CLIVAR REPORT

Climate and Ocean: Variability, Predictability, and Change

Workshop Report

Report on the First Tropical Atlantic Observing System (TAOS) Review Workshop

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Executive summary

Rationale and motivation for the TAOS review

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

To that end, a Tropical Atlantic Observing System (TAOS) review was proposed by the CLIVAR Atlantic Region Panel (ARP) and will be organized by the CLIVAR ARP in close cooperation with the PIRATA consortium. CLIVAR ARP will take the lead and coordinate the review, evaluate scientific progress since the last review, and recommend actions to advance sustained observing efforts in the tropical Atlantic. The ARP will seek to involve the International Ocean Carbon Coordination Project (IOCCP), the Integrated Marine Biosphere Research Program (IMBeR) and Surface Ocean - Lower Atmosphere Study (SOLAS), among others, as key partners in the review process. The review will complement other reviews focusing on different elements of the Atlantic observing system to take place in the next several years (for example, RAPID-AMOC and OSNAP). It will benefit from parallel efforts being carried out in the Pacific and Indian Oceans, namely the Tropical Pacific Observing System TPOS 2020 project, and the Indian Ocean Observing System (IndOOS) review. Results of the TAOS review are also expected to feed into the AtlantOS design strategy that is currently being formulated in advance of the OceanObs'19 conference.

The TAOS review will be forward looking and strategic, and focus on possible changes to the observing system in the next decade. It will consider new observing technologies, observing system requirements from the user community (e.g. weather and climate forecasts), and observational products that will be delivered. The review will be guided by the framework for ocean observing and make recommendations toward an adequate governing mechanism. The review will be comprehensive across all relevant observing system networks, including satellite observations, but with the focus primarily on the in situ observing system, and will consider atmospheric parameters (e.g. winds, surface fluxes) as well as aerosols, biogeochemistry and biology within the framework of a single integrated observing system.

Implementation of the TAOS Review

The review will be conducted by a TAOS Review Committee composed of members of the tropical Atlantic observing community and representatives from GOOS/GCOS, with oversight by the CLIVAR ARP, several of whose members will also serve on the committee. Bill Johns (U. Miami) and Sabrina Speich (LMD/ENS, and ARP Co-chair) were appointed as co-chairs of the review committee. The full review committee is listed in Appendix A.1. Terms of reference (TORs) for the review were developed by the ARP in consultation with the review committee and are listed in Appendix A.2.

This report describes the proceedings from the 1st "kickoff" workshop of the review (see Appendix A.3), held on February 8 and 9, 2018, adjacent to the 2018 Ocean Sciences meeting in Portland, Oregon. A total of 30 participants (See Appendix A.4) attended the workshop at the invitation of the review committee. A 2nd TAOS Review workshop is planned to be held in Marseille, France October 2018 immediately following the annual PIRATA meeting there, after which a final TAOS Review report is expected to be delivered to the CLIVAR ARP by April, 2019.

Goals of the Workshop

The workshop was organized into four main sessions on the following topics:

Session 1: Requirements for the Tropical Atlantic Observing System (co-chairs: S. Speich, M. Balmaseda)
Session 2: Tropical Atlantic Observing System Networks: Current Status and plans to 2030 (chair: B. Johns)
Session 3. Data Flow and Information Products (chair: N. Smith)
Session 4. Governance, Review, and Resourcing (chair: K. Hill)

Most of the time during the workshop was devoted to topics 1 and 2, with the goal of accomplishing at this first workshop a thorough review of:

(1) the state of knowledge of the tropical Atlantic regarding key science and operational drivers relevant to societal applications, and

(2) the present state of the tropical Atlantic observing system and its capabilities for delivering the necessary data and information products toward these applications.

In the ensuing discussions the participants were asked to consider the question: What is the key information that is being (a) successfully provided and (b) missing from the Tropical Atlantic observing system for these science/societal drivers?

Presentations were given on a wide range of topics covering the modes of tropical Atlantic variability and their known climate consequences, issues related to operational weather and extreme event forecasting, data assimilation, climate projection, and biogeochemical and biological/fisheries applications. The various elements of the present TAOS including mooring arrays, autonomous devices, satellite observations, and vessel-based observations were also thoroughly reviewed. On the second day of the workshop the mechanisms and effectiveness of data delivery from the existing tropical Atlantic observing system, and considerations on possible future governance and resourcing for the TAOS, were also briefly discussed.

Session summaries prepared by the session chairs outlining the main outcomes and recommendations from the workshop are provided in the main body of this report, and extended abstracts from each of the presenters in sessions 1 and 2 are included in Appendices A.5 and A.6. The workshop was a successful first step in evaluating the present TAOS and considering possible future enhancements or modifications to the TAOS. The general conclusion from this workshop was that the observational community in the tropical Atlantic is a relatively tightly knit group that currently enjoys a high degree of collaboration and effective leveraging of its resources, but that the TAOS as a whole could benefit from further integration across its various data platforms and efforts to enhance and streamline data delivery.

1. Requirements for the Tropical Atlantic Observing System (Chairs: S. Speich and M. Balmaseda)

The purpose of Session 1 of the workshop was to provide a comprehensive view of the scientific and societal requirements for a Tropical Atlantic Observing System. This summary is based on the following presentations (with lead presenter):

- Societal impact and importance of observing the Tropical Atlantic (Moacyr Araujo)
- Tropical Atlantic variability and change (Paulo Nobre)
- Role of the Tropical Atlantic in the climate system (Belen Rodriguez-Fonseca)
- Impact of Tropical Atlantic biases in climate predictions/projections (Noel Keenlyside)
- The Tropical Atlantic as a key driver of global climate – implications for observations (Jeff Knight)
- Capabilities for seamless forecasting from days to seasons: the role of ocean observations (Magdalena A. Balmaseda)
- 2017 Atlantic Hurricane Season Review and National Hurricane Center Ocean Observations Requirements for Improved Forecasts (Scott Stripling & Ping Chang)
- Evaluation of the Tropical Atlantic observing system from ocean data assimilation perspective: Marine applications (Marie Drevillon)
- Biogeochemical applications in the Tropical Atlantic: Requirements, synergies, and gaps (Toste Tanhua)
- Biology and Fisheries applications: Requirements, synergies, and gaps (Jörn Schmidt, remote connection)
- Related observational programs (IMBeR, SOLAS, POGO) (Carol Robinson)
- Atmospheric and marine boundary layer processes (Paquita Zuidema)

Sustained observations of the thermal, dynamical, chemical and biological state of the Tropical Atlantic Ocean are required to meet needs for global, regional and local information. Observations of neighboring oceans, of the atmosphere, and of land-surface conditions are also required to complement the observations made directly of the Tropical Atlantic. The observations are used to monitor present conditions, to enhance understanding, to improve modeling and data assimilation, and thereby to support monitoring and prediction of the Tropical Atlantic and places farther afield, and to support projections of future climate. The information derived brings important societal benefits by (i) fostering marine ecosystem health and biodiversity; (ii) promoting human health; (iii) improving the adaptation to and mitigation of climate change; (iv) reducing risks from extreme weather and climate events; (v) enhancing water, food, and energy security; and (vi) advancing maritime safety, management of marine resources and the Blue Economy.

The Tropical Atlantic must be monitored as part of the global climate system. Most basic are observations of sea-surface temperature and observations to determine the oceanic uptake of carbon dioxide. The former are used to estimate global-mean surface temperature and the latter are used together with estimates of anthropogenic emissions and land sinks to account for change in the concentration of carbon dioxide in the atmosphere. Both are fundamental to taking stock of progress in the implementation the Paris Agreement under the United Nations Framework Convention on Climate Change.

Observations of sea-surface temperature variations in the Tropical Atlantic are important for other reasons. They are crucial for the forecasting of hurricanes, for which observations of oceanic mixed-layer temperatures and a range of atmospheric observations are also required. The devastating impacts of these storms are felt beyond the confines of the Tropics, over the Caribbean Sea and coastal regions of Central and North America in particular for systems that originate in the Tropical Atlantic. Influences on weather at more northerly latitudes are also felt when hurricanes recurve and make the transition to extratropical cyclones.

Variations in sea-surface temperature over the Tropical Atlantic are linked through atmospheric convection and circulation with variations in rainfall over adjacent continental regions such as Amazonia, Northeast Brazil, the Sahel and the countries bordering the Gulf of Guinea, thereby influencing human health and agricultural production. Linkages exist more remotely to the tropical Pacific and Indian Oceans. A link to the extratropical Atlantic and Europe exists through the convective excitation and subsequent propagation of Rossby-wave disturbances.

It has become evident as well that efforts to observe the subsurface coastal and open-ocean regions are also important to forecast and monitor sub-seasonal to interdecadal variability and climate change. Sea-surface temperature and carbon fluxes are strongly affected by air-sea exchanges but also by the underlying ocean vertical structure and dynamics. Indeed, observations of subsurface physical and biogeochemical variables are essential to understand and predict air-sea interactions and the mean-state, variability and changes of ocean currents, tropical cyclones, transports and global budgets. These observations are also key to understanding and monitoring the complex tropical Atlantic interhemispheric exchanges that play an essential role in the Atlantic and global Meridional Overturning Circulations (AMOC and MOC respectively) and the related meridional transports of heat, freshwater, carbon as well as other biogeochemical compounds. In particular, they are key in addressing the regional imprint on the Earth Energy Imbalance (EEI).

Variability of the physical state of the ocean involves currents, temperature and salinity, the fluxes of momentum, radiation, sensible heat and freshwater between atmosphere and ocean, and the freshwater flux from rivers. Air-sea interaction is the mechanism by which processes in one fluid drive processes in the other, occurring primarily through mixing in turbulent boundary layers both in the atmosphere and in the ocean. Such interactions in the tropical oceans have been thought to be at large-scale. However, there is increasing evidence that ocean mesoscale processes (10-100 km scales) play an important role, but in ways that remain to be better understood and quantified. To improve weather forecasts and seasonal to interdecadal prediction there is a need to observe, simulate and advance our understanding on air-sea interactions in the tropical Atlantic at these scales, in particular to unveil their impact on the ocean upper boundary layer (OBL), their contribution to air-sea fluxes and atmospheric shallow and deep convection.

Atmospheric and fluvial fluxes are important also for the air-sea interactions and the biogeochemical state of the ocean. They affect the regional budget of freshwater and shape locally the OBL that can become shallower in the presence of freshwater-induced Barrier Layers that are generally characterized by high SST. These Barrier Layers seem also to affect air-sea interactions, weather predictions and extreme events. Moreover, these fluxes impact the ocean meridional transport of freshwater.

Sea level is a critical variable that requires routine monitoring. In coastal regions, sea-level rise is a major concern as it is particularly sensitive to regional ocean warming (steric-effect), ocean dynamics, and weather regimes. Sea level observations from satellite altimetry in the open ocean in complement to the sparse *in situ* observations provide important information on the temperature and salinity of the water column. Ocean surface-wave observations are also important in both the open ocean, where they influence transfers between atmosphere and ocean, and in coastal regions where many of their impacts are felt.

Ocean temperatures have local effects on marine ecosystems. Temperatures higher than normally experienced can cause bleaching of corals and harm to the marine life that depends on them. Human activities such as fishing and tourism may suffer as a consequence. Temperature also has direct effects on the metabolism and behavior of many marine species.

These phenomena are particularly important within the coastal and continental slopes, where the largest ecosystems and marine national economic activities take place.

Transfer within the ocean of essential biogeochemical variables such as oxygen and nutrients occurs through transport by currents, mixing, and upwelling and downwelling. Understanding nutrient variability is critically important as the supply of nutrients to the surface waters is the main limitation for primary production. The oxygen content of seawater is also important for marine life, and the zones with minimum oxygen content need in particular to be monitored in view of evidence that they are expanding and that their concentration of oxygen is decreasing.

The tropics are important areas of CO_2 fluxes, associated with significant interannual and seasonal variability. Similarly, for the interior ocean it has been shown that the tropical Atlantic is storing significant amounts of anthropogenic carbon, and the associated decrease in pH and carbonate ion concentration is leading to under-saturation of aragonite in the region. Interior observations of the inorganic carbon system are important for the understanding of these processes. The Tropical Atlantic is also an important area for the flux of the greenhouse gas nitrous oxide, although the variability and magnitude of this flux are poorly determined by present observations. Observations of the biogeochemical variables also allow some unobserved aspects of the physical state of the ocean to be inferred.

Observations of the dynamical and thermodynamical workings of the climate system are needed to diagnose and correct errors in the models that are used for forecasting on a range of timescales and for projections of long-term climate change. Biases in the south-eastern Tropical Atlantic are among the most severe of all biases found in state-of-the-art climate models. There is a consensus that bias in sea-surface temperatures in the equatorial Atlantic is caused by too weak easterly winds in boreal spring, leading to a weak development of the equatorial cold tongue in boreal summer. Ocean stratification errors associated with vertical mixing and surface freshwater biases may also contribute. There is less agreement on the cause of bias in the Angola-Benguela region.

Operational weather forecasting centers are increasingly adopting coupled atmosphere/ocean modeling systems, some of which include interacting ocean surface waves and sea ice. The motivation is to improve existing types of forecast, for example to account for air-sea interactions important for the intensity of tropical cyclones, and to extend the forecast horizon from days to seasons. Although the observational needs of the different forecasting systems vary, all of them revolve around four main activities: initialization of the forecast model, model and data assimilation development, calibration of model output and skill assessment. Both calibration and skill assessment require a set of reforecasts over a sufficiently long period that are initialized from reanalyses of the available observations. Coupled data assimilation is being developed not only for the initialization of the coupled forecasts, but also for the production of future generations of Earth-System reanalyses.

Temperature is generally well captured in ocean reanalyses, especially near the surface, where observations are more fully available to constrain the assimilating model. The analysis of salinity, even more than temperature, was very much improved by the implementation of the ARGO network. However, the analysis of three dimensional velocity structure remains challenging, especially in those areas where geostrophic balance is insufficient to constrain the velocity field from the mass field. Thus, errors remain in the equatorial regions, western boundary currents, and deep currents close to topography gradients. In general, analysis systems do not assimilate all the information available from the observing system, as choices are made to retain only large scales, or only part of the observed signal (removing tides, for example) depending on the model and targeted application. For instance, climate studies generally require different resolutions or tunings than analysis efforts in support of maritime security.

Atmospheric reanalyses are extensively used in a wide range of applications, including the calibration and assessment of forecasting systems as noted above and in the provision of surface fluxes for ocean reanalyses. In turn the atmospheric reanalyses have a requirement from the ocean observing system for consistent multi-decadal time series of sea-surface temperature analyses, including extension to near-real time data. Those atmospheric reanalyses that include key composition variables also have requirements for surface fluxes of variables such as carbon dioxide. As well as serving both operational and research activities, many types of observations will increasingly serve both atmosphere and ocean analysis and forecasting systems as coupled systems become more widely used.

Many of the topics discussed above were reviewed in more detail in the presentations made at the workshop. Summaries of these presentations are included as Appendix A.5 of this report.

The presentations drew the following conclusions concerning observational needs and opportunities:

- Long-term sustained monitoring of the Tropical Atlantic is paramount to improve our capability to predict climate variability and change. The current complex of observing systems offers much of the data needed to monitor the Tropical Atlantic and constrain models, but there are gaps.

- Additional measurements of velocity and salinity in the upper ocean from PIRATA moorings should be a top priority for improving understanding of the mixed layer heat budget. With the addition of several current meters on a PIRATA mooring (or a surface downward-looking ADCP, or microstructure sensors), better estimates of shear-induced mixing can be made to help close the heat budget.

- Observations are required to close the momentum budget in the ocean and atmospheric boundary layers. Observations to further constrain heat and freshwater ocean mixed-layer budgets (including surface fluxes) can help reduce biases and enhance ocean reanalysis. Ocean current observations along the southeastern boundary are also important for understanding and simulating equatorial and coastal variability.

- Important gaps in observations lie in the coastal and upper 1500 m of the continental slopes where important fractions of interhemispheric transports and exchanges with the open-ocean take place, where significant marine ecosystems, fisheries and economic activities are located, and where vulnerability of society to extreme events is largest.

- Atmospheric surface-pressure sensors should be included on moored buoys and all drifting buoys. The surface pressure data available from around half the drifting buoys has a high impact on weather forecasts and helps through data assimilation to determine surface winds and their forcing of the ocean.

- Better temperature profiling of the ocean in the narrow equatorial regions is needed as this would provide improved information on the variations in heat content availability that can drive convective variability. Atmospheric boundary layer properties such as winds and moisture are also key drivers of convective variability that could be better determined.

- Further atmospheric properties - the surface manifestations of conditions in the free atmosphere such as radiation and rainfall - are needed over the ocean. Oceanic rainfall is closely related to the mid-tropospheric heating that drives remote influences, but satellite-based observations are uncertain. These observations could benefit from multiple references to buoy-based “ground truth”.

- Observations of the Tropical Atlantic Ocean critical to improve our predictive capability of Atlantic hurricanes include increased observations across their main development region and through to the Gulf of Mexico, including sea-surface temperatures, mixed layer profiles to around 200 m and spectral ocean surface-wave data. Better meteorological measurement of winds, air-temperature, humidity and surface pressure is also required. Enhanced measurements from the PIRATA array should provide timely, higher temporal frequency data and a full suite of meteorological measurements. T-Flex moorings will enhance the measurement capability.

- High-frequency data, particularly on currents, from moorings such as PIRATA are also crucial for validation/calibration. They have also proven useful for data assimilation of temperature and salinity.

- Ocean monitoring and forecasting systems will strongly benefit from higher resolution remote sensing observations such as from SWOT, which will provide a better constraint on small scales for all surface variables. Surface salinity data from remote sensing will be assimilated soon in ocean reanalyses as they have been shown to improve the accuracy of analyses and thereby seasonal forecasts. Coastal observations, in particular of transports and currents, will be taken into account better in the future, and the assimilation of such observations is expected to improve the representations of the general circulation of the whole Atlantic basin.

- Sustained observations of all the biogeochemical Essential Ocean Variables in the Tropical Atlantic have high impact. The design of an observing system that captures their expected variability, and the regions that are most variable or expected to show a trend, still needs to be defined based on the current knowledge of the biogeochemistry of the tropical Atlantic.

- A monitoring system for carbon dioxide is a major need. Additional observations of the stable isotope composition of inorganic carbon (13C) provide information on storage of anthropogenic carbon. There also needs to be an increased effort to include observations of nitrous oxide in the Tropical Atlantic.

- All observational data, inclusive of all variables, needs to be made more accessible, including through contributions to reanalyses and other gridded datasets.

It was further noted in presentations that observational programs in the Tropical Atlantic provide fertile opportunities for capacity building. Initiatives to be undertaken in the TAOS program need to fully exploit the scope for interaction with other programs. Communication between TAOS and complementary international programs, including representation of the programs on the TAOS review committee, should ensure transfer of best practices and enhance opportunities for comparative analysis, method development, training and other aspects of capacity building.

2. Tropical Atlantic Observing System Networks: Current Status and plans to 2030 (Chair: B. Johns)

The purpose of Session 2 of the workshop was to provide a comprehensive review of the existing observing networks within the Tropical Atlantic observing system. Presentations (with lead presenter) were given on:

- Mooring Networks (Moacyr Araujo)
- Satellite Observations (Abderrahim Bentamy)
- Lagrangian observations (Rick Lumpkin)
- Autonomous Platforms and Sensors (Steve Jayne)
- Vessel-based Observations (Renellys Perez)
- Surface flux measurements (Chris Fairall)

2.1 Mooring Networks

Moacyr Araujo reviewed the history of the PIRATA mooring array, which began in 1997 with 10 moorings and reached its current configuration of 18 moorings in 2012. Six of the PIRATA buoys are designated as "flux reference sites" for high-level validation of NWP and satellite surface flux products. In recent years there has been enhancement of the standard surface meteorology and upper ocean T/S measurements at selected PIRATA sites to include fCO_2, O_2, ocean mixing ("chi-pods), and additional near surface current measurements. Subsurface ADCP moorings are also maintained by PIRATA at three sites along the equator (23°W, 10°W, and 0°E). All 18 PIRATA mooring also include OTN (Ocean Tracking Network) acoustic sensors for monitoring marine mammal activity.

The PIRATA network is currently being transitioned to T-Flex moorings which allow a higher real-time data transfer rate (hourly instead of daily-averaged data); 10 moorings are already of T-flex design and the remaining 8 will be phased in over 2019-2021. All PIRATA mooring data is transmitted in near real time to the Global Telecommunications System (GTS) for use by operational centers. The mooring survival rates have been excellent across the array except in the Gulf of Guinea where fishing-related losses and vandalism were a problem early in the program. The historical data return is typically 80% or better except in the Gulf of Guinea where it is ~70% due to the fishing-related mooring losses.

The PIRATA array has now served as the backbone of the in-situ observing system in the tropical Atlantic for more than 20 years, and the PIRATA infrastructure and its maintenance cruises have provided significant leverage and opportunities for related programs such as AMMA, EGEE, TACE, and PREFACE The PIRATA moorings themselves have played a particularly essential role in understanding the surface mixed-layer heat balance in different dynamical regimes around the tropical Atlantic (e.g., Foltz et al., 2018). At this time there are no immediate plans for expansion of the PIRATA array.

Other mooring-based observing systems in the tropical Atlantic were also reviewed, including the MOVE array which measures the deep limb of the AMOC in the western basin at 16°N, and the German RACE and SACUS programs at 11°S which measure the shallow components of the boundary current system on both sides of the basin and the DWBC on the western side, thereby contributing also to the AMOC observing system in the tropical Atlantic. MOVE began as a German contribution to CLIVAR in 2000 and since 2008 has been maintained by the U.S. through the NOAA Climate Program Office. The MOVE data and data products are publicly available on OceanSITES. The RACE measurements at the western boundary on 11°S have been maintained since 2013 and follow up an earlier array deployed there from 2000-2004. Funding to maintain this array beyond 2019 is currently being sought. The SACUS moorings on the eastern boundary at 11°S were also deployed in 2013 and are currently funded until 2021.

The Cape Verde Ocean Observatory (http://cvoo.geomar.de) also maintains a multi-disciplinary mooring at 17° 35', 24° 17' since 2006, with repeated shipboard profile observations of a broad suite of physical and biogeochemical parameters on a monthly basis.

Finally, although not mentioned in the presentation, it was noted in the discussion that the NTAS mooring site at 15°N, 51°W (http://uop.whoi.edu/currentprojects/NTAS/ntas.html), which is supported by the NOAA Climate Program Office and serves as an OceanSITES reference station, has been providing meteorological and upper ocean measurements there since 2001 and should be fully integrated into the TAOS.

2.2 Satellite Observations

Abderrahim Bentamy (via remote presentation) reviewed the set of ocean surface parameters derived from satellite retrievals, focusing mostly on SST, winds, and estimates of surface heat and moisture fluxes. He also reviewed the history of satellite missions over the past 20 years including satellite radiometers, altimeters, scatterometry, and SAR, and planned missions through 2021.

A main focus of Bentamy's presentation was assessment of the accuracy of satellite retrievals (winds, SST, humidity, etc.) and higher-level gridded products such as surface fluxes, focusing in particular on comparisons with tropical buoy arrays (TAO/Triton, PIRATA, RAMA). He noted that "match-ups" with in situ data (especially winds and SST) are essential for validation throughout the life of satellite missions - referred to as Fiducial Reference Measurements (FRMs) - and he noted in addition the very high value of tropical buoys to the satellite assessments since they make up a large fraction of the global moored buoy comparisons.

The accuracy assessments indicate wind speed biases of 0.2-0.4 m/s and RMS errors of typically around 1 m/s for different scatterometer platforms (ERS 1 and 2, QuikSCAT, ASCAT). Comparisons with PIRATA buoys show significantly lower bias than comparisons to NWP products (e.g., ERA-Interim). Satellite-derived surface turbulent heat flux product comparisons show variability in the accuracy of different available products (HOAPS/SeaFLUX/IFREMER/OAFlux/J-OFURO), with the IFEMER and OAFlux products generally showing smallest discrepancies with tropical buoy data and with PIRATA data in particular. However the errors of different products vary in a complex way in association with variations in bulk formula variables (e.g. in different wind speed regimes).

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

In terms of weaknesses and needs for future improvement, Bentamy noted that in addition to further refinement of turbulent flux algorithms, better and higher quality information on sea state and long wave radiative fluxes were key areas for future effort. The degree to which current planning for satellite missions will adequately meet the future observing system needs in the Tropical Atlantic was not discussed in detail at the meeting and should be considered in more detail in follow-up TAOS discussions. E. Lindstrom noted that satellite winds might need more mission attention looking forward, although proposed additions to the sensor suite, including "DopplerSat" (able to measure both winds and surface currents) could be very valuable contributions to the future TAOS. Another question raised in the discussion was whether the existing buoy/drifter observation network in the tropical Atlantic is sufficient for satellite cal-val purposes? In particular, are there any specific regions where more data would help to resolve discrepancies and improve accuracy?

2.3 Lagrangian Observations

Rick Lumpkin reviewed the different kinds of available surface drifters, including the workhorse "holey-sock" drogued drifter of the Global Drifter Program (GDP), CODE drifters, and the newly developed low-cost/biodegradable LASER drifter (www.carthe.org). He then reviewed the available platforms (ships) for drifter seeding of the tropical Atlantic, noting that two key

VOS XBT lines through the tropical Atlantic as well as PIRATA research/servicing cruises are crucial elements of the current re-seeding strategy.

The number of "new" drifters sampling the tropical Atlantic (either through deployment or entry to the TA from outside the tropics) averages about 5 per month. The historical drifter coverage between 20°S - 20°N is an average of ~70 drifters (with a range from about 40 to 130) and approximately 80% coverage of individual 5°x5° boxes (with range from ~60-90%). The major sampling gaps are along the equator due to the strong wind-driven surface divergence there, and in the Gulf of Guinea due to few sustained deployment opportunities in that area.

YoMaHa surface drift data from Argo floats also provides a secondary data source for the tropical Atlantic surface drift data-base and, notably, while they provide many fewer observations than surface drifters, they do not exhibit significant equatorial divergence.

Acoustically tracked subsurface floats (i.e. RAFOS) have been used in the past for specific science programs in the tropical Atlantic, but are not envisioned to be a part of the sustained TA observing system.

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

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

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

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

Rick suggested that the thermistor chain drifters might be a useful addition to the measurement suite for the TA observing system, to provide enhanced upper ocean measurements along the equatorial waveguide. He also noted that only about half of the GDP drifters in the TA are equipped with barometric pressure sensors, and that equipping more drifters with barometers could help to improve weather forecasting efforts. Finally, he emphasized that more deployment opportunities/partners are needed to sustain drifter deployments in the Gulf of Guinea.

It was noted in discussion that by 2020 or so it is expected that satellite sensors capable of simultaneously measuring both winds and surface currents (DopplerSat) will be available, and that this should be taken into account in the future planning for the global drifter program.

2.4 Autonomous Platforms and Sensors

Steve Jayne gave a summary of the status of global autonomous platforms and recent developments in their measurement and sensor capabilities. He noted that the recent ALPS-II workshop (2nd Autonomous and Lagrangian Platforms and Sensors Workshop, Feb. 2017; https://alps-ocean.us) provides a useful resource for updated information on the status of autonomous platforms globally.

Autonomous platforms have the potential to replace many of the current ship-based observations, but have a number of remaining challenges, among them:

(a) power limitations (mostly from batteries), (b) long-term stability of sensors, (c) bio-foiling near the ocean surface, (d) data management and quality control, and (e) sampling of non-core parameters (i.e., other than T and S) in national EEZs.

Argo remains the "workhorse" of global autonomous observations, due to its versatility and cost-effectiveness. Recent advances in Argo capabilities include Iridium communications, biological and biogeochemical sensors, "Deep" Argo (>2000 m), and air-deployable Argo floats. The bi-directional Iridium communications now available provide a number of operational benefits including the possibility to alter mission parameters, greater data flow with higher resolution vertical profiles, sampling closer to the sea surface (1 m), shorter surface time (~15 min, meaning less equatorial divergence), and overall battery savings.

Most of the tropical Atlantic is currently considered to have "good" Argo coverage (i.e. at or above the nominal 3°x3° design), except for the eastern Gulf of Guinea and some interior regions of the South tropical Atlantic. The future "Argo 2020" plan already calls for enhancement of Argo density within 3° of the equator to 1.5 times normal density (i.e., 1.5 floats per 3°x3° square), along with a 2 times enhancement in the Caribbean Sea.

Four different models of "Deep" Argo floats are under development (by JAMSTEC, IFREMER, Teledyne Webb, and SIO) with target accuracies of 0.001°C, 0.002 psu, and 3 dbar using SBE-61 sensor technology (although these targets are still proving elusive due to sensor stability issues). A proposal has been advanced for a global array with 5°x5° nominal coverage and 15 day cycling time.

Argo floats with added biogeochemical sensors "BCG-Argo", that measure O_2, nitrate, pH, chl-a, and particulate matter (with more sensors now under development), have already been deployed in several regional programs - most notably in the Southern Ocean in SOCCOM but some have also been deployed within the tropical Atlantic. The BCG-Argo implementation plan developed in 2016 (www.biogeochemical-argo.org) proposes a global array of 1000 BCG-Argo floats and envisions the full-scale implementation of this array within the next decade. Costs are ~100K/float with an expected 4-year lifetime.

Ocean gliders are now a mature technology for upper ocean sampling and are under ongoing development for full ocean depth. Due to their relatively high cost (~100k) as well as higher operating costs they may be useful for targeted (regional) elements of sustained observing systems but are not expected to be core parts of broad-scale sustained observing systems for the foreseeable future. Wave gliders and Saildrones are also emerging technologies that may be considered as potential future elements of sustained observing systems.

2.5 Vessel-based Observations

Renellys Perez provided a thorough review of the different vessel-based observations in the Tropical Atlantic including those from research vessels and ship of opportunity.

The PIRATA program continues to be the most omnipresent vessel based observing program in the tropical Atlantic, with dedicated annual cruises by France, Brazil, and the U.S. to service the array of 18 PIRATA moorings presently deployed. These cruises also provide a platform for the acquisition of a large number of complementary measurements along repeated ship track lines, and for the deployment of other essential components of TAOS/GOOS including surface drifters and Argo floats. Since its inception in 1997, a total of 55 PIRATA cruises have been completed (27 by France, 17 by Brazil, 11 by US) with annually repeated cross-equatorial sections along 38°W, 23°W, and 10°W. All PIRATA cruises perform CTD casts to observe T, S, O_2, as well as collect underway SST, SSS, pCO_2, and velocity data, and additional XBT profiles are also frequently collected. Many of these observations are transmitted in real-time to GDACs for operational services. These systematically repeated sections, along with others acquired by the U.S., GEOMAR and France as part of focused research programs such as TACE and EGEE, have provided a reference data set for the understanding the surface and subsurface current systems in the tropical Atlantic and for monitoring changes in water mass properties and oxygen distributions across the basin. On PIRATA cruises to date, approximately 300 surface drifters and 200 Argo floats have been deployed within the tropical Atlantic. In addition to the standard physical parameters measured on PIRATA cruises, these cruises have more recently (since 2004) begun to collect ancillary marine biological and biogeochemical data, including nutrients, chlorophyll pigments, and zooplankton and Sargassum algae samples. Atmospheric data from radiosondes and ozonesondes as well as air-sea interaction data from the M-AERI system and turbulent flux sensors on the ships have also been collected on many of the cruises. *A key recommendation emerging from the workshop discussions was that an increased emphasis should be placed on collecting multi-disciplinary vessel-based observations to better serve the needs of the broader TAOS science community and operational centers.*

Additional repeated shipboard measurements are available from the MOVE program since 2000 along 16°N in the western basin, and since 2013 along sections at the western and eastern boundaries near 11°S in support of mooring arrays there by GEOMAR, in collaboration with Brazil and Angola.

Other regular shipboard sampling in the tropical Atlantic comes from the NOAA/AOML high-density XBT transect program, which includes four transects crossing through the tropical Atlantic at latitudes between 20°S to 20°N on an approximately quarterly basis. Six GO-SHIP reference sections collecting a multi-disciplinary suite of observations also cross through the tropical Atlantic which are nominally repeated on a decadal or pentadal basis.

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

2.6 Surface flux measurements

Chris Fairall discussed the NOAA ESRL/PSD air-sea flux program, which for 20+ years has been carrying out state-of-the-art shipboard direct surface flux estimates, including motion compensated 3-D turbulent wind observations, and using these to update and advance the COARE family of flux algorithms. They have performed numerous side-by-side comparisons with research ships and surface buoys, as well as detailed comparisons with satellite and NWP derived flux products.

For example, Fairall showed a statistical comparison against 10 years of collective data from the WHOI Stratus buoy at 20°S, 85°W, which showed small (and mostly negligible) biases in the inferred air-sea fluxes and parameters, except for latent heat flux which tended to be underestimated by the buoy bulk formula (~7-8 W/m2), and compensating bias in long wave radiative flux leading to net surface heat flux biases of <5 W/m2.

Comparisons with meteorological observations on NOAA and UNOLS research vessels show that taken as a whole the R/V fleet has no significant bias in variables used to compute bulk surface fluxes, although individual ships have accuracy problems. TAO buoys in the Pacific also showed acceptable accuracy in all measured surface ocean and meteorological parameters, with the exception of a tendency for a low bias of up to 10 W/m2 in shortwave radiation.

No comparisons of the PSD program fluxes with buoy data in the tropical Atlantic (e.g. PIRATA) have been performed to date - in fact no PSD cruises have been conducted at all in the tropical Atlantic.

Fairall also noted the very large variance between available gridded (NWP, satellite, and blended) flux products in the tropical Atlantic, with standard deviations of daily measurements over most of the tropical Atlantic of > 20 W/m2, emphasizing the need for continued calibration and validation against high-accuracy standards such as the PSD observations.

3. Data Flow and Information Products (Chair: N. Smith)

3.1 Summary of current data availability and access

Marie Drévillon provided a presentation on “Data assimilation in global ocean analysis and forecasting system, for Marine applications: focus on the Tropical Atlantic”. She described ocean (re)analyses which are 3-dimensional gridded products combining many sources of ocean data and information (as much as possible) through data assimilation; in the case of re-analyses, the products are generated after a delay to allow better observational quality and coverage to be achieved (the re-processing step). Such products are useful when a consistent gridded dataset is needed or in circumstances where direct observations are sparse (or not possible) and running with a delay allows more data to be brought to bear.

Marie noted that such oceanographic analyses/reanalyses are available from the Copernicus Marine Environmental Monitoring Service (CMEMS) and other similar systems coordinated under the GODAE OceanView initiative (see Figure 1). The ocean analysis/reanalysis community has also provided several demonstrations of the value of the multi-product/ensemble approach, including for quantification of uncertainty.

Figure 1. Schematic showing the scope and reach of CMEMS. There are now over 10,000 subscribers (top left) with around 200 being added each month, and continuing to rise exponentially, while the top right shows the users are global.

Marie provided examples where CMEMS and similar systems are used to monitor the tropical Atlantic (targeted products), and to help guide the design of observational networks/systems (OSEs, OSSEs, sensitivity studies / reanalyses). There is considerable interest in monitoring products for the carbon cycle, and CMEMS products are used in the Ocean State Report and in developing ocean state indices. The resolution and complexity of such systems are increasing, leading to dissemination issues and greater use of technologies suited to “big data” (e.g., Clouds, Platforms-as-a-Service/PaaS).

Neville Smith provided a presentation on data availability and access within the context of the broader discussion of information flow and products for the tropical Atlantic. He noted that in his brief review of existing arrangements, no significant issues were identified that are specific to the TAOS.

More generally, and from results from AtlantOS, there is evidence of satisfactory progress on integration – e.g., the concept of 'integrators' within the data system. The NOAA/OAR/COD integration strategy through "ERRDAP" provides multiple access and discovery services for near real time data. The work on Best Practices (led by IODE/JCOMM) has the potential to benefit the TAOS. Data Centre capabilities and capacity is mixed through the tropical Atlantic region, pointing to a need for greater involvement/engagement with developing countries. The movement towards open data sharing is uneven through the region (Senegal provides a positive example), sometimes due to technical and/or capacity barriers, but also due to cultural issues around access.

3.2 Recommendations for data/information products and delivery

The work done under WP7 within AtlantOS and within JCOMM/IODE is highly relevant to TAOS and there are good arguments for leaving the lead at that level cf local TAOS action. Other presentations at the Workshop noted:

- Telecommunication/bandwidth limitations, e.g. for PIRATA are mostly solved with T-Flex.
- There is uncertainty around end-to-end delivery (e.g., unexpected data gaps where data is actually being collected); perhaps needing more active monitoring with JCOMMOPS.
- Data protocols are occasionally clunky (e.g. Jörn Schmidt's presentation); ERDDAP and CMEMS are easing some of these problems.
- The search for a more uniform (if not standard) data and metadata form remains a priority for modelers to ease what they see as barriers for assimilation – the developments noted above and the FAIR principles do address this but there is still some way to go.

In summary, the session did not identify any major risks for TAOS from the current approach to information systems, though there are areas that need improvement. The progressive move to integrated systems and services is a positive step, taking advantage of more generic data system services. The session recognized the value of multiple channels and different offerings; in the sense of "acquire once and serve in multiple ways".

The architecture of the data system is opaque and probably needs review. Climate users, including research, highlight the importance of quality, most of which is only possible with off-line scientific interventions (e.g. Argo). The TAOS community needs to make further progress with data exchange and broaden the base of data management support and making better use of the data we have; i.e. aspire to seamless access and interoperability for research and routine use. There was some push back against moving away from platform-based data management (Smith's reference to separation of concerns and rationalization).

The session provided encouragement to submit abstracts around ocean products and data management into OceanObs'19. The FAIR principles (Findable, Accessible, Interoperable and understandable, Reusable) represent the data and information management aspects of the framework for ocean observing (FOO).

There was discussion of understanding use and being user driven (e.g., CMEMS uptake examples). Users often see our data access systems as too complex and not friendly. Could we partner with, e.g. Google for data systems? Our field is complex, but we should ensure our expertise is brought to bear in a positive and enabling way. The modeling community (which was largely absent) encourages us to work harder on making the data easy to access (aggregation; low level consolidated products).

4. Governance, Review, and Resourcing (Chair: K. Hill)

The Governance session included a number of presentations on governance processes or institutional perspectives, followed by a discussion.

Brad de Young, Chair of the Atlantic Blueprint Core Group, presented an overview on the process for developing a Blueprint for Atlantic Observing, which is an international forward strategy building on the outcomes of the European AtlantOS program. The consultation process for the first draft of the AtlantOS BluePrint did not yield consensus or a shared position on how to approach governance, other than the agreement that a heavy top-down approach was unlikely to succeed. However, none of the existing mechanisms seemed fit for purpose. The Blueprint team then returned to basics, starting with a visioning document and concluding with an implementation plan, which responded to some of the concerns and, perhaps not surprisingly, reflects some of the threads of discussions at the TAOS workshop. The visioning document is a strategic statement of the high-level goals and aspirations (the value argument) accompanied by a set of action-benefit lines that will achieve the desired change. A foundation goal is focused on building on the strengths, but not being afraid to embrace change. There was also a short discussion around engaging foundations and funders, like the World Bank, in observing endeavors.

Eric Lindstrom, NASA Program Manager, provided a statement in part drawing on his long experience in development of ocean observing systems, speaking mostly to expectations from the review, before moving on to the NASA perspective. He asked what is the status of TAOS now, and encouraged the review to move forward in thinking of it as a system. He recommended the review identify areas that are being inadequately addressed, from the socio-economic use perspective; from a scientific perspective (new knowledge; evolved science); from a technical perspective (emerging technologies, inefficiencies, redundancies), and from there describe priorities for change. From the NASA perspective, Eric noted the huge change in satellite observing capabilities over the last two decades, and encouraged the group to exploit the opportunities rather than seeing it as the enemy of in situ observations, and noted TPOS 2020 followed an integrated approach. In his view, the Review is timely and important (see first points) but does not require a major project: there are no crises or major, systemic failures, but an opportunity to seek a more systematic approach.

Philippe Dandin spoke on behalf of MeteoFrance and *Institut de Recherche pour le Development* (IRD), and confirmed that IRD continues to be strongly supportive of PIRATA; and saw opportunities for the Review to empower PIRATA. The IRD are looking for those carefully crafted statements on the impact and benefits of TAOS and PIRATA, supported by example. Philippe noted that the review should remember "weather" as an important stakeholder. For MeteoFrance, articulating this impact is critical at a time of resource pressure. Severe weather is a key. He also noted the relevance of EMI (European Met Infrastructure), e.g. a new buoy designed to provide reference (fiducial) SST and other measurements.

David Legler, Director of the NOAA Ocean Observing and Monitoring Division, gave an overview of NOAA's interests and strategic priorities; and activities in sustained ocean observing. Like Eric and Philippe, David emphasized the need to be user focused and systematic, and pointed to the benefits of learning from TPOS and other observing system development activities. Like Eric, David noted the significant change in capabilities since TAOS/PIRATA were conceived and encouraged the Review to exploit that opportunity. David provided specific advice to the review, emphasizing that the Tropical Atlantic Observing system is not just a collection of networks and should be an integrated enterprise delivering data, information, and providing demonstrable value to its stakeholders. He noted that the Framework for Ocean Observing & EOV-framing are essential guides, and the approach and lessons-learned from TPOS should and must be considered. David encouraged the group to think strategically; and particularly for the decade ahead. He would like to see the review identify Requirements and determine how to meet them. The Review also needs to follow an integrated approach, encompassing operations, and delivery of information. David particularly emphasized that Observing systems can and must evolve; but also the review needs to be mindful of AtlantOS planning and policy-level attention/interest (e.g. Galway and EU/US/Canadian agreements, G7, etc) to consider whether TAOS is a standalone entity or part of something bigger. David also noted that this workshop is not the end, and likely just the beginning of the process - a process which NOAA is happy to support and assist.

Katy Hill, from the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS) chaired the discussion on governance aspects that followed. The group discussed the relative merits of focusing on the Tropical Atlantic, versus the Atlantic Basin, noting the Belem statement might provide a foundation for an Atlantic approach. The Workshop agreed TAOS should take a more systematic approach.

The workshop noted that there is a community of scientists who collaborate to measure the tropical Atlantic; from this workshop the evidence is that this community collaborates and works together very effectively; however, consideration of the evolving design of the observing system as a system (c.f. component parts separately) is needed. The challenge is to identify the most effective combination of networks in the presence of global systems like Argo, satellites (ALT, SST, Scatterometer winds, ocean color, etc.), all the while trying to maximize the value for users and stakeholders generally.

The Workshop discussed synergies and differences between approaches taken in the Pacific and Atlantic. In the Pacific, a project (TPOS-2020) was established following a review, in response to a crisis; nevertheless the TAOS group can learn from approaches taken in TPOS 2020, such as consideration of satellite and in situ as an integrated whole, and balancing consideration of the sustained observing with improved process understanding through process studies, as well as piloting/maturing new technologies. Synergies are to be found with the IndOOS approach also. There was general agreement that the IndOOS review approach might be better suited compared to the TPOS 2020 project approach.

Demonstrating value and having good connections to beneficiaries/stakeholders will be an important element of governance, including socio-economic impact studies (or more simply, good examples of derived socio-economic benefits). The Workshop highlighted the importance of leveraging the GOOS strategic mapping, efforts of the GOOS panels in developing EOVs, and Network Specifications. To quote Eric Lindstrom, 'Don't reinvent the wheel, polish the wheel'. The GOOS framework also requires feedback from those who exercise it for particular regions, activities and applications.

The workshop then discussed benefits/concerns of carving up the ocean into lots of pieces for coordination; but at this stage, we are focusing on a review of the observing system from a particular perspective; the outcomes of which will feed into broader governance. Other reviews have and are being conducted to look at particular regions, or capturing particular phenomena in the oceans; all aimed at strengthening the global effort.

At this stage, it is not clear that a Tropical Atlantic project like TPOS-2020 would be needed; but the outcomes of the review will feed into broader activities, such as the Atlantic Blueprint process.

5. Next steps toward the TAOS Review

At the conclusion of Session 4 of the workshop, the next steps toward completion of the TAOS Review were outlined by Bill Johns and discussed.

The next official meeting of the TAOS Review committee and stakeholders will be the 2nd TAOS Review Workshop, to be held alongside the PIRATA Annual meeting in Marseille, France during the week of October 22-26, 2018 and hosted by IRD. This will be the final meeting of the review committee prior to submission of the TAOS Review Report on or about April, 2019. Approximately two full days will be scheduled for the 2nd TAOS workshop, probably at the end of that week following the main PIRATA science meeting.

The main work of the committee prior to the 2nd workshop will be to develop an outline for the final TAOS Review report that will guide the discussions and organization of the 2nd workshop. The outline will follow the GOOS roadmap of articulating the overarching societal drivers for the TAOS and then linking those drivers to specific science and operational drivers that will govern the evolution of the observing system.

A preliminary list of principal science/operational drivers was assembled from discussions at the workshop (listed below), but it was felt that more deliberation needed to be put into this process to develop a more concise and comprehensive list. The plan suggested by the Review co-chairs - and agreed to by the meeting participants - was to have the review committee develop a final list of science/operational drivers, and then appoint task teams (led by 2 members of the review committee and joined by other interested participants at the invitation of the review committee) to draft sections of the final review report that would articulate these drivers and specify the observational requirements to meet them. This would set the stage for the main focus of the 2nd workshop, which is to synthesize the matrix of requirements and to provide recommendations for enhancements or modifications to the TAOS.

Preliminary list of science/operational drivers:

1) Improved prediction on subseasonal to decadal time scales
2) Dynamics and predictability of the Atlantic zonal and meridional modes
3) Tropical Atlantic hydroclimate variability; ITCZ, African and South American monsoons
4) Remote impacts of Tropical Atlantic Variability (ENSO and extratropical connections)
5) Understanding of mixed layer heat balance and dominant processes (seasonal and interannual)
6) Understanding causes of coupled climate model biases
7) Improved TC prediction and landfall distribution; linkages to ENSO/AMM/AMO/MJO
8) Impacts of AMOC variability on the Tropical Atlantic; role of boundary currents in tropical AMOC variability
9) Impacts of TAV on Biogeochemistry, Fisheries and Ecosystems
10) Long-term climate change and impacts: hydroclimate, temperature rise, sea-level rise, CO_2 fluxes, ocean acidity, Oxygen minimum zones, TC frequency and intensity

In addition to the task teams for the science/operational drivers, separate task teams would be charged with drafting recommendations for data delivery, governance and resourcing, and periodic reviews of the TAOS. The review committee will conduct its business through email and teleconferences as needed. In a teleconference following the workshop, it was decided that the drafts of each of these sections should be completed by early September 2018 and circulated prior to the 2nd workshop for comment. Each member of the committee would then be asked to submit - also prior to the workshop - their ideas or recommendations for possible enhancements or modifications to the TAOS, which would then be collated to help structure the discussions at the workshop. Further planning for the 2nd workshop will be coordinated with the PIRATA SSG and IRD and announcements and invitations for the workshop will be forthcoming by summer 2018.

Another point that required clarification after the workshop was the relationship of the TAOS Review to forward planning for the OceanObs'19 conference to be held in Hawaii in September 2019. At the time of this 1st TAOS workshop it was generally assumed that the TAOS Review committee would take the lead in developing a white paper for OceanObs'19 for the tropical Atlantic sector. However, after further discussions among the review committee and other members of the tropical Atlantic observing community, it was decided that the TAOS review should remain formally independent of the OceanObs white paper process, and that other individuals outside the review committee should take the lead in generating a white paper for OceanObs'19 for the tropical Atlantic. Such a group (led by Greg Foltz, NOAA/AOML) has now been formed and is progressing toward a tropical Atlantic white paper for OceanObs.

6. Acknowledgements

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Appendices

A.1 TAOS Review Committee members

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A.2 TAOS Review Terms of Reference (TORs)

1. Review and articulate the existing and anticipated future drivers for the Tropical Atlantic Observing System, encompassing research, operational, and societal applications. Key applications to be considered include: research on tropical Atlantic circulation and variability, coupled atmosphere-ocean variability and change, climate monitoring, modelling and forecasting (climate, ocean, seasonal to decadal and weather prediction), biogeochemistry, and fisheries.
2. Evaluate (review/assess/prioritize) existing and potential requirements for sustained observations of essential ocean variables (EOVs) in the tropical Atlantic Ocean (extending from 25°N to 25°S) - in connection with TPOS-2020 and IndOOS - and update them to reflect new knowledge and identified needs for scientific and societal applications.
3. Evaluate the adequacy of existing observing strategies to deliver requirements for variables, and characterize their impacts. Characterize how in situ (e.g., PIRATA, Argo, drifters, and other data) and remote sensing observing systems are contributing to meet these scientific and functional requirements, and identify gaps, inefficiencies, and vulnerabilities.
4. Provide recommendations on the current suite and configuration of observing systems to enhance their resilience and robustness in order to produce data in the most cost-efficient and sustainable manner within the anticipated envelope of capability and resources.
5. Identify potential enhancement or reconfiguration of the sustained observing system suite to address gaps and new requirements.
6. Evaluate requirements for delivery of data, and derived products and information, in real time and delayed mode (e.g., availability, quality, latency, integration/interoperability); evaluate the existing data systems for fitness for purpose.
7. Assess readiness of new technologies, their potential impact and feasibility in addressing requirements, and their potential to contribute towards addressing gaps, improving robustness/resilience, and/or lowering costs per observation in the tropical Atlantic Ocean region; recommend new technologies with greatest potential to meet critical requirements and suggest approaches to improve the readiness for inclusion in the sustained observing system.
8. Highlight the impacts of the tropical Atlantic observing system on the delivery of information/services of societal importance and relevance. Develop a report of the first TAOS Workshop, with recommendations on the development of a process for the ongoing evaluation of the observing system.

A.3 Workshop Agenda

Time	Title	Speaker(s)
8 February 2018 (Thursday)		
8:30-9:00	Registration	
9:00-9:30	Welcome and Introductions	CLIVAR ARP (Sabrina Speich), TAOS Review Committee (Bill Johns)
Session I: Requirements for the Tropical Atlantic Observing System Chair: S. Speich		
9:30-10.00	Societal impact and importance of observing the Tropical Atlantic	Moacyr Araujo
10:00-10:30	Tropical Atlantic variability and change	Paulo Nobre
10:30-11:00	Role of the Tropical Atlantic in the climate system	Belen Rodriguez-Fonseca
11:00-11:30	Coffee Break	
11:30-12:00	Impact of Tropical Atlantic biases in climate predictions/projections	Noel Keenlyside
12:00-12:30	Tropical-Extratropical Links	Jeff Knight
12:30 - 14:00	Lunch	
	Session I (continued) Chair: M. Balmaseda	
14:00-14:20	Capabilities for seamless forecasting from days to season: the role of ocean observations	Magdalena A. Balmaseda
14:20-14:40	Extreme Events	Scott Stripling/Ping Chang
14:40-15:00	Evaluation of the Tropical Atlantic observing system from ocean data assimilation perspective: Marine applications	Marie Drevillon
15:00-15:30	Biogeochemical applications in the Tropical Atlantic: Requirements, synergies, and gaps	Toste Tanhua
15:30-16:00	Coffee Break	
16:00-16:30 (remote)	Biology and Fisheries applications: Requirements, synergies, and gaps	Jörn Schmidt
16:30-17:00	Presentations from related observational programmes (IMBeR, SOLAS, POGO)	Carol Robinson
17:00-18:00	Discussion: Requirements for existing and emerging drivers; essential ocean variables (EOVs) and system design. What is the key information that is being (a) successfully provided and (b) missing from the Tropical Atlantic observing system for these science/societal drivers? (Recommendations from today's session with a special focus on issues to address in the review)	
18.00-19.00	Review Committee meeting (closed session)	
19:30 - 20:30	Reception	
9 February 2018 (Friday)		
Session 2: Tropical Atlantic Observing System Networks: Current Status and plans to 2030 Chair: B. Johns		
8:30-9:00	Mooring Networks	Moacyr Araujo
9:00-9:20	Satellite Observations	Abderrahim Bentamy
9:20-9:40	Lagrangian observations of the Tropical Atlantic	Rick Lumpkin

9:40-10:00	Autonomous Platforms and Sensors	Steve Jayne
10:00-10:20	Vessel-based Observations	Renellys Perez
10:20-10:40	Surface flux measurements from buoys, ships, and gridded products; Atmospheric and marine boundary layer observations	Chris Fairall/Paquita Zuidema
10:40-11:00	Coffee Break	
11:00-12:00	Discussion: Successes and gaps of the observing system network for science/societal applications; How to fill those gaps/optimize the TAOS? Recommendations for future evolution of the TAOS.	
12:00-13:30	Lunch	
Session 3. Data Flow and Information Products Chair: N. Smith		
13:30-14:00	Current data availability and access (how delivered; present status and future evolution)	Neville Smith
14:00-14:30	Available Analysis Products (how accessed and how used by science/operational community and stakeholders?)	Marie Drevillon
14:30-15:00	Discussion: Gaps in data availability/access and information products? Recommendations for possible improvements in data/information products and delivery.	
15:00-15:30	Coffee Break	
Session 4. Governance, Review, and Resourcing Chair: K. Hill		
15:30-15:45	Perspectives from the Blueprint for Atlantic Observing	Brad de Young
15:45-16:30 (5-10 min each)	Presentations by agencies with interests in engaging: (TBD)	
	National Oceanic and Atmospheric Administration (NOAA)	David Legler
	NASA	Eric Lindstrom
	Météo-France & Institut de recherche pour le développement (IRD)	Philippe Dandin
	Brazil	Moacyr Araujo
	Cape Verde, Namibia	Vito Melo(remote), Brian Mudumbi
16:30-17:00	Discussion: Proposed governance and review mechanisms. Does the proposed TPOS-2020 structure (a TAOS Resources Forum, under guidance of a TAOS Steering Committee), work for the Tropical Atlantic? Alternate governance/review mechanisms?	
17:00-17:40	Summary: Points of consensus, divergence, issues to resolve	
17:40-18:00	Next Steps: Workshop report; OceanObs'19 White paper, Next TAOS Review meeting (Marseille, October 2018); Closing remarks	
18:00	Meeting Adjourns	
19:00-21:00	Review Committee meeting/dinner (closed session)	

A.4 Workshop Attendees

First name	Last name	Group	Affiliation		Email
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A.5 Presentation summaries for Session 1

A.5-1 Societal impact and importance of observing the Tropical Atlantic

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With the contributions: PIRATA-SSG, G. Hounsou-gbo and B. Ferreira (UFPE), J. Hahn, F. Schütte, P. Brandt and J. Karstensen (GEOMAR), E. Rémy (CMEMS), C. Tanajura (UFBA), P. Poli and J-F. Mahfouf (Méteo-France), A. Delpech and P. Lehodey (Mercator/CLS).

The Tropical Atlantic Observing System (TAOS) has strong impact on society. The information provided by satellite and *in situ* observations bring important societal benefits by (i) promoting marine ecosystem health and biodiversity; (ii) promoting human health; (iii) improving the adaptation to and mitigation of climate change; (iv) improving weather and climate extreme forecasts; (v) promoting water, food, and energy security; (vi) promoting marine safety and the Blue Economy.

Far from being exhaustive, some examples of impacts and benefits of tropical Atlantic observations were presented during the 1st TAOS Review Workshop, which are summarized below:

Concerning marine ecosystem health and biodiversity, satellite and PIRATA (Prediction and Research moored Array in the Tropical Atlantic) data have been used to anticipate coral bleaching events and coral mortality. In the southwestern tropical Atlantic, between latitudes 0°S and 8°S, a thermal stress anomaly of greater than 1°C was recorded and bleaching events and coral disease outbreaks are correlated to sea surface temperature (SST) anomalies recorded by a PIRATA buoys located near reef sites (e.g., Rocas Atoll and Fernando de Noronha Archipelago).

Thanks to a fruitful cooperation between PIRATA and German efforts ("SFB754 – Climate-Biogeochemistry Interactions in the Tropical Ocean", which is focused on the oxygen distribution and variability within the eastern tropical Atlantic, long time series of oxygen), a multidecadal time series of oxygen measurements along 23°W buoys allowed to follow the trends of the intensity of oxygen minimum zones (OMZs) as well as to identify the presence of mesoscale dead-zone eddies in the northeast tropical Atlantic.

Tropical diseases such as Dengue have become major public health concerns in many countries. These diseases often show regular seasonal incidence patterns because of the sensitivity of Dengue's mosquito vector to climate. Changes in SST have a well-defined role as a climate driver of precipitation. PIRATA buoys have been used to develop an early warning system for the Dengue disease in the Eastern region of Northeast Brazil. Standard statistical analyses, coupled with the wavelet method to establish the relationship between the SST anomalies measured in the buoys and the Dengue Case Anomalies reported at Recife Metropolitan Region, have been used to establish a solid, multicomponent association between the SST and Dengue incidence, which is non-stationary and only takes place during inter-epidemic periods.

PIRATA is the only long term monitoring in the Tropical Atlantic, to our knowledge, offering time series sufficiently large to enable analysis of Tropical Atlantic variability on multi-decadal to climate-relevant time scales. It is now more than 20 years old, serving as the baseline climate record in the tropical Atlantic. This set of data may serve to future studies involving adaptation and mitigation of climate change. SInce PIRATA was first deployed, more than 3 million PIRATA data files have been delivered from partners websites (INPE-Brazil, IRD-France and NOAA-USA). During the same period, it has been observed an exponential-like growth in the number of published peer-reviewed papers using PIRATA data, enhancing tropical Atlantic science.

In situ measurements obtained from different ocean observing networks (e.g., ARGO, VOOS, PIRATA, etc.) are made available through the Global Telecommunication System (GTS) and Global Data Servers. Those are important contributions for improving weather and climate extreme forecasts. PIRATA data, for example, are transmitted in real-time through the Argos (for original ATLAS buoys) or Iridium (for new T-Flex buoys) systems. The T-Flex moorings, allowing the potential implementation of more sensors with high frequency data transmission in real time, progressively replace the ATLAS moorings since 2015. It has been expected that this new high transmission capability will enhance the capacity to follow in near-real time the occurrence of extreme weather events like tropical cyclones and hurricanes. PIRATA buoys located in the western boundary have been also used to evidence a relationship between oceanic conditions in the northwestern equatorial Atlantic and the seasonal rainfall over the northern part of Brazilian Northeast, allowing large climate events to be forecasted with a delay of a few months.

Different studies have been performed using both Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) to evaluate the impact of real and simulated TAOS network and/or data on weather variability forecasts over the tropical Atlantic. In this context, some specific existing components (observational platforms and/or subregions, etc.) of the TAOS may be evaluated (OSE), and/or future-observing systems can be compared to existing systems to determine if there is value added in the form of improved forecast skill (OSSEs). Some selected recent examples are listed below:

- Rémy et al. (2017) performed two experiments in the tropical Atlantic: (i) first, by removing observing system components everywhere: ARGO, Moorings, CTD/XBT *in situ* observations, sea level anomaly (SLA) observations; and (ii) second, by removing observing system components in a given region (shallow water areas, altimetry observation of SLAs in different ocean regions, ocean *in-situ* observations of mooring temperature/salinity profiles (T/S) in the Tropics. Results indicate that mooring measurements are very important for validation and calibration of operational systems (accuracy and trends) over long time periods (e.g., reanalysis);
- Tanajura et al. (2017) performed numerical OSE focused on PIRATA network by considering the assimilation of SST, ARGO T/S, SLA and PIRATA T/S. Results suggest that longer assimilation runs are needed to better show the impact of PIRATA data, but preliminary results show that locally the impact of PIRATA data is substantial;
- Poli et al. (2018) used the operational ECMWF system (May 2015 and April 2017) to evaluate if the contribution of surface pressure data from different observational networks in the Tropical Atlantic delivers valuable benefits to global weather predictions (by reduction of the 24-hour forecast error *via* data assimilation). The calculated Impact factors (IF = ratio between forecast improvement and relative observational effort) clearly show that the collection of surface pressure data from moored and drifting buoys has a high impact on weather forecasts.
- Mahfouf et al. (2018) designed and performed a backward analysis (optimal initial conditions to reduce forecast error for each parameter or set of parameter observations) to evaluate the impact of ocean buoys (PIRATA, TAO, RAMA, and others…) on 24-hour surface pressure error. Results confirm higher IF values for tropical Atlantic buoys observing data.
- Delpech et al. (2017) performed an OSSE exercise by creating synthetic observations using an ecosystem and population dynamic modeling approach (SEAPODYM-MTL) at the positions of existing observing sites to assess the benefits of using different networks in data assimilation procedures. Results indicate that PIRATA is one of the best observational networks for data assimilation on SEAPODYM-MTL, especially due to its localization and sampling scheme.

Capacity building is an important framework to foster and maintain cooperation among countries bordering the Tropical Atlantic basin. Different components of the TAOS have been used to promote capacity building. Only two examples: (i) the MSc. Ocean, Atmosphere and Climate Science at Cotonou-Benin (https://master-soac-toulouse.obs-mip.fr/m2oa/), which is supported by the French IRD, with the participation of Brazilian and African lectures; almost 100 MSc. students were trained and graduated since 2008, and many of them continued to obtain doctoral degrees in different countries around the world using TAOS data; and (ii) TAOS cruises represent opportunities for students/young scientists training to learn measurement techniques at sea. BR and FR-PIRATA cruises, for example, have been used for training more than 60 African and Brazilian young scientists/students since 2000, and US PNE cruises represent strong contributions for student training during the last 12 years with 55 students trained in shipboard measurements (over 70% of students from underrepresented groups).

Finally, for the near future, one should consider that TAOS can contribute/be enhanced to help achieve UN Sustainable Development Goals (SDGs), in the scope of the next Ocean decade and 2030 Agenda for the planet. It seems a good exercise to imagine how future TAOS can be used to contribute to achieve some SDGs, not only SDG-13 (Climate) and SDG-14 (Life below water), but also those related to Food security, Renewable energies, Innovations, and Blue economic growth (Figure 1).

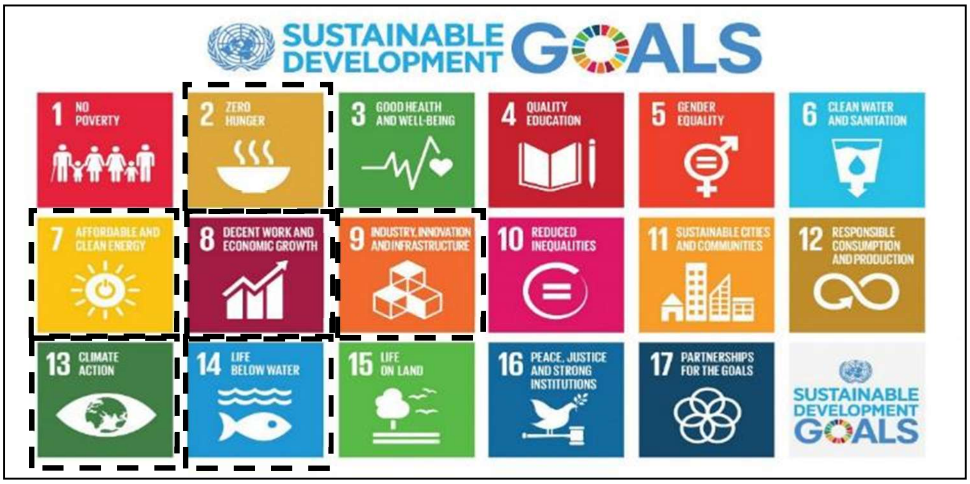

Figure 1. United Nations SDGs.

A.5-2 Tropical Atlantic variability and change

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The presentation began covering historical papers that documented the meridional and zonal modes of interannual to decadal climate variability over the tropical Atlantic. Then, process studies were presented, e.g. the symmetry of the Atlantic Niños, the impact of equatorial waves and mixed layer depth anomalies on SST evolution during Atlantic Meridional Mode (AMM) events, different types of Atlantic cold tongue events, the role of coupled model biases in the misrepresentation of processes leading to equatorial Atlantic interannual variability, and the use of mixed layer heat budget residuals to estimate vertical turbulent cooling of SST.

Then, results of articles about the predictability of Atlantic Niños and connections to continental rainfall were presented. The importance of the correct representation of equatorial convection and precipitation over the continents for the proper simulation of cold tongue and ITCZ dynamics on coupled ocean-atmosphere models was presented. The importance of coupled ocean-atmosphere interactions to predict thermally indirect circulation cells, e.g. the South Atlantic Convergence Zone was discussed next. The connections between South Atlantic SST and continental rainfall predictability was also covered. The impacts of river discharges on Atlantic Ocean biogeochemistry were presented. Finally, the role of hurricanes as important players of the Atlantic climatic system was presented, with the current challenges to represent such energetically intense phenomena on climate models.

In summary, what we don't know and how observations can help:

Processes that contribute to interannual and decadal SST variability in the deep tropics (10S - 10N) are poorly known, yet have a strong influence on the ITCZ and continental rainfall. Additional measurements of velocity and salinity in the upper ocean from PIRATA moorings should be a top priority for improving understanding of the mixed layer heat budget (better estimates of MLD, horizontal advection, mixing). We are only beginning to understand the seasonal cycle of vertical turbulent mixing in the tropical Atlantic and its impacts on SST. Even less is known about mixing on shorter (diurnal, inertial, intraseasonal) and longer (interannual) timescales. With the addition of several current meters on a PIRATA mooring (or a surface downward- looking ADCP, or microstructure), we can estimate shear-induced mixing and start to close the heat budget.

In an era of Global Climate Change We must direct our action to the Earth System: Observing the whole of the oceans, the atmosphere, and the tropical forests: thoroughly; Incorporating the physics of water vapor phase change and other turbulent-scale oceanic phenomena in our global coupled climate models; Attracting and instructing a tsunami of new kids into climate and life sciences.

A.5-3 Role of the Tropical Atlantic in the climate system

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In the Tropical Atlantic, the seasonal cycle of sea surface temperature (SST) and rainfall are strongly coupled. During the months of March-May, the warmest SST anomalies are found furthest south close to the equator. The northeasterly trades are enhanced decreasing the SST in the Tropical North Atlantic through the wind-evaporation-SST (WES) feedback. As a result, the Intertropical Convergence Zone (ITCZ) shifts to its southernmost position, bringing rain to the Brazilian Northeast. In June-August, on the other hand, the southerly trade winds are enhanced developing the equatorial cold tongue through the Bjerknes mechanism, which involves coupled changes in the winds, sea-level pressure, SST and thermocline depth along the equatorial region (Bjerknes 1969). As a consequence the ITCZ migrates to its northernmost position bringing rainfall to western Africa. Deviations from the aforementioned patterns are common and have been associated with the two modes of climate variability in the Tropical Atlantic, the zonal mode and the meridional mode.

The zonal mode, also known as equatorial mode and Atlantic Niño, presents a strong interannual variability and peaks in June-August. For this reason, it has a great impact on the Guinea Gulf rainfall (Ward, 1998; Giannini et al., 2003). This mode has been described as the Atlantic counterpart of the ENSO, since its development involves the Bjerknes feedback, albeit weaker than in the Pacific (Zebiak, 1993; Latif and Grotzner, 2000; Keenlyside and Latif, 2007). It is triggered by changes in the western equatorial winds linked to the St. Helena high-pressure system variability (Carton et al., 1996; Venegas et al., 1997; Ruiz-Barradas et al., 2000; Traskza et al., 2006; Sterl and Hazeleger, 2007) and damped by surface heat fluxes (Frankignoul and Kestenare, 2005).

The Atlantic meridional mode, also known as inter-hemispheric mode, is characterized by SST anomalies of opposite signs about the equator involving the WES feedback triggered by changes in the winds on both hemispheres (Nobre and Shukla, 1997; Kushnir et al., 2003). This mode peaks in March-May and its decay follows the seasonal migration of the ITCZ. The meridional mode strongly affects the northern South American climate and varies in interannual and decadal time scales.

The regional impact of both modes involves the South American and western African Monsoon systems. The South American Monsoon System is active from November to May and for this reason is mostly affected by the meridional mode (Vera et al. 2006; Marengo et al. 2012). A positive phase, characterized by a warm (cold) SST anomaly in the tropical North (South) Atlantic, impedes the southward migration of the ITCZ during March-May, preventing rainfall over the Amazon region and Brazilian Northeast, leading to severe droughts there (Moura and Shukla, 1981; Hastenrath, 2006; Kucharski et al., 2008; Rodrigues et al., 2011; Liebmann and Mechoso, 2011). The opposite is true for a negative phase of the meridional mode (Rodrigues and McPhaden, 2014). On the other hand, an earlier development of a warm phase of the Atlantic Niño can help the southward migration of the ITCZ, bringing excess rain to the Brazilian Amazon and Northeast (Torralba et al., 2013).

The western African Monsoon System, on the other hand, peaks from June to September and for this reason is more strongly affected by the Atlantic Niño (Sultan and Janicot, 2003; Nicholson et al., 2009, 2013; Xue and Janicot, 2016). A warm phase of the Atlantic Niño retains the ITCZ to the south, decreasing the land-sea pressure gradient cause droughts over the Sahel (Janicot et al., 1998; Okukumra and Xie, 2004; Polo et al., 2008; Joly and Voldoire, 2009, 2010; Losada et al. 2010; Rodríguez-Fonseca et al., 2011, 2015). At lesser extent, a positive phase of the meridional mode can increase rainfall over the Sahel.

In addition to their regional impact, the two modes also can impact remote regions through their teleconnection patterns. The remote impact of the zonal mode has been more extensively documented and includes the extratropical Euro-Atlantic circulation (Haarsma and Hazeleger, 2007; García-Serrano et al., 2008, 2011; Losada et al., 2012), the Indian Ocean-Indian Monsoon (Kucharski et al., 2007, 2009), and the Pacific Ocean (Rodríguez-Fonseca et al., 2009; Ding et al., 2011, Polo et al., 2008). The latter has important implications for the ENSO predictability. The teleconnection mechanism involves changes in the Walker circulation, enhancement of westerly wind burst in the western Pacific and the propagation of equatorial oceanic Kelvin waves (Polo et al., 2015). The impact of the Atlantic Niño on the Indian monsoon entails a Gill-type response that leads to upper-level anticyclonic and low-level cyclonic response over South Asia, leading to low-level convergence and increased rainfall (Yadav, 2008; Rajeevan and Sridhar, 2009; Lo et al., 2008; Losada et al., 2009). The teleconnection with the extratropics can be explained by atmospheric stationary Rossby waves triggered by the tropical heating of the Atlantic. Persistence of extratropical anomalies can impact Europe. The meridional mode has been associated with the North Atlantic Oscillation (NAO) and European rainfall (Rodríguez-Fonseca and Castro, 2002; Rodríguez-Fonseca et al., 2006; Losada et al., 2007). More specifically, the Tropical North Atlantic can influence the North Atlantic Oscillation (NAO) by changing the NAO–dipole SST response in spring to a coupled wave train–horseshoe SST response in the following summer and fall, producing a recurrence of the NAO in the next winter (Czaja and Frankignoul, 1999; Wu et al., 2006; Rodriguez-Fonseca et al., 2006; Losada et al., 2007).

Recent research has shown that there is a multidecadal modulation of the tropical Atlantic variability, their teleconnections and impacts. For instance, the Atlantic Niño-ENSO relationship has been found to be non-stationary and seems to take place during negative phases of the Atlantic Multidecadal Oscillation (AMO) (Martín-Rey et al., 2014, 2015). This Atlantic-Pacific equatorial connection seems to affect the western African Monsoon (Suárez-Moreno et al., 2018), rainfall over the Brazilian Northeast (Kayano et al., 2016), the Indian Monsoon (Kucharski et al., 2007) and the summer Euro-Mediterranean rainfall (Losada et al., 2013). On the other hand, the Tropical North Atlantic - ENSO relationship is strong during positive AMO phases (Wang et al., 2017). Finally, the patterns of both zonal and meridional modes seem to vary under different AMO phases (Losada and Rodriguez-Fonseca, 2016; Martín-Rey et al., 2018).

Therefore, the aforementioned discussion highlights the importance of the Tropical Atlantic variability. The long-term continuously monitoring of the Tropical Atlantic is paramount to improve our capability of predict climate and its changes.

A.5-4 Impact of Tropical Atlantic biases in climate predictions/projections

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The simulation and prediction of tropical Atlantic Ocean and its climatic impacts remains a major challenge. Here, I summarise our understanding of the causes of mean state errors in climate models, and their impact on the simulation and prediction of climate on seasonal timescales, and on projections of long-term climate change.

Model biases in the south-eastern tropical Atlantic are among the most severe of all bias found in state-of-the-art climate models [*Richter*, 2015]. The multi-model mean SST climatology from the Coupled Model Intercomparison Project 5 is biased around 2 °C too warm in the eastern equatorial Atlantic and 3 °C too warm in the Angola-Benguela region. These large-errors are associated with corresponding errors in atmospheric circulation and rainfall. The cause of these errors has been assessed from a range of experiments with coupled and uncoupled models, regional and global, and also using initialised prediction experiments. 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. The wind errors are already apparent in uncoupled atmospheric models and are related to the representation of tropical rainfall and insufficient vertical resolution of lower atmosphere [*Harlaß et al.*, 2015]. Ocean stratification errors associated with vertical mixing and surface fresh water biases may also contribute. There is less agreement on the cause of the bias in the Angola-Benguela region [*Xu et al.*, 2014b]. The poor-representation of wind stress is a key factor in many models [*Patricola and Chang*, 2017; *Koseki et al.*, 2018], but errors in subsurface ocean temperature in the equatorial region can also contribute [*Xu et al.*, 2014a]. Apart from this high oceanic resolution (0.1 deg.) is required to reduce errors in the narrow coastal band, while shortwave flux errors associated with poor representation of low-level clouds can contribute to the large-scale error pattern.

The mean state SST errors are much larger than equatorial Atlantic interannual SST variations and they strongly impact simulated equatorial Atlantic variability, by suppressing the importance of dynamical ocean-atmosphere interaction. The observed cold tongue supports a positive Bjerknes Feedback (i.e., dynamical ocean-atmosphere interaction) that underlies the Atlantic Niño phenomenon [*Zebiak*, 1993]. However, the feedback is weaker and more seasonally modulated than in the Pacific, and as a result the Atlantic Niño is much weaker than the Pacific El Niño [*Keenlyside and Latif*, 2007]. In addition, thermodynamic ocean-atmosphere interaction appears to have greater importance in the Atlantic and can explain the first order features of the Atlantic Niño [*Nnamchi et al.*, 2015]. In climate models, there is a deep warm pool in the eastern equatorial Atlantic, instead of an intense cold tongue. As a result, models are found to strongly underestimate the strength of the positive Bjerknes Feedback [*Nnamchi et al.*, 2015; *Deppenmeier et al.*, 2016; *Dippe et al.*, 2017]. Thus although strongly biased climate models are able to simulate Atlantic Niño like variability [*Richter et al.*, 2012], this variability is erroneously governed by thermodynamic ocean-atmosphere interaction. Numerical model sensitivity experiments indicate that reducing model biases enhances dynamical ocean-atmosphere interaction, and improves Atlantic Niño simulation [*Ding et al.*, 2015; *Harlaß et al.*, 2017; *Jouanno et al.*, 2017].

Reducing the large-model biases in the tropical Atlantic is found to enhance seasonal prediction skill. This was shown by comparing predictions with a standard and an anomaly coupled configurations of the Norwegian Climate Prediction Model (NorCPM). The standard model has climatological biases typical of other models. Correcting momentum and SST fields exchanged between oceanic and atmospheric models significantly reduces the climatological errors in the anomaly-coupled version. The mechanisms for equatorial Atlantic variability are thus better represented, although the variability is reduced in strength. This enhances the ability of the model to assimilate ocean observations in this region. A set of seasonal predictions with both standard and anomaly-coupled models indicates that reducing mean state errors leads to a significant improvement in the skill in predicting the Atlantic Niño.

The consequence of tropical Atlantic mean biases for climate projections is undocumented. Comparison of climate change projections with the standard and an anomaly coupled configurations of the Norwegian Earth System Model (NorESM) shows that reducing mean state errors leads to greatly differing climate change projections (present to 2100). The standard model shows a rather uniform warming of around 2.5 °C over the equatorial Atlantic. In contrast, the corrected model shows greater warming in the east, reaching 3 °C in the eastern equatorial Atlantic. These changes are reflected in quite different rainfall response patterns. The standard model shows that climate change will lead to wetter conditions over central Africa and the western Atlantic, and drier conditions over eastern equatorial South America and the south equatorial Atlantic. The corrected model, in contrast, shows greater rainfall changes in the east and over central Africa, and less drying over South America. The underlying mechanisms causing these differences are still unclear.

Key requirements from TAOS

The TAOS has been instrumental in improving our understanding and ability to simulate and predict tropical Atlantic climate. Most important have been observations of upper ocean heat and salt content, and equatorial ocean circulation, and atmospheric circulation, and surface momentum and heat fluxes. To achieve further advances, observations are required to close the momentum budget in the ocean and atmospheric boundary layers. Observations to further constrain heat and freshwater ocean mixed-layer budgets (including surface fluxes) can help reduce biases, and enhance ocean reanalysis. Ocean current observations along the south-eastern boundary are also important for understanding and simulating equatorial and coastal variability.

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A.5-5 The Tropical Atlantic as a key driver of global climate – implications for observations

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It has become the established view that although the Tropical Atlantic Ocean does not possess variability that projects as strongly on global climate as the Tropical Pacific (possessing, of course the El Niño-Southern Oscillation (ENSO)), it has clear influences regionally. For example, the inter-hemispheric gradient of sea-surface temperatures (SSTs) clearly influences the position of the inter-hemispheric convergence zone (ITCZ; the focus of tropical precipitation) and thereby rainfall in adjacent continental regions such as Amazonia, North East Brazil and the Sahel. Furthermore, the Atlantic cold tongue mode (sometimes referred to as the Atlantic Niño) has a clear link with West African rainfall. While these relationships are certainly important for regional climate, it is proposed here that the Tropical Atlantic has a wider role in global climate than hitherto generally recognised.

The fundamental dynamical understanding of the atmospheric response to isolated heating anomalies, such as are provided by anomalous tropical convection, is a theoretically mature. Poleward- and eastward-propagating Rossby waves are generated by these anomalies, allowing rapid (~2 days) teleconnections between the tropics and mid-latitudes. This mechanism is essential to understanding the mid-latitude responses to ENSO, for example, but the potential for the Tropical Atlantic to act as a significant source is less well discussed. If we are to understand the variability of modes of atmospheric circulation such as the winter North Atlantic Oscillation (NAO; for which predictability from ENSO is modest) then the

Tropical Atlantic is appealing, since its location is well-suited to the production of Rossby wave trains that traverse to North Atlantic-European region.

Practical seasonal predictions require multiple links in the chain of influence to be simulated if the patterns of circulation are to be correctly deduced. Fortunately, the variability of basin-scale tropical rainfall in many seasonal prediction systems is well reproduced (although there remain mean biases). Overall, the role of the tropics in influencing extratropical variability is clear from the fact that year-to-year variations in the NAO show a correlation with tropical SSTs of 0.65. Further evidence can be seen in case studies of specific past winter seasons performed in seasonal prediction systems with relaxation of winds and temperatures in the tropical belt to atmospheric reanalysis. Simulations for winters 2013-14 and 2015-16 both show a faithful representation of Northern Hemisphere atmospheric circulation patterns.

Using these types of relaxation experiments, it is possible to focus in on the role of the Tropical Atlantic by performing relaxation over just that region (and confined to the Pacific as the complimentary experiment). What is found that is that 2013-14 and 2015-16 both demonstrate clear Rossby wave links from the Tropical Atlantic sector. This is important as both of these winters saw remarkable high-impact weather in Western Europe, with record-breaking rainfall and storminess. It is clear from the experiments that these conditions owe their intensity to the influences from the Tropical Atlantic. Furthermore, if this link is more generally significant, then it has an implication for climate change. The NAO is potentially sensitive to many changing influences over the next century, but preliminary results show that to some degree the changes seen in different climate models are influenced by their sources of Atlantic Rossby waves, i.e. how climate is simulated to change in the Tropical Atlantic. This suggests that this region may be a key driver of future mid-latitude climate over the eastern North America, the North Atlantic and Europe (the regions affected by the NAO).

It has been argued here that as well as being a key regional driver of climate variability the Tropical Atlantic has a wider role in global climate variability and change. It is crucial therefore that an effective observational system is in place to monitor its behaviour and to allow models to be better constrained. The current complex of observing systems offers much of the data needed for this but there are some gaps. Better temperature profiling of the ocean in the narrow equatorial regions would give improved information on the variations in heat content availability that can drive convective variability. Atmospheric boundary layer properties like winds and moisture are also key drivers of convective variability that could be better determined. Further atmospheric properties, the surface manifestations of the free atmosphere – such as radiation and rainfall – are needed over the ocean. Oceanic rainfall is closely related to the mid-tropospheric heating that drives remote influences, but satellite-based observations are uncertain. These observations could benefit from multiple references to buoy-based 'ground truth' in these regions. All observational data, for whatever variable, needs to be made more accessible, such as a contribution to gridded datasets or reanalyses. The challenges in involved in doing this are substantial, but must be weighed against the risk that data loses impact.

A.5-6 Capabilities for seamless forecasting from days to season: the role of ocean observations

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There is clear demand for reliable weather and climate forecasts at different time scales for a variety of societal applications. The improvement of the observing systems, model development, and computer resources are continuously driving forward the forecasting capabilities. Current operational weather forecasting centres are adopting the so-called “seamless” approach to take advantage of these new capabilities to further improve and extend the forecast horizon from days to seasons. These new generation of forecasting systems include better initialization techniques, incorporate probabilistic methods to cope with the chaotic nature of the atmosphere, and rely on coupled atmosphere-land-ocean-wave-sea ice models to predict the evolving sea-surface-temperature and its impact on the atmosphere.

ECMWF has embraced the seamless Earth System approach for its operational forecasting systems, issuing ensemble forecast of weather and its statistics from days up to one year ahead. At all these forecast ranges, the ocean is an integral part of the forecasting system, and so are the ocean observations. Table 1 shows schematically the main forecast ranges covered by the ECMWF forecasting system, as well as its production frequency. The forecast consist of 50 ensemble members. A subset of the forecast data, with a small delay, also populate public data basis such as those supporting international research programs TIGGE, (Bougeault *et al* 2016) and S2S (Vitart *et al* 2017), as well as that of the European Copernicus Climate Change (C3S) Services .

Table 1: ECMWF Probabilistic Seamless Forecasting System with interactive ocean component. All the forecast consist on an ensemble of 50 (51) members.

System	**Lead Time**	**Production Frequency**	**Public data base**
Medium Range	**15 days**	**Twice daily**	**TIGGE**
Monthly	**45 days**	**Twice weekly**	**S2S**
Seasonal	**7 months**	**Once monthly**	**C3S**
Annual	**13 months**	**Quarterly**	

Although the observational needs of the different forecasting systems vary, all of them revolve around four main activities: initialization of the forecast model; model and data assimilation development; calibration of model output and skill assessment. Both calibration and skill assessment require a set of reforecast over a sufficiently long period. These reforecast are initialized from reanalyses. Reanalyses are widely used for monitoring of the Earth System’s climate, but they are also an integral part of the forecasting systems. Without them the forecast could not be calibrated, nor their skill could be estimated. 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 outcomes also apply to the Tropical Atlantic Observing System. Since that report in 2014, there have been two important developments worth highlighting: one is the role of the ocean in forecast of tropical cyclone intensity, especially critical when using high resolution atmospheric models; the other are the efforts towards a coupled data assimilation system.

The role of the ocean in tropical cyclones

In a recent study, Mogensen *et al* 2017 examine the role of air-sea interaction in the intensity of tropical cyclone in medium range forecast. They find that when the atmospheric resolution is sufficiently high and the ocean mixed layer is shallow, representing the rapid SST cooling induced by the cyclone is instrumental for the prediction of the cyclone intensity. Persisting the SST during the forecast period, as it is the case in the traditional NWP atmospheric forecast, results in an artificial energy source that continues feeding the cyclone and leads to unrealistic increase in the cyclone intensity. As an example, Figure 1 shows the time series of the SST cooling during the hurricane Irma in September 2017. By the 8th of September, warm SST conditions exceeding 30° C were present over the Caribbean. The arrival of Irma induced a sharp cooling event on the 11th of September. Comparison with in-situ observations show that the coupled model was able to produce this cooling, although the details of the timing and amplitude are not perfect. The time series also show the large diurnal cycle in SST, which the ocean model attempts to reproduce. This example illustrates the value of in-situ observations for verification. Observations are also needed to correctly initialize the ocean mixed layer.

Coupling is already operational for ECMWF's ensemble forecasts (ENS, horizontal resolution of 18 km) and is due to be extended to high-resolution forecasts (HRES, horizontal resolution of 9 km) in the next upgrade of ECMWF's Integrated Forecasting System (IFS) planned for summer 2018.

SST conditions at the time of Hurricane IRMA

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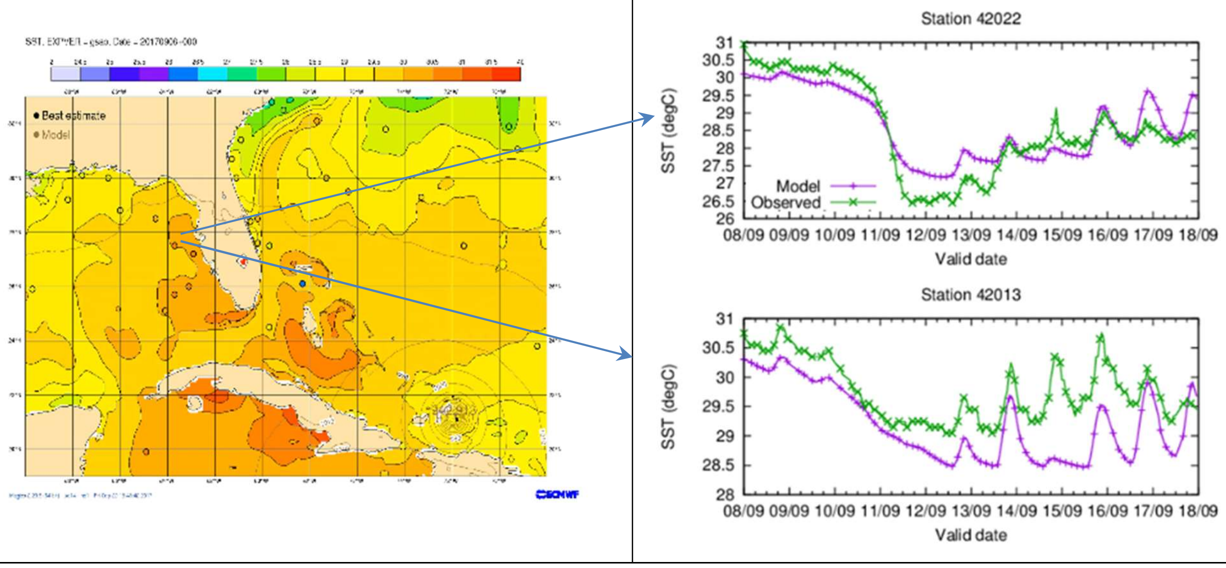

Figure 1: SST conditions associated with the occurrence of hurricane Irma. The left panel shows the analyzed SST on the 8th of September 2017. The right panels show the time series of observed and forecast SST using coupled ocean-atmosphere model. The coupled forecast are able to reproduce the cooling conditions induced by the arrival of Irma.

Coupled data assimilation

A prototype for a coupled data assimilation (CDA) system has been recently developed (Laloyaux *et al* 2016). This CDA system assimilates atmosphere-land-waves-ocean and sea-ice observations to produce simultaneous estimates of these components. The main objective is the coupled initialization of the coupled forecast model, which should improve the consistency between the estimated states, thus reducing initialization shock. CDA is also expected to optimize the use of observations, since an observation from one media can influence other media. The CDA prototype has been used for the production of two pilot Earth System reanalyses CERA-20C and CERA-SAT under the H2020 project ERA-CLIM2 (Buizza *et al* 2018). Initial results are promising, and work is ongoing to enable CDA for the initialization of the coupled forecast and for the production of the future generations of climate Earth-System reanalyses.

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A.5-7 Extreme Events 2017 Atlantic Hurricane Season Review and National Hurricane Center Ocean Observations Requirements for Improved Forecasts

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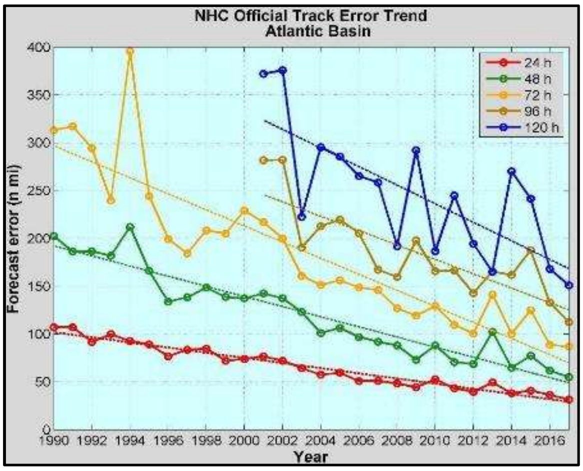
Hurricanes are the most common and regular weather and climate extremes occurred in the Atlantic sector, causing more damage than all other storms combined. Each year hurricanes cause more than $2 billion in damage to just the U.S. alone and that number is expected to grow. As such, improving hurricane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

Forecasts for Atlantic Basin tropical cyclones have continued to improve in recent decades from climate (subseasonal-to-decadal) to synoptic storm (hours-to-days) scale. In particular, synoptic forecasts of hurricane tracks have improved significantly over the past two decades (Figure 1a). In fact, in 2017, the National Hurricane Center (NHC) produced their most accurate hurricane trajectory forecasts on record for Atlantic tropical cyclones, with an average forecast error of 151 nm at 5-day lead time. Improvements in global weather models, in the use of multi model ensembles, and hurricane specific research continue to drive these forecast improvements. However, despite the significant advancements in trajectory forecasts for Atlantic tropical cyclones (TCs), improvement in intensity forecasts of individual storms on synoptic time scales has stagnated in the past decade (Figure 1b). In particular, cases of rapid intensification (RI) are the most challenging intensity forecasts for the NHC, and produce the largest forecast errors. Recent evidence suggests that improved ocean observations and ocean modeling may provide the necessary input for atmospheric models to more accurately simulate air-sea interaction, and lead to improved intensification trends. Experiences at the NHC suggest that increasing ocean observations, both temporally and spatially, from the surface through the thermocline, will provide more realistic initial conditions required by the global weather models, and lead to improved intensity forecasts for Atlantic tropical cyclones.



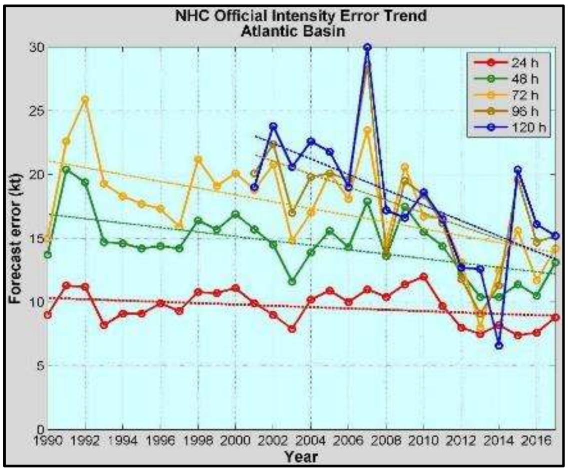


Figure 1. Improvement of synoptic forecast errors of Atlantic hurricane trajectories (a) and intensities (b) since 1990.

The past decades have also witnessed considerable progress in advancing capability for predicting hurricanes and TCs on climate time scales, particularly at seasonal time scales. The basis of seasonal hurricane forecast builds on the notion developed from observational and theoretical studies that TC activity is closely linked to the large-scale environment conducive to TCs, which is determined by background vorticity, vertical wind shear, mid-level moisture, SST and stability of atmospheric column. These environmental factors are strongly influenced by large-scale climate modes in the tropics, such as El Niño – Southern Oscillation (ENSO), Atlantic Meridional Mode (AMM) and Atlantic Multidecadal Oscillations (AMO), which are predicable on seasonal-to-decadal time scales. Earlier studies on seasonal hurricane forecast relied on pure statistical approaches. Operational dynamical seasonal TC forecasting began in early 2000s. More recently hybrid statistical-dynamical models have been developed and applied to operational seasonal TC forecasting. Dynamical and hybrid models now show skill comparable with or even more superior than that of many well known statistical models, particularly at longer lead times. These studies strongly suggest that a large fraction of the climate information needed to make skillful TC forecasts at seasonal or longer time scales lie in the evolution of tropical SST pattern, highlighting the importance of improving TC-season SST forecasts. Despite of these recent progresses, model forecast skill of seasonal TC activity is still relative low at long lead times (anomaly correlation is less than 0.5 for forecasts initialized earlier than March). There is also a pressing need to push seasonal prediction efforts beyond basin-wide TC activity toward the much more challenging and societal relevant goal of improving skill at the regional scale, so that skillful seasonal forecasts of landfalling hurricanes and TCs can be achieved. As computing power continues to increase, high-resolution coupled climate models that are capable of directly resolving and simulating TCs will become increasingly important for TC forecasts at seasonal or long time scales. However, before these models can be readily applied to long-term TC predictions, one must confront with the challenge of reducing model tropical biases. In the tropical north Atlantic, current generation IPCC models suffer from cold SST bias, which severely hamper their simulation and prediction skills of hurricanes. Enhancing observations in the Atlantic hurricane main development region (MDR) can help accelerate the effort toward resolving the Atlantic bias problem.

In viewing of these recent research progresses, we believe that the following observations in the Tropical Atlantic Ocean are critical to further advance and improve our predictive capability of Atlantic hurricanes:

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

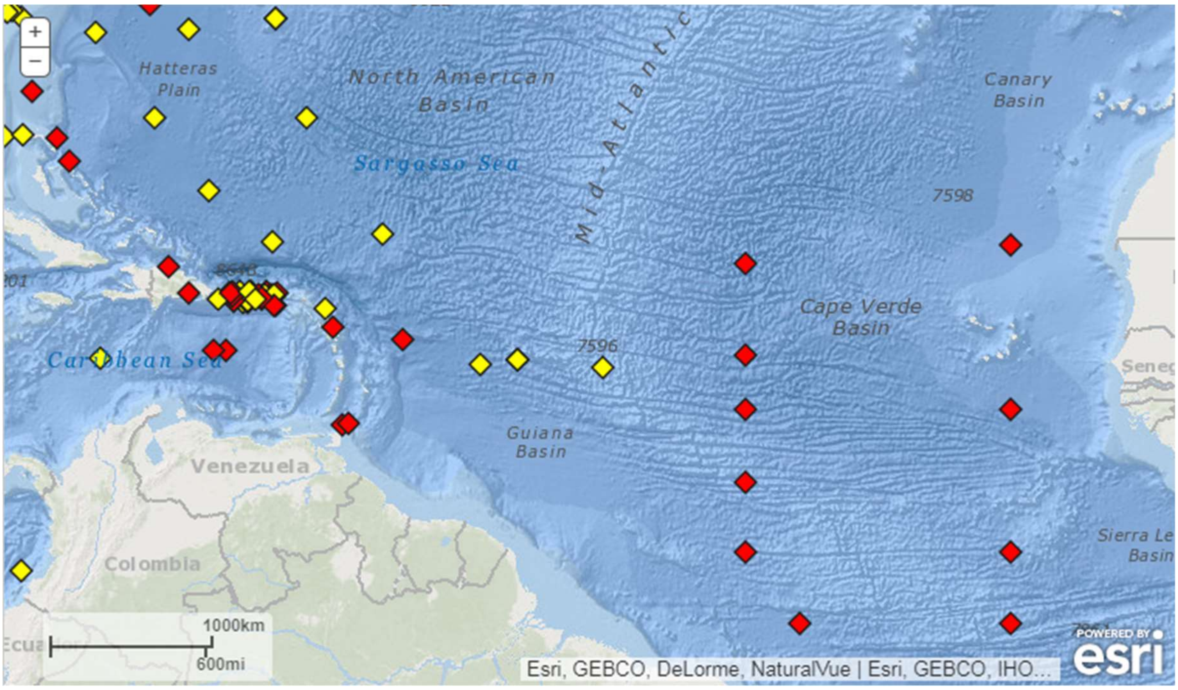


Figure 2. NDBC map indicating locations of NDBC buoys (yellow) and international platforms (red) across the Main Development Region (MDR) for Atlantic tropical cyclones.

A.5-8 Evaluation of the Tropical Atlantic observing system from ocean data assimilation perspective: Marine applications

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In Marie Drévillon's presentation "Data assimilation in global ocean analysis and forecasting system, for Marine applications: focus on the Tropical Atlantic" (authors: Marie Drévillon, Elisabeth Rémy, Eric Greiner, Charly Régnier, Jean-Michel Lellouche and the Mercator Ocean team), the state-of-the-art of 3D analyses with oceanic numerical models and data assimilation was illustrated with Mercator Ocean's global forecasting system.

Mercator Ocean, which had primary responsibility for the global ocean forecasts of the MyOcean and MyOcean2 projects, is delegate of the European Commission since November 2014 to implement the Copernicus Marine Environment Monitoring Service (CMEMS[1]), as part of the European Earth observation program Copernicus. CMEMS observations, analyses and forecasts are intensively used in four main areas of application: (i) maritime safety, (ii) marine resources management, (iii) coastal and marine environment, and (iv) weather, climate and

[1] http://marine.copernicus.eu

seasonal forecasting[2]. In this context, Mercator Ocean is producing and delivering real-time daily services (weekly analyses and daily 10-day forecasts) and long reanalyses (1993-2017) with a state-of-the-art global 1/12° system. As describe by Lellouche et al. (2018) this system uses the version 3.1 of the NEMO ocean model (Madec et al., 2008). The in situ temperature and salinity observations and the satellite SST and Sea Level anomaly observations (and sea ice concentrations in polar regions) are assimilated jointly by means of a reduced-order Kalman filter derived from a SEEK filter (Brasseur and Verron, 2006). A three-dimensional multivariate modal decomposition of the background error and a 7-day assimilation cycle are applied. The system also includes an adaptive-error estimate and a localization algorithm. In addition to this data assimilation system called SAM (Système d'Assimilation Mercator), a 3D-VAR scheme provides a correction for the slowly-evolving large-scale biases in temperature and salinity.

The evaluation of such systems includes routine verification against assimilated and independent in situ and satellite observations as in Fig 1-2-3 (see also Lellouche et al. 2013 or the corresponding CMEMS Quality Information Document[3]), as well as a careful check of many physical processes (e.g. mixed layer depth evaluation as shown in Drillet et al. (2014)). User's scientific studies bring precious additional evaluation feedback (Juza et al., 2015; Smith et al., 2016; Estournel et al., 2016). Finally, several studies have shown the added value of surface currents analyses provided by these systems for drift applications in the Tropical Atlantic (Scott et al., 2012; Drevillon et al., 2013). Worldwide global ocean monitoring and forecasting systems can display various levels of performance depending on the variables (Ryan et al, 2015), but some strengths and limitations appear in Mercator Ocean analyses and reanalyses that are found in many other systems. The 3D temperature variability and state are generally well captured, especially near the surface, as it is where most observations are available to constrain the model. It is important to note that the salinity (even more than the temperature) was very much improved by the implementation of the ARGO network. Equatorial currents are too strong, especially at depth, which has been gradually improved these recent years by improving the data assimilation of sea level anomalies in the tropics (through improvements of the mean dynamic topography in particular). In general, the systems do not assimilate all the information available from the observation system, as choices are made to retain only large scales, or only part of the observed signal (detiding, filtering etc.) depending on the model and on the application aimed at. For instance, climate studies or maritime security would require different resolutions or tunings.

The observations from the Tropical Atlantic Observing System are all very valuable. In particular, HF moorings such as PIRATA are crucial for validation/calibration (observations of currents are particularly valuable, Fig 3), and also proved useful for data assimilation of temperature and salinity. Surface drifters are used for the validation of SST and currents at 15m (Fig 1 and Fig 2). Ocean monitoring and forecasting systems will strongly benefit from higher resolution remote sensing observations (for instance SWOT), which will help better constrain small scales for all surface variables. Surface salinity from remote sensing will be assimilated soon in ocean reanalyses as it was shown to improve the accuracy of the analyses and eventually of the (seasonal) forecast. Coastal observations, in particular transports and currents will be better taken into account in the future and the assimilation of such observations is expected to improve the general circulation of the whole Atlantic basin. Data assimilation improves the average accuracy, but can induce spurious high frequency phenomena (gravity waves, recirculation cells). Furthermore small scales (<1 day and < ¼°) are not really constrained yet. Improvements are expected first from high resolution SST assimilation using a "4D" approach, and the impact of high frequency mooring observations will also be evaluated. Complementary to Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs), process oriented validation of experiments with and without data assimilation are also needed to improve the setup of the data assimilation systems and

[2] http://marine.copernicus.eu/markets/use-cases

[3] http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-024.pdf

help design the evolutions of the observation network. Part of this work is planned in the AtlantOS project and/or GODAE OSE-val TT. On the longer term, the high resolution analysis and forecasting systems at Mercator Ocean will be coupled with an atmospheric boundary layer model, which implies that atmospheric observations at buoys are also very important. Ensemble runs and ensemble data assimilation will be implemented, which will provide new tools to assess the impact of individual oceanic observations in 3D ocean analyses.

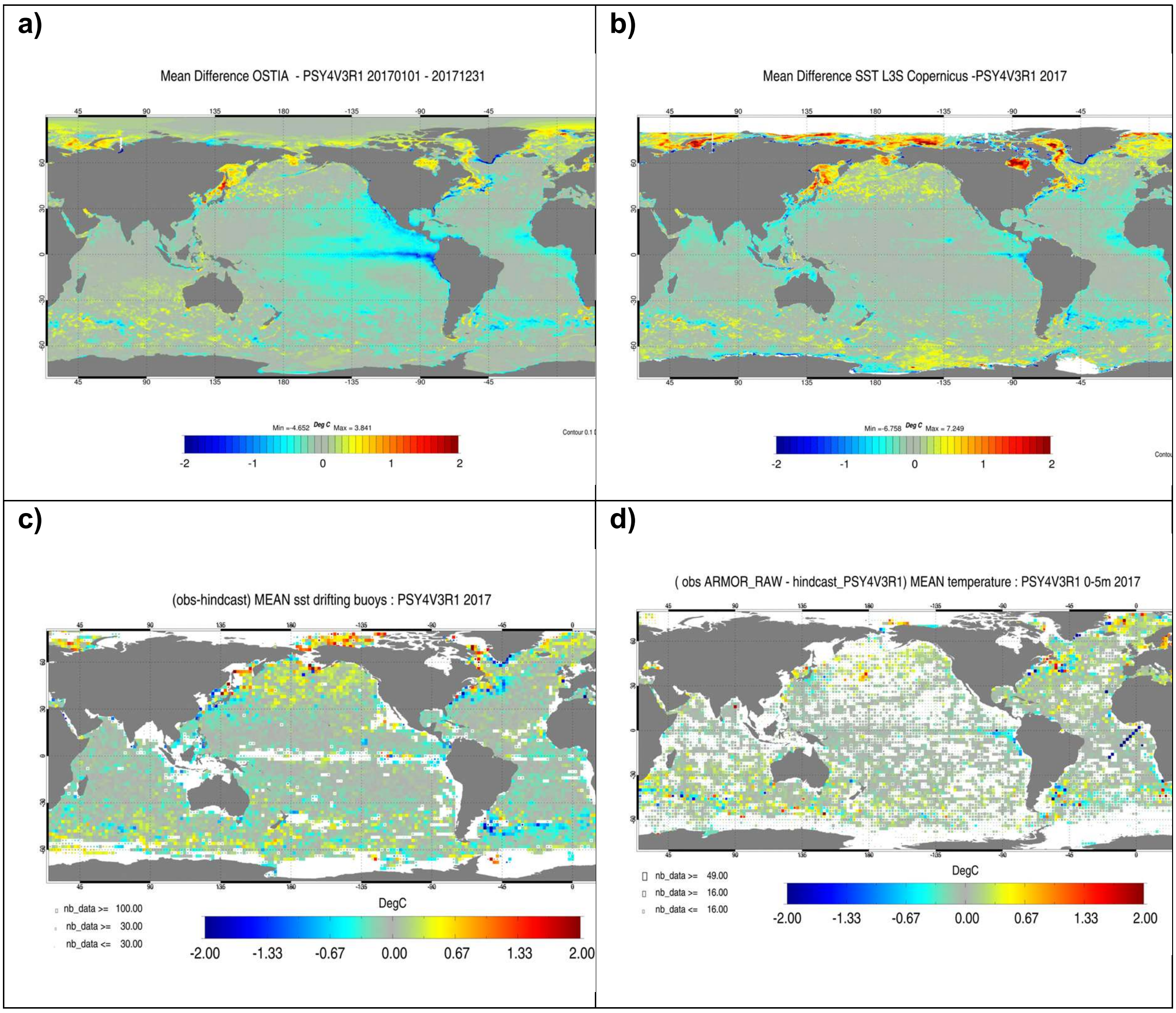

Fig1: Annual mean (2017) near surface temperature differences (°C) in between global 1/12° analyses and (a) OSTIA SST analyses; (b) L3S multi sensor gridded SST; (c). SST from drifting buoys; (d) average 0-5 m ARGO temperatures. All products are available at marine.copernicus.eu.

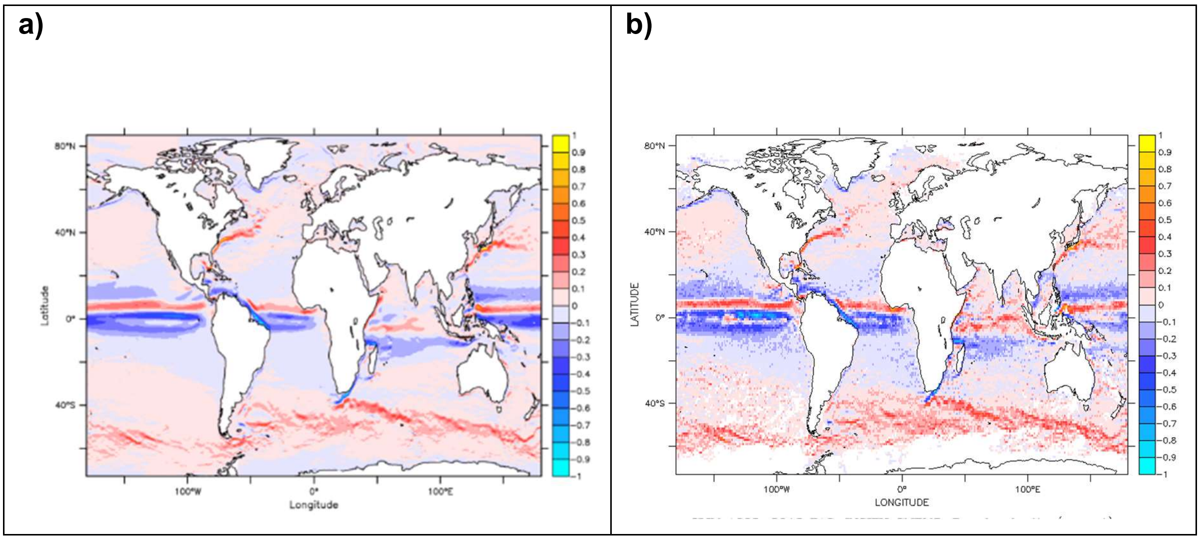

Fig2: Average 1993-2014 zonal velocity (m/s) from GLORYS12 global 1/12° reanalysis (a) and from INSITU TAC drifters reprocessing (b). Both products are available at marine.copernicus.eu.

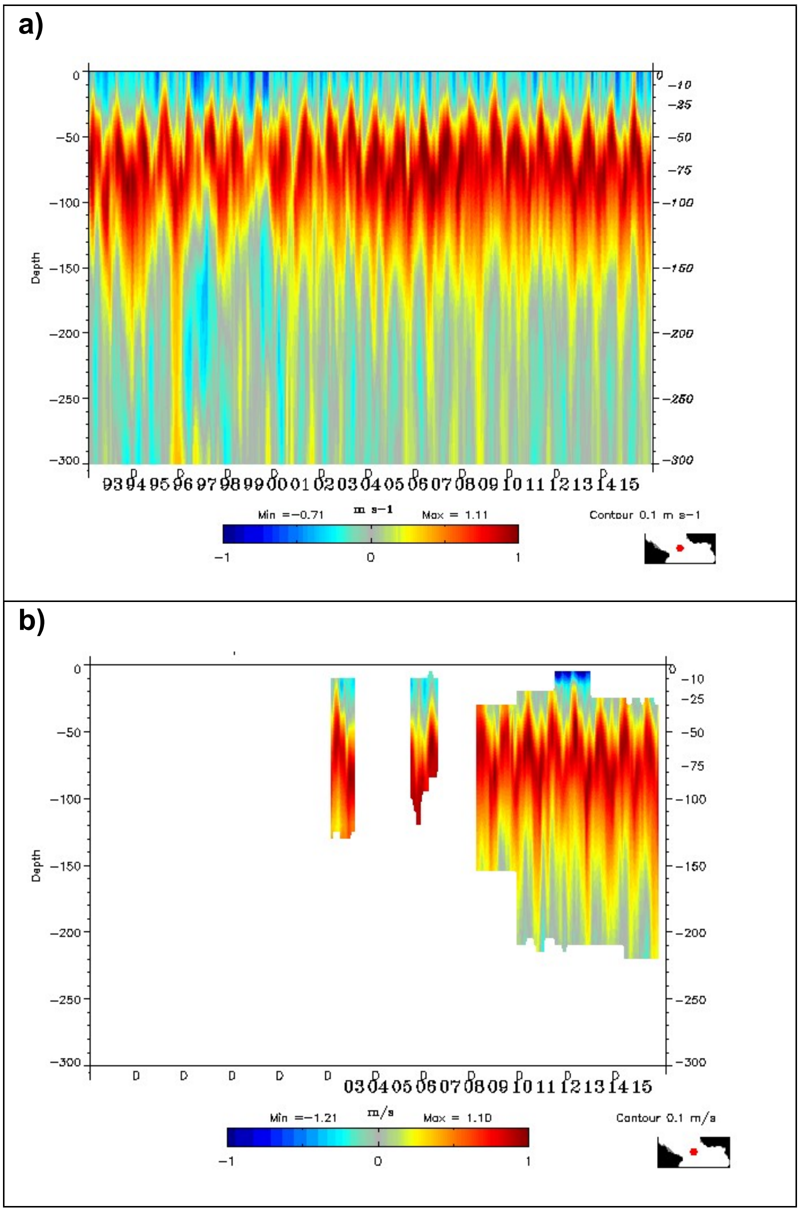

Fig 3: Zonal velocity with depth and time at a PIRATA mooring (23°W 0°N) in the GLORYS2V4 reanalysis at ¼° (a) and observed values at the mooring (b). Both products are available at marine.copernicus.eu.

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A.5-9 Biogeochemical applications in the Tropical Atlantic: Requirements, synergies, and gaps

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The requirements for Biogeochemistry observations in the Tropical Atlantic can initially be discussed around the Essential Ocean Variables as defined by the Global Ocean Observing System (GOOS). These EOVs have been defined based on impact vs. feasibility of these variables for a global ocean observing system. However, these EOVs are global variables, and it is possible that for this region a different set of requirements is needed. The GOOS BGC EOVs are: Dissolved Oxygen, Transient Tracers, Dissolved Organic Carbon, Ocean Colour, Inorganic Carbon, Nitrous Oxide, nutrients and Particulate Matter.

The BGC EOVs can be examined in view of the particular situation in the tropical Atlantic. Starting with oxygen it is an obvious link to the Oxygen Minimum Zones in the eastern part of the tropical Atlantic, and the associated oxygen supply by zonal currents and other processes. There are evidence of expanding OMZs and of decreasing oxygen concentrations in the OMZs. Considering the importance of oxygen for marine life, and as an indicator of ventilation, a observing system of oxygen has a high impact. The oxygen concentration is linked to nutrient concentration variability, partly because of the inverse relationship but also due to processes that change nutrient concentrations in low oxygen waters. Supply of nutrients to the surface waters is the main limitation for primary production, so understanding of nutrient variability is important for the tropical Atlantic.

Related to the issue of variability of ventilation, and on the storage of anthropogenic carbon, regular measurements of transient tracers have a potential high impact in understanding variability of circulation and ventilation.

For the inorganic carbon system, the tropics are important areas of CO_2 fluxes, associated with significant interannual and seasonal variability. A monitoring system for CO_2 is highly needed. Similarly, for the interior ocean it has been shown that the tropical Atlantic is storing significant amounts of anthropogenic carbon, and the associated decrease in pH and carbonate ion concentration that leads to under-saturation of aragonite in the region. Interior observations of the inorganic carbon system are important for the understanding of these processes. Additional observations of the stable isotope composition of inorganic carbon (^{13}C) provides information on storage of anthropogenic carbon

Related to the productivity and export of organic matter to the interior ocean, observations of dissolved organic carbon as well as of particulate matter can provide a knowledge base for variability and trends in these processes.

The tropical Atlantic has also been shown to be an important area for N_2O fluxes although the variability and magnitude of this flux is poorly constrained so that an increased effort to include observations of N_2O in the region seems highly motivated.

In summary, working down the list of BGC EOVs as defined by GOOS it can be stated that sustained observations of these EOVs in the tropical Atlantic all seem to have high impact. The design of an observing system the captures the expected variability of these variables, and the regions that are most variable or expected to show a trend, is not described here and still needs to be defined based on the current knowledge of the biogeochemistry of the tropical Atlantic.

A.5-10 Biology and Fisheries applications: Requirements, synergies, and gaps

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Observing the biological elements of the marine environment spans from phytoplankton over zooplankton, fish and shellfish, benthic organisms to marine birds and mammals. These span several magnitudes in size, from nanometer to several meter in length. Thus, the challenges for observations become immediately obvious. Besides the technical needs to observe marine living organisms, most of the observations currently performed in the tropical Atlantic are based on single projects and process studies and no cross Atlantic, holistic monitoring system exists. However, in some areas like the Benguela Large Marine Ecosystem, countries have been collecting systematically since several years to decades. In addition, global projects like Census of Marine Life (Costello et al. 2010) have collected biodiversity data in the global ocean, including the Tropical Atlantic (Fig 1).

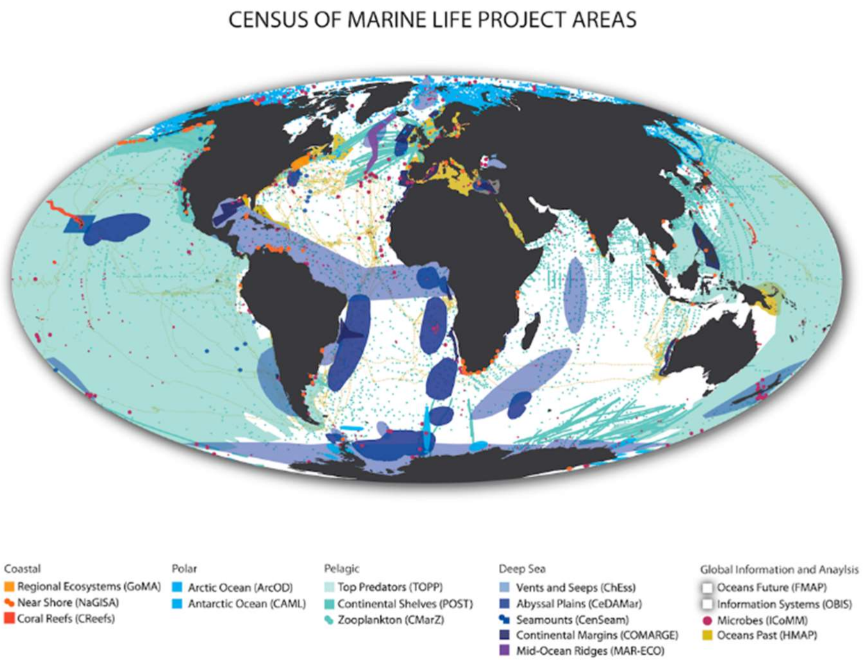

Figure 1: Sampling of the Census of Marine Life Project

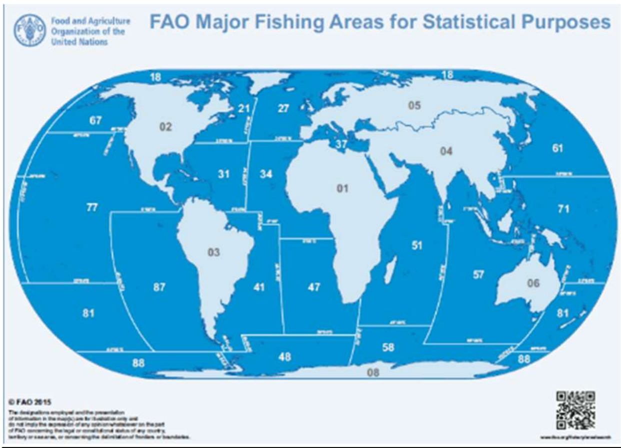

Figure 2: Main statistical areas of the Food and Agriculture Organization of the United Nations (FAO), FAO 2015

With respect to fisheries, the requirements for monitoring and are driven by the management needs. For the assessment of commercial fish stocks, fisheries dependent information like total effort of the fishing fleet and the respective catch is the minimum requirement. In addition many countries perform fisheries independent surveys like trawl surveys or hydroacoustic surveys. Most African countries can't afford a sustained survey program and thus rely on programmes like the EAF Nansen Programme. The importance of fisheries in the Tropical Atlantic can most easily been demonstrated by the total catch and the dependence on the sector in the region. Almost 10 Million tonnes of seafood (from 87.2 million global marine capture production) was harvested in the Central and South Atlantic (FAO major areas 31, 34, 41 and 47, Fig. 1) in 2016 (FAO 2018).

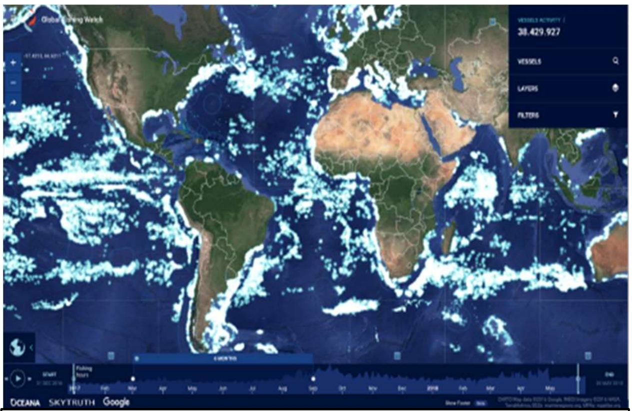

Figure 3: Fishing activities cumulated from March 2017 to September 2017; taken from Global Fishing Watch (http://globalfishingwatch.org/map/)

In addition, the fishing sector has a high importance in the tropical Atlantic coastal countries. The total amount of fishers in

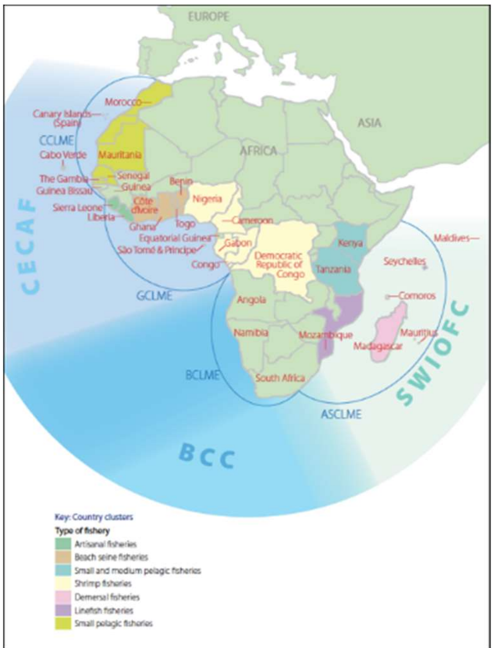

Figure 4: Extend of the EAF Nansen Programme Survey around the African continent

Africa, Latin America and the Caribbean is 8 Million, although not all of them are operating in the Atlantic. But not only these countries fish here, but many foreign fleets, (Korean, Chinese, Russian, European, etc.) also use the resources. Figure 2 shows fishing activities cumulated over a period of 6 months from March 2017 to September 2017 as shown by Global Fishing Watch, which is a good example for a global remote sensing observation system for fishing activities. However, it only shows vessels with an Automatic Identification System (AIS), which only vessels above 300 BRT need to install and run (IMO, SN/Circ.227). Thus, smaller fishing vessels, especially close to the coast cannot be detected.

Fisheries independent surveys collect systematically information about the stocks through trawl and hydroacoustic data collection.

However, to understand processes related to growth and recruitment of commercially important species and thus subsequently to gain an understanding of the ecosystem, additional sampling of the biological, chemical and physical environment is performed. Many of these surveys are only happening through dedicated projects. One example of a survey, which started as a pure fisheries survey and turned into an ecosystem survey is the EAF Nansen Programme. Since 1975 this joint initiative of Norway and the Food and Agriculture Organization of the United Nations (FAO) is performing surveys with the research vessel, *Dr Fridtjof Nansen*, which was specifically built for the programme, around the African continent (Fig 4). The Nansen Programme now collects data on fisheries and ecosystems, pollution and climate variability and change (Table 1).

In conclusion, not all existing programmes and projects have been listed here, but overall, it becomes clear that no holistic observation programme exists for the Tropical Atlantic with respect to biological and specifically fisheries data. Thus, the requirements are better use of existing data, extending surveys for commercial and endangered species, and integration in a larger observation system, considering the requirements of different user groups, society, private sector and of course the scientific community. Current gaps include missing or not enough communication between different scientific communities collecting data, missing data exchange protocols and missing survey protocols.

Table 1: elements collected by the EAF Nansen surveys

Fisheries and ecosystems	Pollution	Climate variability and change
> Abundance, distribution and dynamics of transboundary stocks > Biological parameters and life cycle of main species > Identification of vulnerable marine habitats > Mapping biodiversity, particularly on the sea-floor > Characterization of ecosystems	> Environmental assessment of the impact of oil/gas extraction and other mining activities > Measuring levels of hazardous substances in bottom habitats and in fish, and identifying pollutant pathways > Mapping distribution and density of marine debris, including microplastics	> Examining trends in climate-change related indicators > Assessing how climate variability and change affects marine ecosystems, including food-web dynamics, recruitment, distribution, migration and growth of fish species > Understanding how climate change affects ocean biochemistry processes

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A.5-11 Presentations from related observational programs (IMBeR, SOLAS, POGO)

Carol Robinson
University of East Anglia

A number of global multidisciplinary marine biological and biogeochemical research projects are relevant to TAOS, in terms of data collection, conceptual understanding, comparative analysis, training and capacity building. Carol Robinson gave a presentation outlining the goals and strategies of some of these projects including the SCOR (Scientific Committee on Oceanic Research) and Future Earth sponsored Integrated Marine Biosphere Research (IMBeR; www.imber.info) project, the SCOR, Future Earth, World Climate Research Programme (WCRP) and International Commission on Atmospheric Chemistry and Global Pollution (iCACGP) sponsored Surface Ocean Lower Atmosphere Study (SOLAS; www.solas-int.org), the work of the Biology and Ecosystem and Biogeochemistry Panels of the Global Ocean Observing System (GOOS; www.goosocean.org) and the Partnership for Observation of the Global Oceans (POGO; www.ocean-partners.org).

The IMBeR project works towards the vision of '*Ocean sustainability under global change for the benefit of society*' with a research goal to 'understand, quantify and compare historic and present structure and functioning of linked ocean and human systems to predict and project changes including developing scenarios and options for securing or transitioning towards ocean sustainability'. The Science Plan (2016-2025) is divided into three grand challenges : 1. understanding and quantifying the state and variability of marine ecosystems, 2. Improving scenarios, predictions and projections of future ocean-human systems at multiple scales, and 3. Improving and achieving sustainable ocean governance. IMBeR science is progressed through the work of a number of regional programmes, working groups and endorsed projects. Those of direct relevance to TAOS include the IMBeR endorsed Atlantic Meridional Transect (AMT) programme which has delivered a unique time series (1995-2018) of spatially extensive and internally consistent observations on the structure and biogeochemical properties of plankton ecosystems in the Atlantic Ocean (Robinson et al., 2006; Rees et al., 2018), the regional programmes SIBER (Sustained Indian Ocean Biogeochemistry and Ecosystem Research) and CLIOTOP (Climate Impacts on Top Predators; Hobday et al. 2017), and the working group on upwelling systems. IMBeR contributes to the work of the GOOS BioEco Panel through so-authorship of proposals for phytoplankton, zooplankton, fish, turtle, bird and mammal biomass, diversity, abundance and distribution as essential ocean variables.

POGO is a consortium of major oceanographic institutes around the world, represented by their Directors. The vision is to have by 2030, world-wide co-operation for a sustainable, state-of-the-art global ocean observing system that serves the needs of science and society. The three pillars of POGO are ocean observations, professional training and outreach and advocacy. POGO has strong links to Atlantic Ocean observing systems, having sponsored a Brazilian led working group on the South Atlantic Meridional Overturning Circulation (SAMOC) which resulted in the organisation of a research cruise in collaboration with AtlantOS (www.atlantos-h2020.eu/) and GEOTRACES (www.geotraces.org/) and funding for the 5 year international project SAMBAR (South Atlantic Meridional Overturning Circulation Basin-wide Array). POGO fund early career training on board research ships, including on AMT, with the potential to extend this to shipboard training in the tropical Atlantic.

The goal of SOLAS is to 'achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, and of how this coupled system affects and is affected by climate and global change'. The SOLAS Science Plan (2015-2025) is divided into five research themes: 1. Greenhouse gases and the oceans,

2. Air-sea interface and fluxes of mass and energy, 3. Atmospheric deposition and ocean biogeochemistry, 4. Interconnections between aerosols, clouds and marine ecosystems, and 5. Ocean biogeochemical controls on atmospheric chemistry. As part of an initiative led by GEOMAR (www.geomar.de/en), SOLAS are interested in promoting the extension of the time series observations collected at Cape Verde ocean and atmospheric observatories as part of the network of Atlantic Time-Series Observatories including BATS (Bermuda Atlantic Time-Series Study; http://bats.bios.edu/), ESTOC (European Station for Time series in the Ocean Canary Islands; http://siboy.plocan.eu/ESTOC) and Fernando de Noronha.

Communication between TAOS and these international programmes, including representation of the programmes on the TAOS review committee, will ensure transfer of best practise and enhance opportunities for comparative analysis, method development and capacity building / training.

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A.6 Presentation summaries for Session 2

A.6-1 Mooring Networks

Moacyr Araujo (UFPE), Bernard Bourlès (IRD), Renellys Perez (NOAA).
With the contributions: PIRATA-SSG, Uwe Send and Matthias Lankhorst (SIO), Rebecca Hummels and Peter Brandt (GEOMAR), Björn Fiedler and Johannes Karstensen (CVOO-GEOMAR).

The Tropical Atlantic Current Observation System is comprised of several in situ mooring networks ranging from pilot programs to more established systems. Here we focus on several of the more established networks in the tropical Atlantic.

PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) is today the most organized and comprehensive *in situ* observing network in the tropical Atlantic. PIRATA is a multinational program initiated in 1997 to improve our knowledge and understanding of ocean-atmosphere variability in the tropical Atlantic, a region that strongly influences the regional hydro-climates and, consequently, the economies of the regions bordering the Atlantic Ocean. PIRATA is motivated not only by fundamental scientific questions but also by societal needs for improved prediction of climatic variability and its impacts. PIRATA works thanks to a close collaboration between research institutions in the United States (National Oceanic and Atmospheric Administration -NOAA), Brazil (Instituto Nacional de Pesquisas Espaciais -INPE, with contribution of the Diretoria de Hidrografia e Navegacão -DHN), and France (French Institut de Recherche pour le Développement -IRD and Meteo-France) that have been committed to long-term maintenance of PIRATA since a 2001 Memorandum of Understanding. The network is based around an array of moored buoys providing meteorological and oceanographic measurements transmitted in real-time, disseminated via Global Telecommunication System (GTS) and Global Data Servers. Then, through yearly mooring servicing, high-frequency data are collected and calibrated

PIRATA is now more than 20 years old. It serves as the baseline climate record in the tropical Atlantic through sustained observing of Global Ocean Observing System (GOOS) Essential Ocean and Climate Variables (EOVs and ECVs, respectively). As part of OceanSITES (http://www.oceansites.org/OceanSITES/), PIRATA maintains 18 air-sea exchanges buoys equipped with atmospheric sensors (T, humidity, rain, solar radiation, wind amplitude and direction), and T/S/p sensors down to comprehensive 500 m depth. Some buoys are equipped with surface current-meters, 3 with CO_2 sensors and 3 other ones with O_2 sensors. Data are transmitted in real time through the Argos (for original ATLAS buoys) or Iridium (for new T-Flex buoys) systems and made available through the GTS and to some GDACs, the PIRATA PMEL website, and ftp. The T-Flex moorings progressively replace the ATLAS moorings since 2015; at present 10 buoys are T-Flex, allowing the potential implementation of more sensors with high frequency data transmission in real time. As illustrated on the Figure 1, all buoys are also equipped since 2014 with acoustic receivers at 200 m depth, as contribution to the Ocean Tracking Network (OTN ; see http://oceantrackingnetwork.org/). Two equatorial sites (23°W and 10°W) are also equipped with turbulence sensors (χ-pods), in the framework of an Oregon State University (OSU) Ocean Mixing Group program supported by the US National Science Foundation for a 5 years duration (see http://mixing.coas.oregonstate.edu/). PIRATA also maintains three Acoustic Doppler Current Profiler (ADCP) moorings along the equator, at 23°W (from 2001), 10°W (from 2006) and 0°E (from 2016) which monitor the Equatorial Undercurrent from near the surface down to about 300 m depth. See Servain et al. (1998) and Bourlès et al. (2008, 2018) for more details on the PIRATA program and its evolution.

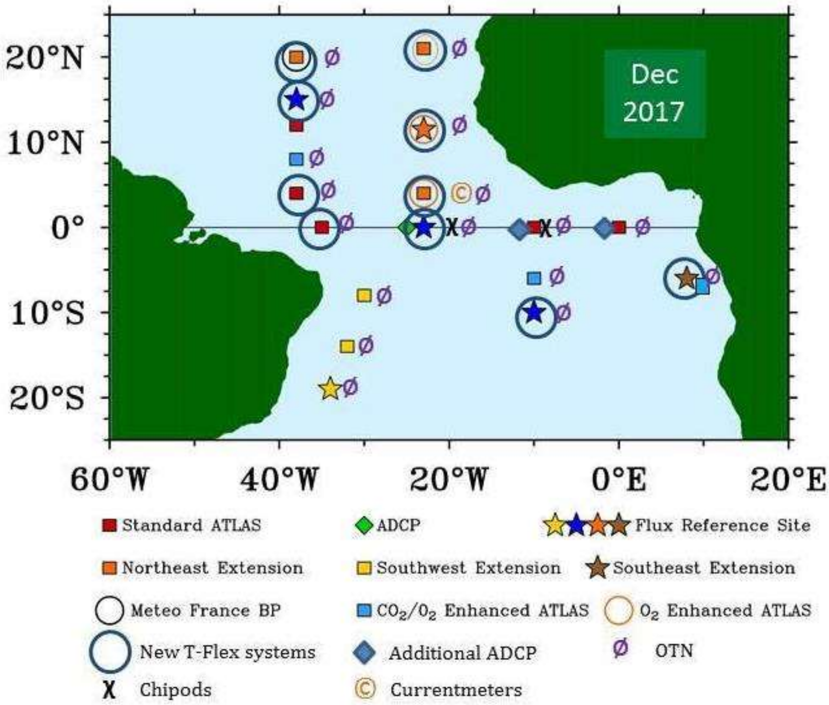

Figure 1. PIRATA mooring network.

In the north tropical Atlantic the MOVE (Meridional Overturning Variability Experiment) is aimed at observing the Atlantic Meridional Overturning Circulation (AMOC) as it flows across 16°N in the western Atlantic basin. This is done with an array of moorings and seafloor PIES instruments located on the 16°N section (Figure 2); the western moorings are near Guadeloupe, the eastern moorings are near promontories of the Mid-Atlantic Ridge. MOVE was started in January 2000 as a German contribution to CLIVAR and transitioned to become a United States effort in the 2006 - 2008 time period. MOVE is now funded through the NOAA Climate Program Office and is an important component of the international AMOC observing system. Presently, MOVE moorings are serviced every second year with research vessels, and there are site visits in the years in between to retrieve data remotely. The mooring data are publicly available at OceanSITES. The next service cruise for the MOVE moorings is scheduled for June 2018. It is anticipated that service cruises will continue to occur every other year (i.e., even years), and that there will be data-retrieval cruises in the intervening years (i.e., the odd years).

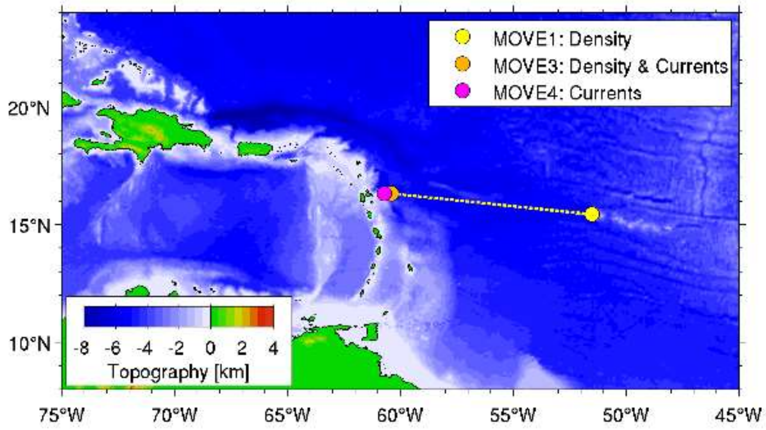

Figure 2. MOVE mooring array.

In July 2013 mooring arrays were deployed at 11°S at the western and eastern boundaries of the tropical South Atlantic Ocean. The Western Boundary Current (WBC) mooring array at 11°S off Brazil was initiated within the German BMBF funded project “RACE” and captures the northward flow of warm and intermediate waters within the North Brazil Under Current (NBUC), the southward flow of North Atlantic Deep Water (NADW) within the Deep Western Boundary Current (DWBC) and the northward flow of Antarctic Bottom Water (Figure 3, left panel). This mooring array is comprised of four tall moorings on the Brazilian shelf recording velocity with four ADCPs and additional single-point current meters, as well as temperature and salinity with MicroCat sensors (Figure 3, central panel). That work is accompanied by shipboard hydrographic and current observations along two zonal sections at about 5°S and 11°S. The transport variability of the different branches of the WBC system, particularly of the NBUC and DWBC on seasonal to decadal time scales, is analyzed with respect to changes of the AMOC in both the South and North Atlantic and/or the southern subtropical cell (STC). A similar array had been deployed at the same location between 2000 and 2004, which allows investigations of transport and water mass variability on longer time scales. Currently, the 11°S array is still funded within the follow-up BMBF project “RACE II” until December 2018. The cruise M145 occurred in February 2018 and the array was redeployed on institutional costs of GEOMAR, Kiel, Germany. Further funding after 2019 is still being sought. The maintenance cruises of the 11°S- WBC array were always carried out in close collaboration with the project “SFB754 – Climate-Biogeochemistry Interactions in the Tropical Ocean”, which is focused on the oxygen distribution and variability within the eastern tropical Atlantic. The measurement programs have been carried out in close cooperation between GEOMAR and UFPE, Recife, Brazil under the umbrella of a memorandum of understanding signed in 2012.

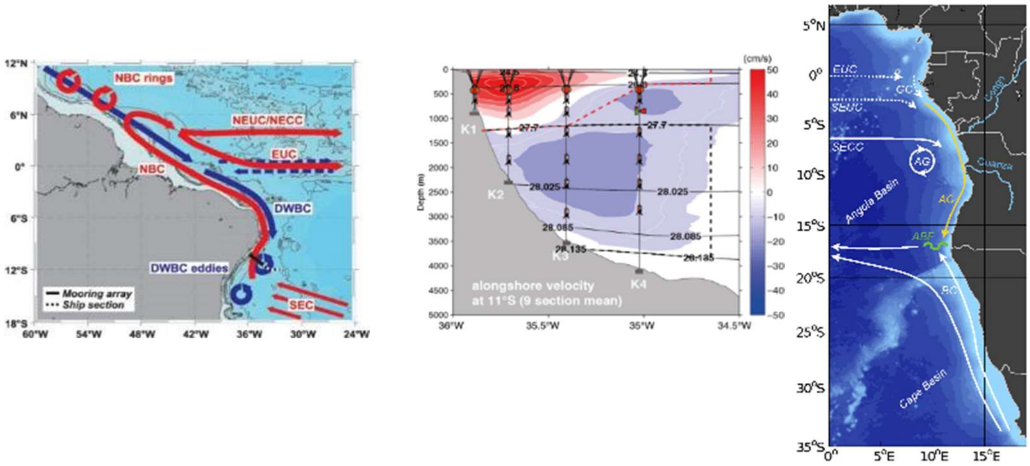

Figure 3. RACE and SACUS mooring arrays.

The Eastern Boundary (EB) mooring array at 11°S off Angola aims at capturing the strength and variability of the Angola Current hugging the continental shelf. Together with shipboard hydrographic and velocity sections, the two ADCP moorings at 11°S are used to analyze the transport variability of the Angola current on intraseasonal to interannual timescales. The assessed variability at the eastern boundary is then put into context with the variability in the equatorial band, especially focusing on the propagation of equatorial and coastally trapped waves as well as the occurrence of interannual phenomena known as Benguela Nino events. The mooring array was commenced within the German BMBF funded project “SACUS” from July 2013 until June 2018, with the upcoming service cruise M148 to redeploy the array being granted for June 2018. Further funding of the 11°S array at the eastern boundary is granted from the German BMBF SPACES program until July 2021. The analysis of the mooring data and the investigation of the role of remote and local forcing for the eastern boundary current variability is carried out in close cooperation with the EU-FP7 funded PREFACE project (2013-2018). The measurement programs have been carried out in close cooperation between GEOMAR and INIP, Luanda, Angola.

Still in the eastern tropical Atlantic, the Cape Verde Ocean Observatory – CVOO (17°35.00’N, 24°17.00’W, Figure 4) is a biogeochemical shipboard open-ocean time-series site in the Eastern Tropical North Atlantic which is based on two pillars: A monthly ship-based sampling program (measurements of temperature, salinity, biological parameters, nutrients, dissolved carbon and oxygen) as well as an oceanographic multi-parameter long-term mooring for in-situ observations (including real-time satellite telemetry). The mooring program was established in 2006. Collected data is set into context of observations at the atmospheric site (CVAO) which measures meteorological parameters, greenhouse and short-lived gases, and aerosols. CVOO is part of JCOMM-related OceanSITES time series network and is an official ICOS station (Integrated Carbon Observation System).

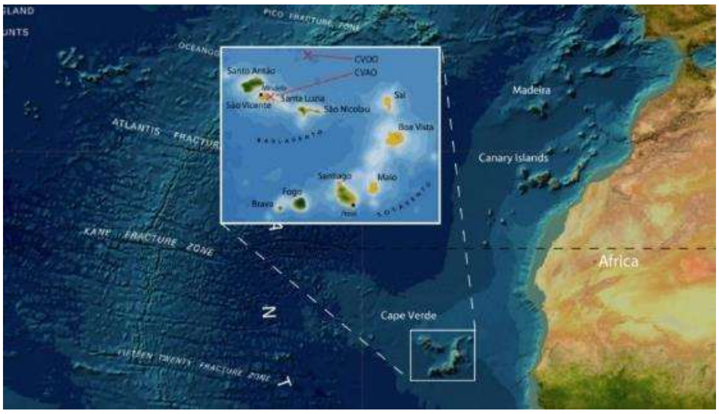

Figure 4. CVOO mooring site.

A.6-2 Lagrangian observations of the Tropical Atlantic

Rick Lumpkin
NOAA/AOML

Lagrangian observations provide the opportunity to map ocean transport pathways and characterize turbulence across scales from the submesoscale to the basin scale, properties which can be very sensitive to parameterizations in numerical models. Lagrangian observations of temperature, velocity, and other properties are also valuable to map spatial variations in these properties, as the observations typically span great distances. This review focuses on the various platforms that provide Lagrangian observations, with a focus on the Tropical Atlantic (TA).

1. <u>Surface Drifters</u>

Examples include the Global Drifter Program (GDP) drifter, the CODE/Davis drifter, and the new LASER/CARTHE-style drifter.

The GDP (http://www.aoml.noaa.gov/phod/gdp) has collected observations in the TA for many years, using drifters drogued at 15m which slip with respect to currents at this depth at <0.1 cm/s in 10 m/s wind. The following deployment opportunities are routinely used to seed drifters in the TA:

- Ship of Opportunity (SOOP) lines AX7, AX8.

- PIRATA research cruises (US, French, Brazilian).
- Brazilian navy cruises (western TA).
- GO-SHIP cruises, esp. A05, A06, A10, A13, A16.
- UK MetOffice: both North and Tropical Atlantic.
- Collaboration with two Senegalese research institutes and Italy's National Institute of Oceanography.
- Misc.: for example in 2018, 5 drifters will be deployed in Gulf of Guinea in collaboration with GEOMAR and the Wildlife Conservation Society.

An animation of drifter coverage in the TA basin for 2006—present indicates where deployments are routinely conducted and the subsequent trajectories, which together account for historical data coverage. There has been an average of 5.1 deployments per month in the TA since January 2006.

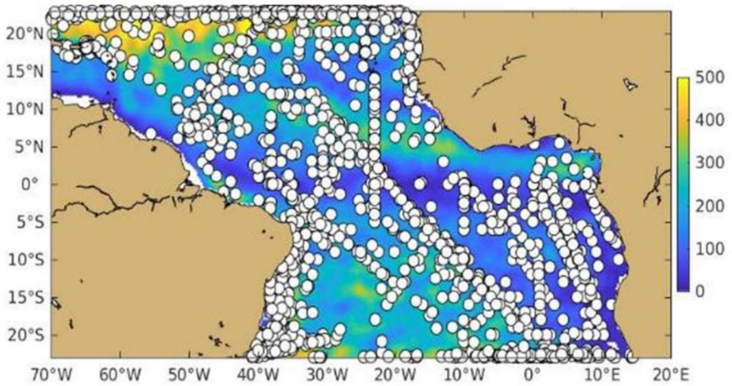

Figure: Shading: density of all GDP observations in drifter days per square degree. Dots indicate deployments, which include drifters entering the TA.

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

Major gaps in GDP coverage in the TA include the equatorial divergence region, which must continuously be reseeded, and the Gulf of Guinea east of the AX8 line from Cape Town to the US east coast.

The new LASER drifter, designed as part of the CARTHE project (http://carthe.org), is a small, low-cost, mostly biodegradable drifter that samples the upper 1m. Approximately 1000 were deployed in the Gulf of Mexico in 2016 and used to map circulation variations and oceanic stirring.

2. Argo floats

Velocity measurements from Argo floats are included in data sets such as YoMaHa created by the IPRC. This includes surface trajectories and displacements at the parking depth. While not Lagrangian in the sense that the trajectory is fully resolved, transport can be inferred. It should be noted that, as the Argo array transitions to Iridium, shorter surface times are required and surface displacements will be less robust to high-frequency aliasing.

3. Acoustically-tracked floats

SOFAR-type floats give continuous trajectories at depth, unlike Argo floats, requiring deployment of sound sources in basins of interest. As a consequence, their observations have typically been confined to particular regions over the power life of the sound sources, rather than as a sustained part of the ocean observing system.

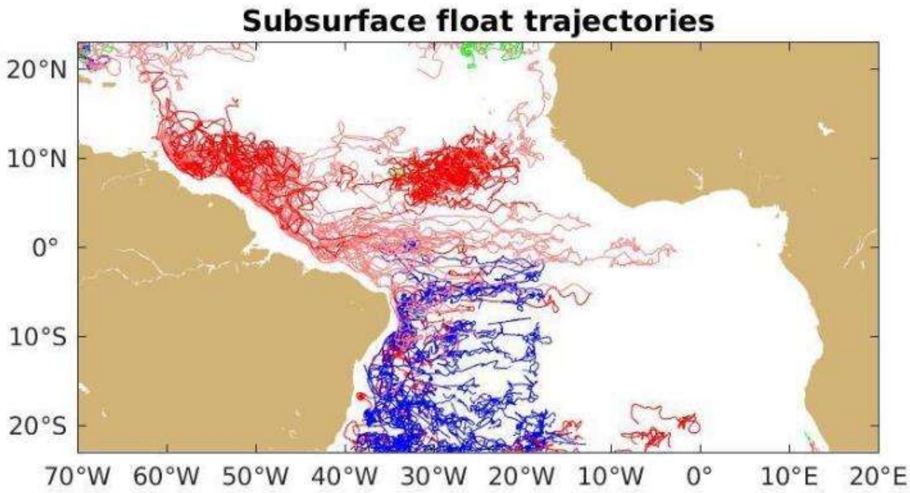

Figure: Acoustically tracked subsurface float trajectories in the TA, in the WHOI database

SUMMARY: TA Lagrangian observations we have now

The Global Drifter Program collects Lagrangian observations over much of the Tropical Atlantic thanks to collaborations with SOOP, PIRATA, GO-SHIP, and various agencies. Observations are relatively sparse on the equator and in the Gulf of Guinea.

Argo float displacements are far more sparse than drifter velocities, but do not exhibit significant equatorial divergence.

Field campaigns such as the Deep Basin Experiment have collected acoustically-tracked trajectories at depth in some limited parts of the Tropical Atlantic.

SUMMARY: future needs for Lagrangian observations in the TA

Other types of drifters could be used for targeted observations. For example, thermistor chain drifters might not diverge significantly from the equator, and would provide many more near-surface observations than Argo floats.

Deployment partners and opportunities are needed to sustain drifter deployments in the Gulf of Guinea.

Much of the Tropical Atlantic remains unsampled by acoustically-tracked floats. Future efforts will reveal much about deep transport pathways, particularly east of the Mid-Atlantic Ridge.

A.6-3 Autonomous Platforms and Sensors

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Woods Hole Oceanographic Institution, USA

A good review of the current state of autonomous platforms and sensors can be found in the report from the 2nd Autonomous and Lagrangian Platforms and Sensors workshop was held at Scripps in February 2017 (Rudnick et al., 2018; https://alps-ocean.us) and in the special issue of *Oceanography* on ALPS, June 2017, volume 30 #2. Autonomous (and Lagrangian) platforms have the capability to replace most of the ship-based ocean observations. The development of new sensors of various biological, chemical and physical properties permit the large scale observation and monitoring of the ocean climate system.

Significant challenges remain in the widespread use of autonomous systems. In particular:

- Power – mostly from batteries, limits system endurance and longevity
- Long-term stability for sensors, often systems are not recovered, so post-mission calibration is not possible, requiring stable sensors and reference datasets
- Bio-fouling in upper ocean, any system in the ocean for significant time experiences bio-fouling which degrades system performance and sensor calibration
- Data management and quality control is essential to the long term success of an observing system
- EEZs for non-core variables, currently only temperature and salinity are covered

The Argo Program has revolutionized large-scale physical oceanography through its contributions to basic research, national and international climate assessment, education, and ocean state estimation and forecasting (Riser et al., 2016). Extensions of the array into seasonally ice covered regions and marginal seas as well as increased numbers of floats along the equator and around western boundary current extensions have been proposed. Of particular interest for the Tropical Atlantic Observing System is the proposed doubling of the float density within ±10° of the equator (Jayne et al., 2017). In addition, conventional Argo floats, with their 2,000 m sampling limit, currently observe only the upper half of the open ocean volume. Recent advances in profiling float technology and in the accuracy and stability of float-mounted conductivity-temperature-depth sensors make it practical to obtain measurements to 6,000 m. Another extension to the Argo Program is the addition of a diverse set of chemical sensors to profiling floats in order to build a Biogeochemical-Argo array to understand the carbon cycle, the biological pump, and ocean acidification.

Gliders are another autonomous system that can be a building block of an observation system. They are small, inexpensive buoyancy-driven autonomous underwater vehicles that are optimized around endurance and overall cost. Their strengths are: steerabilty and maneuverability; access remote and difficult locations; persistent observing; real-time data return; flexible and scalable. However, there are a few limitations: slow; small, low-power payloads; not easy to use, as specialized knowledge is needed to operate; their long-time reliability while improving is still not high; and they cost on order $100,000 per unit plus roughly $100,000 per year to operate. An example of an observing system in the Atlantic Ocean that has been started is the Gulf Stream monitoring with gliders (Todd and Locke-Wynn, 2017).

Autonomous platforms are beginning to address air-sea measurements as well, with examples being Wave Gliders which harvest energy from the surface wave for (Thomson and Girton, 2017) and the Saildrone which performs like a small autonomous sailboat (Mordy et al., 2017).

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A.6-4 Vessel-based Observations

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Research vessels and container ships transiting the tropical Atlantic Ocean provide platforms to collect Essential Ocean and Climate Variables (EOVs and ECVs, respectively) in under sampled parts of the ocean. Vessel-based observations are provided in quasi-real time through the GTS to GDACs, are used by operational weather/climate centers (e.g., ECMWF, INPE/CTPEC) and oceanography centers (e.g., MERCATOR in France), and are also used by the science community in delayed mode after the data have been quality controlled. Vessel-based observations may be focused towards meeting the objectives of a specific observing program. More often, tropical Atlantic cruises are highly collaborative, with teams of international scientists working together to collect oceanic and atmospheric observations. ***One recommendation that emerged from the first TAOS Review Workshop is that an increased emphasis needs to be placed on collecting multi-disciplinary vessel-based observations to better serve the needs of the broader TAOS science community and operational centers.*** Towards that end, we need to cast a wider net for TAOS discussions and include scientists involved in interdisciplinary shipboard observational programs in the tropical Atlantic (e.g., the Atlantic Meridional Transect).

PIRATA (Prediction and Research Moored Array in the Tropical Atlantic) is a multinational program initiated in 1997 to improve our knowledge and understanding of ocean-atmosphere variability in the tropical Atlantic. Dedicated annual cruises to service and maintain the 18 PIRATA moorings allow for the complementary acquisition of a large number of measurements along repeated ship track lines, and also provide platforms for the deployment of other essential components of the Global Ocean Observing System (GOOS, Figure 1).

As of February 2018, 55 PIRATA cruises (27 by France, 17 by Brazil, 11 by US) have been carried out in the tropical Atlantic. The annually repeated PIRATA sections are nominally along 38°W, 23°W, and 10°W. Note, repeated transects have also been obtained in the tropical Atlantic by GEOMAR and the University of Miami during TACE and other projects like EGEE, GOSHIP, CLIVAR. All PIRATA cruises perform conductivity-temperature-pressure (CTDO2) casts to observe T, S, O_2, as well as collect underway SST, SSS, current, pCO_2, and velocity data. Many of these observations are transmitted in real-time to GDACs for operational services. Because these sections are systematically repeated, they are used to monitor water mass changes (warming/salinity anomalies) and changes to the oxygen minimum zone and calibrate and provide spatial context for mooring data. CTDO2 casts are typically every 0.25° to 0.5° degree along repeated or specific sections and at the mooring sites, and typically down to 1500-2000 m depth (during 2017 PIRATA-BR cruise, CTDO2 full-depth casts were collected). Since February 2018, 1683 CTD profiles have been collected during PIRATA cruises. There are very few subsurface velocity measurements in the tropical Atlantic, and much of what we know about the equatorial current system is from repeated lowered and shipboard ADCP sections in the tropical Atlantic. These velocity sections allow for estimation of the mean strength of equatorial currents, characterization of their spatial structure, and understanding of their relationship with tropical Atlantic hydrography.

Research vessels and container ships contribute to the Argo program by offering yearly cruises from which to deploy floats in the tropical Atlantic. With global coverage, Argo floats provide crucial information about global heat budget and water mass changes and are assimilated into many operational reanalyses/forecast products. PIRATA cruises have deployed approximately 200 Argo profiling floats in the tropical Atlantic, as well as collected CTD profiles that are used for Argo calibration and validation. Two deep (4000 m) Argo floats with total dissolved oxygen sensors will be deployed in March 2018 during the PIRATA-FR cruise. These will be the first deep Argo floats deployed in the tropical Atlantic region.

PIRATA cruises also provide the opportunity to contribute to the Global Drifter Program/Data Buoy Cooperation panel by deploying drifting buoys. The wind-driven divergent circulation in the tropical Atlantic requires frequent seeding of surface drifters to maintain the global array. Most of the drifters deployed in the tropical Atlantic by PIRATA are equipped with barometers. The data obtained from drifters are crucial for satellite calibration and model initialization/validations, and the operational centers have demonstrated their high impact on weather forecast skill. Since 1999, over 300 drifters have been deployed by PIRATA in the tropical Atlantic.

EXpendable BathyThermographs (XBTs) are often deployed during PIRATA cruises in concert with CTDs to do fall rate experiments and for cross-calibration of measurements. XBTs have also been launched in between CTDO2 stations to augment the resolution of temperature transects. Approximately 4000 XBT profiles have been collected on PIRATA cruises. XBT data are also provided in real-time to GDACs for the operational centers.

Beyond the standard physical parameters, PIRATA cruises are opportunities to contribute to other operations of interest for biogeochemistry (BGC), biology, primary production, and water color. Typically, these ancillary data are collected at a subset of the CTDO2 stations. Nutrients (Nitrate, Nitrite, Phosphate, Silicate) are systematically measured since 2004 during the yearly PIRATA-FR cruises, either from sea surface water samplings or as vertical profiles from CTD bottle casts. Chlorophyll pigments (through phytoplankton pigments) have also been analyzed during PIRATA-FR cruises since 2011. As for nutrients, they are measured either from sea surface water samplings (every 2° in latitude/longitude along the track line) or as vertical profiles from CTD bottle casts. Biological samples (zooplankton, Sargassum algae) have also been collected during recent PIRATA-FR cruises. The 2017 PIRATA-BR allowed several ancillary measurements down to 5,500m depth, including S, O_2, pH and nutrients in addition of other data collected for GEOTRACES. PIRATA-US is interested in developing the capability to collect BGC/nutrient data during their yearly cruises.

PIRATA cruises also contribute to atmospheric processes and ocean-atmosphere exchange studies. During many of the PIRATA cruises, atmospheric measurements are obtained using radiosondes and ozonesondes (measuring aerosols, temperature, ozone concentrations in the atmosphere) often in collaboration with other science programs (e.g., AEROSE). During PIRATA cruises, approximately 1000 radiosondes and 200 ozonesondes have been launched. PIRATA-FR cruises have contributed to a national program dedicated to the analysis of the air-sea exchanges and the intraseasonal variability preceding the West African Monson & Atlantic Cold Tongue onsets. During the 2017 PIRATA-BR cruise, turbulent fluxes at the air sea interface were measured from a meteorological tower on the ship. The AEROSE group has partnered with PIRATA-US to generate a comprehensive data set of complementary atmospheric measurement and oceanographic observations to characterize atmospheric aerosols of African origin – in particular Saharan dust aerosols transported across the Atlantic Ocean. AEROSE also collects visible/near IR measurements to support the calibration and validation (dust aerosol corrections) of satellite data which are important for detecting upwelling/biological activity. On PIRATA-US cruises, the M-AERI group measures spectra of infrared emission from the ocean and atmosphere from which skin SST can be derived, as well as atmospheric water vapor and cloud liquid water data while the ship is underway. From this data, M-AERI has developed a “Saharan Dust Index” which can be used to correct MODIS SSTs and improve their agreement with drifting buoy SSTs. Accurate measurements of SST from satellites are necessary for weather forecasting, oceanographic research, air-sea exchange studies, and investigations of the changing climate.

The second part of the presentation focused on vessel-based observations collected as part of other long-term observing networks in the tropical Atlantic.

MOVE (Meridional Overturning Variability Experiment) has been measuring the lower limb of the Atlantic Meridional Overturning Circulation (AMOC) as it flows across 16°N in the western Atlantic basin since 2000. Annually, a research vessel conducts a cruise to collect mooring data and/or to recover and redeploy moorings. The research vessels typically record ship-based data such as meteorology, thermosalinograph, and ADCP data. In case of UNOLS vessels, these are typically made available through the R2R program (rolling deck to repository). For calibration and validation of the mooring data, the service cruises perform a number (typically ten per cruise) of well-calibrated CTD casts with water samples. These have so far been available only internally, but the project recently started publishing them at NCEI.

Since 2013, Western Boundary Current (WBC) and Eastern Boundary (EB) mooring arrays have been deployed at 11°S at the western and eastern boundaries of the tropical South Atlantic Ocean. Regular research cruises have been carried out within the region to maintain these arrays and collect additional shipboard observations. In the west, shipboard hydrographic and current observations are collected annually along two zonal sections at about 5°S and 11°S. The western boundary measurement programs have been carried out in close cooperation between GEOMAR and UFPE, Recife, Brazil under the umbrella of a memorandum of understanding signed in 2012. In the east, shipboard hydrographic and current observations along 11°S have been carried out in close cooperation between GEOMAR and INIP, Luanda, Angola. A trans-basin full-depth hydrographic cruise to estimate the AMOC transports along 11°S has been proposed for 2019. These measurements will help establish the connectivity between the boundary currents and AMOC at 11°S, as well as AMOC and at other latitudes (e.g., SAMBA, MOVE, RAPID, OSNAP).

GO-SHIP hydrographic data sets contribute to overlapping scientific and technical objectives focused on quantifying the ocean state and how it is changing, including: heat/freshwater storage and fluxes, carbon system and biogeochemical studies, and water mass ventilation. Six GO-SHIP reference sections cross the tropical Atlantic and generate carbon inventories and transport estimates.

Ships provide an underway platform for surface CO_2 measurements – and moorings provide time series of surface CO_2 at discrete locations. The Surface Ocean CO_2 Atlas (SOCAT) (www.SOCAT.info) provides quality-controlled, surface ocean pCO_2 observations that have been collected by the international marine carbon research community. SOCAT data is publicly available, discoverable and citable, and the global data set is updated annually.

Globally SST/SSS from thermosalinographs are collected from research and commercial ships. GOSUD (Global Ocean Surface Underway Data) is a program which collects underway SST and SSS from merchant ships in real time and in delayed mode. Some of the ships are equipped with pCO_2. CORIOLIS collects and validates (from sea surface water samples) the SST/SSS data acquired by all the French Research vessel-mounted thermosalinographs during cruises and transits, including PIRATA-FR cruises. The resulting Sea Surface Salinity and Temperature from French REsearch Ships (SSST-FRESH) dataset is very valuable for the calibration and validation of the new satellite observations delivered by the Soil Moisture and Ocean Salinity (SMOS) and Aquarius missions.

Together with national and international partners, NOAA/AOML maintains 12 High Density XBT transects, and deploys 8,000 XBTs annually. These lines are used to monitor WBCs, the tropical Atlantic current system, assess ocean heat content in the upper 800m, and reduce uncertainties/biases and improve data quality by improving the fall rate equation and using higher quality probes. These observations are complementary to data collected using other observational platforms. There are four High Density XBT transects that cross through the tropical Atlantic: AX07 (since 1997), AX08 (since 2000), AX10 (since 1996), and AX97-MOVAR (since 2004).

The Cape Verde Ocean Observatory (CVOO) at 17° 35.00' N, 024° 17.00' W is a BGC shipboard open-ocean time-series site in the Eastern Tropical North Atlantic which is based on two pillars: A monthly ship-based sampling program (measurements of temperature, salinity, biological parameters, nutrients, dissolved carbon and oxygen) as well as an oceanographic multi-parameter long-term mooring for in-situ observations (including real-time satellite telemetry). The Cape Verdean research vessel Islândia is equipped with state-of-the-art oceanographic instruments to collect samples for marine parameters as well as a state-of-the-art echosounder for fisheries surveys.

In summary, the community is collecting a tremendous amount of data in the tropical Atlantic from ships. Because of the regularity of research and commercial cruises, they are great platforms for deploying and collecting ancillary measurements in the tropical Atlantic (Figure 1). They also provide high resolution measurements along ship track lines that can be used for mooring/satellite data calibration, model initialization/validation, and to improve weather and climate forecasts.

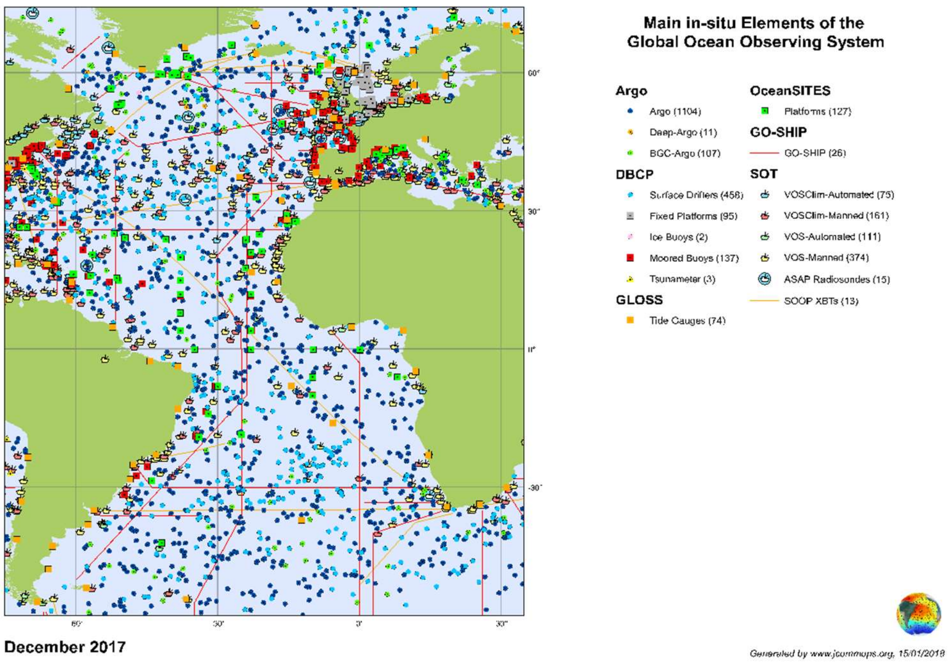

Figure 1. The main elements of GOOS in the Atlantic Ocean as of December 2017.

A.6-5 Surface flux measurements from buoys, ships, and gridded products

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Surface fluxes and their coupling to atmospheric and oceanic boundary layer processes are a critical part of the Tropical Atlantic Observing System (TAOS). In this talk we presented information about accuracy of flux products, recent US CLIVAR WG on Eastern Tropical Ocean Biases findings, recent atmospheric field campaigns, and regions of particular interest (equatorial Atlantic, upwelling regions).

The first part consisted of and overview of the PSD air sea flux program: How it fits with Tropical buoy array, ORS buoys, SAMOS, gridded flux products. Advances in the science of air-sea interaction and observing technology that include state-of-the-art ship-based direct flux measurements; momentum, energy, water, trace gas surface budgets; side-by-side with ships, buoys, satellites, NWP, flux products; a flux database for science, parameterization, community comparisons; and the COARE family flux algorithms.

The second part was a review of recent studies on biases in net surface energy budget found in climate models. It was shown that biases are considerable larger than credible observational estimates and clouds are the dominant source of uncertainty. A new field program planned for the N. Atlantic called EUREC4A (Elucidating the Couplings between Clouds, Convection and Circulation) was discussed. A second program COLOCATE (Clarify-Oracles-Lasic-Aeroclo-Seals) to investigate smoke and clouds above the southeast Atlantic was also discussed.

Finally, we discussed the need for diurnally-resolved measurements of the atmospheric boundary layer, full-flux (with downwelling infrared flux) buoy measurements, and more atmospheric boundary layer measurements in upwelling regions.