Report of the Atlantic Implementation Panel

Table of Contents

1 AIP Achievements

The CLIVAR Atlantic Implementation Panel (AIP) is a part of the CLIVAR organization. The panel is in charge of implementing the CLIVAR science plan in the Atlantic sector. During the last 10 years, the primary function of the panel has been to promote, recommend and oversee the implementation of observational systems in the Atlantic Ocean sector and major research initiatives on Atlantic climate variability and predictability. The AIP works in close collaborations with other CLIVAR panels, regional and global programs. Important achievements have been made over the past decade in development of the Atlantic observing system, ocean and climate modeling systems and interdisciplinary multinational climate research programs. We highlight some of the major accomplishments as follows.

1.1 HIGHLIGHTS

1.1.1 RAPID AMOC

One of the major research activities supported by the AIP over the past decade is the development of an observing system for the Atlantic Meridional Overturning Circulation (AMOC). A main component of the AMOC observing system is the trans-basin array along 26.5°N established in 2004. Additional AMOC observing networks include time series arrays deployed in a variety of locations such as the Denmark Strait (e.g. Jochumsen et al. 2012), at 35°N (e.g. Toole et al., 2011; Peña-Molino et al., 2012), at 16°N (e.g. Kanzow et al., 2008; Send et al., 2011), and at 35°S (Meinen et al. 2013).

As of April 2014 the RAPID-MOCHA-WBTS program will have completed 10 years of continuous measurement of the AMOC structure and variability at 26.5°N, using satellite winds to derive the Ekman transport, a trans-basin mooring array to monitor the mid-ocean transport, and subsea cable across the Straits of Florida to monitor the Gulf Stream transport (Cunningham et al., 2007). The array also allows continuous estimates of the meridional heat transport across 26.5°N and the respective contributions by the overturning (vertical) and gyre (horizontal) components of the circulation (Johns et al., 2011). Recently updated results for the AMOC at 26.5°N are contained in McCarthy et al. (2012) and Smeed et al. (2014), and a Progress in Oceanography article is in preparation that summarizes the latest improvements in methodology for both the AMOC and the meridional heat transport (MHT) estimates.

The time series to date shows substantial interannual variability, with a significant downtrend since 2005 (Smeed et al., 2014), punctuated by a sharp minimum in both the AMOC and MHT in the winter of 2009/2010 (Figs. 1 and 2). The causes of these changes are currently the subject of intense investigation by both the modeling and observational communities. The AMOC changes at 26.5°N appear to be linked to changes in subtropical gyre heat content (Cunningham et al., 2013), which may have impacted the subsequent atmospheric circulation and NAO state through re-emergent heat content anomalies (Taws et al., 2011). The seasonal cycle of the AMOC and MHT at 26.5°N has also been quantified and the dominant underlying mechanisms explained (Kanzow et al., 2010; Johns et al., 2011).

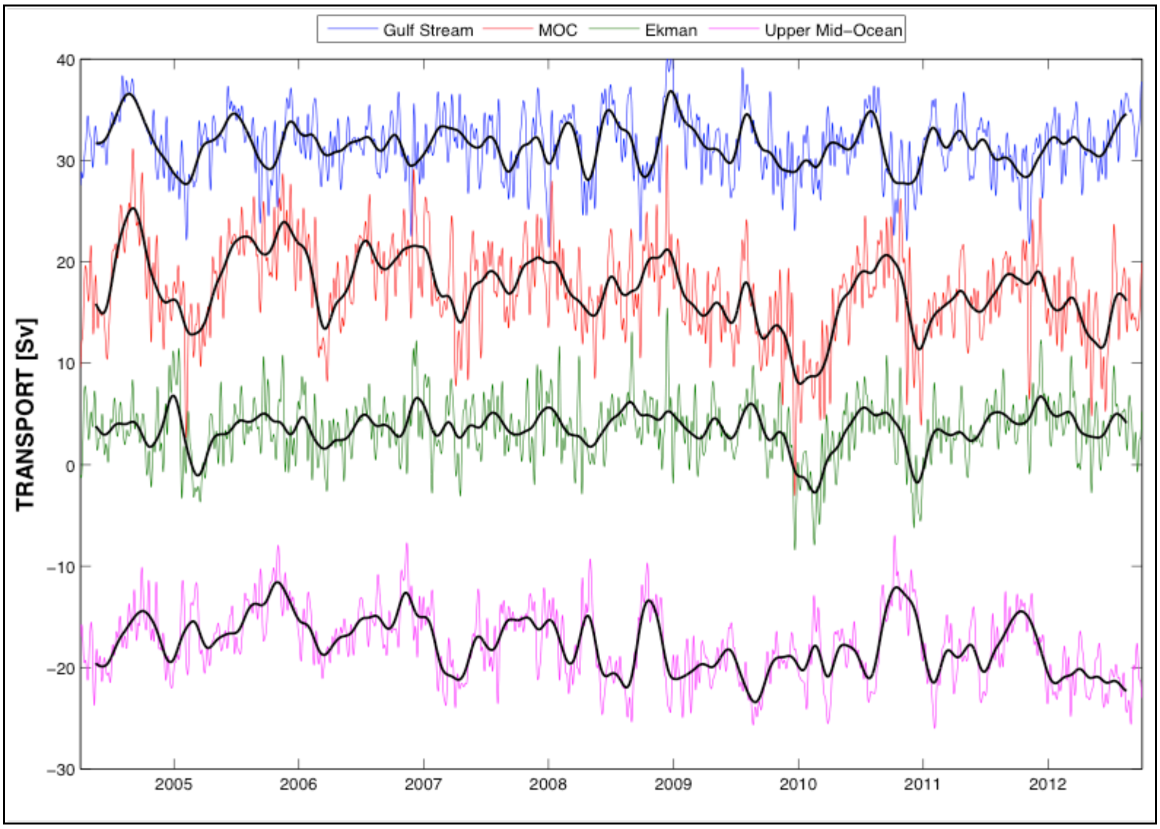

Figure 1. The latest RAPID time series including the AMOC (red), Gulf Stream (blue), Ekman (green) and upper mid-ocean (magenta) transports. Colored lines are ten-day values. Black lines are 90-day low-pass filtered values.

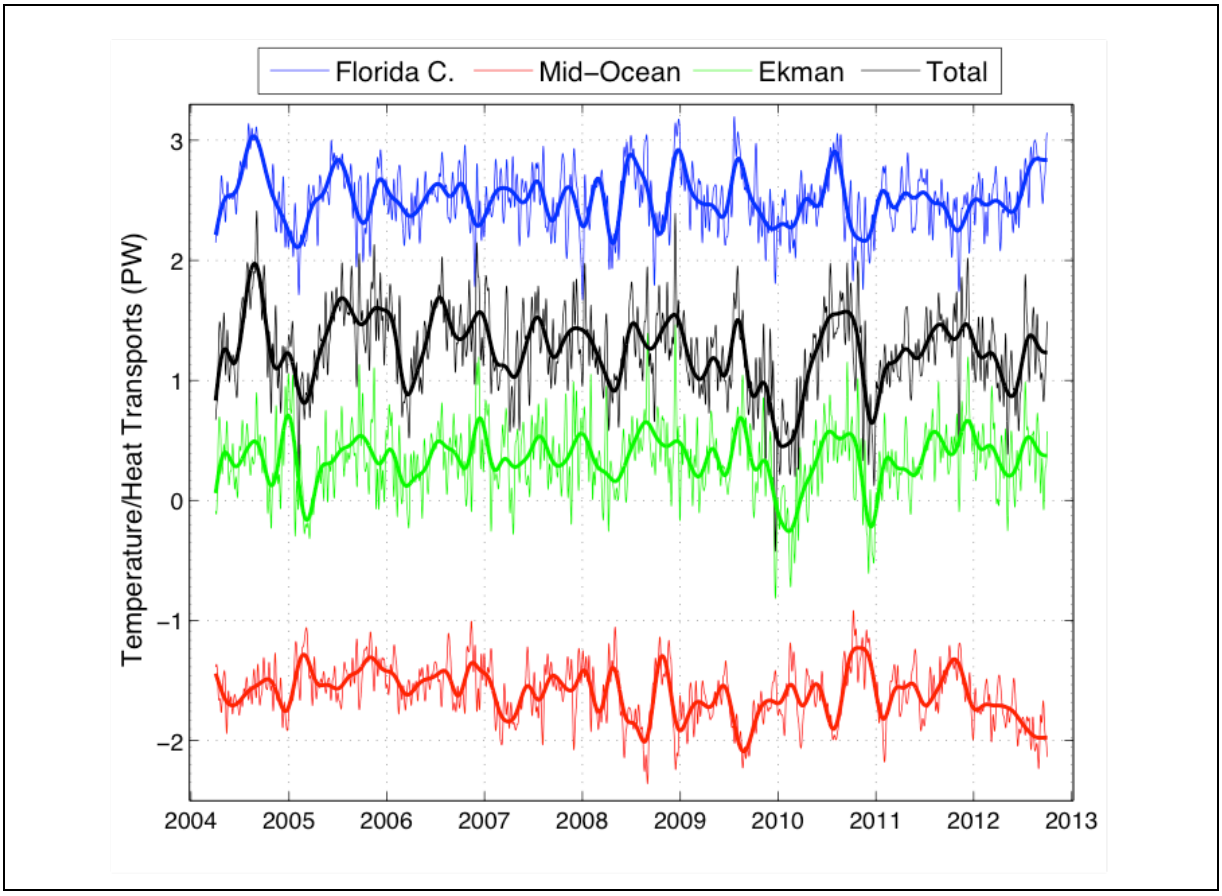

Figure 2. Time series of the MHT (black), and the contributions by the temperature transport of the Florida Current (blue), the Ekman layer (green), and the mid-ocean region from the Bahamas to Africa

(red). High-frequency data are 10-day averages and smooth curves represent 90-day low pass filtered data.

1.1.2 Subpolar North Atlantic Studies

The subpolar North Atlantic is a key region of climatic importance. With 20 years of altimetric record now available and the completion of the ARGO network, changes of the subpolar gyre heat and freshwater content are much better quantified. Since the early nineties, the freshening trend has been reversed (Holliday et al, 2008) and a significant warming has observed in the eastern subpolar gyre (Thierry et al, 2008), coinciding with changes in the circulation (Hakkinen and Rhines 2009). The mechanisms for this variability have been investigated by numerical model simulations, but many unresolved issues remain, such as the respective roles of exchanges with the polar regions vs the subtropics. Coupled ocean-atmosphere numerical simulations are now beginning to demonstrate some skills in predicting this variability (e.g., Yeager et al 2012).

The variability of the gyre circulation, the AMOC and the heat flux has been quantified from a joint analysis of hydrographic and velocity data from six repeats of the Greenland to Portugal OVIDE/A25 section (1997–2010), satellite altimetry and Argo float measurements (Mercier et al 2013). The extent and time scales of the AMOC variability in 1993–2010 were then evaluated using a monthly index of the AMOC in density coordinates (MOCσ) derived from altimetry and Argo data. The MOCσ index, validated against the estimates from repeat hydrographic surveys, shows a large variability of the MOCσ at OVIDE on monthly to decadal time scales (Fig. 3). The intra-annual variability is dominated by the seasonal component with peak-to-peak amplitude of 4.3 Sv (1 Sv = 10^6 m^3 s^{-1}). On longer time scales, the MOCσ index varies from less than 15 Sv to about 25 Sv. It averages to 18.1 ± 1.4 Sv and shows an overall decline of 2.5 ± 1.4 Sv (95% confidence interval) between 1993 and 2010. The heat flux estimates from repeat hydrographic surveys, which vary between 0.29 and 0.70 ± 0.05 PW, indicate that the heat flux across the OVIDE section is linearly related to the MOCσ intensity (0.054 PW/Sv).

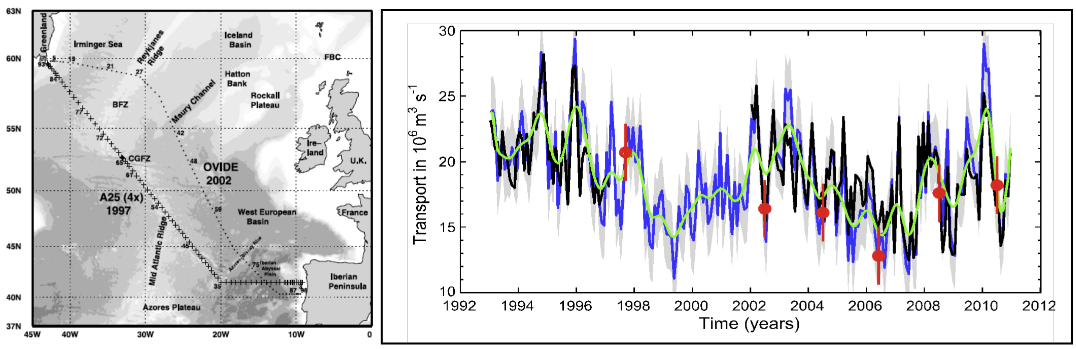

Figure 3: (Left panel) Ovide (dots) and A25 (crosses) hydrological station locations plotted on bathymetry (500 m intervals). CGFZ: Charlie-Gibbs Fracture Zone; BFZ: Bight Fracture Zone. FBC: Faroe-Bank Channel. (Right panel) Time series of the monthly transport of the upper limb of the MOC in density coordinates across the OVIDE section from Greenland to Portugal. The blue curve is the MOC computed from AVISO combined with the monthly mean velocity fields derived from ISAS and averaged over the 2002–2010 time span. The grey envelope indicates the uncertainty that was defined as the maximum error in the estimate for 2002–2010 (2.6 Sv). The green curve is the low-pass filtered time series using a 2-year running mean. The black curves are the MOCσ computed from AVISO and WOA pentadal analysis (1993–1996) and from AVISO and ISAS data sets (2002–2010). The MOCσ estimates from inversions of the OVIDE hydrographic sections and the associated errors are in red (Mercier et al, 2013)

1.1.3 Tropical Atlantic Climate Studies

Tropical Atlantic is another region of active research supported by the AIP. Recent studies have revealed that the southeast tropical Atlantic has experienced the most pronounced and robust warming trend over the 20th century among all the tropical oceans, with a maximum warming rate of more than 1.0°C per century [*Deser et al.*, 2010] (Fig. 4). This warming trend is more significant during the last half of the 20th century and has brought detectable changes in the atmospheric circulation and rainfall patterns in the region [*Tokinaga and Xie*, 2011]. In particular, the ITCZ has shifted southward and land precipitation has increased (decreased) over the equatorial Amazon, equatorial West Africa, and along the Guinea coast (over the Sahel) (Deser et al. 2010, Tokinaga and Xie 2011). The sea surface temperature (SST) trend in the tropical Atlantic can have an effect on climate extremes, such as Atlantic hurricane activity [*Emanuel*, 2005]. Atlantic SST conditions also play an important role in shaping summer climate conditions over much of North America and Europe [*Sutton and Hodson*, 2005]. A recent study (Chang et al. 2011), based on multi-IPCC CMIP3 20th century climate simulations, argues that at least half the observed trend may be attributed to 20th century climate forcings. However, large uncertainties exist in the model-based analyses, because the climate models, on which the analyses are based, suffer severe bias problems in the tropical Atlantic.

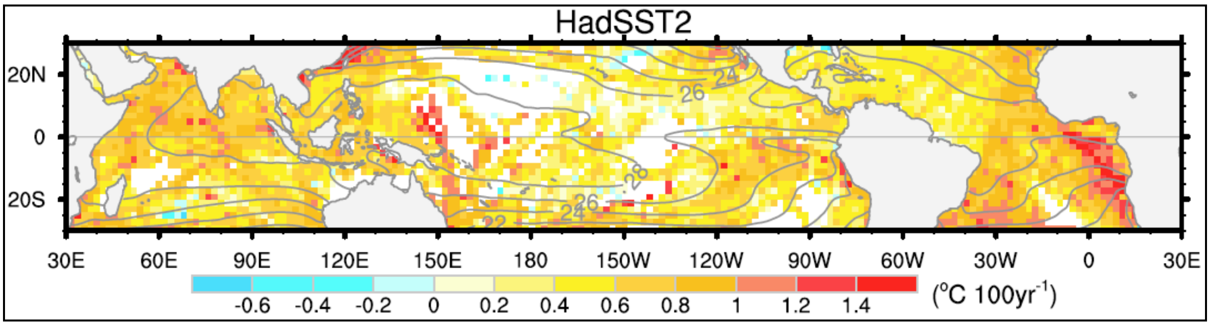

Figure 4. Estimated SST trends in global tropical oceans from Hadley Centre SST version 2 (HadSST2) [Rayner et al., 2006] (Adopted from [Deser et al., 2010]).

Recognizing the importance and urgency of resolving the tropical Atlantic bias issue, a concerted effort has been made within the CLIVAR Atlantic community over the past decade to understand causes of the bias. This includes the successful completion of the CLIVAR TACE program (2006-2011). The program made many important contributions to our understanding of variability and predictability of the eastern tropical Atlantic climate system. The invaluable observational data sets collected during the TACE program are vital for improving climate models in the region. A particular intriguing discovery of TACE observation studies is the potential role of interannual variability of equatorial deep jets in Atlantic climate variability (Brandt et al. 2011). Few current-generation climate models are capable of simulating deep equatorial ocean variability, highlighting a new area for model improvement. Many of the results from the TACE program are published in a special issue of Climate Dynamics (2014).

In March 2011 a CLIVAR workshop dedicated to tropical Atlantic Bias studies was carried out, which led to the establishment of the US CLIVAR Eastern Tropical Ocean Synthesis (ETOS) Working Group (see more detailed discussion below). A list of publications have appeared recently (Chang et al. 2007, Richter and Xie 2008, Breugem et al. 2008, Wahl et al. 2011, Richter et al. 2011, Patricola et al. 2012, Toniazzo and Woolnough, 2013; Xu et al. 2013, Richter et al. 2014, Xu et al. 2014 and more). These studies have identified a number of dynamical causes for the Atlantic biases, which can lead to improvements of global climate models.

Another important coordinated research activity within the tropical Atlantic sector over the past decade is Atlantic hurricane studies. Along with ENSO related interannual SST variations in tropical Pacific, interannual-to-multidecadal Atlantic SST variability strongly affects Atlantic tropical cyclones (TCs) (Landsea et al. 1999; Goldenberg et al. 2001; Vitart and Anderson 2001; Emanuel 2005; Webster et al. 2005; Vimont and Kossin 2007; Klotzbach and Gray 2008). Vimont and Kossin (2007) recently showed that the Atlantic Meridional Mode (AMM) has the most dominant impact on Atlantic TC activity among all the Atlantic modes of variability, because the AMM describes the cross-equatorial SST gradient variability that relates closely to the position of the ITCZ. More recently, Patricola et al. (2014) show that ENSO and AMM can constructively influence Atlantic TC activity and strong La Niña and strongly positive AMM together produce extremely intense Atlantic TC activity. Despite of these recent progress, there remains much work to fully understand climatic controls on seasonal Atlantic TC activity, and future projections of TCs by IPCC models are marked by a lack of consensus. To address these challenges, the US CLIVAR Hurricane Working Group was established in 2011. The working group has designed coordinated climate model experiments and the results from these experiments are described in a special issue of Journal of Climate (see below for a more detailed discussion).

1.1.4 South Atlantic MOC (SAMOC) pilot studies

Pilot arrays designed to measure the density structure and the flows in the South Atlantic and along GoodHope and Drake Passage were among the cornerstones for what has become known as the international South Atlantic MOC (SAMOC) initiative. Pilot arrays at the eastern and western boundaries of the basin along 34.5°S (Fig. 5) were deployed in February 2008 and March 2009, respectively (e.g. Speich and Dehairs, 2008; Meinen et al., 2012). The western array, known as the Southwest Atlantic MOC array, has been making measurements continuously from March 2009 to the present; the eastern array, deployed as part of the GoodHope program, was in place from February 2008 through December 2010. The two arrays overlapped in time for approximately 20 months from March 20, 2009 to December 2, 2010. These records, when analysed together with wind and other observations, provide the first opportunity to estimate the daily time series of basin-wide MOC transport at 34.5°S using in situ observations.

Data from two boundary arrays deployed along 34.5°S were combined to produce the first continuous in situ time series observations of the basin-wide meridional overturning circulation MOC in the South Atlantic (Meinen et al. 2013). Daily estimates of the MOC between March 2009 and December 2010 range between 3 Sv and 39 Sv (1 Sv = 106 m3 s-1) after a 10-day low-pass filter is applied. Much of the variability in this ~20 month record occurs at periods shorter than 100 days. Approximately two-thirds of the MOC variability is due to changes in the geostrophic (baroclinic plus barotropic) volume transport, with the remainder associated with the direct wind-forced Ekman transport.

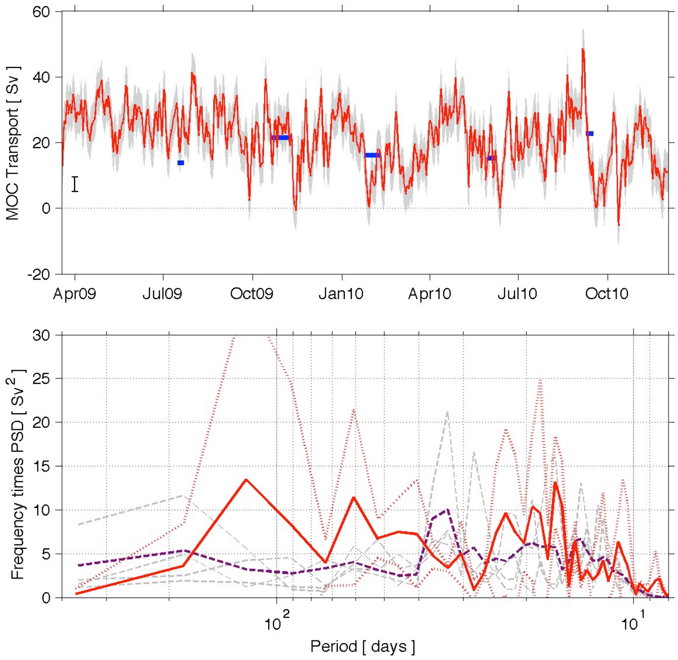

Figure 5. Upper panel – Transport time series of the MOC at 34.5°S (red line) with estimated daily error bars (gray shading). Black vertical error bar at left illustrates the estimated bias accuracy as discussed in Meinen et al. (2013). Also shown are five MOC estimates determined from trans-basin XBT sections where the horizontal length of the bar illustrates the start and end times of each trans-basin cruise. Lower panel – Variance preserving spectrum of the MOC transport time series (red solid line) calculated using a one-year window with 50% overlap. Also shown are the 95% confidence limits (red dotted lines). Thin gray dashed lines show spectra of the MOC at 26.5°N for comparison using four 623-day-long segments of the complete record; thick purple dashed line shows the spectrum for the complete 7-year record at 26.5°N. (Figure adapted from Meinen et al. 2013).

1.1.5 Atlantic Decadal Climate Variability and Prediction

On decadal timescales, climate is potentially dominated by natural internal variations that occur without any changes in greenhouse gases, or by other external factors such as changes in aerosols (either man-made or following volcanic eruptions) or changes in solar activity. These short-term variations may either oppose or exacerbate the long-term trend from greenhouse gases, the latter potentially producing unprecedented extreme events. Decadal climate prediction therefore aims to provide policy makers and planners with the most accurate information possible on the climate for the next decade or so, taking into account both natural internal variability and all external forcing factors.

Standard climate model projections (IPCC 2007) do simulate natural internal variability, but on average it will not be in phase with reality. In order to predict the evolution of natural internal variability it is necessary to start from the present state of the climate system. This is achieved by initializing climate models with observations. Internal variability is not necessarily predictable, but any skill would narrow the near-term uncertainties in climate change projections. Initialization may also narrow uncertainties by correcting errors in model responses to previous external forcing factors. Decadal climate prediction is much less mature than seasonal forecasting, but there is currently a substantial international effort to build and evaluate climate predictions for the coming years to a decade or two (Meehl et al 2013, Smith et al 2012).

In order to assess likely forecast skill many groups have performed retrospective forecast experiments following the CMIP5 protocol (Taylor et al 2012). In these, skill is most improved by initialization in the North Atlantic Ocean, and especially the sub-polar gyre (Doblas-Reyes et al 2013). This is consistent with diagnostic studies and idealized experiments with coupled climate models, and is physically underpinned by potential predictability of the AMOC (Pohlmann et al 2013).

Case studies show that the two major changes in the Atlantic subpolar gyre (SPG) that have occurred since 1960, namely a cooling during the 1960s and a warming in the mid-1990s, could have been predicted in advance, and that initialization of ocean dynamics was crucial for the success of these forecasts (Robson et al 2012, 2014, Yeager et al 2012). Furthermore, the Atlantic subpolar gyre is predicted to cool over the coming years (Hermanson et al 2014, Wouters et al 2013).

Important climate impacts, including rainfall in the Sahel, Amazon, North America and Europe, and Atlantic hurricane activity, are believed to be influenced by North Atlantic and SPG temperatures (Knight et al 2006, Zhang and Delworth 2006). Skill over land is limited in present decadal prediction systems, but there is some evidence that impacts following major SPG cooling and warming events are at least partially captured (Robson et al 2013, 2014, Müller et al 2014). Decadal predictions also show promise at predicting Atlantic hurricane frequency (Smith et al 2010, 2014, Vecchi et al 2013).

Winter climate over Europe and North America is dominated by the North Atlantic Oscillation (NAO). The NAO exhibits decadal variability, but is not predictable in present decadal prediction systems. However, key developments in seasonal forecasting over the last year suggest that the NAO is highly predictable (with anomaly correlations greater than 0.6) at least a month ahead (Scaife et al 2014, Riddle et al 2013). Work is currently underway to try to extend these predictions beyond the seasonal timescale.

1.1.6 Biophysical interaction and upwelling

Increasing atmospheric CO_2 and the associated climate warming have already and will continue to occur in the coming decades and centuries, which has strong impacts on the ocean's biogeochemical cycles and ecosystems. Among the observed and expected changes are rising ocean temperatures, ocean acidification, and ocean deoxygenation, causing substantial changes in the physical, chemical and biological environment (Gruber 2011). The evaluation of oxygen observations taken during the last decades indicates a long-term variability, as found for example in the North Atlantic likely associated with the NAO (Stendardo and Gruber, 2012), and a general oxygen reduction in oxygen minimum zones (OMZ) of the tropical oceans (Fig. 6, Stramma et al. 2008). Up to now, the observed oxygen trends can not be reproduced by state-of-the-art biogeochemical models, which limits our ability to identify mechanisms for the ongoing changes and to predict future changes (Stramma et al. 2012a). Low-oxygen conditions of tropical OMZs are particularly important as they affect diversity and habitat of marine species (Vaquer-Sunyer and Duarte 2008, Stramma et al. 2012b) and play an essential role in nitrogen and carbon cycles (Paulmier et al. 2011, Lam and Kuypers 2011).

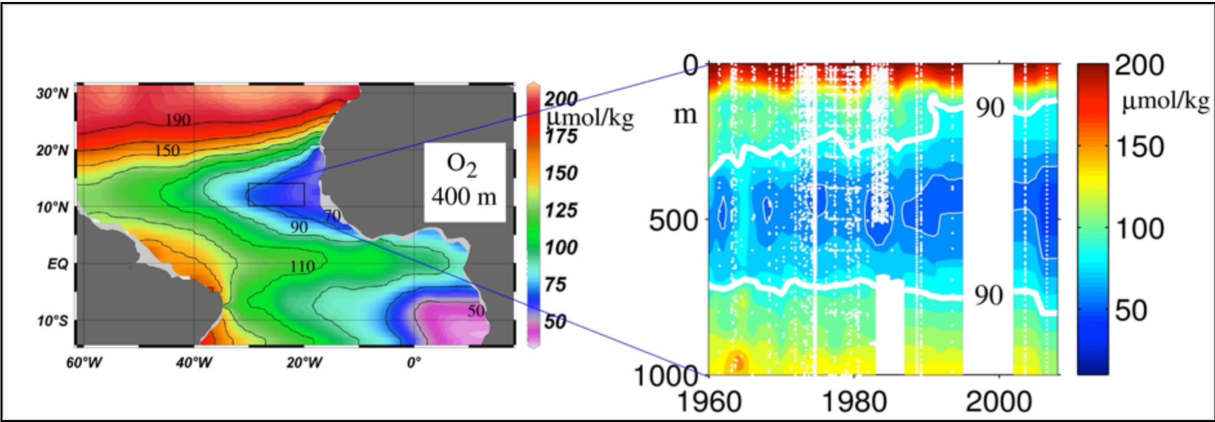

Figure 6. Climatological mean dissolved oxygen concentration (µmol kg^{-1}) in the tropical Atlantic at 400 m depth (left) and oxygen concentration changes versus time (1960-2008) and depth in the eastern tropical North Atlantic 10° to 14°N, 20° to 30°W (right) (after Stramma et al. 2008).

OMZ are often found in close proximity to coastal upwelling regions. In those regions, upwelling favorable winds force warmer near surface waters offshore to be replaced by colder, lower oxygenated, high nutrient rich waters. This often results in high primary production and sometimes in hypoxia (Chan et al., 2008). Similarly coastal hypoxia might be generated by poleward flow of warm, low oxygen water on seasonal to decadal time scales as found for the Benguela upwelling system in the South Atlantic (Rouault 2012, Monteiro et al. 2008). The marine ecosystem was found to respond to environmental changes (Binet, 2001; Boyer, 2001; Salvanes et al, 2014). Salvanes et al (2014) show that decadal environmental variation and predation pressure affect the goby population in the Northern Benguela, which has expanded over the last decade while that of horse mackerel has contracted. These changes co-occurred with a general warming in the north and central shelf areas (north of 24.5 ^{0}S) that can be due to an increased poleward flow or a weakening of the upwelling favorable winds. On that note, it is challenging to characterize recent climate change of the upwelling cell (a few hundreds km or less) as various wind and SST products give opposite trends (i.e. Barton et al, 2013; Cropper et el, 2014 for the Northwest Africa upwelling or Belkin 2009 and Santos 2011 for the Benguela upwelling). It also seems that over the last 30 to 50 years some of the major upwelling have warmed up while some have cooled down, which contradicts Bakun (1990) hypotheses of upwelling intensification due to land warming and associated increased pressure gradient from ocean to land.

By highlighting the importance of climate related changes in the ocean's biogeochemical cycles and ecosystems, CLIVAR established, in close cooperation with IMBER, the tiger team on marine biophysical interactions and the dynamics of upwelling systems. This working group can build on an increasing number of national and international research programs linking physical ocean studies with biogeochemistry, ecosystem and fishery studies.

1.2 ATLANTIC OBSERVING SYSTEMS

One of the main tasks of AIP was to oversee the Atlantic observing system, make recommendations to fill gaps in the observing system, and review and endorse emerging programs. While the North Atlantic was traditionally well covered by observations, of special concern was the observing system in the South Atlantic. However during recent years, also due to the stronger involvement of Brazil, Argentina, South Africa the observing system in the South Atlantic greatly developed.

In response to the EU Horizon2020 call BG-8-2014 "Developing in-situ Atlantic Ocean Observations for a better management and sustainable exploitation of the maritime resources", a proposal will be developed by the leading European institutions in close cooperation with US and international partners. The goal of this effort is to enhance the international integrated Atlantic Ocean Observing System of Systems by exercising the Framework of Ocean Observing and supporting the Global Ocean Observing System (GOOS) as the ocean component of GEOSS and the GEO Blue Planet initiative. The regional focus will be on the whole Atlantic Ocean from Fram & Davis Strait west of Gibraltar to a virtual line connecting the tips of S. America and S. Africa. Such effort has the potential to significantly enhance the efficiency and capability of all observing networks with a particular focus on strengthening the international partnerships within each of the networks and growing their ambitions to cover the North and South Atlantic fully.

1.2.1 OSNAP

OSNAP is a US-led collaboration with UK, Dutch, German, French and Canadian scientists aimed at measuring the flow of heat, mass and freshwater in the subpolar North Atlantic Ocean using moored instrumentation, subsurface floats, gliders and hydrographic surveys. The OSNAP line (Fig. 7) consists of two legs: OSNAP West extends from southern Labrador to southwestern Greenland and OSNAP East from southeast Greenland to the coast of Scotland. The two legs are situated to capitalize on a number of existing or planned long-term observational efforts in the subpolar North Atlantic: the Canadian repeat AR7W program in the Labrador Sea (although the OSNAP West line has been shifted slightly southeastward to capture the export of all LSW from the Labrador Sea); the German Labrador Sea western boundary mooring array at 53°N; the US Global OOI (Ocean Observatories Initiative) node to be placed in the southwest Irminger Sea; the repeat A1E/AR7E and OVIDE (Figure 3) hydrographic sections across the Irminger and Iceland Basins (approximately coincident with OSNAP East); and the Ellett line in the Rockall region.

Flow through these lines will be connected via subsurface RAFOS floats that will track the pathways of the overflow waters and help interpret observed variability in fluxes across the OSNAP lines. The project will investigate the link between changes in production of North Atlantic Deep Water and the AMOC, on interannual timescales. It is aimed at understanding the variability of the AMOC, its meridional connectivity with the subtropical Atlantic, and its potential impact on the climate system, including the marine biogeochemistry and the cryosphere. Measurements will start in summer 2014 and continue until summer 2018.

The OSNAP observing system is complemented by observations of the overflow system between Greenland and Iceland and between Iceland and Scotland. The measurements in place are part of the European NACLIM program (2012-2017) and include hydrographic and current measurements in the Denmark Strait, along the Hornbanki section (north of Iceland), at Iceland-Faroe Ridge, in the Faroe Shetland Channel and the Faroe-Bank Channel, and at the Wyville-Thomson Ridge.

The OSNAP observing system will also be complemented by observations in the vicinity of the Reykjanes Ridge (French RREX project). The measurements will be realized between 2015 and 2017 and include hydrographic and current measurements along and across the Reykjanes Ridge.

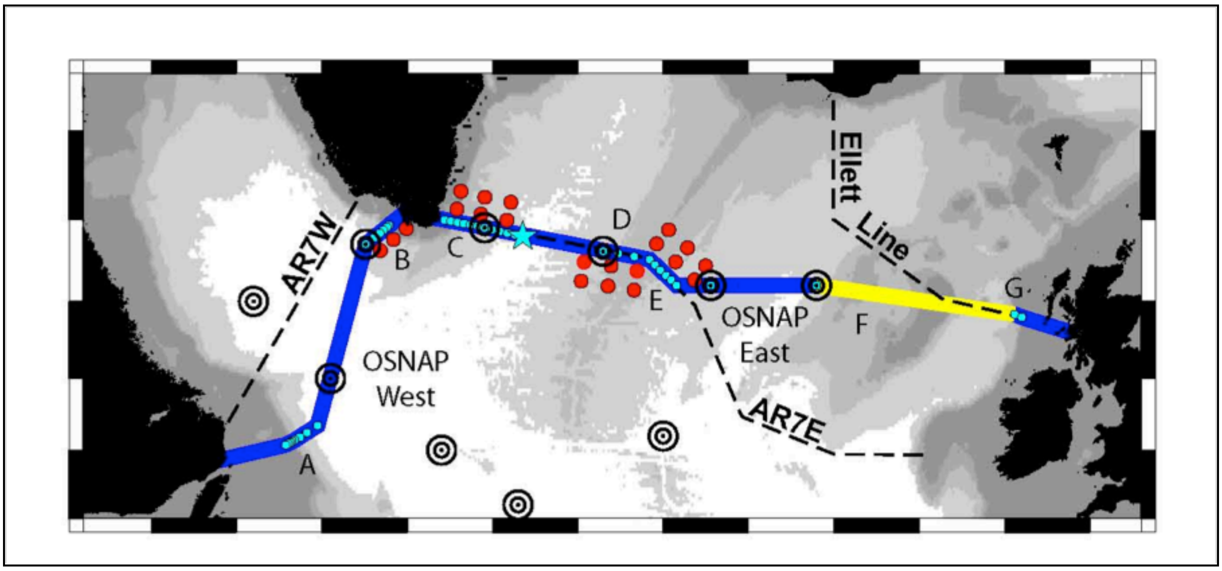

Figure 7. Guide to OSNAP elements: (A) Existing German 53°N western boundary array to be supplemented by a Canadian shelfbreak array; (B) US West Greenland boundary array; (C) US/UK East Greenland boundary array; (D) Netherlands western Mid-Atlantic Ridge array; (E) US eastern Mid-Atlantic Ridge array; (F) UK glider survey over the Hatton-Rockall Bank and Rockall Trough; (G) UK Scottish Slope current array. Red dots: US float launch sites. Blue star: US OOI Irminger Sea global node. Black circles: Sound sources.

1.2.2 RAPID-MOCHA-WBTS Array at 26°N

Since 2004, the meridional overturning circulation has been measured along 26.5°N in the subtropical North Atlantic using a combination of Gulf Stream transport through Florida Strait using a submarine telephone cable and repeat direct velocity measurements, deep western boundary currents by direct velocity measurements, basin wide interior baroclinic circulation from moorings measuring vertical profiles of density at the boundaries and on either side of the Mid-Atlantic Ridge, barotropic fluctuations using bottom pressure recorders and Ekman transports by various wind products. Figure 8 shows a schematic diagram of the components of the program (Smeed et al, 2014). The project was funded from 2004 to 2008 in the framework of the Rapid Climate Change (RAPID) thematic program of the Natural Environment Research Council (NERC), the National Science Foundation (NSF) Meridional Circulation and Heat Flux Array (MOCHA) and by the NOAA Office of Climate Observations' Western Boundary Time Series (WBTS). Funding has since been extended by NERC, NSF and NOAA till 2014 and beyond as part of the Rapid-WATCH program to provide a decade long timeseries of measurements.

This project has resulted in increased understanding of the observed variability of the MOC and its associated heat transport on seasonal and interannual time scales. Plans are underway to augment the existing array to measure ecosystem relevant marine chemistry with measurements of oxygen, nutrients and perhaps even carbon species.

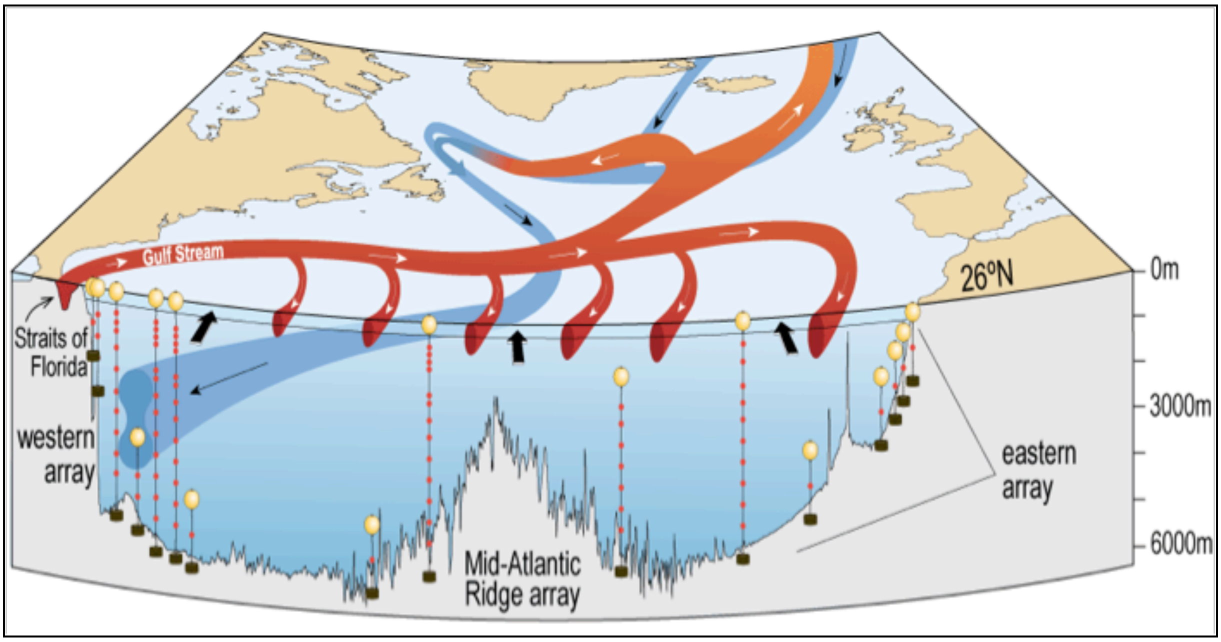

Figure 8. Schematic diagram illustrating the component parts of the AMOC-MOCHA-WBTS 26N observing system. Black arrows represent the Ekman transport (predominantly northward). Red arrows illustrate the circulation of warm waters in the upper 1100 m, and blue arrows indicate the main southward flow of colder deep waters. The array of moorings used to measure the interior geostropic transport is illustrated too (Smeed et al 2014)

1.2.3 Tropical observing system

During the past decade the tropical Atlantic observing system has been greatly developed. The Prediction and Research Mooring Array in the Tropical Atlantic (PIRATA), launched in 1997, is now recognized as the backbone observing network in the tropical Atlantic for both climate research and operational climate and ocean prediction. The PIRATA (see http://www.pmel.noaa.gov/pirata/) was developed as a multinational cooperation among USA, Brazil and France. This multinational cooperation continues to grow thanks to the long-term close collaboration and a MoU among these countries. A 10-ATLAS buoy network in its initial phase between 1997 and 2005 has grown into a 18 permanent ATLAS buoy observing system combined with one acoustic Doppler current profiler (ADCP) mooring on the Equator at 23°W. Recommendations for the future development of the PIRATA array include enhanced measurements of the air-sea heat and freshwater exchange, improved near surface current observations, and the inclusion of biogeochemical measurements, like e.g. oxygen and CO_2 measurements.

On the basis of the PIRATA network, other multinational observing programs, such as the CLIVAR Tropical Atlantic Climate Experiment (TACE), had been developed over the past decade under the guidance of the AIP. One of the main goals of TACE was to improve the observational database and to carry out dedicated process studies designed to enhance our understanding of the eastern tropical Atlantic climate system. The regional focus of TACE thus was on the central and eastern equatorial Atlantic (Fig. 9) where the development of the Atlantic cold tongue (ACT) during boreal summer is a defining character of system’s variability. The year-to-year variability of the ACT sea surface temperature (SST) is known to have an impact on climate variations in the region, including the strength and onset of the West African Monsoon (WAM). However, climate model forecast skills in the region are dismal because of several model biases.

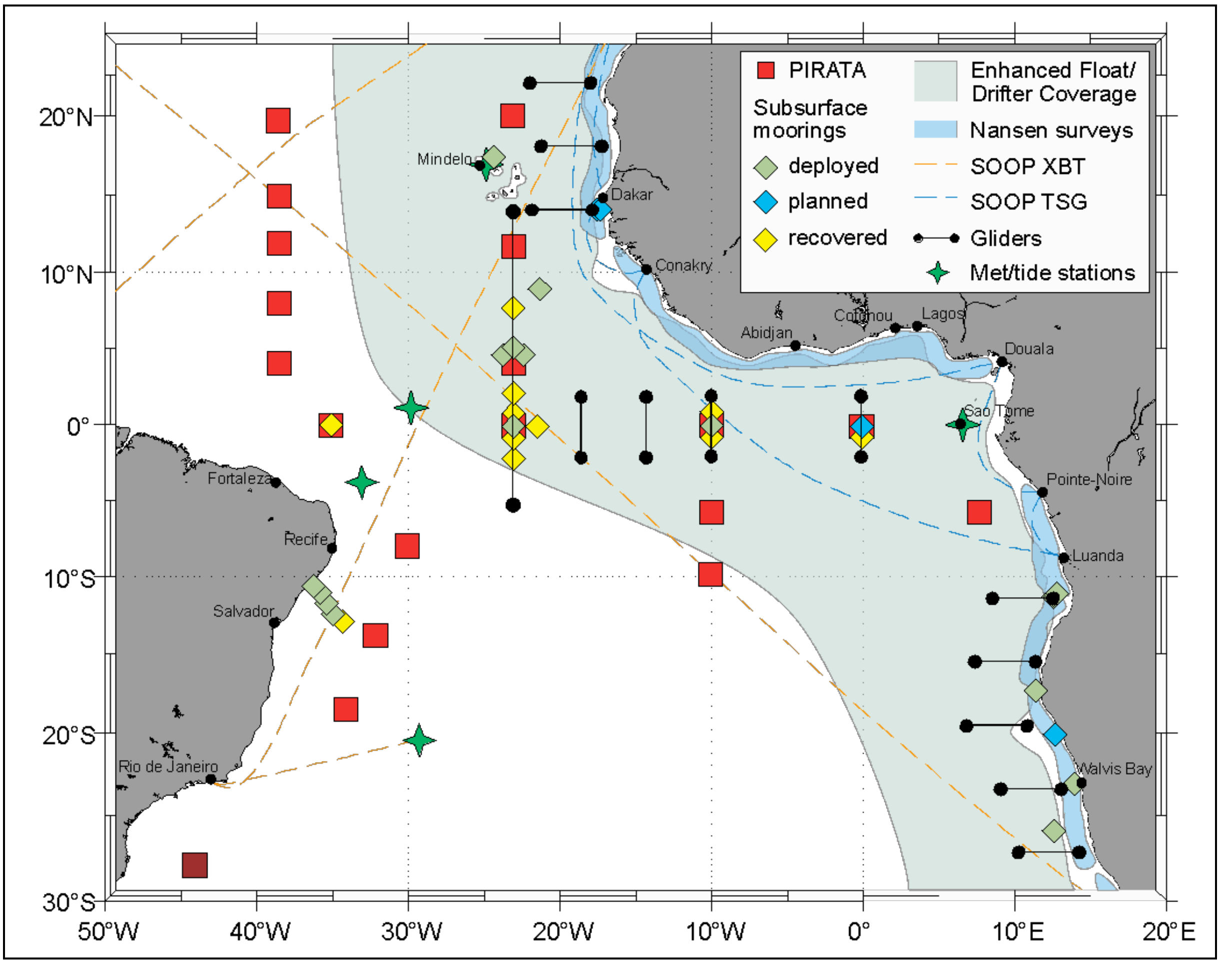

Figure 9. Observational network in the tropical Atlantic including the PIRATA network, the observational program during TACE, and more recent observations particularly in the eastern tropical South Atlantic.

While during TACE the eastern equatorial observing system was further developed, severe gaps in the observing system were still present in the eastern boundary coastal upwelling regions of both hemispheres, particularly in the Southeast Atlantic. Different national and multi-national programs are initiated, including German SACUS-SPACES, German-French-West African AWA and EU PREFACE programs, which are multidisciplinary studies linking physical, biogeochemical, ecology and fishery studies. The physical observing program of these studies include mooring networks along the continental slope of Southwest Africa and enhanced shipboard and glider measurements (Fig. 9). Of particular importance to those programs is the North-South cooperation that includes a substantial effort in building scientific capacities in the different West African nations.

1.2.4 SAMOC

Expanding the MOC observing system has proven challenging, however key components of the MOC are being measured by time series arrays deployed in the North Atlantic at a variety of locations. In the South Atlantic comparable arrays were missing, even if time series measurements have been obtained across Drake Passage and south of South Africa where inter-ocean exchanges of mass, heat and salt crucial to the global MOC occur (e.g. Chereskin et al., 2009; Swart et al. 2011) and, in the South Atlantic, regular trans-basin sections with hydrographic and expendable bathythermograph (XBT) observations have been collected at selected latitudes such as 11°S (SACUS-SPACES and RACE projects funded by the German Ministry of Education and Research including mooring arrays at the eastern and western boundaries, respectively), 24°S (e.g. Bryden et al., 2011; McCarthy et al., 2011), 30°S (McDonagh and King, 2005), and 34.5°S (e.g. Baringer and Garzoli, 2007; Garzoli et al., 2013).

Recent observing system design studies have suggested that, of the South Atlantic latitudes, 34.5°S would be ideal for capturing MOC variability at the 'mouth' of the Atlantic basin (Perez et al., 2011). This location is also well supported by theoretical analyses that suggest that crucial MOC stability evaluations would be best applied as far from the equator in the South Atlantic as possible (e.g. Dijkstra, 2007; Drijfhout et al., 2011). This location has been therefore selected to implement an array of mooring and ship observations to measure the density structure and the flows in the South Atlantic. This array has been defined as the "South Atlantic MOC Basin-wide Array" (SAMBA). This array together with that along GoodHope and Drake Passage were among the cornerstones for what has become known as the international South Atlantic MOC (SAMOC) initiative. The overall SAMOC Project is intended to study the variability of the Meridional Overturning Circulation in the South Atlantic and its impacts on climate change, from regional to global scales. It is an international effort in which participate institutions from Argentina, Brazil, France, Germany, Russia, South Africa, Spain, and the USA.

A SAMBA pilot study was undertaken by US (NOAA-AOML), Argentina (National Hydrographic Institute), and France (IFREMER and ANR/IPEV/INSU) between 2009 and 2010 with a limited number of PIES and CPIES deployed at the eastern and western boundaries of the 34.5°S section (3 PIES and 1 CPIES on the western boundary, 2 CPIES on the eastern). The results have demonstrated succesfull in assessing South Atlantic MOC variability (Meinen et al 2013). The SAMBA array is now developing. The western array was recently augmented with three additional Brazilian CPIES instruments as well as a bottom pressure gauge and and bottom-mounted acoustic Doppler current profiler up on the continental shelf to improve estimation of the flows in the western region. While the eastern pilot boundary array was removed in December 2010, a new array is currently being deployed: 8 French CPIES and two bottom were deployed acoustic Doppler current profiler in September 2013; South Africa will complete the eastern array on the slope and shelf with an important number of tall-moorings and acoustic Doppler current profilers during 2014; the new eastern array will stretch from the upper shelf as far offshore as the Walvis Ridge (Fig. 10). Thanks to these existing and planned/future contributions, the developing SAMBA array will soon produce more complete, and accurate, measurements of the MOC at 34.5°S.

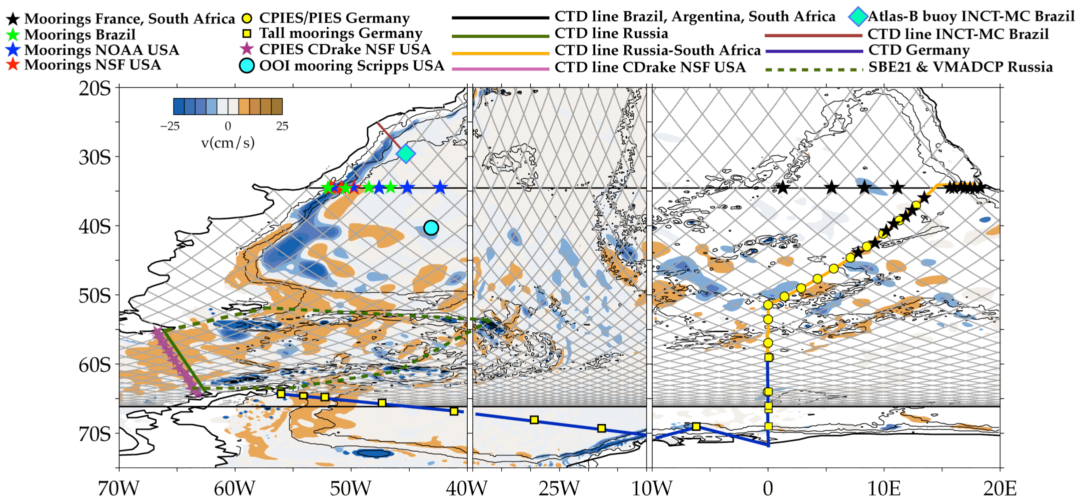

Figure 10. Schematic of the broader SAMOC proposed observing network. In particular, the SAMBA moorings array along 34.5°S and the oblique Goodhope transect will be instrumented by the end of 2014 (with the exception of the NSF moorings whos funding is still pending). Note the x-axis scale is stretched over western and eastern boundaries. Stars indicate the different components of the array. Color contours are of 27-year mean OGCM For the Earth Simulator (OFES) meridional velocity at 200 m depth. JASON ground-tracks are overlaid as light gray lines.

Furthermore, to assess the impact of the Indo-Atlantic exchange on the South Atlantic MOC, an additional seven PIES will be deployed in 2014 along the oblique portion of the GoodHope transect, which is located under one of the Jason-2 ground tracks, from 34.5°S out to the Agulhas Ridge. These additional PIES will cover the entire Agulhas Ring corridor defined by Dencausse et al., (2011).

Other proposals to NSF have been submitted or are being developed for funding to augment the SAMBA array or to complement it in working towards the broader goals of the SAMOC initiative with new observations in previously underexplored, but very dynamically active, regions of the South Atlantic. For example in the Zapiola gyre and the confluence region of the Brazil Current and Malvinas Current, large cross-frontal exchanges appear to occur particularly in the first quasi-stationary meander trough and crest. The eddy-driven exchanges produce strong inversions in T,S profiles, arguably from interleaving along isopycnals of waters from contrasting sources. Subsequently downstream of these exchanges, enhanced mixing will occur. A process-study is being designed involving moored and mobile observations and modeling to study the exchange mechanisms and possible longer-term modulation of water mass properties over the course of a few years. These exchanges should have profound influence upon both the Southern Ocean/ ACC, and upon the meridional overturning circulation in the Atlantic.

1.2.5 Argo, surface drifter, repeat hydrography, XBT lines

Besides the dedicated regional observational networks described above, the integrated global observing system is based on a number of important in-situ observations including autonomous platforms like e.g. Argo floats (http://wo.jcommops.org/cgi-bin/WebObjects/Argo) and surface drifter (http://www.aoml.noaa.gov/phod/dac/index.php), high-density XBT transects (http://www.aoml.noaa.gov/phod/hdenxbt/index.php), repeat hydrography as part of the GO-SHIP programme (http://www.go-ship.org). Most of regional observing networks as well as dedicated process studies heavily rely on the existence of these elements of the observing system and a long-term sustainability of these observations is required.

1.3 OCEAN AND CLIMATE MODEL DEVELOPMENT

The AIP has supported and promoted a number of ocean and climate modeling activities over the past decade. The following gives a few highlights of these activities:

1.3.1 Atlantic Bias Workshop

CLIVAR workshop devoted to brainstorm climate model bias issues in the tropical Atlantic was jointly developed by the AIP and VAMOS. The workshop was held in March 2011 in Miami. The objectives of the workshop are: 1) Identify an international network of interested, active researchers; 2) Develop a coherent synthesis of the state-of-the-art knowledge on the Atlantic biases and their causes for the southeast and eastern tropical Atlantic, as well as a set of sharpened hypotheses; 3) Articulate an effective way forward, including further model analysis, further reanalysis/satellite analysis, coordinated model experiments, new field programs, and modification of existing observational networks, e.g., TACE; 4) Define the appropriate geographical focus or foci (e.g, the Benguela coast, and/or the Amazon), and their spatial extent(s). The outcomes of the workshop include: 1) A report highlighting similarities and differences between GCM performance in the tropical Atlantic and Pacific, including an in-depth and up-to-date discussion of causes and relevant physical processes; 2) Formation of the US CLIVAR ETOS Working Group focusing on eastern tropical ocean bias studies; 3) Recommendations for future actions on reducing model biases.

1.3.2 US CLIVAR ETOS Working Group

The US CLIVAR Eastern Tropical Oceans Synthesis (ETOS) Working Group (WG) was formed in 2012, following the recommendation of the Atlantic Bias Workshop report. The WG consists of more than 20 researchers from 7 countries. Its goals are to: 1) Promote collaboration between observationalists and modelers, and atmospheric scientists and oceanographers, active in the southeast oceanic basins; 2) Coordinate a model assessment of surface flux errors for the equatorial Atlantic, mining all available observations; 3) Identify recent model improvements and common and persistent model errors both, CMIP5 and higher-resolution coupled models; 4) Provide recommendations of cases for community simulation and evaluation using eddy-permitting ocean models, sharing specified model conditions and output datasets. The WG has identified and assembled satellite, buoy and research cruise datasets and assembling plots of readily available CMIP3 and CMIP5 simulations for annual and seasonal-mean values of SST, cloud cover, surface winds, thermocline depth.

1.3.3 US CLIVAR Hurricane Working Group

The Hurricane Working Group of U.S. CLIVAR was established to obtain an improved understanding of interannual variability and trends in the tropical cyclone activity from the beginning of the 20th century to the present, and an improved understanding of the causes of the predicted future changes in the characteristics of tropical cyclones under a warming climate. The group has coordinated a series of working papers and workshops to define the current scientific understanding of these issues and to design coordinated climate model experiments to determine the climatically-relevant forcing factors. A series of coordinated experiments were performed, using a number of fine-resolution climate models, to examine the common responses to imposed idealized future climate forcings: a simulation in which the sea surface temperature of the model was increased; one in which the carbon dioxide content was doubled but the sea surface temperature was kept at present-day values; and another in which both were increased. The results show that most model experiments simulate future decreases in tropical cyclone numbers, but when the sea surface temperature is increased alone, the models were much less likely to simulate an increase in numbers. A special issue of J. Climate is devoted to the hurricane working group study.

1.3.4 Brazilian Earth System Model – BESM

The Brazilian Earth System Model (BESM) is an initiative/contribution to generate global climate change scenarios with emphasis on the enhancement of scientific knowledge of regional processes acting over worldwide climate variability (e.g., Convection over Amazon, South American Monsoon System, SACZ, Atlantic Niño, tropical-south Atlantic exchanges). The model development is based on the experience of INPE/CPTEC coupled ocean atmosphere modeling, adding land processes, atmosphere aerosols and chemistry, ocean biogeochemistry and ice component models. BESM is currently composed of CPTEC Atmospheric GCM coupled to NOAA's GFDL MOM4p1 via GFDL's FMS coupler; the land surface processes are dealt with both sSIB and IBIS models within the AGCM, while ocean biogeochemistry and ice are dealt with MOM4p1's TOPAZ and ISI component models. Atmospheric chemistry and aerosols are being implemented from NCAR's MOZART and Max Plank Institute HAM models. BESM is developed under the leadership of INPE and counts with contributions from other research institutions and Universities in Brazil. The model has been used to study the dynamics of the South Atlantic Convergence Zone (SACZ) (Nobre et al., 2012), well as to generated the first ever contributions of Brazil to CMIP5 (Nobre et al., 2013). The main research agenda of the BESM team is focused on the dynamics of Tropical Atlantic Climates and the effects of continent-atmosphere-ocean coupling through atmospheric bridges and river discharges. BESM is also used operationally to generate seasonal climate predictions at INPE, with ENSO prediction and the Atlantic Dipole SST anomalies pattern among its main products. More recently, BESM has also been used to produce thirty-days weather predictions for Brazil. The use of PIRATA data to validate BESM simulations has been extremely valuable. BESM is funded by three major research programs in Brazil: The Brazilian Research Network on Global Climate Change (Rede CLIMA), FAPESP Research Program on Global Climate Change (PFPMCG), and the National Institute for Science and Technology on Climate Change (INCT-MC).

1.3.5 Collaboration and Interaction with WGOMD

The CLIVAR Working Group on Ocean Model development has proposed a framework for ocean-ice model intercomparison and validation, called CORE (Coordinated Ocean Reference Experiments). The CORE 2 protocol addresses the ocean-ice variability of the past 60 years forced by an observed atmospheric dataset (derived from NCEP and satellite observations, Large and Yeager, 2009). 16 ocean modelling groups worldwide have performed 300-years long global simulations, cycling 5 times over the 60-years forcing dataset. The scientific analyses will be published in a special issue of *Ocean Modelling*. The first paper, by Danabasoglu et al, 2014, focuses on the mean circulation and water masses of the North Atlantic in CORE simulations. Significant differences exist between the model solutions, that can be attributed to different subgrid scale parameterizations and grid resolution. All models, most of which are ocean components of earth system models that were used for IPCC AR5, have significant biases and tend to underestimate the northward heat transport. A dedicated analysis of the North Atlantic variability is underway, and a paper focused on the South Atlantic and its exchanges with the Indian Ocean is planned.

1.4 PROCESS STUDIES

Besides long-term observing systems, there are a number of process studies dedicated to better understand important processes in the climate system. Such process studies, among which is also the CLIVAR TACE program described above, might lead to recommendations and improvements of for maintaining particular relevant elements of the observing system.

1.4.1 CLIMODE

CLIMODE (http://www.climode.org) is a process study to investigate the dynamics of Eighteen Degree Water (EDW), the subtropical mode water of the North Atlantic. EDW is a canonical example of subtropical mode waters, which are found in regions of significant air-sea exchange adjacent to strong baroclinic fronts in all the world's oceans. EDW is created in the winter just south of the Gulf Stream, by convection in the presence of strong shear, with competing effects of vertical/lateral mixing and advection/stirring colluding to set its properties. This project stems from two years of CLIVAR planning (with advice and support of both the CLIVAR Atlantic Implementation Panel and US CLIVAR) to develop an experiment to attack key processes that are poorly understood and poorly represented in ocean climate models - i.e. the treatment of convection, eddy and mixing processes in setting properties of subtropical mode waters, the associated air-sea interaction, and the exchange of fluid between the mixed layer and the upper ocean.

Extensive observational campaign (with 107 days at sea including two winter cruises) was conducted in the 5-year period beginning October, 2004 as a collaborative effort among 17 PIs from 9 institutions (The CLIMODE Group 2009). For the subsequent 4 years, the second phase of the CLIMODE was devoted to analyzing various newly obtained observations along with the hierarchy of model simulations. The CLIMODE observations encompassed winters with active EDW formation (Joyce et al. 2009) as well as very weak renewal (Billheimer and Talley 2013). Various researches ranging from revising the COARE air-sea flux algorithm to the assessing realism of the IPCC-class climate models have resulted in improved understanding of the air-sea interaction, ocean dynamics, and numerical modeling associated with formation, circulation, and destruction of EDW. The findings are published in more than 40 journal articles (see the webpage for the list) including the special issue in the Deep-Sea Research II (http://www.sciencedirect.com/science/journal/09670645/91).

1.4.2 SPURS

Changes in the global water cycle associated with global warming become detectable in trends of sea surface salinity. To understand relative roles of surface freshwater fluxes and oceanic processes in producing SSS trends, the Salinity Processes Upper-ocean Regional Study (SPURS) has been established in 2012. SPURS that focuses on the North Atlantic salinity maximum aims to provide accurate surface flux estimates and new assessments of vertical and horizontal mixing in the ocean, which will help to elucidate the utility of ocean salinity in quantifying the changing global water cycle. SPURS is funded by NASA in collaboration with NSF, NOAA and also involving European participation (e.g. France, Spain). Along with the AQUARIUS/SAC-D mission, a collaboration between NASA and the Argentinian Space Agency CONAE and the Soil Moisture and Ocean Salinity, or SMOS, mission that is part of ESA's Living Planet Programme, SPURS will provide new insights into the Earth's global water cycle and the relationship to climate.

1.4.3 AMMA

The African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM) and its variability with an emphasis on daily-to-interannual timescales. AMMA started in 2002 with its first phase ending in 2010. AMMA focus on atmosphere and land processes aimed to improve the prediction of the West African Monsoon and its societal relevant impacts. It was performed in cooperation with PIRATA and TACE. Large effort was put in building up capacities in the different West African nations and AMMA can be seen as a great example of successful North-South cooperation. AMMA developed close partnerships between those involved in basic research of the West African Monsoon, operational forecasting and decision making, and it established blended training and education activities for African technical institutions and schools.

1.4.4 GOAmazon

The Green Ocean Amazon (GOAMAZON) field experiment is currently on the way near the city of Manaus, Brazil (3° 6' 47" S, 60° 1' 31" W), extending through the wet and dry seasons from January 2014 through December 2015. It is a joint research endeavor among US/DOE, Brazilian and German organizations. Its aim is to conduct an integrated experiment to examine the coupled atmosphere-cloud-terrestrial tropical systems. The experiment is designed to enable the study of how aerosols and surface fluxes influence cloud cycles under clean conditions, as well as how aerosol and cloud life cycles, including cloud-aerosol-precipitation interactions, are influenced by pollutant outflow from a tropical megacity. These observations will provide a data set vital to constrain tropical rain forest model parameterizations for organic aerosols, cloud and convection schemes, and terrestrial vegetation components and how these are perturbed by pollution. This research program is expected to lead to a better understanding of climate model biases in simulating Amazon deep convection.

1.4.5 RREX

The French Reykjanes Ridge Experiment project (2015-2018) aims at investigating the interactions between the ocean currents and the Reykjanes Ridge, a topographic feature of the North-Atlantic Ocean. The Reykjanes is thought to be an important region for the Meridional Overturning Cell (MOC), a key component of the Earth System, but the flow dynamics along and over the Reykjanes Ridge is poorly understood and its representation in ocean models is flawed. Laboratory experiments and idealized simulations combined with a new and ambitious dataset and realistic models outputs will be used altogether to document and understand how does the Reykjanes Ridge control the large-scale circulation and influence, through turbulent mixing, water mass transformation, and to identify and quantify the key ocean model parameters involved in the representation of the dynamics of the flow around the Reykjanes Ridge. The current meter moorings that will be deployed on both sides of the Reykjanes Ridge as part of the RREX project will complement the OSNAP array (Figure 7).

1.5 ACHIEVEMENTS

1.5.1 Development of the South Atlantic observing system

During recent years the South Atlantic observing system have been substantially improved. Besides the SAMOC international initiative described above, several multinational programs have been established very recently. Among them are the EU PREFACE and German SACUS-SPACES programs focusing on the eastern boundary upwelling system with strong cooperation with African coastal countries, and the German RACE program focusing on the western boundary circulation off Brazil.

In addition to these programs, Brazilian institutions and US NOAA coordinate the Monitoring of the upper Ocean transport VARiability in the western South Atlantic (MOVAR) project. Starting on August 2004, the project has supported up to 41 cruises between Rio de Janeiro and Trindade Island (20^{o}S, 30^{o}W; NOAA/AOML AX97 transect). These observations shed new light on the nature of the Brazil Current (BC) variability at tropical latitudes. Also, a strong South Atlantic Subtropical Gyre Northern Cell (SASG-NC) was revealed by absolute dynamic topography (ADT) composites, with a high value sea-level “crest” crossing the AX97 line. Results support the idea that BC variability is associated with its core spatial fluctuations, which can exceed 150 km, and that the current is not always present as a poleward jet across AX97. Also, variability may be related to both changes of the SASG-NC and to the development of a cyclonic eddy off Cape Sao Tomé.

Two international projects funded by the Inter-American Institute for Global Change Research - 1) Export of shelf waters from the western South Atlantic shelf: A one way ticket? and 2) Variability of Ocean Ecosystems around South America (VOCES) - underlie the cooperation of research groups from Argentina, Brazil, Chile, Peru, Uruguay and USA. These initiatives aim at the processes that control the exchanges between the continental shelves and the western and eastern boundary currents and between Large Marine Ecosystems around South America. The studies are based on the combined analysis of in-situ and satellite observations together with high resolution numerical simulations. Results reveal significant export events of buoyant shelf waters along the Brazil/Malvinas Confluence. The export of shelf waters may have a significant impact on the fate of planktonic species and therefore on the reproductive success of commercially significant species. Expelled shelf waters are also the most likely route for large amounts of carbon absorbed from the atmosphere over the highly productive Patagonia continental shelf, which subsequently spread in the western South Atlantic (Matano et al., 2010; Costa Campos et al., 2013; Piola et al., 2013; Combes et al., 2014).

The formation of an oceanographic institution is a rare event in the history of oceanography. The recent formation of a National Institute for Ocean Research and Hydroways (INPOH) in Brazil may be considered a milestone in oceanography, and should have important consequences on the ongoing and future researches in the Tropical and South Atlantic. Brazil is on the verge of setting up the INPOH to support multi-platform ocean observing and forecasting systems totally driven by science, for societal and Governmental needs, in the provision of real time data and long term time series, deemed essential to address key scientific and environmental challenges in our maritime area of interest. Also, a deeper understanding of vulnerabilities and risks pertaining to global climate change and climate impacts (e.g. ocean acidification, sea-level rise, shifts in commercially important marine species, etc.) and other anthropogenic impacts, including those related to sustainable resource exploitation (e.g. aquaculture, fisheries, deep-sea mining, etc.) are of major interest to Marine Economy in Brazil. It is also worth noting that Brazil has just finalized the procurement and purchase process of acquiring a new Research Vessel, to be dedicated to global and national programs in the Tropical and South Atlantic.

1.5.2 Progress towards resolving climate model bias in the tropical Atlantic

The concerted effort organized by the AIP has led to considerable progress towards the understanding of the tropical Atlantic bias problem. It is now more clear that the warm SST bias along the equatorial Atlantic cold tongue is closely linked to atmospheric model biases in simulating deep convection over the Amazon and Congo basin that affect the strength of the equatorial trades (Richter and Xie, 2008). The ITCZ bias in atmospheric model simulations, which causes the ITCZ to migrate into the southern hemisphere, can also lead to equatorial trade wind bias, contributing to the equatorial SST bias (Doi et al. 2012, Richter et al. 2012, Grodsky et al. 2012). On the other hand, the warm SST bias in the southeastern tropical Atlantic close to the African coast, which is more persistent and more severe than its equatorial counterpart, appears to have an oceanic origin. This is in contrast to the similar bias in the southeastern tropical Pacific, which is often attributed to under-representation of stratocumulus decks in GCMs. A significant difference between the southeast Pacific and Atlantic is that the latter features a more complex ocean circulation. In particular, a surface current convergence forms around 16°S, where the poleward Angola current and the equatorward Benguela current meet and give rise to the Angola-Benguela frontal zone (ABFZ). The strong temperature gradient and the associated frontal- and meso-scale features near the ABFZ present a challenge for observations and models (Xu et al. 2013). The EU PREFACE program launched in 2013 is in response to this challenge. The extensive field observations and modeling studies embraced by the EU PREFACE promise new progress in reducing climate model biases in the eastern tropical Atlantic.

1.5.3 Advancement in Interdisciplinary Research

During recent years the cooperation between CLIVAR and IMBER/SOLAS continuously increased. A major component of CLIVAR SSG-19 meeting was a joint session with IMBER (Integrated Marine Biogeochemistry and Ecosystem Research). The outcome of this session was the formation of task teams, with a mandate to formulate a strategic approach to future joint working groups between the two programs. On of these task teams is the tiger team on marine biophysical interactions and the dynamics of upwelling systems that is aimed to foster interdisciplinary research in oceanic upwelling regions.

During recent years there is a general increase in interdisciplinary research, which becomes obvious in the different observing systems. Traditionally physical ocean observing systems, like e.g. RAPID-MOCHA-WBTS and OSNAP, were enhanced and will be further enhanced with biogeochemical measurements particularly focusing on air-sea exchange of CO_2 and other greenhouse gases. Several PIRATA buoys are equipped with oxygen or CO_2 sensors and annual TACE/PIRATA meetings included dedicated sessions for biogeochemistry studies in the tropical ocean. A dedicated interdisciplinary program is the German SFB754 Climate-Biogeochemistry Interaction in the tropical Ocean (1st phase 2008-2011, 2nd phase 2012-2015) that aims to understand the deoxygenation of the tropical oceans by dedicated studies of ventilation physics and heteroptrophic respiration with focus on biogeochemical cycles in oxygen minimum zones (Oschlies et al. 2012). Moreover, today, many European ocean research programs include a close link between physical process understanding and impact of climate variability and change on ecosystem and fisheries, which includes NACLIM program in the North Atlantic as well as PREFACE and AWA programs in the eastern boundary upwelling systems.

1.5.4 Enhancement in International Collaboration

One of the main goals of AIP was to improve the collaboration between US and Europe as well as between northern and southern hemisphere. The development of the AMOC program described above is an excellent example of a great collaboration between scientist and funding agencies from many countries that ensures the best use of available resources. Multinational efforts like OSNAP or TACE require a distinct international coordination and the AIP strongly aims to contribute to such efforts. Recently, there is a great progress also in the development of the South Atlantic observing system that is based also on the progress in countries like Brazil, Argentina, and South Africa.

2 Future plans and priority areas

2.1 Understanding Role of the AMOC in Climate

Over the past five years, substantial progress has been made towards realizing the goal of instrumenting a comprehensive AMOC observing system in the subtropical North Atlantic (26N Rapid), subpolar North Atlantic (OSNAP) and the subtropical South Atlantic (SAMOC). A high priority area in the near-term is to fully implement these observing systems, synthesize the in-situ observations and combine them with ocean state estimation models to improve our understanding of the AOMC changes that have been observed. AMOC variability has now linked as a “fingerprint” associated with sea-level, surface and sub-surface temperature anomalies. More effort will be devoted to the use of multi-model analysis and historical data to see if a proxy for AMOC variability in the past can be constructed from historical time series. Modelling studies aimed at understanding and predicting AMOC variability continue to provide model-dependent results. A coordinated and focused set of experiments across a hierarchy of models is needed to develop a common set of metrics for intermodal comparison (e.g. AMOC variability in density space), the determine best practices for model initialization and bias correction. Ongoing intercomparisons and verifications studies of IPCC AR5 decadal prediction experiments can help assess the robustness and model dependency in AMOC predictions.

2.2 Tropical biases in climate models

Although considerable new knowledge and observations have been gained over the past decade in understanding causes of climate model biases in the tropical Atlantic, how to transfer these new knowledge and observations into model improvements remains a formidable challenge. The current generation IPCC-class climate models suffer from enormous bias problems in the tropical Atlantic. In fact, the biases in CMIP5 remain as severe as those in CMIP3 in the eastern tropical Atlantic (Fig. 11) (Toniazzo and Woolnough, 2013, Xu et al. 2014). These biases are fully developed within a season (Toniazzo and Woolnough, 2013), severely undermining model forecast skills of climate variability at seasonal or longer time scales. Some of the biases may be simply related to insufficient model resolutions, which may be alleviated to some extent by increasing model resolutions, while others require improvements of model physics at a more fundamental level. A strategy is needed to enhance interactions between modeling centers and field observational programs in order to accelerate the progress of solving tropical bias problem.

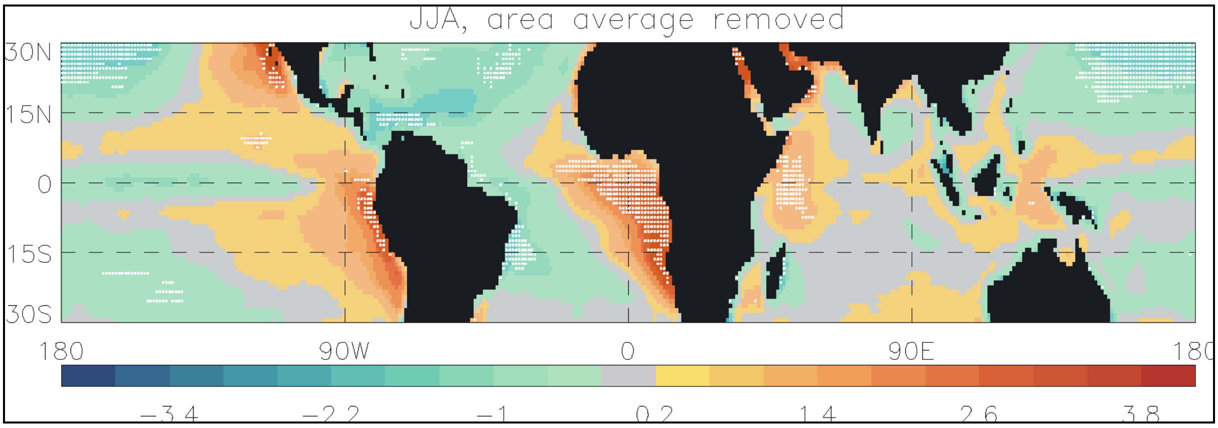

Figure 11. Difference between simulated and observed mean SST for June/July/August. The warm bias is pervasive (stippled areas is where all models have the same bias) in CMIP5 just as it was in CMIP3 (Toniazzo and Woolnough, 2013).

2.3 Improving seasonal-to-decadal climate prediction in the Atlantic Sector

Key developments in seasonal forecasting over the last year suggest that the NAO is highly predictable at least a month ahead (Scaife et al 2014, Riddle et al 2013). However, skill is only achievable with a very large ensemble, and there is a mismatch between correlation and signal to noise ratio (Scaife et al 2014). The most likely explanation for this is that the model atmospheric response to the relevant driving factors, such as Atlantic SSTs, is too weak. Resolving this issue may lead to further improvements in seasonal forecasts of the NAO, and may enable skill to be extended beyond the seasonal range. Although decadal predictions show some promise for predicting North Atlantic SSTs, it is currently unclear whether recent variations in these may have been predominantly driven by anthropogenic aerosols (Booth et al 2012, Dunstone et al 2013, Zhang et al 2013). Further work to understand aerosol effects is needed to resolve this issue in order to gain confidence in predictions for the coming decade.

2.4 Climate extreme prediction and attribution and sea-level rise in the Atlantic Sector

Improved understanding and prediction of extreme events, as well as adapting to extremes and reducing societal vulnerability to extremes are a near-term high priority research area identified by the AIP. Although much progress has been made on delineating relationships between climate extremes, such as Atlantic hurricanes, Atlantic blocking and cold air outbreaks, heat waves, droughts, etc., and modes of Atlantic climate variability, many issues remain unresolved and climate model projections on future changes of climate extremes remain highly uncertain. Much work is needed to improve the availability and quality of observations data sets for extreme events. Higher spatial and temporal resolution observations are needed, as well as improved observations of key processes, including land-atmosphere, ocean-atmosphere and land-ice interactions. Much work is also needed to improve climate model simulation and prediction skills of extreme events, which requires not only enhancing model resolutions, but also improving parameterizations of fine-scale processes that are important to determine both strength and timing of many extreme events. Additionally, innovative analyses and new diagnostics are needed to allow models to be confronted with the new observational products. Finally, downscaling approaches need to be further developed and improved.

2.5 Capacity building

AIP collected information regarding capacity building from the different programs and projects having particular interaction with developing countries surrounding the Atlantic

Ocean. Particular focus was on efforts aimed at developing capacity that help to enable people, governments, international organizations and non-governmental organizations to increase technical capabilities in observing techniques and data analysis as well as their abilities to understand the role of the ocean in the climate system and consequences of climate variability and change.

Research cruises that are performed within several European and national projects are ideal activities to invite students, scientists, and engineers from developing countries to participate in modern research programs. Several cruises were performed during recent years performed within cooperative projects, including for example German GEOMAR and IOW research cruises off Southern Africa, or yearly cruises in the tropical Atlantic as part of the international PIRATA program. A particular topic is the EAF Nansen project that is executed by FAO in close collaboration with the Institute of Marine Research (IMR) of Bergen, Norway and funded by the Norwegian Agency for Development Cooperation (Norad). This project focus on fisheries, but at the same time collect important physical oceanography datasets. The participation of scientists from different African countries clearly helps to enhance regional capacities of modern observational techniques and data analysis.
Another aspect is the successful training of Brazilian scientists and engineers in handling and constructing PIRATA buoys that were produced by PMEL. Recently the first Brazilian ATLAS-B buoy was deployed at 28.5°S, 44°W. This is an important step in the development of a national Brazilian observing system including surface buoys contributing to the global observing system.

Another important aspect of capacity building is teaching of students during summer schools and by guest lectures at different African Universities. A substantial effort was done by IRD when establishing a regional Master degree and Doctoral training program in Physical Oceanography and Applications at Cotonou in Republic of Benin. This program, established by the International Chair in Mathematical Physics and Applications (UNESCO chair, Cotonou University) and the Université Paul Sabatier (Toulouse, France), has been opened in 2008 and since then a good number of African students (10 per year) finished the master program and partly continued within different PhD programs of several nations (e.g. France, Benin, Brazil, Cameroon, Germany,…).

In 2010 the Nansen-Tutu Centre for Marine Environmental Research in South Africa has been set up as a joint venture between the Nansen Environmental Centre in Norway and South African partners. It is directed by a South African and is aimed in building capacity locally. The Nansen-Tutu Centre is based in Cape Town and operates as a program complementing the developing South African marine research framework. A similar joint effort (joint laboratory ICEMASA) has been set-up between the French Institute for the Development (IRD), French universities and the University of Cape Town. Both centres have complementary scientific objectives.

An important aspect of capacity building is freely available software for ocean and climate modeling as well as freely available results from model simulations. A particular success in this regard is the application of ROMS modeling in different African nations and the freely distributed ocean model results, e.g. from the MERCATOR and NEMO-based model systems.

2.6 Deep ocean observing network

Deep ocean observations and scientific requirements were presented in the OceanObs'09 Community White Paper by Garzoli and coauthors. The rationale for the need of a deep ocean observational network is that half of the ocean volume is below 2000 m depth and the deep ocean currents control climate changes on long term time scales (decadal to millennia). The status of the global heat content remains uncertain due to the paucity of measurements. Argo network revolutionized the observation network in the upper ocean so most of the global ocean heat content estimates are limited to the upper km of the ocean. There are indications of increased freshwater input at the high latitudes of the oceans and the deep ocean accounts for more than half of the total (natural) oceanic carbon inventory. Particular strong changes are identified within the Antarctic Bottom Water range (Purkey and Johnson, 2013). Most of recent studies rely on deep hydrography from research cruises.

Technological advances during the past few years have made float prototypes available, which could probe the deep ocean down to 4000 m or 6000 m. It is now feasible to make use of these technologies and a preparatory phase of abyssal Argo measurements within the Atlantic Ocean is underway (French NAOS project, European E-AIMS project). This preparatory phase needs to demonstrate the floats being capable of making the required measurements and to perform a design study for the optimal design of the abyssal ocean observing system. Those observations will be articulated and coordinated with the assimilation community who needs to have measurements of the deep ocean.

3 Contribution to the CLIVAR Research Foci and/or WCRP Grand Science Challenges.

AIP will concentrate on CLIVAR research foci 1 to 5 and will place some emphasis on 6 and 7 (see below). A number of new panel members started in 2013/14 that will enable the panel to focus on these CLIVAR research foci. An identified gap is the missing link of AIP with the paleoclimate community, which should be solved in the near future.

There are some extensions to the CLIVAR research foci suggested from the AIP, which include:

- Dynamics and *prediction* of regional sea level variability
- Gulf Stream and North Atlantic Current variability and impact on storms (particularly winter extratropical storms)
- Climate impact of an ice-free Arctic
- Atlantic tropical storm in a future climate
- ENSO impact on Atlantic

CLIVAR Research Foci

1. Intraseasonal, seasonal and interannual variability and predictability of monsoon systems
2. Decadal variability and predictability of ocean and climate variability
3. Trends, nonlinearities and extreme events
4. Marine biophysical interactions and dynamics of upwelling systems
5. Dynamics of regional sea level variability
6. Consistency between planetary heat balance and ocean heat storage
7. ENSO in a changing climate

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