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CLIVAR Exchanges

Special Issue: Tropical Atlantic Ocean Observing System (TAOS)

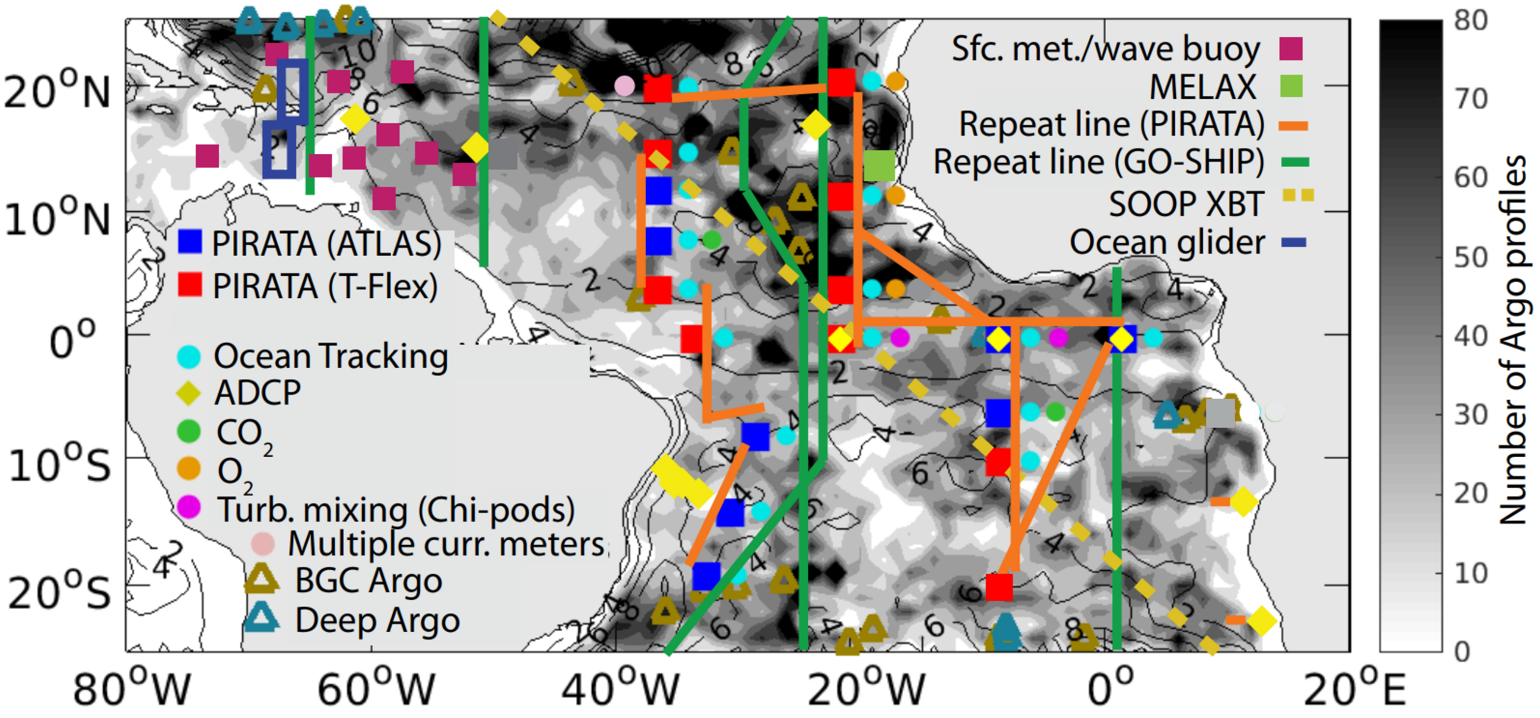

Figure provided by G. Foltz

World Climate Research Programme

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CLIVAR (Climate and Ocean: Variability, Predictability and Change) is the World Climate Research Programme's core project on the Ocean-Atmosphere System

Editorial

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The tropical Atlantic influences the weather, climate, ecosystems, and economy of its bordering regions, and it also regulates larger-scale phenomena affecting the North Atlantic and other tropical regions. The tropical Atlantic also connects the Atlantic meridional overturning with the global ocean circulation and receives freshwater input from some of the world's largest rivers. In an era where climate change is accelerating, and its impacts are becoming more and more impactful and threatening, in particular for tropical regions, there is more than ever a critical need for sustained observations of environmental variables within the Tropical Atlantic. Observations underpin all weather, climate, water, and ecosystem services and products. Without collecting and sharing these observations, the ability to understand, predict, mitigate, and adapt to changes in the climate system is limited.

This has been the basis for developing the Prediction and Research Moored Array in the tropical Atlantic (PIRATA; Bourlès et al. 2008) which started in 1997. PIRATA, which has evolved over the years to address the most critical outstanding scientific questions and to improve predictions, is now the backbone of the tropical Atlantic Observing System (TAOS). TAOS is motivated by goals intended to improve forecasts of phenomena going from weather and extremes predictions to tropical Atlantic interannual to decadal variability and climate change; multidecadal variability and its links to the meridional overturning circulation; air-sea fluxes of CO_2 and their implications for the fate of anthropogenic CO_2; the Amazon River plume and its interactions with biogeochemistry, vertical mixing, and hurricanes; the highly productive eastern boundary and equatorial upwelling systems; and oceanic oxygen minimum zones, their impacts on biogeochemical cycles and marine ecosystems, and their feedbacks to climate.

The past success of the tropical Atlantic observing system results from an international commitment to sustained observations and scientific cooperation, a willingness to evolve with changing research and monitoring needs, and a desire to share data openly with the scientific community and operational centers. The observing system must continue to evolve in order to meet an expanding set of research priorities and operational challenges. This collection of articles discusses the tropical Atlantic observing system, including emerging scientific questions that demand sustained ocean observations, the potential for further integration of the observing system, and the requirements for sustaining and enhancing the tropical Atlantic observing system.

TAOS was last reviewed in 2006 by CLIVAR and GOOS through OOPC (Ocean Observations Panel for Climate), primarily focusing on PIRATA. 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 also evolved since 2006, as well as the TAOS observing system itself. From 2018 to 2020, a new TAOS review was proposed and organized by ARP in close cooperation with the PIRATA consortium. The purpose of the review was to assess and evaluate scientific progress since 2006 and to recommend actions to advance sustained observing efforts in the Tropical Atlantic (Johns et al. 2021).

This special issue of CLIVAR Exchanges on TAOS, based on its 10-year review, aims to disseminate the important findings from the TAOS review report more widely and highlight the societal relevance of TAOS.

Description of the articles

The special issue of Exchanges contains ten articles documenting the history and current status of TAOS, the key science and operational driver, as well as the recommendations for future TAOS development derived from the TAOS Review report.

The first article is an introduction to TAOS, provided by Speich et al., to briefly describe the development, composition and current status of TAOS; its societal relevance in terms of operational services, ocean health and fisheries, climate variability and change and research and discovery; as well as a summary of the key science and operational drivers for TAOS.

Theme 1 Lübbecke et al. provide an overview of the climate dynamics and variations in the tropical Atlantic, including the Atlantic Zonal Mode, Atlantic Meridional Mode, Benguela Niño, Mesoscale and Intraseasonal Variability, Interbasin linkages, which are partly internal to the tropical Atlantic, but also interact with extra-tropics and the other ocean basins.

Theme 2 Rodrigues and Rodriguez-Fonseca review the impacts of tropical Atlantic variabilities on different regions, including the West African monsoon (WAM) system, South America, the Caribbean, Central and North America, as well as the northern mid- and high- latitudes, and identify the observational requirements for understanding and prediction of those impacts.

Theme 3 Hummels et al. discuss the motivation for studying the AMOC in the Tropical Atlantic, reviews the current AMOC observations in the Atlantic along 16°N and 11°S, and provide the recommendations for sustained AMOC observations in the tropical Atlantic.

Theme 4 Cotrim Da Cunha documents the biogeochemical processes in the tropical Atlantic Ocean, including the carbon system, processes that control the dissolved oxygen and nutrient distribution, ecosystem dynamics and fisheries, etc. She also identifies the observational needs required for understanding the various biogeochemical processes and phenomena in the tropical Atlantic.

Theme 5 Schmidt et al. provide an overview of major initiatives and programmes of ecosystem and fisheries observing systems in the tropical Atlantic and highlight the capacity development needs of these systems.

Theme 6 Balmaseda et al. highlight the importance of *in situ* observations for operational seamless forecasting systems, especially for enabling reanalysis, forecast calibration and detection/prediction of extremes. The observational requirements for modelling and initializing the relevant complexity of the tropical Atlantic in the context of seamless predictions are listed.

Theme 7 Keenlyside and Richter describe the current skill in predicting tropical Atlantic climate on seasonal-to-decadal (S2D) timescales and review the elements of the TAOS crucial for monitoring the state of the tropical Atlantic and its prediction on S2D time scales.

Theme 8 Keenlyside and Richter summarize observed and projected long-term changes in the tropical Atlantic Ocean and discusses some of the important impacts. They also discuss the enhancements of TAOS required to reduce uncertainties in climate change consequences in the tropical Atlantic and its impacts.

Theme 9 Foltz et al. provide the future perspectives of TAOS by illustrating the general recommendations to better address the science and operational drives, and the specific recommendations for the enhancement of different components of TAOS, data flow and information products, as well as governance, review and resourcing.

Conclusions and the way forward

This review and call for establishing a fit-for-purpose TAOS come at a time of new and active pan-Atlantic international cooperation in ocean and science, focused on ocean observations and forecasts at multiple levels, to provide the ocean information essential for human wellbeing and safety, sustainable development, constructive management of ocean ecosystems, fisheries, and coastal hazards, and a sustainable blue economy in a changing world.

To encourage the broadest possible participation in building an expanded and more fit-for-purpose TAOS, the review report does not provide a prioritization of the recommendations. Different national and international organizations, agencies, and nations might want to focus on a subset of them that address their own priorities.

Also, the recent TAOS review conducted during 2018-2020 summarized in this special issue, reflects only the current understanding of TAOS' science and societal drivers. Regular reviews of TAOS are recommended approximately once per decade to provide a basis for evaluation of the state of TAOS and to determine the most efficient and effective observational solutions to support prediction systems for the ocean, weather and climate services to the benefit of society and the environment in which we live.

An Introduction to the Tropical Atlantic Ocean Observing System: Past and Present

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The Tropical Atlantic Observing System (TAOS) is a network of sustained observations that is crucial for forecasting and monitoring of weather, ocean, and climate and advancing scientific knowledge. The goal of TAOS is to provide sustained high-quality oceanographic and meteorological measurements that support knowledge-based decision-making and policy development. TAOS is supported by various national agencies and coordinated internationally under the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS) and the CLIVAR-Atlantic Regional Panel (ARP) programs. ARP and GOOS are made up of international groups of scientists and science leaders from countries and institutions within and outside the Atlantic Ocean region. These scientific organizations have a commitment to sustained observations, with ARP focusing in particular on the Atlantic Ocean.

TAOS was last reviewed in 2006 by CLIVAR and GOOS through OOPC (Ocean Observations Panel for Climate), with a primary focus on the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA; Bourlès et al. 2008). 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 as well as the TAOS observing system.

In 2018 a new TAOS review was proposed and organized by ARP in close cooperation with the PIRATA consortium. The purpose of the review was to evaluate scientific progress since 2006 and to recommend actions to advance sustained observing efforts in the Tropical Atlantic (Johns et al. 2021).

The Tropical Atlantic Observing System

The tropical Atlantic, a small basin compared to the tropical Pacific and Indian Oceans, interacts closely with the continental regions that border it, strongly influencing their weather and climate (Fig. 1). At the same time, despite its relatively small size, the tropical Atlantic plays a major role in the global climate system. The Atlantic Meridional Overturning Circulation (AMOC) transports nearly half a petawatt of energy from the Southern Hemisphere to the Northern Hemisphere, and it has a marked, though still poorly understood, impact on variations in the Atlantic and other parts of the globe.

All countries bordering the tropical Atlantic experience important societal challenges driven by regional ocean processes and ocean-atmosphere-land interactions. These are exacerbated by climate change, which induces new emerging threats. 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 (Elsner et al. 2008; Balaguru et al. 2018), and continuing sea-level rise that increases the risk of flooding and coastal erosion. 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 security (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 significant role in mid- and high-latitude climatic events including the occurrence of impactful

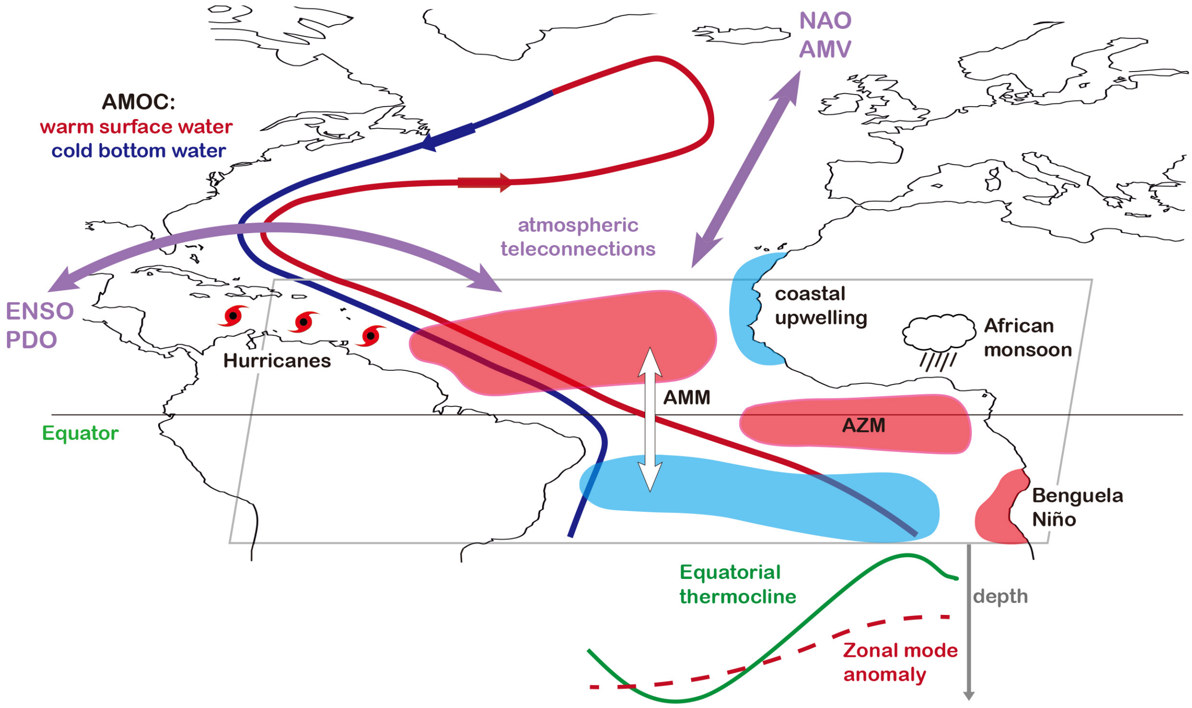

Figure 1. *Important processes and modes of interannual variability in the tropical Atlantic. AMM: Atlantic Meridional Mode; AZM: Atlantic Zonal Mode (or Atlantic Niño); AMOC: Atlantic Meridional Overturning Circulation; ENSO: El-Niño/Southern Oscillation; PDO: Pacific Decadal Oscillation; NAO: North Atlantic Oscillation; AMV: Atlantic Multidecadal Variability.*

extremes throughout the year (Ole Wulff et al. 2017).

To address this broad spectrum of interconnected scientific and societal imperatives, a diverse network of ocean observations and forecasts systems have been developed, building on the PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) network (Bourlès et al. 2019; Foltz et al. 2019). The emergence of a tropical Atlantic observing system can be dated to 1997, with the deployment of the first elements of the PIRATA array (Servain et al. 1998).

Drawing on PIRATA, the subsequent decades have witnessed an explosion in our knowledge of the tropical Atlantic Ocean: its modes of variability and the processes that govern them, its interactions with the atmosphere, its contributions - realized and potential - to improved weather and climate forecasts, its physical and biogeochemical impacts in the global climate system, and its importance for fisheries that are vital to the livelihoods of millions of people on its shores. Among these are an improved understanding of mixed layer heat and freshwater budgets, equatorial and tropical circulations, influence of the tropical Atlantic on 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, oxygen minimum zone dynamics and changes, fisheries variability and evolution, as well as how the tropical Atlantic influences interannual modes of tropical Pacific and Indian Ocean variability and North Atlantic and European extreme precipitation events. Moreover, TAOS observations have been proven necessary for the generation, calibration, and validation of various satellite and/or *in situ* data products. TAOS buoys and cruises 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, and NCEP) in addition to classical meteorological data (provided regionally also by TAOS). Great strides have also been made in coordinating this science among nations and stakeholders.

These advances have been due in part to an expansion of TAOS. 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. 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 ongoing European projects (e.g., H2020 projects TRIATLAS, iAtlantic, AtlantEco, and EuroSea) funded under the All-Atlantic Ocean Research Alliance (https://allatlanticocean.org/main), which includes partners across the Atlantic. Fig. 2 provides an overview of the TAOS.

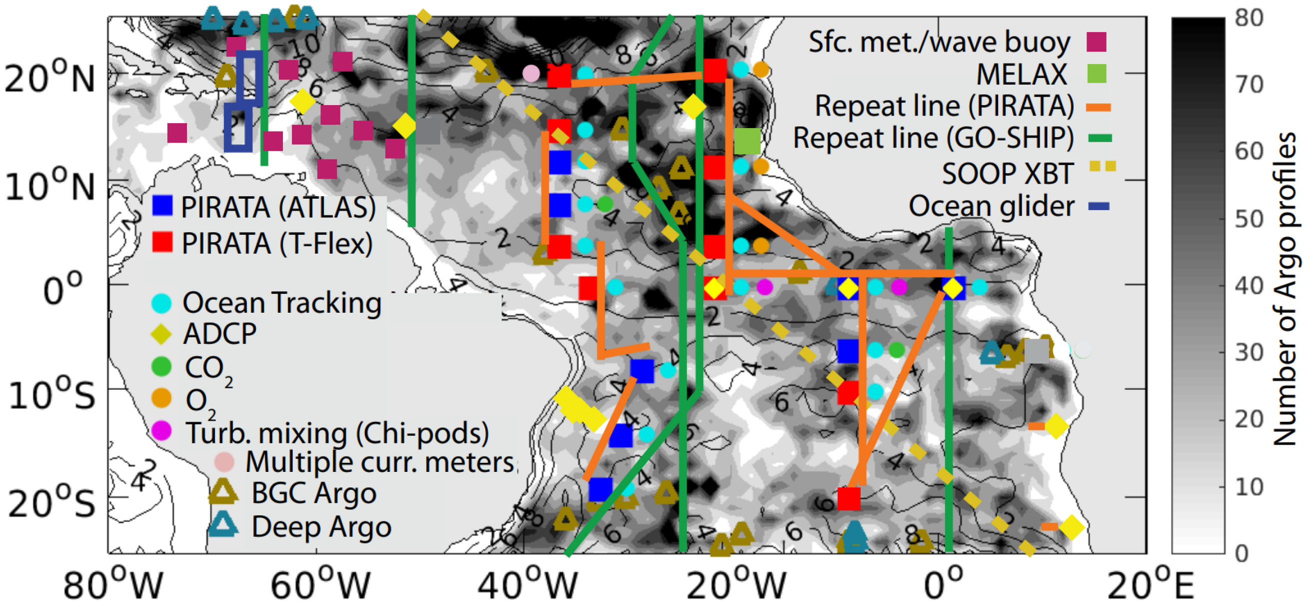

Figure 2. *Key elements of the tropical Atlantic in situ observing system. Gray shading represents the number of Argo profiles made in each 1° box between 2008 and 2017. Contours show the average number of hourly surface drifter observations made in each 1° box per month during 2008-2017. (Figure provided by G. Foltz).*

Scientists involved in TAOS have continuously evolved its structure and function over the 20 years of its existence to address the most important outstanding scientific questions and improve predictions of severe weather in the tropical Atlantic as well as 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 environmental hazards such 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 research to 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 predictions. These gaps cannot be filled by individual nations. The TAOS review was 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 the near future and that can be sustained in the long term under international coordination. It was therefore timely to systematically reassess 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, biology, ecology. The overall aim was to build towards an international ocean observing and forecasting system that is user-focused, truly interdisciplinary, and responsive; 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 and related societal challenges. 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.” TAOS supports the Atlantic

Basin implementation of GOOS, and it contributes to the UN Decade of Ocean Science for Sustainable Development (2021-2030). It is one mechanism to follow up on the recommendations of the OceanObs'19 conference, and it 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).

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 the 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.

Despite these advances in TAOS and its international coordination, recent studies - together with evidence contained within the 2018-2020 TAOS review - consistently show that the existing Tropical Atlantic Observing System is insufficient to ensure skillful predictions across timescales from weather to climate change, and to meet the full range of societal needs. Moreover, the present observing system has significant regional and functional gaps that impede improvements in prediction and in the monitoring of biogeochemistry and marine ecosystems for sustainable management of fisheries and to provide vital information about the regional and global carbon system.

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 economic 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 tropical storms and 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 (Li et al. 2016). All aspects of the tropical Atlantic 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 can lead to enhanced societal benefits. In addition to advancing scientific understanding, the purpose of TAOS is to meet the broad socioeconomic needs of society. The design of the TAOS attempted to recognize the needs of users so that the system is 'fit-for-purpose', cost-effectively providing information that is needed, relevant, and usable. 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 to 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 weather and subseasonal to seasonal predictions of extremes, including 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 for adaptation and services management to a broad spectrum of users, for 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 improve both mitigation and adaptation to climate change as well as climate services. TAOS will help to inform us about how changes in ocean-atmosphere conditions will influence sea-level as well as 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 and uncrewed surface vehicles, for making observations in the paths of hurricanes. New understanding of the ocean circulation has also highlighted links between the deep ocean and climate. Improved numerical modeling techniques have significantly enhanced the quality of ocean and atmospheric forecasts.

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 TAOS is necessary to meet the needs of society. The data from such an observing system will most directly benefit those countries neighboring the tropical Atlantic, helping to improve management of coastal fisheries and ecosystems, forecasting of tropical storms and extreme events, and economic development 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. 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.

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 TAOS was developed to link the observational requirements of the TAOS to the broad societal themes previously introduced. The review committee considered several 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 *CLIVAR Exchange* issue, each of these key drivers and their societal relevance are discussed and potential gaps in information or data related to each one.

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Theme 1: Dynamics of Tropical Atlantic Variability

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1. Atlantic Zonal Mode

Sea-surface temperatures (SSTs) in the eastern equatorial Atlantic are subject to variability that is phase-locked to boreal summer, though there is substantial diversity across events (Valles-Casanova et al. 2020). This variability pattern is referred to as the Atlantic Niño, due to its apparent similarity with El Niño-Southern Oscillation (ENSO) events, but the term Atlantic zonal mode (AZM) is also common and will be used here. Similarities between the AZM and ENSO include the importance of equatorial wind forcing in the western part of the basin and air-sea coupling through the Bjerknes feedback. Figure 1a shows a composite warm event during the peak phase in June-July-August (JJA). SST anomalies are most pronounced in the eastern equatorial Atlantic from 20°W-0 and extend southeastward toward the African coast. Westerly wind anomalies are observed over the western equatorial Atlantic, but they are substantially weaker than in the developing phase in boreal spring (see Richter and Tokinaga 2021). Thus, the wind forcing is not very responsive to SST anomalies during the peak phase, indicative of weak ocean-atmosphere coupling. Studies have shown that air-sea coupling is most active when the intertropical convergence zone (ITCZ) is close to the equator in boreal spring (Richter et al. 2017; Nnamchi et al. 2021). As can be seen from Figure 1a, the precipitation anomalies in JJA are mostly north of the equator (including wet anomalies over North Brazil and the Guinea coast), consistent with the mean ITCZ having migrated northward.

Variability in the equatorial Atlantic was relatively low during recent decades (Tokinaga and Xie 2011; Prigent et al. 2020a), which is consistent with the decline projected by climate models under greenhouse gas forcing (Imbol Nkwinkwa et al. 2021; Crespo et al. 2022; Yang et al. 2022). In 2019 and 2021, however, two very pronounced warm events occurred that were likely the strongest during the satellite observation period (Richter et al. 2022). Continued monitoring of the equatorial Atlantic will be important to determine whether the behavior of the equatorial Atlantic is consistent with climate projections.

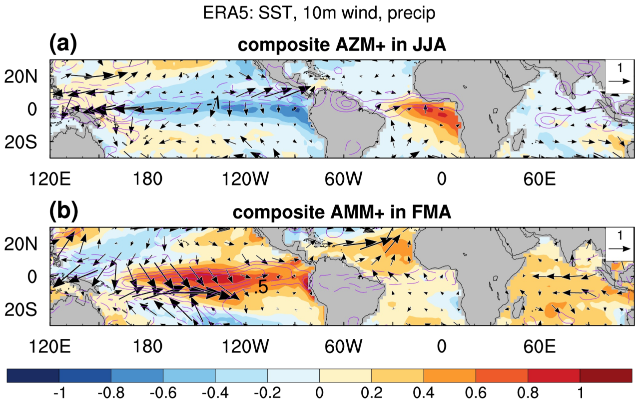

Figure 1. *Anomalies of SST (shading; K), 10m winds (vectors; reference =1 m/s), and precipitation (contours; interval = 0.5 mm/day; negative contours dashed, 0-contour omitted) composited on (a) positive AZM events (years 1984, 1988, 1991, 1995, 1996, 1999, 2007, 2008) averaged over June-July-August, and (b) positive AMM events (years 1979, 1980, 1983, 1988, 1991, 1998, 2010, 2016, 2017) averaged over February-March-April. SST and 10m winds are from the ERA5 reanalysis, precipitation is from GPCP. All anomalies are with respect to the 1988-2017 base period.*

2. Atlantic Meridional Mode

The Atlantic meridional mode (AMM), sometimes described as a dipole, is associated with the cross-equatorial meridional SST gradient between the two hemispheres over the tropical Atlantic. The SST anomalies usually appear with opposite signs in each hemisphere, although their developments are not always simultaneous, and it has been questioned if the northern and southern poles of this dipole dynamically related (Houghton and Tourre 1992; Enfield et al. 1999; Chang et al. 2001). Thermodynamic air-sea interactions represented by the wind-evaporation-SST (WES) feedback is the principal mechanism driving the AMM (Chang et al. 1997, 2000; Chiang et al. 2002; Amaya et al. 2017). During the positive (negative) phase of the AMM, weaker- (stronger-) than-normal northeasterly trade winds are associated with less (more) evaporation and positive (negative) SST anomalies in the tropical North Atlantic. These are linked to stronger- (weaker-) than-normal southeasterly trade winds, more (less) evaporation and negative (positive) SST anomalies in the tropical South Atlantic. A composite AMM event with the associated wind anomalies is shown in Figure 1b. The AMM-type inter-hemispheric SST anomalies significantly affect the position and the intensity of the

ITCZ and thus exert a considerable influence on the precipitation over adjacent continental areas, such as the Brazilian Northeast and the African Sahel (Enfield and Mayer 1997; Kushnir et al. 2006). Positive (negative) SST anomalies in the north (south) tropical Atlantic are associated with an anomalous northward displacement of the ITCZ, leading to drought in Northeast Brazil, and enhanced precipitation in the Sahel. Conversely, SST anomalies during the negative AMM phase displace the ITCZ southward, favoring more precipitation in Northeast Brazil and drought conditions over the Sahel. This scenario is effective when the AMM is particularly pronounced during the typical periods of rainy seasons in Northeast Brazil (February to May) or Sahel (June to September). The AMM, through its influence on vertical wind shear, has also been linked to frequency and intensity of Atlantic hurricane and consequently precipitation over the West Indies and southeast United States (Gray 1990; Kossin and Vimont 2007; Patricola et al. 2014).

3. Benguela Niño

Another El Niño-like phenomenon, closely related to the zonal mode, takes place in the southeastern tropical Atlantic (Shannon et al. 1986). Off the coast of Angola and Namibia, SSTs exceed their climatological value by up to 3^{0}C every few years with strong impacts on the local fisheries (e.g. Binet et al. 2001) and rainfall over Southwestern Africa (Rouault et al. 2009). These so-called Benguela Niños and their cold counterpart, Benguela Niñas, are typically forced by wind anomalies in the western equatorial Atlantic. These generate equatorial Kelvin waves that transmit into coastally trapped waves at the eastern boundary and propagate along the southeastern coast of Africa (Florenchie et al. 2003; Lübbecke et al. 2010; Bachelery et al. 2016; Imbol Koungue et al. 2017). The waves are associated with thermocline depth anomalies that first result in subsurface and eventually surface temperature anomalies. Observations along the Equator and in the southwestern tropical Atlantic as part of the PIRATA array are thus crucial to understand and potentially forecast Benguela Niño and Niña events. In addition, local wind forcing can play an important role in the generation of coastal SST anomalies through anomalous upwelling and heat fluxes between the ocean and the atmosphere (Richter et al. 2010; Lübbecke et al. 2019). Over the last two decades, the SST variability in the Angola Benguela region has decreased due to weaker linkage to the equatorial forcing (Prigent et al. 2020b).

4. Mesoscale and Intraseasonal Variability

The climate modes described above also interact with variability on shorter time and smaller spatial scales, i.e. intra-seasonal and mesoscale variability such as tropical instability waves, inertial waves, coastal trapped waves and mesoscale eddies (e.g.,Weisberg and Weingartner 1988; Jochum et al. 2004). This variability can be generated directly by the wind or through instabilities of the wind-driven currents. Intraseasonal variability influences the interannual time scale (Jochum et al. 2004) and is modulated by the zonal mode (Perez et al. 2012). Of particular relevance in this respect are Tropical Instability Waves (TIWs) in the equatorial Atlantic that are associated with SST anomalies through horizontal advection and vertical mixing and closely coupled to the overlying atmosphere. Intraseasonal Kelvin and coastal trapped waves are also important in the generation of Benguela Niños (Bachelery et al. 2016).

5. Interbasin linkages

SST variability in the tropical Atlantic is connected to the other tropical ocean basins, in particular to ENSO in the tropical Pacific. However, the influence of ENSO on AZM events appears to be inconsistent, the most prominent example being the super El Niño events in 1982 and 1997 being associated with opposite-signed outcomes in the equatorial Atlantic during the following year. This inconsistency has been ascribed to the counteracting thermodynamic and dynamic effects of ENSO on the equatorial Atlantic (Chang et al. 2006), but also to the details of the response in the northern tropical Atlantic (Lübbecke and McPhaden 2012) and the varying persistence of ENSO events (Tokinaga et al. 2019).

As for the impact from the equatorial Atlantic onto ENSO, it has been suggested that AZM events can contribute to opposite-signed ENSO events in the following winter (Rodriguez-Fonseca et al. 2009; Kucharski et al. 2016). The proposed mechanism involves changes in the Walker circulation, which, in the case of positive AZM events, lead to anomalous subsidence and easterly surface winds over the central equatorial Pacific. The composite AZM event (Fig. 1a) shows this association of positive AZM events with La Niña like SST anomalies and easterly wind anomalies in the equatorial Pacific. It has been suggested that this Atlantic influence could add skill to ENSO predictions, provided that the prediction of the equatorial Atlantic is skillful (Keenlyside et al. 2013). It should be noted that the importance of the equatorial Atlantic influences on

ENSO is still under debate, with a recent study suggesting a rather weak influence (Richter et al. 2021). An additional problem in disentangling Atlantic-Pacific interaction is that both ENSO and the AZM tend to develop in boreal spring, making it difficult to assign causality: an ENSO event may have been forced by an incipient AZM event, or vice versa. Thus, there is a need for more modeling and observational studies on the topic.

The equatorial Atlantic may also influence the Indian Summer monsoon through atmospheric Kelvin waves (Pottapinjara et al. 2014). In turn, it has been suggested that the tropical Indian Ocean can trigger AZM events (Liao and Wang 2021; Zhang and Han 2021) through modulation of the Walker circulation.

The AMM is strongly affected by anomalous trade winds, and could be remotely forced by different tropical and extra-tropical teleconnections such as the Pacific–North America (PNA) and Pacific–South America (PSA) patterns. Upper-tropospheric wave trains associated with the PNA and El Niño events (Handoh et al. 2006a,b; Cai et al. 2011) cause upper level divergence over the tropical North Atlantic (TNA) in boreal winter. The meridional pressure gradient decreases at lower levels, weakening the trades and warming TNA through the WES feedback (Amaya and Foltz 2014; Taschetto et al. 2016), corresponding to a positive AMM phase. The link between a positive phase of ENSO and the AMM can be seen in the composite AMM event shown in Fig. 1b. However, the strength and persistence of El Niño events (Lee et al. 2008) as well as the tropical Atlantic mean conditions (Chang et al. 2006a) are crucial to determine the TNA SST response.

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 descending branch over the Amazon region, weakening the north Atlantic Hadley cell, which in turn can trigger a positive phase of the AMM through WES feedback (Wang 2002). The opposite can occur during La Niña events.

El Niño teleconnections in the southern hemisphere are facilitated via PSA wave trains that 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 trade winds. Stronger southerlies can cause cold anomalies over the tropical South Atlantic through the WES feedback, favoring the development of a positive phase of the AMM in boreal spring (Rodrigues et al. 2011). The opposite patterns in PNA and PSA can occur during La Niña events.

Similar to the AZM, the AMM can also influence ENSO via changes in the atmospheric circulation. Cold TNA anomalies during boreal spring have been suggested to contribute to central Pacific warming in the following winter by inducing Pacific wind anomalies and vice versa (Ham et al. 2013) but the importance of this pathway is still under debate (Richter et al. 2021; Zhang et al. 2021).

6. Conclusions

Climate variations in the tropical Atlantic occur on a variety of time scales. They are partly internal to the tropical Atlantic but also interact with the extra-tropics and the other ocean basins. Due to their impact on fisheries and precipitation over the continents it is very important to improve predictions of these variations. This requires a better understanding of tropical Atlantic variability patterns in terms of their underlying mechanisms, their interactions, and their linkages to other basins. To gain further insight into the processes governing climate variability in the tropical Atlantic, sustained observations as part of the Tropical Atlantic Observing System (TAOS) are crucial. Of particular interest are surface and subsurface temperature, salinity, ocean currents, and sea surface height on the oceanic side, and heat fluxes, winds and precipitation on the atmospheric side.

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Theme 2: Impacts of Tropical Atlantic Variability

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Introduction

The tropical Atlantic has an enormous impact on people who live around the ocean and even those who reside far from it (Fig. 1). For example, African and South American countries that border the South Atlantic depend strongly on the sea for societal development, fisheries and tourism. TAV can cause extreme events in these regions, such as droughts, floods, and heatwaves, affecting the water-energy-food security nexus and land and marine biodiversity. The tropical Atlantic also strongly influences the Northern Hemisphere, e.g. in the West African region, USA, the Caribbean and Mexico, most notably because of the enormous impact of tropical cyclones and hurricanes. In the USA alone, hurricanes account for about half of the deaths and economic impacts from weather and climate disasters. Additionally, the tropical Atlantic plays a vital role in modulating global climate and has been, for instance, a key driver of the recent hiatus in global warming. Here we focus on how Tropical Atlantic Variability (TAV) impacts different continental regions. However, it should be noted that the Tropical Atlantic affects other tropical oceans, which have widespread climate influence (Rodríguez-Fonseca et al. 2009; Cai et al. 2019). As such, variability that is intrinsically native to the Tropical Atlantic can influence climate widely via, for example, its effect on the development of El Niño events (see CLIVAR Tropical Basin Interaction Foci for more details). All aspects of the ocean – physical, biogeochemical and biological – impact society.

TAV impact on the West African monsoon (WAM) system

TAV is strongly linked to the West African Monsoon System (WAM). The WAM is characterised by a precipitation dipole pattern with centres 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. 2011, 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 associated with the Atlantic Niño or

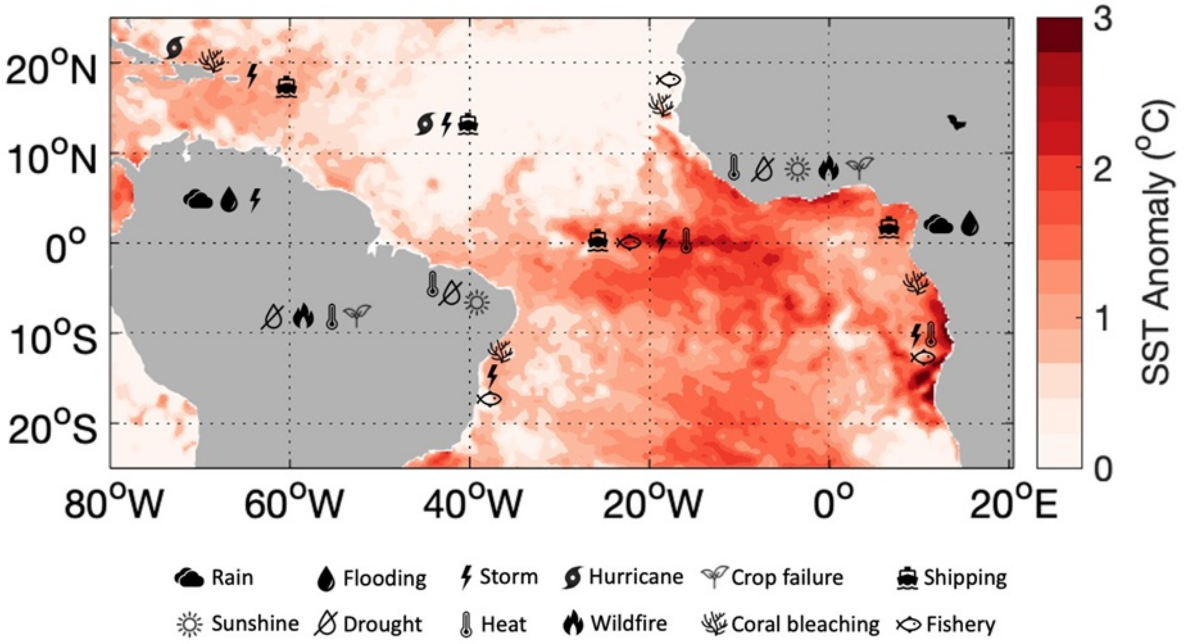

Figure 1. *Main impacts of tropical Atlantic variability and changes on adjacent continents expressed as symbols. In the background, in red colour, Sea Surface Temperature anomalies (SSTA) for 13 Jan 2020, with most of the tropical Atlantic experiencing a marine heatwave event, using Hobday et al. (2016) methodology (Figure provided by R. Rodrigues).*

Atlantic zonal mode. A warm phase of the Atlantic Niño displaces the ITCZ to the south, decreasing the land-sea pressure gradient and 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). Ocean dynamics govern this area of the tropical Atlantic, and to understand the surface variability, it is necessary to know the variability beneath the ocean surface.

The WAM can be affected by modes of variability from other basins, such as ENSO (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 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 1970s (Mohino et al. 2011; Rodriguez-Fonseca et al. 2011). 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 over the entire West Africa 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 significant increase in Sahel precipitation during the rainy season, with drier conditions in the cold phase (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 anthropogenic climate change (Ting et al. 2009). During the 20th century, this trend led to a large SST warming in the South Atlantic relative to the North Atlantic and, as such, weakening the monsoonal flow, which projected drying of WAM. This result was consistent with CMIP5 climate model simulations of the 20th century (Ting et al. 2014).

The discussion of TAV influence on WAM above confirms that the tropical Atlantic plays a vital 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 region's population. The severe droughts of the 1970s and 1980s led to the death of thousands of people and millions of animals (Mortimore 1998). To be able to predict such impacts in the future accurately, 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 short rainy season over the Brazilian Northeast (NE) occurs in the austral fall (March to May) when the ITCZ migrates southward (Nobre and Shukla 1996; Hastenrath 2006; Rodrigues et al. 2011). 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. In contrast, 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 remained north of 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 by high surface temperatures and low atmospheric humidity, favouring 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 and hydroelectricity generation, and directly and indirectly affected the populations living along the rivers of the region. As the rainforests 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 good 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 the 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). Over the last decades, there has been an increase in the occurrence of mega-droughts and mega-floods in the Amazon, 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 easterly atmospheric disturbances, which in turn are linked to the southwestern Atlantic warm pool where SST generally exceeds 27°C (Kouadio et al. 2012; Silva et al. 2018).

Many studies have shown that the precipitation response over 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; Cai et al. 2020). Generally, El Niño events cause a positive meridional SST gradient and droughts in the NE. However, in recent years, the NE has experienced a severe, continued drought triggered by anomalous positive meridional SST gradient during La Niña years (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 (Cai et al. 2019).

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 impacts in the tropical regions described above. 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 et al. (2001). Subsequent studies using observations and climate models validated this association and demonstrated that SST in the tropical North 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 of these SST variations on the intensity of the

North Atlantic subtropical High (NASH). When tropical North Atlantic SST are warmer than normal, the anticyclone weakens. This weakens the transport of Gulf of Mexico moisture into the Great Plains and the 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 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 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 1990s 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 the Caribbean Islands (Spence et al. 2004; Seager et al. 2009; Kushnir et al. 2010). Here too, the Atlantic impact on precipitation is opposing the concurrent effect of ENSO (Giannini et al. 2000 , 2001). Méndez and Magaña (2010) discussed droughts in Mexico and Central America and noted that the significant droughts in northern Mexico coincided with the droughts in the US Great Plains and Southwest. The tropical Atlantic tends to be warmer than normal in these northern Mexico droughts. Méndez and Magaña (2010) 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 precipitation anomalies over land, tropical Atlantic SST significantly influences tropical cyclones (TCs) and hurricane activity in the Atlantic Basin. Many of these storms form off the coast of Africa and move from there toward Central and North American 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 wind speed and storm duration), is directly related to the average seasonal temperature of the water in the tropical Atlantic. In that respect, it is essential to mention that on multidecadal time scales, the overall intensity of Atlantic hurricanes 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 Atlantic tropical cyclones' activity by forcing increased vertical shear over the tropical Atlantic (Patricola et al. 2014).

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 (mainly 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 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, 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 northwest 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.

Conclusions

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 atmospheric Rossby wave production mechanism 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. 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. Improving the number of such observations would be beneficial for constraining the dynamical aspects of tropical-extratropical teleconnections.

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Theme 3: The AMOC in the Tropical Atlantic

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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 sea surface temperature (SST), using idealized ocean models (Yang 1999; Johnson and Marshall 2002) as well as complex coupled climate models (Dong and Sutton 2002; Chang et al. 2008). The simulated basin-wide SST response to a significant reduction in the strength of the AMOC (often resulting from buoyancy forcing such as from "housing experiments", where large volumes of freshwater are added to the subpolar North Atlantic suppressing 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 gradient in turn leads to a southward shift of the Intertropical Convergence Zone (ITCZ) and associated precipitation anomalies over the tropics (e.g., Liu et al. 2017; Good et al. 2022). As these precipitation changes affect low-latitude sea surface salinity, which helps to regulate the AMOC through northward salinity advection, this can provide complex feedbacks on the dynamical future behavior of the AMOC (Vellinga and Wood 2002; Stouffer et al. 2006). However, the SST and precipitation anomaly patterns that develop under such a scenario are quite similar to patterns that have been associated with other interannual and decadal forcing mechanisms in the tropical Atlantic, such as the Atlantic Meridional Mode (AMM), the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) or El Niño Southern Oscillation (ENSO)-related atmospheric teleconnections. The conclusion is that sufficiently large changes in the strength of the AMOC can have important consequences for tropical Atlantic SST.

In addition to the effects of high latitude buoyancy forcing, it appears that 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. (2009) found that the Agulhas leakage has likely increased by 50% (from 14 to 21 Sv) between the 1970's and early 2000's caused by a poleward shift and increase of the southern hemisphere westerlies, which has led to an increased salt transport to the South Atlantic subtropics (Biastoch et al. 2009, Hummels et al. 2015). That trend in Agulhas leakage is expected to continue in the 21st century due to anthropogenic forcing according to climate models (Sen Gupta et al. 2009). As these saltier waters will eventually reach the North Atlantic deep water formation regions with the northward AMOC return flow, they could help to sustain the AMOC against its projected decline due to global warming (Weijer et al. 2002).

Regional wind forcing over the tropical Atlantic also contributes to AMOC changes, 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). Besides the regionally forced wind-driven AMOC anomalies, the tropical AMOC fluctuations were shown to contain remotely forced signals from high-latitude wind forcing.

Other effects of AMOC changes on tropical circulation patterns and water mass properties can be more indirect but still potentially important in oceanic feedbacks 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 eastern tropics, 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 (McCreary and Lu 1994; Fratantoni et al. 2000; Malanotte-Rizzoli et al. 2000; Zhang et al. 2003; Tuchen et al. 2019, 2022). A decrease in the AMOC would lead to a greater symmetry of the cells and an increase in northern hemisphere waters supplied to the Equatorial Undercurrent (EUC) that feeds 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 rapid rise in equatorial Atlantic SST and subsequent impacts on atmospheric processes, including in particular enhanced rainfall in the Gulf of Guinea as well as a weakening of the African monsoonal winds and rainfall over West Africa.

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 (Biastoch et al. 2009; Hummels et al. 2015), there has been an overall warming of Antarctic Intermediate Water (Schmidtko and Johnson 2012), a freshening of North Atlantic Deep Water (NADW; Hummels et al. 2015) in the tropical South Atlantic, and a warming of Antarctic Bottom Water in the Southwest Atlantic (Johnson and Doney 2006; Johnson et al. 2008; 2014; Herrford et al. 2017; Johnson et al. 2020; Meinen et al. 2020; Campos et al. 2021). 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.

2. Current AMOC Observations in the Tropical Atlantic

Within the tropical Atlantic, there are presently two existing contributions to the AMOC monitoring system in the Atlantic along 16°N and 11°S. The details of the current measurements being collected at these two locations, plans for the future, and their linkage to the basin-wide AMOC monitoring system are reviewed below.

2.1. MOVE (Meridional Overturning Variability Experiment, U. Send, M.Lankhorst, Scripps Institution of Oceanography)

MOVE operates the MOC monitoring array in the tropical Western Atlantic along approximately 16°N, with the objective to observe the volume transport fluctuations in the 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 (Fig. 1a). The geostrophic transport fluctuations through the 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 21 years of temperature/salinity data (for relative geostrophic transports), and current meter data (for boundary slope transports); and 18 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 late 2020. Interannual and long-term changes in the circulation and its vertical distribution are clearly visible now in the 21-year record. Fig. 1b 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. The observations indicate a weakening of the southward NADW flow until 2010, with a strengthening since then until about 2020. Bottom pressure sensor data are not used for the long-term fluctuations because the data have to be de-trended; instead, satellite gravimetry data from the GRACE mission were first validated with respect to their decadal trends (Koelling et al. 2020) and then used to validate the decadal-scale variability shown in Fig. 1b. Earlier studies found discrepancies with data and analyses from the RAPID/MOCHA array at 26°N (Frajka-Williams et al. 2018). These discrepancies are diminished with the latest release of the MOVE data, partially due to a re-processing of the MOVE salinity calibrations that caused subtle shifts in the phasing of the long-term trends, but mostly perhaps to the increasing lengths of both time series that allow better comparisons on decadal time scales. A consistent picture seems to emerge that shows weakening decadal MOC trends in the 2000s, followed by strengthening in the 2010s, all superimposed by large variability on shorter time scales.

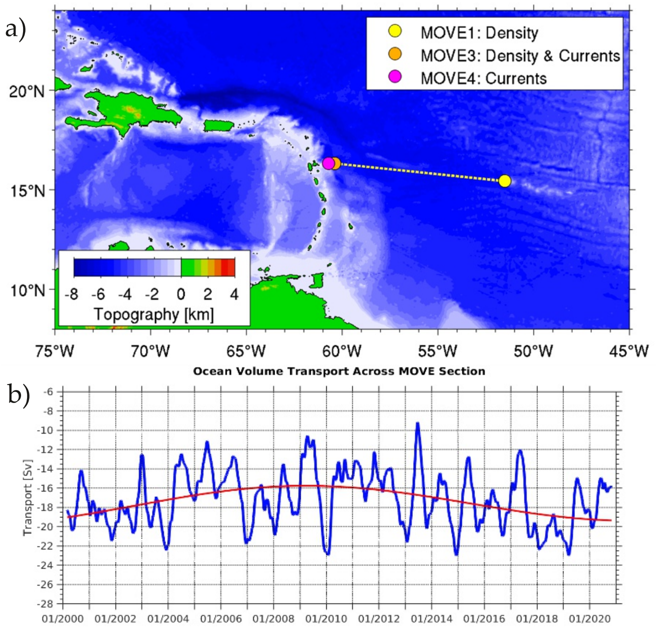

Figure 1. *a) Map of the MOVE array. The goal is to measure the flow at depths of 1200-5000 m across the section shown as yellow dashes. MOVE1, MOVE3, and MOVE4 are mooring sites. Additional PIES (pressure-sensing inverted echo sounder) instrumentation is located at MOVE1 and MOVE3 (Adapted from Send et al. 2011). b) Time series of NADW transport in the depth range 1200-5000 m across the MOVE section (negative southward). The red line indicates decadal-scale variability (adapted from Send et al. 2011). The graph does not use bottom pressure data, but the decadal-scale behavior compares favorably with a reference level derived from satellite gravimetry (not shown).*

2.2. TRACOS (Tropical Atlantic Circulation and Overturning at 11°S, P. Brandt, R. Hummels, 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 the crossroads for the meridional transfer of warm and cold water masses (Fig. 2a) that are part of the AMOC as well as of the southern hemisphere STC. The WBCS has been shown to be the main pathway for the mean northward flowing upper branch of the AMOC in the tropical South Atlantic (Schott et al. 2005; Tuchen et al. 2022).

Intense observations of the western boundary current along the northern Brazilian continental slope started in 2000 in the framework of a German supported project "CLIVAR *marin*" with research cruises along the 5°S and 11°S section, and a mooring array at 11°S. One major finding was that the DWBC breaks up into eddies at around 8°S and that these eddies carry NADW across 11°S (Dengler et al. 2004). After an observational gap since 2004, observational efforts were reinitialized in 2013 within the framework of the project "RACE" and 12 research cruises have been complemented to date with repeat coverage along the 5°S and 11°S western boundary sections. The mooring array was redeployed in July 2013 providing nearly 10 more years of current observations at the same location (Fig. 2). In addition to the western boundary array two moorings were installed in 2013 at the eastern boundary to study the Angola Current within the framework of the project "SACUS" (Kopte et al. 2017, 2018), where one of the moorings is maintained up to date observing the flow at the eastern side of the line.

To examine the relative importance of these boundary currents in driving AMOC variations, the TRACOS line was established – leveraging information from the WBCS/RACE/SACUS programs. As part of TRACOS, two pressure inverted echo sounders (PIES) deployed at 300m and 500m depth on either side of the basin are installed since 2013 to derive the first AMOC transport anomaly time series at 11°S. The AMOC transport anomaly time series based on bottom pressure measurements combined with satellite data (sea level anomalies and winds) was recently published (Herrford et al. 2021) and is dominated by the seasonal cycle with a peak-to-peak amplitude of 14 Sv (Fig. 2e). Note that this is very similar to the peak-to-peak seasonal cycle amplitude observed in the subtropical South Atlantic at 34.5°S (Kersalé et al. 2020).

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 Oceans. Further studies will focus on comparisons of AMOC variations observed by MOVE, TRACOS and extratropical AMOC arrays.

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 boreal summer 2025. Beyond 2025, sustained funding for the observations within this key region is still being sought. The eastern boundary mooring will be maintained at least until 2024.

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 23rd year of operation. It is thus one of the longest running continuous measures of the AMOC in the basin. A 19-year overlap now exists with the RAPID/MOCHA time series at 26°N, and the connection between the two latitudes 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). 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.

The TRACOS array across 11°S is the most recently implemented measurement system for the AMOC in the basin. It is part of the broader South Atlantic Meridional Overturning Circulation (SAMOC) initiative, including the South Atlantic MOC Basin-wide Array (SAMBA) along 34.5°S from 2008-2010 and 2013 to the present, the South Atlantic Gateway Array nominally along 9°W between 20°S and 34.5°S deployed in 2021, 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 TRACOS AMOC estimate at 11°S can be used to investigate, in

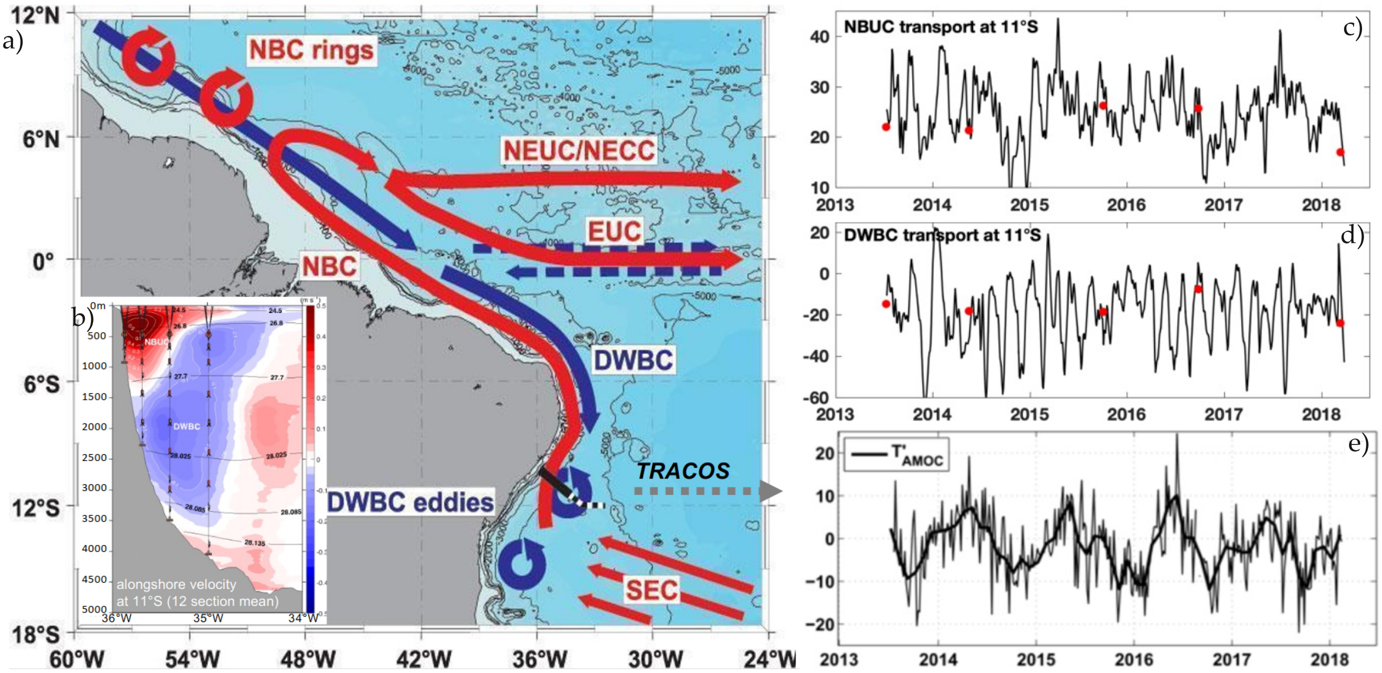

Figure 2. *(a) Circulation in the western tropical Atlantic (from Dengler et al. 2004). Schematic representation of mean currents and eddy generation at the western boundary of the tropical Atlantic with warm water pathways in red and NADW pathways in blue. Black bar (Mooring array) and dotted black/white (Ship section) line at 11°S indicates positions of the measurement program, dotted grey line points towards the measurements at the eastern boundary. 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. b) Average section of alongshore velocity from shipboard observations along 11°S together with the mooring array design. (c-d) Transport time series (update from Hummels et al. 2015) of the moored array for the NBUC (c) and DWBC (d). Red dots mark transports estimated from shipboard observations. e) AMOC anomaly transport time series from Herrford et al. (2021).*

conjunction with results from the other 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.

In addition to AMOC estimates, all of the arrays provide detailed and continuous deep observations of the density, internal pressure, and currents along the western boundary of the Atlantic, which are believed to be critical for understanding AMOC adjustment and coherence processes throughout the basin.

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Theme 4: Tropical Atlantic Ocean Biogeochemistry

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1. Introduction

1.1. How important is the Tropical Atlantic Ocean to its bordering countries?

Despite being the smallest of the Earth's tropical oceans, the tropical Atlantic strongly influences its bordering countries climate and weather as well as the general ocean circulation and climate through the Atlantic Meridional Overturning Circulation (AMOC) and interactions with the tropical Indian and Pacific oceans.

Climate-related extreme events such as droughts, storms, hurricanes, marine heat waves are all related to atmosphere-ocean-land interactions in this region, and climate change is likely to increase them. Ocean acidification and episodes of anoxia, on top of a trend in loss of oxygen, amplify the vulnerabilities at the regional level, especially in nearshore ecosystems already heavily impacted by eutrophication, pollution, and overfishing. All these events impact local economies and food security in the region.

Although there are many ocean observing initiatives in place, such as the PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) network (see ARTICLE 1: Speich et al.) there are still fundamental gaps that limit significant progress in the understanding of societally relevant phenomena and their prediction, including those related to biogeochemical processes. These gaps cannot be filled by individual nations. The Tropical Atlantic Observing System (TAOS) review report has been conceived to assess the 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 the near future and that can be sustained in the long term under international coordination.

1.2. The importance of expanding TAOS

The present Tropical Atlantic Observing system is minimal to ensure skilful predictions across timescales from weather to climate change, and to meet demands of adaptation and resource management. However, the present observing system has important gaps, both regional and temporal, that impede further 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.

In this article we highlight the existing and the needed enhancements for improving regional ocean biogeochemistry observations. These are needed to better characterize the tropical Atlantic role in anthropogenic climate change, and to develop a sustainable management of tropical Atlantic ecosystems and fisheries.

2. Tropical Atlantic Ocean biogeochemistry

2.1. The carbon system in the Tropical Atlantic

The oceans serve as an important sink for atmospheric carbon dioxide, and it is currently estimated that the global oceans take up nearly 25-30% of the anthropogenic carbon that is added to the atmosphere on an annual basis (Gruber et al. 2019; Watson et al. 2020). This carbon is stored in the interior ocean, the residence time depending on the depth at which it is stored (Sabine et al. 2004).

The ocean carbon cycle is complex and dependent on a range of inorganic and organic chemical and biological processes (DeVries 2022). 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. It is also determinant to the amount of ocean-atmosphere exchange in CO_2, one of the main greenhouse gases emitted by human activities (Zeebe 2012).

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 (Gruber et al. 2009; Landschützer et al. 2020, 2013). However, the CO_2 source from the tropical Atlantic has significant temporal and spatial variability (Landschutzer et al. 2016, 2020; Olivier et al. 2022), and this can have a substantial effect on the global carbon budget on annual to interannual timescales.

The increasing dissolved inorganic carbon (DIC) concentration due to input of anthropogenic carbon leads to reduction of the pH value and the availability of carbonate ions – phenomena that are defined as ocean acidification (Doney et al. 2009). This is potentially a large issue for marine organisms, in particular those that have calcium carbonate structures, such as corals. As 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 (Gruber 2011). In addition to that, the 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 (Foltz et al. 2019).

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.

The carbon and oxygen cycles and ecosystems in coastal regions of the tropical Atlantic are influenced by river outflow and upwelling. The region receives about 25% of the global riverine freshwater discharge from three large rivers (Amazon, Congo, and Orinoco; Dai and Trenberth 2002). The rivers also deliver high loads of nutrients, which lead to high oceanic productivity near the river mouths and to a seasonal sink of atmospheric CO_2, as the case of the Amazon River plume (da Cunha and Buitenhuis 2013; Ibánhez et al. 2016; Körtzinger 2003; Olivier et al. 2022). According to the estimates from Monteiro et al. (2022), the contrasting behaviour as a source or sink of CO_2 in this are a result of the surface currents system, in addition to the river plume.

The tropical Atlantic includes two major eastern boundary upwelling systems that support some of the world's most productive fisheries: the Canary and the Benguela (Chaigneau et al. 2009). These systems are particularly vulnerable to ongoing warming, deoxygenation and acidification (Gruber 2011). It is important to understand what drives biological production within these regions in order to understand ecosystem dynamics and also to constrain the regional and global carbon cycles. There are several important factors that control biological production in eastern boundary upwelling regions, including along-shore winds, eddy activity, and mixed layer depth (Lefèvre et al. 2008).

2.2. 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 (Stramma and Schmidtko 2021). 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 (Schmidtko et al. 2017). On the other hand, the regional tropical Atlantic circulation variability may counteract the trend in deoxygenation, such as the strengthening of the Equatorial Undercurrent (EUC), Fig. 1 (Brandt et al. 2021). 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 (da Cunha and Buitenhuis 2013). 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 (Stramma et al. 2012).

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.

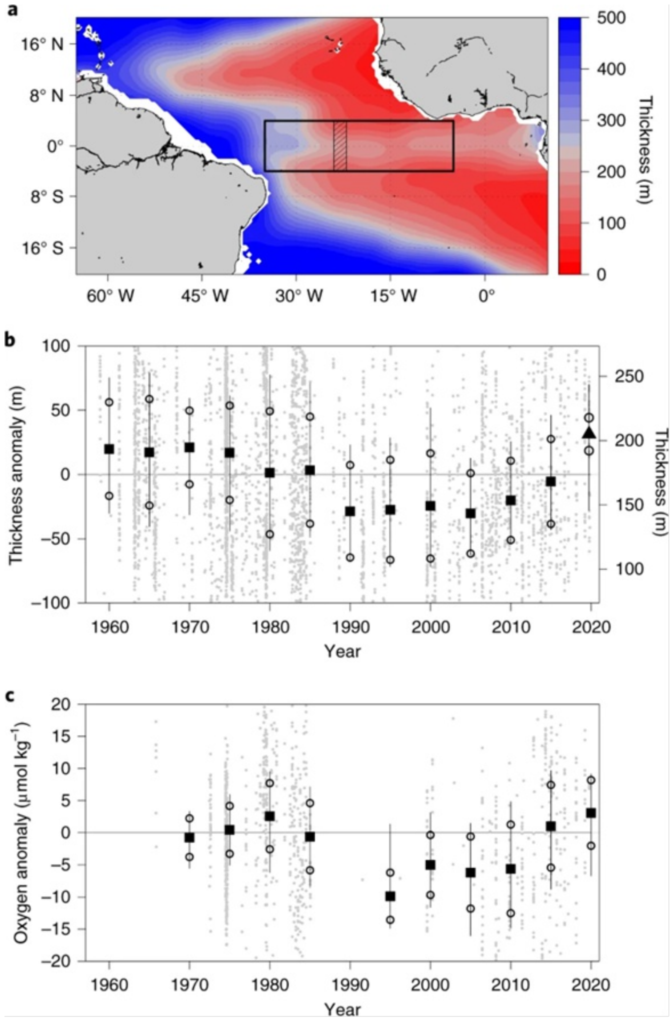

Figure 1. *Surface oxygenated layer thickness (OLT) in the tropical Atlantic, or the depth range between the ocean surface and the shallowest depth of the 120 µmol kg^{-1} oxygen layer. Panel a, Mean OLT (in metres). Panel b, Time series of OLT anomalies in the equatorial region (4° S–4° N, 5–35° W) marked in panel a. Panel c, Time series of the oxygen anomaly in the 100–200 m depth, 4° S–4° N, 22–24° W box marked by the hatched area in panel a. In panels b and c, the 10-yr median anomalies are shown by black squares, the probable errors of the median derived from the median absolute deviation are shown by open circles and the corresponding interquartile range are shown by black vertical lines. Individual data anomalies are shown by grey dots. The triangle in panel b marks the median anomaly of data taken in September–October 2019. Source: Brandt et al. (2021) – Nature Geoscience.*

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 organic 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, especially on its eastern portion, has also been shown to be an important area for N_2O fluxes to the atmosphere (Grundle et al. 2017; Ryabenko et al. 2012), and further effort toward quantifying this flux will be important as N_2O is a potent greenhouse gas.

2.3. Ecosystem dynamics and fisheries

Most living resources extracted from the tropical Atlantic are found in coastal and shelf areas. Therefore, these ecosystems directly support the livelihoods of millions of people by providing income, employment, and food through artisanal and industrial fishing. Currently, there are about eight 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 ten percent of the global marine capture. In addition, coastal ecosystems support income-generating activities including tourism, industry, diving, and game fishing (FAO, 2020).

Together, overfishing 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.

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. 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 and biogeochemical changes in the marine environments.

3. TAOS biogeochemical processes and phenomena

In the tables below there is a list of biogeochemical processes and the need for observational efforts in the tropical Atlantic Ocean. These are required to achieve the terms of reference from the recent TAOS Review Report (Johns et al. 2021). As an example, these actions would help to identify potential enhancement or reconfiguration of the sustained observing system suite, or to assess readiness of new technologies, their potential impact and feasibility in addressing requirements.

PHENOMENA : NATURAL DECADAL VARIABILITY IN OXYGEN AND NITROGEN BIOGEOCHEMICAL CYCLES

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Meridional		**Vertical**	**Temporal**	
Oxygen	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Continuous, minimum: Monthly with mooring maintenance?	Ships/Moorings/ Argo floats/ AOVs
Transient tracers	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Annual ?	10-100 m upper ocean, 300-500m deep ocean

PHENOMENA : BIOGEOCHEMICAL RESPONSE TO CLIMATE CHANGE

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Meridional		**Vertical**	**Temporal**	
Nutrients	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly with mooring maintenance ?	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 with mooring maintenance?	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 with mooring maintenance ?	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 with mooring maintenance ?	Ships/Moorings
Nitrous oxide	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly with mooring maintenance ?	Ships

PHENOMENA : ZONAL CARBON FLUXES

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Meridional		**Vertical**	**Temporal**	
Inorganic carbon *(here the subvariable needed is pCO2 in the ocean and the atmosphere)*, temperature, salinity	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

PHENOMENA : ANTHROPOGENIC CARBON STORAGE

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Meridional		**Vertical**	**Temporal**	
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, preferably DIC and TA)*, dissolved oxygen, dissolved nutrients	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/ Surface drifters/ 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
Subsurface temperature	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/ Surface drifters/ AOVs
Subsurface salinity	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/ Surface drifters/ AOVs
Subsurface dissolved oxygen	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/ Surface drifters/ AOVs
Subsurface nutrients	25 km	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Biannual to decadal	Ships/Moorings/ Surface drifters/ AOVs

PHENOMENA : BIOGEOCHEMICAL RESPONSE TO CLIMATE CHANGE

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Zonal	**Meridional**	**Vertical**	**Temporal**	
Nutrients	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly with mooring maintenance ?	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 with mooring maintenance ?	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 with mooring maintenance ?	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 with mooring maintenance ?	Ships/Moorings
Nitrous oxide	Near boundaries to capture currents, upwelling and OMZ	Specific latitudes	10-100 m upper ocean, 300-500m deep ocean	Monthly with mooring maintenance ?	Ships

PHENOMENA: BIOGEOCHEMISTRY OF THE TROPICAL ATLANTIC VARIABILITY
(a) OMZs, (b) Upwelling Zones, (c) LMEs, (d) Fish stock assessment

ESSENTIAL VARIABLES (EOVS, ECVS)	**RESOLUTION**				**PLATFORMS**
	Zonal	**Meridional**	**Vertical**	**Temporal**	
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 (0-1000m)	Weekly	Ships/Moorings/AOVs
Nutrients (open ocean)	1/4° (merged analysis)	1/4° (merged analysis)	0m (0-1500m)	Weekly	Ships/*Moorings/Argo floats/AOVs*
Nutrients (shelf and coastal)	1/10° (merged analysis)	1/10° (merged analysis)	10m (0-1000m)	Weekly	Ships/*Moorings/Argo floats/AOVs*
Marine carbonate system (open ocean)	1/4° (merged analysis)	1/4° (merged analysis)	0m (0-1500m)	Weekly	Ships/*Moorings/Argo floats/AOVs*
Marine carbonate system (shelf and coastal)	1/10° (merged analysis)	1/10° (merged analysis)	10m (0-1000m)	Weekly	Ships/*Moorings/Argo floats/AOVs*
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
Phytoplankton and zooplankton	Distribution area	Distribution area	0-500 m	Monthly	Satellites/Ships
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	Satellites/ Ships/Drifters/Argo/ Moorings/XCTDs/AOVs

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Theme 5: Ecosystem and Fisheries Observations in the Tropical Atlantic

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1. Background

Observations of Ecosystem and Fisheries Observing Systems in the Tropical Atlantic are mostly carried out on national scales along the continental shelf and international scales in the high sea. There are exceptions where regional programmes support observation and monitoring efforts along the shelf. Overall, the ability to carry out coordinated observations is still limited as is the capacity to access and analyse data from other sources like remote sensing. This chapter gives an overview on major initiatives and programs and highlights capacity development needs.

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 fish 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) and increasingly using co-management tools (Deme and Brehmer 2022). The main RFMO is the FAO Fishery Committee for the Eastern Central Atlantic (CECAF) aimed at promoting the sustainable utilization of the living marine resources within its area of competence by the proper management and development of the fisheries and fishing operations. In the case of tuna species in the Atlantic, this role is played by the International Commission for the Conservation of Atlantic Tuna "ICCAT" (Bekiashev and Serebriakov 1981). We will present this as an extra paragraph in the following work. Coastal ecosystems can be categorized in Large Marine Ecosystems (Hempel and Sherman 2003), which are marine areas with similar ecosystem characteristics. In the tropical Atlantic, two East boundary upwelling systems occur and are highly productive (Auger et al. 2016; Hutchings et al. 2009). Neighbouring countries of some of tropical Atlantic LMEs have developed programs and conventions to regulate the 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 success is the Benguela Current Commission.

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 (Sarré et al. 2018; Franco et al. 2020). To understand current systems, particularly also the effect of human activities including fishing and climate change for the future of ecosystems, an increasing number of ecosystem models have been developed, which are also in need of data for parameterization, calibration and validation. In addition, these models also use input data from coupled climate-ocean models (Keenlyside et al. 2021). It has been recognized that observations of a few essential ecosystem and 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.
- strengthen national logistical means for ocean observations

Even if capacity building is no longer needed in numerous developing countries but but rather, capacity strengthening and making use of the expertise in national and regional institutes (Brehmer et al. 2018), we need to encourage North-South and South-South collaborations.

3. Fisheries

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) 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, Turkish, Russian, European) also target the resources. The fishing activities cumulated over a period of 10 months was shown by Global Fishing Watch, which is a good example for a global remote sensing observation system for fishing activities (Fig. 1). 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) (Mullié 2019). 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.

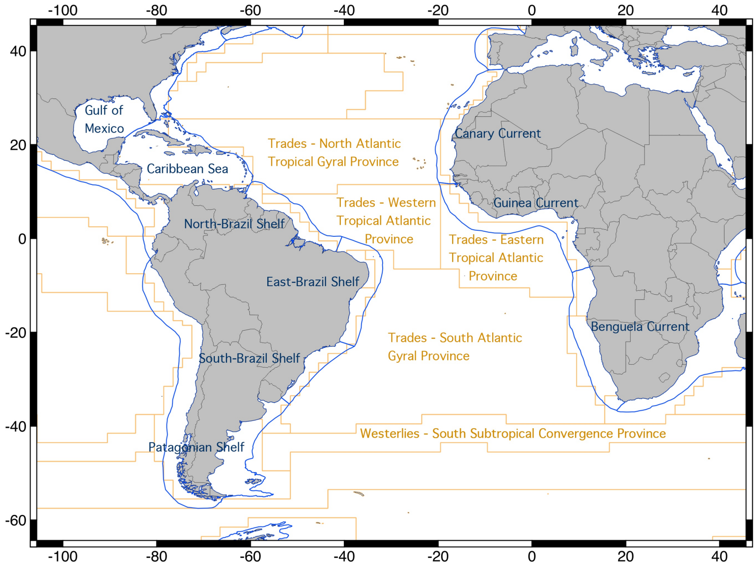

Figure 1. *Fishing activities cumulated from 31 December 2016 to 15 November 2017, taken online from Global Fishing Watch (https://globalfishingwatch.org/; accessed the 07/06/2022).*

4. Ecosystems

4.1. 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) (Fig. 2). 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. 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 activities 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. However, both goals must be simultaneously considered for management purposes, taking into account that an ecosystem in bad health or not sustainably exploited by the fishers, is less productive.

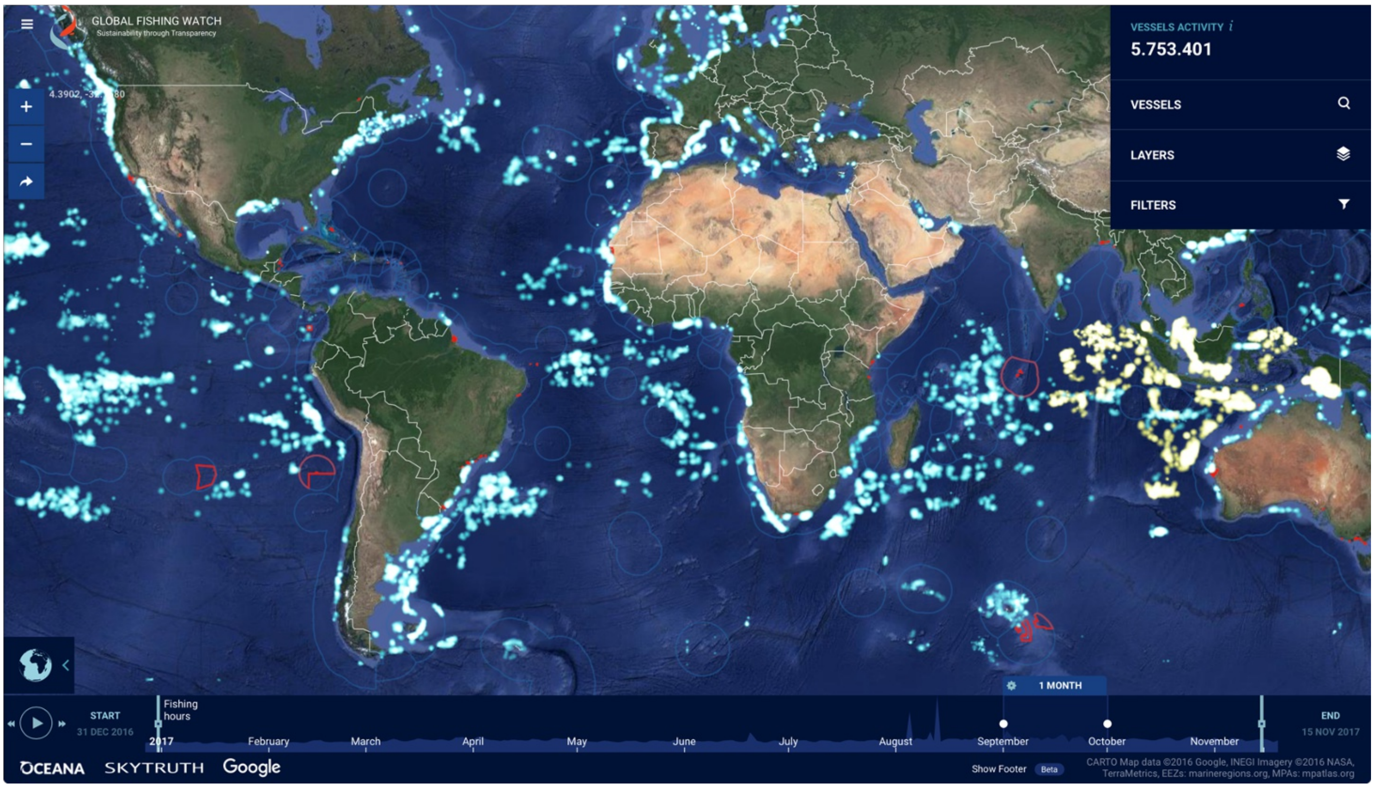

Figure 2. *Map of the Tropical Atlantic Large Marine Ecosystem (LME). Courtesy of J.O. Schmidt.*

4.2. 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 and Cochrane 2005). The success of applying an ecosystem-based assessment to inform Ecosystem Based Fisheries Management (EBFM) depends on (1) simultaneously monitoring of multiple pressures and ecosystem states; and (2) rapid detection and timely prediction of changes in ecosystems states and their impacts on carrying capacity. In the southern part of the Canary Current LME the AWA program has supported EAMME (Ecosystem Approach to the management of fisheries and the marine environment in West African waters) for a decade to promote EBFM.

4.2.1. Observations in fisheries

4.2.1.1. 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 remain understudied.

4.2.1.2. 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, trips, 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. This is information that is normally collected through national fisheries institutes and/or respective government fisheries agencies, with representative fish sampling done either directly on board or through landing sites, and market sampling schemes. In some countries fisheries independent data are collected through trawl and hydroacoustics surveys on the fish stock or egg and larvae surveys on the early life stages of a stock.

4.2.1.3. 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 field 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 too often done with financial support of projects, which do not allow to constitute efficient time series to monitor population dynamics of exploited fish populations. Assessments of the status of stocks in East Atlantic are performed through CECAF Committee.

5. Current or Recent Coordinated Observations

One example of a survey programme, which started as 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 (FAO) of the United Nations is performing sea surveys, which were specifically built for the programme, around the African continent. Other surveys programme exist (e.g., Orstom-IRD since 1970's) and regional initiatives involving national research vessels towards coordinated acoustic surveys in Northwest Africa (Sarré et al. 2008).

TheTropical Atlantic was included in the "Census of Marine Life" a 10-year, 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. Census of Marine Life (Costello et al. 2010) has collected biodiversity data in the global ocean, including the Tropical Atlantic. There are numerous other, mostly smaller projects, like the tripartite AWA and European Preface projects. These consortia had promoted the need of projects clustering and synergy in the Tropical Atlantic (Brehmer et al. 2018), nowadays the "All-Atlantic Ocean Research Alliance" involving countries from both sides of the Atlantic Ocean including Tropical Atlantic, appear as a relevant initiative to develop.

Along the Atlantic coast, only one LME programme from FAO became a commission. The Benguela Large Marine Ecosystem Programme (BCLME) (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. Similar initiatives were done in the Canary Current (CCLME) and Gulf of Guinea (GCLME) with less success.

In the high sea, off national EEZs, we get different fish communities than the small pelagic dominating the continental shelf (Diogoul et al. 2021). Tunas and the other large pelagic fishes, including 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 RFMO, a task in the Atlantic Ocean and Mediterranean Sea undertaken by the ICCAT.

Lastly, 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).

6. Conclusions

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 of ecosystem and fisheries surveys into 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 common survey protocols.

Activities that will help in coordinating and further developing capacity includes i) linking and supporting existing coordinated programmes like the EAF Nansen Programme, the LME Programmes and Regional Fisheries Management Organizations like ICCAT; ii) linking and supporting coordinated national survey program, maintaining at least the current survey effort, identifying gaps and supporting the development of extensions where necessary; iii) linking coordinated communities like the Ocean Tracking Network, iv) 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; and v) develop and carry out a broad consultation on current observing efforts and observing needs.

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Theme 6: Importance of in-situ observations for operational seamless forecasting systems

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Ocean *in situ* observations in the tropical Atlantic have a real impact on seamless forecasts at different time ranges, from days to seasons ahead. Indeed, their impact is visible already in the first 24 hours of the forecasts. Availability of long-term observational records is critical for seamless forecasting, especially for enabling reanalysis, forecast calibration and detection/prediction of extremes.

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. Forecasts with reliable uncertainty estimates at a range of time scales 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 (e.g., famine, epidemics) that may be caused by adverse weather and climate events can be mitigated with early warning systems and disaster preparedness. Equally, adequate planning can aid the exploitation of favorable climate conditions.

Operational weather forecasts, covering atmosphere, land and ocean surfaces, range from minutes (nowcasting) to days, weeks and seasons ahead, and serve various sectors, from marine to aviation, agriculture, water or risk management. Medium-range (10-15 days), subseasonal (up to 1-2 months ahead), and seasonal (up to 6-12 months ahead) forecasts are produced operationally in the major forecasting centers. 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 and 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.

2. New Earth-system seamless paradigm

In order to cover the different forecast time scales in a unified and consistent manner, current operational forecasting centres are adopting the so-called "Seamless Earth System" approach. These forecasting systems include initialization techniques that make full use of observations thanks to sophisticated assimilation techniques, and rely on coupled atmosphere, land, ocean, waves and sea ice models to predict the evolving sea-surface conditions and its impact on the atmosphere. Some of them also include atmospheric chemistry. They also incorporate probabilistic methods to provide estimation of uncertainty. An adequate observing system underpins and drives forward the forecasting capabilities, hand in hand with model development and computer resources.

In the context of earth-system seamless forecasting, the ocean observing system needs to be re-evaluated, since ocean observations have the potential to impact a wider range of temporal-spatial scales and processes. Of particular importance are sustained observations relevant for the modelling and initialization of air-sea interaction processes. For the tropical Atlantic, these observations will directly impact the quality of weather/climate information around the basin and coastal areas, but will also have an impact on the entire globe.

3. Need for observations for initialization, verification, model development and understanding

The observational needs of the different forecasting systems 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 reforecasts over a sufficiently long period. These reforecasts are initialized from reanalysis. Reanalysis is widely used for monitoring of the Earth System's climate, but they are also an integral part of the forecasting systems. Without them the forecasts could not be calibrated, nor could their skill be estimated. Hence, long term is a key for short term forecasting. 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 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 routinely assess the impact of observations on weather. 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. Although the number of *in-situ* observations of the sea-surface appears to be very small compared to altitude and satellite observations (see Fig. 1), their relative contribution to improving the forecasts (by reduction of the 24-hour forecast error via the data assimilation) is much larger than their share in numbers (for details refer to Poli 2018).

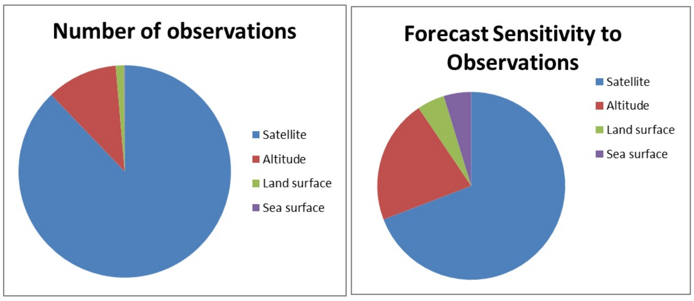

Figure 1. *Number of observations assimilated operationally by ECMWF (left) and contribution of observations to improving the forecasts (right) (from Poli 2018). Here Sea Surface observations refers to in-situ observations.*

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.

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

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 inter-basin 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 transports. 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; Polcher et al. 2011) or the interaction with the ITCZ. Since AMMA, it is striking 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 hamper the teleconnection with the tropical Pacific. (Rodriguez-Fonseca 2010). This brings a clear need for long term sustained monitoring of the tropical Atlantic.

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

Complex topography, model resolution and spatial scales: the basin width and the complex topography 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 those along 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 include 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 reanalysis. 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 constrain 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 forecasting. If wrongly initialized, the information can be projected into the wrong modes, leading to spurious currents and fast adjustments which manifest as errors in seasonal forecasts (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). It has recently been reported that the wrong initialization of the AMOC impact the skill of seasonal forecasts of the North Atlantic sector (Tietsche et al. 2020). In order to develop better assimilation methods that make good use of existing observations, good quality reference timeseries 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 imposes a distinctive meridional component on 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 the characteristic east-west tilt of the 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 encompasses 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 pool: 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 renowned 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 method. The Caribbean ocean circulation is also key for the North Atlantic ocean. It acts as a resonance box that amplifies ocean circulation signals, in what it has been called the Rossby Whistle (Hughes et al. 2016). *Measuring 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 u**pwellings and stratocumulus** areas, the **subduction and mixed layer regimes**. Observation requirements for these areas and processes also apply to the Atlantic basin.

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Theme 7: Predictions of the Tropical Atlantic from seasonal to decadal time scales

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1. Introduction

The tropical Atlantic Ocean is a source of climate predictability on seasonal-to-decadal timescales both locally and globally. The tropical Atlantic affects rainfall and temperature over South America and Africa, and influences Atlantic hurricanes, European climate, and the El Niño Southern Oscillation (ENSO). Realizing this predictability is thus key to the provision of societally useful climate services. The Tropical Atlantic Observing System (TAOS) is integral to realizing skilful predictions, as are accurate models, high-performance computing resources, and data assimilation schemes. Here we briefly describe the current skill in predicting tropical Atlantic climate on seasonal-to-decadal timescales and review the elements of the TAOS crucial for monitoring the state of the tropical Atlantic and its prediction on seasonal to decadal time scales. This paper is based on a chapter in the TAOS report (Johns et al. 2021).

2. Source of prediction skill

The tropical Atlantic hosts a range of patterns of climate variability that can contribute to predictability. These are principally the Atlantic Niño (Lübbecke et al. 2018; Richter and Tokinaga 2021), Atlantic Meridional Mode (AMM) (Servain et al. 1999), and Atlantic multi-decadal variability (AMV) (Knight et al. 2005). These patterns are generally characterized in terms of large-scale sea surface temperature (SST) anomalies, which are formed through dynamical and thermodynamical ocean-atmosphere interactions and are associated with atmospheric teleconnection patterns.

Remotely forced atmospheric teleconnections also influence the tropical Atlantic and are a major source of prediction skill in the region. In particular, ENSO strongly impacts the north tropical Atlantic, but also influences the south tropical Atlantic (Enfield and Mayer 1997; Mo and Paegle 2001; Cai et al. 2020). In addition, changes in radiative forcing from greenhouse gas concentrations and aerosol loadings are important drivers of climate, especially on decadal and longer-timescales (Ting et al. 2009; Tokinaga and Xie 2011; Booth et al. 2012).

Seasonal prediction of SST

The current skill of state-of-the-art seasonal prediction systems is illustrated using output from available multi-model ensembles. Skill in predicting SST at six months lead is greatest over the north tropical Atlantic, where anomaly correlations exceed 0.6 (Fig. 1a). This skill is mainly the result of an ENSO teleconnection: El Niño (La Niña) causes a relaxation (enhancement) of the trade winds, reduced (enhanced) surface turbulent fluxes, and warming (cooling of SST) over the north tropical Atlantic that peaks in boreal

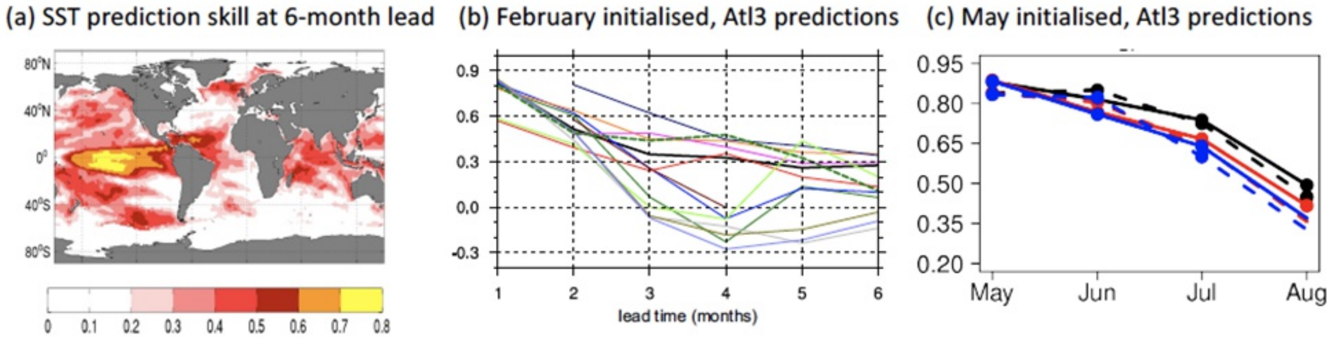
(a) SST prediction skill at 6-month lead (b) February initialised, Atl3 predictions (c) May initialised, Atl3 predictions

Figure 1. (a) 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. (2019). (b) 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; persistence skill is shown for reference (black line). Figure adapted from (Richter et al. 2017a). (c) as in (b) 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).

spring (Alexander et al. 2002; Chang et al. 2003). The AMM and the underpinning wind evaporative feedback may contribute to the predictability of the north tropical Atlantic in boreal spring (Servain et al. 1999; Foltz et al. 2011) as may ocean dynamics in the Guinea Dome (Doi et al. 2010). The strong long-term warming over the north tropical Atlantic also contributes to prediction skill (Wang et al. 2019).

State-of-the-art models are not skilful in predicting SST anomalies in the south tropical Atlantic six months in advance (Fig. 1a), this 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. 2018). Predictions initialised in February show skill in 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 (Fig. 1b). However, the better systems can skilfully predict Atlantic Niño variability from May 1st (Fig. 1c). The low Atlantic Niño predictability has been attributed to several factors: the large importance of internal atmospheric dynamics (Richter et al. 2017b; Richter and Doi 2019; Nnamchi et al. 2021), the existence of multiple mechanisms of comparable importance to the Bjerknes feedbacks (Brandt et al. 2011; Richter et al. 2013; Nnamchi et al. 2015), the inconsistent response to ENSO (Chang et al. 2006; Lübbecke and McPhaden 2012), and large model errors (Dippe et al. 2019; Counillon et al. 2021).

Interannual variability in the equatorial Atlantic is subject to multi-decadal modulation(Tokinaga and Xie 2011; Servain et al. 2014), with periods of low and high variability that may decrease and increase predictability, respectively, as in the equatorial Pacific (Wen et al. 2014). The period 2000-2018 was marked particularly low variability, which was partly due to changes in the equatorial Atlantic thermocline (Prigent et al. 2020). Two very strong events in 2019 and 2021 (Richter et al. 2022), however, may be signs that the equatorial Atlantic is reverting to a regime of increased activity and higher predictability. In both events, wind stress curl anomalies just north of the equator appears to have played an important role. The associated oceanic downwelling and warming can influence the equator either through advection (Richter et al. 2013) or oceanic wave dynamics (Lübbecke and McPhaden 2012). The potential influence of these complex processes highlights the need for *in-situ* observations of the surface and subsurface Atlantic Ocean, not only on the equator itself but in the wider equatorial region.

Multi-year prediction of SST

Near-term or decadal predictions aim to predict climate on multi-annual timescales by accounting both for initial conditions and changes in external radiative forcing (Keenlyside and Ba 2010). This field has developed rapidly from first efforts around 15 years ago to quasi-operational predictions being published in annual reports of the World Meteorological Organisation since 2020 (Hermanson et al. 2022). Near-term predictions have also informed the fifth and sixth assessment reports of the intergovernmental panel on climate change (IPCC).

The current state-of-the-art in predicting Atlantic SST on multi-annual timescales is illustrated using experiments performed for the Decadal Climate Prediction Project contribution to CMIP6 (Boer et al. 2016). These experiments consist of retrospective ten-year long predictions performed each year since 1960 to present. The predictions are initialized with contemporaneous observations and driven with observed historical forcing. The benefit of initialisation is commonly estimated by comparing against standard historical simulations only driven by external forcing. For convenience we present results only from the Norwegian climate prediction model (NorCPM) (Bethke et al. 2021), but they are representative of other prediction systems (Doblas-Reyes et al. 2013; Yeager et al. 2018).

NorCPM shows high levels of skill in predicting SST over the entire Atlantic at 2-5 years lead (Fig 2a). The skill at 6-9 years lead is similarly high (Fig 2b). Over the North Atlantic it reflects skill in predicting AMV out to 10 years lead. External radiative forcing (i.e., greenhouse gases and aerosol loadings) is the main source of the skill over the Atlantic (and elsewhere) (Doblas-Reyes et al. 2013). The subpolar North Atlantic (SPNA) is essentially the only region where initializing the ocean increases skill (Fig. 2c). The skill here derives primarily from the initialization of the oceanic state, and associated ocean heat flux convergence (Yeager and Robson 2017; Zhang et al. 2019).

The mechanisms for multi-annual predictability over the tropical Atlantic are less well established, but external forcing appears to play a dominant role. Increasing greenhouse gases concentrations have driven a long-term warming of the tropical Atlantic, while changes in aerosol loadings were shown to be important in capturing multidecadal variations (Tokinaga and Xie 2011). Some prediction systems indicate ocean initialising enhances skill in predicting SST and subsurface temperatures in the tropical Atlantic on multi-annual timescales (Corti et al. 2015; Yeager et al. 2018). Furthermore, skill in predicting the subpolar North Atlantic can enhance skill over the tropical Atlantic via atmospheric teleconnections (Smith et al. 2010).

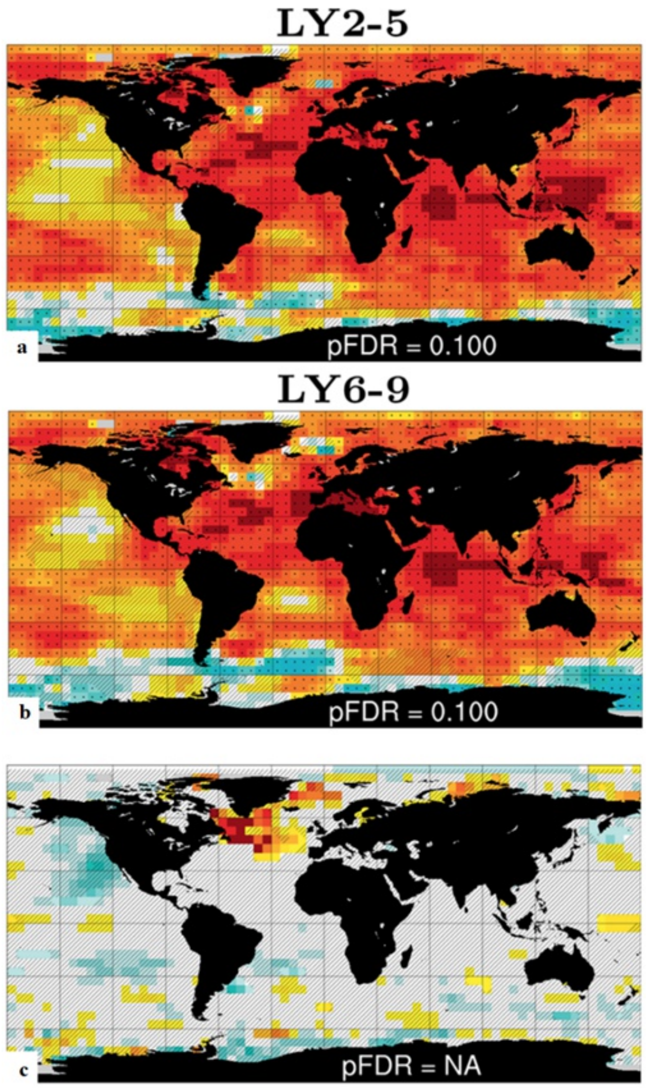

Figure 2. *(a) Anomaly correlation skill of the NorCPM in predicting SST for years 2 to 5. Predictions consist of 20 ensemble members started 1st of November every year from 1960 to 2011. (b) as for (a) but for years 6 to 9.(c) Anomaly correlation skill resulting from initialization of the ocean, estimated as the difference in skill of NorCPM from historical experiments driven only with observed changes in external forcing. The differences shown is for years 6 to 9, but results are similar for years 2 to 5. Figure adapted from Bethke et al. (2021).*

Prediction of tropical Atlantic climate

On seasonal timescales, there is skill in predicting rainfall over South America and West Africa. In particular, rainfall over Brazil, Uruguay, Paraguay, and northern Argentina can be skilfully predicted by combining dynamical and statistical seasonal predictions, with ENSO variability contributing most skill (Coelho et al. 2006). Furthermore, the three major droughts of 1998, 2005, 2010 over Brazil could be predicted one month in advance (Coelho et al. 2012). Statistical schemes using indices of ENSO and equatorial Atlantic SST can predict the Sahel rainy season a few months in advance (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). The Nioro du Rip region of Senegal is one example where such seasonal forecasts can benefit farmers economically (Sultan et al. 2010).

There is high skill in predicting Atlantic hurricane activity on seasonal timescales (Camargo et al. 2007). Multi-model and statistical-dynamical forecasts can predict North Atlantic tropical cyclone frequency during August–October from the previous November (Vitart 2006; Vecchi et al. 2011). Furthermore, high-resolution seasonal forecasts can predict hurricane activity at finer than basin-scale, months in advance (Vecchi et al. 2014). In addition, reducing SST biases contributes to an enhancement in prediction skill (Vecchi et al. 2014). The skill in predicting hurricane activity is connected to skill in predicting underlying tropical Atlantic and Indo-Pacific SST and their influence on vertical wind shear over the region (Gray 1984).

On longer time scales, there is remarkable skill in predicting Sahel rainfall (Yeager et al. 2018). In particular, summer rainfall over the Sahel can be predicted 2-5 years ahead with a correlation skill of ~0.7, and importantly the devastating drought of the 80s could have been skilfully predicted several years before (Sheen et al. 2017). This skill is linked to AMV (Folland et al. 1986; Zhang and Delworth 2006; Mohino et al. 2016). On these timescales, there is also skill in predicting Atlantic hurricane numbers (Smith et al. 2010; Caron et al. 2017). This is linked to skill in predicting the relative warming of the north tropical Atlantic to the rest of the tropical oceans that modulates wind shear over the hurricane main development region (Smith et al. 2010). The skill in predicting these impacts is also likely negatively affected by the large-model biases in the tropical Atlantic (Hsu et al. 2019).

Climate predictions offer the potential to forecast environmental driven marine ecosystems shifts (e.g., related to oceanic conditions and nutrient supplies) and thereby aid fisheries management. For example, Benguela Niño events can be theoretically predicted 1-2 months in advance based on equatorial and coastal wave dynamics (Imbol Koungue et al. 2017), though the influence of local atmospheric forcing (Richter et al. 2010) may reduce predictability. 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). In addition, round sardinella distribution may be predictable months in advance due to the delayed impact of El Niño (López-Parages et al. 2019). Multi-decadal shifts of the ecosystem in this region could also be predictable based on AMV (Abdoulaye Sarre, personal communication).

Skilful predictions of tropical Atlantic climate can enhance prediction globally, because tropical Atlantic influences climate around the globe. Tropical Atlantic rainfall can enhance skill of winter North Atlantic Oscillation, through a Rossby wave induced teleconnection pattern (Knight et al. 2017; Scaife et al. 2017). The tropical Atlantic also 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. 2015). These impacts could potentially 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).

Discussion

There has been great progress in climate prediction over the tropical Atlantic during the past decade. SST can be predicted over the north tropical Atlantic on seasonal timescales, and over most of the tropical Atlantic on multi-annual timescales. Rainfall can be predicted on seasonal timescales over the Sahel, the Gulf of Guinea, Brazil, Uruguay, Paraguay, and northern Argentina. In addition, Sahel rainfall can be predicted with great skill on multi-annual timescales. Hurricane activity can be predicted skilfully on seasonal to decadal timescales. ENSO contributes largely to the skill in predicting tropical Atlantic climate on seasonal timescales, while AMV is most important on multi-annual timescales.

TAOS is key to delivering skilful climate predictions. Observations of the upper ocean temperature and salinity (*in situ* and satellite remote sensed SST and sea surface salinity) are most important for the initialisation of predictions (Fujii et al. 2019). The ocean mixed layer over the north tropical Atlantic provides oceanic memory and is key to accurately capture the impact of ENSO teleconnections. In the equatorial region, upper ocean heat content is a source of predictability for the Atlantic Niño (Ding et al. 2010). Satellite remote sensed sea level height also provides useful information on upper ocean content. These observations together with those of the upper ocean circulation, surface heat and momentum fluxes, radiative fluxes, and atmospheric winds, and precipitation have been critical in understanding tropical Atlantic climate and in improving climate models.

There is great potential and need to improve seasonal prediction in the equatorial and south Atlantic, where skill is very low compared to other tropical oceans (Fig. 1a). Lower skill in this region is expected because the ocean-atmosphere feedbacks underlying equatorial Atlantic variability are weaker and more complex than those in the Pacific (Richter et al. 2014; Lübbecke et al. 2018). In addition, ENSO teleconnections are less consistent than those to the north tropical Atlantic and the Indian Ocean (Chang et al. 2006; Lübbecke and McPhaden 2012; Keenlyside et al. 2020). Nevertheless, TAOS has key limitations in the equatorial and south Atlantic. The upper ocean stratification is poorly constrained and great uncertainty exists in state estimates of equatorial thermocline depth—key to predicting SST anomalies. Furthermore, moorings along the southern African coast could benefit the monitoring, understanding and prediction of Benguela Niño events (Imbol Koungue et al. 2017; Tchipalanga et al. 2018). Continued monitoring in the equatorial Atlantic region will also be crucial to better understand how low-frequency subsurface temperature changes modulate the strength and predictability of Atlantic Niños (Prigent et al. 2020).

Systematic model error could be a major cause of low prediction skill in the equatorial and south Atlantic. These errors are among the most severe of all biases found in state-of-the-art climate models (Richter and Tokinaga 2020). 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; Voldoire et al. 2019). As a result, the equatorial thermocline is too deep and the thermocline feedback is too weak in the models (Deppenmeier et al. 2016; Dippe et al. 2018). These biases affect the simulated variability and reduce prediction skill (Richter et al. 2020; Counillon et al. 2021). Lübbecke et al. (2018) and Richter and Tokinaga (2021) provide a good review of these issues.

In conclusion, climate predictions have skill in predicting climate over the tropical Atlantic on seasonal-to-decadal timescales. TAOS is crucial in enabling climate prediction, through developing scientific understanding and modelling capability and by accurate prediction initialisation. There is an urgent need to improve seasonal predictions in the equatorial and south Atlantic. This can be achieved by reducing systematic model error and through enhancements to TAOS.

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Theme 8: Long-term climate change in the tropical Atlantic

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1. Introduction

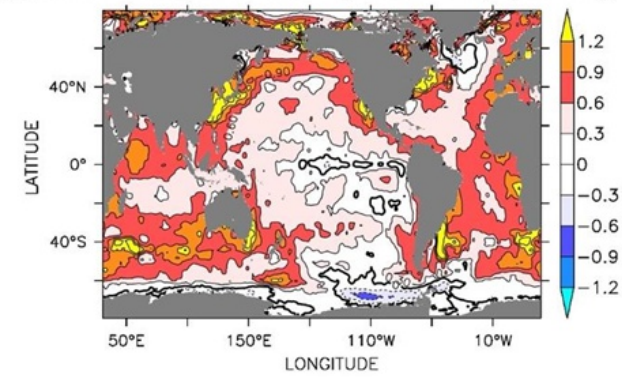
Global warming has been associated with a myriad of changes in the tropical Atlantic Ocean that are projected to accelerate over the next century with major consequences for marine ecosystems and continental climate. The Tropical Atlantic Observing System (TAOS) is key to monitoring and understanding the changes and thereby to help reduce uncertainties in climate projections for the region (Foltz et al. 2019). This article summarizes observed and projected long-term changes in the tropical Atlantic Ocean and discusses some of the important impacts. We also discuss what enhancements of the TAOS are required to reduce uncertainties in the projections of climate change in the tropical Atlantic and its consequences. The article draws heavily on a corresponding chapter of the TAOS report (Johns et al. 2021).

2. Historical changes in sea surface temperature

This section focuses on sea surface temperature (SST) because it is the most reliably observed oceanic parameter during the historical period, and the one most important in driving climatic impacts. Reconstructions based on *in-situ* measurements indicate that over the last century the tropical Atlantic SST has warmed by almost 1°C (Fig. 1). The warming matches the global average increase in SST (Gulev et al. 2021). It is attributed to anthropogenic emissions of greenhouse gases and is well simulated by climate models that consider historical changes in radiative forcing (Eyring et al. 2021).

The tropical Atlantic warmed more rapidly during 1900-1940 and from the 1970s to present compared to the rather muted warming during 1940-1970 (Fig. 1b) (Nnamchi et al. 2016). These multi-decadal fluctuations also coincide with those in global mean SST but their cause is debated. Climate models indicate that they were caused by an interplay between greenhouse gas warming and aerosol-driven cooling in the northern hemisphere (Tokinaga and Xie 2011; Booth et al. 2012; Terray 2012). Observations, on the other hand, suggest that ocean dynamics drove the recent warming, which was offset by the cooling associated with strengthening surface wind speeds (Servain et al. 2014; Lübbecke et al. 2015). Similarly Atlantic multi-decadal variability (AMV) has been linked to the Atlantic meridional overturning circulation (AMOC) and to internal climate dynamics (Zhang 2008; Keenlyside et al. 2015; Zhang et al. 2019; Latif et al. 2022; Omrani et al. 2022).

(a) Sea surf. temperature trend, 1900-2018 (°C/century)



(b) Tropical Atlantic sea surface temperature.

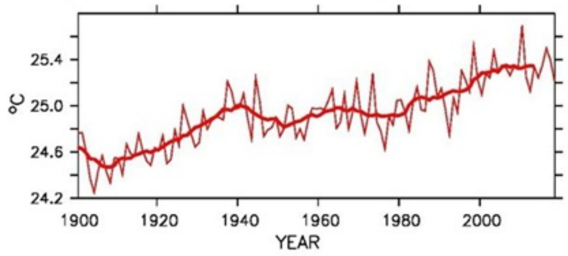


Figure 1. *Historical change in global and tropical Atlantic sea surface temperature (SST): (Upper) Linear trend in SST calculated over the period 1900 to 2018 in degrees per century; (Lower) Annual mean SST averaged over the tropical Atlantic (30°S-30°N) from 1900-2018. The eleven-year running mean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

The warming trend varies geographically and it is strongest along the African coast and in the South Atlantic (Fig. 1a). Observations also indicate a long-term weakening of the equatorial cold tongue in boreal summer since the 1960s, although the weakening was less pronounced during the satellite era (Tokinaga and Xie 2011; Nnamchi et al. 2020). Climate models indicate that the weakening of the equatorial cold tongue is likely caused by the interaction between external forcing and internal climate dynamics (ibid).

There has also been a long-term weakening of SST variability in the equatorial Atlantic in boreal summer and the Angola-Benguela upwelling region in boreal spring. Atlantic Niño variability may have weakened by almost 50% between 1960-2010, associated with weakening of the Bjerknes positive feedback and increased surface heat flux damping (Tokinaga and Xie 2011; Prigent et al. 2020a). The Benguela Niño variability weakened by 30% from the 1980s to present, primarily because of reduced equatorially forced coastal Kelvin waves (Prigent et al. 2020b). Two Atlantic Niño warm events occurred in 2019 and 2021 and were among the strongest in the observed record (Richter et al. 2022). While these two events are not enough to constitute a reversal of the long-term weakening in SST variability, continued monitoring of the region is important.

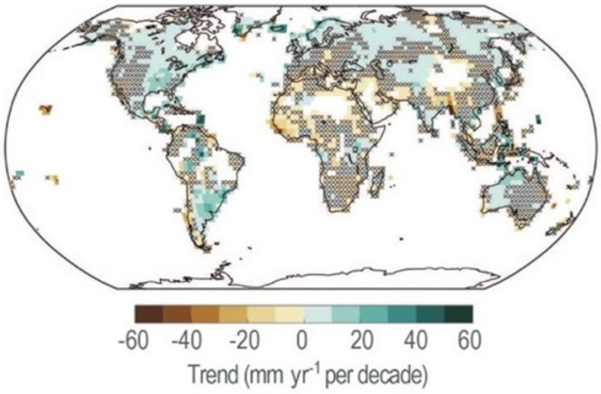
3. Climatic impacts during the historical period

The historical changes in the tropical Atlantic SST have been linked to major local climatic impacts. Long-term observations indicate that precipitation has decreased over tropical western and equatorial Africa, while it has increased over tropical South America (Fig. 2a) (Gulev et al. 2021). These trends appear more pronounced during the period from 1950 to 2010, consistent with a 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).

Multi-decadal variations are a prominent feature of tropical African and Caribbean/Brazilian continental precipitation patterns. Superimposed on the long-term drying trend, Sahel rainfall exhibited a wet period in the 1940s, a severe dry period in the 1980s, and a weak recovery thereafter (Fig. 2b) (Folland et al. 1986; Nicholson et al. 2000; Dong and Sutton 2015). Rainfall over the Northeast region of Brazil, the Caribbean, and over the Central and West North America also exhibited decadal to multi-decadal variations (Enfield et al. 2001; Hetzinger et al. 2008; Lacerda et al. 2015). These changes in precipitation have been linked to AMV (Zhang and Delworth 2006).

Tropical Atlantic SST changes have had major influences on extreme weather events. Hurricanes are a key example. The seasonally integrated total power dissipation of hurricanes has increased with the rise of SST in the tropical North Atlantic since the mid-1970s (Emanuel 2005). This increase is consistent with the predicted increase in the number of intense hurricanes by model-based projections of global warming (Emanuel 1987; Bengtsson et al. 2007; Knutson et al. 2010). At the same time, hurricane activity exhibits pronounced multi-decadal variability that has been linked with the underlying SST and its impact on vertical wind shear (Goldenberg et al. 2001; Kossin and Vimont 2007; Latif et al. 2007; Ting et al. 2015).

(a) Precipitation trend from 1901-2019



(b) Sahel precipitation anomalies (June-October).

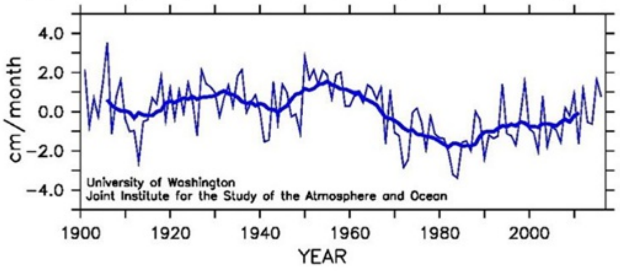


Figure 2. *Historical changes in global and Sahel precipitation: (a) trend in precipitation for the period 1901 to 2019 from the CRU TS monthly high-resolution gridded multivariate climate dataset (Harris et al. 2020). Statistically significant trends (95% level) are shaded, x indicates not statistically significant trends. Figure is adapted from figure 2.15a IPCC AR6 (Gulev et al. 2021). (B) Sahel precipitation anomalies averaged from June-October and over the domain 20°-10°N, 20°-10°W. The eleven-year running mean is indicated by the solid lines. Data are from University of Washington (Mitchell 1997)*

The impact of long-term changes in the tropical Atlantic SST is far reaching. The tropical Atlantic warming during the recent decades has been linked to SST changes over the Pacific and Indian Oceans (Li et al. 2015; Wu et al. 2019), and in turn to the global warming hiatus between the late 20th and the early 21st centuries (Kosaka and Xie 2013; Medhaug et al. 2017). These changes may have driven a stronger coupling between the interannual variability in both basins and thereby enhanced the seasonal predictability during the 1980's and 1990's (Cai et al. 2019). In addition, AMV has been linked to changes around the globe, as far reaching as the Indian and East Asian summer monsoon (Zhang and Delworth 2006; Keenlyside et al. 2015), as well as to variations in tropical inter-basin teleconnections (Martín-Rey et al. 2014). These global impacts appear mostly related to north tropical Atlantic SST (Ruprich-Robert et al. 2017).

4. Future changes in tropical Atlantic SST and associated climatic impacts

Climate change projections indicate that the tropical Atlantic will continue to warm over the next century as anthropogenic emission of greenhouse gases continue. Multiple generations of models predict a warming rate following the global mean pattern, consistent with historical changes (Lee et al. 2021). This corresponds to ~4°C (~3°C) warming by the end of century from 1850 (2000), following the high emission scenarios (RCP8.5 and SSP585) of the Coupled Model Comparison Projects (CMIP) 5 and 6. The model ensemble mean response shows a rather uniform warming pattern (Fig. 3a) (Crespo et al. 2022), which differs from the historical warming pattern (Fig. 1a).

The recent observed weakening of the equatorial and southeastern Atlantic SST variability is also projected to continue. A regionally refined global climate model indicates that coastal Angola Benguela SST variability will reduce by ~18% by the end of the century under the SSP585 scenario (Prigent et al. 2022), while Atlantic Niño variability is projected to weaken by ~14% by the end of the century following RCP8.5 and SSP585 scenarios from the CMIP5 and CMIP6 (Crespo et al. 2022). The weakening of equatorial Atlantic SST variability has been linked to the warming of the upper ocean that reduces the influence of thermocline variability on SST (Crespo et al. 2022), but also to the stabilization of the troposphere that reduces zonal wind variability (Yang et al. 2022).

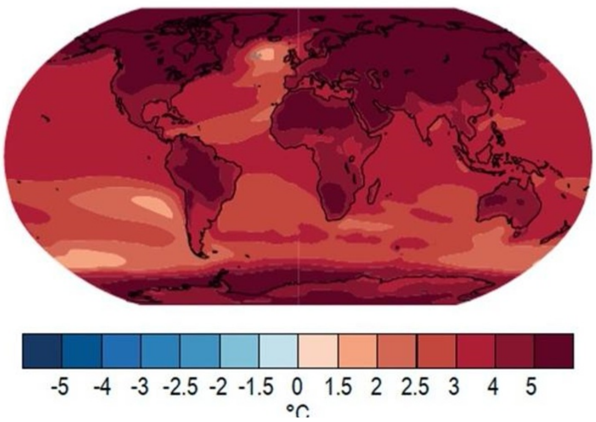
Despite continued improvements, the latest generation of climate models still exhibit large climatological warm SST biases in the eastern equatorial Atlantic, with too weak surface trade winds and a too deep thermocline (Richter and Tokinaga 2020). These biases influence the climate change projections through suppressing the thermocline feedback. Climate change projections with less biased models show stronger warming of eastern equatorial Atlantic SST (Park and Latif 2020; Imbol Nkwinkwa et al. 2021). Furthermore, Atlantic Niño variability is predicted to decrease much more (by 24-48%) when model bias is accounted for (Crespo et al. 2022).

Equatorial Atlantic precipitation is projected to increase by more than 20% and to decrease in the subtropics by 20-40% under a 4°C global warming by the end of the century (Fig. 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. The oceanic changes follow the global warming driven intensification of the hydrological cycle, with dry regions becoming drier and wet regions becoming wetter (Held and Soden 2006). Climate change projections indicate that meridional shifts in the Atlantic ITCZ will become more frequent as the SST warms faster north of the equator (Liu et al. 2022). At the same time, the weaker Atlantic Niño variability is expected to lead to less rainfall variability in the Gulf of Guinea (Worou et al. 2022).

Climate change projections of precipitation over South America and Africa have large uncertainties in many regions bordering the tropical Atlantic (Fig. 3b). However, there is a robust drying over the northern part of South America. Results based on CMIP5 multi-model mean and high-resolution regional model experiments (Akinsanola and Zhou 2018, 2019a, 2019b) support the dry (wet) projected conditions in the Sahel (Guinea coast) sub-regions of West Africa seen in CMIP6 (Fig. 3b). This change in rainfall pattern was attributed to the enhancement of moisture convergence and surface evaporation (Akinsanola and Zhou 2018, 2019a). 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).

The continuous warming of the tropics is expected to lead to an 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 tropical cyclones and thus can only indirectly assess future changes in tropical cyclone 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 tropical cyclones 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) argue, 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 an increase in the number of intense hurricanes.

(a) Surface temperature in 4°C warmer world



(b) Precipitation in 4°C warmer world

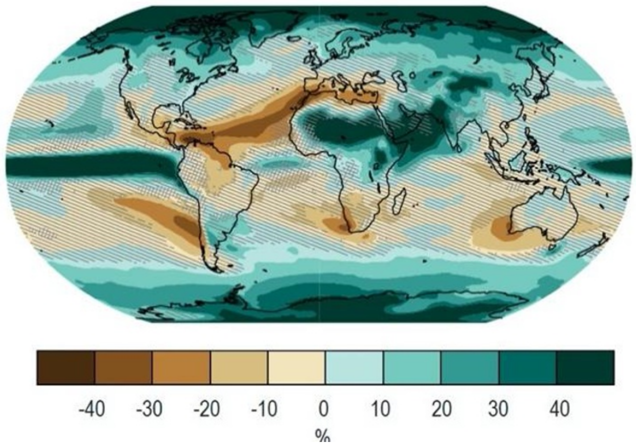


Figure 3. *Projected changes in (a) surface temperature and (b) precipitation in a 4°C warmer world. The results show the multi-model mean from the coupled model inter-comparison project version 6. Diagonal hashing indicates not statistically significant changes and crossing indicates regions with conflicting signals. Figure is adapted from figures 4.32 and 4.33 from Ch. 4 of the IPCC AR6 (Lee et al. 2021).*

5. Long-term changes in other oceanic indicators

In this section we briefly discuss long-term changes in sea surface salinity (SSS), AMOC, and sea level. SSS is an indicator of climate change, reflecting changes in the hydrological cycle and ocean circulation. Historical observations since 1950 show that SSS has increased substantially over the entire tropical Atlantic, contrasting changes in the Pacific and Indian Ocean, where significant freshening has been observed (Gulev et al. 2021). Climate change projections indicate that SSS in the tropical Atlantic will continue to increase (Ranasinghe et al. 2021) caused by the enhancement of the hydrological cycle (Terray 2012). 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.

The AMOC plays a crucial role in global climate as it drives the net northward oceanic heat transport (Zhang et al. 2019). It is linked to long-term variations in tropical Atlantic Ocean heat content, SST, and SSS and to the position of the overlying ITCZ (Johnson and Marshall 2002; Vellinga and Wu 2004; Zhang 2007; Frierson et al. 2013). Estimates of AMOC are highly uncertain prior to the deployment of the RAPID array in 2004 (Frajka-Williams et al. 2019). However, there is agreement that the AMOC underwent pronounced multi-decadal variability during the last century, although the different estimates—ocean reanalysis, long-term ocean model hindcasts, and fingerprint-based reconstructions—exhibit large discrepancies (Latif et al. 2006; Zhang 2008; McCarthy et al. 2015; Danabasoglu et al. 2016; Karspeck et al. 2017; Caesar et al. 2018). Long-term trends in AMOC over the last century are uncertain, but it is very likely that the AMOC will decline over the next 100 years in response to global warming (Fox-Kemper et al. 2021). This will lead to a warming of the tropical and South Atlantic, to changes in the tropical Atlantic Ocean circulation, and to a southward shift in the ITCZ (Stouffer et al. 2006; Chang et al. 2008), affecting continental rainfall and tropical basin interactions (Svendsen et al. 2014; Orihuela-Pinto et al. 2022). A southward ITCZ shift may also influence the equatorial trades by decreasing their mean strength, assuming that the currently observed relationship between the ITCZ latitude and the trade winds continues to hold (Richter et al. 2014).

Sea level rise is one of the major consequences of global warming. Our understanding of sea level rise in the tropical Atlantic over the last century is hampered by severely limited tide gauge records (Thoreux et al. 2018). The available records suggest that sea level has risen at around 2.1 mm yr^{-1} since 1927 along the northwest African coast, faster than the estimated 1.73 mm yr^{-1} in global sea level rise between 1901 and 2018 (Thoreux et al. 2018; Fox-Kemper et al. 2021). Satellite altimeter measurements indicate a nearly spatially uniform rise in sea level of approximately 2.0 mm yr^{-1} over the tropical Atlantic between 1993 and 2018 (Cazenave et al. 2018). Climate change projections indicate 77 cm (median value) global mean sea level rise by 2100 relative to the 1995-2014 period under the SSP585 emission scenario, with slightly larger increases in the tropical Atlantic compared to the other basins, but still with large uncertainties (Fox-Kemper et al. 2021).

6. Summary and discussion

The tropical Atlantic warmed by around 1°C since 1900, primarily because of anthropogenic emissions of greenhouse gases. Far greater warming of the tropical Atlantic is projected following commonly used emission scenarios. Superposed on the long-term warming were strong multi-decadal variations in SST, caused by a combination of internal climate dynamics and external radiative forcing (mainly from anthropogenic aerosols loadings). These long-term changes in tropical Atlantic SST have profound and far-reaching climatic impacts, including hurricanes, droughts and floods over bordering continents, and changes in the tropical Pacific and Indian Oceans.

Despite progress in understanding and modelling long-term changes in the tropical Atlantic, there are several areas that require further research. The relative importance of external forcing and internal climate dynamics in driving decadal SST variations in the tropical Atlantic is poorly known. The contribution of ocean dynamics and aerosol forcing to the accelerated warming of the tropical Atlantic during recent decades is debated. To what extent changes in the AMOC have contributed to historical variations in the tropical Atlantic is unclear, and the influence of the projected weakening of the AMOC on the region is uncertain.

More effort is also required to understand and model the climatic impacts of long-term tropical Atlantic SST changes. Model error is a key source of uncertainty, with state-of-the art models exhibiting large warm SST biases in the eastern equatorial and south Atlantic, cold SST bias in the northern tropical Atlantic, and a southward displaced ITCZ. These influence the representation of tropical Atlantic variability and teleconnection patterns, which in turn introduces uncertainties in projected changes in rainfall patterns in the region, in tropical storms and hurricanes, and in Indo-Pacific SST.

The long-term changes in the tropical Atlantic also impact marine ecosystems, but these are poorly known as long-term observations of the marine ecosystem are sparse. Along the African coast the R/V Dr Fridtjof Nansen (FAO, Nansen Project, www.fao.org/in-action/eaf-nansen/en/) has carried out particularly useful stock assessment for almost three decades using fisheries acoustics sea surveys. These data have revealed shifts in small pelagic fish stocks along the coasts of Northwest Africa (A. Sarre, pers. comm.) and Angola (M. Ostrowski, pers. comm.) related to SST trends. Furthermore, marine heatwaves in the tropical North Atlantic have increased during the last 35 years (Oliver et al. 2018) and these are a major stressor on marine organisms, including coral bleaching, disease outbreaks, and forced migration (Comte and Olden 2017; Hughes et al. 2018). Recent studies have shown that climate change will profoundly affect global ecosystems, mainly through its effects on the ocean temperature (and its stratification), acidity (pH) and dissolved oxygen level (Gattuso et al. 2015). However, 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). The EU funded TRIATLAS project (triatlas.w.uib.no) is one major effort to address these knowledge gaps.

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. Here upper ocean temperature, salinity, and surface flux observations are important. Moored arrays are crucial to monitor basin scale changes in the overturning circulation. Continental climate observations need to be enhanced to better understand climatic impacts. In addition, we recommend the recovery of undigitized historical data and enhancing the paleo-proxy archives to better understand changes over the historical period. Bio-ecological times series on biomass assessment and spatial distribution of key marine species must be maintained using standardized procedure (Brehmer et al. 2019) and related to essential environmental variables, to better understand and evaluate the impact of long-term climate change on the marine ecosystem, their marine resources, and services.

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Theme 9: Tropical Atlantic Ocean Observing System: Future Perspectives

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The previous articles have described the current status of the TAOS and a set of key science and operational drivers that should guide its future development. There remain 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 benefits. 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 important 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.

1. General Recommendations

Based on the science and operational drivers summarized in previous sections, the key recommendations for the future TAOS are listed below. We do not provide a prioritization of the recommendations because all are important and different. To encourage the widest possible participation in TAOS, different organizations, agencies, or nations may want to focus on a subset of recommendations that address their own priorities.

2. Tropical Atlantic Variability and AMOC

- *Better constrained and validated surface heat flux measurements and estimates of subsurface thermal variability* are required for improved understanding and prediction of SST anomalies associated with TAV modes (Meridional Mode, Atlantic Niño, Benguela Niño).
- *Continuous long-term, large-scale monitoring of SST* is needed for improved predictions of West African rainfall. Continuous monitoring of tropical Atlantic salinity and ocean circulation is also mandatory for accurate forecast systems and monitoring of the regional hydrological cycle, which is connected to rainfall over land.
- *Characterization of the location and strength of deep convective systems* across the tropical Atlantic will help improve understanding and prediction of the extratropical influence of TAV. An increase in the number of radiosonde observations in the tropical Atlantic would be beneficial for constraining the dynamical aspects of tropical-extratropical interactions.
- *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.

- *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, and remote sensing of the surface velocity field is a high priority for future satellite missions.
- *Sustained measurements of the AMOC in the tropical Atlantic,* in conjunction with those at other latitudes, are needed to understand the meridional coherence of the AMOC, the dynamics of the basin-wide AMOC response to changes in forcing, and the impact of the AMOC on TAV.

Carbon System, Biogeochemistry, Ecosystem Dynamics, and Fisheries

- *An optimized observing system* is required to quantify the variability of tropical CO_2 fluxes, including sub-decadal interior deep ocean carbon storage.
- *Sustained measurements and improved geographical coverage of key biogeochemical variables* including dissolved oxygen, transient tracers and nutrients are required to understand the processes that influence oxygen concentrations and the interplay with nutrients. Measurements of particulate matter, dissolved organic carbon, and microbe biomass and diversity are also needed.
- *A joint definition of observing needs with the fisheries and biodiversity communities* is recommended to identify opportunities between fishery surveys and more climate-driven observing needs, especially within the highly-productive eastern upwelling zones.
- *Continued evolution of fisheries management* from a traditional single species approach to an ecosystem-based view that puts fish stocks in the context of other organisms (prey, predators, and competitors) and their environment. Promotion of open-access policies for ecological and fisheries data is strongly recommended.
- *Development of a broad review and consultation* on current observing efforts and observing needs related to tropical Atlantic fisheries, involving inter-governmental and regional bodies. Coordinated national survey programs need to be linked and supported.

Ocean Heat Content, Sea Level Rise, and Climate Change

- *The TAOS must provide 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 the pathways by which it is transported for effective monitoring and understanding ocean heat content and sea level change in the tropical Atlantic.
- *A sustained TAOS is key to monitoring climate change* in the tropical Atlantic and improving 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.

Improved Predictions on Subseasonal to Decadal Time Scales

- *Sustained observations of the ocean-atmosphere system* in the tropical Atlantic are required for forecasts on all time scales, through their impact on initialization of forecast models, calibration of model output, skill assessment, and model and data assimilation development. Continued observations of subsurface fields (including ocean temperature and currents) are crucial to initializing seasonal and decadal predictions.
- *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 coupled climate model biases. Improving the ability of climate models to predict "Atmospheric Rivers" - plumes of intense water vapor transport emanating from the tropics - should also be a top priority for Atlantic basin climate research.
- *Extension of the observational network and measurement campaigns* in the equatorial Atlantic, including 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.

3. Recommendations for Enhancement of the TAOS

Addressing these general recommendations will require enhancement of the current TAOS, and in general more consistent observations across all societal requirements. The platform-specific enhancements described below should be carried out in the broader context of user requirements defined by essential ocean variables (EOVs; https://www.goosocean.org) and essential climate variables (ECVs; https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables). Detailed discussion of the EOVs and ECVs for the TAOS are provided in the TAOS Review Report.

Moored Platforms: The Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) constitutes the main deployment of moored resources in the tropical Atlantic, and it has been continually improved and updated throughout its 25-year lifetime. 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:

- Enhanced vertical sampling of upper ocean temperature and salinity on all PIRATA moorings so that the mixed layer depth and underlying stratification can be determined with greater accuracy.
- 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 obtained on two equatorial moorings.
- Barometric pressure and downwelling longwave radiation sensors on all PIRATA surface buoys, allowing them to serve as flux reference sites.
- pCO_2/fCO_2 sensors should be installed on an extended set of PIRATA moorings.
- Additional BGC sensors should be selectively added to PIRATA moorings, including dissolved oxygen, pH, and nitrate.

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 to provide real-time information relevant for hurricane forecasting in an area where rapid intensification of TCs can take place before landfall (Fig. 1). This is also a region where barrier layers frequently occur due to advected Amazon waters and where subsurface heat content observations would be particularly valuable. It is also recommended to permanently maintain the new pilot PIRATA mooring recently established at 10°W, 20°S to improve the capacity to predict extreme rainfall in tropical South America and to help constrain upper-ocean transports in the South Atlantic.

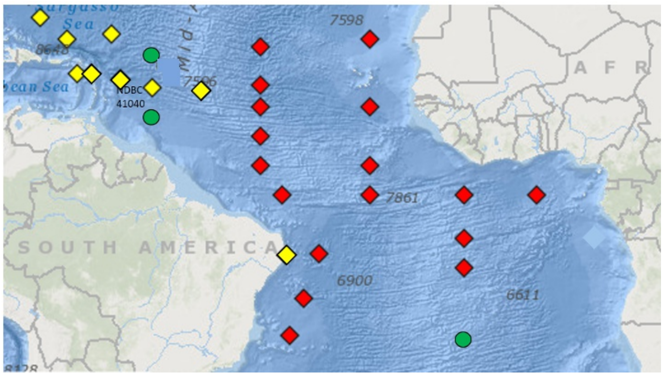

Figure 1. *Green circles in the northwestern tropical Atlantic show recommended new PIRATA sites to establish a new buoy line along ~53°W with NDBC buoy 41040 (yellow diamond). Green circle in the South Atlantic shows the recommended new long-term PIRATA buoy at 20°S, 10°W. Other yellow diamonds are the locations of existing surface meteorological buoys. Red diamonds show the locations of existing PIRATA buoys.*

Drifters: The surface drifter network maintained 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 that measure barometric pressure.
- Continue efforts to optimize the SVP drifter array seeding in the tropical Atlantic using "drifter value" maps.
- Deploy an increased number of drifters in the northeastern tropical Atlantic during boreal spring of each year, providing enhanced data for tropical cyclone prediction (including barometric pressure) in summer and fall as they spread westward.
- Explore the feasibility of deploying an array of thermistor-chain drifters along the equatorial waveguide to increase the number of SST and upper-ocean temperature observations.

Argo: Argo plays a vital role in the tropical Atlantic and global observing systems and is a particularly effective and efficient measurement platform for obtaining much-needed information on biogeochemical processes through 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 endorsed and recommended full implementation of the "Argo 2025" vision (Roemmich et al. 2019). 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 (Fig. 2). 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. Deep Argo will provide much-needed data to track deep water property changes and heat storage on sub-decadal time scales.

Vessels: As the PIRATA program constitutes one of the largest commitments of ship resources in 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. In addition, full-depth sampling at selected stations is desired. The GO-SHIP and VOS XBT programs provide vital sampling and measurements along repeated transects in the tropical Atlantic and should be sustained.

Satellite observations:

- *Sea surface height:* The altimeter mission constellation has continuity missions planned through 2030. The Surface Water Ocean Topography (SWOT) mission (planned launch date November 2022) will provide submesoscale measurements with a 21-day repeat cycle.
- *Sea surface temperature:* The continuity of infrared SST missions is ensured (e.g., with the operational NOAA series satellites), while passive microwave (PMW) SST mission continuity is less secure. 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.
- *Wind:* Despite several ongoing and planned scatterometer missions, resolving the diurnal cycle remains an issue because it requires multiple scatterometers with equatorial crossing times that are separated relatively evenly through a 12-hour period. Three to four scatterometers could provide 90% or more coverage of the global ocean at 6-hour intervals.
- *Sea surface salinity:* There are no commitments to missions beyond Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP), but missions are being planned. Improved and expanded measurements of surface salinity are needed to address issues on the water cycle,

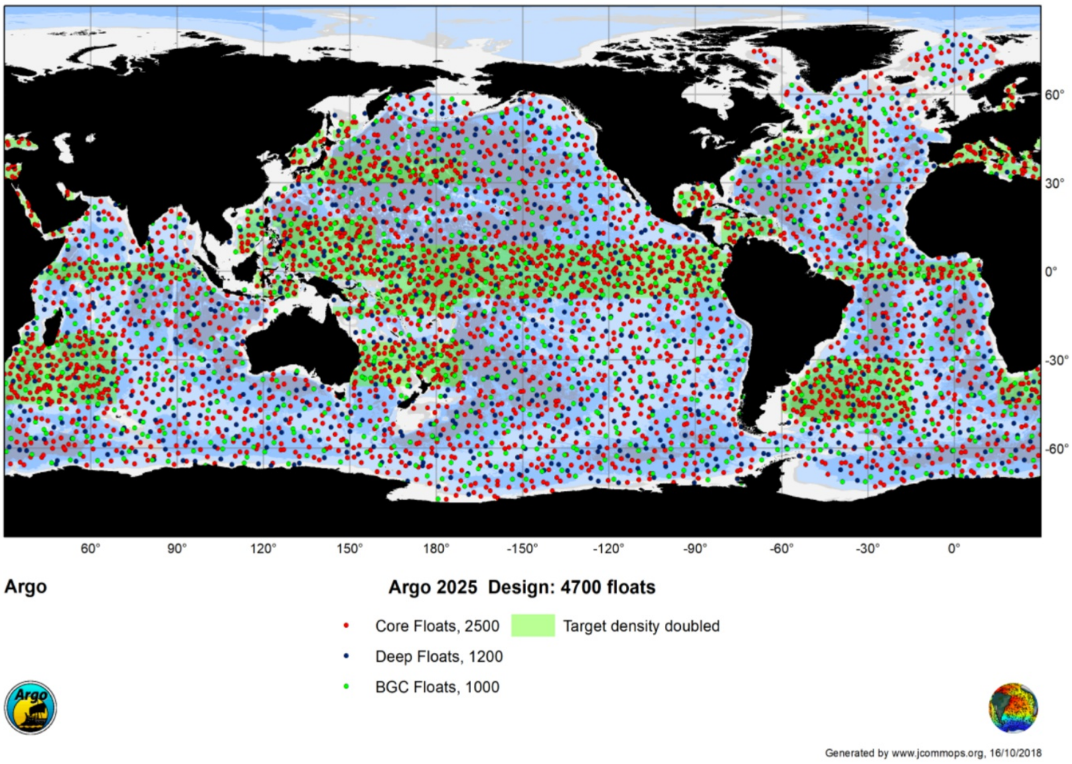

Figure 2. *The "Argo 2025 Design" sampling vision for the global oceans (Roemmich et al. 2019), indicating regions of higher resolution Argo sampling (green shading) and the approximate distribution of core Argo, BGC-Argo, and deep-Argo floats.*

subseasonal to decadal prediction, and climate change, and continued satellite SSS missions with improved accuracy are therefore vital to the TAOS.

- *Surface ocean currents:* A satellite capability for continuous broad-scale direct surface velocity measurements would be extremely valuable for the TAOS due to limits of geostrophy near the equator. New missions should be supported as key future elements of the TAOS.

Other observing platforms: Newer observing platforms such as uncrewed surface vehicles (e.g., saildrones, wavegliders) and ocean gliders should be considered as part of both targeted regional process studies and in a sustained mode. 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. Saildrone technology in particular has advanced rapidly over the past several years to enable continuous monitoring of the upper ocean and near-surface atmosphere for several months at a time in some of the harshest conditions on Earth. The data have proven reliable and valuable for research and forecasting (e.g., Meinig et al. 2019; Zhang et al. 2019; De Robertis et al. 2021; Sutton et al. 2021; Foltz et al. 2022). Process studies are also an essential part of observing and prediction systems in order to test new observing technologies, drive new scientific understanding, and improve model parameterizations.

Improved data assimilation: For most applications relevant to society, it is the reanalyses and forecasts produced by operational centers that are most valuable. It is therefore essential that analyses and forecasts that assimilate the observations extract the maximum value from the 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, particularly for subsurface fields that are not as well constrained as those at the surface. There is an urgent need for advanced data assimilation studies to help determine the resolution of the required observations. Such an effort might consist of three components:

- An observing system simulation experiment (OSSE) framework in which data are extracted from a base (nature) model run and ingested into other models to explore the required temporal and spatial resolution of data to recover the "correct" model state in reanalysis mode.
- An observing system experiment (OSE) framework whose results are applied to assess the influence of particular observational platforms on ocean analysis and subsequent forecast skill.
- A specific co-design process that uses OSEs, OSSEs, and subject matter experts to incorporate variables that are not yet approachable through these techniques (e.g., biogeochemistry and fisheries). Links to the UN Ocean Observing Co-Design Programme and to coastal efforts undertaken for fisheries by bordering nations are recommended, as is an expansion of the variables measured during fisheries surveys.

4. Recommendations for Data Flow and Information Products

Most of the data collected by the observing elements of the TAOS is available online to users either through platform-specific data websites or through integrated data products served by operational and data centers. There are not any major TAOS-specific issues regarding data and information management; most of the TAOS challenges are shared by the global community (e.g., Tanhua et al. 2019; Snowden et al. 2019; de Young et al. 2019):

- Data management is poorly funded in the context of its vital role in the ocean observing system.
- TAOS data should be Findable, Accessible, Interoperable, and Reusable (known as FAIR Principles).
- There is often a reluctance or inability to invest effort in properly documenting the data (metadata).

The following recommendations were made for addressing these challenges:

- 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 management should conform with the FAIR Principles. Data stewardship, and the engagement of all TAOS stakeholders in data management, are central priorities for the sustainability of TAOS.
- 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.
- Implementation of improved systems for monitoring TAOS data production.

5. Recommendations for Governance, Review, and Resourcing

The core elements of TAOS have matured over the past 25 years and many countries in North and South America, Europe, and Africa are now contributing. However, closer coordination and stronger partnerships with African, North and South American, and Caribbean communities are needed. Closer interactions with end-users and more efficient evaluations of the observing system are also recommended. These could be achieved in part through the Global Ocean Observing System (GOOS) and its three United Nations Decade programs. TAOS would benefit from a governance structure that will ensure a high level of coordination among the observing system components, provide guidance for future evolution of the observing system, and advocate for resources to help sustain the observing system. The TAOS would benefit from links with the tropical Pacific and Indian Ocean observing systems (TPOS and IndOOS). These connections could foster the exchanges of best practices, technology, and experience and motivate the establishment of a working group to build a Pantropical Observing System.

The establishment of a "TAOS Forum" is recommended. The 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 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 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.

Regular major reviews of TAOS are recommended. These will enable assessments 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 approximately once per decade with five-year mid-term assessments. They 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.

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