modelling techniques have significantly enhanced the quality of ocean and atmospheric forecasts.

2.1 Operational Services

The most immediate and direct impact on society of ocean observing is typically through operational services, primarily through weather and ocean forecasting. Delivery of weather forecasts and hazard warnings increasingly rely on information from the oceans. This is particularly true in the tropical Atlantic, where improved forecasts of tropical cyclones offer direct benefits to many nation states. TAOS data support weather prediction through the provision of surface temperature data and boundary layer observations and through the validation of remote sensing observations over the ocean. Considering the tropical Atlantic, from the perspective of the Caribbean, central America and the United States, for example, it is clear that the most important interest lies with hurricane forecasts. The economic impact of hurricanes is growing amid concerns that there may be changes in the number or intensity of hurricanes associated with climate change. Hurricanes are one of the most hazardous events in the tropical and extratropical Atlantic, causing more than $2,000,000,000 in damage each year in the U.S. alone. Improving hurricane forecasts at both synoptic and climate time scales is a top priority for Atlantic climate and weather research, which require improved observations in the tropical Atlantic.

Changes in ocean-atmosphere conditions in the tropical Atlantic modify continental weather patterns and cause extreme events, having large societal impacts mainly in regions with low Human Development Index, such as northern South America, Central America and West Africa. Tropical Atlantic conditions have contributed to the decline in rainfall in the African Sahel and Brazilian Northeast, leading to catastrophic droughts and famines, human loss and economic and political destabilization. These disasters have required global mobilization of aid, have resulted in the displacement of populations, and contributed to global migration. Changes in tropical Atlantic conditions can cause floods and landslides in moist West African and South American climates, including the Amazon, leading to loss of life due to drowning and diseases, creating substantial economic losses in economies with limited resilience, as well as affecting biodiversity (Ta et al., 2016; Utida et al., 2019; Barange et al., 2018; SROCC, IPCC 2019)

Further, extreme winter hydroclimate events in mid-latitudes are often associated with atmospheric rivers (ARs), which are plumes of intense water vapor transport emanating from the tropics and Gulf of Mexico/West Caribbean region. In fact, a majority of extreme precipitation events that occurred along the western European seaboard, the Mediterranean, and the Middle East during boreal winter have been preceded by ARs - which also affect South Africa and South America. Therefore, improving the ability of forecast models to predict ARs will contribute to improved water resource management and flood/drought hazard assessment not only in the tropical Atlantic but throughout the North Atlantic and surrounding continents.

Shipping is another important beneficiary of an effective TAOS. Maritime transport carries over 80 percent of global trade by volume and more than 70 percent by value. The tropical Atlantic 'trade winds' route is one of the busiest open ocean shipping regions in the world. For example, more than 14,000 ships pass through the Panama Canal each year. There are increasing demands on services in support of maritime safety and marine environmental emergency response.

Operational ocean models are increasingly used in many different industries, providing services to fish harvesters, offshore oil operations and the transportation sector. Fisheries interests can also benefit from these models as can pollution dispersal management and the response to marine Search and Rescue (SAR). Around the tropical Atlantic basin, in western and central Africa, northeastern South America, the Caribbean, and mid-latitude regions, where weather conditions and climate are connected to the tropical Atlantic ocean, forecasts with reliable uncertainty estimates are of great value to society, allowing institutions and governments to plan actions to minimize risks, manage resources and increase prosperity and security. Human and economic losses that may be caused by adverse weather and climate events can be mitigated with early warning systems (e.g. famine, epidemics) and disaster preparedness. The potential benefits apply to all time scales, including weather prediction, seasonal forecasts, and long-term climate trends.

2.2 Ocean Health and Fisheries

Monitoring ocean variables relevant to biological productivity, marine biodiversity, the resilience of marine ecosystems, and the long-term health of these ecosystems is necessary as they support human life, livelihoods and sustainable development.

Fisheries in the tropical Atlantic account for approximately 10 million tons of seafood (from 87.2 million tons of global marine capture production; http://www.fao.org/fishery/statistics/global-capture-production/en)of economic benefit and employment of coastal communities. Most living resources are extracted in coastal and shelf areas and thus these ecosystems support the livelihoods of millions of people directly by providing income, employment and food. Almost ten million tons of seafood (from 87.2 million of global marine captures) were harvested in the Central and South Atlantic in 2016. The total number of fishers in Africa, Latin America and the Caribbean is eight million, although not all of them operate in the Atlantic. Coastal ecosystems also support income-generating activities including tourism, industry, diving, game fishing, and recreational fishing.

In West Africa in particular, distant water fishing fleets exert a major pressure on stocks but there is growing concern that climate change will add important and possibly irreversible pressure. The total landings exceed 9 million tons annually and yet this region is among the most vulnerable to potential climate-induced changes in fisheries (Allison et al., 2009). Indeed, pelagic fish are a major component in the region for food security (Ba et al. 2017). While there is some fishery-dependent data available, for example catch and bycatch data, it is important that fishery-independent and other marine environmental data be collected to track ecosystem health and climate influences on fishery productivity. The TAOS can enable the integration and coordination of a wide range of environmental data that can be made available to stakeholders and fisheries management in the region. Such environmental data is crucial for assessing ecosystem health and to enable the setting of effective fisheries policy. The Small Island States in the Caribbean are reliant on healthy ecosystems, particularly coral reefs, both for the tourism industry and to support small scale fisheries. The West African nations are particularly dependent on subsistence and small-scale fisheries supported by coastal upwelling systems.

Changes in circulation and mixing in the tropical Atlantic have direct impacts on the ventilation and oxygen supply to the ocean. In particular, in regions of already low levels of dissolved oxygen, changes in habitat (vertical compression) for large predatory fish have been documented. There is evidence for wide-spread declines in oxygen, which most forecasts suggest will likely worsen. Regionally the vertical supply of nutrients in upwelling regimes, and any change to this supply, will have direct impacts on commercially relevant fish stocks. This could very negatively impact the large marine ecosystems along the African coastlines (Canary, Guinea and Benguela Current Systems). Tracking these changes should enable fisheries managers to better avoid catastrophic outcomes and to respond to changes. Monitoring changes in carbon-dioxide is also important, as anthropogenically derived CO_2 continues to be taken up by the ocean, thereby influencing production cycles and ocean acidity. Tracking the changing ocean biogeochemical health will help in the development of adaptive fisheries management regimes.

2.3 Climate Variability and Change

Over the past century, the tropical Atlantic has experienced long-term warming of SST, increase in SSS, and rise of sea-level that are consistent with anthropogenic global warming. An important societally-relevant expression of these long-term changes is their impact on the frequency and intensity of extreme events. These range from hydrological extremes, such as short-term droughts and intervals of flooding, to oceanic “heat waves” and most pointedly, the change in the number and destructive potential of tropical cyclones. There is evidence that these long-term changes are also associated with changes in the marine environments, which have adversely impacted marine life and fisheries.

There are many active modes of tropical Atlantic variability that influence both regional and global climate. The Atlantic Niño and Atlantic Meridional Mode can have remote influences on climate variability in other ocean basins, including ENSO in the Pacific. Maintaining and enhancing observations in the tropical Atlantic that lead to better predictions of Atlantic Niño and Meridional modes can help improve ENSO prediction. Benguela Niños have large impacts on local fisheries and on rainfall variability over southwestern Africa. Understanding and potentially forecasting their development is thus of high socio-economic importance.

The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the Atlantic-wide ocean circulation that plays a key role in the global climate system through its poleward transport of heat. Significant changes in the strength of the AMOC are expected to lead to widespread climate changes particularly over the North Atlantic and adjacent continental regions. Monitoring AMOC variability in the tropical Atlantic as part of an evolving basin-wide AMOC monitoring system is therefore a key requirement for the TAOS.

Monitoring of the ocean state in the tropical Atlantic and its interaction with the atmosphere are necessary to understand both regional climate variability and long-term climate change. The provision of improved sub-seasonal to seasonal forecasts is one of the areas in which there will be growing demand for delivery information services, impacting problems such as water resource management, agriculture/aquaculture planning, forest fire mitigation, and investment and distribution of emergency response resources. This is particularly true, for example, for prediction of the West African Monsoon and seasonal variability in the intensity of the Atlantic hurricane season.

There has been significant progress in our understanding of tropical Atlantic coupled ocean-atmosphere variability that shapes climate and weather patterns. Improved modelling of the ocean's surface and sub-surface dynamics and effective coupling with atmospheric models provides important benefits to the skill of atmospheric seasonal forecasts, and information for monitoring of impacts on ecological systems. Monitoring changes in the tropical Atlantic Ocean over decades is critical to understanding a changing climate and related impacts such as sea level rise, and for informing future projections on the regional scale.

Seasonal-to-decadal predictions of SST are skillful over parts of the tropical Atlantic, and these contribute to useful predictions of continental climate and Atlantic tropical cyclone activity and provide potential for skillful predictions of the marine ecosystem. On longer time scales, the Atlantic Multidecadal SST Variability (AMV) has been connected with AMOC variability and has been shown to be predictable. However, more fundamental research is still required to understand how the Earth system responds on decadal timescales. Such long-term forecasts offer the opportunity for socio-economic planning that is aligned with regional investments and social policy considerations.

2.4 Research and Discovery

Monitoring of the ocean is most effective when integrated with scientific research and discovery because of the added value that scientific understanding brings to the quality of information available to societal users. The enthusiasm and commitment of scientists also helps to invigorate the monitoring programs. Bringing together research and monitoring benefits both activities and yields a more effective ocean observing system.

While there is general agreement that exchanges of heat and other properties at large scales are most important in the climate system, there is growing evidence that processes that occur at much smaller scales (10-100 km) may also play an important role. It is therefore important to embed scientific research projects within larger scale monitoring efforts to address these smaller-scale dynamical processes. The data and models upon which we presently rely are built upon the understanding that we have of key ocean processes. New models and new interpretations will rely upon new research and discoveries in the tropical Atlantic. Research into fundamental processes such as air-sea fluxes and diurnal variability in the upper ocean will be essential for improving the model physics in support of fully coupled forecast systems. The ultimate goal of this research will be to apply new understanding of marine systems and climate variability not only to advance scientific understanding, but also to enhance the societal services that can be provided, to enhance operational services, and to improve the ocean observations themselves.

While new data and new understanding of ocean dynamics is necessary to meet societal requirements for ocean information, it is also important that we work to improve our numerical models of the physical and biogeochemical ocean and the coupling of the oceans with the atmosphere. Developments in coupled forecasting systems have led to forecasting of storm tracks over the ocean and coastal regions with greater accuracy, facilitating the generation of warnings and impact-based forecasts for affected areas. The integration of Argo float data from the global ocean has greatly improved the quality of the 7-10-day weather forecasts upon which we now rely. Ensemble-based forecast systems provide risk and scenario-based information to support decision-making. Coupled ocean-atmosphere models of different timescales place new demands on the upper ocean observing system, data delivery, and the science underpinning the models.

2.5 Summary

There are many ways in which the tropical Atlantic is relevant to those who live around the Atlantic Ocean, not only those in the tropics but also for those who reside at great distances from it. An effective Tropical Atlantic Observing System (TAOS) is necessary to meet the needs of society. The data from a TAOS will most directly benefit those countries neighboring the tropical Atlantic, helping to improve societal management of coastal fisheries and ecosystems, tropical storms and extreme events, and transportation and economic activities. It will also serve many who live great distances from the tropical Atlantic, including, for example, coastal communities along the U.S. eastern seaboard who will benefit from improved hurricane forecasts. The TAOS will also lead to improved knowledge of climate dynamics and the role that this region is playing in the changing global climate system. The TAOS will contribute to the Global Ocean Observing System (GOOS) and benefit from global sharing of environmental data and the development of new information services. A coordinated and collaborative partnership built upon the principles outlined here will foster the development of a TAOS that can better meet the future needs of society.

3. Key Science and Operational Drivers for the TAOS

Sustained observations of the thermal, dynamical, chemical and biological state of the Tropical Atlantic Ocean are required to meet societal needs for global, regional and local information. To consider in more detail the observational needs, a set of "key science and operational drivers" for the TAOS was developed to link the observational requirements of the TAOS to the broad societal themes described in Chapter 2. The review committee considered a number of different ways to organize these "key drivers" into a limited yet comprehensive set of topics, and eventually settled on the following list:

1. Dynamics of Tropical Atlantic Variability
2. Climate Impacts of Tropical Atlantic Variability
3. The AMOC in the Tropical Atlantic
4. The Carbon System in the Tropical Atlantic
5. Biogeochemical Processes in the Tropical Atlantic
6. Ecosystem Dynamics and Fisheries
7. Ocean Heat Content and Sea Level Rise
8. Improved predictions on subseasonal to decadal time scales
9. Long-term climate change and impacts

In this chapter, each of these key drivers and their societal relevance is briefly described. Appendix 1 contains a more comprehensive discussion of each driver including the state of knowledge on each topic and potential gaps in information or data related to each one. To save space, references are not included in the following summaries and the reader is referred to the corresponding sections of Appendix 1 for references to cited literature and supporting figures.

3.1 Dynamics of Tropical Atlantic Variability

The interannual climatic variability of the tropical Atlantic Ocean is typically classified according to two main modes, a “zonal” mode (commonly termed "Atlantic Niño") and a "meridional" mode (sometimes referred to as the "dipole" mode).

The Atlantic zonal mode (AZM), representing approximately 20 to 30% of the total interannual variance of tropical Atlantic SST and precipitation variability, is similar to the El Niño – Southern oscillation (ENSO) in the Pacific. In its canonical form, it is associated with equatorial oceanic waves and a dynamical thermocline-wind-SST feedback (Bjerknes feedback), although it is more strongly damped in the Atlantic than in the Pacific. Surface temperature (SST) anomalies in the Atlantic cold tongue region associated with the Atlantic zonal mode strongly affect the timing and intensity of the West African Monsoon. A warm phase of the Atlantic Niño displaces the Intertropical Convergence Zone (ITCZ) to the south, decreasing the land-sea pressure gradient and causing droughts over the Sahel and excess rainfall over the Gulf of Guinea.

The Atlantic meridional mode (AMM), also representing approximately 20 to 30% of the total interannual variance, is characterized by an inter-hemispherical gradient of SST and associated surface wind anomalies in both hemispheres between approximately 25°N-5°N and 5°N-20°S, on seasonal, interannual and even multi-year time scales. It is sustained or amplified by an ocean-atmosphere thermodynamic coupling known as the Wind-Evaporation-SST feedback (WES), but the processes leading to a change in its phase are not well understood and may involve ocean advective processes. The inter-hemispherical anomalies of SST significantly affect the position and the intensity of the ITCZ and thus exert a considerable influence on precipitation over adjacent continental areas, such as the Brazilian Northeast (NEB) and the African Sahel. The brief rainy season over the NEB occurs in austral fall (March to May), when the ITCZ migrates southward. During the years in which the meridional SST gradient is negative from March to May, i.e., when there are cold SST anomalies in the tropical North Atlantic and warm anomalies in the tropical South Atlantic, the ITCZ moves further southward, bringing rainfall to the NEB. Severe droughts occur when the tropical North Atlantic is anomalously warm during this season, preventing the displacement of the ITCZ.

The meridional mode also has significant impacts in the Amazon region, where severe droughts have been associated with exceptionally warm waters in the tropical North Atlantic. Conversely, extreme floods can occur in years when the tropical South Atlantic waters are anomalously warmer than their northern counterparts, i.e., during a negative phase of the AMM. Interannual variability of the SST in the tropical North Atlantic Ocean also influences precipitation over the West Indies and the southeastern region of the USA by modulating the frequency and intensity of tropical cyclones.

Both the AZM and AMM can also be remotely influenced by different tropical and extratropical teleconnection patterns. The main source of variability comes from ENSO, but other teleconnections can also affect the TAV, such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Variability (AMV).

Another main mode of TAV is the Benguela Niño, which causes periodic warming in the SE Atlantic along the Angolan coast and within the Benguela upwelling system. They are commonly associated with Atlantic Niños forced by wind stress changes in the western equatorial Atlantic, which generate equatorial Kelvin waves propagating eastward along the Equator and then southward along the African coast as coastally trapped waves. Benguela Niños have large impacts on local fisheries and on rainfall variability over southwestern Africa. Understanding and potentially forecasting their development is thus of high socio-economic importance.

The tropical Atlantic is also marked by strong intraseasonal variability in both the atmosphere and ocean. Tropical Instability Waves (TIWs) are a prominent feature of the oceanic intraseasonal variability west of about 10°W. They are generated by barotropic and baroclinic instabilities of the wind-driven zonal flow, which intensify during boreal summer (June-August) concurrently with the development of the equatorial Atlantic cold-tongue. Farther to the east, strong quasi-biweekly variability (10-20 days) of SST occurs in the equatorial region east of 10°W that appears to be linked to forced Yanai (mixed Rossby-gravity) waves. The dynamics underlying these fluctuations are not yet fully understood, but recent studies have indicated that they may involve localized air-sea coupling triggered by a quasi-biweekly variability of the South Atlantic subtropical high. Both TIWs and the quasi-biweekly oscillations in the eastern tropical Atlantic cause large modulations of SST along the northern edge of the equatorial cold tongue and in the Gulf of Guinea.

The Madden-Julian Oscillation (MJO), with periods between 30 and 90 days, is the dominant mode of intraseasonal variability in the global tropical atmosphere and can exert a significant impact on warm season climate variability in the tropical Atlantic. The MJO affects the West African Monsoon and associated convection, rain, winds and African easterly wave activity, and explains up to 30% of the 30–90-day precipitation variance in the West African Monsoon region. A significant MJO-related modulation on tropical cyclones has also been identified over the western part of the Atlantic, including the Gulf of Mexico and Caribbean Sea and over the Atlantic main development region (MDR).

Societal benefits in areas around the tropical Atlantic on intraseasonal to interannual time scales rely to a large degree on predictability of TAV, especially that of SST and related precipitation patterns, including influences of all the above modes of variability as well as remote influences (e.g., ENSO). Prediction skill in the TA (discussed further in section 3.8) remains relatively low, especially for the zonal mode, due to a number of factors, including the large importance of internal atmospheric dynamics, the existence of multiple mechanisms of comparable importance to the Bjerknes feedback, the variable TAV response to ENSO, and large model errors. A sustained and integrated TAOS is needed to investigate the interplay of processes that govern the development of TAV modes in individual years and for specific events, and to provide direct observations against which model results can be compared and validated.

3.2 Climate Impacts of Tropical Atlantic Variability

The climate impacts of TAV are substantial, affecting the lives and livelihoods of hundreds of millions of people in adjacent continents and beyond. Besides the regional climate impacts of the Atlantic zonal and meridional modes noted above, the tropical Atlantic has an influence on other tropical oceans, which themselves have widespread climate influence. As such, variability that is intrinsically native to the tropical Atlantic can influence climate widely, via, for example, its influence on the development of El Niño events. Warming of the equatorial Atlantic region often appears together with cooling in the Tropical Pacific and a warming in the Indian Ocean, and vice versa for a cooling in the equatorial Atlantic. A mechanism involving alteration of atmospheric convection over the western equatorial Atlantic and subsequent changes in the Walker circulation and tropical Pacific Ocean surface wind stress is also apparent.

In addition to its regional tropical Atlantic impacts, the connection between TAV and Central and North American climates is also statistically significant, particularly on multi-year to multi-decadal time scales. An important societal impact of the multidecadal variation of tropical Atlantic SST in North America is associated with the occurrence of drought in the US Southwest and northern Mexico, through the influence that these SST variations have on the intensity of the North Atlantic subtropical high. When tropical North Atlantic SSTs are warmer than normal, the anticyclone weakens, and this correspondingly weakens the transport of Gulf of Mexico moisture into the Great Plains and southwestern US as well as the uplift associated with the southerly flow on the western flank of the anticyclone. The result is reduced precipitation over regions that lie west of the Mississippi River. While the major driver of interannual to decadal precipitation variability over the western US is ENSO, the Atlantic modulates the intensity of the ENSO impact. The most intense droughts in the western US were the Dust Bowl drought of the 1930s and the Texas drought of the 1950s that was also felt in the Southwest and the Plains. These droughts occurred in decades during which El Niños (which usually bring a wet winter climate to the US southern tier states) were absent or weak and SSTs in the northern tropical Atlantic were warmer than normal.

Equally important to its impact on seasonal and multi-year precipitation over the US mainland, tropical Atlantic SST significantly influences tropical storm and hurricane activity in the entire Atlantic basin. The intensity of these storms, in terms of overall destructive potential (a function of storm wind speed and storm duration) is directly related to the average seasonal temperature of the water in the northern tropical Atlantic. Warmer than normal tropical Atlantic SSTs compete with the impact of warm SSTs in the eastern equatorial Pacific; El Niños, with their warmer than normal eastern tropical Pacific SSTs, have a restraining effect on the activity of Atlantic tropical cyclones through forcing increased vertical wind shear over the tropical Atlantic.

The tropical Atlantic is also important as a driver of climate impacts in Europe. Tropical convective events can excite atmospheric Rossby waves that propagate into mid-latitudes, buckling the jet stream and causing changes in surface weather patterns. Particular high-impact cases include the winter of 2013-14, which was the wettest winter on record in the United Kingdom and brought high rainfall and storms widely across western Europe, leading to severe flooding and damage. This was linked to a Rossby wave train emanating from the tropical Atlantic forced by unusual patterns of tropical convection. Further examples of extreme winter events linked to conditions in the tropical Atlantic include flooding in early winter in Northwest Europe in 2015 and incidences of heat waves and drought conditions in summer in Central Europe.

Therefore, besides the regional impacts of tropical Atlantic variability and its important role in tropical teleconnections, it is clear that a well-observed tropical Atlantic is necessary if we are to understand and, ultimately, make accurate predictions of impacts and risks for seasonal weather in mid-latitudes.

3.3 The AMOC in the Tropical Atlantic

The Atlantic Meridional Overturning Circulation (AMOC) plays an important role in the global climate system through its large transport of heat northward across the equator. Significant changes in the strength of the AMOC are expected to lead to widespread climate changes particularly over the northern hemisphere Atlantic and adjacent continental regions.

The basinwide SST response to a significant reduction in the AMOC - typically forced in models by "fresh water hosing" (the addition of large volumes of freshwater to the subpolar North Atlantic leading to a suppression of deep convection) - is an interhemispheric dipole pattern with pronounced cooling in the northern hemisphere and more moderate warming in the equatorial and South Atlantic. The anomaly in cross-equatorial SST (cooler water north of the equator and warmer water south of the equator) in turn leads to a southward shift of the ITCZ and associated precipitation anomalies over the tropics that are similar to patterns associated with other interannual forcing mechanisms, such as changes in the Atlantic Meridional Mode (AMM) or NAO or ENSO- related atmospheric teleconnections. The dynamics underlying this response have been linked to the so-called "equatorial buffer" mechanism, wherein AMOC changes at high latitudes are rapidly communicated through the North Atlantic by ocean wave dynamics but lag in the southern hemisphere, leading to a mismatch in the strength of the AMOC in the two hemispheres and a corresponding divergence of meridional heat flux across the equator.

In addition to the effects of high latitude buoyancy forcing and basinwide winds on the AMOC, AMOC variability in the tropics can also be remotely forced from the south by variability in Agulhas leakage to the Atlantic from the Indian Ocean. Recent studies suggest that the Agulhas leakage has increased by nearly 50% from the 1970's to early 2000's due to the poleward shift and increase in strength of the southern hemisphere westerlies, and that the increased salt transport to the South Atlantic via this increased Agulhas leakage has led to an overall salinification of the South Atlantic subtropics. This trend in Agulhas leakage is expected to continue and possibly intensify in the 21st century due to anthropogenic forcing. As these saltier waters reach the North Atlantic in the upper limb of the AMOC and eventually propagate to the deep water formation regions, they could help to sustain the AMOC against its projected decline due to global warming. The increased Agulhas leakage may have also contributed to the overall warming of the tropical Atlantic in the past several decades, by supplying warmer (as well as saltier) waters to the tropical thermocline that eventually upwell along the equator.

A significant change in the AMOC can also be expected to impact the structure of the shallow overturning cells that link the tropics and subtropics – the so-called "subtropical cells" (STCs) - that connect the subduction zones of the eastern, subtropical oceans with upwelling zones in the tropics. The present STC pattern in the Atlantic, in which the southern STC cell is dominant over the northern cell, is believed to be a direct result of the AMOC, which cuts off most of the supply of thermocline waters to the equator from the northern subtropics. A decrease in the MOC would lead to a greater symmetry of the cells and an increase in northern hemisphere waters supplied to the equatorial thermocline. Model studies suggest that the increased warm advection from the warmer and saltier northern STC cell would then result in an accelerated rise in equatorial Atlantic SST and subsequent impacts on atmospheric processes, including in particular an intensification of the West African monsoon.

Therefore, even though remote from the probable forcing regions of AMOC variability, the tropical Atlantic is in fact a focal point for impacts of AMOC variability due to the equatorial buffer mechanism and likely AMOC/STC interactions, and sufficiently large changes in the strength of the AMOC can be expected to have important consequences for tropical Atlantic SST.

3.4 The Carbon System in the Tropical Atlantic

The ocean carbon cycle is complex and dependent on a range of inorganic and organic chemical and biological processes. Although carbon is not a limiting constituent in the ocean for biology, the carbon chemistry determines the pH and alkalinity of the ocean, influencing the saturation state of calcium carbonate which is essential for the large proportion of biological life that forms calcium carbonate skeletons.

The oceans serve as an important sink for atmospheric carbon dioxide, and it is currently estimated that the global oceans take up nearly 25% of the anthropogenic carbon that is added to the atmosphere on an annual basis. This carbon is stored in the interior ocean, the residence time depending on the depth at which it is stored. While the global oceans are a net sink for atmospheric CO_2, the tropical Atlantic is an area of general outgassing of CO_2 from the ocean. It is the second largest source, after the tropical Pacific, of oceanic CO_2 to the atmosphere, releasing about 0.10 Pg C yr^{-1} in the 18◦S -18◦N region. However, the CO_2 source from the tropical Atlantic has significant temporal and spatial variability, and this can have a substantial effect on the global carbon budget on annual to interannual time-scales.

The increasing dissolved inorganic carbon (DIC) concentration due to input of anthropogenic carbon leads to reduction of the pH value – ocean acidification. This is potentially a large issue for marine organisms, in particular those that have calcium carbonate structures, such as corals. Ocean acidification leads to reduced values of the calcium carbonate saturation state, and in certain areas of the tropical Atlantic where it is already relatively low - in particular within the eastern oxygen minimum zones - further decreases in pH could have a negative effect on calcium carbonate building organisms. As these oxygen minimum zones expand over time due to the impacts of global warming, these regions of the tropical Atlantic may become particularly sensitive to ocean acidification.

The key measurements of the carbon system that are needed are the surface pCO_2 (for the air sea CO_2 flux) and water column measurements of DIC, total alkalinity and pH (for ocean carbon inventory and acidification). To understand the changes in the carbon system occurring in the tropical Atlantic and their role in regional ecosystems and global CO_2 uptake, it will be important to continue, and improve, measurements of these ocean carbon parameters as part of a sustained TAOS.

3.5 Biogeochemical Processes in the Tropical Atlantic

In addition to the carbon system, important biogeochemical processes in the tropical Atlantic include those that control the dissolved oxygen and nutrient distributions. Dissolved oxygen (O_2) is fundamental to all aerobic life and thus plays a major role in marine microbial ecology and the biogeochemical cycling of elements such as carbon, nitrogen, phosphorus and sulphur. Time series data over the past 50 years show declining O_2 in many regions of the world's oceans, and a significant increase in the extent of oxygen minimum zones (OMZs) in the eastern tropical Atlantic. The shallower parts of the OMZs overlap with the euphotic zone and hence have a direct impact on ecosystems, carbon export, nutrient recycling, and the release of CO_2 and other climate-relevant trace gases, such as nitrous oxide, to the atmosphere.

Nutrients are delivered to the surface layers of the tropical Atlantic through upwelling and vertical mixing, riverine inputs, and dust deposition from the African continent. The riverine input is particularly important in the tropical Atlantic since it receives almost 25% of the global riverine discharge via three major rivers (the Amazon, Orinoco, and Congo), leading to high productivity in the nearby oceanic regions with implications for carbon and nutrient cycling. The major upwelling regions, including the central and eastern equatorial Atlantic and the coastal upwelling zones in the east (the Canary, Guinea and Benguela upwelling systems) also show high productivity and support some of the world's most important fisheries.

Considering the importance of dissolved oxygen for marine life, monitoring changes in dissolved oxygen, the physical, biological and biogeochemical factors which influence dissolved oxygen concentrations, and the biogeochemical processes affected by decreasing dissolved oxygen, is crucial. Understanding the physical and biogeochemical processes that control biological productivity in the eastern upwelling zones is also important to improve ecosystem models for these regions and to constrain local and global carbon budgets.

Sustained measurements and improved geographical coverage of key biogeochemical variables including dissolved oxygen, transient tracers and nutrients are needed to understand the ocean mixing and ventilation processes that influence oxygen concentrations, and the impact of low oxygen concentrations on nutrient concentrations, particularly on nitrogen supply to the surface ocean. Measurements of particulate matter, dissolved organic carbon and microbe biomass and diversity are also needed to develop a more quantitative understanding of the mechanisms linking dissolved oxygen concentration, remineralization efficiency and microbial community structure. The tropical Atlantic Ocean has also been shown to be an important area for N_2O fluxes to the atmosphere, and further effort toward quantifying this flux will be important as N_2O is a potent greenhouse gas.

3.6 Ecosystem Dynamics and Fisheries

Most living resources extracted from the TA are in coastal and shelf areas and thus these ecosystems support the livelihoods of millions of people directly by providing income, employment and food through artisanal and industrial fishing. Currently there are about 8 million fishers in Africa, Latin America and the Caribbean, although not all of them are operating in the Atlantic. During 2016, almost ten million tons of seafood were harvested in the Central and South Atlantic, accounting for more than 10 percent of the global marine capture. In addition, coastal ecosystems support income-generating activities including tourism, industry, diving, and game fishing.

Together, fishing and changing environmental conditions (e.g., chemical contamination, hypoxia, toxic algal blooms, ocean warming and acidification) are placing wild fish stocks under unprecedented stress.

In the tropical Atlantic as well as elsewhere, marine ecosystem management is confronted with a trade-off between conservation and exploitation, often to the disadvantage of conservation targets. Modern fisheries management is increasingly transitioning from traditional single species management of capture fisheries to an ecosystem-based approach to fisheries management, in which fishing is managed in the context of interactions of fish stocks with other organisms (prey, predators, and competitors) and their environment. Successful application of this approach requires adequate and sustained monitoring of ecosystem states and multiple pressures, as well as rapid detection and timely predictions of changes in ecosystem states and how they may affect fisheries.

The most basic observational needs in relation to management of living resources is the assessment of the fisheries themselves, including fishing capacity, fishing effort, and catch. To assess a given stock, additional information on length, weight and age of caught individuals of a given species and how much of each length, weight or age are caught, is needed. In some countries, fisheries independent data is collected through trawl and hydroacoustic surveys on the adult and juvenile individuals of a stock or egg and larvae surveys on the early life stages of a stock. However, to understand the long term development of stocks, additional information on ecosystems is needed, including phytoplankton, zooplankton, micronekton, and benthic organisms, as well as physical changes in the marine environments.

To get information on population dynamics, regular annual surveys are necessary to collect information on the development of a cohort in a given stock, estimate migration, growth and mortality through tagging studies, and perform nested studies on the influence of environmental variables on life history parameters. Many of these studies are normally not carried out regularly and often done without sufficient financial support to effectively monitor the population dynamics of exploited fish species and to quantify trends in pressures, states, and impacts. This remains a challenging problem for managing fisheries and other living marine resources, especially in developing countries with limited resources.

While there are a number of previous and/or active programs providing data for fisheries or ecosystem management within the tropical Atlantic (including the highly successful AWA project, EAF Nansen program along the west African coast, the Benguela Current Large Marine Ecosystem Program, the International Commission for the Conservation of Atlantic Tunas catch and tagging studies, and the hydroacoustic Ocean Tracking Network), no basin-wide, integrated observation program exists for the tropical Atlantic with respect to biological and fisheries data and to relate physical, biogeochemical and ecological components of the marine ecosystems. Improvements in the observing capacity for fisheries and ecosystems will require better use of existing data, extending surveys for commercial and endangered species, and integration in a larger observation system that considers the requirements of different user groups, decision makers, society, the private sector and scientific communities.

3.7 Ocean Heat Content and Sea Level Rise

Oceanic heat content is an important quantity for understanding and predicting climate variability and change. On a global basis, the ocean is the greatest reservoir of heat within the climate system and it is by far the greatest sink of energy input from anthropogenic (i.e., greenhouse gas and aerosol) forcing. This oceanic absorption of heat mitigates the impact of global warming on atmospheric temperatures but at the same time delays the equilibrium response to the earth’s energy imbalance by decades because of the ocean’s thermal inertia. Thus, knowing where heat is entering and exiting the ocean across the air-sea interface, quantifying the rate at which heat is stored in the ocean, and determining the pathways by which it is transported, are critical from a climate perspective.

The increased storage of heat in the ocean also contributes to sea level rise through thermal (steric) expansion of sea water, which accounts for roughly one third to one half of the observed global sea level rise over the past few decades. Global mean sea level is currently rising and even accelerating.

Most of the heat taken up by the oceans due to anthropogenic forcing has occurred in the Southern Ocean and secondarily in the North Atlantic. The pattern of oceanic heat stored is similar, but not identical to, the pattern of oceanic heat uptake because of the role of circulation in transporting heat to other parts of the world ocean. Thus, all ocean basins have shown significant increases in heat content, penetrating to greater depths with time, since at least the 1990s. The greatest percentage of this heat is stored in the upper 2000 m but a significant amount of heat is also accumulating at greater abyssal depths as well.

SST, heat content in the upper 700 m, and sea level all trended significantly upward in the tropical Atlantic between 30°N and 20°S since the 1960s. The physical mechanisms accounting for these trends however are not well understood. While SST and heat content have risen, so has evaporative cooling, suggesting surface fluxes are responding to, rather than causing, warming of the TA over the past several decades. Likewise, trade wind stress has increased in the TA over the same period, which would be expected to cool the eastern equatorial Atlantic via intensified coastal and equatorial upwelling, but that has not been observed. Clearly, some nonlocal processes must be important in causing these trends, perhaps related to changes in the AMOC.

The impact of a changing heat content in the tropical Atlantic is multiple. At a most basic level, changes in heat content are reflected in SST, with the magnitude of the SST variations depending on the depth over which heat is stored. The Atlantic Meridional Mode results from the storage of heat in the surface mixed layer, and its maintenance by the WES feedback leads to interannual to decadal time scale variability in tropical Atlantic SST and related climate impacts. It is also known that the intensity of hurricanes is strongly influenced by the storage of heat above the 26°C isotherm, referred to as the tropical cyclone heat potential.

Along the equator, the evolution of the Atlantic Niño or zonal mode is dynamically linked to variations in upper ocean heat content through recharge oscillator processes similar to those that operate in the tropical Pacific related to ENSO. Sea surface temperature variations in the Atlantic cold tongue region associated with Atlantic Niños in turn affect the west African monsoon and Sahel drought. Heat content variations along the equator lead SSTs by 4-5 months, thus providing a source of predictability not only for Atlantic Niños but for their impacts on regional rainfall.

There is great uncertainty in our understanding of relevant oceanic and atmospheric processes that affect air-sea exchanges of heat, ocean heat content and its transport, and how ocean heat uptake affects SST and sea level rise across the broad range of time and space scales relevant to climate. TAOS provides an observational underpinning that enables progress on these issues.

Critical are the satellite missions that provide multi-decadal, continuous records of key variables such as surface height from altimetry, surface wind speed and direction from scatterometry, SST from spaceborne microwave and infrared sensors, surface salinity and precipitation, and other related measurements such as ocean color. Sustained in situ measurements are likewise critical for measurements of upper ocean heat content, water mass variability, air-sea heat fluxes, and ocean circulation.

The suite of measurement systems that presently make up the sustained in situ TAOS (Argo floats, drifters, moorings, island and coastal tide gauge stations, ship-of-opportunity measurements and repeat hydrography) have provided these observations routinely in a generally cost-effective way. TAOS has moreover evolved with time, first with the establishment of PIRATA in the mid-1990s and then with

Argo in the mid-2000s. Introducing newer technologies that are fit for purpose and rigorously field tested, such as gliders and deep Argo floats, are logical next steps. Ensuring that collection of data by these in situ systems, in combination with space-based missions, resolves to the maximum extent possible the space and time scales relevant to climate variability and change in the tropical Atlantic, is a significant challenge in overall system optimization.

3.8 Improved predictions on subseasonal to decadal time scales

3.8.1 Weather forecasts

There is clear and growing demand for reliable weather and climate forecasts at different time scales for a variety of societal applications. This is true around the tropical Atlantic basin, in western and central Africa, northeastern South America, the Caribbean, and mid-latitude regions where weather conditions and climate are connected to the tropical Atlantic. Ocean forecasts with reliable uncertainty estimates are of great value to society, allowing institutions and governments to plan actions to minimize risks, manage resources and increase prosperity and security. Human and economic losses that may be caused by adverse weather and climate events can be mitigated with early warning systems (e.g. famine, epidemics) and disaster preparedness. Equally, adequate planning can aid the exploitation of favorable climate conditions.

Given the coupled nature of the ocean-atmosphere system, the ocean plays an active role in the forecasting systems at all lead-times. The WMO Statement of guidance for Global Numerical Weather Prediction[1] (NWP) clearly states the importance of ocean observations, underlying that requirements of global NWP are becoming more similar to those of seasonal and inter-annual forecasting.

Ocean in situ observations, namely gathered from moored and drifting buoys, in the tropical Atlantic basin do appear to have a real impact on global numerical weather forecast at 24 hours, as shown by their relative weight in the assimilation process compared to other observing systems, including satellites. Availability of long-term observations is also a critical need for weather forecasts, especially for enabling reanalysis and reforecasts that permit the extraction of extremes.

Forecast Sensitivity to Observation (FSO) studies for the PIRATA buoys in both the ECMWF and Météo-France global weather forecast suites show that, although the number of PIRATA sea surface observations is small compared to those derived from satellites, the contribution of these sea-surface observations to improving the forecasts (by reduction of the 24-hour forecast error via the data assimilation) is much larger than the proportion of these observations to the total number of data.

The tropical Atlantic Ocean plays a critical role for weather prediction in all the surrounding regions, at time scales ranging from days to months ahead. This brings a clear need for long term sustained monitoring of the tropical Atlantic Ocean. Modelling and initializing the state and complexity of the tropical Atlantic Ocean is especially challenging.

3.8.2 Tropical cyclones and extreme events

Hurricanes are the most common and regular extreme weather events occurring across the Atlantic Basin, causing more damage than all other storms combined. Each year hurricanes cause more than $2 billion in damage to just the U.S.A. alone and that number is expected to grow. As such, improving

[1] http://www.wmo.int/pages/prog/www/OSY/SOG/SoG-Global-NWP.pdf

hurricane forecasts at both synoptic and climate time-scales is a top priority of Atlantic climate and weather research.

Forecasts for Atlantic Basin tropical cyclones (TCs) have continued to improve in recent decades, from climate scale (subseasonal-to-decadal) to synoptic storm scale (hour-to-days) in particular during the past two decades. Improvements in global weather models, in the use of multi-model ensembles, and hurricane specific research continue to drive these forecast improvements. However, despite the significant advancements in track forecasts for Atlantic tropical cyclones, improvement in intensity forecasts of individual storms on synoptic time scales have been only modest. In particular, cases of rapid intensification (RI) are the most challenging intensity forecasts for the National Hurricane Centre (NHC) and other forecasters, and produce the largest forecast errors.

Recent evidence suggests that improved ocean observations and ocean modeling may provide the necessary input for atmospheric models to more accurately simulate air-sea interaction, and lead to improved intensification trends.

The past decades have also witnessed considerable progress in advancing the capability for predicting hurricanes and TCs from subseasonal to climate time scales, particularly at seasonal time scales. Such predictability is related to environmental factors that are strongly influenced by large-scale climate modes in the tropics, such as the Madden–Julian Oscillation, ENSO, AMM and AMO, some of which are predictable on seasonal-to-decadal time scales. Recent studies show that skillful TC forecasts at seasonal or longer time scales lie in the evolution of tropical SST patterns and the state of the AMOC in the high-latitude North Atlantic.

Hurricanes are not the only extreme climate phenomenon within the Atlantic sector. Extreme hydroclimate events are often associated with atmospheric rivers (ARs), which are plumes of intense water vapor transport emanating from the tropics. In fact, a majority of extreme precipitation events occurring along the western European seaboard during boreal winter are preceded by ARs via the North Atlantic Corridor connecting the Gulf of Mexico with western Europe. They also contribute to drought occurrence in the Parana, the Iberian Peninsula, and the Mediterranean coast of Europe, when they are inactive over the Atlantic. Therefore, improving the ability of climate models to predict ARs will have important implications for water resource management and flood/drought hazard assessment, and should also be a top priority for Atlantic Basin climate research.

3.8.3 Seasonal to decadal prediction

Predictability of tropical Atlantic climate on seasonal to decadal timescales arises mainly from dynamics within the Atlantic (e.g., Atlantic Niño, AMM, and AMV), remote forcing from the Pacific associated with ENSO, and external forcing of the climate system (increases in greenhouse gases and changes in aerosol loadings). Current state-of-the-art climate prediction systems represent these sources of predictability to a certain extent. However, these models also exhibit climatological biases in the tropical Atlantic that are 2 to 3 times larger in magnitude than observed variability. These model biases are the largest of all tropical oceans.

These prediction systems also exhibit the least seasonal predictive skill in the tropical Atlantic of all the tropical basins. The greatest skill in predicting SST is found over the northern tropical Atlantic where correlations exceed 0.5 at six-months lead. This is related mainly to the ENSO teleconnection, but also results in part from the strong long-term warming trend in the tropical Atlantic. There is little skill in predicting SST anomalies in the southern tropical Atlantic at these time scales, however. This is related to poor skill in predicting the Atlantic Niño that peaks in boreal summer and dominates interannual variability in this region. This poor skill is also likely related to the large model biases. Nevertheless, analysis of model simulations and observations have shown that tropical SST provides quite a high level of predictability of rainy season rainfall over northeast Brazil and West Africa. Seasonal rainfall predictions represent a very important economic benefit to farming, flood and drought resilience, and disease mitigation in the tropical Atlantic.

Near-term climate prediction (also called decadal prediction) is in a pre-operational phase, being a relatively new field with the first publications around 10 years ago. The near-term predictions performed for the IPCC AR5 Decadal Climate Prediction Project have shown that SST variations over large parts of the North Atlantic can be predicted up to a decade in advance. This is associated with skill in predicting the AMV and is derived both from initial conditions and external forcing.

Climate based predictions of marine ecosystems have great potential as aids to fisheries management. The marine ecosystem is influenced by both anthropogenic (e.g., fisheries and pollution) and environmental factors. Coastal variability off Northwest and Southwest Africa are two examples of predictable environmental factors that can potentially lead to skillful ecosystem predictions.

It is now well recognized that the tropical Atlantic influences tropical Pacific interannual and decadal variability. Tropical Atlantic biases impact these teleconnections and need to be reduced in order to capture the Atlantic contribution to predictability in the Pacific sector and globally. The results summarized here further highlight the need to improve prediction skill in the tropical Atlantic.

3.9 Long-term climate change and impacts

The tropical Atlantic climate has undergone long-term changes that are projected to accelerate under future global warming. The impact of these changes extends from the marine ecosystem to continental climate. The TAOS is key to monitoring and understanding these changes and reducing uncertainties in climate projections for the region.

3.9.1 Long-term climate changes

Historical reconstructions of in-situ measurements of SST indicate that over the last century the tropical Atlantic Ocean has warmed by almost 1°C with the strongest warming along the African coast and South Atlantic. This warming rate is close to the global average increase in SST and is largely consistent with climate model simulations.

However, this warming has not been uniform in time. Observed variations coincide with trends in global mean temperature, but also with large-scale AMV fluctuations in North Atlantic SST. The cause of the multi-decadal trends is still under debate and includes influences from both anthropogenic and natural causes.

Sea surface salinity (SSS) is a key indicator of climate change, as it is largely controlled by changes in the hydrological cycle. SSS changes impact upper ocean stratification and can have implications for basin wide circulation. Historical observations since 1950 show SSS in the tropical Atlantic has increased faster than in other tropical basins. These changes can be due to climate change, internal climate variability and variations in continental precipitation.

Models and theory indicate that changes in the AMOC could explain some of the long-term trends and multi-decadal changes. Direct observations of AMOC are insufficient to identify such relations, and there are large-uncertainties in ocean reanalysis and long-term ocean model hindcasts on these timescales.

Sea level in the tropical Atlantic has undergone a long-term rise superimposed on multi-decadal shifts. However, our understanding of sea level rise over the region during the last century is hampered by severely limited tide gauge records.

3.9.2 Climatic Impacts

The long-term changes in the tropical Atlantic Ocean have been associated with changes in marine ecosystems and coastline and continental climates on both sides of the basin. It has also been argued that tropical Atlantic changes influenced the tropical Pacific Ocean. Long-term observations of African and South American tropical climates are sparse and have been declining further recently. This makes proper assessment and attribution of changes over the historical period difficult. The available observations show that over the period from 1901 to 2010, land surface temperatures over West Africa and Brazil have warmed on average by more than 1°C, which is larger than the global mean increase of around 0.9°C.

Superimposed on these long-term trends are multi-decadal variations in temperature and rainfall over West Africa, North East Brazil, and the Caribbean region. These decadal to multi-decadal variations coincide with those of the tropical Atlantic Ocean. They also modulate the impact of ENSO on the continent.

Long-term observations of the marine ecosystem are even more sparse, and this makes the detection and attribution of trends difficult. However, recent studies on stock assessment along the African coast show that the warming of SST off Northwest Africa appears to have driven a northward shift in key small pelagic fish stocks over the region.

The last 35 years have seen an increase in marine heatwaves in the tropical North Atlantic that is expected to increase further in response to global warming. Marine heatwaves are a major stressor on marine organisms, including impacts on coral bleaching, disease outbreaks, and forced migration. The responses of marine organisms and biogeochemical cycles to climate change remain largely unknown.

Long-term changes in the tropical Atlantic climate can potentially affect the patterns of interannual variability and associated teleconnections (Sec. 3.2 and 3.3). Lack of comprehensive long-term observations and large biases in climate models (Sec. 3.8) mean that only a few studies have addressed this. These have indicated that the recent warming of the tropical Atlantic is causing a weakening of Atlantic Niño variability.

Recent studies have also indicated a growing importance of the tropical Atlantic Ocean in the global climate system. In particular, observations and model experiments suggest that the warming of the tropical Atlantic during the last three decades drove SST changes over the Pacific and Indian Oceans, possibly slowing the rate of global warming between the late 20th and the early 21st century and driving a stronger coupling between interannual variability in both basins and thereby enhanced seasonal predictability.

An important consequence of the long-term and multidecadal changes in tropical Atlantic SST is their impact on climate extremes, in particular on hurricane activity.

3.9.3 Future changes

Model based projections indicate that continued anthropogenic emission of greenhouse gases will drive major changes in the tropical Atlantic climate in the coming century and that these will have major environmental and socio-economic consequences. Overall, multiple generations of models robustly predict a continuation of the long-term warming of the tropical Atlantic. Oceanic rainfall is projected to increase over the equatorial Atlantic at a rate of 3 to 6% per degree of global warming, and to decrease in the subtropics. Continental rainfall is projected to decrease over most of South and Central America and parts of West Africa, and to increase over parts of the Sahel and eastern equatorial Africa. Yet, large uncertainties exist in the patterns of climate change over the tropical Atlantic and surrounding continents.

Better predictions of future changes in the rainfall patterns, intensity, variability, and/or frequency are particularly important for society and the overall economy, especially for West Africa that is highly vulnerable due to low adaptive capacity and national domestic productivity that is closely linked to the maritime economy and/or coastal infrastructures.

Global warming will continue to drive sea level rise over the tropical Atlantic, and for the CMIP5 RCP4.5 scenario (Representative Concentration Pathway at +4.5 W m^{-2}) a further near uniform increase of at least 20 cm is expected by the end of the century.

Recent studies at the global scale have shown that climate change will profoundly affect global ecosystems, mainly through its effects on the ocean temperature (and stratification), acidity (pH) and dissolved oxygen level. This will have impacts on the distribution, abundance and catchability of exploited fish species with, for example, a respective decrease (increase) in fish populations at low (high) latitudes. Therefore, quantifying the potentially negative impact of climate change on regional fisheries resources is essential for the nations surrounding the tropical Atlantic, especially for the Atlantic African countries.

Theory and models suggest that the continuous warming of the tropics may result in an increase in the number of intense hurricanes, while the number of tropical storms may decrease due to an overall increase in atmospheric stability. However, climate models used in global climate change projections do not reliably resolve actual hurricanes and thus can only indirectly assess future changes in their activity. Further, despite the model improvements made in CMIP5 with respect to CMIP3, most of the climate models are not yet able to correctly simulate the main aspects of TAV and associated impacts. A sustained TAOS that can observe changes in the frequency or intensity of TAV modes in relation to longer term climate change is essential to ground-truth models and to understand how TAV and its impacts may evolve in the future.

4. The Present TAOS

4.1 Mooring Networks

PIRATA

The PIRATA mooring array has served as the backbone of the in-situ observing system in the tropical Atlantic for more than 20 years. It is maintained by a collaborative agreement between Brazil, France, and the U.S.A. The PIRATA array began in 1997 with 10 moorings and reached its current configuration of 18 moorings in 2013 (Fig 4.1). Six of the PIRATA buoys are designated as flux reference sites for high-level validation of Numerical Weather Prediction and satellite surface flux products. These sites include longwave radiation sensors, barometric pressure, currents measured at 12 m, and four additional temperature and conductivity sensors to better resolve the mixed layer depth. In recent years there has been enhancement of the standard surface meteorology and upper ocean T/S measurements at selected PIRATA sites to include fCO_2, O_2, ocean mixing ("chi-pods"), and additional near surface current measurements. Subsurface ADCP moorings are also maintained by PIRATA at three sites along the equator (23°W, 10°W, and 0°E). All 18 PIRATA moorings also include OTN (Ocean Tracking Network) acoustic sensors for monitoring marine mammal activity. A thorough review of the PIRATA array including its historical evolution and current configuration can be found in Bourlès et al. (2019).

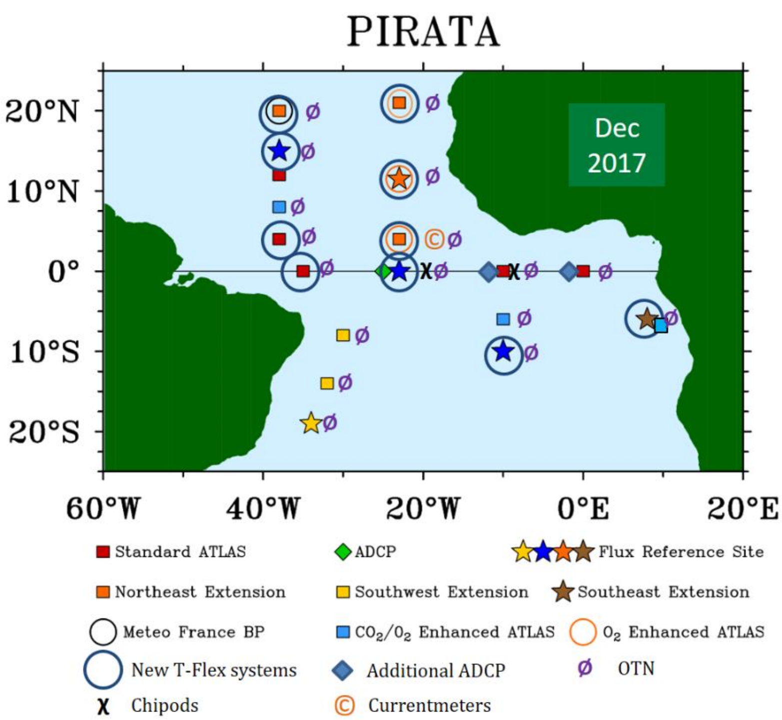

Figure 4.1. The PIRATA array in December 2019, indicating the mooring types and enhanced instrumentation that is deployed at specific sites.

The PIRATA network is currently being transitioned to T-Flex moorings which allow a higher real-time data transfer rate (hourly instead of daily-averaged data); 11 moorings are already of T-flex design and the remaining 7 will be phased in over 2021-2022. All PIRATA mooring data are transmitted in near real time to the Global Telecommunications System (GTS) for use by operational centers. The mooring survival rates have been excellent across the array except in the Gulf of Guinea in the early 2000s and in the West from the mid-2010's due to fishing-related losses and vandalism. The overall historical data return is typically 80% or better.

The PIRATA array is designed to resolve the fast zonal propagation of oceanic signals along the equator, while at off-equatorial locations they provide essential measurements across a wide range of climate regimes. These include the low-wind, high-rainfall regime under the Inter Tropical Convergence Zone （ITCZ), the northeastern and southeastern regions of the basin with cool SSTs, low clouds, and large concentrations of aerosols, and the northwestern tropical Atlantic where tropical storm systems intensify as they approach the Lesser Antilles and Caribbean Sea. The PIRATA moorings themselves have played a particularly essential role in understanding the surface mixed-layer heat balance in different dynamical regimes around the tropical Atlantic (Foltz et al., 2018).

Boundary Arrays and other moored platforms

Additional mooring-based observing systems in the tropical Atlantic include the MOVE array which measures the deep limb of the AMOC in the western basin at 16°N, and the WBCS/RACE/SACUS programs at 11°S which measure the shallow components of the boundary current system on both sides of the basin and the DWBC on the western side, thereby contributing also to the AMOC observing system in the tropical Atlantic (Fig. 4.2). MOVE began as a German contribution to CLIVAR in 2000 and since 2008 has been maintained by the U.S.A. through the NOAA Climate Program Office. The MOVE data and data products are publicly available on OceanSITES. The WBCS/RACE measurements at the western boundary on 11°S have been maintained since 2013 and follow up an earlier array deployed there from 2000-2004. Funding to maintain this array beyond 2020 is currently being sought. The SACUS moorings on the eastern boundary at 11°S were also deployed in 2013 and are currently funded until 2022.

Woods Hole Oceanographic Institution maintains the NTAS mooring site at 15°N, 51°W (http://uop.whoi.edu/currentprojects/NTAS/ntas.html), which has been providing meteorological and upper ocean measurements there since 2001 (Fig. 4.2). It is supported by the NOAA Climate Program Office and serves as an OceanSITES reference station.

The Cape Verde Ocean Observatory (http://cvoo.geomar.de) also maintains a multi-disciplinary mooring at 17° 35', 24° 17' since 2006 (Fig. 4.2), with repeated shipboard profile observations of a broad suite of physical and biogeochemical parameters on a monthly basis. Additionally, maintenance of the MELAX buoy in the Canary Current upwelling System at 14° N, 17° W has been attempted since 2015, measuring surface wind, solar radiation, humidity, and rainfall; and ocean temperature, salinity, currents and dissolved oxygen.

Finally, the U.S. National Data Buoy Center (NDBC) maintains several surface moorings in the NW tropical Atlantic eastward of the Lesser Antilles (Fig. 4.2), within the main development region (MDR) for tropical cyclones, that measure surface meteorological parameters and SST.

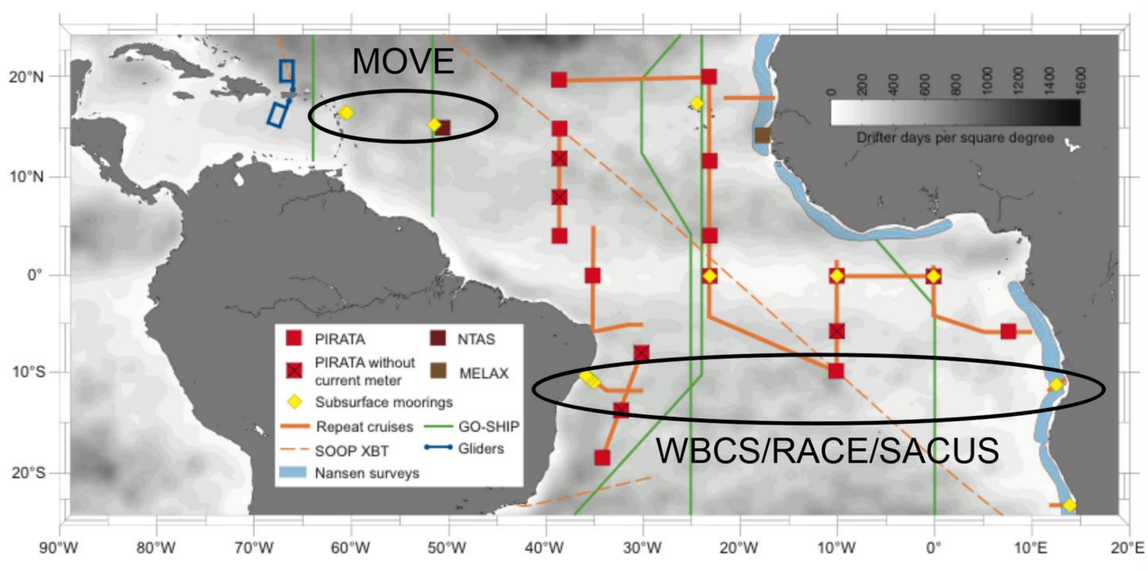

Figure 4.2. Elements of the tropical Atlantic observing system (after Foltz et al., 2019). Shading indicates average surface drifter density; orange lines show repeat cruise tracks used for servicing moorings; dashed orange lines show XBT lines; green lines show full-depth repeat hydrography cruise tracks (GO-SHIP). Yellow diamonds show locations of subsurface velocity and hydrographic moorings, including those associated with the MOVE and WBCS/RACE/SACUS AMOC monitoring arrays.

4.2 Surface Drifters

The Global Drifter Program (GDP, http://www.aoml.noaa.gov/phod/gdp and http://gdp.ucsd.edu/ldl_drifter/index.html) has been collecting observations in the tropical Atlantic since 1990, using drifters drogued at 15m which slip with respect to currents at this depth at <0.1 cm/s in 10 m/s wind. A number of deployment opportunities are routinely used to seed drifters in the tropical Atlantic, including primarily:

- Ship of Opportunity (SOOP) lines AX7, AX8.
- PIRATA research cruises (US, French, Brazilian).
- Brazilian navy cruises (western TA).
- GO-SHIP cruises, esp. A05, A06, A10, A13, A16.
- UK MetOffice: both North and Tropical Atlantic.
- Collaboration with Senegalese research institutes and Italy's National Institute of Oceanography.

The drifter coverage in the tropical Atlantic from 2006—present (Fig. 4.3) indicates where deployments are routinely conducted and the subsequent historical data coverage. The number of "new" drifters sampling the tropical Atlantic (either through deployment or entry to the tropical Atlantic from outside the tropics) averages about 5 per month. The historical drifter coverage between 20°S - 20°N is an average of ~70 drifters (with a range from about 40 to 130) and approximately 80% coverage of individual 5°x5° boxes (with a range from ~60-90%; Fig 4.4). The major sampling gaps are along the equator due to the strong wind-driven surface divergence there, and in the Gulf of Guinea due to advection by strong currents out of this area. Periodic sampling gaps also occur in the SE tropical Atlantic due to limited sustained deployment opportunities in that region.

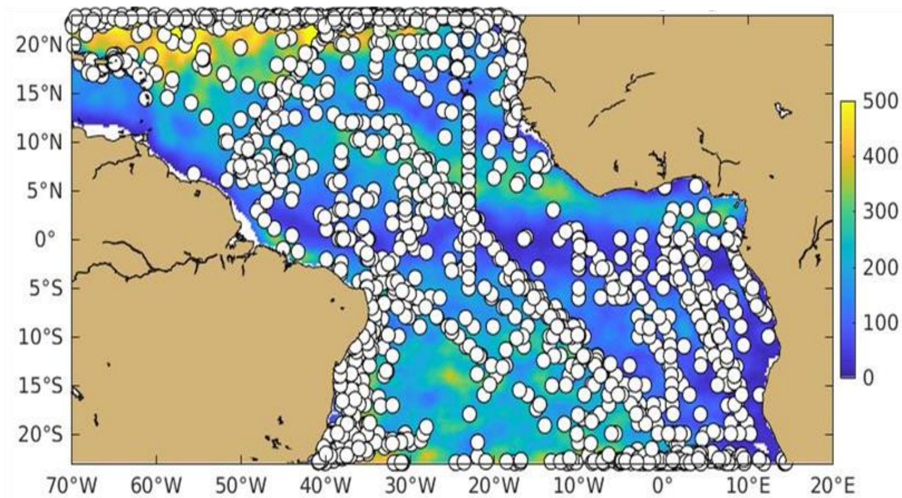

Figure 4.3: Shading: density of all GDP observations in drifter days per square degree. Dots indicate deployments, which include drifters entering the tropical Atlantic.

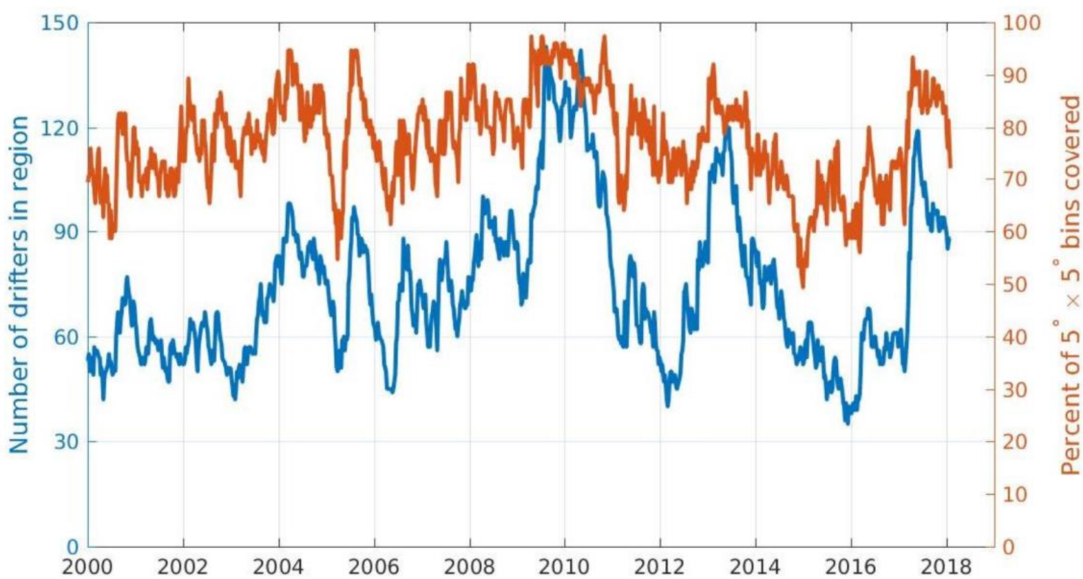

Figure 4.4. Historical summary of the number of active surface drifters in the tropical Atlantic region (blue), and the percentage of 5° x 5° spatial bins occupied by drifters.

In addition to the standard GDP drifter, which measures SST and currents at 15m depth, approximately half of the drifters measure barometric pressure to improve weather forecasting efforts. A much smaller number measure wind speed and direction, salinity at the surface and 5m depth, temperature profiles in the upper 150m, and directional wave spectra.

Surface drift data from Argo floats also provides a secondary data source for the tropical Atlantic surface drift data-base and, notably, while they provide many fewer observations than surface drifters, they do not exhibit significant equatorial divergence. However, as the Argo array transitions to Iridium data transmission, shorter surface times are required and the resulting surface displacements will be less robust due to high-frequency aliasing.

New modifications to the GDP surface drifters that have been tested and/or used in limited applications include:

(a) "Thermistor-chain" drifters that measure temperature every 15m down to 150 m. (These have been tested so far only in tropical cyclone observational programs and are not true surface Lagrangian devices; nevertheless, they may not diverge from the equator like standard drifters do.)

(b) Salinity drifters with salinity sensors added at the base of the floats (recently used in the SPURS program), and

(c) "Wave drifters" developed at SIO's Lagrangian Drifter Laboratory that can provide directional wave spectrum estimates using GPS data. (These drifters are undrogued and so have enhanced wind/wave slip; nevertheless, many GDP drifters lose their drogues over time and in principle could function as wave drifters thereafter.)

4.3 Argo floats

The Argo program began its first deployments in the early 2000s and the current global array now consists of nearly 4000 floats. Argo floats drift at a fixed depth (typically at 1000 m) and periodically profile through the upper 2000 m of the water column, measuring temperature and salinity (vs. pressure) as standard variables. Data are transmitted in near real time when the floats come to the surface between profiling cycles, typically at 10-day intervals. Deployments are conducted primarily from research and volunteer ships, coordinated by the International Argo Steering Team. Approximately 800 Argo floats are deployed each year to maintain the global array, by 26 countries, and many other nations contribute logistical support and ship access.

Most of the tropical Atlantic is currently considered to have good "core" Argo coverage (i.e. at or above the nominal 3°x3° design; Fig. 4.5). The present float coverage as of May 2019 is shown in Fig. 4.6. The future vision for the global Argo array ("Argo 2025" plan; http://www.argo.ucsd.edu/AIC_Rep_AST20.pdf) calls for enhancement of Argo density within 3° of the equator to 2 times normal density (i.e., 2 floats per 3°x3° square), along with a 2 times enhancement in the Caribbean Sea.

Recent advances in Argo capabilities include Iridium communications, biological and biogeochemical sensors, "Deep" Argo (>2000 m), and air-deployable Argo floats. The bi-directional Iridium communications that are now available provide a number of operational benefits including the possibility to alter mission parameters, greater data flow with higher resolution vertical profiles, sampling closer to the sea surface (1 m), shorter surface time, and overall battery savings.

Four different models of "Deep" Argo floats are under development (by JAMSTEC, IFREMER, Teledyne Webb, and SIO) with target accuracies of 0.001°C, 0.002 psu, and 3 dbar. Argo floats with added biogeochemical sensors "BGC-Argo", that measure O_2, nitrate, pH, chl-a, and particulate matter (with more sensors now under development), have already been deployed in several regional programs

- most notably in the Southern Ocean in SOCCOM but some have also been deployed within the tropical Atlantic. The BGC-Argo implementation plan developed in 2016 (www.biogeochemical-argo.org) proposes a global array of 1000 BGC-Argo floats and envisions the full-scale implementation of this array within the next decade. There are currently 10 deep Argo floats and 21 BGC-Argo floats operating in the tropical Atlantic.

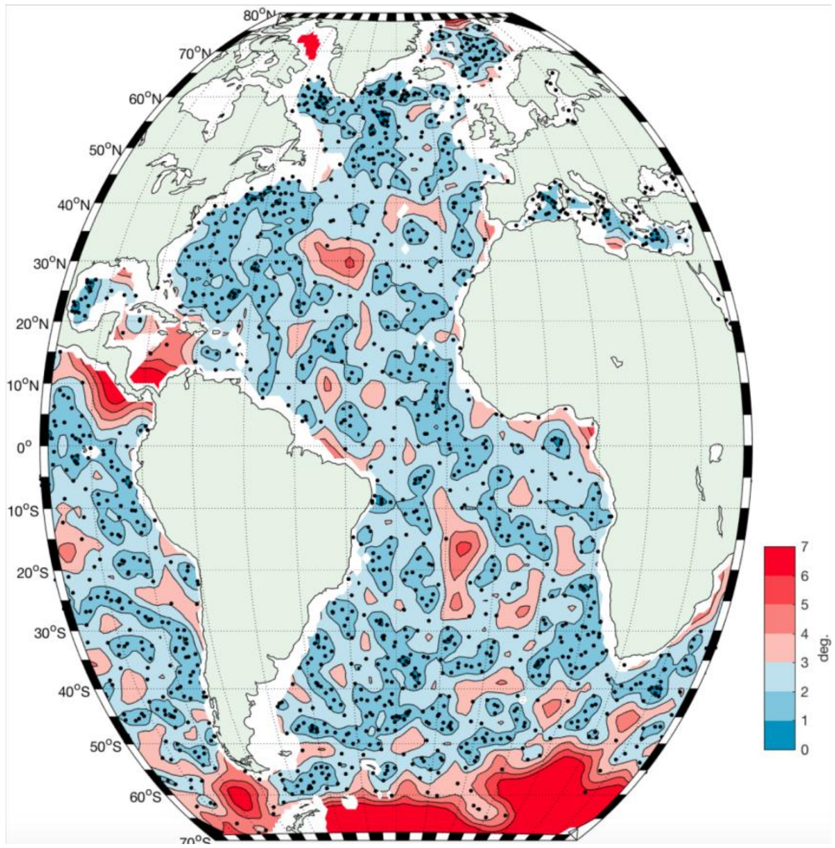

Figure 4.5. Snapshot of Argo float locations in the Atlantic from January 2018. Color shading indicates the mean distance to the nearest 4 Argo floats; blue shaded areas indicate coverage at or above the nominal 3° x 3° density, red areas indicate below nominal coverage.

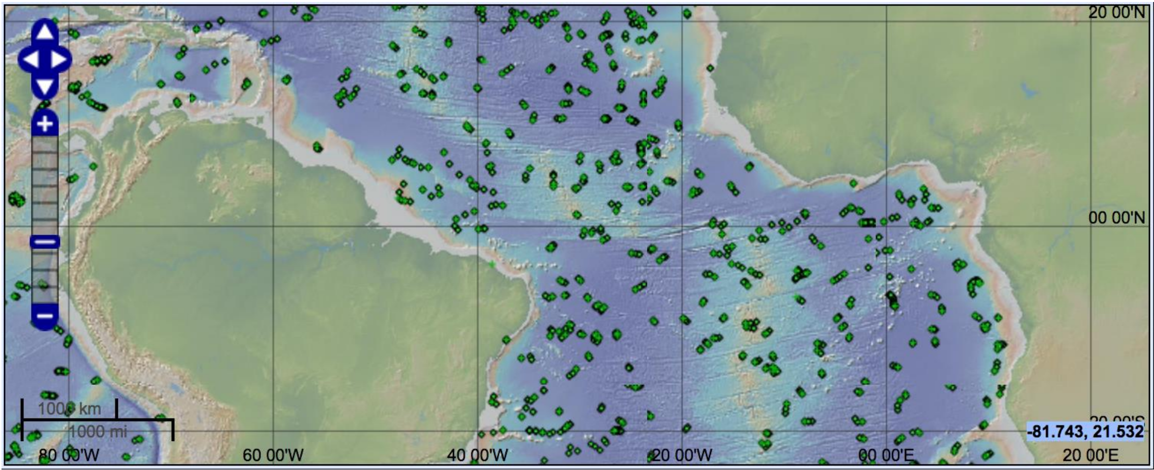

Figure 4.6. Distribution of Argo floats May, 2019.

4.4 Vessel-based Observations

Research vessels and container ships transiting the tropical Atlantic Ocean provide platforms to collect Essential Ocean and Climate Variables (EOVs/ECVs) in under-sampled parts of the ocean. A subset of the vessel-based observations are provided in quasi-real time through the GTS to GDACs, are used by operational weather/climate centers (e.g., ECMWF, INPE/CTPEC) and oceanography centers (e.g., MERCATOR), and are also used by the science community in delayed mode after the data have been quality controlled.

The PIRATA program continues to be the most omnipresent vessel based observing program in the tropical Atlantic, with dedicated annual cruises by France, Brazil, and the U.S.A. to service the array of 18 PIRATA moorings presently deployed. These cruises also provide a platform for the acquisition of a large number of complementary measurements along repeated ship track lines, and for the deployment of other essential components of the TAOS including surface drifters and Argo floats. On PIRATA cruises to date, over 400 surface drifters and 240 Argo floats have been deployed within the tropical Atlantic. The PIRATA infrastructure and its maintenance cruises have also provided significant leverage and opportunities for related scientific programs such as AtlantOS, AMMA, EGEE, TACE, and PREFACE.

Since its inception in 1997, a total of 60 PIRATA cruises have been completed (30 by France, 17 by Brazil, 13 by U.S.A.) with annually repeated cross-equatorial sections along 38°W, 23°W, and 10°W (Fig 4.2). All PIRATA cruises perform $CTDO_2$ casts to observe T, S, O_2, as well as collect underway SST, SSS, pCO_2, and velocity data, and additional XBT profiles are also frequently collected. Surface meteorological parameters are also collected, and many of these observations are transmitted in real-time to GDACs to support operational services. In addition to the standard physical parameters, these cruises have more recently (since 2004) begun to collect ancillary marine biological and biogeochemical data, including nutrients, chlorophyll pigments, and zooplankton and Sargassum algae samples. Atmospheric data from radiosondes and ozonesondes as well as air-sea interaction data from the M-AERI system and turbulent flux sensors on the ships have also been collected on many of the cruises.

Additional repeated shipboard measurements are available from the MOVE program since 2000 along 16°N in the western basin, and since 2013 along sections at the western and eastern boundaries near

11°S in support of mooring arrays there by GEOMAR, in collaboration with Brazil and Angola (Fig 4.2). The Cape Verde Ocean Observatory (CVOO) also conducts a monthly ship-based sampling program (measuring temperature, salinity, biological parameters, nutrients, dissolved carbon, and oxygen) at its open-ocean time-series site in the eastern Tropical North Atlantic (17° 35’ N, 24° 17’ W).

Other regular shipboard sampling in the tropical Atlantic comes from the NOAA/AOML high-density XBT transect program, which includes three transects in the tropical Atlantic occupied on an approximately quarterly basis (Fig. 4.2). One of these transects (AX08) crosses the entire central tropical Atlantic on a track from South Africa to North America. Five meridional GO-SHIP reference sections collecting a multi-disciplinary suite of observations also cross through the tropical Atlantic (Fig 4.2), which are nominally repeated on a decadal or pentad basis. The Atlantic Meridional Transect (AMT) program also conducts similar multi-disciplinary observations on repeated annual cruises from the U.K. to the South Atlantic, typically in boreal fall, that cross through the central tropical Atlantic basin.

Finally, the Global Ocean Surface Underway Data (GOSUD) program collects SST and SSS data from equipped merchant ships, some of which also collect pCO_2 data, on a number of transects through the tropical Atlantic (Fig. 4.7).

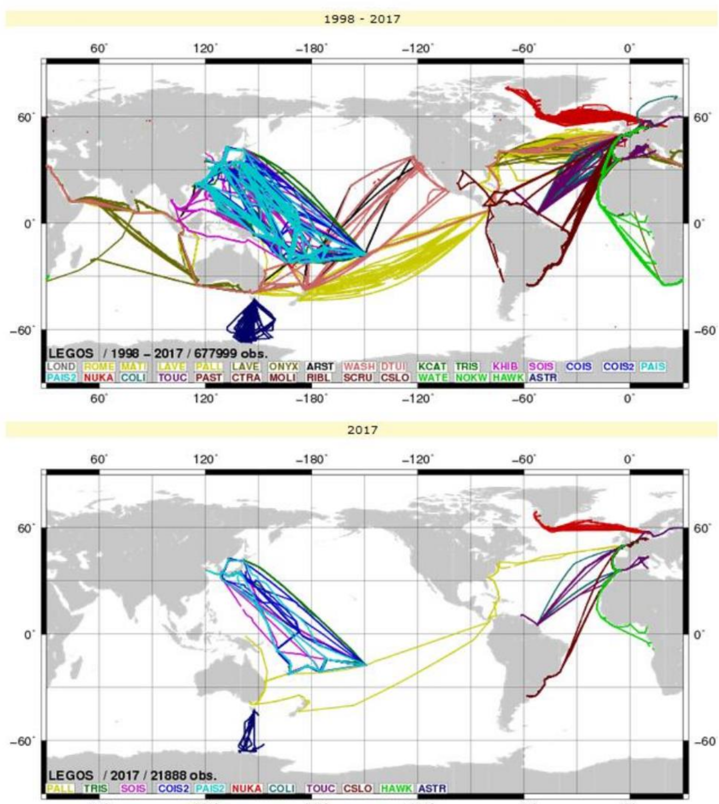

Figure 4.7. Global GOSUD transects, 1998-2017 (top) and active transects during 2017 (bottom).

4.5 Satellite Observations

Satellite observations are an integral element of the TAOS that are synergistic to the in-situ observing system. Comparisons with in situ data (especially winds and SST) are essential for validation throughout the life of satellite missions - referred to as Fiducial Reference Measurements (FRMs). Tropical buoys are of particularly high value to the satellite assessments since they make up a large fraction of the global moored buoy comparisons.

The main variables and blended products (multi-mission satellite merged products or satellite-in situ blended products) measured by satellites are described below along with the satellite platforms and sensing technologies supporting them.

Wind

Wind speed and direction have been provided by Ku- or C-band) scatterometers on a series of satellite missions, including the European Remote sensing Satellite (ERS)–1 (1992–1996) and ERS–2 (1995–2000), the NASA SeaWinds–1 scatterometer on the QuikSCAT satellite (1999–2009), the European Space Agency's (ESA's) series of three Advanced Scatterometers (ASCAT) onboard the MetOp satellites (2006 onward), and OceanSat–2 (OSCAT; 2009-2014) and SCATSAT-1 (2016 onward) by the Indian Space Research Organization. The recently launched (2018) Chinese-French Oceanography Satellite (CFOSAT) also carries a K-0u band scatterometer.

Several blended wind products are routinely produced and available:

1) **Cross-Calibrated Multi-Platform Wind (CCMP) analysis** (http://www.remss.com/measurements/ccmp/)
2) **IFREMER blended wind analysis** (http://apdrc.soest.hawaii.edu/datadoc/ifremer_LOPS_blended_wind_6hourly.php),
3) **NOAA's blended wind analysis** (https://www.ncdc.noaa.gov/data-access/marineocean-data/blended-global/blended-sea-winds), and
4) **OAFLUX wind analysis** (http://oaflux.whoi.edu/wind.html).

Some of these products include only satellite winds (both from scatterometers and radiometers). Others (e.g., CCMP version 1 (Atlas et al. 2011) and CCMP version 2 by the Remote Sensing Systems) also include buoy winds. All blended products use atmospheric reanalysis or analysis winds as "background" to fill gaps where satellite winds are not available and where directions are not available (i.e., from radiometers).

The overall agreement between satellite and buoy winds is about 1-1.5 m/s. However, the consistency is less in rainy regions, especially for the shorter-wavelength, higher-frequency Ku-band (compared to the C-band). This is in part due to some contamination of satellite winds in rainy conditions and the enhanced sampling difference between satellite and buoy winds associated with transient, small-scale convective rain cells. Recent L-band satellites such as the Soil Moisture and Ocean Salinity (SMOS) mission (2010 onward) and Soil Moisture Active Passive (SMAP) (2015 onward), and the L-band reflectometry mission Cyclone Global Navigation Satellite System (CYGNSS) (2016 onward) now provide hurricane/cyclone wind speed measurements that can capture wind speed higher than those retrieved from the Ku- or C-band scatterometers.

Sea Surface Temperature (SST)

Remotely sensed SST has been provided by infrared (IR) radiometers on satellites since 1981, including primarily the five-channel Advanced Very High Resolution Radiometer (AVHRR), and from additional IR and visible IR sensors on satellites such as the ATSR, AATSR, Sentinel-3 SLSTR, Aqua/Terra MODIS, VIIRS, Himawari-8, and GOES. Satellite-based IR sensors provide high spatial resolutions (~ 1 km) but are obscured by clouds.

Passive microwave (PMW) radiometers (primarily C-band) provide all-weather SST measurements, but at much lower resolution (~50 km). PMW SST sensors flown on satellites include the microwave imager (TMI) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite (1999-2015), the Advanced Microwave Scanning Radiometer (AMSR) onboard NASA's EOS Aqua spacecraft (AMSR-E, 2002-2011), and the AMSR-2 onboard the Japan Aerospace Exploration Agency's (JAXA's) Global Change Observation Mission – Water (GCOM-W1) spacecraft (from 2012 onward).

Combined microwave and microwave-infrared gridded SST products are available going back to 1998 and 2002, respectively (http://www.remss.com/measurements/sea-surface-temperature/oisst-description/). The horizontal resolutions are 25 km for the microwave product and 9 km for the microwave-infrared dataset. The WindSat satellite also provides PMW SST measurements (2003 onward).

The Group for High Resolution SST (GHRSST) project provides various level-4 blended SST analysis (https://podaac.jpl.nasa.gov/GHRSST). NOAA also provides a blended satellite and in-situ SST, the OISSTV2: https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html.

Sea Surface Height (SSH)

Precision satellite altimetry missions (Ku-band) have been providing SSH measurements continuously since late 1992 by a series of altimeter missions such as TOPEX/Poseidon (1992-2006) and the operational Jason series: Jason-1 (2001-2013), Ocean Surface Topography Mission (OSTM/Jason-2) (2008 onward), and Jason-3 (2016 onward). Jason Continuity Series (Jason-CS/Sentinel-6) is planned beyond Jason-3 (planned to launch date in 2020). Other satellite altimeter missions (either Ku- or Ka-band) such as SARAL/ALtiKa, ENVISAT, CryoSat, CryoSat-2, and Sentinel-3 also contribute to the satellite altimetry constellation. Merged altimetry SSH products are available through the Copernicus Marine Environmental Monitoring Service (CMEMS): http://marine.copernicus.eu/faq/ssaltoduacs-integrated-sealevel-anomalies-products-changes-updates/ (formerly AVISO product).

Precipitation

Precipitation estimates from satellites are derived from cloud-top properties such as infrared and microwave brightness temperatures, as well as microwave emissions from rain drops and scattering from ice. Microwave observations are available from SSM/I (1987 - present), Advanced Microwave Sounding Unit (AMSU-B) and follow-on instruments (1998 - present), and the TRMM (1997 - 2015). TRMM included a precipitation radar along with a microwave radiometer (TMI) and a visible/infrared radiometer (VIRS), thus allowing the first estimation of rain profiles in addition to surface precipitation.

A three-hour precipitation field at 0.25° spatial resolution over the tropics and subtropics is available from TRMM through 2015 (https://pmm.nasa.gov/TRMM/realtime-3hr-7day-rainfall). The Global Precipitation Measurement (GPM) mission was launched in February 2014 and carries a dual-frequency precipitation radar and microwave imager, which is able to sense total precipitation within all cloud layers. GPM extends the capabilities of TRMM sensors, including sensing light rain, and for the first time, is able to quantify microphysical properties of precipitation particles. GPM data can be accessed at: https://pmm.nasa.gov/data-access/downloads/gpm.

Sea Surface Salinity (SSS)

Satellite SSS measurements come from three L-band satellites: SMOS, Aquarius, and SMAP. SMOS (L-band radiometry) has been providing SSS measurements at ~40 km resolution since 2010. This was followed by Aquarius (L-band radiometry with an integrated L-band radar, i.e., combined active-passive) for 2011-2015, with a resolution of approximately 150 km. SMAP (2015 onward) is similar to Aquarius in terms of combined active-passive design but provides higher resolution (~40 km) SSS measurements (however the radar stopped functioning 3 months into the operation).

SSS blended analysis products can be found at the following locations:

https://smos-diss.eo.esa.int/oads/access/

https://www.catds.fr/

https://podaac.jpl.nasa.gov/aquarius, and

https://podaac.jpl.nasa.gov/SMAP.

Chlorophyll

Satellite estimates of surface chlorophyll-a (chl-a) concentration are derived from infrared sensors such as those on the Moderate Resolution Imaging Spectroradiometer (MODIS Terra and Aqua, from 2000 and 2002 onward, respectively), and since 2012 on the Visible Infrared Imaging Radiometer Suite (VIIRS). Full coverage of the tropical Atlantic is achieved in approximately 2-8 days at a horizontal resolution of 4 km. Previous satellites measuring chl-a include the Coastal Zone Color Scanner (1978–1986), Sea-viewing Wide Field-of-view Sensor (SeaWiFS, 1997–2010), and Medium Resolution Spectroradiometer (MERIS, 2002–2012). Blended satellite chl-a products are available, such as those from the European Space Agency's Ocean Color Climate Change Initiative (OC CCI, https://esa-oceancolour-cci.org/).

Ocean mass/bottom pressure:

Ocean mass and bottom pressure have been measured by the GRACE (2002-2017) and GRACE Follow-On (2018 onward) satellites with spatial resolutions of a few hundred kilometers. Data are available at: https://podaac.jpl.nasa.gov/GRACE.

Near-surface temperature and humidity

Near-surface air humidity and temperature cannot be retrieved directly by satellites, but are estimated from satellite-measured total column water vapor or total precipitable water (Liu, 1986; Liu et al., 1991) using passive microwave radiometers such as SSM/I and the Special Sensor Microwave Imager Sounder (SSMIS), AMSR-E, and AMSR-2. The Advanced microwave sounding unit (AMSU) radiometers and follow-on sensors flown on the NOAA series of polar orbiting meteorological satellites since 1998 have provided profiles of temperature and humidity that help to improve estimates of near-surface humidity and temperature (Jackson et al., 2006). Near-surface air humidity and temperature can be downloaded at: ftp://ftp1.esrl.noaa.gov/.

Clouds and aerosols

Cloud and aerosol properties over the ocean are monitored by visible and infrared radiometers on several satellites, including AVHRR, MODIS and VIIRS. Derived variables include cloud-top temperature, height, effective emissivity, phase (ice vs. water, opaque vs. non-opaque), cloud fraction, effective cloud-particle radius, and cloud optical thickness. The International Satellite Cloud Climatology Project (ISCCP) provides global data at 2.5° resolution going back to 1983 (https://isccp.giss.nasa.gov/products/onlineData.html). The MODIS Aerosol Product (https://modis-atmosphere.gsfc.nasa.gov/products/aerosol) monitors the ambient aerosol optical thickness over the oceans globally and over the continents. The aerosol size distribution is also derived over the oceans, and the aerosol type is derived over the continents. Fine aerosols (anthropogenic/pollution) and course aerosols (natural particles; e.g., dust) are also derived.

Surface Radiative Fluxes

Satellites do not directly measure radiative fluxes at the ocean's surface. However they can be estimated from radiative transfer calculations based on satellite-derived TOA irradiance, cloud and aerosol properties, and the atmospheric state from either satellite data or reanalysis. Surface radiation budget estimates are produced by the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) radiative transfer model (Kato et al., 2013). CERES instruments were launched aboard the Tropical Rainfall Measuring Mission (TRMM) in November 1997, on the EOS Terra satellite in December 1999, and on the EOS Aqua spacecraft in 2002. Outgoing longwave radiation (OLR) - a proxy for deep convection in the tropics - has been measured by AVHRR since 1974 and is available daily at a 2.5° resolution.

Surface Turbulent Fluxes

Satellite-derived surface turbulent heat flux estimates are available from a number of sources (HOAPS, SeaFLUX, IFREMER, OAFlux, J-OFURO). Comparisons with in situ flux estimates show variability in the accuracy of different available products, with the IFREMER and OAFlux products generally showing smallest discrepancies with tropical buoy data and with PIRATA data in particular. However, the errors of different products vary in a complex way in association with variations in bulk formula variables (e.g. in different wind speed regimes).

From the set of available products, including NWP estimates, a multi-product ensemble (called OHF/MPE) is now being operationally produced on a daily basis on a 1/4°x1/4° global grid (wwz.ifremer.fr/oceanheatflux), which capitalizes on the strengths and error characteristics of the various products. The OHF/MPE product appears to have superior agreement with all OceanSITES buoy measurements relative to any of the individual products.

5. Recommendations for the TAOS

The foregoing sections of this report have described the current status of the Tropical Atlantic Observing System and a set of key science and operational drivers that should guide the future development of the TAOS. The extensive reviews of these science and operational drivers (Appendix 1) have revealed a number of challenges that need to be met by the evolving TAOS to provide critical and timely information that can be applied toward societal benefit. In particular, while much of the present TAOS has been built with a focus on providing information on physical variables relevant to weather forecasting and the climate system, there is a need to expand its capabilities for measurement of biogeochemical variables relevant to ocean biology and fisheries, ecosystem management, and the regional and global carbon system. At the same time, there are still incremental improvements needed in the physical measurement system to enhance capabilities for prediction of climate variations and extreme events that affect all of the countries surrounding the tropical Atlantic and beyond.

As a first step in defining the future requirements of the TAOS, a set of Essential Ocean Variables/Essential Climate Variables (EOV/ECV's) was constructed with reference to each of the Key Science and Operational Drivers identified in the review. These EOV/ECV tables are assembled in Appendix 2, where the estimated requirements for each EOV/ECV are specified in terms of their temporal and spatial resolution, with indications of potential platforms that are suitable for their measurement.

Requirements expressed in terms of EOV/ECVs help develop a process for ongoing evaluation of the observing system in liaison with users of the data, based on the optimum suite of platforms for required variables, spatial and temporal scales and accuracy.

In addition to the specification of requirements based on EOVs/ECVs, a set of general recommendations drawn from each of the driver sections is articulated below, followed by specific recommendations organized around observing platforms.

5.1 General Recommendations

Dynamics of Tropical Atlantic Variability

- Better constrained and validated surface heat flux measurements are needed within the tropical Atlantic observing system to improve understanding and prediction of SST anomalies associated with TAV modes, and particularly that of the meridional mode.
- Better constrained estimates of subsurface thermal variability along the equatorial waveguide are needed to detect Kelvin waves that can induce Atlantic Niño and/or Benguela Niño.
- Remote sensing of the surface velocity field, e.g. by using Doppler radar measurements, is a high priority for future satellite missions.
- High resolution surface wind observations along the Benguela low-level jet region off the coast of Southern Africa are needed for validating satellite and reanalysis wind products and to help in understanding and reducing warm SST biases in the region.
- Besides the recognized ECVs, more time series measurements of microstructure and turbulence in the upper ocean are needed to improve the understanding of mixed layer heat and salinity budgets.

Climate Impacts of Tropical Atlantic Variability

- Skill in predicting the WAM and Sahel rainfall requires continuous long-term, large-scale monitoring of SST variability. Continuous monitoring of tropical Atlantic salinity is also mandatory to achieve an accurate forecast system and to infer the state of the regional hydrological cycle and thereby the availability of moisture to feed rainfall over land.
- The extratropical influence of TAV requires good characterization of the location and strength of deep convective systems across the tropical Atlantic. Better instrumentation for oceanic surface rainfall measurements within the TAOS are needed that could provide the vital comparisons for improving satellite products.
- An increase in the number of radiosonde observations in the tropical Atlantic would be beneficial for constraining the dynamical aspects of tropical-extratropical interactions.
- Continued research is needed to overcome the deficiencies in numerical climate prediction models' simulation of the tropical Atlantic mean ocean and atmosphere climate conditions, climate variability, and extremes.

The AMOC in the Tropical Atlantic

- Sustained measurements of the AMOC in the tropical Atlantic - in conjunction with those at other latitudes (e.g. RAPID, SAMOC, OSNAP) - are needed to understand the meridional coherence of the AMOC on different time scales and the dynamics of the basin-wide AMOC response to changes in forcing.
- The two AMOC measurement systems presently active in the tropical Atlantic – the MOVE array at 16°N and the WBCS/RACE/SACUS array at 11°S - should be continued. Further development of the 11°S array could benefit from an OSSE study using high-resolution ocean models to determine how to optimize the AMOC estimate along 11°S and if any additional measurements may be required.

The Carbon System in the Tropical Atlantic

- An optimized observing system is needed to quantify the tropical CO_2 flux on annual time-scales, involving a combination of high-quality pCO_2 observations obtained from volunteer observing ships, expanded time-series pCO_2 data from moorings, and potentially additional pCO_2 observations from autonomous surface vehicles (ASVs) to fill spatial and temporal gaps. Data from BGC Argo floats in the region can also be useful for constraining estimates of surface fluxes.
- Sub-decadal observations of interior ocean carbon storage in the deep and intermediate waters of the tropical Atlantic are needed, which can largely be accomplished by an expansion of the BGC-Argo network in the tropical Atlantic (25% of Argo to be BGC Argo), along with the current repeat hydrography (GO-SHIP) sampling of the tropical Atlantic, with the addition of a zonal section along about 10°N.

Biogeochemical Processes in the Tropical Atlantic

- Sustained measurements and improved geographical coverage of key biogeochemical EOVs including dissolved oxygen, transient tracers and nutrients are needed to understand the ocean mixing and ventilation processes that influence oxygen concentrations, and the impact of low oxygen concentrations on nutrient concentrations.
- Measurements of particulate matter, dissolved organic carbon and microbe biomass and diversity are also needed to develop a more quantitative understanding of the mechanisms linking dissolved oxygen concentration, remineralization efficiency and microbial community structure.
- Full implementation of BGC-Argo in the tropical Atlantic will be a key step in providing the broad-scale biogeochemical data needed in the TAOS. An increased effort to include observations of N_2O in the region is also recommended.
- A joint definition of observing needs with the fisheries and biodiversity communities is recommended to identify joint opportunities between fishery surveys and more climate driven observing needs, especially within the highly-productive eastern upwelling zones.

Ecosystem Dynamics and Fisheries

- Fisheries management in the tropical Atlantic must continue its evolution from traditional single species management of capture fisheries to an ecosystem-based approach to fisheries management, in which fish stocks are managed in the context of other organisms (prey, predators, and competitors) and their environment.
- Improved management of living resources across the tropical Atlantic requires a better assessment of the active fisheries themselves, including fishing capacity, fishing effort, and catch, as well as more fisheries-independent data on life stages (egg-larvae-juvenile-adult) of fish stocks acquired through trawl and hydroacoustic surveys. Promotion of open data policies for ecological and fisheries data is strongly recommended.
- There is a need to develop and carry out a broad review and consultation on current observing efforts and observing needs related to tropical Atlantic fisheries, involving inter-governmental bodies such as the Ministerial Conference on fisheries cooperation among African States bordering the Atlantic Ocean (ATLAFCO), as well as regional bodies such as the Sub Regional Fisheries Commission (SRFC) in the CCLME, the Fisheries Committee for the West Central Gulf of Guinea (FCWC) in the GCLME, and the Benguela Current Commission (BCC) in the BCLME. Similar efforts are recommended for the western tropical Atlantic fisheries sectors.
- Coordinated national survey programs need to be linked and supported, including existing programmes like the EAF Nansen Programme, the LME Programmes and Regional Fisheries Management Organizations like ICCAT.

Ocean Heat Content and Sea Level Rise

- Monitoring and understanding ocean heat content and sea level change in the tropical Atlantic requires that the TAOS provides sufficient information on where heat is entering and exiting the ocean across the air-sea interface, the rate at which heat is stored in the ocean, and determining the pathways by which it is transported.

- Satellite missions are critical to provide multi-decadal, continuous records of key variables such as surface height from altimetry, surface wind speed and direction from scatterometry, and SST from spaceborne microwave and infrared sensors.
- Sustained in situ measurements are likewise critical for measurements of upper ocean heat content, water mass variability, air-sea heat fluxes, and ocean circulation. The suite of measurement systems that presently make up the sustained in situ TAOS (Argo floats, drifters, moorings, island and coastal tide gauge stations, ship-of-opportunity measurements and repeat hydrography) have provided these observations routinely in a generally cost-effective way. Introducing newer technologies that are fit for purpose and rigorously field tested, such as gliders and deep Argo floats, are logical next steps.

Improved predictions on subseasonal to decadal time scales

- Sustained observations of the ocean-atmosphere system in the tropical Atlantic are required for forecast activities on all time scales, through their impact on initialization of forecast models, calibration of model output, skill assessment and model and data assimilation development. Ocean *in situ* observations, gathered from moored and drifting buoys in the tropical Atlantic, do appear to have a real impact on global numerical weather forecast at 24 hours, as shown by their relative weight in the assimilation process compared to other observing systems, including satellites.
- Continued observation of subsurface fields (including ocean temperature and currents) are crucial to initializing seasonal and decadal predictions. Regions of particular importance are the equator (5°S-5°N) for seasonal predictions and the southern tropical Atlantic for multi-year predictions.
- Optimal use of TAOS observations can be achieved through "Seamless Earth System" approaches to forecasting, spanning time scales from subseasonal to decadal, which should be a continued developmental focus at operational centers.
- Modelling relies on parameterizations, which need to be continuously improved with the aid of both sustained observations and targeted observational campaigns.
- Improving hurricane forecasts at both synoptic and climate time-scales is a top priority of Atlantic climate research. Enhanced observations in the Atlantic hurricane main development region are needed to improve forecast capabilities and to help resolve the cool SST bias problem in the northern tropics, which presents a major obstacle in applying coupled climate models to long-term TC prediction.
- Improving the ability of climate models to predict "Atmospheric Rivers" - plumes of intense water vapor transport emanating from the tropics – has important implications for water resource management and flood/drought hazard assessment, and should be a further top priority for Atlantic Basin climate research.
- Extension of the observational network and measurement campaigns in the equatorial Atlantic, including into coastal areas, will be crucial to overcome long standing climate model biases in the region. A key aspect of these model biases may be linked to misrepresentation of atmospheric vertical momentum transport, which should be a focus of observational process studies and coupled model development.

Long-term climate change and impacts

- A sustained TAOS is key to monitoring climate change in the tropical Atlantic and to improve climate models, thereby reducing uncertainties in future projections of climate change.
- Maintaining existing observational records is of paramount importance to ensure the continuous monitoring of long-term changes.
- Basin scale measurements of upper ocean temperature and salinity, SSH, and the overturning circulation are essential components of the TAOS for monitoring long term climate change.

5.2 Recommendations for enhancement of the TAOS

5.2.1 Moored platforms

The PIRATA array constitutes the main deployment of moored resources in the tropical Atlantic, and it has been continually improved and updated through its lifetime (e.g., by the ongoing transition to T-Flex buoys as described in Chapter 4). Insofar as it will remain the principal moored observing system for the TAOS in the foreseeable future, it is critical that maximum benefit be gained from this observing system through enhanced deployment of sensors for interdisciplinary process studies and monitoring. To this end, the following recommendations are made for enhancements to the present PIRATA array:

- Vertical sampling of upper ocean temperature and salinity should be enhanced on all PIRATA moorings so that the mixed layer depth and underlying stratification can be determined with greater accuracy. This has been implemented so far on only a few of the moorings (with ~9 T/S sensors deployed over the upper 100m of the water column) and should be installed on all other moorings as soon as possible. This enhancement should go hand-in-hand with the enhanced T-Flex data reporting capabilities so that information on the diurnal cycle in the upper ocean can be delivered on a near-real time basis.
- Near-surface current measurements (at least one point current meter at ~5 m depth) should be installed at all PIRATA sites.
- Additional ocean turbulence sensors should be deployed on a subset of PIRATA moorings to extend the existing pilot measurements with chi-pods already obtained on two of the equatorial moorings. These sensors could be gradually rotated around to different sites over time to examine the mixing characteristics in different regimes.
- All PIRATA surface buoys should be equipped with sensors for barometric pressure and downwelling longwave radiation, allowing them to serve as flux reference sites.
- pCO_2/fCO_2 sensors should be installed on an extended set of PIRATA moorings to complement the three sites where they are currently deployed. Such data would help to understand the spatial and temporal variability of pCO_2 around the basin and assist in the planning for an optimized long-term carbon monitoring program in the tropical Atlantic.
- Additional BGC sensors should be selectively added to PIRATA moorings, including dissolved oxygen, pH, and nitrate, to expand time-series observations relevant to ocean deoxygenation, nutrient balances, and the global carbon cycle.

In addition to the above enhancements at existing PIRATA sites, it is recommended that a line of surface meteorological buoys with subsurface data equivalent to that collected on PIRATA buoys be established along about 53°W between 11°N and 17°N (Fig. 5.1), to provide real time information relevant for hurricane forecasting in the western MDR region just upstream of the Lesser Antilles, where rapid intensification of TC systems often takes place. This is also a region where barrier layers frequently occur in relation to advected Amazon waters and where subsurface heat content observations would be particularly valuable.

There are already two buoys deployed in this vicinity, the NTAS buoy at 14.8°N, 51°W and the NDBC buoy 41040 "North Equatorial One" at 14.5°N, 53°W, and their placement at nearly the same latitude and very nearby longitudes seems less than optimal for providing the needed coverage of the region. Relocation of one of these buoys, along with the placement of one or two PIRATA buoys to the north and south of this location along 53°W, should be considered as a way to expand the buoy coverage and enhance the meridional coverage in this critical region. It is recommended that a scoping effort be carried out collectively between PIRATA, NDBC, and NTAS to consider the options for developing such a buoy line along 53°W.

Additionally, it is recommended that a PIRATA meteorological and subsurface buoy be established at 10°W 20°S, to improve the capacity to predict extreme rainfalls in tropical South America, in particular northeast Brazil. Extreme rainfall events in northeast Brazil are positively related to the SST anomalies in the southeastern tropical South Atlantic with a lead of 3 to 6 months, that are transported northwestward across the basin by southern branch of the SEC. New time series measurements at the proposed 10°W, 20°S site would be especially valuable to accurately determine air-sea fluxes in the Saint-Helene anticyclone that affect the development of these SST anomalies, and to validate analysis/reanalysis products used for research and forecast model initialization. The line of buoys along 10°W extending from 20°S to the equator will also be valuable to constrain upper ocean transports in the South Atlantic and monitor the properties of the thermocline waters flowing northwestward in the upper branch of the AMOC that are derived from Agulhas leakage.

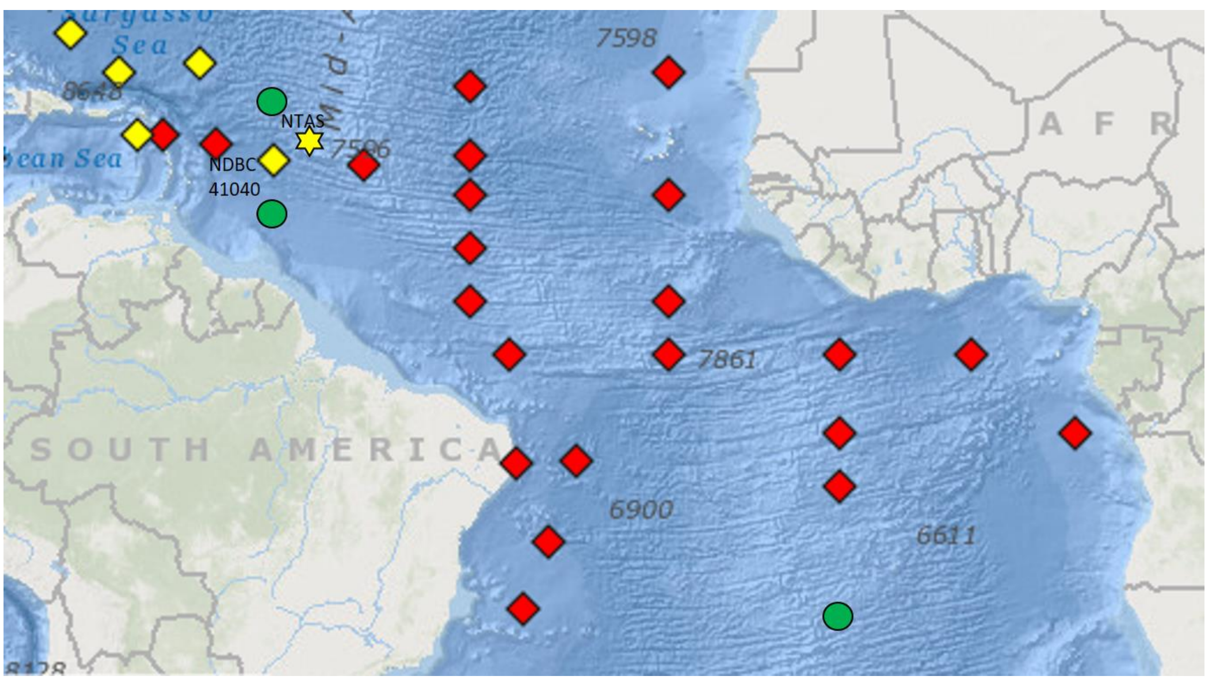

Figure 5.1. Green symbols show recommended new PIRATA sites to combine with the NTAS/NDBC buoys to establish a new buoy line along ~53°W, and the recommended new PIRATA buoy at 20°S, 10°W

5.2.2 Drifters

The surface drifter network maintained in the tropical Atlantic by the NOAA SVP remains a highly valuable component of the TAOS, supplying information on surface currents, SST, and barometric pressure that is vital for a range of applications from weather forecasting to satellite calibration. Recommendations for the future tropical Atlantic drifter array include the following:

- Increase the number of SVP drifters in the tropical Atlantic that measure barometric pressure. Currently about 60% of SVP drifters deployed in the tropical Atlantic include barometric pressure measurements and these data show very high value in forecast sensitivity experiments; ideally all SVP drifters deployed in the region should include barometric pressure (SVPB drifters).
- Continue efforts to optimize the SVP drifter array seeding in the tropical Atlantic using "drifter value" maps such as produced by NOAA at https://www.aoml.noaa.gov/phod/gdp/value_maps.php, which indicate high-priority regions for new deployments based on factors including current drifter ages and projected drifter movement. Areas that routinely require enhanced seeding are the equatorial region where drifters rapidly spread meridionally due to wind-driven equatorial surface divergence, and in the Gulf of Guinea where more deployment partners and opportunities are needed to sustain the required drifter density.
- An effort should be made to deploy an increased number of drifters in the northeast tropical Atlantic during boreal spring of each year, that would provide enhanced data for TC prediction (including barometric pressure) in summer and fall as they spread westward across the tropical Atlantic toward the Caribbean Sea.
- The feasibility of deploying an array of thermistor-chain drifters along the equatorial waveguide should be explored as a way to increase the number of SST and upper ocean temperature observations available near the equator. Such drifters, although not functioning in the same way as SVP drifters (i.e., not providing a useful estimate of near-surface currents) might not diverge significantly from the equator and would provide many more near-surface observations than Argo floats.

5.2.3 Argo

The TAOS review recognized the vital role that Argo plays in the tropical Atlantic and global observing system, and views Argo as a particularly effective and efficient measurement platform for obtaining much needed information on biogeochemical processes in the region through a broad scale deployment of BGC-Argo floats. Due to their lack of significant equatorial divergence, Argo floats can also provide a mechanism to enhance the resolution of subsurface temperature and salinity profiles near the equator.

As such, the TAOS Review endorses and recommends full implementation of the "Argo 2025" vision (https://www.frontiersin.org/articles/10.3389/fmars.2019.00439/full) of a globally integrated Argo program including approximately 2500 core Argo floats, 1000 BGC-Argo and 1250 Deep Argo floats (Fig. 5.2). This plan includes a doubling of the Argo density in the near-equatorial regions (globally), as well as in other key areas including western boundary current regimes and within the Caribbean Sea.

Although it will require a substantial increase in resources and partnerships, the implementation of BGC-Argo as envisioned in the Argo 2025 design is realistically the only way that consistent, broad-scale data on biogeochemical processes at the desired temporal and spatial scales can begin to be gathered at the basin scale. The enhanced Argo density near the equator will also help to resolve subsurface temperature and thermocline variability associated with development of the zonal mode, and deep Argo will provide much needed data to track deep water property changes and heat storage on sub-decadal time scales.

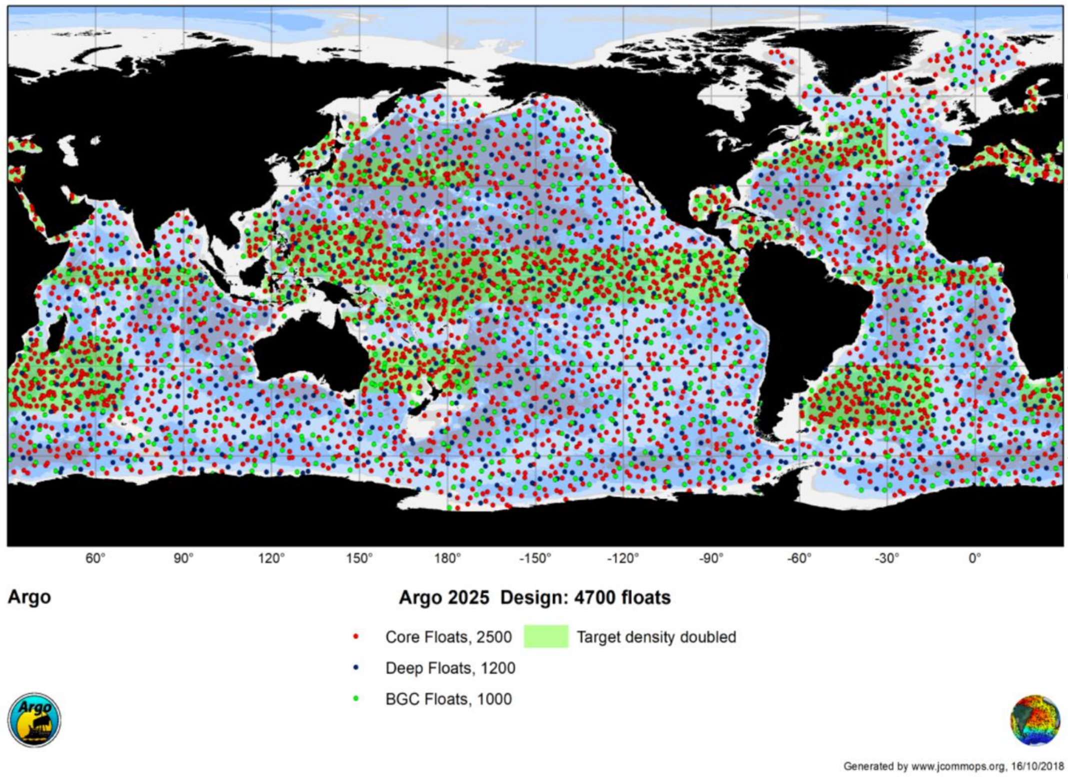

Figure 5.2 The “Argo 2025 Design” sampling vision for the global oceans, indicating regions of higher resolution Argo sampling (green shading) and the approximate distribution of core Argo, BGC-Argo, and deep-Argo floats.

5.2.4 Vessels

As the PIRATA program constitutes one of the largest commitments of ship resources to the tropical Atlantic, a continued effort should be made to expand measurements of biogeochemical, biological, and atmospheric data on these cruises in addition to the physical oceanographic measurements that are routinely made along the repeated ship track lines.

All PIRATA cruises currently perform conductivity-temperature-pressure ($CTDO_2$) casts to observe T, S, O_2, as well as collect underway SST, SSS, current, pCO_2, and velocity data. Typically the $CTDO_2$ stations extend to maximum depths of 1500-2000 m, but recently (on the 2017 Brazilian mooring cruise and from 2018 onward on French mooring service cruises) the stations have been extended to full depth or 4,000m depth, for Deep-Argo profiles validation, including water samples for pH, nutrients, and trace elements. Nutrients have been systematically measured since 2004 during the yearly PIRATA-FR cruises, either from sea surface water samples or as vertical profiles from CTD bottle casts at a subset of CTD stations. Chlorophyll pigments (through phytoplankton pigments) have also been analyzed during PIRATA-FR cruises since 2011, along with additional biological samples (zooplankton, Sargassum algae).

During many of the PIRATA cruises, atmospheric profiles have been obtained using radiosondes and ozonesondes (measuring aerosols, temperature, ozone concentrations in the atmosphere), often in collaboration with other science programs (e.g., AEROSE). Additionally, on PIRATA-US cruises, underway M-AERI measurements of spectral infrared emission from the ocean and atmosphere are collected, as well as atmospheric water vapor and cloud liquid water data, for use in correcting satellite infrared SSTs. Turbulent fluxes at the air sea interface were also recently measured from a meteorological tower on the 2017 PIRATA-BR cruise. A summary of the full suite of ancillary measurements collected on PIRATA cruises can be found in Bourlès et al. (2019).

The TAOS review ***recommends that an increased emphasis be placed on collecting multi-disciplinary vessel-based observations, particularly on the annual PIRATA mooring servicing cruises, to serve the needs of the broader TAOS science community and operational centers.***

Additional regular sampling of the following parameters or variables either continuously along the cruise track or at a pre-defined subset of deep stations would be highly valuable:

Seawater samples for:

- Nutrients
- Inorganic carbon and alkalinity analysis (pH, dissolved inorganic carbon, total alkalinity, pCO_2)
- Chlorophyll pigments

Turbulent flux measurements from ship-mounted towers

Radiosonde/ozonsonde vertical profiles

Biological sampling (phytoplankton/zooplankton)

Additionally, full depth sampling of standard parameters (T, S, O_2) and relevant ancillary parameters at an appropriately selected subset of stations, along with full depth lowered-ADCP (LACPD) velocity profiles, is desirable.

GO-SHIP repeat hydrography also provides vital sampling of a full suite of physical and biogeochemical parameters through the tropical Atlantic and should be sustained, along with consideration of an additional zonal section near 10°N.

The VOS XBT program presently occupies three lines in the tropical Atlantic on a regular basis, with a key line being the AX08 section that crosses through the S. Atlantic where there is little data and also cuts meridionally though the center of the basin across the cold tongue, and these measurements should be continued.

For the carbon system, it is further important to maintain, and expand on, the current frequency of high-quality pCO_2 (as well as SST and SSS) from the VOS fleet that transits the tropical Atlantic and on RVs operating in the area.

5.2.5 Satellite observations and future needs

The adequacy of the past and current oceanographic satellite observations in monitoring various EOVs is summarized by the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organization (WMO) and UNESCO's Intergovernmental Oceanographic Commission (IOC) in its Ocean Observing System Report Card 2019 (http://www.jcommops.org/reportcard2019/), which is updated on an annual basis through a synthesis of the health of satellite missions measuring various EOVs. The Report Card also provides an outlook for the future health of the satellite observing system.

For SSH, the altimeter mission constellation is in its golden age with continuity missions planned through 2030. The Surface Water Ocean Topography (SWOT) mission (planned launch date 2021) will provide submesoscale SSH measurements with a 22-day repeat cycle.

For SST, the continuity of IR SST mission is ensured (e.g., with the operational NOAA series satellites). PMW SST continuity is a looming issue, thus its designation as having a "marginal" status in the out years. However, ESA is supporting a mission concept (currently in Phase A) called Copernicus Imaging Microwave Radiometer (CIMR) that includes C-band to continue PMW SST measurements. In addition, JAXA is also supporting a mission concept study in the framework of the GCOM-W series. ***As PMW SST sensing is particularly important in the tropical Atlantic due to a high incidence of cloudy conditions, the continuity of PMW SST sensor missions is vital to the TAOS.***

For wind, ESA's MetOp series will continue the C-band scatterometer wind measurements. Several other scatterometer missions are being planned by China and Russia. Indian ISRO is committed to the OceanSat series scatterometer. Despite these planned scatterometer missions, resolving the diurnal cycle remains an issue because it requires at least 3-4 scatterometers with equatorial crossing times for ascending or descending tracks that are separated relatively evenly through a 12-hour period. Moreover, one scatterometer covers approximately 30% of the global ocean at 6-hourly intervals. Three to four scatterometers (with coordinated orbit spanning across the diurnal cycle) can provide 90% or more coverage of the global ocean at such an interval. Given the three scatterometers in orbits currently with the equatorial crossing times not optimally spaced across the diurnal cycle, the health of the vector wind measurements is indicated as "marginal" in the Report Card. International coordination is essential in achieving such temporal coverage.

For SSS, no mission beyond SMOS and SMAP have been committed by ESA and NASA. However, ESA's CIMR mission concept now includes L-band in its baseline concept. China is also planning L-band SSS missions. As noted in several sections of this report, ***improved and expanded measurements of surface salinity are needed to address issues on the water cycle, subseasonal to decadal prediction, and climate change, and continued satellite SSS missions with improved accuracy are therefore vital to the TAOS***.

New satellite mission concepts for additional ocean variables are also being studied. For example, ESA is supporting a mission concept "Sea surface KInematics Multiscale monitoring" (SKIM) under the Earth Explorer 9 program. SKIM uses Ka-band Doppler altimetry technology to measure ocean surface currents and sea state simultaneously. NASA has been supporting the development of the DopplerSCatt airborne instrument (using Ka-band Doppler scatterometry technology) to measure ocean surface currents and vector winds simultaneously down to submesoscales. The technology is recommended by the US Decadal Survey for Earth Science and Applications from Space 2017-2027 as a candidate for competition in NASA's Explorer class missions.

Having such a satellite capability for continuous broad-scale surface velocity measurements would be of extremely high value for the TAOS - and for the tropics in general - due to limits on the applicability of geostrophy near the equator, and new missions such as SKIM and DopplerScatt should be supported as key future elements of the TAOS.

5.2.6 Other observing platforms

Newer observing platforms such as ocean gliders and ASVs (e.g., SailDrones, Wavegliders) should be considered for potential niche roles in the TAOS, as part of both targeted regional process studies and also possibly in a sustained mode, where they could be particularly valuable in extending in-situ data coverage into poorly sampled coastal regions. For example, gliders have already been used in several ocean mixing studies in the equatorial Atlantic and are currently being used by NOAA with regional partners to provide in-situ profile data in the NE Caribbean region for operational hurricane prediction efforts (https://www.aoml.noaa.gov/phod/goos/gliders/observations.php).

The pathway to broader sustained use of these technologies in observing systems is through pilot studies in targeted regimes where their usefulness and capabilities for extended use can be demonstrated. In the Process Studies section below we indicate a few areas where the potential use of such technologies seems ripe for consideration.

5.2.7 Process Studies

Process studies are an essential part of observing and prediction systems in order to drive new scientific understanding, develop and improve model parameterizations, and test new observing technologies.

Discussions during the TAOS review brought out several possible ideas for process studies or pilot observational studies involving new technologies. Among them are the following:

- Improved quantification of near-surface ocean mixing processes in different tropical Atlantic regimes using microstructure gliders and/or time-series observations of upper ocean shear and stratification such as those enabled by the recent TACOS enhancements on the PIRATA mooring at 4°N, 23°W.
- Investigation of atmospheric vertical momentum transport in the central and western tropical Atlantic to improve model representations of the relevant atmospheric processes and to help improve climate model biases in surface and lower tropospheric winds.
- Pilot studies using ASV technology (e.g., Saildrone) to:
    - sample surface ocean and atmospheric parameters (including pCO_2) in poorly sampled regions in order to fill important gaps in the present observing system
    - sample winds and surface ocean-atmosphere parameters in the SE tropical Atlantic eastern boundary region (Benguela upwelling zone) to improve understanding of processes leading to model biases in that region, possibly together with a targeted glider program
- A pilot study with drifting thermistor chains in the near-equatorial Atlantic to test their capabilities and what their potential impact could be on the reconstruction of subsurface thermal fields.
- A dedicated cruise for quantification of surface energy fluxes, including full turbulence sensors, such as that provided by the PSD Roving Ship Program (Fairall et al., 1997), focused on comparisons with PIRATA buoy fluxes in different regimes. The PSD program has visited the tropical Pacific and Indian Oceans but never the tropical Atlantic, and such a cruise would be highly valuable for comparison/calibration with tropical Atlantic buoy flux observations.

5.2.8 The need for improved data assimilation

A common theme that arose in the TAOS review discussions was the difficulty – even for a panel of experts – to adequately assess the current weaknesses of the TAOS and what kinds of observations are most urgently needed, and where. Since for most applications relevant to society it is the end product of the data and analysis systems that is of greatest value, i.e. the reanalysis and forecast products that are produced by operational centers, it is essential that the maximum value be extracted from the data provided by the observing system in the analysis systems that assimilate this data.

While data assimilation techniques have improved dramatically over the past decade, there is still wide agreement that they are not optimally using the data provided by observing systems (from the TAOS or otherwise), and that different systems often exhibit large differences in analyzed fields, particularly for subsurface fields that are not as well constrained as those at the surface (e.g. SST and SSH). Model biases are also likely to contribute to the suboptimal use of data in present reanalysis systems.

A key illustration of the problem for the tropical Atlantic is shown in Fig. 5.3, taken from the Real Time Multiple Ocean Reanalysis Intercomparison project performed through GODAS (http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html). As shown in the figure, there are rather dramatic differences in the analyzed temperature anomaly field along the equator (averaged between 1°S to 1°N) between the various analysis products, with a resulting signal-to-noise ratio that is effectively zero over most of the entire equatorial domain. Important differences even occur at the locations of PIRATA moorings (at 0°E, 10°W and 23°W) that were actively providing data to the assimilation systems during this time. The example shown (for April 2019) is typical of the model reanalysis differences, and occurs at a particularly important time in the tropical Atlantic, when preconditioning of the thermocline along the equator has an important bearing on the summertime development of the zonal mode and its corresponding climate impacts.

The question then naturally arises as to whether the PIRATA array and additional profile observations available near the equator (e.g. Argo) inherently provide insufficient data to constrain the analyses, or whether the problem lies more fundamentally in the data assimilation systems and/or models used. Clearly, there is an urgent need for advanced data assimilation studies based on established OSSE or OSE frameworks to help resolve these issues and help determine the resolution of the required observations. The few such studies which have been done to date (e.g. the AtlantOS H2020 report on "Synthesis of OSSE results", Aug. 2018; https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D1.5.pdf) show that the impact of mooring observations on monitoring and forecasting systems is highly localized, and does not significantly affect the large-scale structures, suggesting that present assimilation schemes are not sufficiently progressed to extract the maximum information from moorings. Similar issues may apply to the ingestion and optimal use of other components of the basin-wide observing system.

A consensus recommendation from the TAOS review is therefore that a large-scale and adequately-resourced effort needs to be undertaken to investigate deficiencies in data assimilation systems and how existing data available from observing systems can be most effectively used to constrain reanalysis and forecast products. Such an effort might logically consist of two components:

- An OSSE framework in which data are extracted from a base (nature) model run and ingested in other models to explore the required temporal and spatial resolution of data to recover the “correct” model state in reanalysis mode, using current data assimilation schemes. Experiments with different assimilation methods and parameters could also be used to test which strategies can produce more accurate field reconstructions with fewer observations.
- An OSE framework in which results of the above OSSE experiments are applied to assess the influence of particular observational platforms and discrete observations on ocean analysis and subsequent forecast skill.

As part of such an effort it will be important to have specific “targets” for model skill assessment that involve key regional phenomena and observables (e.g., the temperature structure along the equator as in the above example), and it is recommended that the regional CLIVAR panels (in this case of the tropical Atlantic, the ARP) work to develop such indices that can be used as benchmarks in these recommended OSSE/OSE studies. Assessing the role of model errors in reanalysis or forecast skill should also be a critical part of this effort.

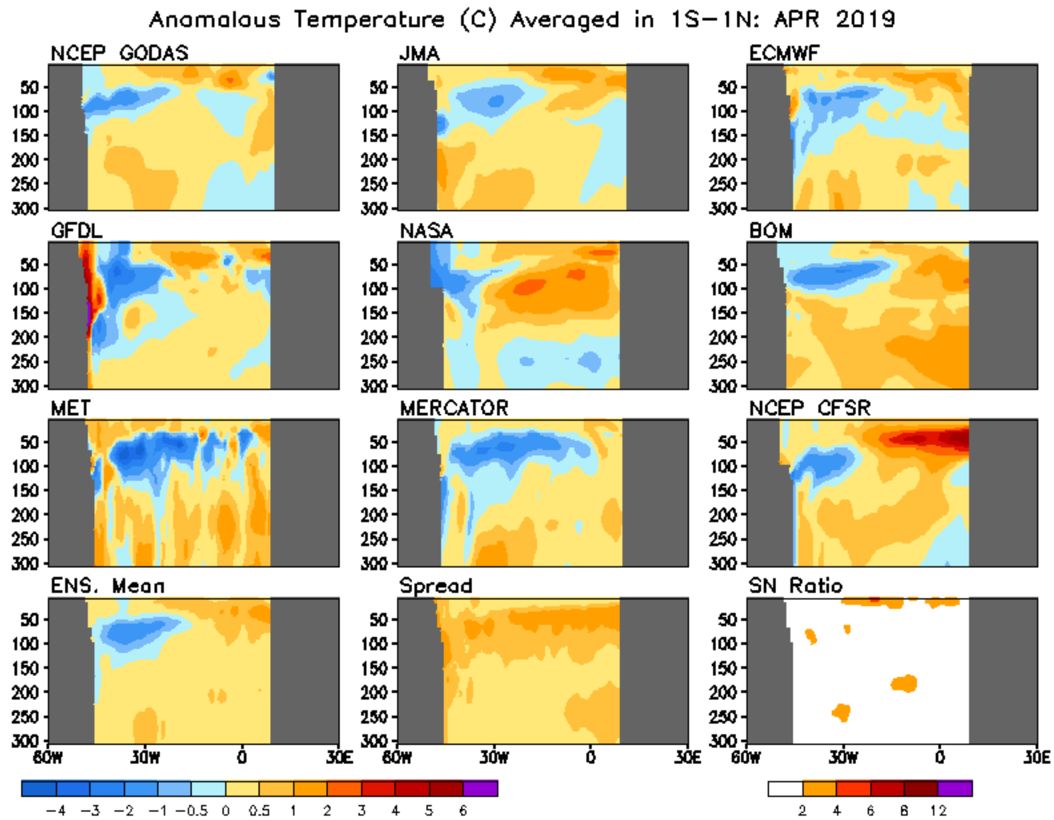

Figure 5.3 Monthly temperature anomaly along the equator in the Atlantic for April 2019, from 10 different operational analyses. The spread and signal-to-noise ratio of the analysis products are shown in the last two panels.

6. Data Flow and Information Products

6.1 Summary of current data availability and access

Most of the data collected by various observing elements of the TAOS is available online and is made available to users either through platform-specific data websites or through integrated data products served by operational and data centers.

The various data types and products and where they are accessible are listed below.

6.1.1 Moored Platforms

PIRATA: https://www.pmel.noaa.gov/tao/drupal/disdel/

NTAS: http://uop.whoi.edu/currentprojects/NTAS/ntas.html

NDBC: https://www.ndbc.noaa.gov/

CVOO: http://cvoo.geomar.de

MELAX: (no data online)

OCEANSITES: https://dods.ndbc.noaa.gov/oceansites/

MOVE: http://www.oceansites.org/tma/move.html

WBCS/RACE/SAUCUS (11 S): http://www.oceansites.org/tma/11s.html

6.1.2 Argo and other in situ sub-surface data

Quality-controlled Argo profile data

Interactive data display and delivery:

http://www.argodatamgt.org/Access-to-data/Argo-data-selection

FTP from GDAC servers:

Coriolis : ftp://ftp.ifremer.fr/ifremer/argo

US GODAE: ftp://usgodae.org/pub/outgoing/argo

Mapped Argo products

http://www.argo.ucsd.edu/Gridded_fields.html (contains a large selection of gridded Argo products (including Argo-only and merged with other hydrographic profile data)

In situ sub-surface ocean data

EN4 profiles and analyses (https://www.metoffice.gov.uk/hadobs/)

Copernicus Marine Insitu NRT & CORA product

6.1.3 Surface drifters

Quality-controlled drifter data (with regional subset access)
https://www.aoml.noaa.gov/phod/gdp/interpolated/data/subset.php

Surface current climatology from drifters

https://www.aoml.noaa.gov/phod/gdp/mean_velocity.php

ftp://ftp.aoml.noaa.gov/phod/pub/lumpkin/drifter_climatology

6.1.4 Ship data

PIRATA shipboard station data

https://www.seanoe.org/recordview, search:PIRATA

http://pirata.ccst.inpe.br/en/data-2/

https://www.aoml.noaa.gov/phod/pne/cruises.php

Go-Ship (including Carbon system data)

http://www.go-ship.org/DataDirect.html

XBT

https://www.aoml.noaa.gov/phod/goos/xbtscience/data.php

GOSUD

http://www.gosud.org/Data-access

SOCAT

https://www.socat.info/index.php/data-access/

6.1.5. Satellite Data and Blended Products

Winds

Cross-Calibrated Multi-Platform Wind (CCMP) analysis (http://www.remss.com/measurements/ccmp/)

IFREMER blended wind analysis (http://apdrc.soest.hawaii.edu/datadoc/ifremer_LOPS_blended_wind_6hourly.php),

NOAA's blended wind analysis (https://www.ncdc.noaa.gov/data-access/marineocean-data/blended-global/blended-sea-winds)

OAFLUX wind analysis (http://oaflux.whoi.edu/wind.html)

SST

GHRSST (https://podaac.jpl.nasa.gov/GHRSST).

HadSST/HadISST

(https://www.metoffice.gov.uk/hadobs/)

NOAA OISSTV2 (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html)

SSH

http://marine.copernicus.eu/faq/ssaltoduacs-integrated-sealevel-anomalies-products-changes-updates/

Precipitation

https://pmm.nasa.gov/TRMM/realtime-3hr-7day-rainfall

https://pmm.nasa.gov/data-access/downloads/gpm

SSS

https://smos-diss.eo.esa.int/oads/access/

https://podaac.jpl.nasa.gov/aquarius

https://podaac.jpl.nasa.gov/SMAP

Chlorophyll

https://esa-oceancolour-cci.org/

Ocean mass/bottom pressure

https://podaac.jpl.nasa.gov/GRACE

Clouds and Aerosols

https://isccp.giss.nasa.gov/products/onlineData.html

https://modis-atmosphere.gsfc.nasa.gov/products/aerosol

6.1.6 Biogeochemical data

BCG-Argo data

ftp://usgodae.org/pub/outgoing/argo

ftp://ftp.ifremer.fr/ifremer/argo

Analysis products

MERRA-NOBM (NASA Ocean Biogeochemical Model) Reanalysis:
https://gmao.gsfc.nasa.gov/reanalysis/MERRA-NOBM/data/

6.1.7 Fisheries

EAF Nansen Survey data

http://preface.imr.no/index.php/EAF_Nansen_Data_Service (restricted access)

ICCAT

https://www.iccat.int/en/accesingdb.html

OBIS

https://obis.org

6.1.8 Integrated data access and services

Copernicus/CMEMS

http://marine.copernicus.eu

ERDDAP

https://www.ncei.noaa.gov/erddap/index.html

6.2 Recommendations for data/information products and delivery

6.2.1 Overview and general principles

This Review has not found any major TAOS-specific issues regarding data and information management; most of the TAOS challenges are shared with the global community. Several community white papers were prepared for the OceanObs'19 conference reviewing and discussing these challenges (Tanhua et al., 2019b; Pinardi et al., 2019; Snowden et al., 2019; Vance et al., 2019; Pearlman et al., 2019; de Young et al., 2019). de Young et al. (2019) discuss the issues within the context of AtlantOS, of which TAOS is a regional subset, and Chapter 8 of the TPOS 2020 2nd Report (http://tpos2020.org/project-reports/second-report/; hereafter TPOS_2R8) discusses related issues for that region.

These ideas are further developed here within the context of TAOS and recommendations are made around needed action. Implicit in this discussion is the conclusion that it is more effective to provide advocacy and support for global actions and efforts that will benefit TAOS indirectly compared with initiating additional bespoke activities focused on TAOS platforms and systems.

It should be noted that global coordination and facilitation mechanisms may not always maintain the regional TAOS stakeholder engagement and interest, nor maintain the strong partnerships with science that are so essential for maintaining high-quality data streams. The level of Tropical Atlantic data center capabilities and capacity are mixed, pointing to a need for greater involvement/engagement, particularly with developing countries. The movement towards open data sharing is uneven through the region, sometimes due to technical and/or capacity barriers, but also due to cultural and/or historical issues around access.

Tanhua et al. (2019b) and Snowden et al. (2019) reached similar conclusions with respect to investment in data management: namely that, with only a few exceptions, data management is poorly funded in the context of its critical role in the ocean observing system and, therefore, that ocean data are often not processed (or reprocessed) at a level that realizes the true potential and benefit, and in a form suitable for true interoperability and reusability (see also TPOS_2R8). We support these views and the ***TAOS Review concludes that, as an underlying principle, around 10% of the investment in the TAOS observing infrastructure should support data and information management, including for new technologies.***

TAOS data should be Findable, Accessible, Interoperable, and Reusable (known as FAIR). The importance and fundamental role of the FAIR principles were discussed in general by Tanhua et al. (2019b) and by de Young et al. (2019) in the context of the Atlantic. We wish to reinforce the need for all stakeholders to engage with and support data management, and to do so in accordance with principles that maximize the value of data (e.g., the FAIR Principles). The ***TAOS Review concludes that data stewardship, and the engagement of all TAOS stakeholders in data management, are central for the sustainability of TAOS and that TAOS data management should conform with the FAIR Principles.***

More generally, and from results from AtlantOS, there is evidence of satisfactory progress on integration – e.g., the concept of 'integrators' within the data system (de Young et al., 2019; see below). The NOAA/OAR/COD integration strategy through "ERRDAP" provides multiple access and discovery services for near real time data. Work on best practices (led by IODE/JCOMM) has the potential to benefit TAOS (see Pearlman et al., 2019 for more detail).

6.2.2 Ease of access to the data system and TAOS data

There are many good examples of 'best practice' data management for TAOS, such as PIRATA (section 4.1), Argo (section 4.3) and various satellite systems (section 4.5). We have not identified any major risks for TAOS from the current approach to information systems, though there are areas that need improvement. The move to integrated systems and services is a positive step, taking advantage of more generic data system services. We recognize the value of multiple channels and different offerings; the sense of acquire once and serve in multiple ways. However, there are some aspects of access that warrant attention.

The architecture of the data system is opaque and probably needs review. There is uncertainty around end-to-end delivery (for example, unexpected data gaps); data access protocols are sometimes restrictive and difficult to navigate (e.g. Jörn Schmidt presentation at the first TAOS Workshop); and modelers have identified what they see as barriers for assimilation. The TAOS is encouraged to work harder on making the data easy to access (including aggregation and low level consolidated products).

Climate users, including research, highlight the importance of quality, most of which is only possible with off-line scientific interventions, such as practiced by the Argo consortium. The TAOS climate record depends critically on the quality control provided by such processes. Moreover, the integrity of climate data records is often secured and enhanced through such delayed-mode processing.

TAOS aspires for a better understanding of data use and for the data system architecture to be user driven. Users often see our data access systems as too complex and not friendly. Our field is complex, but we should ensure our data management expertise is brought to bear in a positive and enabling way for users.

6.2.3 Integrated Data Systems

Tanhua et al. (2019b) motivated their paper with a list of challenges facing ocean data management:

- Wide diversity
- Multitude of disparate data management structures
- Increased volume of data
- New sensors creating new formats
- Widely used formats not universally applicable
- Gap between data-producing scientists and downstream users of the data
- Development of common protocols takes time
- Best practices poorly defined

The TAOS Review has encountered each of these in one form or another. Chapter 4 bears testament to the diversity and volume of data now embraced within TAOS, including emerging data streams. Section 6.1 reveals the distributed, and disparate nature of the approach to making data available. While there has been progress in standardizing formats (e.g. through use of the GTS and NetCDF standards) and developing guidance on best practices (Pearlman et al., 2019), there is often a reluctance or inability to invest effort in properly documenting the data (metadata). As Tanhua et al. (2019b) note, data that are poorly documented can be considered lost and will have little or no value without access to the team that collected the data.

Two specific examples are provided by PIRATA. Access to PIRATA cruise underway and station data (see section 4.4) is not integrated (each country has its own data access site and formats, etc.). It would be more effective and accessible if it was integrated as is done with the PIRATA mooring data, and “complete” in terms of data types available. Second we note that while the PIRATA mooring data delivery site (https://www.pmel.noaa.gov/tao/drupal/disdel/) provides user-friendly FAIR access to all PIRATA mooring data, it does not serve all mooring data in the tropical Atlantic (a similar issue was noted for the tropical Pacific; see TPOS_2R8). While there are other systems for merging mooring data (e.g., OceanSites), the TAOS system would benefit from a single data service for all tropical Atlantic mooring data, where users could access and readily display or download specific data.

The JCOMM and the new WMO Information System (WIS) are endeavoring to establish global information and management systems that will provide a cost-effective way to increase and improve accessibility, interoperability, visibility, utility and reliability. The ***TAOS Review concludes that the TAOS community should work with these global efforts to maximize the benefits from TAOS data.***

TPOS_2R8 and de Young et al. (2019) discuss attributes of more integrated and seamless approaches to data management (Fig 6.2.1). The WMO Information System (see Pinardi et al., 2019; Tanhua et al., 2019b) provides core real-time capability with strict guidance on input and access. Systems such as ERRDAP potentially provide more flexible and user-friendly input interfaces to complement those of WIS. TAOS users could access data from the WIS, from dedicated data services, and from ocean data services. In principle, the functionality would be seamless.

The AtlantOS schematic (Fig. 6.1, bottom) similarly shows a set of tools for bringing platform data into the data exchange backbone, combined with a set of tools providing general user capability. Standards would apply across the systems.

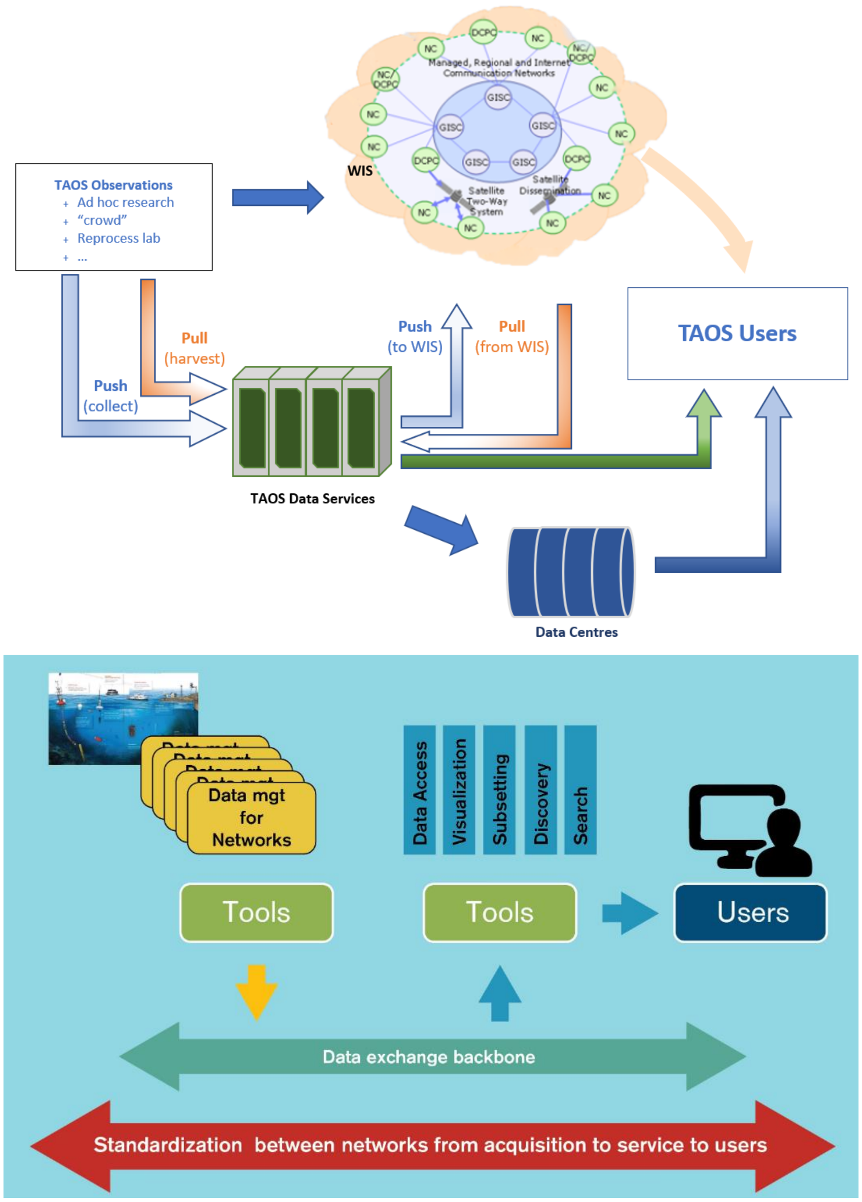

Figure 6.1 Top: A schematic from TPOS_2R8 showing how ocean data systems and the WIS may operate together, covering different data sources, and both real-time and delayed-mode (climate) streams. Bottom: schematics of the target ocean data flow from observations to users (in yellow: observing network data systems; in blue: integrators; in green and red: harmonization and integration elements). Source: AtlantOS/de Young et al. (2019)

There is potential to use such approaches as a virtual data management environment whereby distributed data providers can use a third-party managed and maintained environment to, first, get data and metadata into the system, and second to provide generalized access. Basic data management tools and facilities are provided by the system to data providers, associated users, and other interested parties to reduce barriers to access. With the appropriate back-end infrastructure the data would become findable, accessible and (to some extent) interoperable and reusable simply by the scientist/data provider properly documenting the data and making it available through an interoperable data platform. The *quid pro quo* in such an arrangement is that the scientist/data provider gets cost-effective (perhaps even free) access to a data management service (at the cost of some set-up work) while the community "common good" is served by including a broader set of inputs.

The basic idea is that such a system would become a system of choice, and for cloud and Virtual Research Environments (VREs) and their more general equivalents to become mainstream; see Vance et al. (2019) for a more detailed discussion. The ***TAOS Review concludes that the TAOS community should adopt a strategy that supports greater integration, more consistent adoption of standards and best practice, and technologies that provide virtual data management environments.***

6.2.4 Processing and Products

Users often access TAOS data through assembled/process data sets and higher level products (section 6.1). Ocean, atmosphere and climate (sometimes coupled) analysis and prediction systems use a variety of techniques to develop these products, with varying levels of sophistication and accuracy.

Re-processing and re-analyses are now important elements of data and information systems and the path from data collection to societal use. Re-processing data allows for re-assembly and merging of data communicated in real-time and data received in delayed mode (for example, high-quality subsurface mooring data), taking advantage of levels of quality control/assurance that are not possible in real-time, and application of new techniques that may not have been available at the time of collection. Reanalyses are 3-dimensional gridded products combining many sources of ocean data and information through data assimilation; the products are generated after a delay to allow better observational quality and coverage to be achieved (the re-processing step). Such products are useful when a consistent gridded dataset is needed or in circumstances where direct observations are sparse (or not possible) and running with a delay allows more TAOS data to be brought to bear.

The uptake of such datasets and products continues to grow. Figure 6.2 shows one such example (see section 6.1 for other references) drawn from the Copernicus Marine Environmental Monitoring Service (http://marine.copernicus.eu/) which covers both data and product access. The growth of both subscriptions and downloads continue to accelerate. The users come from over 180 countries and there are over 2,900 regular users (Fig. 6.3). In the case of CMEMS, dedicated service desks are provided to facilitate access and better use, but they too recognize further efforts are required (CMEMS, 2019).

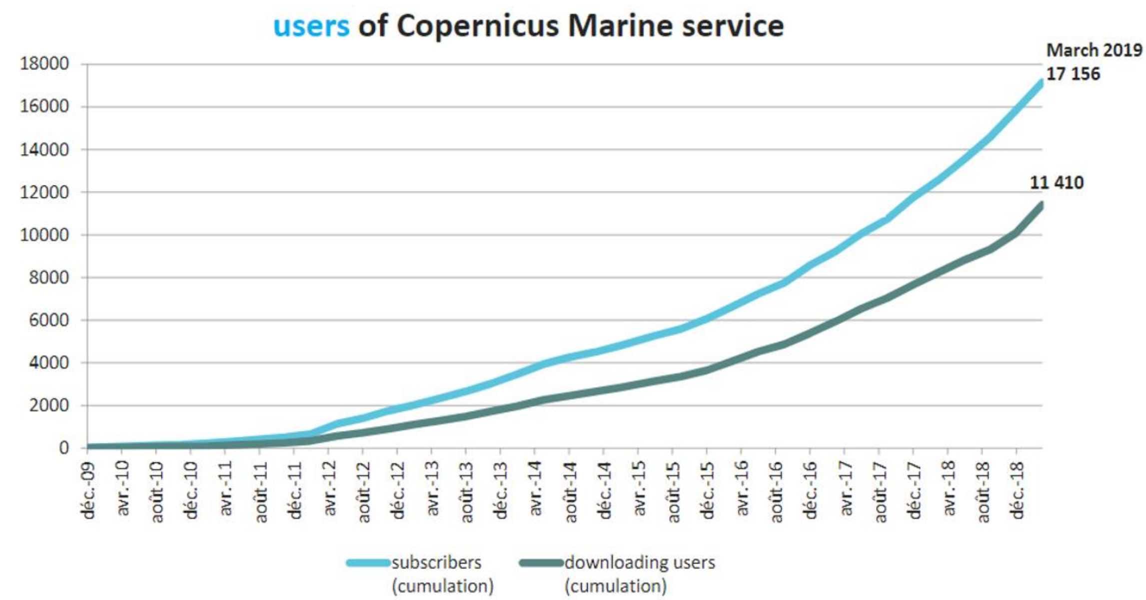

Figure 6.2 Schematic showing the growth of user uptake in CMEMS as reflected in downloads (green) and service subscription (aqua). From CMEMS (2019), credit D. Obaton and M. Fabardines.

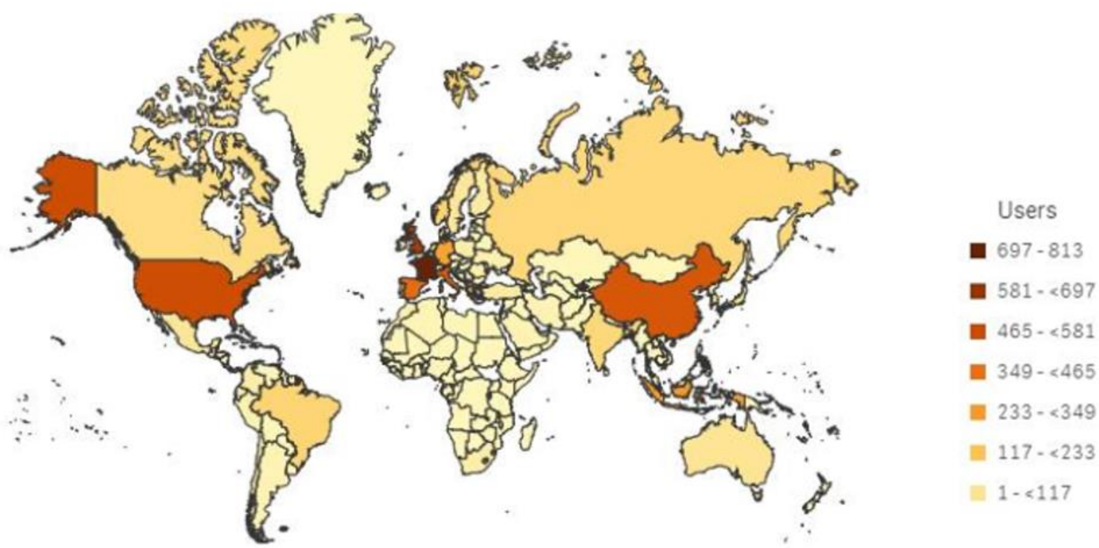

Figure 6.3 Geographical distribution of CMEMS users (from L. Crosnier and A. Delamarche, CMEMS, 2019)

Such global systems provide valuable services for TAOS data providers and the TAOS user community more generally. CMEMS and similar systems are used to monitor the variability and state of the tropical Atlantic (targeted products), and to help guide the design of observational networks/systems (OSEs, OSSEs, sensitivity studies / reanalyses). There is considerable interest in monitoring products for the carbon cycle, and CMEMS products are used in the Ocean State Report and in developing ocean state indices (for example, von Schuckmann et al., 2018). The resolution and complexity of such systems are increasing, leading to dissemination issues and greater use of technologies suited to "big data" (e.g., Clouds, Platforms-as-a-Service/PaaS).

TAOS should have better diagnostics on the use of ocean data by TAOS stakeholders (TAOS and other global platforms). JCOMMOPS provides tools to monitor TAOS platforms and data production, while CMEMS and similar production systems provide opportunities to better monitor uptake and exploitation of TAOS data. The ***TAOS Review concludes that improved systems for monitoring TAOS data production and use should be in place.***

6.2.5 Conclusions

The ***TAOS Review concludes:***

(1) As an underlying principle, around 10% of the investment in the TAOS observing infrastructure should support data and information management, including for new technologies.

(2) TAOS data management should conform with the FAIR Principles, and that data stewardship, and the engagement of all TAOS stakeholders in data management, are a central priority for the sustainability of TAOS.

(3) The TAOS community should adopt a strategy that supports greater integration, more consistent adoption of standards and best practice, and technologies that provide virtual data management environments.

(4) Improved systems for monitoring TAOS data production and use should be in place.

7. Governance, Review and Resourcing

In this chapter we address the need of a governance system for TAOS. We start this chapter with a first section that describes the current governance of each major core element of TAOS constituting today the backbone of the observing system. In a second section, the Review proposes a possible way forward for the TAOS governance and resourcing. A last section, where the TAOS Committee suggests a periodic review of the observing system, concludes the chapter.

7.1 Summary of current governance and resourcing structure for TAOS elements

7.1.1 PIRATA

PIRATA (Pilot Research Moored Array in the tropical Atlantic) is a multinational program between Brazil, France and the United States of America, established to improve our knowledge and understanding of ocean-atmosphere variability in the tropical Atlantic (Servain et al., 1998). After a "pilot phase" from 1997 to 2001, during which the 10 buoys of the backbone array were fully implemented, institutions in the three supporting countries decided to extend the program for a 5-year "consolidation phase" to allow for a meaningful demonstration that the data would contribute significantly to both scientific research and operational applications. After its evaluation by CLIVAR and OOPC in 2006, the network progressively evolved, and the number of buoys increased to 17 in 2007. PIRATA was subsequently renamed the "Prediction and Research Moored Array in the Tropical Atlantic" (Bourlès et al. 2008). An 18th buoy, funded by Benguela Current Large Marine Ecosystem in 2006, was deployed in the Southeast, off Congo, during a one-year test in 2006-2007; this location was re-established in 2013 with a 2nd buoy funded by the "Enhancing Prediction of Tropical Atlantic Climate and its Impacts" programme (PREFACE; https://preface.w.uib.no/) under the European Union's 7th Framework Programme (FP7).

PIRATA began in 1997 thanks to the prior financial support of National Oceanic and Atmospheric Administration -NOAA (US), Instituto Nacional de Pesquisas Espaciais -INPE and Diretoria de Hidrografia e Navegacão -DHN (Brazil), French Institut de Recherche pour le Développement -IRD, Meteo-France and Centre National de la Recherche Scientifique -CNRS (France). PIRATA is maintained from 1997 by a close collaboration between institutions in the US (NOAA), Brazil (INPE, with a contribution from DHN) and France (IRD and Meteo-France). These institutions established a formal partnership in 2001 through a Memorandum of Understanding (MoU) to provide long term support for PIRATA. The MoU was signed for a five year period, and then extended until 2008. It was renewed in 2009 and extended again for a further five years in 2014. The present MoU is available until July 2019 and is now in the process of being renewed. All partners are funded by their Governments through national research organizations, i.e. NOAA in US, IRD (3/4 of functioning) & Meteo-France (1/4 of functioning) and the French Research Ministry (vessel time) in France and MCTIC (through INPE) & DHN (vessel time) in Brazil.

The MoU document contains the terms of organization and management of PIRATA. A PIRATA Resources Board (PRB) is established with Terms of Reference (TOR). The initial members of the PRB are managers representing INPE, IRD, Meteo-France, and NOAA. Although the PRB is presently composed of representatives from institutions only in Brazil, France, and the United States, it will welcome other institutions and other nations if they wish to contribute to the PIRATA Program. The Chairman of the PRB is designated by the PRB members. The principal tasks of the PRB are: i) to review the requirements for the implementation of PIRATA; 2) to coordinate resources that may be applied to the Program; 3) to encourage scientific and technological initiatives in the participating countries to meet the objectives of PIRATA; 4) to report on its activities to the Heads of the institutions providing resources.

The PRB is guided by the scientific objectives and research strategy formulated by the PIRATA Scientific Steering Group (PIRATA-SSG), which is regarded as the main scientific and operational body to advise the PRB. The PIRATA-SSG is formed by researchers, managers, and representatives of operational agencies of the Parties or other institutions who are recognized as scientific and operational experts in the area of the tropical Atlantic climate. Members are nominated by the PIRATA-SSG in consultation with appropriate international sponsoring bodies participating in GOOS, GCOS, and CLIVAR, and are approved by the PRB. The Chairperson of the PIRATA-SSG is designated by the SSG members. The PIRATA-SGG currently consists of 13 members: 4 for each partner country and one from Germany. The principal tasks of the PIRATA-SSG are: 1) to ensure accomplishment of the scientific and technical objectives as described in the PIRATA Scientific and Implementation Plan, and as accepted by the Parties; 2) to coordinate the technical and logistic support necessary to maintain the array; 3) to ensure the rapid dissemination of PIRATA data (in real-time where possible) to serve both research and operational applications; 4) to promote the utilization of PIRATA data in national and international climate research and operational prediction programs; 5) to evaluate, encourage, and promote pilot extension projects that could enhance the original PIRATA array; 6) to coordinate with other ongoing and planned observational efforts in the tropical Atlantic region; 7) to invite collaborations with other nations and institutions interested in implementing a sustained climate observing system in the tropical Atlantic; 8) to cooperate with international organizations such as the CLIVAR Atlantic Panel, the GOOS/GCOS/WCRP Ocean Observations Panel for Climate (OOPC), and the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) to ensure an integrated approach to observing the climate system in the tropics; 9) to report regularly on the status of the PIRATA array and scientific results to the PRB, GCOS, GOOS, JCOMM and CLIVAR.

Finally, each supporting country has a PIRATA National Coordinator. The national coordinators are members of the PIRATA-SSG. INPE serves as the coordinator of PIRATA in Brazil, and the national coordinator is indicated by INPE to be the representative of PIRATA-Brazil. The support of DHN, critical to the success of PIRATA, is arranged through INPE. IRD serves as the coordinator of PIRATA in France, in association with Météo-France, and the national coordinator is indicated by IRD to be the representative of PIRATA-France. NOAA serves as the coordinator of PIRATA in the United States. A national coordinator is indicated by NOAA to be the representative of PIRATA-United States of America.

The coordination between the Parties is ensured jointly through the PRB and the SSG, especially through the chairmen of these two committees and the national coordinators.

PIRATA leadership has continuously evolved the array to keep pace with changing scientific priorities and taken advantage of new technologies as they become available, and the program is well managed with a stable base of support in three countries.

7.1.2 International Argo Project (Argo)

The Argo Program is a global array of free-drifting profiling floats that measures the temperature and salinity of the upper 2000 m of the ocean. Since its inception, the primary goal of the Argo Program has been to create a systematic global network of profiling floats that can be integrated with other elements of the Global Ocean Observing System (Argo Science Team 1998). The current array consists of approximately 3,800 floats with a nominal coverage of $3° \times 3°$ of the ice-free ocean (Riser et al. 2016).

The Argo Program has collected over 2 million hydrographic profiles that are archived in the Global Data Assembly Center (GDAC) repository and are freely available to the public. The network provides upper-ocean data within 24 hours of data transmission from the floats.

The International Argo Program is governed by the Argo Steering Team (AST) that provides scientific leadership and oversees the development and implementation of the global array operated by national and regional Argo projects. The AST is composed of scientists and technical experts from national projects contributing to Argo, along with the chairs of the Argo Data Management Team, the Argo Program Director, the Argo Technical Coordinator, and representatives from CLIVAR and GODEA.

As Argo has matured over the past 18 years, it has expanded into new areas of research that were not envisioned in the original planning for the program. The Argo array continues to evolve and enhancements to the Argo array have been suggested to improve the observation of certain energetic regions. In particular, expanding the array into marginal seas, increasing the float array density around western boundary current extensions (such as the Gulf Stream), and a doubling in the equatorial region is also being discussed (Jayne et al. 2017). Additionally, float technology has continued to advance with deep and biogeochemical models being developed. The full-ocean depth (6,000 m) float models are currently being deployed in pilot arrays (Johnson et al. 2019), with a large-scale deployment planned for the Brazil Basin. At the same time, biogeochemical profiling floats are also being added to the Argo program (Riser et al. 2018). The success of Argo is largely built on international cooperation and the free sharing of the data. The program has evolved from modest beginnings to a present that was not then fully envisioned, and with a future that is still evolving.

The terms of reference for the ARGO Steering Team can be found at: http://www.argo.ucsd.edu/scienceteam.html

7.1.3 Global Drifter Program (GDP)

The global drifter array is primarily supported by the United States' National Oceanic and Atmospheric Administration (NOAA)'s Global Drifter Program (GDP), funded by NOAA's Global Ocean Monitoring and Observing (GOMO) program. The objectives of the GDP are to maintain a global 5x5 degree array of ~1300 satellite-tracked surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations, and provide a data processing system for scientific use of these data. These data support weather forecasting, ocean state estimation, seasonal to interannual climate predictions, and climate research and monitoring. Drifter data are available at http://www.aoml.noaa.gov/phod/gdp. The drifter data management plan is described in Keeley et al. (2010).

A GDP drifter consists of a surface float attached by a tether to a holey-sock drogue (sea anchor) centered at 15m depth (Niiler 2001; Lumpkin and Pazos 2007). The surface float includes alkaline batteries, GPS, an Iridium satellite modem, a tether strain sensor for drogue presence detection, and a thermistor that measures sub-skin SST. Around 50—60% of the drifters also have barometers for sea level atmospheric pressure; these observations have been demonstrated to significantly improve weather forecasts (Centurioni et al. 2017). The drogue ensures that SSV can be derived from position changes with <1 cm/s error in 10 m/s wind (Niiler et al. 1995; Lumpkin et al., 2013). Modern drifters provide hourly measurements of SST and location (Elipot and Lumpkin 2008; Elipot et al. 2016). The GDP relies on numerous national and international partners such as weather agencies to provide deployment opportunities worldwide, fund additional drifters, and fund the addition of barometers to GDP-purchased drifters. These efforts are coordinated through the Data Buoy Cooperation Panel (DBCP) of the World Meteorological Organization and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The DBCP TOR can be consulted at the following address: https://www.jcomm.info/index.php?option=com_oe&task=viewGroupRecord&groupID=104.

7.1.4 Suggested enhancement of interactions with other observing structures

TAOS should also connect and work with other "governance" structures currently in place for other aspects of the observing system. For example, it should link with the International Ocean Carbon Coordination Project (IOCCP: http://www.ioccp.org/index.php/about-us/tors) that promotes the development of a global network of ocean carbon observations for research through technical coordination and communication services, international agreements on standards and methods, and advocacy and links to the global observing systems. Also, discussions need to be undertaken with the International Council for the Exploration of the Sea (ICES) which is an intergovernmental marine science organization, meeting societal needs for impartial evidence on the state and sustainable use of our seas and oceans (https://www.ices.dk/explore-us/strategicplan/Pages/default.aspx). ICES aims to advance and share scientific understanding of marine ecosystems and the services they provide and to use this knowledge to generate state-of-the-art advice for meeting conservation, management, and sustainability goals. Links with ICES and its regional mirrors will help TAOS to effectively meet societal needs.

7.2 Recommendations for TAOS Governance

The core elements of TAOS have matured over the past 20 years and many countries in North and South America, Europe and Africa are now contributing in one way or another. There are also opportunities for introducing new technologies and expanding scientific horizons, but resources to develop ocean observing systems are at the same time limited and under pressure.

TAOS would therefore benefit from a governance structure that will ensure a high level of coordination among various observing system components, provide guidance for future evolution of the observing system, and that will advocate for resources to help to sustain the observing system over time. Various elements of TAOS have individually been well managed, e.g. Argo and the Global Drifter Program at the global GOOS level and the PIRATA moored array as a strong regional partnership. It is not anticipated that a TAOS governance structure would replace these robust project-specific network focused activities.

However, there is an opportunity now to consolidate progress in developing the individual components of TAOS by establishing a framework that will encourage their co-evolution, taking into account emerging technologies and expanding knowledge of the tropical Atlantic Ocean and its interactions with the overlying atmosphere.

On the global level, ocean observing governance is largely served by the evolving GOOS and GCOS frameworks with strong partnership through the GEO Blue Planet Initiative and other global actors such as the International Oceanographic Commission (IOC). In recent years, basin scale governance arrangements have emerged. The AtlantOS H2020 project (https://www.atlantos-h2020.eu) has started to articulate that vision for the whole Atlantic. It now continues within the AtlantOS program (http://www.atlantos-ocean.org; De Young et al., 2019). Such a vision should include the requirements of the TAOS. Additionally, there is scope to enhance the activities in subregions of the Atlantic and for the tropical subregion to grow its ambition and innovate its implementation.

We recommend therefore the establishment of a "TAOS Forum" whose purpose would be to foster close coordination among observing system elements, provide a vehicle to share information on implementation strategies, challenges, and best practices, help to define new observing system initiatives, and advocate for resources necessary to sustain the overall effort. The Forum would be populated by 1) scientists involved in the implementation of the observing system, 2) agency representatives who have some control of resources that can be applied to help build and sustain the observing system, and 3) end users who make use of the data and/or data products generated from the observing system. The TAOS Forum would be open to all interested parties but would include at least one representative from each of the major observing system components that comprise TAOS (Argo, Drifter, PIRATA) and agencies providing funding at a national level to TAOS (NOAA, MétéoFrance, IRD, CNRS, Ifremer, INPE, DHN).

A TAOS Forum would benefit from sponsorship by stakeholder groups that have a vested interest in developing and sustaining TAOS. As TAOS will serve the needs of both the research and operational communities, it should be closely linked to the emerging AtlantOS governing framework. Logical sponsors would be GOOS and IOC for the global perspective and engagement of its observing networks, the CLIVAR Atlantic Regional Panel (ARP) and similar thematic programs such as SOLAS, IMBeR and regional fisheries organizations. There would likely be need for some modest administrative support for this governance structure so that TAOS Forum members can focus their attention on high level science and implementation issues rather than organizational issues.

An appropriate frequency for TAOS Forum meetings is two years. The meetings venue should move between PIRATA meetings, large conferences like EGU/AGU, and other relevant program meetings like AtlantOS, SOLAS and IMBeR, trying to visit regularly each of the four continents (Africa, Europe, North and South America including the Caribbean Islands states).

In order to expand TAOS towards regional requirements and to be more inclusive of different societal demands, the TAOS Forum should engage in a regulated manner with JCOMM and WMO Integrated Global Observing System (WIGOS) in discussions of future governance. It should also extend invitations to its meetings to a large set of tropical Atlantic bordering countries or organizations (including the Caribbean Islands states).

The future TAOS governance should encourage increased participation in the TAOS from bordering countries of the tropical Atlantic to whatever resource level may be possible - even if initially very limited - including the nations of west Africa, South America and the Caribbean. It should also facilitate more active participation in data access and usage by bordering countries, including capacity development for accessing the data and observing technology. Ongoing international research activities in the region such as TRIATLAS, and iAtlantic projects as well as the newly developed programs in the UN Decade of Ocean science for sustainable development, should be used as opportunities to build up such an effort to efficiently include more nations in TAOS governance and participation.

Since tropical Atlantic ocean observations, in EEZ’s and international waters, are largely funded and implemented by nations, it is essential that coordination and governance of TAOS meets the needs of nations and a diverse group of stakeholders. The TAOS governance needs to embrace the complete value chain of ocean observations from requirement setting and system design, management of observing networks, through delivery of data and information with a regular evaluation process of the system (Tanhua et al., 2019a) adapted to address the regional specific scientific and geopolitical contexts. One efficient pathway in such effort might be a better connection with the LME consortia in the tropical Atlantic region. This would provide one efficient mechanism by which the relevance of the TAOS can be "down-scaled" to a more country- or LME-specific scale.

The TAOS Forum should provide at the end of each meeting written documentation on meeting discussions, interaction with TAOS information end users, and recommendations for sustaining and improving the TAOS, which can serve as a mechanism to follow up on these activities and recommendations, and evaluate their effectiveness. Such documentation will also review how TAOS covers all requirement needs and also how it is connected with other observing systems in the tropics (e.g., TPOS, IndOOS) or at the Atlantic Ocean scale (AtlantOS). Such documentation should be made available openly via a TAOS website to which superusers such as CLIVAR, Copernicus Marine Environment Monitoring Service (CMEMS: https://www.copernicus.eu/en/services/marine), GOOS, GCOS can access and point to.

It is further proposed that a TAOS Resources Forum be established, advising the TAOS Forum and other sponsors (GOOS, WCRP, WIGOS, IOC) on potential technical solutions that can fulfill the evolving scientific requirements.

The next decade, with the launching of the UN Ocean Decade (2021-2030), should represent a period particularly favorable to the development and consolidation of TAOS.

7.3 Recommendations for periodic TAOS review

The TAOS Review Committee recommends that regular major review processes of TAOS take place. Such reviews will enable an assessment of successes, failures and gaps of TAOS in relation to evolving societal requirements and with respect to new technology and scientific developments and demand.

These reviews should take place at a decadal pace. These reviews will provide a basis for evaluation of the current state of TAOS and to determine the most efficient and effective observational solutions to support prediction systems for ocean, weather and climate services, to constructively manage ocean ecosystems, fisheries, and coastal risks, and to develop a sustainable blue economy.

Appendix 1: Scientific Drivers for the Tropical Atlantic Observing Systems (TAOS)

A1. Dynamics of Tropical Atlantic Variability

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A1.1 Zonal and meridional modes

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The interannual variability of the tropical Atlantic region was for a long time considered of little significance compared to its dominant annual cycle (e.g. Horel et al., 1986; Servain and Legler, 1986). Nevertheless, the fluctuations that occur from year to year and those in the longer term are by no means unimportant (Servain and Séva, 1987). The interannual climatic variability of the tropical Atlantic Ocean is typically classified according to two main modes, an "equatorial" or “zonal” mode and a "meridional" mode (also called "dipole" mode). These two modes, which contribute almost equally 20 to 30% each to the total interannual variability, are discussed below.

A1.1.1 The equatorial mode

The first of the two modes (corresponding to approximately 20 to 30 % of the interannual total variance) of the interannual climate variability is similar to the El Niño – Southern oscillation (ENSO) in the Pacific, with a mainly zonal orientation in the equatorial Atlantic basin (Zebiak, 1993; Chang et al., 1997). Both ENSO and the Atlantic Niño mode are damped oscillators, but the Atlantic is more strongly damped than the Pacific primarily because of the weaker thermocline feedback (Lübbecke and McPhaden, 2013). Early studies had already indicated the importance of the equatorial waves and the forcing of the remote wind in equatorial Atlantic Ocean, thereby demonstrating a general dynamic similarity with the Pacific (Servain et al., 1982; Hirst and Hastenrath, 1983; McCreary et al., 1984). The equatorial mode is therefore often called the “Atlantic Niño mode”. A recent review of the mechanisms and teleconnections of this mode is provided by Lübbecke et al. (2018a).

This equatorial mode in the Atlantic Ocean, like the meridional mode or “dipole” mode which is described below, varies on an intra-seasonal to multi-annual frequency, with an enhanced spectral power at period of 2 to 3 years (which is shorter than that for ENSO). During a warm phase, the trade winds in the western equatorial basin off Brazil are anomalously weak and the SST close to the equator is exceptionally warm (around +1 to +3°C at the monthly scale). This is particularly true in the eastern basin where a rise of the surface sea level is also observed. During a cold phase, the trade winds are anomalously strong, and the SST is abnormally low. The beginning of a warm or cold event can occur within only a few weeks. It is generally associated with the generation and subsequent eastward propagation of wind-forced equatorial Kelvin waves, followed by the westward propagation of Rossby waves reflected at the African coast (Figure 1.1). As the modulation of the interannual signal by the seasonal cycle being relatively strong (contrary to the Pacific), the significant SST anomalies are often confined during boreal summer and autumn (Zebiak, 1993) when the cold tongue is present, and the surface-subsurface coupling is strongest (Keenlyside and Latif, 2007). In consequence, such an interannual signal is most of the time an increase (or on the contrary a weakening) of the annual seasonal signal (Burls et al., 2012). The strength of the South Atlantic anticyclone may also impact the timing of the cold tongue onset and the intensity of its development in the eastern equatorial Atlantic via anomalous tropical wind power (Lübbecke et al., 2014).

A good illustration of this interannual equatorial variability was the period 1983-1984. In fact, the evolution of the seasonal cycle during these two years was very different. The first year (1983) was considered as "normal" (that is close to a climatic average). On the other hand, the second year (1984) showed pronounced disturbances in the SST, the winds, the deep convection, and the ocean currents, reminiscent of El Niño events in the Pacific (Philander, 1986; Lamb et al., 1986; Weisberg and Colin, 1986; Hisard et al.,1986; Katz et al., 1986; Horel et al., 1986; Verstraete, 1992; Delécluse et al., 1994). Other events of the same type were listed and analyzed, in particular that of 1968 (Servain, 1984), 1995 (Gammelsrød et al., 1998) and 2001 (Rouault et al., 2007). Most of these events were linked to warm anomalies in the Angola-Benguela region, termed “Benguela Niños”. As illustrated in Figure A1.1, a propagation of the signal from the equator along the southwestern African coast can be explained by coastal Kelvin waves (Florenchie et al., 2003, 2004; Imbol Koungue et al., 2017), which was clearly shown, for example, for the warm events of 2001 (Rouault et al., 2007) and 2011 (Rouault et al., 2017). Interestingly, Benguela Niños tend to peak before the surface warm anomalies at the equator, which is most likely related to the difference in thermocline depths and a different seasonality of interannual SST variability in the two regions. While Benguela Niños peak in austral summer to fall, warm events at the equator are phase-locked to austral winter when the equatorial thermocline is shallow (Lübbecke et al., 2010).

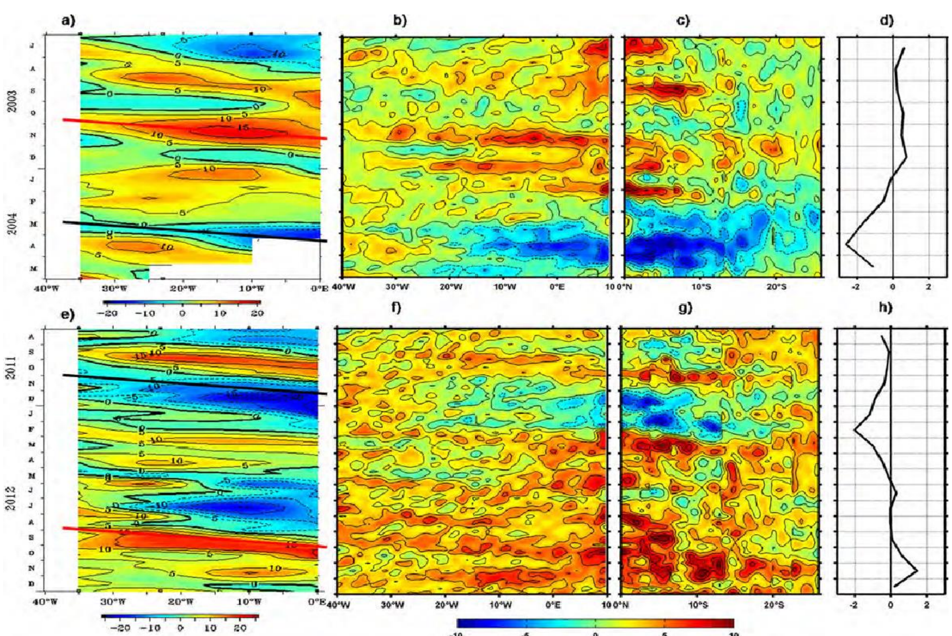

Figure A1.1: Top: from left to right, a) Longitude time Hovmöller diagram of 5 day means of Z20 anomalies (m) along the equator inferred from PIRATA moorings and interpolated between mooring locations, (b) SSH anomalies (cm) inferred from AVISO along the equator averaged between 18ºS and 18ºN, (c) latitude time Hovmöller diagram of SSH anomalies (cm) inferred from AVISO averaged within 18 coastal fringe, and (d) time series of SST anomalies (ºC) averaged from 10ºS to 15ºS within 1º coastal fringe for the period July 2003 to May 2004. Bottom: The same plots are represented, but for the period August 2011 to December 2012. The red and black tick straight lines represent eastward phase speed estimates (m/s). From Imbol-Koungue et al. (2017), their Figure 4.

Numerical experiments by means of coupled ocean-atmosphere models (CGCM) confirm that the equatorial mode of the Atlantic Ocean is dynamically similar to ENSO, in spite of strong differences between the two tropical basins in terms of the average state of the atmosphere-ocean system and in the reflections of waves on both sides of the equator (Zebiak, 1993; Xie et al., 1999; Latif and Grötzner, 2000). One of these differences lies in the zonal positioning of the coupled anomalies. In the case of the Atlantic Ocean, the dynamic coupling (i.e. via the wind stress) occurs essentially in the western part of the basin, while for the Pacific this coupling is situated near the center of the ocean. These numerical results suggest that the interannual variations of the Atlantic Ocean are partially governed by delayed-oscillator dynamics involving a combination between the dynamics of the upper ocean and equatorial upwelling. Current results suggest that the local interactions in the Atlantic Ocean are not strong enough to generate the observed level by the variability, including along the equator. This means that disturbances of remote origin must be also considered. The most obvious source of such disturbances at the same interannual time scale is ENSO. Diverse diagnostic, statistical and numerical studies showed strong relationships between temperature anomalies related to El Niño in the equatorial Pacific, and anomalies of surface wind and SST in the northern tropical Atlantic Ocean (Enfield and Mayer, 1997; Uvo et al., 1998; Saravanan and Chang, 2000; Huang et al., 2002; Wang, 2002; Mélice and Servain, 2003; Chang et al., 2006a; Lübbecke and McPhaden, 2012). Indeed, strong negative values (resp. positive) of the SOI in November-March is often followed by a strengthening (resp. weakening) winds in the western equatorial Atlantic Ocean during the next months (Servain et al., 1996). Indeed, the above mentioned Atlantic Niño of 1984 could be partly simulated by only using the forcing of the ENSO of 1983 (Delécluse et al., 1994). The forcing from ENSO onto the equatorial Atlantic is however not consistent for all events. Chang et al. (2006a) argue that the fragile relationship is a result of destructive interference between atmospheric and oceanic processes in response to El Niño. In Lübbecke and McPhaden (2012) this weak relationship is shown to be partly attributable to a delayed negative feedback in the tropical Atlantic that is active in years with a warm or neutral response in the eastern equatorial Atlantic. One can conclude that a combination of local ocean-atmosphere interactions and equatorial remote forcing via either atmospheric Walker circulation or tropospheric temperature mechanism (Chiang and Sobel, 2002) is at the origin of the equatorial mode of interannual variability in the tropical Atlantic Ocean. It should be noted that other sources of anomalies, for example connected to the quasi-biennial variability (Servain, 1991), and linked to the extratropical variabilities such as the NAO in the North Atlantic are also candidates to examine (Déqué and Servain, 1989). A recent study by Nnamchi et al. (2016) suggests that the Atlantic Niño may be viewed as a possible intrinsic equatorial arm of the South Atlantic Ocean Dipole (SAOD). Another mechanism that potentially can generate equatorial SST variability on interannual-to-decadal time scales was proposed by Brandt et al. (2011a). The novelty of this mechanism lies in the fact that it is intrinsic to the ocean dynamics and related to equatorial deep jets, which are observed in the ocean. These vertically alternating deep zonal jets of short vertical wavelength propagate their energy upwards and thereby can affect SST.

A1.1.2 The meridional mode

The other mode of interannual climate variability in the tropical Atlantic Ocean (which also represents approximately 20 to 30 % of the total interannual variance) is characterized by an inter-hemispherical gradient of the atmospheric and oceanic conditions at the air-sea interface. This mode has previously been called (although improperly in terms of pure dynamics or pure statistics) "the Atlantic Ocean dipole" (Moura and Shukla, 1981; Servain, 1991). It involves coherent spatial variations of SST and surface wind anomalies in each of both hemispheres between approximately 25°N-5°N and 5°N-20°S, on seasonal, interannual and even multi-year time scales (Servain, 1991).

These anomalies usually appear with opposite signs in each hemisphere, although their developments are not always simultaneous, and there is controversy to consider if the northern and southern poles of this dipole were or not dynamically related (Houghton and Tourre, 1992; Enfield et al., 1999; Chang et al., 2001). The extent to which the coupled atmosphere-ocean feedback influences the meridional mode dynamics varies among coupled climate models, largely because of the uncertainty in computing surface turbulent heat fluxes. We know however that the physical processes responsible for climatic variations associated with the meridional mode are thermodynamic in nature and rely on feedbacks between various variables such as inter-hemispheric SST gradient, surface winds, and surface turbulent heat fluxes (Chang et al., 1997). The wind-evaporation-SST (WES) feedback is the principal mechanism driving this inter-hemispheric mode in the tropical Atlantic (Chang et al., 1997; 2000; Chiang et al., 2002; Amaya et al., 2017). During the positive (negative) phase of the inter-hemispheric mode, weaker (stronger) than normal northeasterly trade winds are associated with less (more) evaporation and a positive (negative) anomaly of the SST in the tropical North Atlantic, whereas a stronger (weaker) than normal southeasterly trade winds, more (less) evaporation and negative (positive) anomaly of SST is observed in the tropical South Atlantic. Because the positive (negative) phase of the inter-hemispheric mode is established during such a phase, the ITCZ is abnormally displaced to the north (south).

The inter-hemispherical anomalies of the SST which affect significantly the position and the intensity of the ITCZ thus exert a considerable influence on the precipitation over adjacent continental areas, such as the Brazilian Northeast (NEB) and the African Sahel (Lamb, 1978a, b; Moura and Shukla, 1981; Lough, 1986; Folland et al., 1986; Wolter, 1989; Servain, 1991; Enfield and Mayer, 1997; Kushnir et al., 2006). As shown in Figure A1.2, a situation in which the anomalies of SST are positive in the north and negative in the south is always associated with an abnormal northward displacement of the ITCZ, leading to an episode of drought on NEB, and an increase in the precipitation in Sahel. Conversely, SST anomalies of opposite signs display the ITCZ southward, favoring more precipitation in NEB and generating a drought condition over Sahel. This double scenario over NEB and Sahel is obviously more effective when the Atlantic dipole is particularly pronounced during the typical periods of rainy seasons in NEB (February to May) or in Sahel (June to September).

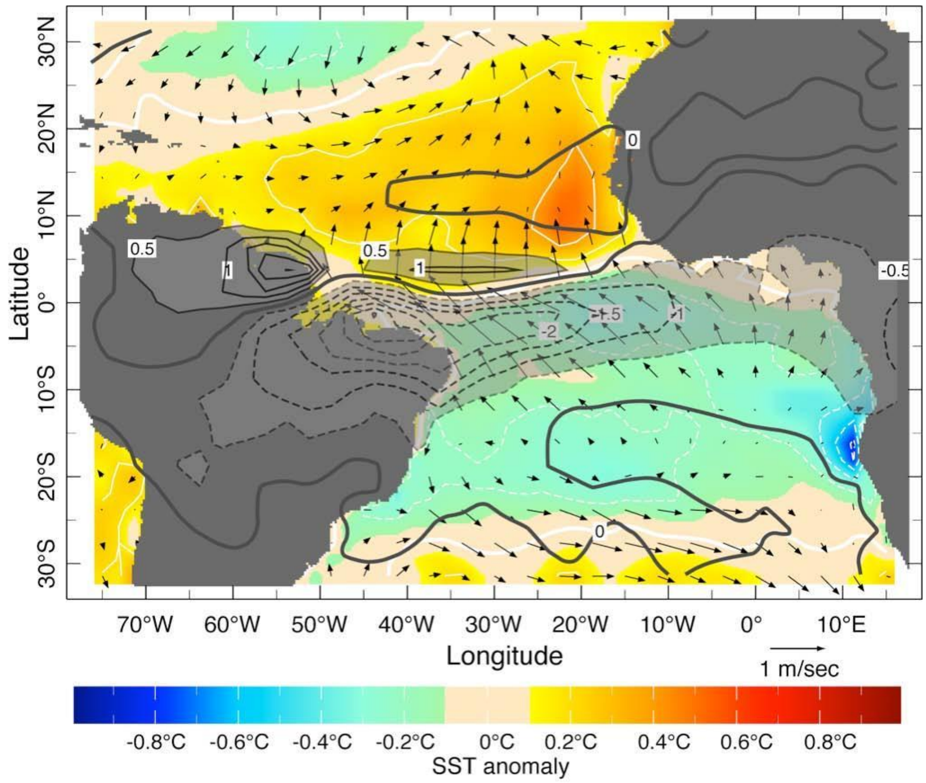

Figure A1.2: The dominant pattern of surface ocean–atmosphere variability in the tropical Atlantic region during boreal spring (March–April). The gray contours depict the first EOF of the regional rainfall anomaly (from GPCP data, 1979–2001) in mm day_1. Contours every 0.5, negative contours are dashed, and the zero contour is omitted. The colored field is the associated SST anomaly, derived by regression analysis. Units are °C (see scale below; white contours every 0.2° are added for further clarity). Arrows depict the associated seasonal surface wind anomaly in m s_1 (arrow scale below frame). Percent variance explained is 33. From Kushnir et al. (2006), their Figure 15a.

Furthermore, the interannual variability of the SST in the tropical North Atlantic Ocean influences also potentially the precipitation over the West Indies and the southeast region of the USA by modulating the frequency and the intensity of cyclones during the usual period of cyclogenesis (from June to November) (Gray, 1990). Recent studies (Kossin and Vimont, 2007; Vimont and Kossin, 2007, Patricola et al., 2014) have firmly established the impact of the Atlantic Meridional Mode on Atlantic hurricanes, because of its influence on vertical wind share and other environment conditions conductive to hurricanes.

A1.1.3 The relationship between the two Atlantic modes and with the Pacific El Niño

It is very possible, given the similarity in timescales and spatial overlapping, that the equatorial mode can be dynamically connected to the inter-hemispherical mode. Diagnostic (Servain et al., 1999; 2000; 2003) and numerical studies (Servain et al., 2000; Murtugudde et al., 2001; Ayina and Servain, 2003) showed that such a relation could be verified, at least partially. From Foltz and McPhaden (2010) and Burmeister et al. (2016), the interaction between the boreal spring meridional mode and the summer Atlantic Niño is mediated by directly wind-forced equatorial Kelvin waves and the delayed negative feedback from western boundary reflections of wind-forced Rossby waves.

Finally, several works showed a potential of equatorial Atlantic variability to enhance El Niño prediction, especially from the late 1970's (Mélice and Servain 2003; Rodríguez-Fonseca et al. 2009; Keenlyside et al. 2013). During the positive phase of the Atlantic Niño, the boreal summer SST affects the Walker circulation with an ascending branch over the Atlantic and a descending branch over the central Pacific, which drives the westward wind anomalies over the equatorial Pacific (Rodríguez-Fonseca et al. 2009; Ding et al. 2012). Such a change in the atmospheric circulation favors negative anomalies of the SST (La Niña conditions) in the eastern equatorial Pacific by increasing the east-west thermocline slope. According to Rodriguez-Fonseca et al. (2009), this connection is especially evident since the 1960-1970 climate shift. Nonetheless, Keenlyside et al. (2013) indicated that the Atlantic Niño does not act as a triggering of the Pacific Niño but contributes to modulate ENSO events. A recent study by Patricola et al. (2017) further shows that SST anomalies associated with the Atlantic meridional mode can exert a remote influence on hurricanes in the Eastern North Pacific by remotely affecting the vertical wind shear in that region.

A1.2 Benguela Nino

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Ocean temperatures off the southwestern African coast are characterized by a strong gradient between the warm tropical Atlantic and the cold Benguela current at the Angola Benguela Front at about 17ºS. Every few years, SST off the coast of Angola and Namibia reach values of up to 5ºC higher than normal (Fig. A1.3). Warm anomalies are observed as far south as 25ºS. These warm events have been named Benguela Niños (Shannon et al., 1986) by analogy to their Pacific counterpart. They tend to peak in austral summer to fall (Rouault., 2012; Imbol Koungue et al., 2017). The colder counterpart is called Benguela Niña. Rouault et al. (2009) noted that Benguela Niño often precedes Atlantic Niño and Lübbecke et al. (2010) explained that this is due to a shallower thermocline off Angola than at the equator and those two phenomena should be seen as one. Benguela Niños have large impacts on local fisheries (Boyer and Hampton, 2001) and on rainfall variability over southwestern Africa (Rouault et al., 2009). Understanding and potentially forecasting their development is thus of high socio-economic importance and the couple of months lead time between the decrease in winds along the Equator, deepening of thermocline observed by PIRATA and the development of SST anomalies along the Angolan and Namibian coastline offer some predictability (Rouault et al., 2007, 2017; Imbol Koungue et al., 2017). Benguela Niños are mainly generated by wind stress changes in the western equatorial Atlantic (Lübbecke et al., 2010; Imbol Koungue et al., 2017). Wind stress variations in the western equatorial Atlantic generate equatorial Kelvin waves propagating eastward along the Equator. These waves are associated with thermocline deepening and thus subsurface temperature anomalies. They propagate along the African west coast as coastal trapped waves (Bachèlery et al., 2016a) up to the Angolan coast and generate strong SST anomalies due to a shallow thermocline there and up to the northern part of the Benguela upwelling system. Based on model outputs, Rouault l. (2012) attribute the warming off Namibia to southward advection of subsurface warm water. The latest strong Benguela Niños occurred in Austral summer 2010/2011 (Rouault et al., 2017). The 2010/2011 events were first detected by the PIRATA array of mooring in October, 2 months before the peak of the events. The link between equatorial Atlantic Ocean variability and the coastal region of Angola and Namibia from 1998 to 2012 was systematically established by Imbol Koungue et al. (2017) and PIRATA was instrumental to that matter. Imbol Koungue et al. (2017) defined an index of equatorial Kelvin wave activity based on PIRATA. Along the equator, results show a significant correlation between PIRATA monthly dynamic height anomalies, altimetric monthly Sea Surface Height anomalies

(SSHA) and SSHA calculated with an Ocean Linear Model. This allowed us to interpret PIRATA records into equatorial Kelvin wave. Estimated phase speed of eastward propagations from PIRATA equatorial moorings remains in agreement with the linear theory, emphasizing the dominance of the second baroclinic mode and propagation speed of about 1.5 m/s. Measurements at the Angola Benguela Front are lacking to better understand mechanisms linking the Angola region to the Benguela upwelling and the hypothesis put forward by Rouault (2012) or Bachelery et al. (2016a) rely solely on model and sea surface temperature estimated in a very cloudy region. While mooring measurements exist recently off Namibia and Angola (Junker et al., 2017; Kopte et al., 2017; Tchipalanga et al., 2018), they need to be sustained and complemented to be better adapted to the study of Benguela Niños and Niñas. Cruise data exists of Angola and Namibia and should also be better exploited.

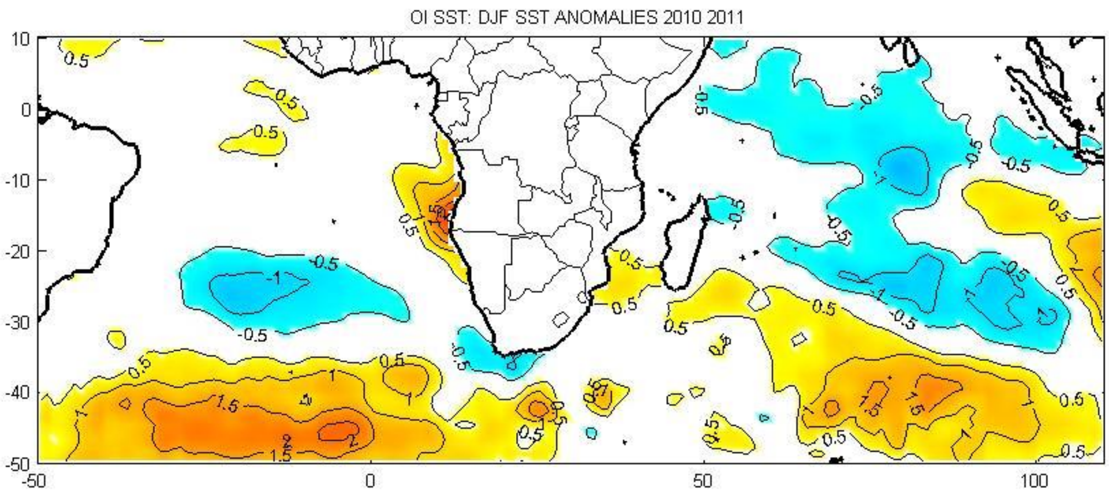

Figure A1.3: Normalized detrended seasonal SST anomalies in Austral summer (December to February) from climatology showing SST anomalies superior to 1 standard deviation of the West coast of Southern Africa centered on the Angola Benguela Front.

A1.3 Mesoscale/intraseasonal variability

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The tropical Atlantic is marked by strong intraseasonal (ISV, time scales ranging from 10 to 90 days) and mesoscale variability (MV) in both atmosphere and ocean, which is well observed by in-situ/satellite observations (Legeckis and Reverdin, 1987; Weisberg et al., 1987; Weisberg and Weingartner, 1988; Menkes et al., 2002; Caltabiano et al., 2005; Grodsky et al., 2005; Brandt et al., 2006; Athie and Marin, 2008; Wu and Bowman, 2007; Han et al., 2008; Bunge and Clark, 2009; Perez et al., 2012; Hormann et al., 2013; Lee et al., 2014; Wenegrat and McPhaden, 2015; Imbol Koungue et al., 2017; Tuchen et al., 2018). ISV and MV in the tropical Atlantic can be generated directly by the wind or through instabilities of the wind-driven currents. They encompass processes like inertial and planetary waves, mesoscale eddies, tropical instability waves (TIWs), equatorial and coastally trapped waves. Most of these phenomena are fairly well represented by numerical models given fine enough horizontal and/or vertical resolution (Jochum and Malanotte-Rizzoli, 2003; Jochum et al., 2004; Seo et al., 2007; Dutrieux et al., 2008; von Schuckmann et al., 2008; Athié et al., 2009; Eden and Dengler, 2008; Ascani et al., 2015; Greatbatch et al., 2018).

A recent analysis of high-resolution SST and surface winds (Diakhaté, et al. 2016) indicates that energetic ISV of SSTs within the tropical Atlantic basin can be identified along the equatorial upwelling zone and the two coastal upwelling zones off the north and south Africa coast, i.e., the Senegal-Mauritania and the Angola-Benguela upwelling systems, respectively. Along the equator, the SST ISV seems to show two different characteristics, one west of 10°W with dominant period of 20-60 days and another east of 10°W with dominant period of 10-20 days (Athié and Marin, 2008). Near the Angola-Benguela front, the SST ISV is dominated by 30–64 days regime (Hermes and Reason, 2009), whereas near the Senegal-Mauritania front the SST ISV has a spectral peak between 30 and 80 days (Diakhaté, et al., 2016).

Perhaps most studied is the equatorial ISV west of 10°W associated with TIWs. They are generated by barotropic and baroclinic instabilities of the wind-driven zonal flow, which intensify during boreal summer June-August concurrently with the development of the equatorial Atlantic cold-tongue (Düing et al. 1976, Caltabiano et al., 2005; Wu and Bowman, 2007; von Schuckmann et al., 2008; Perez et al., 2012; Hormann et al., 2013; Diakhaté et al., 2016). The underlying physical mechanisms responsible for the SST anomalies are TIW-induced horizontal advection and vertical mixing (Weisberg and Weingartner, 1988; Foltz et al., 2003; Jochum et al., 2004; Peter et al., 2006; Seo et al., 2007; Giordani et al., 2013; Jouanno et al., 2013; Hummels et al., 2014). There is a well-defined surface wind, cloud and rainfall response to the SST anomalies and the vertical mixing mechanism within the marine atmospheric boundary layer (Sweet et al., 1981; Hayes et al., 1989; Wallace et al., 1989; Xie, 2004) which seems to be mainly responsible for the coupling between the atmospheric boundary layer and SST. The co-varying wind-SST pattern shows a well-defined westward propagation at a speed of 30-60 cms^{-1}, consistent with TIW dynamics. Climate models have demonstrated some skill in simulating the co-variability between the winds and SST (Seo et al., 2007, Wu et al., 2008).

On interannual time scales, the TIW-induced ISV can be modulated by Atlantic Niño (Wu and Bowman, 2007; Perez et al., 2012). Conversely, ISV in the tropical Atlantic have been shown to influence interannual variability in the upper ocean (Jochum et al., 2004). Downward propagation of intraseasonal energy associated with TIWs energizes the deep equatorial circulation consisting of latitudinally alternating zonal jets and vertically alternating equatorial deep jets (EDJs) (Ascani et al., 2010, 2015; Greatbatch et al., 2018; Tuchen et al., 2018). Atlantic EDJs oscillate on interannual time scales with period of 4.5 years and have also been observed to propagate their energy upwards and influence equatorial SSTs and climate (e.g., Brandt et al., 2011b).

Driving mechanisms for ISV in other tropical Atlantic regions are less well understood. The strong quasi-biweekly variability (10-20 days) of SST observed in the equatorial region east of 10°W during May – July was found to be related to Yanai (mixed Rossby-gravity) waves (Bunge et al., 2006; Guiavarc'h et al., 2008; Han et al., 2008; Athié et al., 2009). de Coëtlogon et al. (2010) suggested that air-sea coupling triggered by the quasi-biweekly variability linked to large-scale atmospheric fluctuations in the South Atlantic plays a crucial role for ocean-atmosphere ISV in the Gulf of Guinea. The coastal ISV near the Angola-Benguela and Senegal-Mauritania front instead appears to be more of a response to atmospheric forcing rather than a coupled phenomenon (Diakhaté, et al. 2016). However, intraseasonal equatorial Kelvin waves can also transmit energy southward as coastally trapped waves and trigger 2-3 months long Benguela Niño warming events (Polo et al., 2008; Bachelery et al., 2016a; Imbol Koungue et al., 2017).

The Madden-Julian Oscillation (MJO) with periods between 30 and 90 days is the most dominant mode of ISV in the global tropical atmosphere and can exert a significant impact on warm season climate variability in the tropical Atlantic. The West African Monsoon, for example, and associated convection, rain, winds and African easterly wave activity are found to be remotely influenced by the MJO (Matthews, 2004; Maloney and Shaman, 2008). Maloney and Shaman (2008) estimate that the MJO explains about 30% of the 30–90-day precipitation variance in the West African Monsoon region. A significant MJO-related modulation on tropical cyclones has also been identified over the western part of the Atlantic, including the Gulf of Mexico and the Caribbean Sea (Maloney and Hartmann, 2000; Mo, 2000) and over Atlantic main development region (MDR) (Mo, 2000; Maloney and Shaman, 2008). Maloney and Shaman (2008) show that about half of the amplitude of vertical shear variations in the Atlantic MDR during 30–90-day precipitation events are attributable to the MJO. In addition to MJO's remote influence, shorter timescale ISV of period 10-25 days is well documented in rainfall and winds over tropical and subtropical West Africa and adjacent regions of the Atlantic. This ISV is accompanied by an enhancement of African easterly wave activity (Sultan and Janicot, 2003) and thus is likely to be caused by variability in African easterly waves (Lavaysse et al., 2006). In the ocean, African easterly waves excite near-inertial waves that contribute to elevated turbulent mixing in the upper thermocline and significantly cool SST, particularly in boreal summer (Hummels et al., 2018). Finally, it is worth mentioning that ISV is not limited to the warm season. During boreal winter, atmospheric rivers (ARs; Lavers and Villarini, 2013), which are plumes of intense water vapor transport emanating from the tropics, are another important source of ISV (Zhu and Newell 1998; Ralph et al., 2004; 2005). Within the North Atlantic sector, a narrow pathway connecting the Gulf of Mexico/West Caribbean region to the western European seaboard has been identified as the main route of AR moisture transport (Gimeno et al., 2010a; Eiras-Barca et al., 2016). The connection between modes of climate variability and ARs is still very poorly understood, particularly in the Atlantic. Lavers and Villarini (2013) found that the North Atlantic Oscillation (NAO) affects Atlantic AR activity. However, the extent to which tropical Atlantic variability may affect ARs along the North Atlantic Corridor has not been explored. Given that the moisture source is located in the Atlantic warm pool region, an improved understanding of how ocean-atmosphere interactions can affect the planetary boundary layer moisture budget in the region seems to be key.

The key essential climate variables (ECVs) for studying the physical aspects of ISV and MV in the tropical Atlantic are near-surface temperature, salinity, sea surface height, ocean velocity, rain, heat flux, and wind stress. However, ISV and MV can penetrate well below the surface and can enhance turbulent mixing in the thermocline due to enhanced shear and they can generate and/or maintain the deep equatorial circulation. The latter was found to be important for the mean state and the long-term variability of the distribution of oxygen and other tracers (Gouriou et al., 2001; Brandt et al., 2010; 2012). Hence, it is important to observe subsurface temperature, salinity, and velocity to develop a better understanding of these phenomena. Submesoscale dynamics in and around ISV and MV enhance local turbulent mixing and vertical advection and thus increase vertical fluxes of heat, salt, and nutrients (Klein and Lapeyre, 2009). Additionally, MV and ISV alter ambient vorticity in the water column and thus interact with the local internal wave field leading to wave breaking and trapping while enhancing turbulent mixing (Armi et al., 1988; Kunze et al., 1995; Kawaguchi et al., 2016; Sheen et al., 2015). To date, however, diapycnal transport pathways in and around MV and ISV remain largely unknown. Time series measurements of velocity and microstructure and turbulence in the upper ocean are needed to fully understand the impact of ISV and MV in the tropical Atlantic on turbulent mixing.

Given that some ISV and MV inducing phenomena are observed far afield of where they were generated, it is essential to pair satellite and in situ data together. The present in situ TAOS mooring network (e.g., PIRATA, GEOMAR, NTAS) is able to observe high resolution time series of rain, heat flux, winds, surface temperature and salinity, with limited resolution of the vertical structure of subsurface temperature and salinity at select moored buoys. Only a subset of moorings measure near-surface velocity and very few moorings make subsurface velocity or microstructure/turbulence measurements. The horizontal spacing between existing Tropical Atlantic moorings is fairly coarse (e.g., 10-15 degrees longitude and 4°-10° latitude apart). While it is possible to detect horizontal propagation of some events along the equator with the present mooring configuration, it is not possible to compute horizontal shears and gradients. Lagrangian measurements from drifters and Argo profiling floats and shipboard measurements provide invaluable data about the horizontal/vertical structure of mesoscale phenomena but cannot resolve the temporal evolution of ECVs at fixed locations. Satellites provide excellent spatial coverage of surface ECVs from which one can trace events observed in one part of the tropical Atlantic back to their origin and estimate horizontal shears and gradients across the tropical Atlantic. However, their temporal resolution is limited, and they do not provide information about subsurface EOVs. Particularly, near the equator where geostrophic methods largely fail, remote sensing of the surface velocity field, e.g. by using Doppler radar measurements, is a high priority for future satellite missions.

A1.4 Teleconnections

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The main modes of Tropical Atlantic variability (TAV) are caused by different air-sea interaction mechanisms. The Meridional Mode is linked to Wind-Evaporation-SST feedback (WES) (Xie, 1999; Okumura et al., 2001; Mahajan et al., 2009), whereas the Zonal Mode is associated with equatorial oceanic waves and dynamical thermocline-wind-SST feedback (Bjerknes feedback, Bjerknes, 1969; Lübecke et al., 2018a). These mechanisms are strongly affected by anomalous local winds, which in turn can be remotely forced by different tropical and extra-tropical teleconnection patterns. The main source of variability comes from ENSO, but other modes can also affect the TAV, such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO).

ENSO can trigger upper-troposphere wave trains, being the Pacific–North Atlantic (PNA) pattern the characteristic of the northern hemisphere (Handoh et al., 2006a,b; Cai et al., 2011). During El Niño events, the PNA causes divergence in upper levels over the tropical North Atlantic (TNA) in boreal winter. Consequently, the meridional pressure gradient decreases at lower levels, weakening the trades and warming TNA, through the WES feedback (Hastenrath, 2006; Handoh et al., 2006a; Amaya and Foltz, 2014; Taschetto et al., 2016). The anomalous warming of the TNA can, in turn, initiate a positive phase of the Meridional Mode in boreal spring (Enfield and Mayer, 1997; Huang, 2004). However, the strength and persistence of ENSO phenomenon (Lee et al., 2008) as well as the tropical Atlantic mean conditions (Chang et al., 2006a) are crucial to determine the TNA SST response. The opposite is true for La Niña events.

The ENSO teleconnections in the southern hemisphere are the Pacific–South American (PSA) wave trains, which correspond to the second and third leading patterns of circulation variability (Karoly, 1989; Kiladis and Mo, 1998; Mo, 2000; Mo and Hakkinen, 2001) and are linked to the eastern and central Pacific ENSO, respectively (Rodrigues et al., 2015). During some El Niño events, the PSA can enhance the South Atlantic Anticyclone and thus the southeasterly trades. Stronger southerlies can cause cold anomalies over the tropical South Atlantic through the WES feedback, favoring the development of a positive phase of the Meridional Mode in boreal spring (Rodrigues et al., 2011). Once again, the opposite situation can occur during La Niña events.

ENSO can also induce changes in equatorial convection, shifting the Walker circulation and impacting the tropical Atlantic Ocean (Klein et al., 1999; Saravanan and Chang, 2000; Wang, 2006). For instance, during El Niño events, the eastward shift of the Pacific Walker cell places the branch of descent air over the Amazon region, weakening the north Atlantic Hadley cell, which in turn can trigger a positive phase of the Meridional Mode through WES feedback (Wang et al., 2002). The opposite can occur during La Niña events.

In relation to the Zonal mode, ENSO can generate an anomalous intensification of easterly winds in western equatorial Atlantic, exciting a downwelling oceanic Rossby wave that propagates eastward and could promote the development of an Atlantic Niño in summer months (Latif and Groztner, 2000; Polo et al., 2008). However, this relationship is not consistent and appears to be modulated by ENSO properties (Lee et al., 2008), the strength of South Atlantic Anticyclone (Lubbecke et al., 2014), the possible activation of a negative feedback mechanism (Lübbecke and McPhaden, 2012), and the upper ocean state in the equatorial Atlantic (Chang et al., 2006).

In contrast to the mechanisms involving ocean dynamics and teleconnections with the Zonal Mode, Nnamchi et al. (2015; 2016) suggested that thermodynamic feedbacks excited by stochastic atmospheric perturbations (driving surface heat fluxes) could explain a large part of the SST variability in the eastern equatorial Atlantic. This highlights the importance of an accurate representation of the South Atlantic Anticyclone for the correct assessment of the tropical Atlantic (Cabos et al., 2017).

Large-scale low frequency variability patterns such as the AMO can modulate ENSO and the TAV (Dong et al., 2006; Martín-Rey et al. 2014; 2018). In particular, a recent study has evidenced a modification in the tropical Atlantic variability modes due to changes in the background state (Martín-Rey et al., 2018). During negative AMO phases, a shallower mean thermocline enhances the equatorial variability, which could make the tropical Atlantic more susceptible to ENSO forcing, which forces a new overlooked mode in the tropical Atlantic, denoted as Horse-Shoe pattern.

North Atlantic Oscillation (NAO) is the main pattern of the extratropical climate variability in the Northern Hemisphere and, although is mainly driven by internal processes, it can be also triggered by ENSO. At interannual scales, NAO-associated strengthening (weakening) of the trade winds can change the latent heat fluxes responsible for creating negative (positive) SST anomalies in the north tropical Atlantic (Cayan, 1992; Carton et al., 1996; Czaja et al., 2002). This teleconnection (Figure A1.4) can also be modulated (Xie and Tanimoto, 1998). At decadal timescales, a positive (negative) NAO would lead to a positive (negative) AMO-like SST pattern through the strengthening (weakening) of the AMOC (Delworth et al., 2017). However, the effect of the ocean circulation is less obvious over the tropical North Atlantic, which would be more affected by other processes as heat fluxes, in agreement with a Pan-Atlantic mode described by Xie and Tanimoto (1998).

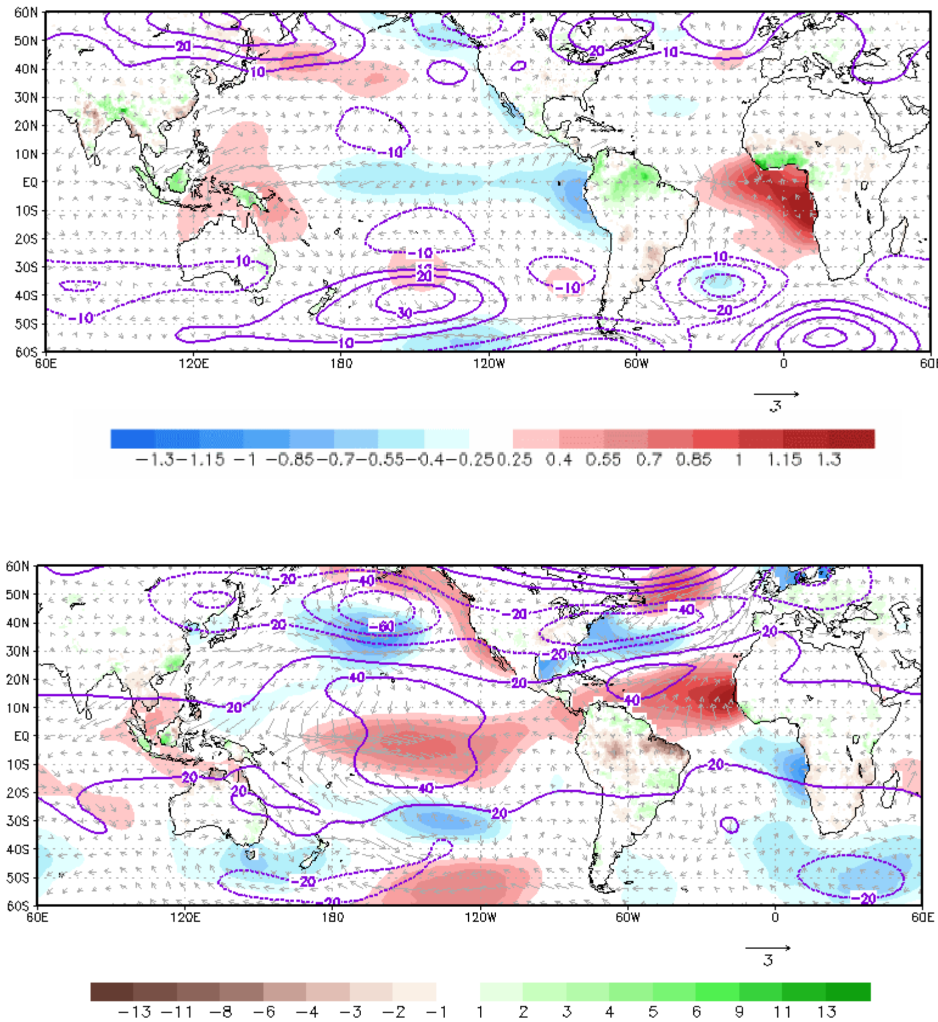

Figure A1.4: Global projections of Tropical Atlantic Variability modes. Figures are calculated from composites of events in which principal component presents values > 1std minus events in which the principal component presents values <-1std. The modes are calculated from Had-SST data using a 11-yr high pass filter and computed along the annual cycle. Top: composite of the leading mode in June-July-August for anomalous SST (shading over ocean), anomalous rainfall from University of Delaware (shading over land) and anomalous surface wind and 200 hPa geopotential height from NCEP 20th Century Reanalysis. Bottom: as Top but for the second mode. Bottom: The strong variability corresponds to boreal summer (JAS, top) and spring seasons (MAM, bottom).

A2. Climate Impacts of Tropical Atlantic Variability

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A2.1 Introduction

In the previous section, it was shown that the Tropical Atlantic possesses a rich physical variability arising from ocean-atmosphere interactions within the region as well as remote influences. The mechanisms of these modes of variability are understood to a degree, and at least part of their evolution is potentially predictable. Here, the impacts of this variability on climate over land are described. These impacts are substantial, affecting the lives and livelihoods of hundreds of millions of people in adjacent continents and beyond (Kushnir et al. 2006 and see Figure A2.1).

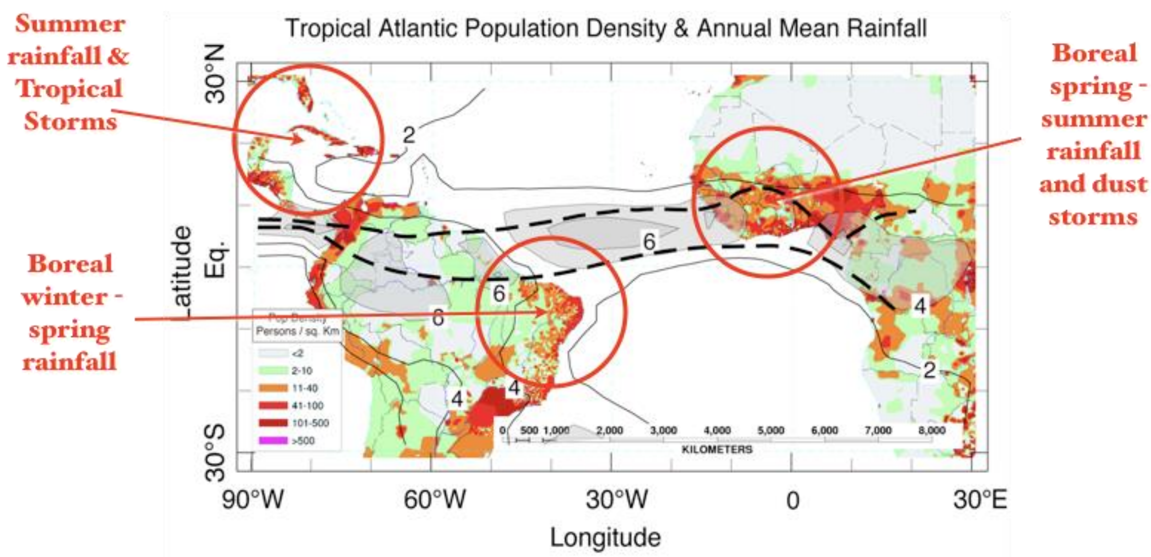

Figure A2.1: The mean annual distribution of rainfall in the tropical Atlantic region (contours and grey shading) superimposed on a map of population density. The figure demonstrates the effect that TAV can have on the densely-populated regions surrounding the tropical Atlantic Basin.

In what follows, we show how Tropical Atlantic variability (TAV) impacts different continental regions by discussing these regions in turn. It should be noted, however, that the Tropical Atlantic has an influence on other tropical oceans, which themselves have widespread climate influence. As such, variability that is intrinsically native to the Tropical Atlantic can influence climate widely, via, for example, its influence on the development of El Niño events. Warming of the Equatorial Atlantic region often appears together with cooling in the Tropical Pacific and a warming in the Indian Ocean, and vice versa for a cooling in the equatorial Atlantic (see, for example, Polo et al., 2008, 2015; Rodríguez-Fonseca et al., 2009). A mechanism involving alteration of atmospheric convection over the Western Equatorial Atlantic and subsequent changes in the Walker circulation and Tropical Pacific Ocean surface wind stress is apparent. The meridional dipole mode has also been linked to ENSO through ITCZ variations and equatorial coupled ocean–atmosphere feedback.

A2.2 Impacts of TAV – linkages, associations:

TAV impact on West African monsoon (WAM) system:

Between 1968 and 1972 a severe drought hit the semi-arid Sahel region in West Africa inflicting catastrophic cost in human and wildlife lives (Nicholson 1981). After some relief, droughts hit the same region again in the early to mid-1980s. This protracted drought period surprised the region's farmers and pastoralists who grew accustomed to a long, decade and a half sequence of relatively rainy summers (Watts 1987). As scientists were fast to point out, the surprising and devastating change from affluent rainfall to sever drought had a lot to do with changes in worldwide tropical SST, but in particular the rapid cooling of SST in the North Atlantic, including in the north tropical ocean region, that began after 1965 (Folland et al. 1986, Giannini et al., 2003).

TAV is strongly linked to the West African Monsoon System (WAM). The WAM is characterized by a precipitation dipole pattern with centers over the Sahel and the Gulf of Guinea. The abrupt shift of the Intertropical Convergence Zone (ITCZ) from the Guinea Coast to the Sahel at the end of June, determines the peak of rainfall in the Sahel from July to September (Sultan and Janicot 2000; Okumura and Xie 2004; Nicholson and Dezfuli 2013; Rodriguez-Fonseca et al.2015; Suarez-Moreno et al. 2018). The convergence of the northeasterly winds with the moisture flow from the colder eastern equatorial Atlantic Ocean determines the ITCZ shifts and therefore the precipitation over West Africa. Thus, the WAM is strongly affected by sea surface temperature (SST) anomalies in the Atlantic cold tongue region that are associated with the Atlantic Niño or Atlantic zonal mode. A warm phase of the Atlantic Niño displaces the ITCZ to the south, decreasing the land-sea pressure gradient causing droughts over the Sahel and excess rainfall over the Gulf of Guinea (Okumura and Xie, 2004; Polo et al. 2008; Losada et al. 2010; Rodríguez-Fonseca et al. 2015). This area of the tropical Atlantic is governed by ocean dynamics, and to understand the surface variability, it is necessary to know the variability beneath the ocean surface.

The WAM can be affected by other modes of variability from other basins such as ENSO (Rowell 2001; Giannini et al. 2003; Mohino et al. 2011a). The WAM peaks in boreal summer and ENSO's mature phase is in boreal winter, so the WAM relationship is not as strong with ENSO as that with the Tropical Atlantic. However, recent studies have shown that the strong link between the precipitation dipole pattern and the tropical Atlantic has weakened after the 1970's . At the same time, a monopolar pattern over West Africa has become more frequent, co-varying with SST anomalies in the global tropics (Losada et al. 2012a). Enhanced summer rainfall is linked to warmer SST anomalies in the tropical Atlantic and the Maritime Continent, and colder anomalies in the tropical Pacific and western Indian Oceans. Thus, there is a non-stationary relationship between WAM precipitation and SST anomalies in the Tropical Atlantic (Losada et al. 2012a).

On long-time scales, the Atlantic Multidecadal Oscillation/variability (AMO/AMV), which extends into the North Tropical Atlantic, plays a role in the aforementioned changes. Over Africa, the warm phase of the AMO is associated with a large increase in Sahel precipitation during the rainy season, with drier conditions in the cold phase (Folland et al. 1986; Knight et al. 2006; Martin and Thorncroft 2014; Ting et al. 2009; Mohino et al. 2011b). In particular, low pressure anomalies in the tropical North Atlantic develop during warm AMO periods, increasing the strength of the low-level West African westerly jet and associated moisture flux at around 10°N, resulting in increased precipitation over the Sahel (Grist and Nicholson 2001; Pu and Cook 2012; O'Reilly et al. 2017). A long-term warming trend is also evident in the tropical Atlantic. This trend has been attributed to greenhouse gas global warming (Hulme et al. 2001; Ting et al. 2009). Ting et al. find that during the 20th century, this trend led to a large SST warming in the south Atlantic relative to the North Atlantic and as such, projected drying of WAM and that this was consistent with CMIP5 climate model simulations of the 20th century (Ting et al. 2014).

Seasonal prediction of WAM strength and onset is now a routine activity in West African climate fora. The knowledge acquired from the aforementioned theoretical studies guides forecasters to make better predictions using Tropical Atlantic observations with statistical and dynamical prediction methods (Colman et al., 2017). Several prediction systems show skill in predicting long-term changes in Sahel rainfall (Gaetani and Mohino 2013; Martin and Thorncroft 2014; Otero et al. 2016). Such skill is mainly coming from the accurate forecast of Atlantic variations in SSTs (García-Serrano et al. 2015; Mohino et al. 2016), for which a continuous long-term large-scale monitoring of SST variability is crucial. Recently, Li et al. (2016) shows that Sahel precipitation is also correlated with sea surface salinity (SSS) in the subtropical North Atlantic and tropical South Atlantic, based on the fact that water evaporating from the ocean sustains precipitation on land leaving an imprint on the SSS. This study shows that because of the physical connection between salinity, ocean-to-land moisture transport, and local soil moisture feedback, seasonal forecasts of Sahel precipitation can be improved by incorporating SSS into prediction models. Therefore, the continuous monitoring of not only temperature but also salinity in the Tropical Atlantic is mandatory to achieve an accurate forecast system.

The discussion of TAV influence on WAM above confirms that the tropical Atlantic plays a key role in the climate of West Africa during the rainy season. Given that in the Sahel region a major part of the economy is built on subsistence farming, rainfall variations and droughts have an extreme impact on the population of the region. The severe droughts of the 1970s and 1980s led to the death of thousands of people and millions of animals (Mortimore 1998). In order to be able to accurately predict such impacts in the future, a robust, reliable monitoring system that can well describe the variability of the tropical Atlantic SST and other ocean variables is needed as well as continued research to overcome deficiencies in climate models used for prediction.

TAV impact on South America:

The South American climate is also strongly linked with TAV. The brief rainy season over the Brazilian Northeast (NE) occurs in the austral fall (March to May), when the Intertropical Convergence Zone (ITCZ) migrates southward (Nobre and Shukla 1996; Hastenrath 2006). The meridional tropical Atlantic SST gradient associated with the Atlantic SST meridional mode (AMM, Kossin and Vimont, 2007) is the dominant force driving the ITCZ position and the NE Brazil rainfall. During the years in which the meridional SST gradient is negative from March to May, i.e., when there are cold SST anomalies in the tropical North Atlantic and warm anomalies in the tropical South Atlantic, the ITCZ moves further southward, bringing rainfall to the NE. Severe droughts occur when the tropical North Atlantic is anomalously warm during this season, preventing the displacement of the ITCZ.

The rainy season in the Amazon occurs from December to April. The most severe droughts over the Amazon occurred in 2005 and 2010 and were associated with exceptional warm waters in the north Tropical Atlantic (Marengo et al. 2008, 2011). During these events the ITCZ stayed away from the Amazon. An area of about 3.0 million km^2 was affected by drought in 2010 and 1.9 million km^2 in 2005 (Lewis et al., 2011). The impact of these extreme dry events was particularly noticeable in unusually low stream flows and river levels in the Amazon and several of its major tributaries. This was also accompanied with high surface temperatures and low atmospheric humidity, which favored increased evaporation. Navigation along large sections of the central Amazon River had to be suspended, which led various countries of the Amazon region (Brazil, Bolivia, Peru, and Colombia) to declare a state of public emergency. The droughts left thousands of people short of food, caused problems with agriculture, generation of hydroelectricity, and also affected directly and indirectly the populations living along the rivers of the region. As the rain forests dried, severe wildfires broke out in the region, damaging hundreds of thousands of hectares of forest. These wildfires produced extensive smoke that affected human health and closed airports, schools, and businesses. These ecological impacts affected the feasibility of sustainable forest management in the region, which is currently advanced as a promising basis for the regional economy (Marengo et al. 2008, 2011).

Conversely, extreme floods can occur in years when the tropical South Atlantic waters are relatively warmer than their northern counterparts, i.e., during a negative phase of Atlantic Meridional Mode (AMM). For instance, the recent events of 2009, 2012 and 2014 were associated with warm tropical South Atlantic (Marengo and Espinoza 2016). When it occurred, the 2009 event was considered the worst flood in a century. However, flooding in 2012 surpassed the record set in 2009. The level of the Negro River at Manaus on May 2012 reached 29.87 m, the highest mark since the data record started (1902). These extreme events impact urban and rural areas of the Amazon, in particular people living near the river banks. For instance, an increase in cases of leptospirosis (a bacterial disease) was reported during the 2012 event. They also caused changes in Amazon wildlife populations. It was observed that terrestrial mammal populations decreased by 95% as floods intensified (Bodmer et al. 2018). There has been an increase in occurrence of mega-droughts and mega-floods in the Amazon over the last decades suggesting that this is linked to the intensification of the hydrological cycle under climate change. The role of the Tropical Atlantic in the aforementioned climate variability and extremes is not yet fully clear and can only be determined with adequate and continuous monitoring of its properties.

Over the coastal areas of the NE, extreme events can occur as a response to other mechanisms, such as atmospheric instability lines, breeze occurrences, and atmospheric easterly waves (Kouadio et al. 2012; Hounsou-Gbo et al. 2016). For instance, extreme rainfall events are positively related to the SST anomalies in the southeastern tropical South Atlantic with a lead of 3 to 6 months (Hounsou-Gbo et al. 2015). Those extreme events are excited by the atmospheric easterly disturbances, which in turn are linked to the southwestern Atlantic warm pool where SST generally exceeds 27°C (Kouadio et al. 2012; Cintra et al. 2015; Silva et al. 2018).

Many studies have shown that the precipitation response over the northern South America is a combination of the effects of the ENSO on the tropical North Atlantic and SST anomalies due to intrinsic Atlantic internal variability (Giannini et al. 2004; Rodrigues et al. 2011). Generally, El Niño events cause a positive meridional SST gradient and droughts in the NE. However, in the recent years, the NE has experienced a severe continued drought that was triggered by anomalous positive meridional SST gradient during a La Niña year (Rodrigues and McPhaden 2014; Martins et al. 2018). The seasonal forecast failed to predict the drought in 2012 because of the models' low skill in simulating the meridional SST gradient in the Tropical Atlantic. Rodrigues and McPhaden (2014) show that it is possible to predict the sign of the NE rainfall anomaly during ENSO events using a simple SST index three months in advance. The 2005 and 2010 Amazon droughts were not directly linked to El Niño events. ENSO teleconnections to the tropical Atlantic have changed in decadal time scales but this is not yet well understood (Losada et al. 2012; Suarez-Moreno et al. 2018).

TAV impact on The Caribbean, Central and North America

The observed association between tropical Atlantic SST variability and the climate of North and Central America, as measured by correlation, is not as strong as the tropical impacts described above (Marshall et al. 2001). However, the connection between TAV and Central and North American climates is statistically significant, particularly on multi-year to multi-decadal time intervals. An important phenomenon, in this case, is the link of the climate over land with AMV (Knight 2006; Ting et al. 2009). The AMV association with annual precipitation variability in Central and North America was highlighted by Enfield at al. (2001). Subsequent studies using observations and climate models validated this association and demonstrated that SST in the North tropical Atlantic is forcing land precipitation variability (Sutton and Hodson 2005; Seager et al. 2009; Kushnir et al. 2010; Ruprich-Robert et al. 2017).

The most important societal impact of the multidecadal variation of tropical Atlantic SST in North America, is associated with the occurrence of drought in the US Southwest and Northern Mexico (Seager and Ting 2017). This association is connected with the influence that these SST variations have on the intensity of the North Atlantic subtropical High (NASH). When north tropical Atlantic SST are warmer than normal, the anticyclone weakens. This weakens the transport of Gulf of Mexico moisture into the Great Plains and southwestern US as well as the uplift associated with the southerly flow on the western flank of the anticyclone. The result is reduced precipitation over the regions that lie west of the Mississippi River. While the major driver of interannual to decadal precipitation variability over the western US is ENSO, the Atlantic modulates the intensity of the ENSO impact (Seager et al. 2009; Kushnir et al. 2010). The most intense droughts in western US were the Dust Bowl drought of the 1930s and the Texas drought of the 1950s (that was also felt in the Southwest and the Plains). These droughts occurred in decades during which El Niños (which usually brings a wet winter climate to the US southern tier states) were absent or weak and the AMV was in a positive phase, with warmer than normal tropical Atlantic SST. Both droughts severely affected farmers' livelihood in the Great Plains. During the Dust Bowl years, wide-spread abandonment of farms and farmlands occurred. Mass migration of families happened when farmers moved from the Plains westward to California where the drought did not hit. The 1950's drought was economically devastating to the State of Texas and was recorded as the most severe drought of the 20th century in that state.

The variability in the westward extension of the NASH and orientation of the anticyclone's east-west axis, also affects rainfall patterns over the continent on interannual to decadal time scales. North-south movement of the anticyclone axis causes alternating dry-wet seasons in the northern and southern parts of the eastern US (Li et al., 2012). The most recent, severe drought in the Southeast US occurred in the 1990's resulting in extreme heat and water shortages.

In Central America and the Caribbean, the impact of TAV is dipolar. Northern Central America varies in phase with north tropical Atlantic SST and Southwest US. The effect of TAV is opposite in the southern regions of Central America and in the Caribbean Islands (Spence et al. 2004; Seager et al., 2009; Kushnir et al., 2010 and see Figure A2.2). Here too, the Atlantic impact on precipitation is opposing the concurrent effect of ENSO (Giannini et al., 2000 and 2001). Méndez and Magaña (2010) discussed droughts in Mexico and Central America and noted that the major droughts in northern Mexico coincided with the droughts in the US Great Plains and Southwest. In these northern Mexico droughts, the tropical Atlantic tends to be warmer than normal. Méndez and Magaña mention the seesaw relationship between northern Mexico and the southern portions of Central America, which experience wet conditions when there is a drought in the north.

In addition to the impact on seasonal and multi-year anomalies of precipitation over land, tropical Atlantic SST significantly influence tropical cyclones (TCs) and hurricane activity in the entire Atlantic Basin. Many of these storms form off the coast of Africa and move from there toward Central and North America continents as they intensify by drawing energy from the warm tropical waters. Consequently, they are able to inflict serious damage when they make landfall. These damages are associated with the storms' winds, rainfall and coastal surge driven by the force of the wind over the ocean surface. The intensity of these storms, in terms of overall destructive potential (a function of storm windspeed and storm duration) is directly related to the average seasonal temperature of the water in the tropical Atlantic. In that respect, it is important to mention that on multidecadal time scales, the overall intensity of Atlantic hurricane has changed in phase with the AMV (Goldenberg et al., 2001). Warmer than normal tropical Atlantic SSTs compete with the impact of warm SSTs in the eastern equatorial Pacific. El Niños, with their warmer than normal east tropical Pacific SSTs, have a restraining effect on the activity of Atlantic tropical cyclones through forcing increased vertical shear over the tropical Atlantic (Patricola et al., 2014).

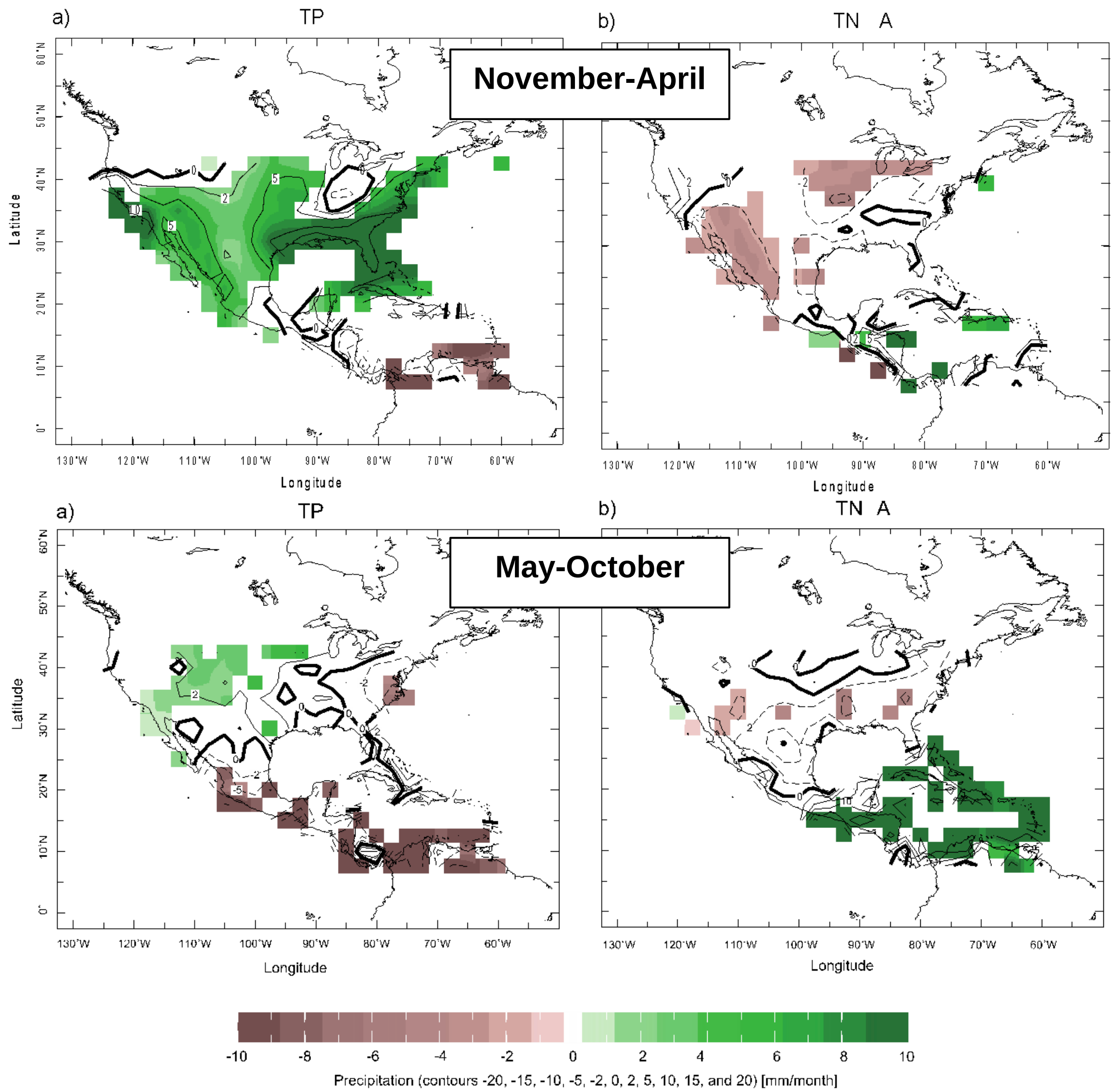

Figure A2.2: The multiple regression between precipitation and the tropical Pacific (TP, left) and tropical North Atlantic (TNA, right) SST indices (see text for definition) for the (top) November through April half year and (bottom) May-October). Data are from the UNAM precipitation data set and for 1945 to 2002. The regression coefficient in mm/month per standard deviation of the SST index is both contoured and colored but coloring is applied only where the relationship is significant at the 5% level.

TAV impact on Northern mid- and high-latitudes

In the previous sections, we have seen how variability in the Tropical Atlantic Ocean-Atmosphere system can create climate impacts on adjacent continents. It is becoming apparent, however, that the Tropical Atlantic is also important as a driver of climate impacts in mid- and high-latitudes. Weather and climate in these regions (particularly Europe and Eastern North America) are dictated by variations in the path and intensity of the mid-latitude jet stream, and thereby the North Atlantic storm track. These can be influenced by a range of remote conditions, such as the El Niño-Southern

Oscillation (e.g. Fereday et al., 2008) and the tropical Atlantic (Hoskins and Sardeshmukh, 1987). It has long been understood that massive tropical convective events excite atmospheric Rossby waves (e.g. Sardeshmukh and Hoskins, 1988). The energy carried by these, generally stationary waves, can propagate into mid-latitudes, buckling the jet stream and causing changes in surface weather patterns. Indeed, since conditions in the tropics often change only slowly, these patterns can persist up to seasonal timescales. Scaife et al. (2016) showed that tropical rainfall patterns can account for a substantial amount of the variations in the average boreal winter (December to February) North Atlantic Oscillation (NAO), a leading measure of the year-to-year changes in mid-latitude weather. Further, particular high-impact cases have been shown to have origins in the Tropical Atlantic. Winter 2013-14 was the wettest winter on record in the United Kingdom and brought high rainfall and storms widely across Western Europe, leading to severe flooding and damage (Huntingford et al. 2014) with an estimated cost of 1.7 billion Euros (Fenn et al. 2016). Knight et al. (2017) showed that the very deep, persistent cyclonic pattern linked to these impacts was part of a Rossby wave train emanating from the Tropical Atlantic sector (Figure A2.3), which was itself the result of unusual patterns of tropical convection. Further examples of extreme winter events linked to conditions in the Tropical Atlantic include flooding in early winter in North West Europe in 2015 (Maidens et al. 2018). In addition, the incidence of heatwave and drought conditions in summer in Central Europe has been linked to wave-like patterns originating in the Tropical Atlantic sector (Ole Wulff et al., 2017). This strongly suggests that conditions in the Tropical Atlantic are highly significant in the occurrence of impactful mid-latitude extremes throughout the year.

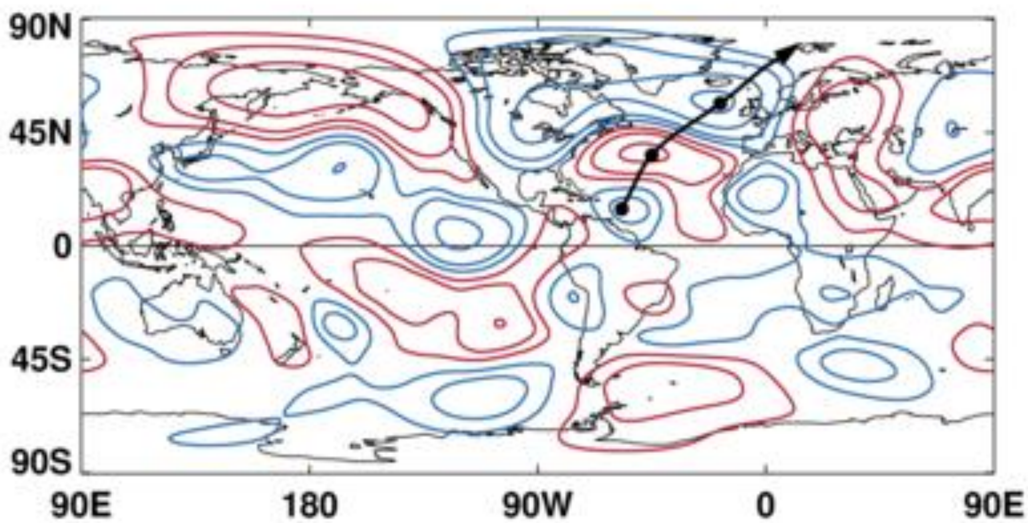

Figure A2.3: Average upper tropospheric stream flow patterns observed in winter (DJF) 2013-14. Cyclonic (negative) anomalies are plotted with blue contours and anticyclonic (positive) anomalies are plotted with red contours. The theoretically computed propagation path a the Rossby wave with is shown by the curved black arrow. See Knight et al. 2017 for full details. Adapted from Knight et al. 2017.

The findings above imply that a well-observed Tropical Atlantic is necessary if we are to understand and, ultimately, make accurate predictions of the risk of impacts from seasonal weather in mid-latitudes. In particular, the mechanism of atmospheric Rossby wave production implies a need for good characterisation of the location and strength of deep convective systems across the Tropical Atlantic region. Satellite observing platforms can provide this to some extent through outgoing longwave radiation (OLR) measurements, and more so via satellite estimates of rainfall.

Nevertheless, there are considerable uncertainties in the algorithms for making these estimates, and reference to ground truth via surface rainfall gauges is essential. Clearly, however, surface-based estimates of rainfall over remote oceanic regions such as the Tropical Atlantic are very sparse. Better instrumentation for oceanic surface rainfall measurements within the Tropical Atlantic observing system could provide the necessary comparisons to improve satellite products. Availability of other *in situ* atmospheric measurements (such as from radiosondes) is also extremely limited over the ocean in the deep tropics, and improvement of the number of such observations would be beneficial for constraining the dynamical aspects of tropical-extratropical interactions.

A3. The AMOC in the Tropical Atlantic

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A3.1 Motivation for studying the AMOC in the Tropical Atlantic

The Atlantic Meridional Overturning Circulation (AMOC) plays an important role in the global climate system through its large transport of heat northward across the equator. Significant changes in the strength of the AMOC are expected to lead to widespread climate changes particularly over the northern hemisphere Atlantic and adjacent continental regions (Manabe and Stouffer, 1995; Vellinga and Wood, 2002, 2008; Stouffer et al., 2006; Kuhlbrodt et al., 2009; Jackson et al., 2015).

Several studies have focused in particular on the impact of variations in the AMOC on tropical Atlantic SST, using both uncoupled ocean models (Yang, 1999; Johnson and Marshall, 2002) and coupled models (Dong and Sutton, 2002; Chang et al, 2008). An important aspect of the ocean's dynamical response to a change in the AMOC is the so- called "equatorial buffer" (Kawase, 1987; Johnson and Marshall, 2002), which limits the rapid communication of AMOC signals across the equator between the two hemispheres. The initial response to change in deep water production in the North Atlantic consists of an equatorward-propagating baroclinic Kelvin (or more generally, coastally trapped) wave along the western boundary. Upon reaching the equator it is transmitted to the eastern boundary via an equatorial Kelvin wave and poleward in the basins by coastally trapped waves, and then westward into the ocean interior by long Rossby waves. As a result of this process, a rapid adjustment of the AMOC occurs throughout the northern hemisphere ocean, via the Kelvin wave response (on the order of a few months), while the response in the southern hemisphere is much slower, set by the Rossby wave time scale (of order several years). Consequently, there is a "mismatch" in the strength of the AMOC in the two hemispheres for a number of years, and a corresponding convergence or divergence of meridional heat flux across the equator during this time period. The feedback of this process to the atmosphere can lead to coupled changes in SST and atmospheric circulation patterns and an amplification of the response (Dong and Sutton, 2002).

The basinwide SST response to a significant reduction in the AMOC - typically forced in models by "fresh water hosing" (the addition of large volumes of freshwater to the subpolar North Atlantic leading to a suppression of deep convection) - is an interhemispheric dipole pattern with pronounced cooling in the northern hemisphere and more moderate warming in the equatorial and South Atlantic (Figure A3.1). The details of the SST response differ slightly among models but generally show maximum cooling in the subpolar North Atlantic and a secondary cooling maximum in the NE trade wind region, and maximum warming in the SE tropical Atlantic with westward extension along the equator.

The anomaly in cross-equatorial SST (cooler water north of the equator and warmer water south of the equator) in turn leads to a southward shift of the ITCZ and associated precipitation anomalies over the tropics (Figure A3.1). The SST and precipitation anomaly patterns that develop under such a scenario are quite similar to patterns that have been associated with other interannual forcing mechanisms, such as changes in the Atlantic Meridional Mode (AMM) or NAO or ENSO- related atmospheric teleconnections. AMOC fluctuations in coupled-model control simulations without additional water hosing (e.g., Zhang (2010)) also show a similar equatorial-buffer type AMOC response to high-latitude buoyancy forcing, but with smaller amplitude AMOC changes of ±2 Sv in the tropics and an additional lag between the subpolar and subtropical North Atlantic due to the presence of interior NADW pathways. The conclusion to be drawn from these studies is that sufficiently large changes in the strength of the AMOC can have important consequences for tropical Atlantic SST. The equatorial region, though remote from the probable forcing regions of AMOC variability, is in fact a focal point for oceanic heat storage changes as a consequence of the delayed adjustment of the AMOC throughout the basin.

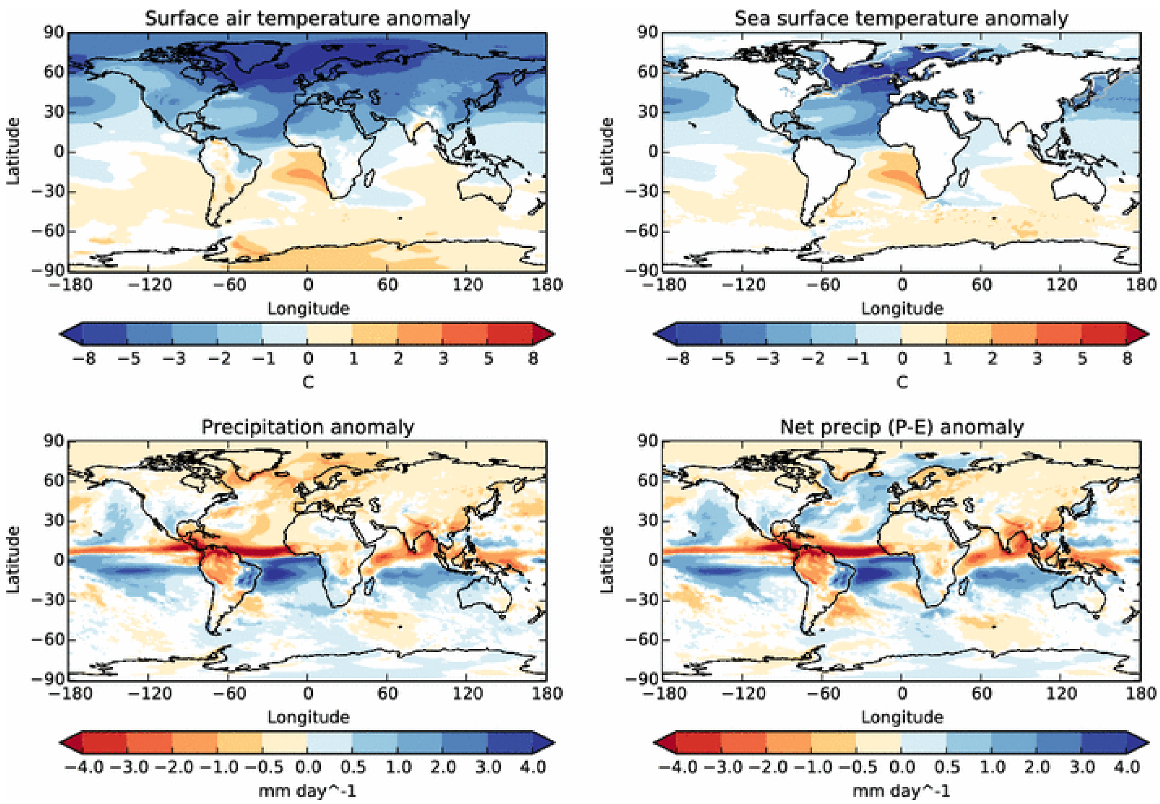

Figure A3.1: Change in global surface air temperature (*top left*, °C), sea surface temperature (*top right*, °C), precipitation (*bottom left*, mm/day) and net precipitation (precipitation–evapotranspiration) (*bottom right*,mm/day), for years 60-90 after a freshwater-induced AMOC slowdown. From Jackson et al. (2015).

Wind forcing can also contribute to AMOC changes in the tropical Atlantic, and modeling studies suggest that wind forcing is in fact the dominant AMOC forcing mechanism on interannual time scales while buoyancy forcing is dominant on decadal to multidecadal time scales (Biastoch et al., 2008a; Yeager and Danabasoglu, 2014; Zhao and Johns, 2014; Zhao, 2017). Zhao (2017) showed in a forced OGCM study that wind-driven AMOC fluctuations with amplitudes of ±3 Sv occur in the tropics on dominant time scales of 2-10 years. The wind-driven tropical AMOC fluctuations are found to be mostly coherent between 15°S to 30°N and contain nearly equal contributions from Ekman and non-Ekman (geostrophic) flows. Besides the regionally forced wind-driven AMOC anomalies, the tropical AMOC fluctuations were shown to contain remotely forced signals from high-latitude wind forcing that propagated southward and crossed the equator in a manner consistent with the equatorial buffer mechanism.

In addition to the effects of high latitude buoyancy forcing and basinwide winds on the AMOC, AMOC variability in the tropics can also be remotely forced from the south by variability in Agulhas leakage to the Atlantic from the Indian Ocean (Biastoch et al., 2008b). Biastoch et al. showed interannual-to-decadal AMOC anomalies of ~ ±1.5 Sv generated by variability in Agulhas leakage region that propagated as thermocline depth anomalies across subtropical South Atlantic, which were then transmitted northward to the equator by coastally trapped waves along the South Atlantic western boundary.

Trends in the Agulhas leakage may also be taking place due to the poleward shift and increase in strength of the southern hemisphere westerlies that has occurred during the last several decades (Biastoch et al, 2009; Durgadoo et al, 2013). Biastoch et al (2009) found that the Agulhas leakage had likely increased by 50% (from 14 to 21 Sv) between the 1970's and early 2000's, but that most of this excess transport was recirculated within the southern hemisphere "supergyre" rather than directly affecting the AMOC strength. However, the increased salt transport to the South Atlantic by the increased Agulhas leakage has led to an overall salinification of the South Atlantic subtropics (Biastoch et al. 2009, Hummels et al., 2015). This trend in Agulhas leakage is expected to continue and possibly intensify in 21st century due to anthropogenic forcing (Sen Gupta et al., 2009). As these saltier waters reach the North Atlantic in the upper limb of the AMOC and eventually propagate to the deep water formation regions, they could help to sustain the AMOC against its projected decline due to global warming (Weijer et al., 2002). The increased Agulhas leakage may have also contributed to the overall warming of the tropical Atlantic in the past several decades, by supplying warmer (as well as saltier) waters to the tropical thermocline that eventually upwell along the equator (Lübbecke et al., 2015).

Other effects of a change in the AMOC on tropical circulation patterns and water mass properties can be more indirect but still potentially important in oceanic feedback to the atmosphere. For example, it is likely that a change in the AMOC would substantially impact the structure of the shallow overturning cells that link the tropics and subtropics – the so-called "subtropical cells" (STCs). The STCs connect the subduction zones of the eastern, subtropical oceans with upwelling zones in the tropics (Figure A3.2), thereby providing the cool subsurface water that is required to maintain the tropical thermocline (Fratantoni et al., 2000; Malanotte-Rizzoli et al., 2000; Zhang et al., 2003; Schott et al, 2004; Perez et al., 2014). They are closed by poleward surface currents, largely Ekman transports, that return the upwelled waters to the subtropics.

The present STC pattern in the Atlantic, in which the southern STC cell is dominant over the northern cell, is believed to be a direct result of the AMOC, which cuts off most of the supply of thermocline waters to the equator from the northern subtropics (Fratantoni et al, 2000; Malanotte-Rizzoli et al., 2000; Zhang et al., 2003). A decrease in the MOC would lead to a greater symmetry of the cells and an increase in northern hemisphere waters supplied to the EUC that feed equatorial upwelling. Conversely, an increase in the AMOC would likely shut down the northern cell altogether and force a redistribution of its upwelling branch to areas farther north of the equator. Chang et al. (2008) showed that the response of the tropical Atlantic to an AMOC slowdown would likely consist of a two-stage process, where warming along the equator caused by the initial AMOC reduction would rapidly accelerate once the AMOC decreased below a certain threshold that allowed the northern STC cell to become reestablished. The increased warm advection from the warmer and saltier northern STC cell would then result in a rapid rise in equatorial Atlantic SST and subsequent impacts on atmospheric processes, including in particular an intensification of the West African monsoon. Rabe et al. (2008) showed that the Atlantic STCs can also vary on decadal time scales in response to equatorial winds, with changes in Ekman divergence between 10°S-10°N leading changes in subsurface STC equatorward flow and corresponding changes in equatorial heat content. However, the magnitude of the STC transport changes in the Atlantic were found to be relatively small (± 2 Sv) compared to the much larger STC changes (of ≥10 Sv) that have been documented in the equatorial Pacific (McPhaden and Zhang, 2004).

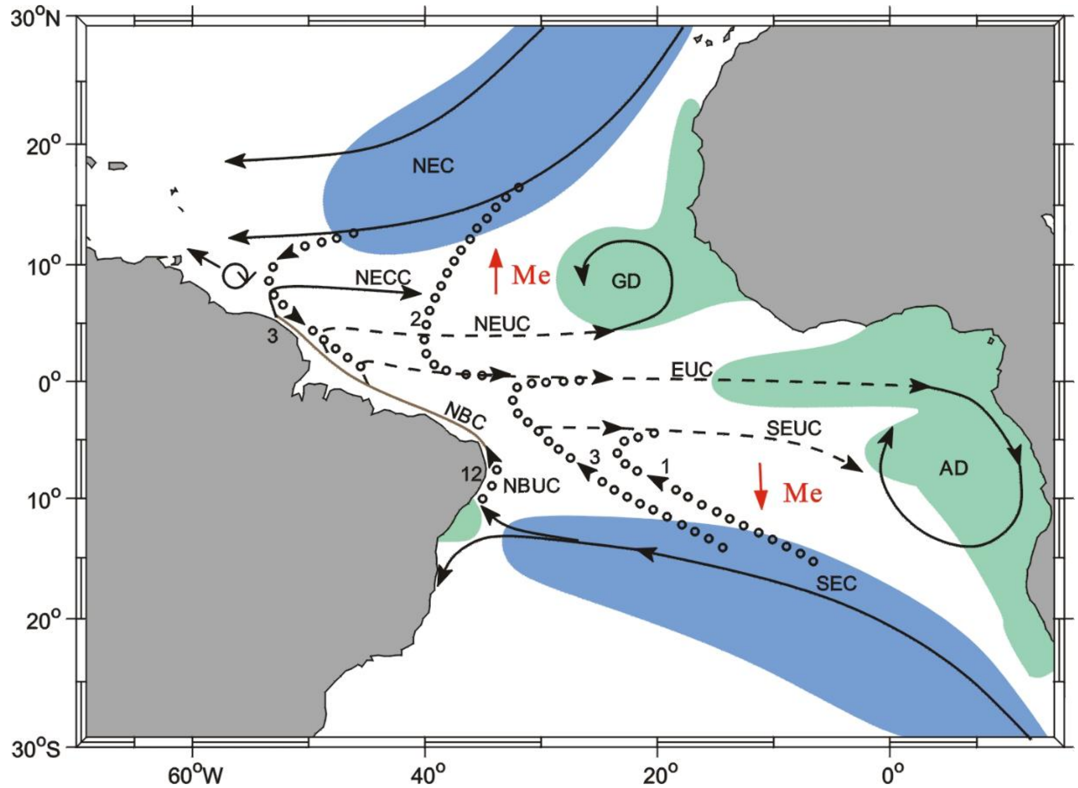

Figure A3.2: Schematic representation of the Atlantic STC circulation with subduction (blue), upwelling (green) zone, Ekman transports (red), and main circulation branches that participate in the STC. Interior equatorward thermocline pathways dotted. After Schott et al. (2004).

The STCs also interact with even shallower overturning cells confined to the tropics, the Tropical Cells (TCs). They are associated with downwelling driven by the decrease of the poleward Ekman transport 4–6° off the equator (Molinari et al., 2003; Perez et al., 2014). Interestingly, although the TCs are strong in zonal integrations along constant depths, they are much diminished in integrations carried out along isopycnal layers, indicating that they have little influence on heat transport (Hazeleger et al., 2001). Their existence implies that any measure of STC strength must be defined poleward of the TC convergences, that is, closer to the dynamical intersection between the tropics and subtropics (near 8–10°).

Finally, while it is expected that changes in the upper ocean limb of the AMOC and the STCs are most vital to climate variability in the tropical Atlantic, there is increasing evidence for trends in water mass composition in deeper layers of the Atlantic that may be linked to variability in the AMOC. Besides the increase in salinity of South Atlantic central waters noted earlier (Biastoch et al. 2009, Hummels et al., 2015), there has been an overall warming of AAIW (Schmidtko and Johnson, 2012), a freshening of NADW in the tropical South Atlantic (Hummels et al., 2015), and a warming of AABW (Johnson and Doney, 2006; Johnson et al., 2008;2014; Herrford et al., 2017). Dissolved oxygen has also shown a particularly strong decline in the NADW layers of the South Atlantic in the past 30 years (Schmidtko et al., 2017, Oschlies et al., 2018), in contrast to the increased ventilation of NADW and higher oxygen values seen in the deep North Atlantic that have recently progressed into the equatorial Atlantic (Hummels et al, 2015; Oschlies et al., 2018). Therefore, an understanding of changes in AMOC strength and/or pathways is vital to understanding and interpreting changes in water properties throughout the water column in the tropical Atlantic.

A3.2 Current AMOC Observations in the Tropical Atlantic and their linkage to the basin-wide AMOC observing system

Within the tropical Atlantic, there are presently two existing contributions to the AMOC monitoring system in the Atlantic, the MOVE array at 16°N and the WBCS/RACE/SACUS programs (more recently referred to as the TRACOS program) along 11°S. The details of the current measurements being collected at these two locations, plans for extended measurements, and their linkage to the basin-wide AMOC monitoring system are reviewed below.

A3.2.1 MOVE (Meridional Overturning Variability Experiment)

Uwe Send and Matthias Lankhorst,
Scripps Institution of Oceanography

MOVE operates the MOC monitoring array in the tropical West Atlantic along 16°N, with the objective to observe the transport fluctuations in the North Atlantic Deep Water (NADW) layer. Two "geostrophic end-point moorings" and bottom pressure sensors, plus one traditional current meter mooring on the slope have been used to cover the section between the Lesser Antilles (Guadeloupe) and the Mid-Atlantic Ridge (Figure A3.3). The geostrophic transport fluctuations through this section are determined using dynamic height and bottom pressure differences between the moorings. It has been shown that on long timescales this is a good approximation to the total southward, and by mass balance also northward, MOC transport (Kanzow et al., 2006; Send et al., 2011). The data collected by MOVE are made freely available through the OceanSITES data portals.

To date, the array has collected 18 years of temperature/salinity data (for relative geostrophic transports), 18 years of current meter data (for boundary slope transports), and 15 years of bottom pressure data (for barotropic transports, a data gap exists from 2005-2007). Due to the built-in redundancy, data are available from early 2000 until mid-2018. Interannual and long-term changes in the circulation and its vertical distribution are clearly visible now. Joint analyses with other arrays like RAPID at 26°N, with projects in the Labrador Sea, and also with modeling teams are under way, in order to inter-relate the changes, assess the basin-scale significance of the data and understand the differences (Elipot et al., 2017; Frajka-Williams et al., 2018).

Figure A3.4 shows the NADW transport inferred from MOVE measurements, referenced to the depth (4950m) of the approximate water mass boundary between the southward-flowing NADW and the northward flowing AABW. Long-term variability is evident, with a dominant period of roughly 20 years. Some numerical simulations show similar low-frequency MOC fluctuations. There appears to be a weakening of the southward flow until 2005/6, with a strengthening since then until at least 2013/14; the most recent data are suggestive of a renewed weakening. At first sight these results are in contradiction with data and analyses from the RAPID array, where a weakening of the MOC has been observed since 2004. Frajka-Williams et al. (2018) conclude that it is not yet certain whether the discrepancies between the two latitudes are due to differences in the observational strategies or due to actual circulation features that lead to convergences/divergences between the two arrays. Resolving these discrepancies remains a research priority for MOVE. MOVE is presently funded by the Global Ocean Monitoring and Observing Program of NOAA, and although funding is received in increments, the MOVE observations are expected to continue for the foreseeable future.

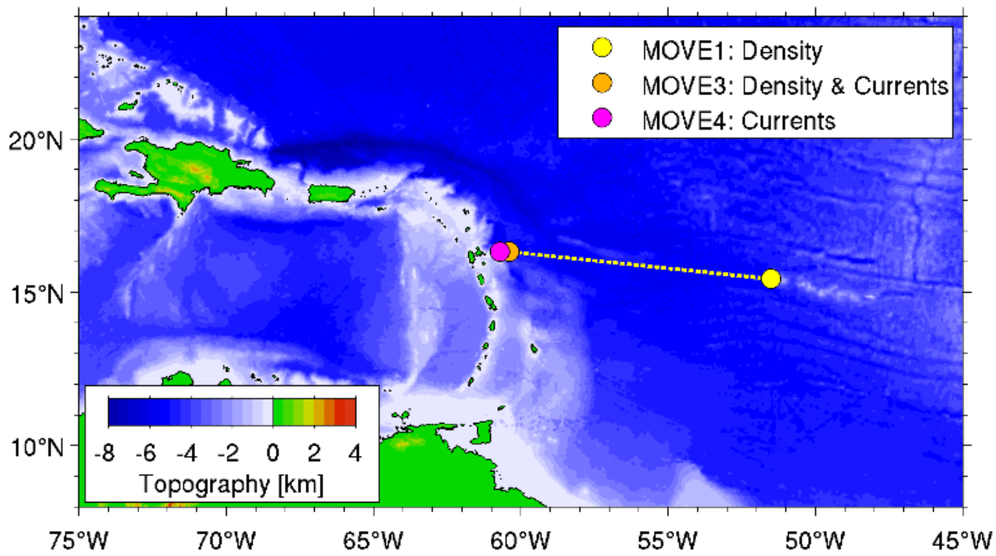

Figure A3.3: Map of the MOVE array. The goal is to measure the flow at depths of 1200-5000 m across the section shown as yellow dashes. MOVE1, MOVE3, and MOVE4 are mooring sites. Additional PIES (pressure-sensing inverted echo sounder) instrumentation is located at MOVE1 and MOVE3. (Adapted from Send et al., 2011)

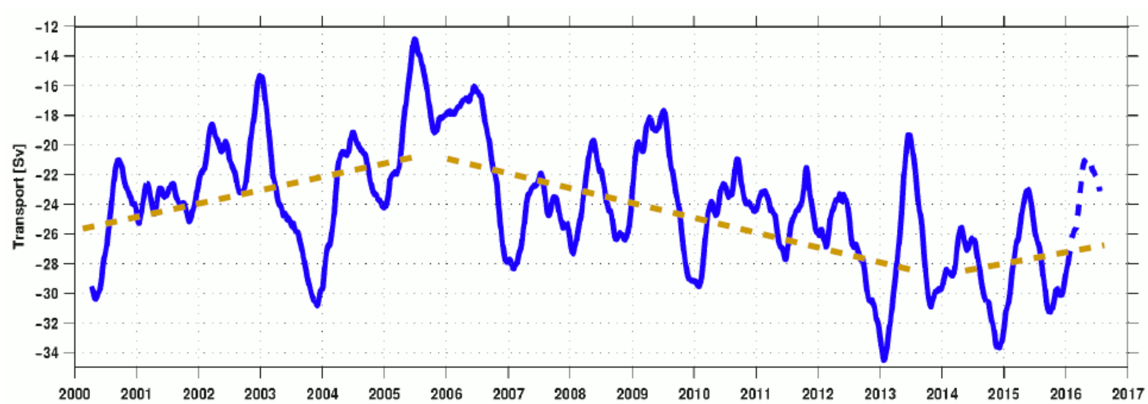

Figure A3.4: Time series of NADW transport in the depth range 1200-5000 m across the MOVE section (negative southward). The blue dashes denote acoustically retrieved data; more recent data are still being processed. The dashed orange lines indicate decadal-scale variability, although the details of fitting trend lines are somewhat arbitrary. (Adapted from Send et al., 2011)

A3.2.2 WBCS/RACE/SACUS Program at 11°S

Rebecca Hummels and Peter Brandt,
GEOMAR

One of the key regions of the wind-driven and thermohaline circulation of the Atlantic Ocean is the Western Boundary Current System (WBCS) off Brazil. This region serves as a crossroads for the meridional transfer of warm and cold water masses (Figure A3.5) that are part of the AMOC as well as of the southern hemisphere STC. Hence, the upper ocean flow within the North Brazil Under Current (NBUC) can be decomposed into contributions from the AMOC, the southern wind-driven

STC, and the Sverdrup related transport (Schott et al., 2005). In particular, it has been shown to be the main pathway for the mean northward flowing upper branch of the AMOC in the tropical South Atlantic. Modeling studies suggested that decadal to multidecadal buoyancy-forced changes in the basin-scale AMOC transport manifest themselves in NBUC transport variability (e.g. Rühs et al., 2015). The relation is, however, masked by a strong interannual to decadal wind-driven gyre variability affecting the NBUC. While questioning the NBUC transport as a "direct" index for the AMOC, model analysis supports its potential merit for an AMOC monitoring system, provided that the wind-driven circulation variability is properly accounted for (Rühs et al., 2015). These results agree with previous model studies, which also showed that on shorter time scales such as interannual, the variability of the tropical circulation including the NBUC is mainly wind-driven (Biastoch et al., 2008; Hüttl and Böning, 2006).

Intense observations of the western boundary current along the northern Brazilian continental slope started in 2000 with 5 research cruises between 2000 and 2004 occupying the 5°S and 11°S section, and a mooring array that was maintained during that period at 11°S within the framework of the project CLIVAR marin. One major finding was that the lower branch of the AMOC in terms of the DWBC breaks up into eddies at around 8°S and that these eddies accomplish the deep water transport across 11°S (Dengler et al. 2004). Since 2013 the observational efforts have been reinitialized within the framework of the project "RACE" and up to date 5 more research cruises along the 5°S and 11°S repeat sections have been conducted. In addition, the mooring array has been redeployed in July 2013 providing 5 more years of current observations at the same location. Together these two observational periods provide the basis to investigate the interannual to decadal variability of the WBCS at this location. Recent estimates (for 2013-2016) yield a mean southward transport of North Atlantic Deep Water (NADW) of 19.2 ± 2.3 Sv and a northward transport of warm and intermediate waters within the NBUC of 25.8 ± 1.2 Sv (Figure A3.6). Hummels et al. (2015) found that on average transports of the NBUC and the DWBC have not changed between the two observational periods (Figure A3.6). The DWBC eddies - that are predicted to disappear with a weakening AMOC (Dengler et al. 2004) - are still present with similar characteristics in the recently collected velocity records. In addition to direct velocity measurements, time series of NBUC transport variability spanning several decades were estimated from historical hydrographic observations by Zhang et al. (2011). In their study, multidecadal NBUC variability has a range of about 6.7 Sv, which was found to be in general agreement with forced ocean model results (Hummels et al. 2015).

For climate research, it is particularly important to understand the meridional coherence of AMOC signals, with the tropical observing system at 11°S representing a link between North and South Atlantic MOC variability. The data of the WBCS at 11°S together with numerous other observations including winds from satellite observations, all available hydrographic data, data from pressure inverted echo sounders (PIES) deployed at 300m and 500m depth on either side of the basin, as well as moored velocity measurements at the eastern boundary at 11°S within the framework of the German SACUS program (Kopte et al. 2017, 2018) will be used to provide a comprehensive AMOC estimate at 11°S from 2013 up to date. The four moorings placed off the Brazilian Shelf each equipped with an upward looking ADCP and several single point current meters, which provide the database for the WBCS investigations, will be maintained until autumn 2019. Beyond 2019, sustained funding for the observations within this key region is still being sought. The eastern boundary mooring will be maintained at least until 2022.

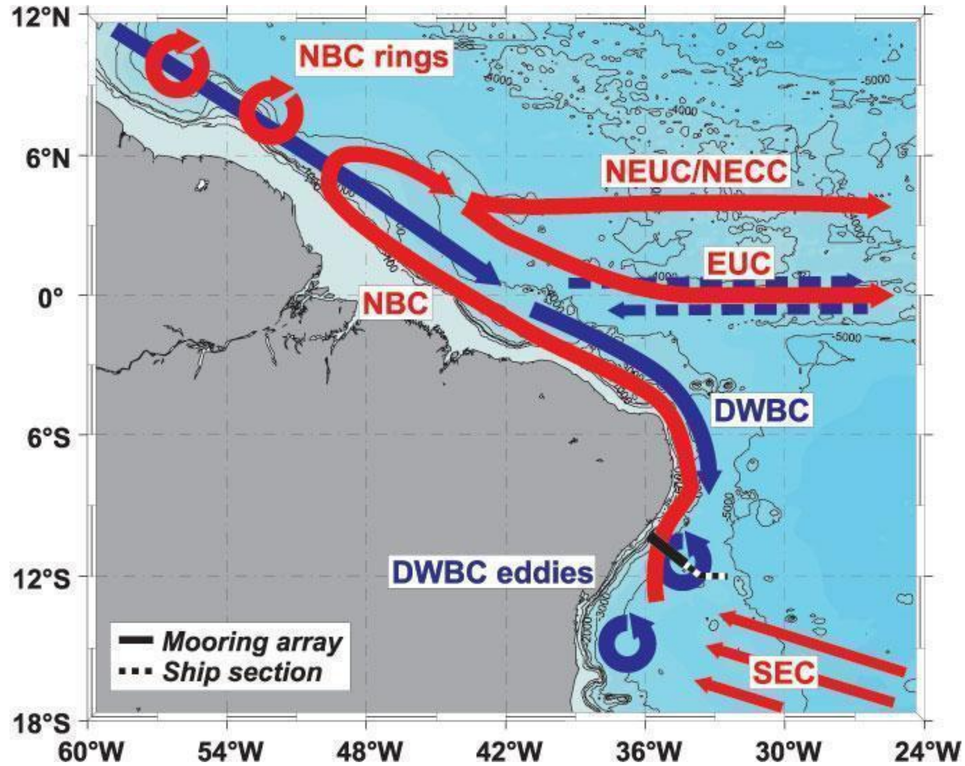

Figure A3.5: Circulation in the western tropical Atlantic. Schematic representation of mean currents and eddy generation at the western boundary of the tropical Atlantic with warm water pathways in red and NADW pathways in blue. Black bar and dotted black line at 11°S indicates positions of the measurement program. Current branches indicated are the South Equatorial Current (SEC), the North Brazil Current (NBC), the Equatorial Undercurrent (EUC), the North Equatorial Undercurrent (NEUC) merged with the North Equatorial Counter Current (NECC) and the Deep Western Boundary Current (DWBC) with alternating zonal flows marked at the Equator. Depth contours are also shown.

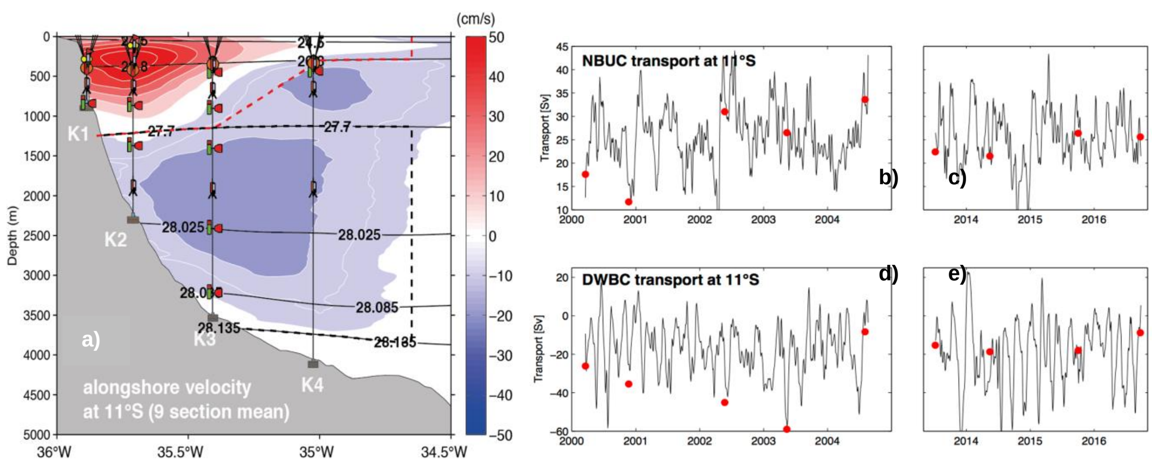

Figure A3.6: a) Average section of alongshore velocity from shipboard observations together with the mooring array design. Red/black dashed lines mark boxes for NBUC/DWBC transport calculations. (b-e) Transport time series (update from Hummels et al. 2015) of the moored array for the NBUC (b-c) and DWBC (d-e). Red dots mark transports estimated from shipboard observations.

A3.3 Recommendations for sustained AMOC observations in the tropical Atlantic

The MOVE array is already a well-established component of the MOC observing system in the Atlantic, and in its 19th year of operation is one of the longest running continuous measures of the AMOC in the basin. A 14-year overlap now exists with the RAPID/MOCHA time series at 26°N, and the connection between the two latitudes - or lack thereof - is a subject of intense interest as it provides the only such comparison of decadal length that is available within the basin (Elipot et al. ,2017; Frajka-Williams et al., 2018). MOVE is not a full trans-basin array, and therefore cannot use a basin wide mass balance as the RAPID array does to constrain the overall strength of the AMOC. It provides a measure of the deep limb in the western basin only, and some of the variability of the NADW transport observed there could be balanced by NADW transport fluctuations in the eastern basin. Modeling results (Kanzow et al., 2006) suggest, however, that on time scales of ≥3 years the NADW transport in the western basin provides a good approximation of the total NADW transport across the full basin as well as its variability. Frajka-Williams et al. (2018) found that differences in AMOC trends between 16°N and 26°N could likely be explained by differences in referencing assumptions for the two arrays. Further, they found coherent signals in the density field between the two latitudes suggesting a lagged relationship at 16°N relative to 26°N. A continuation of the MOVE measurements is therefore strongly recommended as it is one of the few locations where AMOC measurements of greater than a decade in length are available. Understanding the meridional coherence of the AMOC on different time scales and dynamics of the basin-wide AMOC response to changes in forcing will ultimately require multidecadal time series. Extension of MOVE to a full trans-basin array is probably not practical, as it would require measurements across the Antilles passages to South America in order to capture important contributions to the upper limb there. However, some synergy exists with mooring observations at the Cape Verde Ocean Observatory (CVOO), which captures a part of the geostrophic flow in the eastern basin when combined with MOVE. These comparisons are limited by the water depth and thus vertical coverage at CVOO. Efforts to minimize differences in processing and calibration are nevertheless recommended to exploit synergies between CVOO and MOVE and possibly validate the model results from Kanzow et al. (2006).

The WBCS/RACE/SACUS array across 11°S is the most recently implemented measurement system for the AMOC in the basin and initial results from this array are expected to be available within the next year. It is part of the broader SAMOC (South Atlantic Meridional Overturning Circulation) initiative, including the South Atlantic MOC Basin-wide Array (SAMBA) along 34.5°S, and the repeated eXpendable BathyThermograph (XBT) and hydrographic lines that span the South Atlantic at various latitudes as well as the interocean exchanges through Drake Passage and south of Africa. Other projects contributing to SAMOC include satellite measurements of winds, surface height, and gravity/bottom pressure, as well as in situ observations from drifting buoys and Argo profiling floats.

The WBCS/RACE/SACUS AMOC estimate at 11°S can be used to investigate, in conjunction with results from the subtropical RAPID and SAMBA arrays, the coherence of AMOC signals in the Atlantic as well as a possible convergence of the associated heat transport in between the different AMOC arrays. The AMOC changes observed at 11°S will be particularly valuable in detecting interhemispheric divergences in the AMOC strength - associated with processes such as the equatorial buffer mechanism - that can result in feedback to the atmosphere through ocean heat storage. In addition, all of the arrays, including MOVE, provide detailed and continuous deep observations of the density and internal pressure fields along the western boundary of the Atlantic, which are believed to be critical for understanding AMOC adjustment and coherence processes throughout the basin.

The 11°S array is therefore seen as a very important new addition to the AMOC observing system and continued support for it is strongly recommended. Further development of the 11°S array could benefit from an OSSE study using high-resolution ocean models - as has been done for the RAPID, OSNAP, and SAMBA arrays - to determine how to optimize the AMOC estimate along 11°S and if any additional measurements may be required.

A4. The Carbon System in the Tropical Atlantic

Toste Tanhua[1], Carol Robinson[2], Nathalie Lefevre[3,4], Rik Wanninkhof[5]

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The global ocean is an important component of the carbon cycle; the inventory of carbon in the ocean exceeds that of the atmosphere roughly 50-fold, (*Sabine and Tanhua*, 2010; *Tanhua et al.*, 2013). There is an annual net uptake from the atmosphere to the ocean of roughly 2-3 Pg C annually due to anthropogenic perturbations. This carbon is stored in the interior ocean, the residence time depending on the depth of where it is stored. The ocean carbon cycle is complex and dependent on a range of inorganic chemistry as well as organic and biological processes. Although carbon is not a limiting constituent in the ocean for biology, the carbon chemistry mainly determines the pH and alkalinity of the ocean, influencing for instance the saturation state of calcium carbonates essential for much biological life.

The tropical Atlantic is an area of general outgassing of pCO_2 from the ocean to the atmosphere, although with significant temporal and spatial variability. This variability has a significant effect on the global carbon budget over annual time-scales, and there is a need to design an observing system that can quantify the tropical CO_2 flux on annual time-scales.

Although the tropical Atlantic has a high capacity to take up carbon in the surface layer since it is warm and salty, it has limited connection to the deep ocean. However, recently ventilated bottom, deep and intermediate waters are transported to the tropical Atlantic from the formation regions in the south and north. These waters do contribute to the interior ocean storage of anthropogenic carbon, and although the concentration tends to be relatively modest (*Schneider et al.*, 2012), the storage is sufficient to motivate sub-decadal observation of interior ocean carbon.

The increasing dissolved inorganic carbon (DIC) concentration due to input of anthropogenic carbon leads to reduction of the pH value – ocean acidification. This is potentially a large issue for marine organisms, in particular those that have calcium carbonate structure, such as corals. Ocean acidification leads to reduced values of the calcium carbonate saturation state, Ω. When this value drops below one, the calcium carbonate (mostly either calcite or aragonite) becomes under-saturated. This happens at depth in the ocean, and in the tropical Atlantic there is a large relatively shallow area in the western tropical Atlantic in the oxygen minimum zone where the Ω is particularly low, so that if expanding, it can have negative effects on calcium carbonate building organisms. The OMZ might be particularly sensitive to ocean acidification.

A4.1 The Current Carbon Observing System in the Tropical Atlantic

There are two main components of the inorganic carbon system that can be observed; surface and interior ocean. Furthermore, it is important to recognize that the inorganic carbon system has 4 measurable variables: total dissolved inorganic carbon (DIC), total alkalinity (TA), partial pressure of CO_2 (pCO_2), and pH. With knowledge of temperature, salinity and pressure, it is, in principle, possible to calculate any other component of the inorganic carbon system with observations of two of the four variables mentioned above since the thermodynamic equilibrium constants of the inorganic carbon system is reasonably well defined. This provides a multitude of choices in designing the observing system. However, one has to recognize that there are combinations of the four measurable variables that are not as well suited as others due to uncertainties in the constants. This is particularly true for the combination of pCO_2 and pH that leads to relatively large uncertainties in the calculation. This is unfortunate, since for these two variables there are reasonable mature sensor technology.

Of the four measurable variables, there is a range of instruments, measurement techniques and sensors available that can support the observations:

DIC: so far there are only prototype sensors available for use on autonomous platforms. It is likely that these sensors will mature in the next decade for deployment on moorings or surface platforms. Mature methods for discrete measurements on water samples are available.

TA: Although well established methods are available for measurements on discrete water samples, pilot phase alkalinity sensors are proved to be a good complement for surface vehicles or moorings, and it is anticipated that this system will continue to develop in the next decade, facilitating regular observations of TA.

pH: Well-defined methods for measurements on discrete water samples, although a current debate about details of this method, impacting the accuracy, is ongoing. It is anticipated that dedicated studies will resolve this debate within a few years. There are reasonable accurate and precise sensors for autonomous platforms working a couple of different principles, so that there is a possibility to deploy (fast) pH sensors on platforms like gliders and floats and more accurate, but slower, sensors suited for deployment on moorings.

pCO_2: Well established (mature) systems to use on manned vessels, and large moorings do exist. In addition, a range of smaller sensor based instrumentation are available, usable for autonomous surface platforms or moorings. Currently pilot experiments are being conducted for undulating platforms, such as floats and gliders. It is likely that pCO_2 sensors will be fit-for-purpose for undulating platforms in a decade.

There is a range of observing platforms that have capability to deliver on inorganic carbon observations, the most important ones are:

Research Vessels (RVs): Obviously, this platform can deliver all the above variables. Importantly, RVs are the current only way to observe carbon below 2000 meter depth, and the obvious platform for accurate DIC, pH and TA observations in the interior ocean.

Ships of Opportunity (SOOP): This is the key network for surface ocean pCO_2 observations, a (small) number of ships that cross the area are equipped with pCO_2 sensors.

Autonomous Surface Vehicles (AUVs): pCO_2, pH and TA can be observed with good precision from AUVs. As this technology matures, it offers a great potential for good spatial and temporal coverage of surface ocean carbon. Two main technologies are used, wave or wind propulsion.

Moorings: There is already a system of moorings in the tropical Atlantic that offers a great platform for high temporal coverage of pCO_2 and pH (surface and interior) and Alkalinity (surface only).

Drifters: Some drifters can be equipped with pCO_2 sensors. Disadvantage is that the sensor is mostly lost and cannot be steered.

Gliders: Potential to install pH sensors. Sensors for the other measurables are currently too slow, although reasonable algorithms exist to use O, T, S and P to derive TA.

Floats: BGC Argo do offer a unique possibility to observe the interior ocean for pH. Similar to gliders, reasonable algorithms exist to use O, T, S and P to derive TA and from there calculate the inorganic carbon system. Furthermore, BGC Argo has shown potential to deliver surface ocean pCO_2, again using MLR techniques with variables measured by BGC Argo.

Considering the capability of the platforms mentioned above to measure other EOVs, requirements from other users and costs, we can start to draw a straw-man design for a fit-for-purpose observing system for the tropical Atlantic.

4.1.1 Surface ocean Inorganic Carbon observing system

The first important component of the inorganic carbon system is the surface ocean pCO_2 concentration. This value will determine the flux of CO_2 between the ocean and the atmosphere, although knowledge of wind stress is needed for turning CO_2 gradients into flux (noting that recent results suggest that other factors, such as surface ocean roughness and biological films, do influence the flux, although still poorly quantified or parameterized). For surface ocean observations, the key variable to observe is pCO_2. A reasonable idea of the inorganic carbon system can be achieved by estimating the alkalinity from salinity and temperature and empirical relations. However, direct measurements of either DIC or TA increase the value of the pCO_2 observations.

The best source of data here is the SOCAT database, see Figure A4.1, where observations from vessels and moorings are available. Figure A4.1 shows all the pCO_2 data available for the tropical Atlantic Ocean, including the location of moorings with pCO_2 sensor. In addition to these observations, the use of autonomous surface vehicles are underway, using wave gliders and Saildrone technology. Figures A4.2 and A4.3 show time-series obtained from moorings, clearly illustrating the high seasonal and sub-seasonal variability in both pCO_2 and CO_2 flux. Recent work additionally suggests large interannual variability, suggesting connection to ENSO variability (*Ibánhez et al.*, 2017).

It is difficult to judge the fitness-for-purpose of the current surface ocean pCO_2 observing network in the tropical Atlantic since the answer will depend on the phenomena of interest. The observing system in coastal upwelling regions is close to non-existent so that reasonable assessment and forecast of extreme events such as low pH events are challenging. For the uptake of CO_2 by the tropical Atlantic, it is fair to say that the current system falls short of providing a sufficient observational estimate of the CO_2 uptake to within +/-10%, although I am not aware of any systematic study to quantify this uncertainty. A recent OSSE study[2] on improvements of surface ocean pCO_2 data suggest that the SOCAT data (assuming continuous observing effort) with addition from BGC Argo (25% of the Argo array with BGC) and moorings is a useful mixture. Interestingly enough, the study found that addition of the mooring data in the tropical Atlantic improved the result in the tropical Atlantic, but still with uncertainties of up to 5 µatm. The study did not conclude what would be needed to decrease the uncertainty in the area, and did not take into account the possibility of an ASV network.

[2] https://www.atlantos-h2020.eu/download/deliverables/AtlantOS_D1.5.pdf

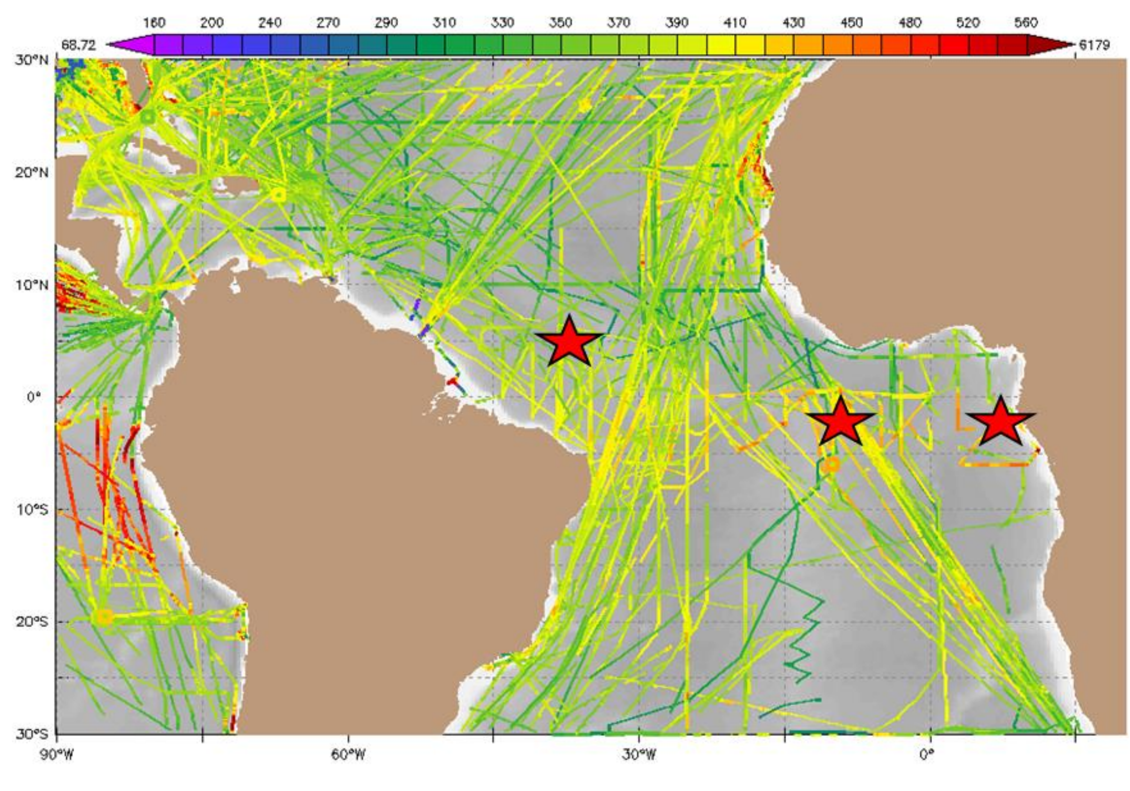

Figure A4.1: pCO_2 observations available in SOCATv6 for the tropical Atlantic. The color-bar indicates the pCO_2 concentrations, yellow and orange colors indicating out-gassing areas. The red stars mark the location of moorings with pCO_2 instruments.

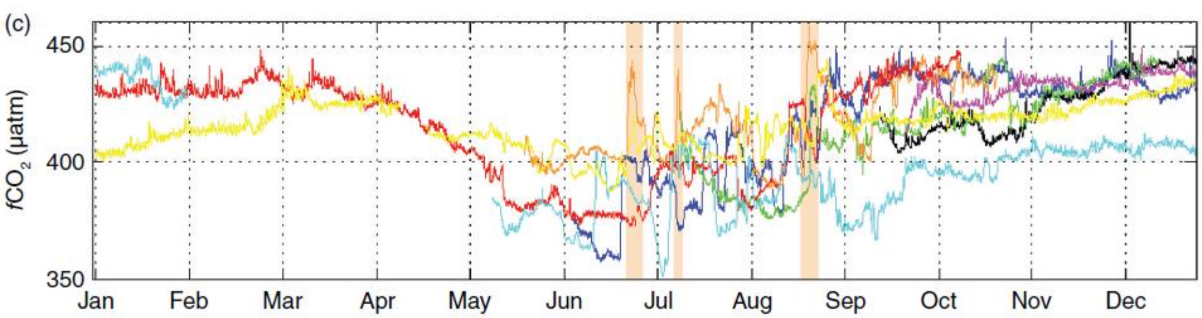

Figure A4.2: pCO_2 concentration over time on a mooring at 6°S, 10°W (*Lefèvre et al.*, 2016).

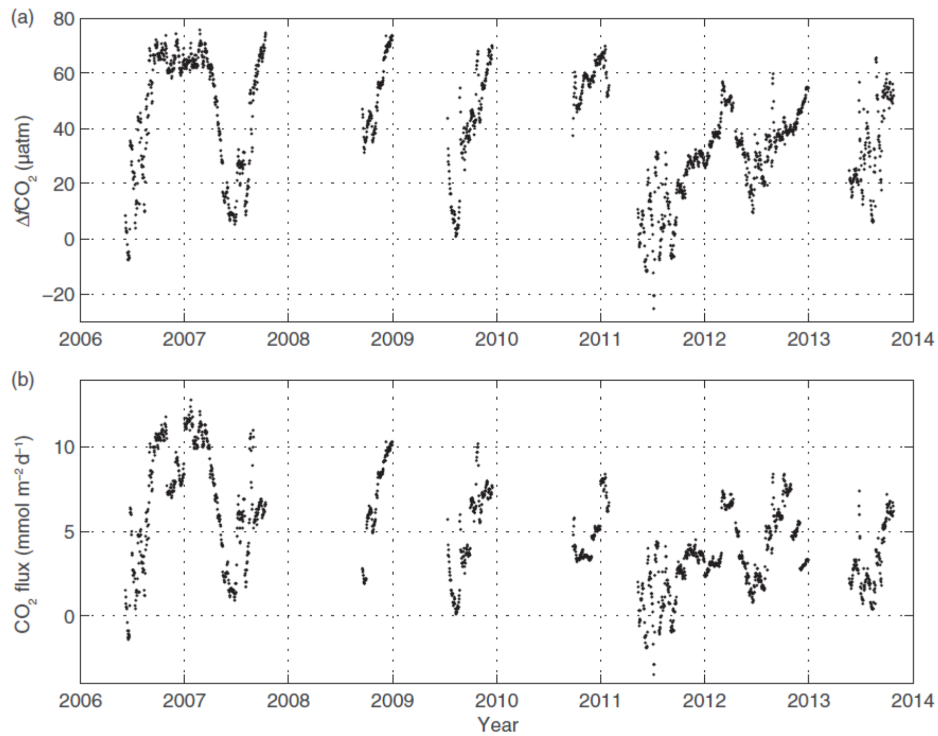

Figure A4.3: The same time-series as in Figure A4.2 plotted over time and as flux (*Lefèvre et al.*, 2016)

4.1.2 Interior Ocean Inorganic Carbon observing system

The second important component is the inorganic carbon system in the interior ocean that determines the amount of (anthropogenic) carbon stored in the ocean and regulates the pH, carbonate concentration and other biological relevant variables. For interior ocean observations, the preferred pair of inorganic carbon measurables are DIC and TA – they are both state variables and can be measured with good accuracy. However, several groups are measuring pH and TA with good results, and some groups are additionally measuring pCO_2 due to the large dynamic range (i.e. a good variable to track temporal changes in inorganic carbon).

The main ocean observing system for interior ocean inorganic carbon is the repeat hydrography program GO-SHIP[3], see Figure A4.4. In addition, several other ship-going activities in the area contribute to interior ocean observations, although to a slightly less extent compared to what GO-SHIP provides. Realizing that these lines are expensive, they are the back-bone for interior ocean observations of inorganic carbon. In the future, the BGC-Argo network has a great potential to increase the spatial and temporal coverage of observations in the region. It is important to realize that the BGC-Argo network is dependent on cooperation with the GO-SHIP network for deployment of the floats and, more importantly, for providing the reference measurements required to calibrate and validate the BGC-Argo observations.

The key data source for interior ocean carbon data is the annually updated data product GLODAP; see Figure 4.5 for the location of stations in the tropical Atlantic Ocean of GLODAPv2 (Olsen et al

[3] http://www.go-ship.org/index.html

2016). GLODAP contains interior ocean carbon relevant data, and the data product has passed careful QC procedures to assure the highest possible internal consistency of the data.

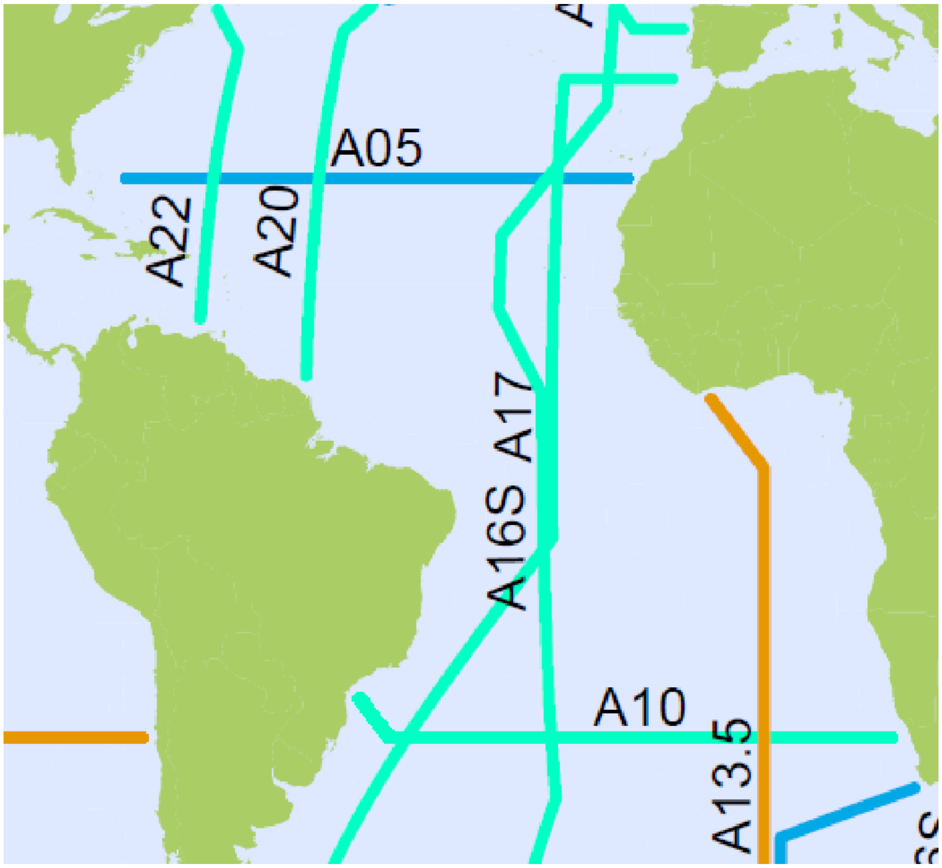

Figure A4.4: The location of the tropical Atlantic sections of the GO-SHIP program. Each of these lines is slated for decadal repeats.

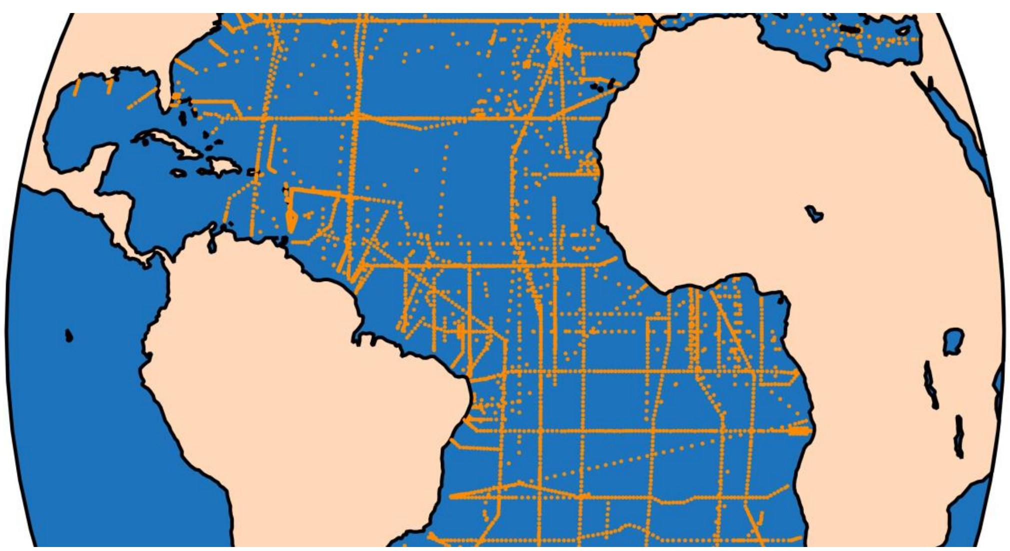

Figure A4.5: The station network in the GLODAPv2 data product. Most of these stations contain interior ocean carbon relevant observations.

A4.2 Key Societal Relevance for Carbon Observations

- The carbon flux between the atmosphere and ocean is very important for climate. This is a large scale phenomena and not really local only.
- The inorganic carbon system is important for biology, in particular ocean acidification. Information on the inorganic carbon is potentially important for fishing, aquaculture and the like. However, locally in the tropical Atlantic the water tends to have high pH levels, and be relatively far away from the point when calcite and aragonite become under-saturated, at least on the surface. The upwelling regions (particularly on the African coast) is an exception, where undersaturated waters can reach the surface and impact biology on a large scale.

A4.3 Recommendations for the TAOS with regard to Carbon.

A dedicated study to find a reasonable balanced observing system would be needed to design the surface ocean pCO_2 observing system in an optimal way. Since this is not yet done, the recommendations here should be seen as a qualified guess and initial suggestion.

A4.3.1 Surface ocean pCO_2:

It is important to maintain the current frequency of high-quality pCO_2 from the VOS fleet that occasionally transits the tropical Atlantic. The time-series data from the moorings have large value in deciphering temporal variability, and should be maintained in a similar form to current, and additional pCO_2 observations on additional moorings with at strategic locations (likely using existing PIRATA moorings). The VOS and moorings would constitute a core observing system. Recognizing that the temporal and spatial gaps in the observing system is the largest issue for accurately determining the flux rather than the precision of individual observations (assuming no bias in the data), it calls for additional observations using flexible and relatively inexpensive sensors. In this regard, a small fleet of ASVs could provide a versatile and resilient system delivering sufficient information to constrain the tropical Atlantic CO_2 flux.

In particular, there is a need to improve the observing system close to the coasts. Additionally, there is a clear need to expand the observations to include TA on a subset of the observations in order to understand the inorganic carbon system.

Recommendation for surface ocean pCO_2 observations:

- At a minimum, maintain current effort of VOS observations
- Maintain and extend the time-series on moorings, particularly close to the coast
- Initiate an observing system based on flexible ASVs
- Add observations of total alkalinity to a subset of the pCO_2 observations

A4.3.2 Interior Ocean inorganic carbon:

An inclusion of BGC-Argo floats in the tropical Atlantic would allow for an increased understanding of spatiotemporal variability on a range of scales that is currently not possible to resolve with the sparse repeat hydrography program. Note that the floats will also contribute to the surface ocean pCO_2 observing system, and effectively link interior ocean observations to surface observations. Note that the continuation of the repeat hydrography program is essential for calibration and validation of the BGC-Argo data stream. The repeat hydrography program should consider at least one zonal line in the tropical Atlantic to fully capture the east-west gradient and compliment the meridional sections currently active. For instance, a number of observations already exist around 10°N, and that could be a possible extension.

Recommendations for interior ocean inorganic carbon observations:

- Maintain the current effort of repeat hydrography in the tropical Atlantic, and add a zonal section, possibly at 10°N.
- Expand to a BGC-Argo array in the tropical Atlantic, goal 25% of Argo to be BGC.

A5. Biogeochemical Processes in the Tropical Atlantic

Carol Robinson[1], Martin Visbeck[2], Toste Tanhua[2], Marcus Dengler[2], Johannes Karstensen[2]

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Dissolved oxygen (O_2) is fundamental to all aerobic life and thus plays a major role in marine microbial ecology and the biogeochemical cycling of elements such as carbon, nitrogen, phosphorus and sulphur. Time series data over the past 50 years show declining O_2 in many regions of the world's oceans, and a significant increase in the aerial extent of oxygen minimum zones (OMZs) in the eastern tropical North Atlantic (ETNA). Stramma et al., (2008) determined the decrease in O_2 for the region of the ETNA between 10-14ºN and 20-30ºW in the depth range 300-700m to be 0.09 – 0.34 µmol kg^{-1} yr^{-1} between 1960 and 2008, while later studies revealed variations in this long term decline at interannual to multidecadal timescales consistent with natural climate variability (Brandt et al. 2015). The latest collation of global ocean dissolved oxygen data shows a decrease of more than 2% (4.8 ± 2.1 petamoles), in the global oceanic oxygen content since 1960 (Schmidtko et al., 2017).

Considering the importance of dissolved oxygen for marine life, its link to ocean ventilation and the microbial processes which change the nutrient supply to the surface ocean and therefore influence primary production (Moore et al., 2018), monitoring changes in dissolved oxygen, the physical, biological and biogeochemical factors which influence dissolved oxygen concentrations and the biogeochemical processes affected by decreasing dissolved oxygen, is crucial. The GOOS biogeochemistry essential ocean variables (EOVs) of dissolved oxygen, transient tracers and nutrients are recommended to directly monitor oxygen concentrations, the ocean mixing which influences oxygen concentrations and the impact of low oxygen concentrations on nutrient concentrations, particularly on nitrogen supply to the surface ocean.

Current models do not reproduce the observed patterns of changes in dissolved oxygen, they underestimate the interannual to decadal variability in dissolved oxygen and they simulate only half of the oceanic oxygen loss inferred from observations (Oschlies et al., 2018). Since these models account for the major physical and chemical processes involved in deoxygenation, but do not include some of the microbial processes and potential biogeochemical feedbacks, incorporation of measurements of the GOOS EOVs of particulate matter, dissolved organic carbon and the emerging EOV of microbe biomass and diversity would enhance quantitative understanding of the mechanisms linking dissolved oxygen concentration, remineralisation efficiency and microbial community structure.

The tropical Atlantic Ocean has also been shown to be an important area for N_2O fluxes (Forster et al., 2009; Rees et al., 2011, Kock et al., 2012) although the variability and magnitude of this flux is poorly constrained (Grundle et al., 2017). An increased effort to include observations of this potent greenhouse gas in the region is also recommended.

A6. Fisheries and ecosystem observations

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A6.1 Background

The following report only represents a general overview of issues related to fisheries and ecosystem observations and cannot be seen as a holistic synthesis of all activities, projects, programs and organizations involved in fisheries and ecosystem observation in the Southern Atlantic Ocean.

A6.2 Relevance of fisheries and ecosystems

Most fisheries are happening in the coastal and shelf areas and are thus often in the Exclusive Economic Zones (EEZs) of countries and as such are under the jurisdiction of only one country. Exceptions are transboundary stocks, which migrate between the EEZs of several countries (e.g. Sardinella spp. in North West Africa, a shared stock between Morocco, Mauritania, Senegal, Gambia and Guinea-Bissau) or are straddling stocks, which migrate between EEZs and the high seas, and highly migratory stocks. The most prominent example of the latter are tuna stocks. Management and thus monitoring are commonly done through regional agreements or Regional Fisheries Management Organizations (RFMOs). In the case of tuna species in the Atlantic, this role is played by the International Commission for the Conservation of Atlantic Tuna (ICCAT). We will present this as an extra paragraph in the following report. Coastal ecosystems can be categorized in Large Marine Ecosystems (Hempel and Sherman, 2003), which are marine areas with similar ecosystem characteristics. Neighboring countries of some of these LMEs have developed programs and conventions to regulate use and extraction of living resources. Many LME programs include extensive scientific projects and together with many national efforts these can include observations and monitoring programs. However, most of these efforts are done through individual programs and only few are maintained as consistent time series. One prominent example for LME programs is the Benguela Current Large Marine Ecosystem Programme. In recent years, the importance of monitoring and observation of commercial and non-commercial species has increased, as the realization of the impact of climate variability has been extended with a steady trend of change, which forces changes in productivity and changes in distribution alike. To understand current systems, particularly also the effect of human activities including fishing and climate change for the future development of ecosystems, an increasing number of ecosystem models have been developed, which are also in need of data to be calibrated and validated. In addition, these models also use input data from coupled climate-ocean models. It has been recognized that observations of a few essential variables (ecosystem, ocean variables) of pressures and state of the ocean are required for an ecosystem based analysis (UNESCO, 2012), and that observations systems should be organized around "essential ocean variables (EOVs)," rather than by specific observing system, platform, program, or region. Implementation of EOVs can be made according to their readiness levels, allowing timely implementation of components that are already mature, while encouraging innovation and formal efforts to improve readiness and build capacity (FOO, 2012; Miloslavich et al., 2018). Thus, there is a clear need for more integration with respect to data collection and analyses. However, there are some challenges with respect to a coordinated Trans-Atlantic observing system, namely, the need to:

- link national and regional coastal observations with open ocean observations;
- link different observation systems and programs with currently different goals;
- integrate observation systems with very different timescales between collection of raw data and availability of processed data;
- collections of a set of pre-defined essential variables that would enable ecosystem and fisheries management.

A6.2.1 Fisheries

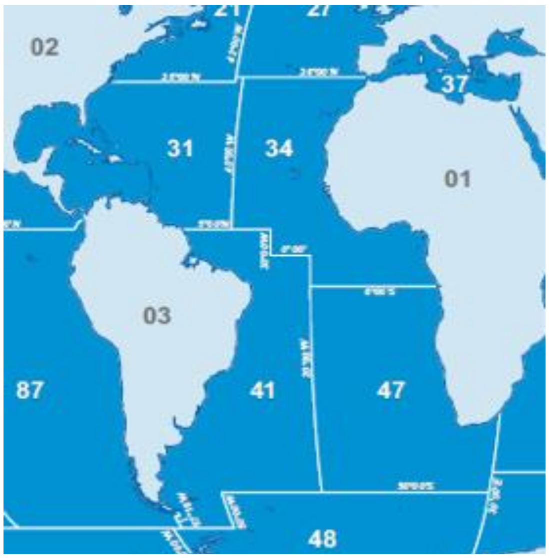

Figure A6.1: Main statistical areas of the Food and Agriculture Organization of the United Nations (FAO), (FAO 2015).

The importance of fisheries in the Tropical Atlantic can most easily be demonstrated by the total catch and the dependence on the sector in the region. Almost ten million tons of seafood (from 87.2 million global marine capture) were harvested in the Central and South Atlantic (FAO major areas 31, 34, 41 and 47, Figure A6.1) in 2016 (FAO 2018).

In addition, the fishing sector has a high importance in the tropical Atlantic coastal countries. The total amount of fishers in Africa, Latin America and the Caribbean is eight Million, although not all of them are operating in the Atlantic. But not only these countries fish here, many foreign fleets (e.g. Korean, Chinese, Russian, European) also target the resources.

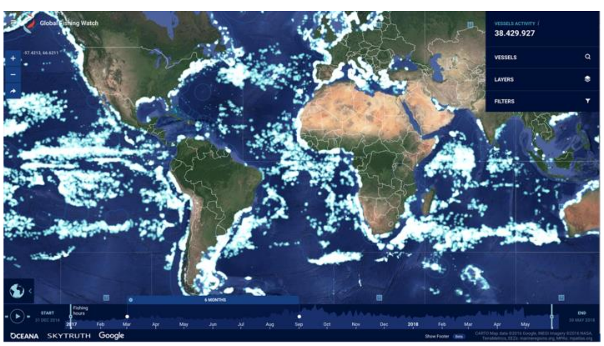

Figure A6.2: Fishing activities cumulated from March 2017 to September 2017; taken from Global Fishing Watch (http://globalfishingwatch.org/map/)

The fishing activities cumulated over a period of 6 months from March 2017 to September 2017 was shown by Global Fishing Watch, which is a good example for a global remote sensing observation system for fishing activities (Figure A6.2). However, it only shows vessels with an Automatic Identification System (AIS), which only vessels above 300 BRT need to install and run (IMO, SN/Circ.227). Thus, smaller fishing vessels, especially those close to the coast, cannot be detected. Moreover, the system can be easily switched off by the crew, even if it appears efficient on e.g. the European fleet operating in the tropical area. More efficient system to monitor fishing activities is the use of Vessel Monitoring System (VMS) even if we can report contrasted operationalization in developing countries. The use of embarked fishing observers remains the more reliable monitoring system to report location and catch.

A6.2.2 Ecosystems

(1) Relevant ecosystems in the tropical Atlantic

Depending on the definition of tropical Atlantic, the area contains roughly 7 – 9 LMEs (Hempel and Sherman, 2003) and 4 – 5 Longhurst provinces in the open Ocean (Longhurst, 1998) (Figure A6.3). Most of the LMEs are shared between different countries, with some of them having developed programs and conventions to coordinate scientific efforts, harmonization of national legislations and to regulate some shared activities, e.g. fisheries.

(2) Role of coastal and shelf sea ecosystems in provision of direct benefits

Most living resources are extracted in coastal and shelf areas and thus these ecosystems are supporting the livelihoods for millions of people directly by providing income, employment and food through artisanal and industrial fishing. In addition, coastal ecosystems also support income generating activities including tourism, industry, diving, game fishing, recreational fishing among others. In all tropical areas as everywhere, the marine ecosystem management is a trade-off between conservation and exploitation (Brehmer et al., 2011), usually in disfavour of the conservation targets. Even if both goals must be considered for management purposes, considering that an ecosystem in bad health or not sustainably exploited by the fishers, is less productive.

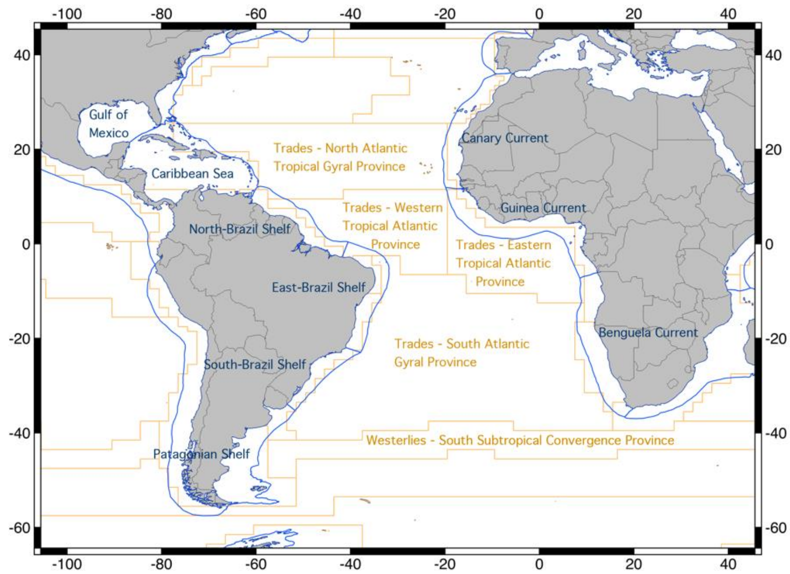

Figure A6.3: Tropical Atlantic large marine ecosystems (LME), map by J.O.Schmidt

A6.3 Observations of Fisheries and Ecosystems

Together, fishing and changing environmental conditions (e.g., chemical contamination, hypoxia, toxic algal blooms, ocean warming and acidification) are placing wild fish stocks under unprecedented stress (Nellemann et al., 2008). This problem is being addressed by transitioning from traditional single species management of capture fisheries to an ecosystem-based approach to fisheries management (EBFM) in which fishing is managed in the context of interactions of fish stocks with other organisms (prey, predators, and competitors) and their environment (Garcia & Cochrane, 2005). The success of applying an ecosystem-based assessment to inform Ecosystem Based Fisheries Management (EBFM) depends on (1) simultaneously monitoring multiple pressures and ecosystem states; and (2) rapid detection and timely predictions of changes in ecosystems states and their impacts on carrying capacity.

Table A6.1 Specification of observing system requirements guided by the data and information needed for ecosystem-based assessment of fisheries (reproduced from UNESCO, 2012).

Observations: *In Situ*	Fisheries dependent catch statistics (observers & landings) • Species, biomass, numbers, size & mean trophic level • By-catch Fisheries independent surveys of harvestable fish stocks • Distribution & abundance of fish eggs, larvae, juveniles & year classes (cohorts) of adult spawners (age structure) • Migration routes between feeding & spawning grounds Environmental data • Water temperature & salinity • Chlorophyll-a • Zooplankton (macro- & meso-) abundance • Abundance of predators
Observations: Remote	• Sea surface temperature, salinity, wind & current fields • Phytoplankton biomass (chlorophyll-a), primary productivity, and frontal products (ocean color radiometry derived) • Spatial mapping of fishing vessels
Model Requirements	• Computation of phytoplankton productivity from chlorophyll-a, photosynthetically active radiation and temperature. • Stock assessments o Virtual population analysis (VPA) requiring data on the number of fish in each cohort & algorithms for relating the variable of interest to the variable measured (e.g., stock size estimated from CPUE) and estimating errors; o Multi-species virtual population analysis (MSVPA) requiring additional data diet (stomach contents) and predation rates. • Ecosystem & trophic dynamics o Ecopath with Ecosym o Atlantis, SEAPODYM, GADGET
Reporting	• Delayed mode (≤ 1 month) for stock assessments used to set annual & seasonal total allowable catches & quotas • Near real-time (< 12 hours) for monitoring compliance & anomalies from historical trends during the fishing season to support adaptive management

A6.3.1 Observations in fisheries

(1) Stock taking of species

The most basic observations that happened over the last centuries are related to stock taking of species, i.e. the exploration of their habitats and related species and their description and categorization. Still in many areas not all species are scientifically described and thus it is difficult to assess the impact of human activities, including fisheries, on these species. Thus, a continued effort is necessary in almost all tropical Atlantic areas, which are still understudied.

(2) Assessing the status of stocks

The most basic observational need in relation to management of living resources is the assessment of the fisheries themselves, including fishing capacity (i.e., how many boats of which types and fishing gear), effort (how many days at sea, how many trips, how many hooks deployed per day, etc.) and catch (which species and how much of each species). To assess a given stock, additional information on length, weight and age of caught individuals of a given species and how much of each length, weight or age are caught, is needed. These are information that are normally collected through national fisheries institutes or respective government fisheries agencies, with representative fish sampling done either directly on board or through landing in ports, and market sampling schemes. In some countries fisheries independent data are collected through trawl and hydroacoustic surveys on the adult and juvenile individuals of a stock or egg and larvae surveys on the early life stages of a stock.

(3) Population dynamics

To get information in relation to population dynamics, regular annual surveys are necessary, which collect information on the development of a cohort in a given stock, estimating migration, growth and mortality through tagging studies and performing nested studies on the influence of environmental variables on life history parameters. In addition, stomach content analysis gives insight into the role of species in the ecosystem and the dependence on specific prey species and susceptibility to predators. Many of these studies are normally not carried out regularly and often done with financial support of projects which do not allow to constitute efficient time series to monitor population dynamics of exploited fish populations.

A6.3.2 Monitoring Technologies

Operational delivery of data and information on the status of the ecosystem requires greater time-space resolution than can be provided by current ship-based surveys and *in situ* sensors alone. While additional sampling from these platforms (ships and sensors on moorings, gliders, and instrumented pelagic animals sometimes called Animal oceanographers or Animal-Borne Sensors) are clearly needed, these observations by themselves will not provide the time-space resolution of essential biological variables required for EBFM (Wang et al, 2019). To address this limitation, additional sampling platforms and autonomous robust sensors are needed, e.g., satellite-based remote sensing (Mouw et al. 2017) and autonomous acoustic sampling (Lembke et al. 2018; Brehmer et al. 2019b).

Satellite-based remote sensing is and will play a critical role in providing data with sufficient time-space resolution to elucidate linkages between climate-driven changes in marine ecosystems and the dynamics of fish and phytoplankton productivity in open sea and non-cloudy areas, as major drawbacks appear in shallow water near the coast. Quantifying stock-recruitment relationships and identifying the environmental factors modifying them is not possible using traditional oceanographic methods by themselves. Satellite-derived estimates of ocean surface currents and frontal zones, sea surface temperature (SST), salinity (SSS), ocean colour radiometry (e.g., phytoplankton biomass and phytoplankton productivity proxies) have made these objectives achievable, and the results can be used to inform ecosystem-based stock assessments. The challenge is in quantifying relationships between these satellite-derived estimates of the distributions of SST, SSS and phytoplankton productivity and the abundance and distribution of higher trophic levels from zooplankton to fish (e.g. Thiaw et al., 2017; Diankha et al. 2018). Four general approaches are available to estimate the production and biomass of fish and other high trophic level organisms from primary production: statistical models (e.g., regressions to Generalised Additive Model of fish landings on primary production), size spectra models, energy mass-balance models and 'end-to-end' or 'physics-to-fish' ecosystem models (Fulton 2010, Kaplan and Marshall 2016) that all depend on or benefit from the provision of satellite data. In addition to stock assessment applications, remote sensing can be used to help fishers locate target species, such as tuna, through the detection of hydrographic features, such as fronts. This approach has the advantages of improving the efficiency of the catch, reducing fuel use and thereby greenhouse gas emissions, as well as potentially reducing bycatch, but should not be considered on fisheries already over exploited. An example of this is Dynamic Ocean Management, where models and real time tagging information are used to derive preferred habitat of by-catch species to identify areas of low-bycatch and high target catch (Hazen et al., 2018). However, it also risks increasing the potential for overexploitation of fish stocks. Clearly, implementation needs to be considered alongside other conservation-based management tools, such as quota systems and using remote sensing to enumerate and track fishing vessels for enforcement purposes.

Combined with satellite-based remote sensing and Continuous Plankton Recorder (CPR) surveys, acoustic technologies have the potential to provide an observing system for marine food webs from phytoplankton to zooplankton to fish. The goal of the proposed Mid-Trophic Automatic Acoustic Sampling (MAAS) Network is to implement a network of platforms (ships of opportunity and fixed platforms) equipped with multi-frequency acoustics (now rather wide band acoustics) that can monitor the distribution and abundance of macrozooplankton (1 – 1000 mm in size) basin wide (Handegard et al., 2013).

A major challenge to sustainable fisheries is maintaining long term and consistent data sets on the vital statistics of population dynamics in order to quantify trends in pressures, states and impacts. The regular collection and acquisition of consistent data (in terms of geographical distribution, temporal sampling and methods of collection) for establishing long term time series of essential variables requires a consistent technical capacity in terms of platforms, sensors, skills and budget. Temporal and geographical gaps and changes to data specifications can cripple and weaken assessments, analyses and model outputs. This remains a challenging problem for managing fisheries and other living marine resources, especially in developing countries with limited resources. As data are collected from autonomous instruments such as those described above, careful consideration must be given to data compatibility and capacity to maintain, service and operate them cost-effectively. The latter will require cost benefit analyses (in particular, their potential saving of ship-time). For successful implementation of EBFM, restructuring of institutions (in many instances) and the implementation of ecosystem modelling capacity, multi-species model development and the improvement of relationships among scientific communities, fishing industries and relevant authorities will be required in many instances.

A6.4 Current or Recent Coordinated Observations

A6.4.1 Nansen Survey

One example of a survey, which started as a pure fisheries survey and turned into an ecosystem survey is the EAF Nansen Programme. Since 1975 this joint initiative of Norway and the Food and Agriculture Organization of the United Nations (FAO) is performing surveys with the research vessels, R/V *Dr Fridtjof Nansen*, which were specifically built for the programme, around the

African continent (Figure A6.4). The second EAF Nansen Programme started in 2017 to implement an ecosystem approach to fisheries (EAF) for the management of selected fisheries in Africa and collect data on fisheries and ecosystems, pollution and climate variability and change.

The Nansen Program also supports the Large Marine Ecosystem Programmes (Bianchi et al 2016) and in 2017 the new *Dr Fridtjof Nansen* vessel has been launched to support the envisaged survey program for the coming years. The vessel is equipped with state-of-the-art technology to sample environmental biotic and abiotic variables, and at least in their strategic plan should consider the shallow part of the continental shelf (0-20 m) which is until now almost completed under studied (Brehmer et al., 2006), even if this area constitute the main fishing ground for the most part of the small scale fishing fleets operating in the tropical Atlantic.

A6.4.2 Census of Marine Life

The Census of Marine Life was a 10-year, US $650 million scientific initiative, involving a global network of researchers in more than 80 nations, engaged to assess and explain the diversity, distribution, and abundance of life in the oceans. The world's first comprehensive Census of Marine Life — past, present, and future — was released in 2010 in London. Initially supported by funding from the Alfred P. Sloan Foundation, the project was successful in generating many times that initial investment in additional support and substantially increased the baselines of knowledge in often underexplored ocean realms, as well as engaging over 2,700 different researchers for the first time in a global collaborative community united in a common goal, and has been described as "one of the largest scientific collaborations ever conducted". Census of Marine Life (Costello et al., 2010) has collected biodiversity data in the global ocean, including the Tropical Atlantic (Figure A6.4).

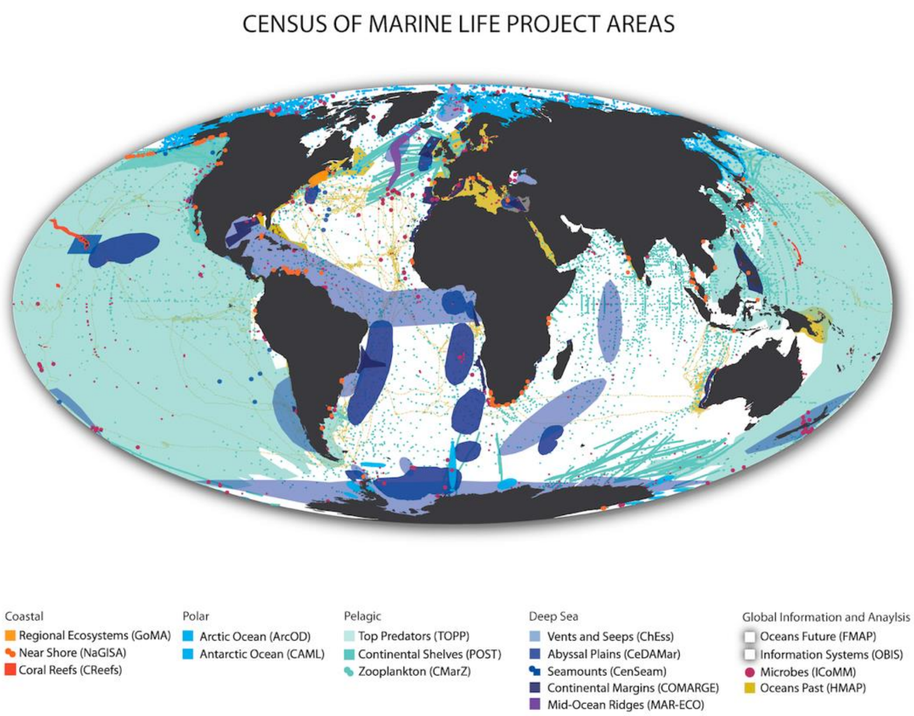

Figure A6.4: Sampling of the Census of Marine Life Project (from http://www.coml.org).

A6.4.3 Benguela Current LME

The Benguela Large Marine Ecosystem Programme (BCLME) was initiated in the Benguela region between 2002 and 2008 (Shannon et al. 2006). The objective was to support Angola, Namibia and South Africa in developing capacity to tackle marine environmental issues in the region, across national boundaries. The ecosystem-based regional programme was funded by the Global Environment Facility (GEF) and supported 75 projects and activities in the region. It also facilitated other projects and initiatives and thus contributed to the generation of a wealth of scientific work, increasing the understanding of the Benguela system and supporting the management of fisheries. The implementation of the Ecosystem Approach to Fisheries (EAF) in the region requires a sustained fisheries and ocean observing strategy (Augustyn et al. 2014).

A6.4.4 Tunas in the Tropical Atlantic

Tunas and the other large pelagic fishes, including the swordfish, billfishes, wahoo and oceanic sharks, such as the blue shark and mako sharks, are highly migratory species and, therefore, the management of their fishery needs to be done by Regional Fisheries Management Organizations, a task in the Atlantic Ocean and Mediterranean Sea undertaken by the International Commission for the Conservation of Atlantic Tunas - ICCAT. Founded in Rio de Janeiro, Brazil, in 1966, the ICCAT Convention entered into force in 1969. Presently, it has 52 Contracting Parties and 5 Cooperating Non-contracting parties (CPCs), being, thus, one of the largest and oldest RFMOs in the World. Article IX of ICCAT Convention requires that all CPCs provide statistical, biological and other scientific information to the Commission, so that it may assess the condition of the exploited stocks and adopt management measures to ensure their conservation and thus the sustainability of the tuna fisheries in the Atlantic Ocean. The task of compiling all data submitted by CPCs and assessing the status of the stocks pertains to the SCRS- the Standing Committee on Research and Statistics, made by the scientists from the different ICCAT Members. Based on the recommendations provided by the SCRS, the Commission, in its yearly meetings, agrees and adopts several management and conservation measures, including definition of Total Allowable Catch (TAC) for different stocks, and the quota allocated to each country.

Besides the more classical collection of catch and effort data, ICCAT has initiated the Atlantic Ocean Tropical tuna Tagging Programme (AOTTP, 2015-2020) in 2015 to tag at least 120,000 tropical tuna fish (mostly bigeye, skipjack and yellowfin) across the Atlantic, during 5 years, using a range of conventional and electronic tags. Additionally, the Programme is collecting, collating and analyzing tag-recapture data. All the data collected are being stored in databases maintained by the ICCAT Secretariat and used to improve the estimation of key parameters needed for input to stock assessments. Fisheries scientists from Atlantic coastal states have been trained in tagging, data collection and the use of tag-recapture data in stock-assessment models.

Activities of AOTTP include the chartering of professional fishing vessels, liaison with recreational anglers, the deployment of tagging and tag-recovery teams, data collection, scientific interpretation, the development and execution of training courses and the instigation of awareness campaigns to promote tag-recovery.

Focal countries are Ghana, Côte d'Ivoire, Senegal, Republic of South Africa, Venezuela, Trinidad and Tobago, Brazil, EU-Spain (Canaries), EU-Portugal (Azores), Cabo Verde and the USA. Commercial baitboats (also known as pole & line vessels) and boats operating with handlines are being used for most of the tagging work since longline and purse seine gears are known to cause more stress to the fish and increase mortality rates. Since there are no baitboats working off the North American east coast, AOTTP has depended on cooperation with recreational game fishers, to tag fish in that area.

The AOTTP is funded by the European Union (DCI-FOOD/2015/361-161), ICCAT CPCs and Contributors.

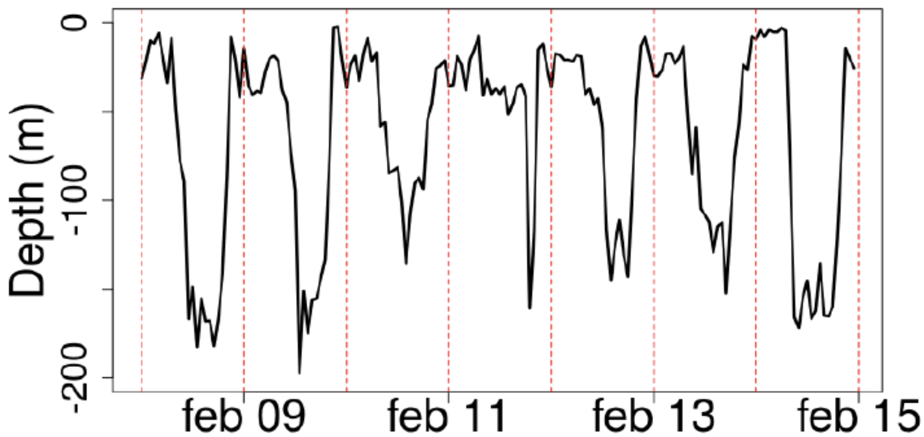

Figure A6.5: Example of data collected by data-logger tag, showing a week of diving behavior of a yellowfin tuna. Temperature data is collected alongside, however the exact position of the data is difficult to estimate, because the data has no link to GPS data (from ICCAT/AOTTP NEWSLETTER No.2, https://www.iccat.int/aottp/AOTTP-Document-Library/Reports/Newsletters/EU-AOTTP-Newsletter-02.pdf)

A6.4.5 Other tagging programmes

Animal tracking networks are spreading around the Atlantic Basin, and will become an important tool to support the understanding of ecosystems and fisheries. The Ocean Tracking Network (OTN) is a GOOS pilot project that combines technologies developed for tagging apex pelagic predators with those developed for smaller animals (Hussey et al., 2015). The former uses satellites to determine where large animals travel in the oceans and monitors the environment (temperature, salinity and chlorophyll) they experience while the latter uses “curtains” of acoustic receivers across continental shelves and near islands to monitor fish migrations and receive and transmit data from larger animals. In Europe, the formation of a European Tracking Network (ETN) is underway. In the US, as part of the Integrated Ocean Observing System (IOOS), an Animal Tracking Network (ATN) is being implemented. In the South Atlantic, Brazil and South Africa are active OTN partners. Thus, once fully deployed, the animal tagging networks will have the capability of tracking the movements of spawning populations that represent three upper trophic levels of the ocean’s food webs.

A6.5 Conclusions

In conclusion, not all existing programs and projects have been listed here only the most illustrative, but overall, it becomes clear that no holistic observation program exists for the Tropical Atlantic with respect to biological and specifically fisheries data even less to relate physical, biogeochemical and ecological components of the marine ecosystems. Thus, the general requirements are better use of existing data, extending surveys for commercial and endangered species (giving more attention on key species for food security), and integration in a larger observation system, considering the requirements of different user groups, decision makers, society, private sector and the scientific communities. Current gaps include missing or not enough communication between different scientific communities collecting data, missing data exchange protocols and missing survey protocols.

Specific recommendations

1) Linking and supporting existing coordinated programmes like the EAF Nansen Programme, the LME Programmes and Regional Fisheries Management Organizations like ICCAT;

2) Linking and supporting coordinated national survey program, maintaining at least the current survey effort, identifying gaps and supporting the development of extensions where necessary;

3) Linking coordinated communities like the Ocean Tracking Network;

4) Reaching out to governmental bodies, both national and international like the Ministerial Conference on fisheries cooperation among African States bordering the Atlantic Ocean (ATLAFCO) as well as regional bodies as the Sub Regional Fisheries Commission (SRFC) in the CCLME, the Fisheries Committee for the West Central Gulf of Guinea (FCWC) in the GCLME, and the Benguela Current Commission (BCC) in the BCLME.

5) Develop and carry out a broad consultation on current observing efforts and observing needs.

A7. Ocean Heat Content and Sea Level Rise

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Oceanic heat content is an important quantity for understanding and predicting climate variability and change. At a most basic level, changes in heat content are reflected in SST, with the magnitude of the SST variations depending on the depth over which heat is stored. Storage of heat in the surface mixed layer gives rise on interannual to decadal time scales in the Atlantic Meridional Mode (AMM; Servain et al, 1999; Xie and Carton, 2004) which is sustained by Wind-Evaporation-SST (WES) feedbacks in the tropical Atlantic (Chang et al, 1997). Variations in the AMM affect the position of the ITCZ and therefore rainfall patterns over West Africa and Northeastern Brazil. The AMM, and more generally SST in the main development region for hurricanes (10°N-20°N, 80°W-20°W), also modulates Atlantic hurricane activity (Foltz and McPhaden, 2006; Vimont et al, 2007), the year-to-year variations of which have enormous societal consequence (Pielke et al, 2008). It is also known that the intensity of hurricanes is strongly influenced by the storage of heat above the 26°C isotherm, referred to as tropical cyclone heat potential (Goni and Trinanes, 2003).

Along the equator, the evolution of the Atlantic Niño or zonal mode is dynamically linked to variations in upper ocean heat content (Ding et al, 2010) through recharge oscillator processes similar to those that operate in the tropical Pacific related to ENSO (Jin, 1997; Meinen and McPhaden, 2000). Sea surface temperature variations in the Atlantic cold tongue region associated with Atlantic Niños in turn affect the west African monsoon and Sahel drought (Giannini et al, 2003). Heat content variations along the equator lead SSTs by 4-5 months, thus providing a source of predictability not only for Atlantic Niños but for their impacts on regional rainfall.

On a global basis, the ocean is the greatest reservoir of heat on the planet and it is by far the greatest sink of energy input from anthropogenic (i.e., greenhouse gas and aerosol) forcing. This oceanic absorption of heat mitigates the impact of global warming on atmospheric temperatures but at the same time delays the equilibrium response to the earth’s energy imbalance by decades because of the ocean’s thermal inertia. Thus, knowing where heat is entering and exiting the ocean across the air-sea interface, quantifying the rate at which heat is stored in the ocean, and determining the pathways by which it is transported, are critical from a climate perspective. The increased storage of heat in the ocean also contributes to sea level rise through thermal expansion of sea water, which accounts for roughly one third to one half of the observed global sea level rise over the past few decades (Church et al, 2011; Cazenave and Le Cozannet, 2014; Chen et al, 2017).

Most of the heat taken up by the oceans due to anthropogenic forcing has occurred in the Southern Ocean and secondarily in the North Atlantic based on both observational (Roemmich et al, 2015) and climate model analyses (Shi et al, 2018). The pattern of oceanic heat stored is similar, but not identical to, the pattern of oceanic heat uptake because of the role of circulation in transporting heat to other parts of the world ocean. Thus, all ocean basins have shown significant increases in heat content, penetrating to greater depths with time, since at least the 1990s (Cheng et al, 2017). The greatest percentage of this heat is stored in the upper 2000 m but a significant amount of heat is also accumulating at greater abyssal depths as well (Purkey and Johnson, 2010).

SST, heat content in the upper 700 m, and sea level all trended significantly upward in the tropical Atlantic between 30°N and 20°S since the 1960s (Servain et al, 2014). The physical mechanisms accounting for these trends however are not well understood. While SST and heat content have risen, so has evaporative cooling, suggesting surface fluxes are responding to rather than causing warming of the tropical Atlantic over the past several decades. Likewise, trade wind stress has increased in the tropical Atlantic over the same period, which would be expected to cool the eastern equatorial Atlantic via intensified coastal and equatorial upwelling, but that has not been observed. Clearly, some nonlocal processes must be important in causing these trends, perhaps related to changes in the Atlantic Meridional Overturning Circulation (AMOC). Luebbecke et al (2015) have shown in modeling experiments with interannually varying wind forcing that the Agulhas Current leakage from the Indian to the Atlantic Ocean has increased by about 45% from the 1960s to the early 2000s, causing upper ocean temperatures to warm in the tropical Atlantic. Thus, even though trade winds in the tropical Atlantic have increased since the 1960s, intensified trades would favor upwelling of warmer subsurface waters, leading to higher rather than lower SSTs.

There is great uncertainty in our understanding of relevant oceanic and atmospheric processes that affect air-sea exchanges of heat, ocean heat content and its transport, and how ocean heat uptake affects SST and sea level rise across the broad range of time and space scales relevant to climate. TAOS provides an observational underpinning that enables progress on these issues. Critical are the satellite missions that to provide multi-decadal, continuous records key variables such of surface height from altimetry, surface wind speed and direction from scatterometry, SST from spaceborne microwave and infrared sensors, surface salinity and precipitation, and other related measurements such as ocean color. Sustained in situ measurements are likewise critical for measurements of upper ocean heat content, water mass variability, air-sea heat fluxes, and ocean circulation. The suite of measurement systems that presently make up the sustained in situ TAOS (Argo floats, drifters, moorings, island and coastal tide gauge stations, ship-of-opportunity measurements and repeat hydrography) have provided these observations routinely in a generally cost-effective way. TAOS has moreover evolved with time, first with the establishment of PIRATA in the mid-1990s and then with Argo in the mid-2000s. Introducing newer technologies that are fit for purpose and rigorously field tested, such as gliders and deep Argo floats, are logical next steps. Ensuring that collection of these in situ systems, in combination with space-based missions, resolves to the maximum extent possible the space and time scales relevant to climate variability and change in the tropical Atlantic is a significant challenge in overall system optimization.

A8. Improved Predictions on Subseasonal to Decadal Time scales

A8.1 Weather forecasts

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Availability of long-term observations is a critical need for weather and climate forecasts, and for enabling reanalysis and reforecast that permit to extract information about extremes.

A8.1.1 Societal Importance of the weather predictions from days to seasons ahead

There is clear and growing demand for reliable weather and climate forecasts at different time scales for a variety of societal applications. The tropical Atlantic basin influences the weather and climate of neighbouring regions, such as Western and central Africa, in North-Eastern South America, in the Caribbean , mid-latitude regions, . Forecasts with reliable uncertainty estimates are of great value to society, allowing institutions and governments to plan actions to minimize risks, manage resources and increase prosperity and security. Human and economic losses that may be caused by adverse weather and climate events can be mitigated with early warning systems (e.g. famine, epidemics) and disaster preparedness. Equally, adequate planning can aid the exploitation of favourable climate conditions.

Operational weather forecasts, covering atmosphere, land and ocean surfaces, range from minutes (nowcasting, typically relevant for aviation) to days and weeks ahead, and serve various sectors, from marine to aviation, agriculture, water or risk management Medium-range (10-15 days) forecasts are produced operationally in the major forecasting centers, as well as forecasts of climate at seasonal (up to 6-12 months lead time) time scales, and more recently, at subseasonal time scales (1-2 months lead time), bridging the gap between weather and climate. As an example, following the international African Monsoon Multidisciplinary Analysis (AMMA) program (Polcher et al., 2011), forecasting activities in Western tropical Africa are being continuously developed in response to an increased demand and to face evolving conditions due to climate change (Parker & Diop-Kane, 2017). Forecasters especially pay attention to high impact events which can be extreme occurrences (e.g. tropical cyclones or droughts) or a succession of adverse events.

A8.1.2 New Earth-system seamless paradigm

Nowadays, forecasting activities heavily rely on numerical suites describing the evolution of the atmosphere, its composition and the other components of the Earth system, namely the ocean, and land surfaces. Given the coupled nature of the ocean-atmosphere system, the ocean plays an active role in the forecasting systems at all lead-times. The tropical Atlantic Ocean is a key player in coastal areas, around the basin and longer distances, having an impact on the entire globe.

In order to cover the different forecast time scales in a unified and consistent manner, current operational weather forecasting centres are adopting a “Seamless Earth System” approach. This new generation of forecasting systems includes better initialization techniques, makes full use of observations thanks to sophisticated assimilation techniques, incorporates probabilistic methods to cope with the chaotic nature of the atmosphere, and relies on coupled atmosphere-land-ocean-wave-sea ice models to predict the evolving sea-surface conditions and its impact on the atmosphere. An adequate observing system underpins and drives forward the forecasting capabilities, hand in hand with model development and computer resources.

A8.1.3 Need for observations for initialization, verification, model development and understanding

Although the observational needs of the different forecasting systems vary, all of them revolve around four main activities: Initialization of the forecast model; Model and data assimilation development; Calibration of model output and skill assessment. Both calibration and skill assessment require a set of reforecast over a sufficiently long period. These reforecasts are initialized from reanalyses. Reanalyses are widely used for monitoring the Earth System's climate, but they are also an integral part of the forecasting systems. Without them the forecast could not be calibrated, nor their skill could be estimated. Hence, long term is a key for short term forecast. For more details on the role of the ocean observations at the different stages of a forecasting system see Balmaseda *et al* 2014, who also discuss the observational needs for the different forecast time ranges. Although their report focuses on the Tropical Pacific, the main outcomes also apply to the Tropical Atlantic Observing System.

The observing system is critical for such numerical suites. The *Statement of guidance for Global Numerical Weather Prediction* (http://www.wmo.int/pages/prog/www/OSY/SOG/SoG-Global-NWP.pdf) is the WMO guidelines for observational requirements for weather prediction, which clearly states the importance of ocean observations, underlying that *requirements of global NWP for ocean observations are becoming more similar to those of seasonal and inter-annual forecasting*. The WWRP came to a similar conclusion for *Coupled data assimilation for integrated earth system analysis and prediction*, insisting on the importance of the upper ocean and the mixed layer resolution (WWRP 2017-3).

Operational centres do permanently assess the impact of observations on weather forecasts to guide the evolutions of the Global Observing System and of global data assimilation systems. They follow various strategies (see a review in Sato and Riishojgaard, 2016). Poli, 2018, and Doerenbecher, 2018, *pers. comm.*, have computed Forecast Sensitivity to Observation (FSO; Cardinali, 2009) for the PIRATA buoys in both the ECMWF and Météo-France global weather forecast suites (Fig. A8.1). Although the number of sea surface observations appears to be very little compared to altitude and satellite observations, the contribution of sea-surface observations to improving the forecasts (by reduction of the 24-hour forecast error *via* the data assimilation) is much larger than the share of these observations in the total numbers (for details refer to Poli 2018; The author namely evaluates the impact of wind vs pressure observations, showing the great importance of pressure measurements in the tropical Atlantic ocean; Doerenbecher also stresses the key importance of wind observations measured on buoys in that basin).

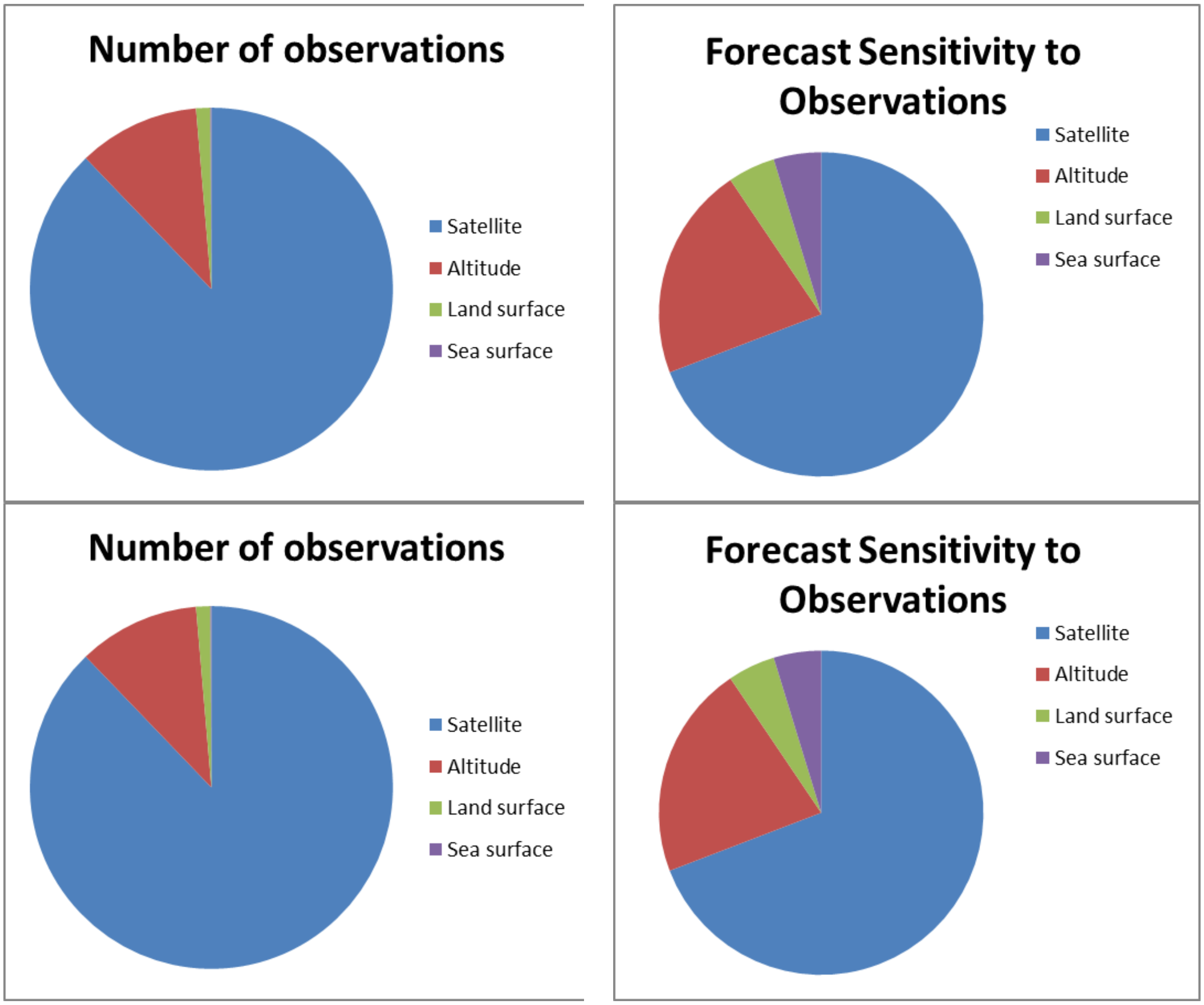

Figure A8.1: Number of observations assimilated operationally by ECMWF (left) and contribution of observations to improving the forecasts (right) (from Poli, 2018).

Based on such work, the value of the PIRATA network in particular is shown and quantified. Such results show that the collection of meteorological data (pressure and wind) from buoys in the Tropical Atlantic delivers valuable benefits to global weather predictions.

A8.1.4 The Tropical Atlantic Ocean in the context of seamless predictions: Observation requirements

The Tropical Atlantic has intrinsic peculiarities and phenomena, which we discuss below, in the context of observational needs for seamless predictions, highlighting the role of the ocean observations for weather predictions and coupled data assimilation, two recent important developments only marginally mentioned in the Balmaseda et al 2014 review.

The Atlantic Ocean is of primary importance for various continents: Africa; South, central and North America; West Indies archipelago; Europe. It connects both hemispheres, from the Arctic ocean to the Antarctic ocean. The tropical Atlantic Ocean is in direct contact with the tropical atmospheric and with the mid-latitude circulations.

The atmosphere and the ocean dramatically interact in the tropical Atlantic region, modulating the atmospheric circulation and spawning a variety of weather phenomena: monsoon circulations, tropical cyclones, atmospheric rivers. The Tropical Atlantic has its own interannual and decadal variability, which affects the basin's climate fluctuations, and influences the interbasin climate variability, a major driver of changes of the large scale global atmospheric circulation, being an important source of predictability at the seasonal time scales, at the same time as a major challenge. It also plays an important role controlling the cross-hemispheric oceanic circulation. It is the origin of several boundary currents and upwelling systems, having direct impact on the regional weather, and some of which playing an important role in the weather and climate of mid-latitude regions in both hemispheres.

Hence, the tropical Atlantic Ocean plays a critical role for weather prediction in all the surrounding regions, at time scales ranging from days to months ahead. The interplay with the weather and climate over Sahel and Western tropical Africa has been extensively studied during AMMA, e.g. the link between the West African monsoon and the Guinean upwelling (Brandt et al. 2010, in Polcher et al. 2011) or the interaction with the ITCZ. Since AMMA results, a striking element is that predictability has decreased over the region, albeit NWP systems have continuously improved. This is due to the reversal of the Atlantic Multidecadal Oscillation (AMO) which hampers the teleconnection with the tropical Pacific. (Rodriguez-Fonseca, 2010). This brings a clear need for long term sustained monitoring of the TAO.

Modelling and initializing the relevant and complexity of the Tropical Atlantic Ocean is especially challenging. Below some aspects that are especially relevant:

Complex topography, model resolution and spatial scales: the basin width and the complex topography and land sea mask requires a fine model resolution, unaffordable in global predictions with current computer capabilities. Modelling relies on parameterizations, which need to be continuously improved, with the aid of *both sustained observations and targeted observational campaigns*. It has a large spectrum of spatial scales, which are difficult to constrain by observations. *Satellite observations provide a glimpse of the variety of spatial scales*. But properly constraining these requires *sufficient in-situ observations of temperature, salinity and currents*. The latter are especially important over boundary currents, including the Equator.

The realm of salinity: One of the most distinctive features of the tropical Atlantic is the comparatively dominant role played by salinity. The equation of state for sea water indicates that over the warm tropical waters, density variations are dominated by temperature changes, salinity playing a secondary role. However, over the Tropical Atlantic, salinity gradients and temporal variations are very large, and should be properly accounted for at risk of introducing large errors in the data assimilation or modelling (Troccoli et al 2002). Salinity controls mixed layer processes, large scale density gradients, circulation, and sea level. Aside from precipitation and evaporation processes, common to the rest of the ocean basins, surface salinity in the tropical Atlantic has specific drivers: the largest river discharges of the planet (Amazon, Congo) occur over this basin. Dust deposition also contributes to the salinity and barrier layers as well as it interplays with cyclogenesis.

Up to now, neither of these are properly represented in models, nor well measured. Monitoring of river discharge is recommended. *Surface salinity observations are needed to reduce the uncertainty of salinity source and sinks, which includes precipitation, river discharge and dust deposition. Adequate and sustained uniform sampling in situ subsurface salinity is essential* to support the assimilation of temperature and sea level. Salinity observations are also needed to constrain the water mass properties of ocean reanalyses. Although the atmosphere response to salinity is negligible at short time scales, in the context of coupled data assimilation, upper level salinity can provide a constraint to the estimation of precipitation and atmospheric circulation.

Cross-Equatorial ocean flow: The Atlantic is the only basin where there is a clear net northward transport of mass and heat. The cross-equatorial flow in the tropical Atlantic is an essential limb of the global thermohaline circulation (THC), and, needless to say, of the Atlantic Meridional Overturning Circulation (AMOC). The thermohaline circulation is associated with sub- to multi-decadal variability, and usually neglected in weather and seasonal discussions. However, the representation of the cross equatorial flow is important for seasonal forecast. If wrongly initialized, the information can be projected into the wrong modes, leading to spurious currents and fast adjustments which manifest in errors in seasonal forecast (Balmaseda et al 2007, 2010). It is well known that assimilating ocean observations, including altimeter data, leads to spurious Equatorial circulations, which corrupts the representation of the Atlantic Meridional Circulation (Karspeck et al 2015). In order to develop better assimilation methods that make good use of existing observations, good quality reference time series at the Equator that help to measure transports and vertical structure are needed. Especially important are measurements near topographic gradients.

Meridional and equatorial asymmetric modes in atmosphere and ocean variations: The geographic distribution of the surrounding continents impinges a distinctive meridional component to the atmospheric and ocean circulations, and their associated variations, which give raise to monsoon circulations, and interannual-decadal variability of the climate system. This is best illustrated by characteristic east-west tilt ITCZ, which means that several degrees of freedom are needed to characterize and predict its seasonal and interannual variations. Modelling the Atlantic ITCZ and its variations is one of the biggest challenges for current models. A set of *mooring arrays at different longitudes across the tropical Atlantic, spanning the range of latitudes which encompass ITCZ variations is recommended. These moorings should measure variables relevant for air-sea interaction (temperature, humidity, winds, fluxes, waves), as well as the upper ocean temperature and salinity, a few of them with deeper profiling, and within the vicinity of the Equator, ocean currents should be provided.*

The Caribbean warm caldron: the Caribbean has a dominant role in the global atmospheric and oceanic circulation. The Caribbean exerts a control on atmospheric circulation at a range of time scales, influencing weather regimes, seasonal and decadal variations (see Chadee and Clark, 2015, and references therein). It is an important *source of Rossby waves*, thus important for predictability at medium and intraseasonal and seasonal time scales. It interacts with the *Madden Julian Oscillation* (Curtis and Gamble 2016), and it is the main source of *atmospheric rivers* in the Atlantic basin (Mahoney et al 2016). It is renown for its key role in the evolution of *tropical cyclones*. Initializing and modelling these important phenomena require *observations of the ocean and atmosphere boundary layer with high temporal sampling*, *including surface fluxes, temperature and salinity,* which help to initialize and model the ocean mixed layer and its variations. These observations would be better assimilated with *coupled data assimilation*, and indeed the Caribbean basin can become a focus region for further development of these methods. The Caribbean ocean circulation is also key for the North Atlantic Ocean. It acts as a resonance box that amplifies ocean circulation signals, in which it has been called the Rossby Whistle (Hughes et al 2016). M*easuring the sea level, as well as the entry and exit transports of mass, heat and fresh-water is recommended to close budgets and contribute to the representation of the Gulf Stream.*

Interbasin variability: the low frequency variability of the global atmospheric circulation is controlled by the balance of diabatic heating between the main three ocean basins, the Tropical Atlantic being one of them. This mode of variability, also known as the Trans Basin Variability (TBV, McGregor et al 2014), has been demonstrated to affect the latitude of maximum intensity of tropical cyclones (Moon et al 2015, and references therein), and the affect periods of prolonged droughts in several areas of the world (see for instance Chikamoto et al 2017). To monitor, understand and predict this inter-basin variability, *sustained observations of large scale SST, winds,* *sea level, mean sea level pressure are key. Sustained observations of satellite and drifting buoys are recommended.*

There are other regions and phenomena equally important for weather and climate that share commonalities with other basins, such as the Equatorial dynamics and its interannual variability, the western boundary currents, the upwellings and stratocumulous areas, the subduction and mixed layer regimes. Observation *requirements for these areas and processes also apply to the Atlantic basin*.

A8.2 Tropical cyclones and hydroclimate extreme events

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A8.2.1 Atlantic Basin extreme events

Hurricanes are the most common and regular weather and climate extremes occurring across the Atlantic Basin, causing more damage than all other storms combined. Each year hurricanes cause more than $2 billion in damage to just the U.S. alone and that number is expected to grow. As such, improving hurricane forecasts at both synoptic and climate time-scales is a top priority of Atlantic climate research.

Hurricanes are well known warm season climate extremes, responsible for torrential rains, severe flooding, wave-induced coastal flooding, and wind inflicted damages across the North American, Central American, and Caribbean coastlines, and can yield extremely large scale damages. However, by no means they are the only extreme climate phenomenon within the Atlantic sector. During cold season, extreme hydroclimate events are often associated with atmospheric rivers (ARs), which are plumes of intense water vapor transport emanating from the tropics (Zhu and Newell 1998; Ralph et al. 2004, 2005). In fact, a majority of extreme precipitation events occurred along the western European seaboard during boreal winter are preceded by ARs (Lavers and Villarini, 2013). A narrow pathway connecting from the Gulf of Mexico/West Caribbean region to the western European seaboard has been labeled as the North Atlantic Corridor, which is known to be main route of AR moisture transport (Figure A8.2) (Gimeno et al., 2010a, 2010b, Eiras-Barca et al., 2016). AR-triggered rainfall, attributed to extreme winter flooding, has been observed in the Iberian Peninsula, Norway, Poland, France, and Great Britain (Lavers & Villarini, 2015; Ramos et al., 2015). A very recent study (Blamey, 2018) shows that around 70% of the top 50 daily winter rainfall extremes in South Africa were in some way linked to ARs. Paltan et al. (2017) recently presented a global analysis of ARs' role in driving global hydrological extremes and find that ARs can not only contribute to extreme floods in several major drainage basins such as the Parana in Brazil and Elbe in Europe, but also contribute to drought occurrence in the Parana, the Iberian Peninsula, the Mediterranean coast of Europe, when ARs are inactive over the Atlantic. Therefore, improving climate models ability to predict ARs will have important implementations for water resource management and flood/drought hazard assessment, and should also be a top priority for Atlantic Basin climate research.

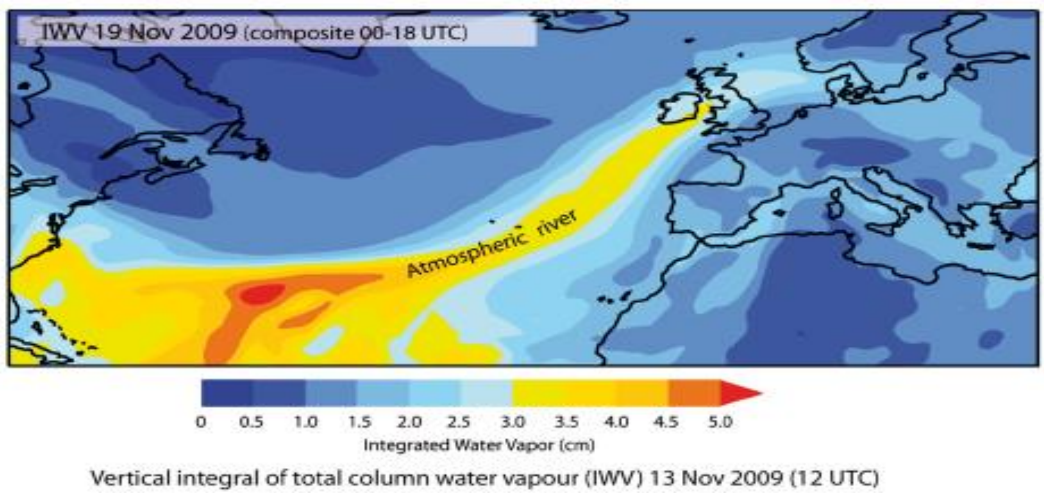
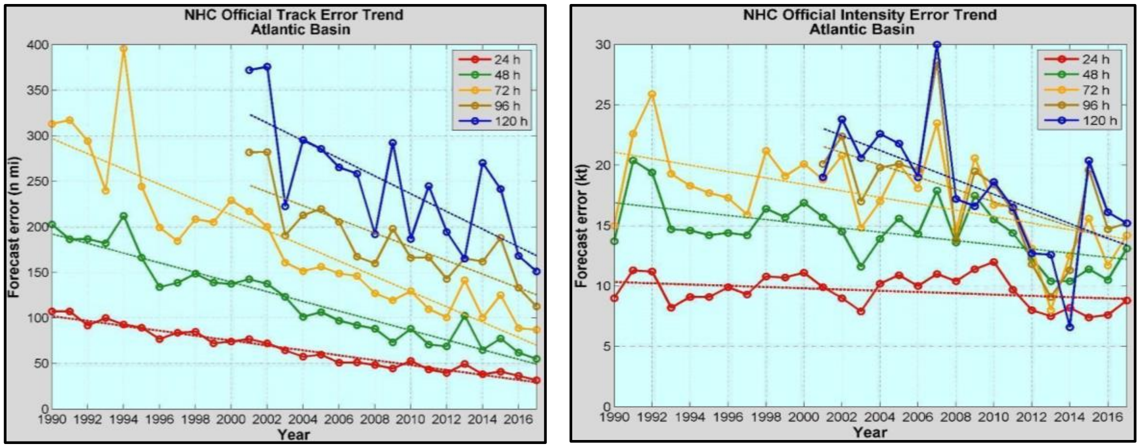


Figure A8.2: A snapshot of vertically integrated water vapor (IWV) on November 13, 2009, showing an example of Atlantic Atmospheric Rivers (adapted from Gimeno et al. 2014).

A8.2.2 Current status of predicting Atlantic TCs

Forecasts for Atlantic Basin tropical cyclones have continued to improve in recent decades, from climate scale (subseasonal-to-decadal) to synoptic storm scale (hours-to-days). In particular, synoptic forecasts of hurricane tracks have improved significantly over the past two decades (Figure A8.3a). In fact, in 2017, the National Hurricane Center (NHC) produced their most accurate hurricane trajectory forecasts on record for Atlantic tropical cyclones, with an average forecast error of 151 nm at 5-day lead time (Cangialosi, 2018). Improvements in global weather models, in the use of multi-model ensembles, and hurricane specific research continue to drive these forecast improvements. However, despite the significant advancements in trajectory forecasts for Atlantic tropical cyclones (TCs), improvement in intensity forecasts of individual storms on synoptic time scales has improved only modestly (Figure A8.3b). In particular, cases of rapid intensification (RI) are the most challenging intensity forecasts for the NHC, and produce the largest forecast errors (Kaplan et al., 2010). Recent evidence suggests that improved ocean observations and ocean modeling may provide the necessary input for atmospheric models to more accurately simulate air-sea interaction, and lead to improved intensification trends (Gall et al., 2013). Experiences at the NHC suggest that increasing ocean observations, both temporally and spatially, from the surface through the thermocline, will provide more realistic initial conditions required by the global weather models, and lead to improved intensity forecasts for Atlantic tropical cyclones.



(a) **(b)**

Figure A8.3: Improvement of synoptic forecast errors of Atlantic hurricane trajectories (a) and intensities (b) since 1990.

The past decades have also witnessed considerable progress in advancing capability for predicting hurricanes and TCs on climate time scales, particularly at seasonal time scales (Klotzbach and Gray, 2009; Vitart et al., 2007; Wang et al., 2009; Vecchi et al., 2011). The basis of seasonal hurricane forecast builds on the notion developed from observational and theoretical studies that TC activity is closely linked to the large-scale environment conducive to TCs, which is determined by background vorticity, vertical wind shear, mid-level moisture, SST and stability of the atmospheric column. These environmental factors are strongly influenced by large-scale climate modes in the tropics, such as El Niño – Southern Oscillation (ENSO), Atlantic Meridional Mode (AMM) and Atlantic Multidecadal Oscillations (AMO), which are predictable on seasonal-to-decadal time scales. Earlier studies on seasonal hurricane forecasts relied on pure statistical approaches (Gray, 1984; Klotzbach and Gray, 2009). Operational dynamical seasonal TC forecasting began in the early 2000s (Vitart and Stockdale, 2001; Vitart et al., 2007). More recently hybrid statistical-dynamical models have been developed and applied to operational seasonal TC forecasting (Wang et al., 2009; Vecchi et al., 2011). Dynamical and hybrid models now show skill comparable with or even superior to that of many well-known statistical models, particularly at longer lead times. These studies strongly suggest that a large fraction of the climate information needed to make skillful TC forecasts at seasonal or longer time scales lies in the evolution of tropical SST patterns, highlighting the importance of improving TC-season SST forecasts. Despite these recent progresses, model forecast skill of seasonal TC activity is still relatively low at long lead times (anomaly correlation is less than 0.5 for forecasts initialized earlier than March) (Figure A8.4).

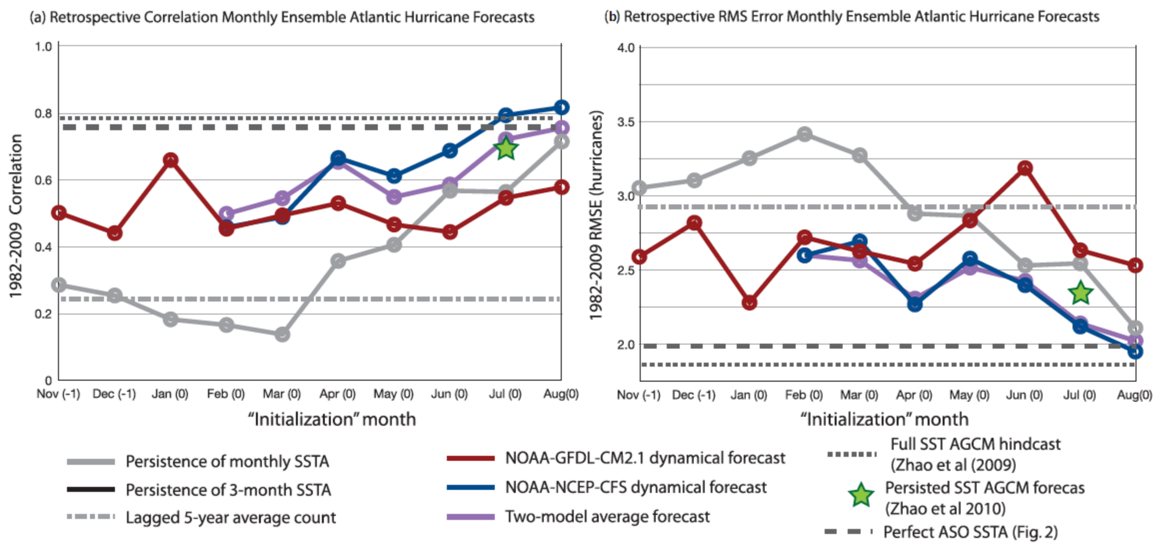


Figure A8.4: Retrospective North Atlantic hurricane forecast skill in a) anomaly correlation coefficient and b) RMS error as a function of initialization month compared to a variety of other estimates of predictability using the GFDL hybrid dynamical-statistical model. (From Vecchi et al. 2011).

At subseasonal time scales, the largest source of predictability for TCs is perhaps the Madden–Julian oscillation (MJO) (e.g., Nakazawa, 1988; Camargo et al., 2009). Observation-based analysis shows a significant MJO-related modulation on tropical cyclones over the western part of the Atlantic, including the Gulf of Mexico and the Caribbean Sea (Maloney and Hartmann, 2000; Mo, 2000) and over Atlantic main development region (MDR) (Mo, 2000; Maloney and Shaman, 2008). Atlantic TC genesis tends to increase (Maloney and Hartmann, 2000; Mo, 2000; Klotzbach, 2010 and Klotzbach and Oliver, 2015) and rapidly intensifying storms appear to be more frequent in the Atlantic (Klotzbach, 2012) when strong MJO activities occur in the Indian Ocean. Maloney and Shaman (2008) show that about half of the amplitude of vertical shear variations in the Atlantic MDR during 30–90-day precipitation events is attributable to the MJO, although Camargo et al (2009) show that the primary contribution of the MJO to the modulation of TCs in the global tropics is through its modulation of mid-level relative humidity. These observation-based studies offer a prospective for subseasonal TC forecast using the MJO as a predictor. Indeed, regional statistical models for subseasonal TC prediction have been developed (Leroy and Wheeler, 2008; Slade and Maloney, 2013) using MJO indices and results show that when an MJO index is added as one of the predictors, a significant but small improvement of skill at lead time up to 3 weeks is achieved. Recently, as a part of the subseasonal-to-seasonal (S2S) prediction project, considerable progress has been made in dynamical model based subseasonal TC forecast studies (Vitart and Robertson, 2018). A skillful TC forecast at subseasonal time scales requires S2S models to display skill in not only predicting the MJO, but also simulating realistic TC genesis climatology and MJO-TC relationship. A very recent comprehensive study of comparing reforecast datasets from six S2S models (Lee et al., 2018) shows that there is indeed a relationship between S2S models' forecast skills and their ability to accurately represent the observed MJO and the MJO-TC relationship. In particular, the ECMWF model is most skillful in reproducing the observed TC genesis climatology and demonstrates skillful TC genesis forecast up to lead time of 5 weeks in the Atlantic and Western North Pacific. However, even with the best model, there are considerable biases in simulating TC genesis climatology. As noted by Vitart et al. (2010), further improvement of model forecast skills can be achieved by bias correction, pointing to the importance of reducing forecast model biases.

At decadal time scales, observations suggest that Atlantic major hurricanes exhibit pronounced multidecadal variation with a rapid decline in the 1960's and an abrupt increase in the 1990s (Gray, 1990; Landsea et al., 1999; Goldenberg et al. 2001). However, the causes of the multidecadal variation remain elusive and are under intense investigation (e.g., Yan et al., 2017). While some studies relate the low-frequency TC variation to internal variability of the climate system (e.g., Holland and Webster, 2007), some attribute it to anthropogenic climate change (e.g., Emanuel 2005; Webster et al. 2005), and others blame it to the AMO caused by the AMOC (e.g., Zhang and Delworth, 2006; Yan et al., 2017). Multi-model ensemble analysis of CMIP5 decadal prediction (DP) experiments have revealed the general importance of initializing the ocean for enhancing model forecast skills at decadal time scales (Kirtman et al., 2013; Meehl et al., 2014). A number of recent studies (Smith et al., 2010, Dunstone et al., 2011; Vecchi et al., 2013; Caron et al., 2014; Hermanson et al., 2014; Yan et al., 2017; Yeager et al., 2018) have highlighted the importance of initializing the state of the AMOC in the high-latitude North Atlantic in order to obtain skillful forecasts of decadal Atlantic hurricane variation. In particular, a number of models have demonstrated skills in predicting the TC shift in the mid-1990s when ocean state is initialized (e.g., Smith et al. 2010; Vecchi et al., 2013). If confirmed, these model results provide direct support to the notion that AMOC-induced SST variability is important for Atlantic TC variability on decadal time scales, which may be predictable many years in advance with accurate ocean initialization, particularly in the high-latitude North Atlantic.

A8.2.3 Predicting atmospheric rivers

The ability of numerical weather prediction (NWP) models to forecast ARs on synoptic time scales has been demonstrated (Wick et al., 2013; Deflorio et al., 2018). It is shown that AR occurrence is relatively well forecasted out to a 10-day lead time, but prediction of AR landfall position and timing is subject to significant errors at a 10-day lead time (Ralph et al., 2010; Wick et al., 2013). An accurate prediction of AR landfall is particularly important because when a vapor-rich AR with lower-tropospheric moist neutrality and strong horizontal winds makes landfall and encounters mountainous terrain, orographic enhancement of rainfall can occur, producing extreme precipitation events and catastrophic flooding. Deflorio et al. (2018) gives a latest global assessment of AR prediction skill on synoptic time scales using the S2S Project global hindcast data from the ECMWF.

On climate time scales, the connection between modes of climate variability and ARs is still very poorly understood (Gimeno et al. 2014), particularly in the Atlantic. Lavers and Villarini (2013) found that the North Atlantic Oscillation (NAO) affects Atlantic AR activity, with ARs tending to affect southern (northern) Europe more effectively during negative (positive) NAO phases. Deflorio et al. (2018) show that AR forecast utility increases at 7- and 10-day leads over the North Atlantic/U.K. region during negative Arctic Oscillation (AO) conditions and during La Niña plus negative PNA conditions. However, the extent to which tropical Atlantic variability may affect ARs along the North Atlantic Corridor has not been explored. Given that the moisture source is located in the Atlantic warm pool region, an improved understanding of how ocean-atmosphere interactions can affect the PBL moisture budget in the region seems to be key. A very recent study by Mundhenk et al. (2018) suggests that the Madden–Julian oscillation (MJO) and the quasi-biennial oscillation (QBO) may serve as useful predictors for empirical subseasonal prediction of landfalling AR activity in the North Pacific. Whether such a finding can also be applied to the North Atlantic sector is unknown and needs to be explored.

A8.2.4 Future challenges and improvements

In view of these recent research progresses, we believe that the following observations in the Tropical Atlantic Ocean are critical to further advance and improve our short-term predictive capability of Atlantic hurricanes (Figure A8.5):

- Increased observations across the MDR through the GOM to include: 1) SST, 2) mixed layer profiles to ~200 m, 3) meteorological measurements of winds, air-temperature, humidity, surface pressure, and 4) spectral wave data;
- Enhanced measurements from PIRATA array to provide 1) timely, higher temporal frequency data, 2) full suite of meteorological measurements, and 3) T-Flex moorings to enhance the measurement capability.

These enhanced observations will allow for improved monitoring of developing, intensifying TCs, and should improve initialization of ocean models leading to improved depiction of ocean-atmospheric interactions.

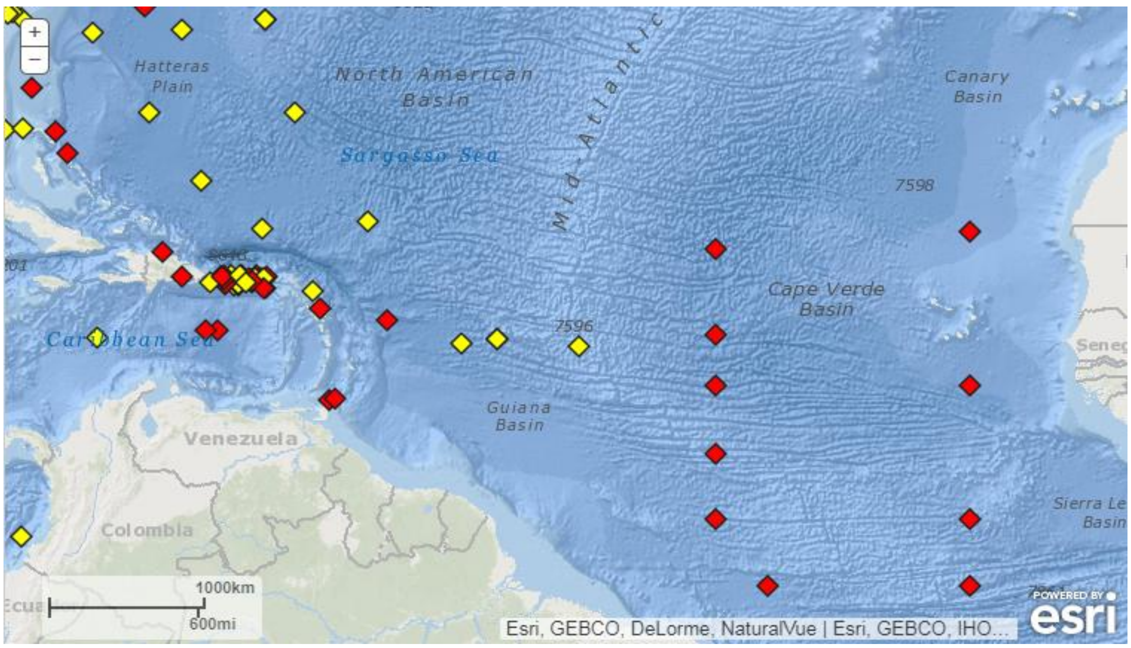


Figure A8.5: NDBC map indicating locations of NDBC buoys (yellow) and international platforms (red) across the Main Development Region (MDR) for Atlantic tropical cyclones.

There is also a pressing need to push seasonal prediction efforts beyond basin-wide TC activity toward the much more challenging and societal relevant goal of improving skill at regional scales, so that skillful seasonal forecasts of landfalling hurricanes and TCs can be achieved. As computing power continues to increase, high-resolution coupled climate models that are capable of directly resolving and simulating TCs will become increasingly important for TC forecasts at seasonal or longer time scales. As SST-forced climate simulations fail to include oceanic feedbacks, they tend to "overpredict" hurricane activity (Zarzycki 2016; Li and Sriver 2018). Coupled atmosphere-ocean climate models are therefore more desirable for seasonal or longer time-scale TC predictions. However, one major obstacle in applying these coupled climate models to long-term TC predictions/projections is the issue of how to overcome model tropical biases. In the tropical north Atlantic, current generation climate models suffer from cold SST bias, which can severely hamper their simulation and prediction skills of hurricanes. Hsu et al. (2018) shows that the cool SST bias in the northern tropical Atlantic can cause an underrepresentation of Atlantic hurricane activity by 65% of the simulated mean. This suggests that the northern tropical Atlantic is a good target for coupled model improvement from the perspective of hurricane prediction on seasonal-longer time-scales. Enhancing observations in the Atlantic hurricane main development region (MDR) can help accelerate the effort toward resolving the cool SST bias problem.

Finally, much of the focus of AR prediction studies has been on the North Pacific and US West Coast and little is known about the predictable dynamics of ARs in the Atlantic. There is a need to improve our understanding of ARs in the Atlantic sector and their relationships with modes of climate variability on subseasonal-to-decadal time-scales. Some recent studies suggest that mesoscale ocean-atmosphere interactions can have impact on extratropical cyclones and winter storm tracks (e.g., Ma et al. 2015, 2017). Given that the occurrence of ARs and explosive cyclogenesis in extratropics are closely related (Eiras-Barca et al., 2018), there is a need to explore the potential impact of mesoscale ocean-atmosphere interactions in the eddy-rich Gulf of Mexico, Caribbean, and Gulf Stream regions on Atlantic ARs and their predictability on climate time-scales. To this end, the planned Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC, US-lead research) and the EUREC4A Ocean-Atmosphere component (EUREC4A-OA, European-lead research) field campaign may be particularly relevant to address the issue of how mesoscale ocean-atmosphere interactions can have an impact on ARs in the Atlantic and how well high-resolution climate models capable of resolving phenomena on scales of a few kilometers can faithfully represent small-scale ocean-atmosphere coupled processes in the Tropical Northwest Atlantic.

A8.3 Seasonal-to-decadal prediction of tropical Atlantic climate

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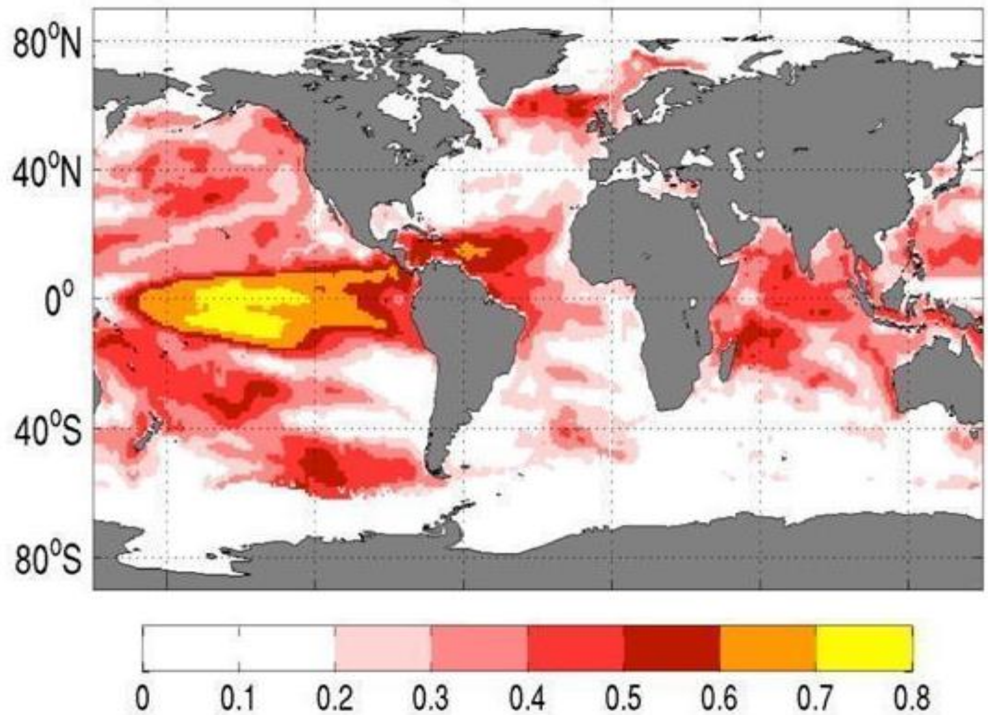
There are several sources of predictability for tropical Atlantic climate on seasonal to decadal timescales. Firstly, there are a range of patterns of climate variability that arise mainly from dynamics within the Atlantic. As introduced in the sections before, these are principally the Atlantic Niño (*Lübbecke et al.*, 2018a), Atlantic Meridional Mode (AMM) (*Servain et al.*, 1999), and Atlantic multi-decadal variability (AMV) (*Knight et al.*, 2005). Secondly, remote forcing from the Pacific associated with the El Niño Southern Oscillation (ENSO) strongly impacts the north tropical Atlantic, but also influences the south tropical Atlantic (*Enfield and Mayer*, 1997). Lastly, external forcing of the climate system has been shown to contribute to variations mainly on decadal and longer-timescales. In particular, anthropogenic caused increases in greenhouse gases as well as changes in aerosol loadings were shown to be important (*Ting et al.*, 2009; *Tokinaga and Xie*, 2011; *Booth et al.*, 2012). Chang et al. (2006b) provide a good review of the dynamics of the first two sources of predictability. The first two parts of the review focus on predictability of sea surface temperature (SST), because it has received most attention and can have important climatic impacts (see sections A3.1 and A3.2).

A8.3.1 Seasonal prediction of SST

Current state-of-the-art seasonal prediction systems represent these sources of predictability to a certain extent, but the tropical Atlantic is the region where these models exhibit the least amount of skill of all of tropics. This is illustrated by the anomaly correlation skill in predicting SST at six months lead from the North American Multimodel Ensemble (*Kirtman et al.*, 2014) (Figure A8.6).

Greatest skill is found over the north tropical Atlantic where correlations exceed 0.5. This skill results mainly from the ENSO teleconnection to this region (*Chang et al.*, 2003), but also from the long-term warming trend that is particularly strong in this region during this period (*Wang et al.*, 2018). The ENSO teleconnection causes a relaxation (enhancement) of the trade winds over the north tropical Atlantic that through local ocean-atmosphere interaction causes anomalous warm (cold) SST that peaks in the boreal spring following El Niño (La Niña) events (*Alexander et al.*, 2002).



Figures A8.6: Anomaly correlation skill in predicting SST six months ahead, averaged over four start dates, and 13 models from the North American Multimodel Ensemble (*Kirtman et al.*, 2014) for the period 1985-2010. Figure is adapted from Wang et al. (2018)

The AMM also peaks in boreal spring (*Sutton et al.*, 2000) and influences the predictability of the north tropical Atlantic. The AMM is an ocean-atmosphere coupled mode of variability involving the Wind-Evaporation-SST (WES) feedback that acts on both short and long-time scales (*Servain et al.*, 1999). The WES feedback in the Atlantic acts to amplify an anomalous meridional SST gradient, through coupling between turbulent fluxes and SST, via wind speed and rainfall changes that are connected to the meridional position of the ITCZ (*Xie and Philander*, 1994). These dynamics mainly involve the mixed-layer (*Foltz et al.*, 2011), and hence memory for predictability is limited to an AR-1 process (*Latif and Keenlyside*, 2011). However, links to ocean dynamics in the Guinea Dome had been proposed to enhance the predictability of the AMM on seasonal timescales (*Doi et al.*, 2010). The AMM can be excited by remote forcing from the North Atlantic Oscillation and ENSO (*Saravanan and Chang*, 2000; *Chang et al.*, 2006b). The local AMM conditions can act to reinforce or cancel the remote ENSO forcing, and thus provide conditional predictability (*Giannini et al.*, 2004; *Barreiro et al.*, 2005).

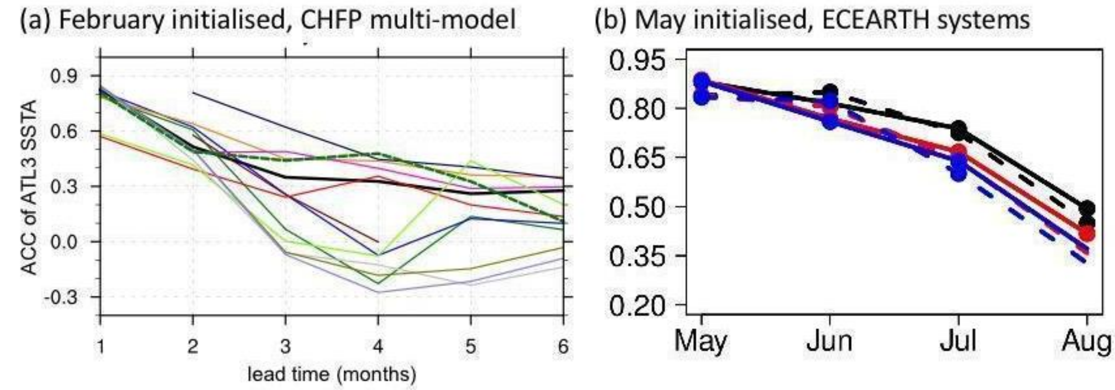


Figure A8.7: (a) anomaly correlation skill in predicting ATL3 (20°W-0°, 3°S-3°N averaged) SST anomalies as function of lead time for seasonal predictions initialized in February from the Climate Historical Forecast Project (CHFP) and the SINTEX-F prediction systems (dashed line); persistence skill is shown for reference (black line). Figure adapted from (*Richter et al.*, 2017). (b) as in (a) but from the ECEARTH model predictions initialized in May for three different resolutions (black, red, blue) and compared against two different SST data sets (solid, dashed). Figure adapted from (*Prodhomme et al.*, 2016).

State-of-the-art models are not skillful in predicting SST anomalies in the south tropical Atlantic six months in advance (Figure A8.6). The poor skill is associated with poor skill in predicting the Atlantic Niño that dominates interannual variability in this region and peaks in boreal summer (*Lübbecke et al.*, 2018a). This is further documented by the skill of seasonal predictions initialized in February from another set of models: anomaly correlation skill for predicting the Atlantic Niño variability drops rapidly and is around 0.4 in May to July for the best models, and is hardly above the persistence skill (Figure A8.7a). Some of the better prediction systems are able to skillfully predict Atlantic Niño variability from May 1st (Figure A8.7b). The low Atlantic Niño predictability has been attributed to several factors: the large importance of internal atmospheric dynamics, the existence of multiple mechanisms of comparable importance to the Bjerknes feedbacks, the inconsistent response to ENSO, and large model errors.

The relative importance and predictability of the various processes internal to the Atlantic is not fully understood (*Lübbecke et al.*, 2018a). The Bjerknes positive and delayed negative feedbacks similar to those in the Pacific are generally thought to dominate the dynamics of the Atlantic Niño (*Zebiak*, 1993; *Keenlyside and Latif*, 2007; *Ding et al.*, 2010). Although these feedbacks provide a basis for seasonal prediction in the equatorial Atlantic, they explain less variance in the Atlantic than the Pacific and are more strongly modulated by the seasonal cycle (ibid). Consistently, a significant fraction of the zonal wind variability in boreal spring in the equatorial Atlantic cannot be explained by SST (*Richter et al.*, 2014). In addition, a range of alternate processes have been also suggested to explain Atlantic Niño variability: thermodynamic ocean-atmosphere interaction (*Nnamchi et al.*, 2015), meridional advection of off-equatorial temperature anomalies (*Richter et al.*, 2013); forcing by reflected equatorial Rossby waves (*Foltz and McPhaden*, 2010); and forcing by equatorial deep jets (*Brandt et al.*, 2011a). There is also a secondary peak in equatorial variability in November-December that is known as the Atlantic Niño II and, although weaker than the primary peak in boreal summer, could be more predictable as they are more closely related to upper ocean heat content (*Jansen et al.*, 2009, Per. comm. Lübbecke). Benguela Niños may be predictable 1-2 months in advance, because many are forced by equatorial and coastal Kelvin waves (*Florenchie et al.*, 2003; *Imbol Koungue et al.*, 2017). However, some Benguela events appear to be dominated by local forcing and therefore less predictable (*Richter et al.*, 2010; *Lübbecke et al.*, 2018b).

Model errors could be a major cause of low prediction skill in the south Atlantic. These errors are among the most severe of all biases found in state-of-the-art climate models (*Richter*, 2015). There is a consensus that the equatorial Atlantic SST bias is caused by too weak easterly winds in boreal spring, leading to a weak development of the equatorial cold tongue in boreal summer (*Richter and Xie*, 2008; *Wahl et al.*, 2011; *Richter et al.*, 2012a; *Toniazzo and Woolnough*, 2014; *Goubanova et al.*, 2019; *Voldoire et al.*, 2019). The wind errors are already apparent in uncoupled atmospheric models and are related to the representation of tropical rainfall (*Richter et al.*, 2012a) and insufficient vertical resolution in the lower atmosphere (*Harlaß et al.*, 2015), possibly resulting in the underrepresentation of vertical momentum transport (*Zermeño-Diaz and Zhang*, 2013; *Richter et al.*, 2014). Ocean stratification errors associated with vertical mixing and surface fresh water biases may also contribute (*Hazeleger and Haarsma*, 2005; *Breugem et al.*, 2006; *Jochum et al.*, 2012). There is less agreement on the cause of the bias in the Angola-Benguela region (*Xu et al.*, 2014b). The poor-representation of wind stress is a key factor in many models (*Patricola and Chang*, 2017; *Koseki et al.*, 2018), but errors in subsurface ocean temperature in the equatorial region can also contribute (*Xu et al.*, 2014a) and shortwave flux errors associated with poor representation of low-level clouds can contribute to the large-scale error (*Zuidema et al.*, 2016) .

These biases have been shown to affect simulated variability and to limit predictability, through suppressing the importance of dynamical ocean-atmosphere interaction. Almost all climate models simulate a too deep thermocline in the eastern equatorial Atlantic and weak cold tongue. As a result, models are found to strongly underestimate the strength of the positive Bjerknes Feedback (*Nnamchi et al.*, 2015; *Deppenmeier et al.*, 2016; *Dippe et al.*, 2017). Thus, although strongly biased climate models are able to simulate Atlantic Niño like variability (*Richter et al.*, 2012b), this variability may be erroneously governed by thermodynamic ocean-atmosphere interaction (*Jouanno et al.*, 2017). Numerical model sensitivity experiments indicate that reducing model biases enhances dynamical ocean-atmosphere interaction and improves Atlantic Niño simulation (*Ding et al.*, 2015; *Harlaß et al.*, 2017; *Jouanno et al.*, 2017). Reducing the large-model biases in the tropical Atlantic is found to enhance seasonal prediction skill. This was shown by comparing predictions with a standard and an anomaly coupled configurations of the Norwegian Climate Prediction Model (*Dippe et al.*, 2019; pers. comm. Keenlyside).

Another reason for the low predictability in the equatorial Atlantic is the inconsistent ENSO response in this region: while El Niño tends to cool the equatorial Atlantic by driving stronger trade winds it may also warm the region through increased tropospheric heating (*Chang et al.*, 2006a) and by exciting Rossby-waves that reflect into downwelling Kelvin waves (*Lübbecke and McPhaden*, 2012). These competing effects can explain the insignificant (in-phase) correlation between the Atlantic Niño and ENSO. Apart from ENSO forcing, the AMM can also affect the Atlantic Niño variability and predictability during some periods, for instance, through the impacts of the AMM on the ITCZ (*Servain et al.*, 1999) or through equatorial wave dynamics (*Foltz and McPhaden*, 2010) (*Richter et al.*, 2013) or reflected equatorial Rossby waves. However, it is unclear how these impacts limit or enhance predictability in the equatorial and southern tropical Atlantic.

A8.3.2 Multi-year prediction of SST

Near-term or decadal prediction is in a pre-operational phase, being a relatively new field with the first publications around 10 years ago (*Smith et al.*, 2007; *Keenlyside et al.*, 2008). The near-term predictions performed for the IPCC AR5 has shown that SST variations over large parts of the North Atlantic can be predicted up to a decade in advance (*Doblas-Reyes et al.*, 2013). This is associated with skill in predicting AMV and is derived both from initial conditions and external forcing (*Yeager and Robson*, 2017). The skill in the North Atlantic subpolar gyre derives primarily from the initialization of the oceanic state, and associated ocean heat flux convergence (*Yeager and Robson*, 2017). The mechanisms for predictability of the subtropical North Atlantic is less well established, but external forcing appears to play a dominant role. Anthropogenic caused increases in greenhouse gases have driven a long-term warming of the tropical Atlantic, while changes in aerosol loadings were shown to be important in capturing multidecadal variations (*Ting et al.*, 2009; *Tokinaga and Xie*, 2011; *Booth et al.*, 2012).

Results from the CESM decadal prediction large ensemble illustrate the current status of skill in predicting Atlantic SST 5 to 9 years in advance (*Yeager et al.*, 2018). The yearly retrospective predictions covering the period from 1954 to present show high-levels of skill in predicting SST over the entire Atlantic (Figure A8.8a). The skill over most of the Atlantic results mainly from external radiative forcing (i.e., greenhouse gases and aerosol loadings). The subpolar North Atlantic (SPNA) stands out as the region where the skill improvement associated with initializing the ocean is greatest, but there are indications that initialization of upper ocean heat content in the subtropical south Atlantic is an important source of skill on decadal time scales (Figure A8.8b). Other studies have shown that initialization can enhance skill in subsurface equatorial Atlantic (*Corti et al.*, 2015). Furthermore, skill in predicting the subpolar North Atlantic can enhance skill over the tropical Atlantic via atmospheric teleconnections (*Smith et al.*, 2010).

A8.3.3 Prediction of the tropical Atlantic climate and impacts on marine ecosystems and remote regions

As discussed in section A3.1 and A3.2, TAV impacts the climate of surrounding continents, marine ecosystems, and also remote regions – Africa, South America, ENSO, and ISM; and also remote forcing from the Pacific and extra-tropical Atlantic impacts the climate of the region. The prediction skill associated with these impacts has been assessed to varying degrees and is briefly summarized here.

The major influences on interannual variability of continental rainfall are the Atlantic Niño, AMM, ENSO, and Benguela Niño. The onset phase of Atlantic Niños tends to enhance the southward migration of the ITCZ due to the warm SST anomalies on and south of the equator. This increases rainfall over the Gulf of Guinea and delays the onset of the West African Monsoon while increasing rainfall over the Brazilian Amazon and Northeast Brazil (*Kucharski et al.*, 2009; *Brandt et al.*, 2011b; *Rodríguez-Fonseca et al.*, 2015; *Torralba et al.*, 2015). The AMM impacts rainfall over Brazil, with a positive AMM favoring earlier migration of the ITCZ causing dryer conditions over Northeast Brazil (*Nobre and Shukla*, 1996; *Rodrigues et al.*, 2011). Benguela Niño events impact rainfall over south-western Africa (*Rouault et al.*, 2003; *Rouault et al.*, 2009). ENSO events have been associated with significant rainfall anomalies over both South America and West Africa. Janicot et al. (1998) show that the eastward shift of the Walker cell during El Niño events is associated with anomalous subsidence over the tropical Atlantic that suppresses convection over West Africa. Likewise, the reduction of rainfall over tropical South America during El Niño has been linked to the shift in the Walker cell (*Ropelewski and Halpert*, 1987).

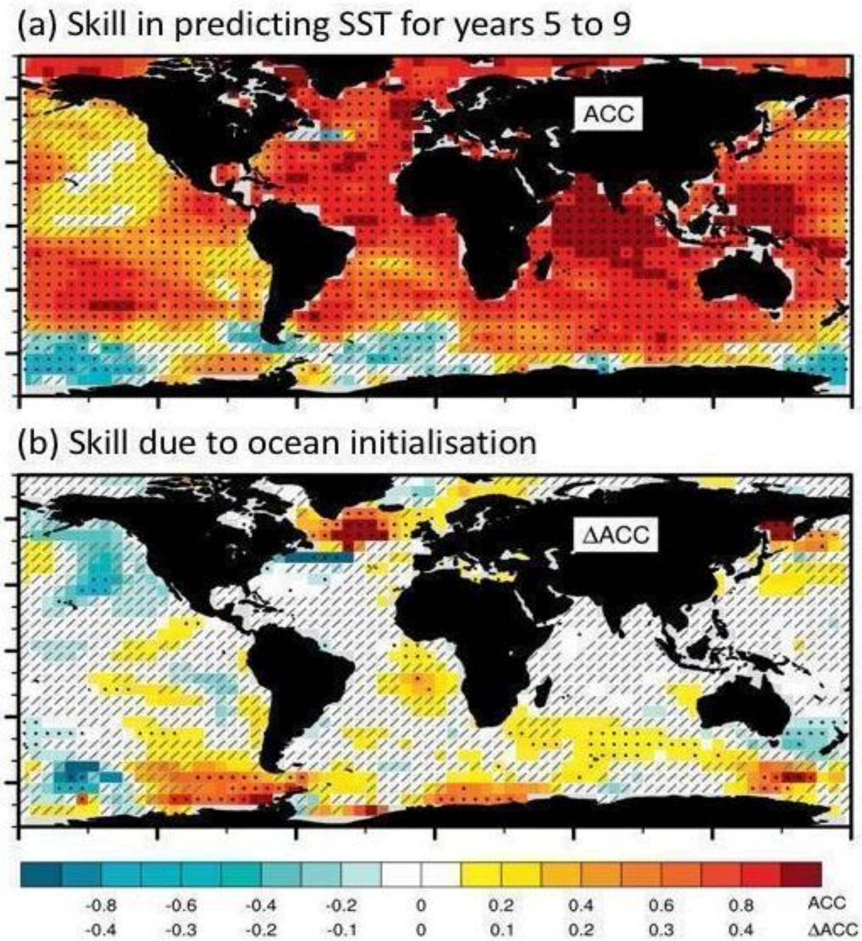


Figure A8.8: (a) Anomaly correlation skill in predicting SST for years 5 to 9 from the CESM Decadal Prediction Large Ensemble experiment that consist of 40 distinct member ensemble predictions started 1st of November every year from 1954 to 2008. (b) Anomaly correlation skill resulting from initialization of the ocean. Note the two colour scales for (a) and (b). Boxes without a gray slash are significant at the 10% level; dots further indicate points whose p values pass a global (70°S–70°N) field significance test. Figure adapted from Yeager et al. (2018).

Seasonal prediction skill of rainfall has been achieved in some regions based on skill in predicting tropical SST and its remote impacts. Analysis of model simulations and empirical analysis of observations have shown that tropical SST provides quite a high level of predictability of rainy season rainfall over northeast Brazil (*Folland et al.*, 2001). Consistently, statistical predictions based on Pacific and Atlantic SST combined with dynamical seasonal predictions show that rainfall over tropical Brazil and southern Brazil, Uruguay, Paraguay, and northern Argentina show the most predictability on seasonal timescales; however, ENSO variability appears to dominate skill (*Coelho et al.*, 2006). Seasonal prediction systems are able to predict one month in advance the three major droughts of 1998, 2005, 2010 over Brazil (*Coelho et al.*, 2012).

Seasonal prediction skill of rainfall over West Africa has been mostly related to skill in predicting equatorial Atlantic SST and ENSO. Statistical schemes using indices from both regions achieve skillful forecasts a few months in advance for the Sahel rainy season (*Suárez-Moreno and Rodríguez-Fonseca,* 2015). Multi-model dynamical prediction systems are able to reasonably predict Gulf of Guinea rainfall in July to September from forecasts started May 1st (*Philippon et al.*, 2010). These systems show little skill in predicting Sahel rainfall in the same season, but have good skill in predicting large-scale circulation indicators for the WAM (ibid). An example of the economic benefit to farmers that may be obtained through these seasonal rainfall forecasts is the Nioro du Rip region of Senegal (*Sultan et al.*, 2010).

Seasonal predictions of Atlantic hurricane activity show relatively high skill (*Camargo et al.*, 2007). This is because the frequency of Atlantic hurricanes is determined by some key environmental factors that are largely predictable on seasonal time scales: the underlying SST in the north tropical Atlantic can be predicted several months in advance, as discussed above; and vertical wind shear over the region is controlled by predictable SST conditions locally and over the Pacific and the quasi-biennial oscillation (*Gray*, 1984). The statistical-dynamical forecasts are able to predict North Atlantic tropical cyclone frequency during the August–October season, from as early as November of the previous year (*Vecchi et al.*, 2011). Multi-model forecasts are shown to improve skill (*Vitart*, 2006). High-resolution seasonal forecasts systems are able to skillfully predict tropical cyclone activity at finer than basin-scale over the north tropical Atlantic, months in advance (*Vecchi et al.*, 2014). In addition, reducing SST biases contributes to an enhancement in prediction skill (ibid).

On longer time scales, AMV has long been associated with rainfall anomalies in the Sahel region (*Lamb*, 1978b; *Folland et al.*, 1986; *Zhang and Delworth*, 2006). Observations suggest that during positive phases of the AMV the accompanying warming of the northern tropical Atlantic leads to a northward shift of the ITCZ, resulting in increased rainfall over the Sahel. Additionally, the positive phase of the AMV is associated with increased activity of African easterly waves and reduced vertical wind shear over the northern tropical Atlantic. Together with the anomalously warm SSTs, these factors lead to an increase in tropical Atlantic hurricanes (*Goldenberg et al.*, 2001; *Martin and Thorncroft*, 2014). These impacts also extend to the Indian summer monsoon (*Zhang and Delworth*, 2006).

There is also corresponding skill in predicting Sahel rainfall on these timescales (*Sheen et al.*, 2017; *Yeager et al.*, 2018), as well as Atlantic hurricane numbers (*Smith et al.*, 2010; *Caron et al.*, 2017). The impact on Sahel rainfall has been linked to the skill in predicting AMV (*Mohino et al.*, 2016). The skill in predicting hurricane variability is linked to skill in predicting the relative warming of the north tropical Atlantic to the rest of the tropical oceans that also contributes to changes in wind shear over the hurricane main development region (*Smith et al.*, 2010). The skill in predicting these impacts is likely affected by the large-model biases in the tropical Atlantic. This is suggested by the fact that simulated Atlantic hurricane activity is typically much weaker than observed, which has been attributed to the cold SST bias in the northern tropical Atlantic (*Hsu et al.*, 2018).

Climate based predictions of marine ecosystems have great potential as aid to fisheries management. The marine ecosystem is influenced by both anthropogenic (e.g., fisheries and pollution) and environmental factors. Coastal variability off north west and south west Africa are two examples where predictable environmental factors can lead to potentially skillful ecosystem predictions. As discussed above, Benguela Niño events can be predicted 1-2 months in advance and these coastal extreme events significantly impact regional marine primary production (*Bachèlery et al.*, 2016a; *Bachèlery et al.*, 2016b) and fisheries (*Ostrowski et al.*, 2009; *Blamey et al.*, 2015). While off north west Africa, El Niño events in the Pacific offer the potential to predict round sardinella distribution months in advance (*López-Parages et al.*, 2019). In this region, multi-decadal shifts of the ecosystem could also be predictable based on long-term environmental shifts (*Sarré et al.*, 2018).

Skillful predictions of tropical Atlantic variability can lead to worldwide improvements in skill. In particular, skillful seasonal predictions of rainfall in the tropical Atlantic can enhance the skill of winter North Atlantic Oscillation, through Rossby way induced teleconnection patterns (*Knight et al.*, 2017; *Scaife et al.*, 2017). Furthermore, it is now well recognized that the tropical Atlantic influences tropical Pacific interannual (*Rodriguez-Fonseca et al.*, 2009; *Ding et al.*, 2012; *Ham et al.*, 2013) and decadal variability (*McGregor et al.*, 2014; *Chikamoto et al.*, 2015; *Li et al.*, 2016b). In particular, the recent warming of the tropical Atlantic appears to have driven a strengthening of the Pacific trade winds, cooling of eastern tropical Pacific SST, and the global warming hiatus (ibid). Furthermore, Atlantic impacts have been shown to increase prediction skill in the Pacific on seasonal and multi-year timescales (*Keenlyside et al.*, 2013; *Chikamoto et al.*, 2015; *Martín-Rey et al.*, 2015). Tropical Atlantic biases impact these teleconnections (*McGregor et al.*, 2018) and need to be reduced in order to capture the Atlantic contribution to predictability in the Pacific sector and globally. The results summarized here further highlight the need to improve the prediction skill in the tropical Atlantic.

A8.3.4 Societal relevance

The societal relevance is well summarized in section 3.2, which details the impact of tropical Atlantic variability. This section discusses the predictability of those variability patterns. Societal relevance derives from improved predictions in the region, which will allow for better preparedness and mitigation efforts.

A8.3.5 Recommendations for the observing system

The following are key to predicting tropical Atlantic climate and to achieve further improvements in prediction skill:

- Observations of upper ocean temperature and salinity over the tropical Atlantic for initializing predictions. Observations over the extra-tropical north Atlantic are also essential, because of this region’s influences on the tropical Atlantic.
- Observations at the southwest African coast are needed, as neither ocean currents nor planetary boundary layer winds are well understood, and model SSTs are strongly biased.
- Observations of aerosols, and cloud cover and properties are needed to better understand and represent external forcing on climate predictability, especially on multi-year and longer time scales
- Observations that clarify how the momentum budget in the ocean and atmospheric boundary layer is maintained. This will help reduce model biases and lead toward a deeper understanding of variability mechanisms.
- Observations to constrain heat and freshwater ocean mixed-layer budgets (including surface fluxes) can help reduce biases, and enhance ocean reanalysis
- Ocean current observations important for equatorial and coastal variability
- Observations of large-scale ocean circulation (wind driven and buoyancy) are important for understanding multi-year variability and predictability in the tropical Atlantic

A9. Long-term climate change and impacts

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The tropical Atlantic climate has undergone long-term changes that are projected to accelerate under future global warming. The impact of these changes extends from the marine ecosystem to continental climate. The Tropical Atlantic Observing System (TAOS) is key to monitoring and understanding these changes and reducing uncertainties in climate projections for the region. Here a brief summary is provided of long-term changes and their impacts. We cover the oceanic and climatic variables and highlight some ecosystem changes in eastern boundary upwelling systems. Relevant discussion of bio-geochemistry and dissolved oxygen in the tropical Atlantic is covered by sections A3.4 and A3.5.

A9.1 Historical changes

Historical reconstructions of *in-situ* measurements of sea surface temperature (SST) indicate that over the last century the tropical Atlantic Ocean has warmed by almost 1°C, with the strongest warming along the African coast and South Atlantic (Figure A9.1) (*Nnamchi et al.*, 2016). This warming rate is close to the global average increase in SST. The observed trends in SST over the historical period (Figure A9.1) are largely consistent with climate model simulations (*Keenlyside and Ba*, 2010) and have been attributed to anthropogenic emissions of greenhouse gases (Ch 10, *IPCC*, 2013).

The warming of the tropical Atlantic has not been uniformed in time: there were two warming periods from around 1900 to 1940 and from 1970's to present, and a period from 1940 to 1970 of rather little warming (Figure A9.1). These changes coincided with similar trends in global mean temperature, but also with large-scale basin-wide fluctuations in North Atlantic SST – referred to as Atlantic Multi-decadal variability (AMV) (*Keenlyside and Ba*, 2010). The most recent warming occurred over both the tropical South and North Atlantic, and was greatest on the eastern and equatorial upwelling regions and during boreal summer (*Tokinaga and Xie*, 2011).

The cause of the multi-decadal trends is still under debate. As discussed in section 3.8, AMV could result for internal climate dynamics or from external forcing (*Ting et al.*, 2009). In particular, climate models are able to capture the most recent tropical Atlantic warming pattern when external forces are prescribed (*Terray*, 2012). These experiments suggest that the warming pattern is associated with both increases in greenhouse gases warming offset by greater aerosol cooling in the northern hemisphere than in the southern hemisphere (*Tokinaga and Xie*, 2011). As discussed in section 3.7, observations suggest that the warming in the tropical Atlantic was associated with an increase in upper ocean heat content and connected with a strengthening of surface wind speeds, which would tend to cool the ocean; thus this suggests that the observed warming was instead driven by changes in ocean circulation (*Servain et al.*, 2014; *Lübbecke et al.*, 2015).

Sea surface salinity (SSS) is a key indicator of climate change, as it is largely controlled by changes in the hydrological cycle (*Yu*, 2011). Furthermore, SSS changes impact upper ocean stratification and can have implications for the basin wide circulation. Historical observations since 1950 show SSS in the tropical Atlantic has increased faster than in other tropical basins (*Durack and Wijffels*, 2010; *IPCC*, 2013). The SSS changes in tropical Atlantic over the period 1970-2002, while consistent with that expected from climate change but are not sufficiently large to be distinguished from internal climate variability (*Terray et al.*, 2012). Long-term changes in SSS have also been linked to continental precipitation (Sec. 3.2) (*Li et al.*, 2016a).

Changes in ocean circulation and their relation to the Atlantic Meridional Overturning Circulation (AMOC) are discussed in detail in section 3.3. Models and theory indicate that changes in the AMOC could explain some of the long-term trends and multi-decadal changes in the tropical Atlantic (*Kawase*, 1987; *Johnson and Marshall*, 2002; *Zhang*, 2007; 2010). Direct observations of AMOC are insufficient to identify such relations, and there are large-uncertainties in ocean reanalysis and long-term ocean model hindcasts on these timescales (*Keenlyside and Ba*, 2010; *Danabasoglu et al.*, 2016; *Karspeck et al.*, 2017). Fingerprints of the AMOC based on model and historical observations provide indirect evidence that historical AMOC variability was dominated by multi-decadal variations (*Latif et al.*, 2006; *Zhang*, 2008). Long-term hydrographic data indicate water masses at depth in the tropical Atlantic are undergoing long-term changes that could be related to the AMOC (Sec. 3.3).

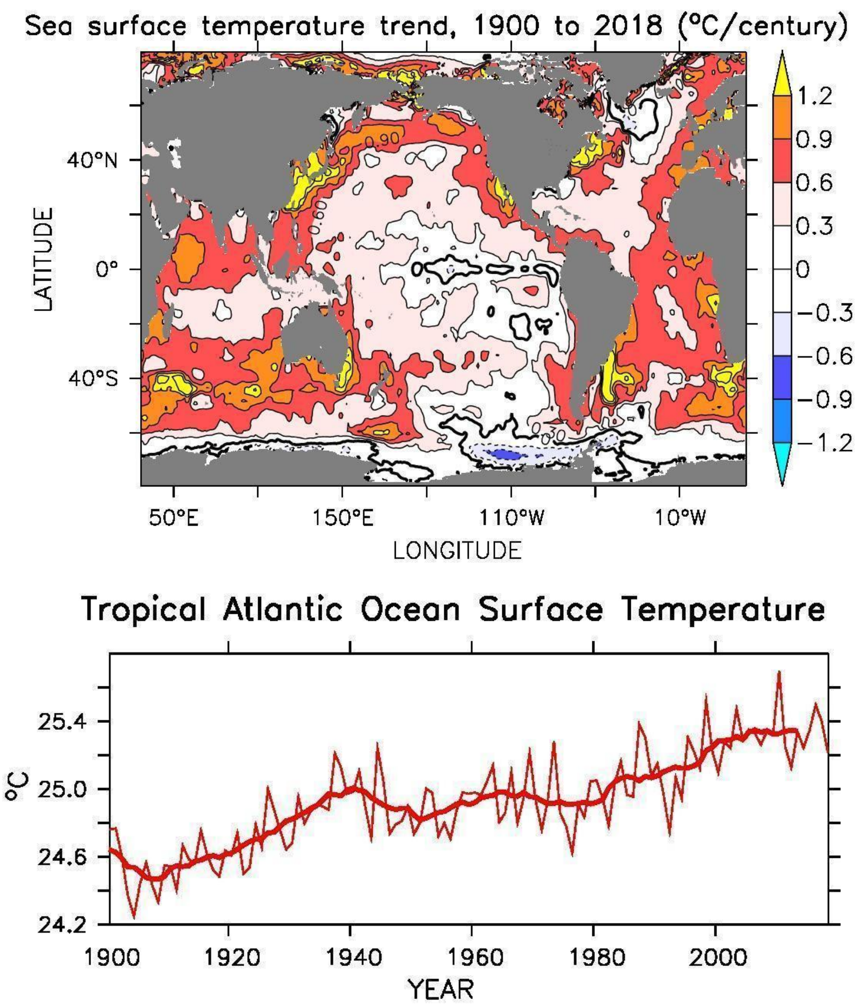


Figure A9.1: Historical change in global and tropical Atlantic sea surface temperature (SST): (Upper) Linear trend in SST calculated over the period 1900 to 2018 in degrees per century; (Lower) Annual mean SST averaged over the tropical Atlantic (30S-30N) from 1900-2018. The eleven-year running mean is indicated by the solid lines in the lower panel. SST data are from HadISST (*Rayner et al.*, 2003).

Sea level in the tropical Atlantic has undergone long-term rise superposed with multi-decadal shifts. However, our understanding of sea level rise over the tropical Atlantic over the last century is hampered by severely limited tide gauge records, especially along the African and South American coasts; for example, the tide gauges in Dakar (Senegal) and in Takoradi (Ghana), are the only ones in West Africa with temporal series longer than 40 years (*Thoreux et al.*, 2018). The available records suggest that sea level has risen at around 2.1 mm yr^{-1} since 1927 along the north west African coast and this rate is greater than the estimated 1.7 mm yr^{-1} in sea level rise globally (*Church and White*, 2011; *IPCC*, 2013; *Marcos et al.*, 2013), with even higher rates during the most recent 20 years (*Thoreux et al.*, 2018). A long-record from South American coast at 34°S indicates that sea level rose at around 1.6 mm yr^{-1} between 1905 and 1987 (*Raicich*, 2008). Satellite altimeter measurements since 1993 provide an estimate of sea level globally. These data indicate that sea level has been rising at a nearly spatially uniform rate of approximately 2 mm yr^{-1} over the tropical Atlantic between 1993 and 2018, and this is close to the global sea level rise during this period (*Cazenave et al.*, 2018). As described in section 3.7, the storage of heat in the ocean can account for roughly one third to one half of the observed global sea level rise over the past few decades.

A9.2 Climatic Impacts

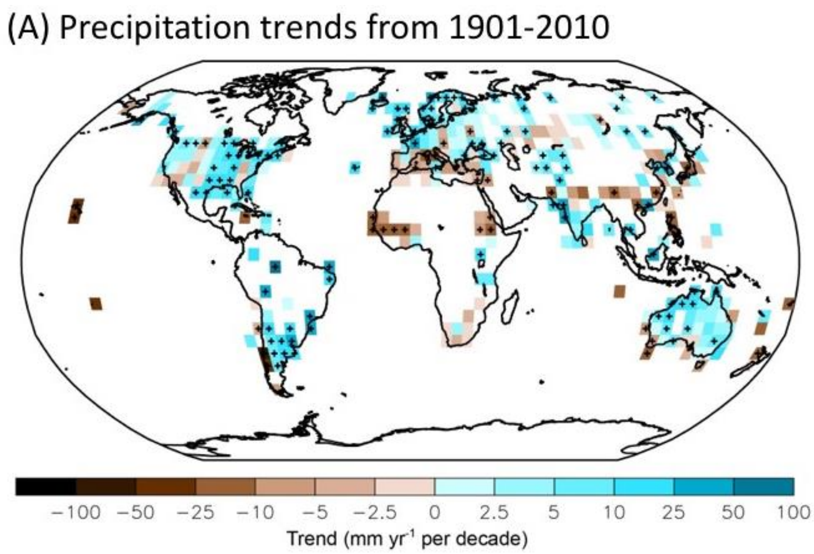
The long-term changes in the tropical Atlantic Ocean have been associated with changes in marine ecosystems, coastline and in continental climates on both sides of the basin. It has also been argued that tropical Atlantic changes influenced the tropical Pacific Ocean. Long-term observations of African and South American tropical climates are sparse and have been declining further recently (e.g., *Nicholson et al.*, 2018). This makes proper assessment and attribution of changes over the historical period difficult. Over the period 1901 to 2010, land surface temperatures over West Africa and Brazil have warmed on average by more than 1°C which is larger than the global mean increase of around 0.9°C (Ch. 2, *IPCC*, 2013). Station based rainfall data from 1901 to 2010 indicate a trend towards dryer conditions in parts of West Africa and the Caribbean and wetter conditions in parts of North East Brazil and the Gulf of Guinea (Figure A9.2). These trends appear more pronounced during the period 1950 to 2010, and they are consistent with southward shift in the Atlantic Intertropical Convergence Zone (ITCZ) and the SST warming patterns discussed above (*Bader and Latif*, 2003; *Giannini et al.*, 2003; *Pomposi et al.*, 2015). There is however a large uncertainty in these trends as they are not present in some reconstructed data sets (Ch. 2, *IPCC*, 2013).

Multi-decadal variations are a prominent feature of Tropical African and Caribbean/Brazilian continental climate. Increased land surface temperature warming trends over Africa and South America coincided with the warming periods described above, and the period 1940 to 1970's coincided with weaker warming of global mean surface temperature (Ch. 2, *IPCC*, 2013). There are also pronounced multi-decadal variations in rainfall over West Africa, North East Brazil, and the Caribbean region (Sec. A3.2). In particular, superimposed on the long-term drying trend, Sahel rainfall exhibited a wet period in the 1940's, a severe dry period in the 1980's, and weak recovery thereafter (Figure A9.3b) (*Folland et al.*, 1986; *Nicholson et al.*, 2000; *Dong and Sutton*, 2015). Rainfall over the North East of Brazil (*Lacerda et al.*, 2015), the Caribbean (*Hetzinger et al.*, 2008), and over Central and West North America (*Enfield et al.*, 2001) also exhibited decadal to multi-decadal variations that modulate the impact of El Niño Southern Oscillation (ENSO) on the continent (*Kushnir et al.*, 2010). As described in section 3.2 these variations were all related to tropical Atlantic SST, as well SST in the tropical Pacific Ocean.

Long-term observations of the marine ecosystem are sparse, and this makes the detection and attribution of trends difficult. Along the African coast the R/V Dr Fridtjof Nansen (FAO, Nansen Project, http://www.fao.org/in-action/eaf-nansen/en/) has carried out particularly useful stock assessment along the Africa coast for almost three decades using fisheries acoustics sea surveys.

These data have been used to show that the warming of SST along North West Africa appears to have driven a northward shift in *Sardinella aurita*, and other key small pelagic fish stocks for the region (*Sarré et al.*, 2019). These data also reveal similar shifts in Sardinella along the Angolan coast (Marek Ostrowski (IMR) *pers. comm*.). The last 35 years have seen an increase in marine heatwaves in the tropical North Atlantic that is expected to increase further in response to global warming (*Oliver et al.*, 2018). Marine heatwaves are major stressor on marine organisms, including coral bleaching, disease outbreaks, and forced migration (*Comte and Olden*, 2017; *Hughes et al.*, 2018). The responses of marine organisms and biogeochemical cycles to climate change remains largely unknown (*Auger et al.*, 2016; *Brochier et al.*, 2018; *Foltz et al.*, 2019).

Long-term changes in tropical Atlantic climate can potentially affect the patterns of interannual variability and associated teleconnections (Sec. 3.2 and 3.3). Lack of comprehensive long-term observations and large biases in climate models (Sec. 3.7) mean that only a few studies have addressed this. Atlantic Niño variability appears to have weakened during the period 1950 to 2009, as the eastern tropical Atlantic Ocean warmed (*Tokinaga and Xie*, 2011). The AMV modulates not only the characteristics of the Atlantic Niños, but also its inter-basin teleconnections (Indian and Pacific). In particular the Atlantic Niño-ENSO relationship has been found strongest during negative AMV phases (*Martín-Rey et al.*, 2014; *Losada and Rodríguez-Fonseca*, 2016), when equatorial Atlantic SST variability is enhanced (*Martín-Rey et al.*, 2017; *Lübbecke et al.*, 2018a).



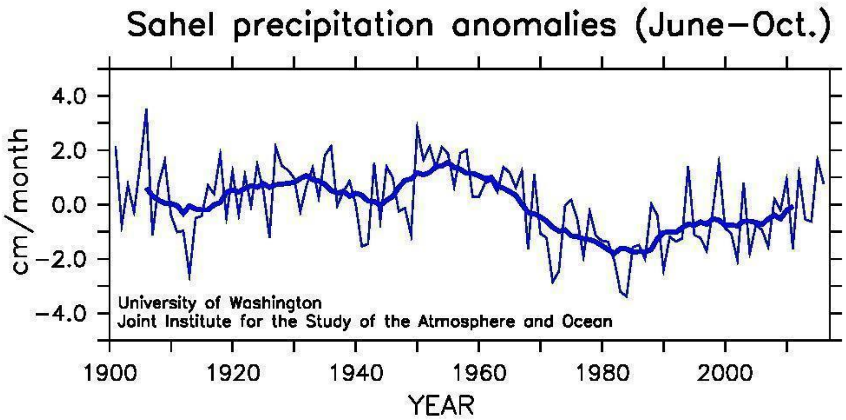


Figure A9.2: Historical change in rainfall over West African: (a) Trend in precipitation for the period 1901 to 2010 from the Global Historical Climatology Network (*Vose et al.*, 1992). White areas indicate incomplete or missing data. Black + indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). Figure is adapted from figure 2.29 IPCC AR5 (*IPCC*, 2013). (b) Sahel precipitation anomalies averaged from June-October and over the domain 20-10°N, 20°W-10. The eleven-year running mean is indicated by the solid lines. Data are from University of Washington (*Mitchell*, 1997).

Recent studies have also indicated a growing importance of the tropical Atlantic Ocean in the global climate system, particularly in the tropical areas (*Cai et al.*, 2019). In particular, observations and model experiments suggest that the warming of the tropical Atlantic during the last three decades drove SST changes over the Pacific and Indian Oceans (*Li et al.*, 2016b). It was argued that these changes drove the slowing in the rate of global warming between the late 20th and the early 21st century (*Kosaka and Xie*, 2013; *Medhaug et al.*, 2017). These changes may also have driven a stronger coupling between interannual variability in both basins and thereby enhanced seasonal predictability (*Cai et al.*, 2019). Model experiments show that when it comes to the global impact of the AMV, it is the North tropical Atlantic expression of the phenomenon that is responsible for teleconnections to the North Pacific, the surrounding continents and the Indian summer monsoon (*Ruprich-Robert et al.*, 2017).

An important consequence of the long-term and multidecadal changes in tropical Atlantic SST is their impact on climate extremes. Some of these impacts, such as the increases in the frequency of droughts and floods in parts of the basin, were reviewed in chapter A3.2. Here we briefly review the impact of warming on tropical cyclones (TCs), referred to as hurricanes in the Atlantic. Multidecadal variability in Atlantic intense hurricane (i.e., hurricanes which reach surface winds ≥ 50 ms^{-1}) was described by Goldenberg et al. (2001). They suggested that the SST changes associated with AMV caused the rapid transition from the relatively inactive 1971-1994 period to the highly active seasons thereafter. Kossin and Vimont (2007) pointed more directly at the cross equatorial SST gradient in the tropical Atlantic as a governor of TC activity (measured by seasonal mean storm frequency, storm duration, and storm intensity) and that this measure is well related to interannual variations in storm activity. Emanuel (2005) argued that the seasonally integrated total power dissipation of TCs has increased in step with the rapid rise of SST in the tropical North Atlantic since the mid-1970s. These observations seemed consistent with the growing understanding that SST warming with climate change is expected to lead to the rise in the number of intense hurricanes (*Emanuel*, 1987; *Bengtsson et al.*, 2007; *Knutson et al.*, 2010). Model simulations under CMIP5 (Coupled Model Intercomparison Project Phase 5 from IPCC) show that the changes in TC activity during the 20th century, as measured by the theoretical TC Potential Intensity metric (*Emanuel*, 1988), has been influenced primarily by AMV related SST and atmospheric conditions and not by anthropogenic warming (*Ting et al.*, 2015). The impact of anthropogenic warming on TC activity appears masked by wind shear changes that are controlled by the relative warming of the tropical Atlantic compared to other basins (*Latif et al.*, 2007). Sobel et al. (2016) argued in addition, that the competition between the warming impact of greenhouse gas increase and the cooling induced by aerosols in the tropical North Atlantic relative to the tropical South Atlantic Ocean (see Figure A9.1) caused a negligible change in TC Potential Intensity and thus uncertain impact on the intensity distribution of observed storms.

A9.3 Future changes

Model based projections indicate that continued anthropogenic emission of greenhouse gases will drive major changes in tropical Atlantic climate in the coming century and that these will have major environmental and socio-economic consequences. Overall, multiple generations of models robustly predict a continuation of the long-term warming in the mean state of the tropical Atlantic basin. According to the last IPCC report, the tropical Atlantic will warm at a rate close to the global mean and more or less uniform across the basin (Figure A9.3a) (Ch 12, *IPCC*, 2013). Oceanic rainfall is projected to increase over the equatorial Atlantic at rate of 3 to 6 % per degree of global warming, and to decrease in the subtropics (Figure A9.3b). Continental rainfall is projected to decrease over most of South and Central America and parts of West Africa, and to increase over parts of the Sahel and eastern equatorial Africa. However, large uncertainties exist in the patterns of climate change over the tropical Atlantic and surrounding continents (*Hawkins and Sutton*, 2009). In addition, although there is some model agreement on the projected changes in SST and precipitation, these models exhibit even larger biases in the tropical Atlantic (*Richter*, 2015) (see Sec. A3.7). Recent studies indicate that these biases introduce large regional uncertainties in climate change projections for the tropical Atlantic (Mojib Latif *pers. comm*.; Teferi Demissie *pers. comm*.).

Climate change projections indicate that SSS in the tropical Atlantic will continue to increase, as a result of the enhancement of the hydrological cycle (*Terray*, 2012; *IPCC*, 2013). This is associated with an increased moisture transport from the tropical Atlantic to the Pacific (*Richter and Xie*, 2010) that will enhance the climatological difference in SSS between the basins and may counteract the project weakening of the AMOC under global warming (*Latif et al.*, 2000).

There are few studies on future changes in ocean circulation in the tropical Atlantic. At a basin scale, global warming is expected to lead a reduction of the strength of the AMOC (*Schmittner et al.*, 2005; *Schneider et al.*, 2007; *IPCC*, 2013; *Reintges et al.*, 2017). The reduced poleward heat transport could lead to warming of the tropical and South Atlantic, with associated large-scale shifts in atmospheric circulation (*Stouffer et al.*, 2006). Ocean-atmosphere interaction in the tropical Atlantic and salinity biases can impact AMOC changes and recovery (*Mecking et al.*, 2016; *Mecking et al.*, 2017). The weakening of the AMOC can also interact with the wind driven subtropical cells that can lead to rapid changes in continental rainfall (*Chang et al.*, 2008).

Global warming will continue to drive sea level rise over the tropical Atlantic and for CMIP5 RCP4.5 scenario (Representative Concentration Pathway at +4.5 W m^{-2}) we expect a further near uniform increase of 20 cm by the end of the century (*IPCC*, 2013). We are not aware of studies focusing on future sea level rise over the tropical Atlantic Ocean. However, studies of global sea level rise indicate that uncertainties exist in the pattern of sea level change over the tropical Atlantic that are similar to those of the other tropical oceans (*Bordbar et al.*, 2015).

Better predictions of future alteration and changes in the rainfall pattern, intensity, variability, and or frequency is particularly important for society and the overall economy, especially for West Africa that is highly vulnerable due to low adaptive capacity (*Sylla et al.*, 2016; *Akinsanola and Zhou*, 2018) and sometimes a strong part of global domestic product is related to maritime economies and/or coastal infrastructures. There is a general agreement that global warming will cause the intensification of the global hydrological cycle associated, with dry regions becoming drier, wet regions becoming wetter, and the intensity of extreme rainfall events increasing (*Neelin et al.*, 2003; *Held and Soden*, 2006; *Chou et al.*, 2009; *Chadwick et al.*, 2012). Since the Sahel (Guinea coast) sub-regions of West Africa are relatively dry (wet), it is logical to expect drying (more moisture) in the interior and at the coast (*Giannini*, 2010). This result is found in the multi-model ensemble mean (Figure A9.3b) and in high-resolution regional model experiments (*Akinsanola and Zhou*, 2018; 2019a; b). This robust positive response of West Africa rainfall to global warming was attributed to the enhancement of moisture convergence and surface evaporation (*Akinsanola and Zhou*, 2018; 2019b). Studies have suggested a changing wet season, with predominantly negative (positive) anomalies occurring at the beginning (end) of the rainy season (*Biasutti et al.*, 2009; *Akinsanola and Zhou*, 2019a). There is also a projected increase in consecutive dry days and extreme rainfall events (ibid). There is however great disagreement among models on even the sign of rainfall change over the Sahel (*Kamga et al.*, 2005; *Cook and Vizy*, 2006; *Monerie et al.*, 2017).

Fishery is increasingly crucial for the economy and the food security of Atlantic African coastal countries which benefit from e.g., the productive Canary Current upwelling system (from Morocco to Guinea Bissau). Indeed, because of the Sahelian food crisis, the demographic pressure on the coastal fringe increased the effort of artisanal fishing (*Binet et al.*, 2012; *Failler*, 2014; *Ba et al.*, 2017), which adds up to the industrial fishing and illegal fishing in some countries. Therefore, there is a strong interest in understanding the fisheries resources distribution and its modifications that will occur as a result of climate change during the 21st century. Indeed, recent studies at global scale have shown that Climate Change will profoundly affect global ecosystems, mainly through its effects on the ocean temperature (and stratification), acidity (pH) and dissolved oxygen level (*Gattuso et al.*, 2015). This will reflect on the distribution, abundance and catchability of exploited fish species with, for example, a respective decrease (increase) in fish populations at low (high) latitudes (*Cheung et al.*, 2010). Therefore, quantifying the potentially negative impact of Climate Change on the regional fisheries resources is essential for Atlantic African countries as well as but at a lower level for Brazil and Caribbean islands. Notably however, climate biogeochemical and fish population projections are known to be tarnished by a high level of uncertainties (*Bopp et al.*, 2013), especially if only one climate projection is considered or at regional scale (scale at which global climate models can display systematic biases), i.e., this last scale which fits with the wide majority of exploited fish stocks.

As theory suggests, the continuous warming of the tropics is expected to give rise to increase in the number of intense hurricanes, but the number of tropical storms is expected to decrease, as the atmosphere becomes more stable (*Bengtsson et al.*, 2007). However, climate models used in global climate change projections do not reliably resolve actual TCs and thus used only indirectly to assess future changes in TC activity (*Knutson et al.*, 2010). In the tropical Atlantic region, downscaling of CMIP3 model runs showed that future warming will lead to a reduction in the total number of TCs but an increase in the number of intense hurricanes (*Bender et al.*, 2010). This result was later confirmed, albeit with less confidence, when a new assessment of the subject was made based on CMIP5 models (*Knutson et al.*, 2013). *Sobel et al. (2016)* argues, based on the metric of Potential Intensity, that with the increase in greenhouse gas concentration in the tropical atmosphere, SST warming globally will overcome the cooling effect due to aerosols and this will potentially lead to the increase in the number of intense hurricanes.

Despite the model improvements made in CMIP5 with respect to CMIP3, most of the climate models are not able to correctly simulate the main aspects of tropical Atlantic variability (TAV) and associated impacts (see Sec. 3.8). This is likely the main reason why there are very few studies dealing with long-term changes in tropical Atlantic variability. The models that best represent the AMM show a weaker AMM variability for future climate conditions (*Breugem et al.*, 2006). Model biases are too strong to properly assess changes in the Atlantic Niño. Long term changes in the teleconnections associated with tropical Atlantic variability modes are expected as a result of global warming, but large uncertainties exist (*Lübbecke et al.*, 2018a; *Cai et al.*, 2019). The impact of Atlantic Niño variability on El Niño is however projected to weaken (*Jia et al.*, 2019). Single-model sensitivity experiments show that Atlantic Niño characteristics at the end of twenty- first century remain equal to those of the twentieth century, though changes in the climatological SSTs can lead to changes in the associated teleconnections (*Mohino and Losada*, 2015). It has been shown a weakening of the AMOC can change the mean background state of the tropical Atlantic surface conditions, enhancing equatorial Atlantic variability, and resulting in a stronger tropical Atlantic–ENSO teleconnection (*Svendsen et al.*, 2014), but large uncertainties still exist.

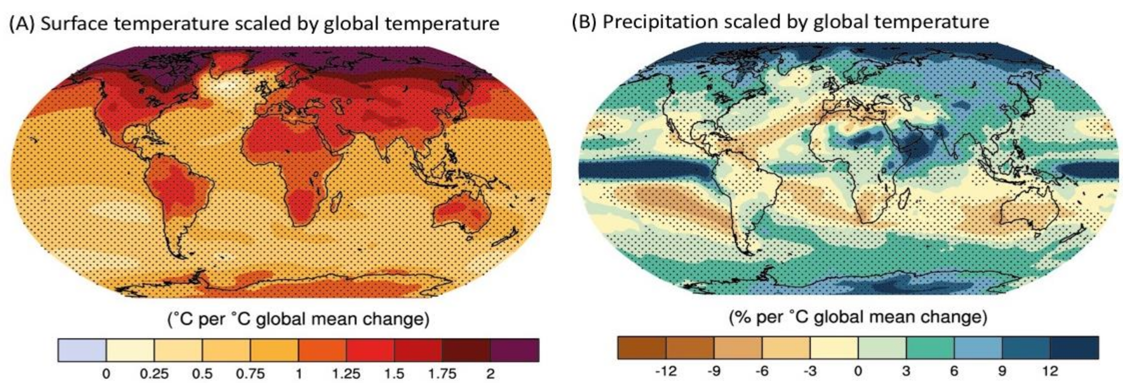


Figure A9.3: Projected changes in (a) surface temperature and (b) precipitation for 2081-2100 relative to 1986-2005. The patterns are scaled by the global mean change in temperature. The results show the multi-model mean from the IPCC coupled model intercomparison project version 5. Mean changes larger than the 95% percentile of the distribution of models are stippled. Figure is adapted from figure 12.10 IPCC AR5 (*IPCC*, 2013).

A9.4 Summary and Societal relevance

- Since the late 19th century, during the instrumental period, tropical Atlantic Ocean SST displayed gradual, long-term warming that was likely due to the increase in atmospheric greenhouse gas concentrations. This gradual warming was modulated by a multidecadal fluctuation that led to variations in the warming rate and, in particular, to a break in the warming in the mid-20th century.
- The warming of the basin was also not uniform in space. It was large in the tropical South Atlantic Ocean and smaller in the north.
- The time and space modulation of the basin warming was a combination of variability generated by processes internal to the climate system and the response to external forcing, primarily from temporally and spatially non-uniform aerosol distribution.
- Tropical Atlantic SST changes were associated with changes in precipitation over the ocean and the surrounding continents from North, Central and South America to West and Central Africa.
- Although less well observed than SST, there were also long-term changes in SSS (since 1950's) and sea level rise (since the 1920's) that are consistent with global warming, while the corresponding changes in ocean circulation are unknown.
- There is also indication from comparing model experiments with observations that these long-term changes in tropical Atlantic SST affected the climate of the tropical and extratropical Pacific Ocean and the Indian Ocean environment.

- The important societally-relevant expression of these long-term changes are in their impact on the frequency and intensity of extreme events. These range from hydrological extremes, such as short-term droughts and intervals of flooding, to oceanic "heat waves" and most pointedly, the change in the number and destructive potential of tropical cyclones.
- There is evidence that these long-term changes are also associated with changes in the marine environments and the coastline, which have adversely impacted marine life, their ecosystems and associated fisheries and thus sometimes the national GDP.
- In the future, the tropical Atlantic basin is expected to continue its warming, which will increasingly change the climate over the adjacent land areas, including on the one hand extended drying, particularly in the Caribbean and Central America and, on the other hand, increased flooding due to intensification of the hydrological cycle, associated with the increase moisture carrying capacity of the warming atmosphere. We also expect a decrease in the overall number of hurricanes but an increase in the number of intense hurricanes.
- We also expect a continued rise in sea level, increase in SSS, and a weakening of the AMOC, which is expected to contribute to changes in upper ocean heat content and American and African continental rainfall patterns.
- While the coupled climate models used in CMIPs have overall been able to simulate many of the observed changes in the region, they have been continually plagued by marked oceanic and atmospheric systematic errors and biases, which affect the confidence in their detailed regional predictions and projections.
- In order to monitor the changes in regional climate and the worldwide consequences and verify model long-range predictions and projections, sustained observations of the tropical Atlantic Ocean and surrounding land areas are needed. These need to provide basic information that will allow us to step back and support model outputs intended to verify, explain and attribute the expected and unexpected changes in the climate of the tropical Atlantic region.

A9.5 Recommendations for the observing system

Observations are key to monitoring climate change in the tropical Atlantic and to improve climate models and thereby reduce uncertainties in future projections of climate change. Maintaining existing observational records is of paramount importance to ensure the continuous monitoring of long-term changes. The follow variables are of particular importance:

- Surface and subsurface ocean temperature to understand the mechanisms behind long-term changes, and to distinguish between internal and external driven climate variability.
- Ocean salinity as an indicator of long-term changes in the hydrological cycle and because of its importance for the ocean circulation.
- Sea Surface Height and to maintain long-term tide gauge records, so as to monitor sea level rise.
- Surface flux measurements are important for understanding changes in ocean heat and salt content, and associated climatic changes.
- *In-situ* arrays to monitor basin scale changes in the overturning circulation.
- Enhance continental climate observations, which have been declining. Lack of these data has limited understanding of the impacts of climate change.

In addition, we recommend the recovery of unused historical data and increasing the paleo-proxy archives in order to better understand changes over the historical period. Obviously, bio-ecological times series on biomass assessment and spatial distribution of key marine exploited (or not) species must be maintained when it exists, using standardized procedure (*Brehmer et al.*, 2019a) and related to essential environmental variables listed above, to better understand and evaluate the impact of long-term climate change on the marine ecosystem, their marine resources and services. Lastly, we encourage the recovery of historical coastline dynamics as well as historical event of littoral submersion and cyclone/hurricanes intensity.

Appendix 2: Essential Ocean and Climate Variables (EOVs & ECVs)

In the last 20 years, the ocean observing system has evolved from a platform centric and single-project perspective to an integrated observing system. Such an integrated observing system should follow the GOOS Framework for Ocean Observing (FOO; Lindstrom et al., UNESCO, 2012) which emphasizes the identification of user requirements by considering time and space scales and by organizing it around "essential ocean variables (EOVs: https://www.goosocean.org)". Among all of the oceanic variables to be measured, the Essential Ocean Variables have been underlined as being essential for ocean observation in a global context. They include ocean physics, biogeochemistry, ocean biology and ecosystems, and address the variables to be measured, the approach to measuring them, and how their data and products will be managed and made widely available. Some of these variables coincide with GCOS Essential Climate Variables (ECVs; GCOS, 2010a,b; Bojinski et al., 2014; https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables). The idea is to express the observing system requirements in terms of EOVs and ECVs and, to the extent possible, to express them in terms of spatial and temporal sampling, regime dependencies, accuracy, quality and the need for continuity.

Here, we explore the EOVs/ECVs that are at stake in the TAOS identified phenomena. The spatio-temporal resolution specified for each EOVs/ECVs is that "desired" but not necessarily already in place. This table is intended to help start the rationalization and prioritization required to build and maintain a sustained observing system that maximizes the support for fundamental research, climate monitoring, ocean and atmosphere forecasting on different timescales, and benefit evolving societal requirements.

From this first collection of recommended EOVs/ECVs to meet a fit-for-purpose but feasible observing-system rationalization, there is the need to refine for each phenomena what are the desired versus breakthrough and threshold spatio-temporal resolution. There is also the need to define for each EOV/ECV the desired, breakthrough and threshold variable precisions.

The table is still far from complete. Its refinement in terms of societal requirements-phenomena and associated EOVs/ECVs, as well as the existing or required observing platforms to undertake the measurements, needs to evolve continuously in the coming years. This, in particular, needs to take into account societal requirements across the entire basin, from coast-to-coast, and any new requirements that may arise in the future. The final process of the TAOS rationalization will be to inverse these Phenomena/EOVs-ECVs tables into an EOVs-ECVs matrix or any analogue specific EOVs-ECVs mapping that integrates all the phenomena requirements into the best fit-for-purpose set of requirements for the Tropical Atlantic Ocean. This needs to be undertaken via discussions of TAOS stakeholders, funding organisms, and scientific experts. The discussions should be based on the most quantitative assessments of a fit-for-purpose TAOS. These should also include (albeit non exclusively) Observing System Experiments (OSEs) and Observing System Simulated Experiments (OSSEs).

Nota bene: In black are EOVs in red are ECVs. These two types of variables sometimes redound (i.e., surface stress and surface wind direction and intensity). However, all these variables are undergoing an evolution under a new WMO process that is integrating EOVs under this Observing Systems Capability Analysis and Review (OSCAR) umbrella.

Phenomena

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
Dynamics of Tropical Atlantic Variability (a) Equatorial and meridional modes (b) Benguela Niño (c) Mesoscale/ intraseasonal variability (d) Teleconnections	Sea surface temperature	25 km	25 km	Surface	Hourly to daily	Satellites/ Ships/Moorings/Argo floats/Drifters/AOVs
	Subsurface temperature	100 km	100 km	10m (0-500m)	Hourly to daily	Ships/Moorings/Argo floats/Drifters/AOVs
	Sea surface salinity	100 km	100 km	Surface	Hourly to daily	Satellites/ Ships/Moorings/Argo floats/Drifters/AOVs
	Subsurface salinity	100 km	100 km	10m (0-500m)	Hourly to daily	Ships/Moorings/Argo floats/Drifters/AOVs
	Surface currents	100 km	100 km	Surface	Hourly to daily	Satellites/ Ships/Moorings/Argo floats/Drifters/AOVs
	Subsurface currents	100 km	100 km	10m (0-1000m)	Hourly to daily	Ships/buoy-drifters/AOVs/moorings
	Sea surface height	25 km	25 km	Surface	Daily	Ships/Moorings/Argo floats/drifters/AOVs
	Sea state	25 km	25 km	Surface	Daily	Satellites
		Ship tracks, mooring locations	Ship tracks, mooring locations	Surface	Hourly to daily	Ships/buoys/moorings
	Air temperature (near surface)	25 km	25 km	Surface	Hourly to daily	Ships/Moorings/Argo floats/drifters/AOVs
	Air pressure (near surface)	25 km	25 km	Surface	Hourly to daily	Ships/Moorings/Argo floats/drifters/AOVs
	Ocean heat flux	25 km	25 km	Surface	Hourly to daily	Satellites/Ships/Moorings/Argo floats/drifters/AOVs
	Surface radiation budget	25 km	25 km	Surface	Hourly to daily	Satellites/Ships/Drifters/ Moorings/AOVs
	Precipitation	Ship tracks and mooring locations	Ship tracks and mooring locations	Surface	Hourly to daily	Ships/Moorings

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Water vapor (near surface)	Ship tracks and mooring locations	Ship tracks and mooring locations	Surface	Hourly to daily	Ships/Moorings/AOVs
	Surface stress	25 km	25 km	Surface	Hourly to daily	Ships/Moorings/AOVs
	Wind speed and direction (near surface)	25 km	25 km	Surface	Hourly to daily	Satellites/Ships/Moorings/Drifters/AOVs
	3D wind (air column)	50 km along ship tracks	50 km along ship tracks	1 km	Daily	Ships
	Air Temperature (air column)	50 km along ship tracks	50 km along ship tracks	1 km	Daily	Ships
	Water vapor (air column)	50 km along ship tracks	50 km along ship tracks	1 km	Daily	Ships
	Cloud properties	50 km along ship tracks	50 km along ship tracks	1 km	Daily	Satellites/Ships
	Aerosol properties	50 km along ship tracks	50 km along ship tracks	1 km	Daily	Satellites/Ships
Climate Impacts of Tropical Atlantic Variability	Sea surface temperature	100 km	100 km	Surface	Daily (with option for sub-daily for special purposes).	Satellite/ships/buoy/moorings/AOVs
	Subsurface temperature	100 km	100 km	20m (0-200m) 200m (>200m)	Daily (equator or boundary) + weekly (interior)	Ships/Moorings/Argo floats /AOVs
	Sea surface salinity	100 km	100 km	Surface	Weekly	Ships/Moorings/Argo floats /gliders/AOVs
	Subsurface salinity	100 km	100 km	20m (0-200m) 200m (>200m)	Weekly	Ships/Moorings/ Argo floats /gliders /AOVs
	Surface currents	100 km	100 km	Surface	Weekly	Satellite/Ships/Moorings /Argo floats/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Subsurface currents	Key surface locations in surface current system/ 100 km open ocean	Key locations in surface current system/ 100 km open ocean	20m (0-200m) 200m (>200m)	Weekly	Ships/Moorings/Argo floats/AOVs
	Ocean surface stress	200 km	200 km	Surface	3 hourly	Satellites/ Ships/Drifters/Moorings /AOVs
	Wind vector and intensity (near surface)	200 km	200 km	Surface	3 hourly	Satellites/Ships/Drifters/ Moorings/AOVs
	Air temperature (near surface)	200 km	200 km	Surface	3 hourly	Satellites/Ships/Mooring s/Drifters/AOVs/Reanal yses
	Air pressure (near surface)	200 km	200 km	Surface	3 hourly	Satellites/Ships/Mooring s/Drifters/AOVs/Reanal yses
	Water vapor (near surface)	200 km	200 km	Surface	3 hourly	Ships/Moorings/AOVs/ Reanalyses
	Precipitation	200 km	200 km	Surface	3 hourly	Satellites/Ships/Mooring s/Reanalyses
	Surface radiation budget	200 km	200 km	Surface	3 hourly	Satellites/Ships/Mooring s/Reanalyses
	3D wind (air column)	500 km	300 km	1 km	2xDaily	Ships
	Air Temperature (air column)	500 km	300 km	1 km	2xDaily	Ships
	Water vapor (air column)	500 km	300 km	1 km	2xDaily	Ships
	Cloud properties	500 km	500 km	1 km	2xDaily	Satellites/Ships
	Aerosol properties	500 km	500 km	1 km	2xDaily	Satellites/Ships

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
AMOC	Sea surface temperature	Near boundaries to capture western and eastern boundary currents; across interior, ~3° (Argo)	Specific latitudes	Surface	Boundaries: continuous (daily); interior: weekly-monthly	Satellite/Ships/Moorings/Drifters/Argo floats/XBTs/XCTDs/AOVs
	Subsurface temperature	Near boundaries to capture western and eastern boundary currents; across interior, ~3° (Argo)	Specific latitudes	50-100 m upper ocean; 300 m deep ocean	Boundaries: continuous (daily); interior: weekly-monthly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Surface salinity	Near boundaries to capture western and eastern boundary currents; across interior, ~3° (Argo)	Specific latitudes	Surface	Boundaries: continuous (daily); interior: weekly-monthly	Satellite/ Ships/Moorings/Argo floats/Drifters/XCTDs/AOVs
	Subsurface salinity	Near boundaries to capture western and eastern boundary currents;	Specific latitudes	50-100 m upper ocean; 300 m deep ocean	Boundaries: continuous (daily); interior: weekly-monthly	Ships/Moorings/Argo floats/XCTDs/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
		across interior, ~3° (Argo)				
	Surface currents	Near boundaries to capture western and eastern boundary currents; across interior, 300 km (Argo, SVP)	Specific latitudes	Surface	Boundaries: continuous (daily); interior: weekly-monthly	Satellite/Ships/Moorings/Argo floats/AOVs
	Subsurface currents	Near boundaries to capture western and eastern boundary currents; across interior, ~3° (Argo, SVP)	Specific latitudes	50-100 m upper ocean; 300 m deep ocean; surface and 1000m across interior	Boundaries: continuous (daily); interior: weekly-monthly	Ships/Moorings/Argo floats/AOVs
	Bottom pressure	At western and eastern boundaries	Specific latitudes	Optimized (~500 m)	Continuous (daily)	BPR
	Sea level height	25 km	25 km	Surface	Weekly	Altimeter

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
Carbon fluxes	Inorganic carbon (*here the subvariable needed is pCO_2 in the ocean and atmosphere*)	From 25 km to 300 km (25 km near boundaries to capture western and eastern boundary currents; across interior, 300 km)	Specific latitudes	Surface	Monthly	Ships/Moorings/Surface drifters/AOVs
Anthropogenic carbon storage	Subsurface inorganic carbon (*Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), Partial pressure of carbon dioxide (pCO2) and pH.* *(At least two of the four Sub-Variables are needed.*)	From 25 km to 300 km (25 km near boundaries to capture western and eastern boundary currents; across interior, 300 km)	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/Argo floats/AOVs
	Subsurface transient Tracers	From 25 km to 300 km (25 km near boundaries to capture western and eastern boundary currents; across interior, 300 km)	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships (GO-SHIP) /Moorings

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	**Meridional**	**Vertical**	**Temporal**	
	Subsurface temperature	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/Argo floats/AOVs
	Subsurface salinity	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/Argo floats/AOVs
	Subsurface dissolved oxygen	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/Argo floats/AOVs
	Subsurface nutrients	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/Argo floats/AOVs
Natural decadal variability in oxygen and nitrogen biogeochemical cycles;	Oxygen	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Continuous , minimum : Monthly w ith mooring maintenanc e ?	Ships/Moorings/Argo floats/AOVs
	Transient tracers	Near boundaries to capture	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Annual ?	Ships

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	**Meridional**	**Vertical**	**Temporal**	
Biogeochemical response to climate change		currents, upwelling and OMZ				
	Nutrients	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly w ith mooring maintenanc e ?	Ships/*Moorings/BGC Argo floats/AOVs*
	Particulate matter	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Continuous , minimum : Monthly w ith mooring maintenanc e ?	Satellite/Ships/Moorings /BGC Argo floats/AOVs
	Dissolved organic carbon (D)	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly w ith mooring maintenanc e ?	Ships
	Microbe biomass and diversity (emerging EOV)	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly w ith mooring maintenanc e ?	Ships/Moorings
	Nitrous oxide	Near boundaries to capture currents,	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly w ith mooring maintenanc e ?	Ships

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
		upwelling and OMZ				
Biochemistry of the Tropical Atlantic Variability a) OMZs b) Upwelling Zones **c)** LMEs	Oxygen (open ocean)	1/4° (merged analysis)	1/4° (merged analysis)	10m (0-1000m)	Weekly	Ships/Moorings/Argo floats/AOVs
	Oxygen (shelf and coastal)	1/10° (merged analysis)	1/10° (merged analysis)	10m (0-200m)	Weekly	Ships/Moorings/AOVs
	Nutrients (open ocean)	1/4° (merged analysis)	1/4° (merged analysis)	0m (0-1500m)	Weelly	Ships/*Moorings/Argo floats/AOVs*
	Nutrients (shelf and coastal)	1/10° (merged analysis)	1/10° (merged analysis)	10m (0-200m)	Weekly	Ships/*Moorings/Argo floats/AOVs*
Fish Stock Assessment	Fish abundance	Distribution area	Distribution area	NA	Annual	Commercial fisheries, Scientific surveys (hydroacoustic and trawl surveys)
	Fish growth	Distribution area	Distribution area	NA	Annual, multiannua l	Tagging experiments, Age and length readings from commercial fisheries, market sampling or scientific surveys (hydroacoustic and trawl surveys)
	Fish recruitment	Distribution area	Distribution area	NA	Annual, half-yearly	Ichthyoplankton-Surveys, juvenile surveys
	Fish distribution	Dependent on the area	Dependent on the area	Dependent on the area	Annual, multiannua l	Commercial fisheries, Scientific surveys (hydroacoustic and trawl surveys)
	Fishing effort	Distribution area	Distribution area	NA	Daily	Commercial fisheries
	Fish catch	Distribution area	Distribution area	NA	Daily	Commercial fisheries

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Sea surface temperature	Distribution area	Distribution area	Surface	Monthly	Satellites/ Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
	Subsurface temperature	Distribution area	Distribution area	Full depth	Monthly	Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
	Sea surface salinity	Distribution area	Distribution area	Surface	Monthly	Satellites/ Ships/Drifters/Argo/Moorings/XCTDs/AOVs
	Subsurface salinity	Distribution area	Distribution area	Full depth	Monthly	Ships/Drifters/Argo/Moorings/XCTDs/AOVs
	Dissolved oxygen	Distribution area	Distribution area	Full depth	Monthly	Ships/Moorings/BGC Argo floats/AOVs
	Dissolved inorganic carbon	Distribution area	Distribution area	Full depth	Monthly	Ships/BGC Argo floats/AOVs
	Nutrients	Distribution area	Distribution area	Full depth	Monthly	Ships/BGC Argo floats/AOVs
	Phytoplankton	Distribution area	Distribution area	0-500 m	Monthly	Satellites/Ships
Sea level	Sea surface height (basin-scale)	100 km	100 km	Surface	Monthly	Satellites/Tide gauges/ Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
	Sea surface height (variability of the circulation)	100 km	100 km	Surface	Weekly	Satellites/Tide gauges/ Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
	Sea surface height (fronts/eddies/tropical instablity waves)	10 km	10 km	Surface	Weekly	Satellites/Tide gauges/ Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
	Sea surface height (extreme events)	10 km	10 km	Surface	Hourly	Satellites/Tide gauges/ Ships/Drifters/Argo/Mo

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
						orings/XBTs/XCTDs/AOVs
	Sea surface height (coastal shelf exchange processes)	10 km	10 km	Surface	Hourly	Satellites/Tide gauges/ Ships/Drifters/Argo/Moorings/XBTs/XCTDs/AOVs
Air-sea fluxes of energy	Sea surface temperature (basin-scale)	100 km	100 m	surface	Hourly	Satellites/Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Sea surface temperature (fronts/eddies/tropical instability waves)	10 km	10 km	surface	Daily	Satellites/ Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Sea surface temperature (coastal shelf exchange processes)	1 km	1 km	surface	Hourly	Satellites/Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Sea surface temperature (upwelling)	10 km	10 km	surface	Weekly	Satellites/Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Sea surface temperature (climate Dynamics)	300 km	300 km	Surface	Monthly	Satellites/Ships/Moorings/Argo floats/Drifters/XBTs/XTCDs/AOVs
	Sea surface salinity	25 km	25 km	surface	Daily	Satellites/ Ships/Moorings/Argo floats/XCTDs/AOVs
	Subsurface salinity	25 km	25 km	10-20m upper 300m	Daily	Ships/Moorings/Argo floats/XCTDs/AOVs
	Surface currents	25 km	25 km	Surface	Daily	Satellite/Moorings/Argo floats/Drifters/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Subsurface currents	25 km	25 km	10-20 m over the vertical extent of currents	Daily	Moorings/Argo floats/AOVs
	Ocean surface stress	25 km	25 km	Surface	Daily	Satellites/ Drifters/Moorings/AOVs
	Wind direction and intensity (near surface)	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/ Moorings/AOVs
	Air temperature (near surface)	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Drifters/AOVs/Reanalyses
	Air pressure (near surface)	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Drifters/AOVs/Reanalyses
	Water vapor (near surface)	25 km	25 km	Surface	Daily	Ships/Moorings/AOVs/ Reanalyses
	Precipitation	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Reanalyses
	Surface radiation budget	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Reanalyses
Heat storage	Subsurface temperature (basin-scale)	300 km	300 km	Full depth	Monthly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Subsurface temperature (water mass variability)	100 km	100 km	10 m	Monthly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Subsurface temperature (stratification)	10 km	10 km	10 m	Weekly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Subsurface temperature (upwelling)	10 km	10 km	1 m	Weekly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	**Meridional**	**Vertical**	**Temporal**	
	Subsurface temperature (mixed layer)	10 km	10 km	1 m	Weekly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
Numerical Weather Prediction and extremes	Sea surface temperature	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Subsurface temperature	25 km	25 km	10-20m upper 300m	Daily	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Sea surface salinity	25 km	25 km	surface	Daily	Satellites/ Ships/Moorings/Argo floats/XCTDs/AOVs
	Subsurface salinity	25 km	25 km	10-20m upper 300m	Daily	Ships/Moorings/Argo floats/XCTDs/AOVs
	Surface currents	25 km	25 km	Surface	Daily	Satellite/Moorings/Argo floats/Drifters/AOVs
	Subsurface currents	500 km along equator & coastal wave guides, 100-200 km across currents	500 km along equator & coastal wave guides, 100-200 km across currents	10-20 m over the vertical extent of currents	Daily	Moorings/Argo floats/AOVs
	Sea surface height	25 km	25 km	Surface	Daily	Satellites
	Ocean surface stress	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/ Moorings/AOVs
	Inorganic Carbon	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/AOVs
	Ocean surface heat flux	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/AOVs
	Wind direction and intensity (near surface)	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/ Moorings/AOVs
	Air surface pressure	25 km	25 km	Surface	Daily	Ships/Drifters/Moorings/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Water vapor (near surface)	25 km	25 km	Surface	Daily	Ships/Drifters/Moorings/AOVs
	Air temperature (near surface)	25 km	25 km	Surface	6 hourly	Satellites/ Drifters/Moorings/AOVs
	Surface radiation budget	25 km	25 km	Surface	6 hourly	Satellites/Ships/Drifters/ Moorings/AOVs
	Precipitation (near surface)	25 km	25 km	Surface	6 hourly	Satellites/Ships
	3D wind (air column)	25 km	25 km	1 km	2xDaily	Ships
	Air Temperature (air column)	25 km	25 km	1 km	2xDaily	Ships
	Water vapor (air column)	25 km	25 km	1 km	2xDaily	Ships
	Cloud properties	25 km	25 km	1 km	2xDaily	Satellites/Ships
	Aerosol properties	25 km	25 km	1 km	2xDaily	Satellites/Ships
Operational prediction and monitoring of tropical Atlantic climate on seasonal-to-decadal timescale	Sea surface temperature	25 km	25 km	Surface	Daily	Satellites/ Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Subsurface temperature	100 km	100 km	300m 20-50m from 300-500m	Weekly Monthly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
		2°	2°	50-100m from 500-2000m	Monthly	Ships/Moorings/Argo floats/XBTs/XCTDs/AOVs
	Sea surface salinity	25 km	25 km	Surface	Daily	Satellites/ Ships/Moorings/Argo floats/Drifters/XCTDs/AOVs
	Subsurface salinity	25 km	25 km	10-20m upper 300m	Weekly	Ships/Moorings/Argo floats/XCTDs/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Surface currents	25 km	25 km	Surface	Daily	Satellites/Ships/Moorings/Argo floats/Drifters/AOVs
	Subsurface currents	500 km along equator & coastal wave guides, 100-200 km across currents	500 km along equator & coastal wave guides, 100-200 km across currents	10-20 m over the vertical extent of currents	Daily	Ships/Moorings/Argo floats/Drifters/AOVs
	Sea surface height	25 km	25 km	Surface	Daily	Satellites/ Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Ocean color	25 km	25 km	Surface	Daily	Satellites
	Ocean surface heat flux	25 km	25 km	Surface	Daily	Satellites/ Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Ocean surface stress	25 km	25 km	Surface	6 hourly	Satellites/Ships/Moorings/Argo floats/Drifters/AOVs/Reanalyses
	Surface wind direction and intensity	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/ Moorings/AOVs/Reanalyses
	Surface radiation budget	100 km	100 km	Surface	Weekly	Satellites/Ships/Drifters/ AOVs
	Cloud properties	100 km	100 km	Tropospheric column	Weekly	Satellites/Ships
	Aerosol properties	100 km	100 km	Tropospheric column	Weekly	Satellites/Ships

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
	Carbon Dioxide, Methane and other Greenhouse gases	100 km	100 km	Tropospheric column	Monthly	Satellites/Ships
Vertical momentum transport in the equatorial Atlantic troposphere	3D wind	10 km	10 km	10 m	Hourly	Satellites/Ships/Airplanes
	Sea surface temperature	10 km	10 km	10 m	Hourly	Satellite/Ships/Moorings/Drifters/Argo floats/XBTs/AOVs
Winds along the southwest African coast and their response to underlying SST	Surface wind direction and intensity	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/Moorings/AOVs/Reanalyses
	Ocean surface stress	25 km	25 km	Surface	Daily	Satellites/Ships/Drifters/Moorings/AOVs/Reanalyses
	Sea surface temperature	25 km	25 km	Surface	Daily	Satellite/Ships/Moorings/Argo floats/XBTs/AOVs
	Subsurface temperature	25 km	25 km	10-20m upper 300m 20-50m from 300-500m 50-100m from 500-2000m 100-200m below 2000m	Monthly	Ships/Moorings/Argo floats/XBTs/AOVs
Tropical Atlantic long-term changes	Sea surface temperature	100 km	100 km	Surface	Monthly	Satellite/Ships/Argo floats/Moorings/Drifters/XBTs/AOVs
	Subsurface temperature	100 km	100 km	10-20m upper 300m 20-50m from 300-500m	Monthly	Ships/Argo floats/Moorings/Drifters/XBTs/AOVs

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
				50-100m from 500-2000m 100-200m below 2000m		
	Sea surface salinity	100 km	100 km	Surface	Monthly	Satellite/Ships/Argo floats/Moorings/Drifters /XCTDs/AOVs
	Subsurface salinity	200 km	200 km	10-20m upper 300m 20-50m from 300-500m 50-100m from 500-2000m 100-200m below 2000m	Monthly	Ships/Argo floats/Moorings/Drifters /XCTDs/AOVs
	Ocean surface stress	100 km	100 km	Surface	Monthly	Satellites/Ships/Moorings/Drifters/AOVs
	Ocean surface heat flux	100 km	100 km	Surface	Monthly	Satellites/Ships/Moorings/Drifters/AOVs
	Surface currents	100 km	100 km	Surface	Monthly	Satellites/Ships/Moorings/Drifters/AOVs
	Subsurface currents	100 km	100 km	50-100 m upper ocean; 300 m deep ocean; surface and 1000m across interior	Monthly	Ships/ Moorings/Drifters/AOVs
	Sea surface height	25 km	25 km	Surface	Monthly	Satellites/ Ships/Moorings/Argo floats/Drifters/XBTs/XCTDs/AOVs
	Ocean surface heat flux	25 km	25 km	Surface	Monthly	Satellites/ Ships/Moorings/Argo

Phenomena	Essential Variables (EOVs, ECVs)	Resolution				Platforms (one or more)
		Zonal	Meridional	Vertical	Temporal	
						floats/Drifters/XBTs/XCTDs/AOVs
	Ocean surface stress	25 km	25 km	Surface	Monthly	Satellites/Ships/Moorings/Argo floats/Drifters/AOVs/Reanalyses
	Precipitation	100 km	100 km	Surface	Monthly	Satellites/Ships
	Surface radiation budget	100 km	100 km	Surface	Monthly	Satellites/Ships/Drifters/AOVs
	Air surface pressure	100 km	100 km	Surface	Monthly	Ships/Drifters/Moorings/AOVs
	Water vapor (near surface)	100 km	100 km	Surface	Monthly	Ships/Drifters/Moorings/AOVs
	Air temperature (near surface)	100 km	100 km	Surface	Monthly	Satellites/ Drifters/Moorings/AOVs
	Surface radiation budget	100 km	100 km	Surface	Monthly	Satellites/Ships/Drifters/Moorings/AOVs
	Aerosol properties (including dust originating over land)	100 km	100 km	Tropospheric column	Monthly	Satellites/Ships
	Cloud properties	100 km	100 km	Tropospheric column	Monthly	Satellites/Ships
	Carbon Dioxide, Methane and other Greenhouse gases	100 km	100 km	Tropospheric column	Monthly	Satellites/Ships

Appendix 3: Terms of Reference

1. Review and articulate the existing and anticipated future drivers for the Tropical Atlantic Observing System, encompassing research, operational, and societal applications. Key applications to be considered include: research on tropical Atlantic circulation and variability, coupled atmosphere-ocean variability and change, climate monitoring, modelling and forecasting (climate, ocean, seasonal to decadal and weather prediction), biogeochemistry, and fisheries.
2. Evaluate (review/assess/prioritize) existing and potential requirements for sustained observations of essential ocean variables (EOVs) in the tropical Atlantic Ocean (extending from 25°N to 25°S) - in connection with TPOS2020 and IndOOS - and update them to reflect new knowledge and identified needs for scientific and societal applications.
3. Evaluate the adequacy of existing observing strategies to deliver requirements for variables, and characterize their impacts. Characterize how in situ (e.g., PIRATA, Argo, drifters, and other data) and remote sensing observing systems are contributing to meet these scientific and functional requirements, and identify gaps, inefficiencies, and vulnerabilities.
4. Provide recommendations on the current suite and configuration of observing systems to enhance their resilience and robustness in order to produce data in the most cost-efficient and sustainable manner within the anticipated envelope of capability and resources.
5. Identify potential enhancement or reconfiguration of the sustained observing system suite to address gaps and new requirements.
6. Evaluate requirements for delivery of data, and derived products and information, in real time and delayed mode (e.g., availability, quality, latency, integration/interoperability); evaluate the existing data systems for fitness for purpose.
7. Assess readiness of new technologies, their potential impact and feasibility in addressing requirements, and their potential to contribute towards addressing gaps, improving robustness/resilience, and/or lowering costs per observation in the tropical Atlantic Ocean region; recommend new technologies with greatest potential to meet critical requirements and suggest approaches to improve the readiness for inclusion in the sustained observing system.
8. Highlight the impacts of the tropical Atlantic observing system on the delivery of information/services of societal importance and relevance. Develop a report of the first TAOS Workshop, with recommendations on the development of a process for the ongoing evaluation of the observing system.

Appendix 4: List of Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
ADCP	Acoustic Doppler Current Profiler
AEROSE	Saharan Dust AERosols and Ocean Science Expeditions
AGU	American Geophysical Union
AMM	Atlantic Meridional Mode
AMMA	African Monsoon Multidisciplinary Analyses
AMOC	Atlantic Meridional Overturning Circulation
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AMSU	Advanced Microwave Sounding Unit
AMV	Atlantic Multidecadal SST Variability
ARP	CLIVAR Atlantic Region Panel
ARs	Atmospheric Rivers
ASCAT	Advanced Scatterometers
AST	Argo Steering Team
ASVs	Autonomous Surface Vehicles
ATLAFCO	Ministerial Conference on Fisheries Cooperation Among African States Bordering the Atlantic Ocean
AtlantOS	Optimising and Enhancing the Integrated Atlantic Ocean Observing Systems
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AZM	Atlantic Zonal Mode
BCC	Benguela Current Commission
BGC	Biogeochemical
CCLME	Canary Current Large Marine Ecosystem
CCMP	Cross-Calibrated Multi-Platform Wind
CERES	Clouds and the Earth’s Radiant Energy System
CFOSAT	Chinese-French Oceanography Satellite
CIMR	Copernicus Imaging Microwave Radiometer
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMEMS	Copernicus Marine Environmental Monitoring Service

CMIP	Coupled Model Intercomparison Project
CNRS	Centre National de la Recherche Scientifique
COD	Climate Observations Division, NOAA
CTD	Conductivity, Temperature, and Depth
CTDO2	Coriolis-Temps Différé Observations Océaniques
CPTEC	Centro de Previsão do Tempo e Estudos Climáticos
CVOO	Cape Verde Ocean Observatory
CYGNSS	Cyclone Global Navigation Satellite System
DBCP	Data Buoy Cooperation Panel
DHN	Diretoria de Hidrografia e Navegacão
DIC	Dissolved Inorganic Carbon
DWBC	Deep Western Boundary Current
EAF	Ecosystem Approach to Fisheries Management
EBAF	Energy Balanced and Filled
ECMWF	European Centre for Medium-Range Weather Forecasts
ECVs	Essential Climate Variables
EEZ	Exclusive Economic Zone
EGEE	Gulf of Guinea climate and ocean circulation study
EGU	European Geosciences Union
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
EOVs	Essential Ocean Variables
ERDDAP	Environmental Research Divisions Data Access Program, NOAA
ERS	European Remote sensing Satellite
ESA	European Space Agency
FAIR	Findable, Accessible, Interoperable, and Reusable
FAO	Food and Agriculture Organization
fCO_2	fugacity of CO_2
FCWC	Fisheries Committee for the West Central Gulf of Guinea
FRMs	Fiducial Reference Measurements
FSO	Forecast Sensitivity to Observation
GCLME	Guinea Current Large Marine Ecosystem
GCOM	Global Change Observation Mission

GCOS	Global Climate Observing System
GDAC	Global Data Assembly Center
GDP	Global Drifter Program
GEO	Group on Earth Observations
GEOMAR	GEOMAR Helmholtz Centre for Ocean Research Kiel
GHRSST	Group for High Resolution Sea Surface Temperature
GODAS	Global Ocean Data Assimilation System
GOES	Geostationary Operational Environmental Satellite
GOMO	Global Ocean Monitoring and Observing program, NOAA
GOOS	Global Ocean Observing System
GOSUD	Global Ocean Surface Underway Data
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GTS	Global Telecommunications System
HOAPS	Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICES	International Council for the Exploration of the Sea
IFREMER	The Institut français de recherche pour l'exploitation de la mer
IMBeR	Integrated Marine Biosphere Research
IndOOS	Indian Ocean Observing System
INPE	Instituto Nacional de Pesquisas Espaciais
IOC	Intergovernmental Oceanographic Commission of the UNESCO
IOCCP	International Ocean Carbon Coordination Project
IODE	International Oceanographic Data and Information Exchange
IPCC AR5	The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
IR	Infrared Radiometers
IRD	French Institut de Recherche pour le Développement
ISRO	Indian Space Research Organisation
ISCCP	International Satellite Cloud Climatology Project
ITCZ	Inter Tropical Convergence Zone
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAXA	Japan Aerospace Exploration Agency

JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JCOMMOPS	WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology in situ Observations Programme Support Centre
J-OFURO	Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations
LACPD	Lowered-ADCP
LMD/ENS	Laboratoire de Météorologie Dynamique at the Ecole Normale Supérieure
LME	Large Marine Ecosystem
M-AERI	Marine-Atmospheric Emitted Radiance Interferometer
MDR	Main Development Region
MERIS	MEdium Resolution Imaging Spectrometer
MJO	Madden-Julian Oscillation
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVE	Meridional Overturning Variability Experiment
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NDBC	National Data Buoy Center
NEB	Brazilian Northeast
NetCDF	Network Common Data Form
NHC	National Hurricane Centre
NOAA	National Oceanic and Atmospheric Administration
NOBM	NASA Ocean Biogeochemical Model
NTAS	Northwest Tropical Atlantic Station
NW	Northwestern
NWP	Numerical Weather Prediction
OAFlux	Objectively Analyzed air-sea Fluxes
OAR	Oceanic and Atmospheric Research, NOAA
OC CCI	Ocean Color Climate Change Initiative
OHF/MPE	Ocean Heat Flux/Multi-Product Ensemble
OLR	Outgoing Longwave Radiation
OMZs	Oxygen Minimum Zones
OOPC	Ocean Observations Physics and Climate Panel, GCOS

OSCAT	Oceansat-2 Scatterometer
OSE	Observing System Experiment
OSNAP	Overturning in the Subpolar North Atlantic Program
OSSE	Observing System Simulation Experiment
OSTM	Ocean Surface Topography Mission
OTN	Ocean Tracking Network
pCO_2	pressure of Carbon Dioxide
pH	Potential of Hydrogen
PIRATA	Prediction and Research Moored Array in the Tropical Atlantic
PMW	Passive Microwave
PRB	PIRATA Resources Board
PREFACE	Enhancing Prediction of Tropical Atlantic Climate and its Impacts
PSD	Physical Sciences Division, NOAA
RACE	Regional Atlantic Circulation and Global Change
RAPID-AMOC	Rapid Climate Change - Atlantic Meridional Overturning Circulation Programme
RCP4.5	Representative Concentration Pathway at +4.5 W m^{-2}
RI	Rapid Intensification
SACUS	Southwest African Coastal Upwelling System
SAMOC	South Atlantic Meridional Overturning Circulation
SAR	Search and Rescue
SARAL	Satellite with ARgos and ALtiKa
SE	Southeastern
SIO	Scripps Institution of Oceanography, USA
SKIM	Sea surface KInematics Multiscale monitoring
SLSTR	Sea and Land Surface Temperature Radiometer
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling
SOLAS	Surface Ocean - Lower Atmosphere Study
SOOP	Ship of Opportunity
SPURS	Salinity Processes in the Upper Ocean Regional Study
SRFC	Sub Regional Fisheries Commission
SSG	Scientific Steering Group

SSH	Sea Surface Height
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager Sounder
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STC	Subtropical Cell
SVP	Surface Velocity Programme, NOAA
SWOT	Surface Water Ocean Topography
TA	Tropical Atlantic
TACE	CLIVAR Tropical Atlantic Climate Experiment
TACOS	Tropical Atlantic Currents Observations Study
TAOS	Tropical Atlantic Observing System
TAV	Tropical Atlantic Variability
TC	Tropical Cyclone
TIWs	Tropical Instability Waves
TMI	TRMM Microwave Imager
TOA	Top-of-Atmosphere
TOR	Terms of Reference
TPOS	Tropical Pacific Observing System
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIIRS	Visible Infrared Imaging Radiometer Suite
VOS	Voluntary Observing Ship
VREs	Virtual Research Environments
WAM	West African Monsoon
WBCS	Western Boundary Circulation System
WCRP	World Climate Research Programme
WES	Wind-Evaporation-SST
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
XBT	Expendable Bathythermograph

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