# Tropical Atlantic Climate Experiment (TACE)

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## Introduction

More than 10 years ago it was recognized that there was a need for a focused observational and modeling effort in the tropical Atlantic, to advance the predictability of climate variability in the surrounding region and to provide a basis for assessment and improvement of coupled models. The scientific foundation of such an effort was developed in the Tropical Atlantic Climate Experiment (TACE) white paper by Fritz Schott and co-authors in 2003. The TACE implementation workshop in February 2005, held in Miami marked the starting point of a truly international five-year (2006 – 2011) research program under the auspices of CLIVAR. TACE with its backbone, the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA), was closely linked to other initiatives in the tropical Atlantic like the French EGEE (Etude de la circulation océanique et de sa variabilité dans le Golfe de Guinée) program and the African Monsoon Multidisciplinary Analyses (AMMA).

One of the main goals of TACE was to improve the observational database and to carry out dedicated process studies enhancing our understanding of the tropical Atlantic climate system. The regional focus of TACE was on the central and eastern equatorial Atlantic (Fig. 1) characterized by the development of the Atlantic cold tongue (ACT) during boreal summer. The year-to-year variability of the ACT sea surface temperature (SST) is linked to climate variations including the strength and onset date of the West African Monsoon; however, its prediction is strongly limited by large biases in coupled climate models.

Here we report about the 2012 Tropical Atlantic Variability (TAV) meeting that was held jointly with the PIRATA-17 meeting from 10th to 13th September 2012 in Kiel, Germany. The meeting focused on advances in observing, simulating, understanding and predicting TAV and provided an opportunity to assess progress toward achieving TACE's goals. The meeting was organized around five themed sessions:

1) Climate Variability and Change in the Tropical Atlantic

2) Tropical Atlantic Teleconnections

3) Predictability, Coupled and Uncoupled Model Biases

4) Oceanic and Atmospheric Processes Affecting Climate Variability

5) Physical-Biogeochemical Interaction

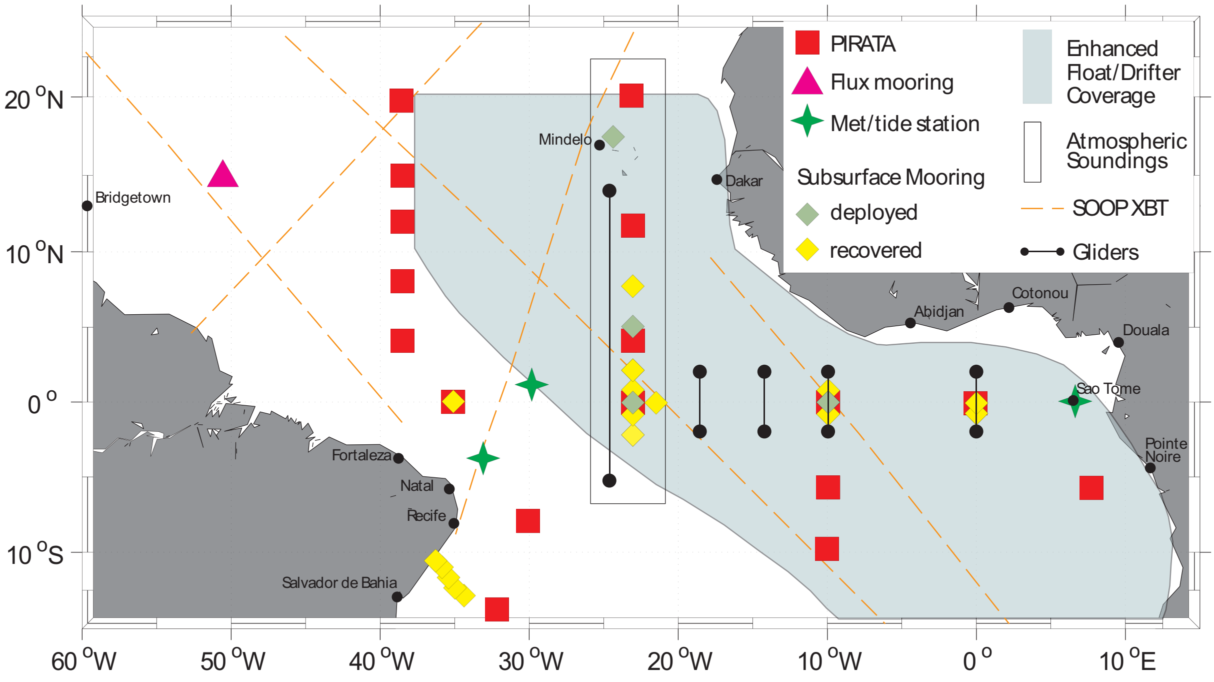
This report summarizes the progress to date in TACE based on the presentations at the conference. Highlights from the first three sessions are grouped together in the following section, followed by a summary of Session 4. We also briefly describe the status of the biogeochemistry in the tropical Atlantic, despite not being formally part of TACE, because it points toward the increasing importance of multidisciplinary research in the tropical Atlantic for understanding and predicting climate. The scientific program, abstracts as well as most presentations are available at the meeting website: https://conferences.geomar.de/conferenceDisplay.py?ovw=True&confId=0.

## Tropical Atlantic Climate Variability and Teleconnections, Predictability and Model Biases

### Climate Variability and Change in the Tropical Atlantic

Session 1 on climate variability and change in the tropical Atlantic centered around the recent progress in documenting and understanding of modes of variability and long-term climate change within the region. Enhanced observations and modeling studies during the TACE period have led to some new understanding of underlying physical processes governing modes of TAV. For example, Lumpkin (2012) showed, using a synthesis product of the surface geostrophic circulation, that the interannual variability of the North Equatorial Countercurrent is linked to the appearance of the Atlantic meridional mode and zonal mode. Lübbecke (2012) analyzed stability properties of the Atlantic zonal mode and concluded that it is more strongly damped compared to its counterpart in the Pacific – ENSO. Rouault (2012) presented observational evidence that the development of Benguela Niños is closely linked to the advection of warm Angolan water in the Northern Benguela region across the Angola-Benguela Front (ABF), suggesting that anomalous advection of heat near the ABF can be a key process during the onset of Benguela Niños. Queiroz (2012) presented a multi-dataset analysis of surface ocean variability along the West African coast that revealed a significant surface ocean warming trend in the region since 1982. This coastal warming trend appears to be a part of a larger scale warming pattern over the entire Eastern tropical Atlantic basin as shown by Servain (2012). Servain (2012) further showed that the warming trend is most significant during the warm season. The warming features are consistent with earlier studies by Deser et al. (2010) and Tokinaga and Xie (2011). Subsequent discussions focused on potential causes of the warming trend. One possible cause, as

Figure 1. Observational network in the tropical Atlantic during TACE.




suggested by Tokinaga and Xie (2011), may be related to the aerosol forcing, while the other may be related to slow changes in ocean circulations, such as the Atlantic Meridional Overturning Circulation. The latter is supported by a modeling study by Campos (2012) who showed an increase in the Agulhas leakage and a poleward shift of the oceanic Subtropical Convergence Zone. Finally, Treguier (2012) presented some intriguing modeling results on Congo River plume dynamics. Interannual variations of sea surface salinity (SSS) along the equator and the Gulf of Guinea coast are found to be independent on river discharge variations, but are the result of larger scale advection anomalies.

**Tropical Atlantic Teleconnections**

Session 2 on teleconnections focused on the influences of the Pacific El Niño/Southern Oscillation (ENSO) and other modes of climate variability on the tropical Atlantic as well as the impact of tropical Atlantic climate variability on surrounding oceans and continents. It is well known that ENSO has an impact on the surface layer of the tropical Atlantic; Kröger (2012) elaborated on these impacts by describing how the details of wind stress teleconnections from the Pacific affect the tropical and subtropical cells in an ocean model. Keenlyside (2012) showed, through seasonal prediction experiments with a climate model, that equatorial Atlantic SST could significantly improve the prediction of major El Niños across the boreal spring predictability barrier by impacting the Equatorial Pacific atmospheric circulation during this critical development phase of ENSO events. Subsequent discussion emphasized the need to quantify the relative importance of tropical Atlantic vs. tropical Indian Ocean impacts on the ENSO cycle, both of which have been highlighted by independent groups.

**Predictability, Coupled and Uncoupled Model Biases**

Section 3 focused on the coupled models' SST bias over the eastern equatorial and SE tropical Atlantic and their impacts on predictability. Latif (2012) showed that the reduction of coupled model systematic errors is essential for the generation of useful predictions. Voldoire (2012) showed that the systematic errors that eventually lead to large SST biases over the eastern equatorial Atlantic, are already present during the early stages of the CNRM-CM5 coupled model integrations. Nobre (2012) showed that SST error growth in INPE's (Instituto Nacional de Pesquisas Espaciais) coupled model was insensitive to increased atmospheric $CO_2$ concentration. Richter (2012) examined the outputs of CMIP5 model pre-industrial control simulations, reporting that one of the major reasons for the reversed SST gradient over the equatorial Atlantic appears to be the weaker than observed equatorial easterlies in March-April-May. Toniazzo (2012) showed that the development of coupled model errors evolves from several time-scales, from days to years, and that the fully developed error patterns appear very similar in different models. Finally, Chang (2012) showed for a high-resolution ocean model that in addition to the contributions of atmospheric model biases, systematic oceanic errors also make a significant contribution to the bias problem. In particular, (1) a strong warm bias at the ABF front, maintained by the local wind and the convergence of Angola and Benguela Current, is caused by an overshooting of the Angola Current in ocean models and (2) an alongshore warm bias to the south of the front is caused by the model deficiencies in simulating the sharp thermocline along the equator, the strong thermal gradient beneath the Angola current, and the complex circulation system within the Benguela upwelling zone.

## Process studies

TACE was designed to better understand processes relevant for the mean climate system including seasonal mixed layer heat and freshwater budgets, interannual variations in the tropical circulation, and its underlying dynamics. The observational program consisted of improved profiling float and surface drifter coverage, glider measurements, high-density XBT lines, subsurface moorings along the equatorial wave-guide, and repeated research cruises during different seasons with hydrographic, microstructure, and biogeochemical measurements. Studies analyzing the large amount of new data acquired during the TACE period together with data from the pre-existing PIRATA buoy array, remote-sensing data and a new

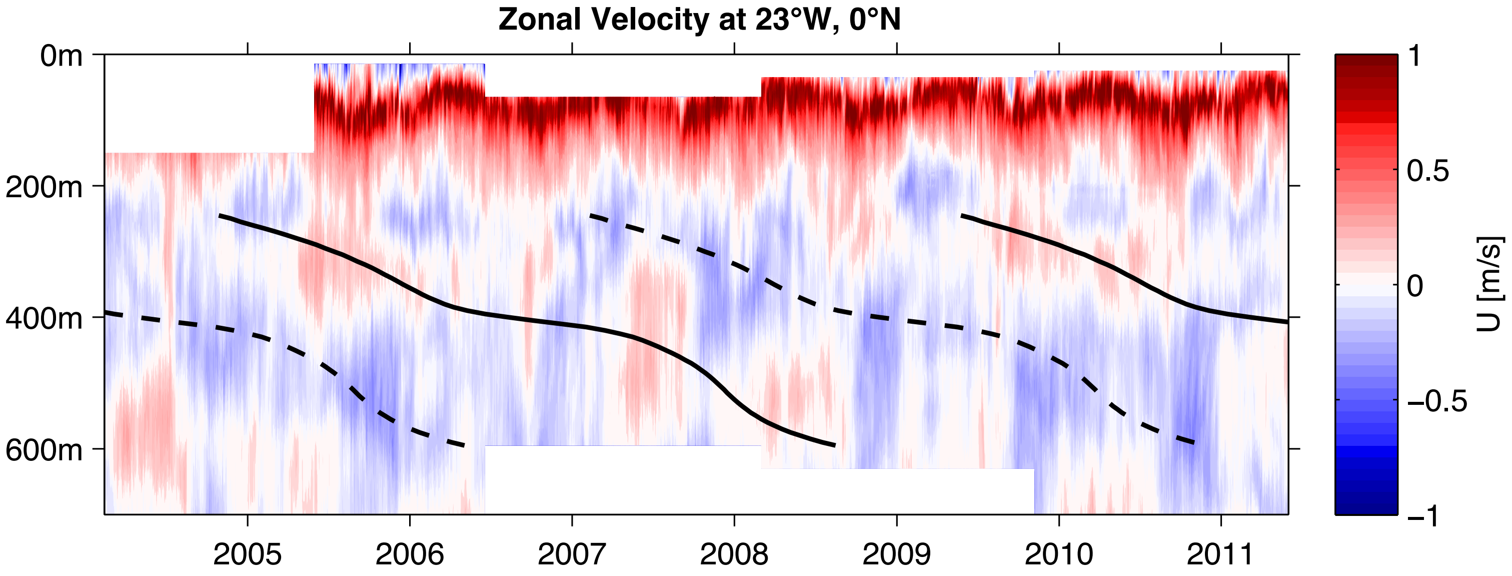



Figure 2. Zonal velocity measured at the equator, 23°W with moored ADCPs. The eastward flow of the EUC at about 80 m depth is characterized by a strong seasonal cycle. Below the EUC, the phase propagation of EDJ is marked by solid and dashed lines that are obtained from a 4.5-year harmonic fit (update from Brandt et al., 2011).

generation of high-resolution model simulations were mostly presented within session 4: "Oceanic and Atmospheric Processes Affecting Climate Variability". The session was split into two sub-sessions: a) Surface mixed layer heat budgets and mixing processes and b) Tropical Atlantic circulation and dynamics.

**Surface mixed layer heat budgets and mixing processes**

Seasonal and interannual variations in the mixed layer heat and freshwater budget were addressed in several presentations using different observational and modeling methods. Particularly, microstructure measurements carried out during different cruises as part of TACE and on autonomous gliders provided a much-improved understanding of mixed layer budgets. Hummels (2012) presented the mixed layer heat budget from observations and concluded that the observed diapycnal heat flux contributes crucially to the budget within the ACT (equator, 23°W, 10°W and 0°), while the budget is dominated by atmospheric forcing in the southern ACT region at 10°S. An extensive measurement program within the ACT region was carried out during the ACT onset in boreal summer 2011 (mid-May and mid-July). Two consecutive cruises complemented by a glider-swarm experiment delivered an unprecedented number of contemporaneous microstructure profiles, hydrographic and current data. Dengler (2012) presented an analysis of observations taken near the PIRATA buoy at the equator, 10°W. The strong SST cooling from end of May to mid-July, from 26°C to below 22°C, could be largely explained by strong bursts of turbulence extending from the mixed layer into the upper thermocline. These turbulent bursts occurred predominately, but not exclusively, during nighttime. Vertical shear of horizontal velocity was particularly enhanced in the upper 40m of the water column with the shear caused by zonal flow variability playing a dominant role. The results contrasted with results from the Pacific cold tongue (PCT) presented by Moum (2012) showing a much more pronounced role of tropical instability waves and associated meridional flow variability in producing a diapycnal heat flux that could alone maintain the PCT.

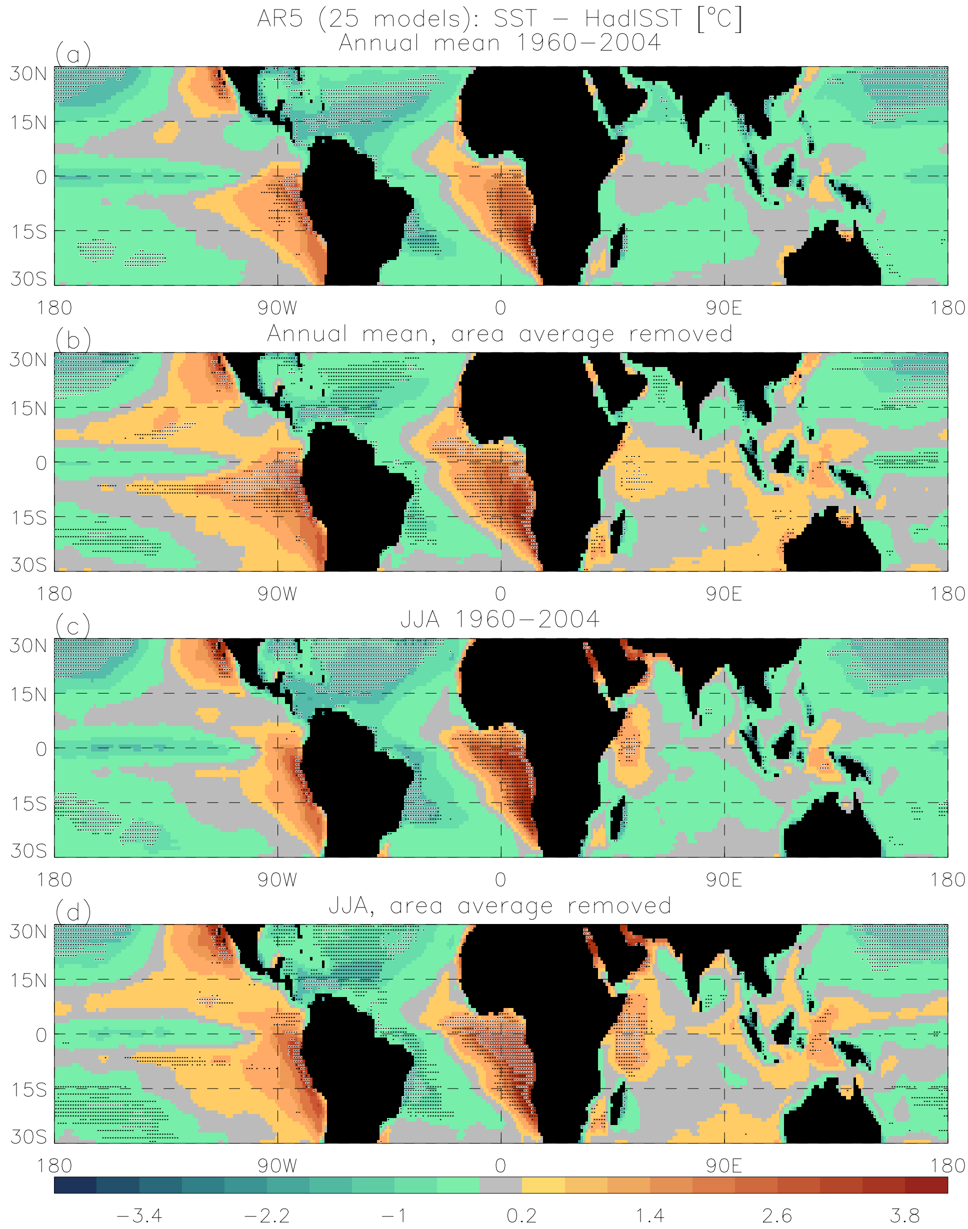
High-resolution model simulations were employed to study the effect of different types of intraseasonal equatorial waves in causing cooling events in the ACT, and to study the role of vertical velocity in the ACT formation. Simulations by Jouanno (2012) suggest that intraseasonal waves significantly contribute to the mixed layer heat budget. Cooling events due to diapycnal mixing are particularly strong in the shear zone above the Equatorial Undercurrent (EUC) and during boreal summer when the westward surface flow is strongest. The vertical shear above the EUC is similarly modulated by different types of intraseasonal waves, including wind-generated mixed Rossby gravity waves, inertia-gravity waves, and equatorial Kelvin waves. An investigation of the Ekman balance in the ACT was presented by Caniaux (2012), where the equatorial upwelling was found to be an indirect response to the wind forcing. The associated vertical velocity preconditions the oceanic mixed layer for the strong diapycnal mixing occurring later during the onset of the ACT.

The session also underlined the growing focus on salinity in the community. In terms of datasets, Xie (2012) presented a new SSS monthly blended product from NOAA, that enriches significantly the existing in-situ and satellite datasets. Hernandez (2012) described the current efforts at Mercator to keep providing a global ocean reanalysis, ongoing since 1992. In terms of processes, Lazar (2012) focused on the North Atlantic Warm Pool barrier-layer, detailing how the remarkable winter subsurface temperature inversions resulted from fresh water capping and yearlong penetrative solar radiations. A mixed layer salinity budget over the ACT during the ACT onset in 2011 was computed from observations by Schlundt (2012), indicating that alike heat budget subsurface mixing processes were of paramount importance to close the freshwater budget.

**Tropical Atlantic circulation and dynamics**

Subsurface moorings and repeated shipboard observations were used to observe circulation variability during the TACE period. Current meter mooring arrays were installed at different longitudes focusing in particular on the strength of the EUC supplying the upwelling within the ACT. Brandt (2012) presented moored velocity observations from 23°W carried out between 2005 and 2011 and analyzed the relation between EUC

Figure 3. Difference between simulated and observed mean SST. 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, 2012).




transport variations and TAV. Interannual transport anomalies are found to be seasonally dependent with maximum variability during boreal summer. Regression of wind and SST anomalies onto EUC transport anomalies revealed northward wind anomalies in June (i.e., early onset of the African monsoon), and colder SSTA in the ACT associated with a strong EUC. Further, November EUC transport vs. the next April SST and winds showed warm SSTA in the Tropical North Atlantic (TNA) region, consistent with Okumura and Xie (2006) who argued that Atlantic Niño tends to evolve into a meridional mode event.

A joint analysis of the 23°W mooring data and similar moored current observations at 10°W and 0° were presented by Johns (2012). The variability of the EUC transport is more semiannual at 23°W and more annual at 0°E. In boreal spring, during the annual wind relaxation, the EUC transport is approximately the same across the basin while in fall there is a sharp decrease toward the east. Year-to-year variability was associated with a stronger reduction of the EUC in July/August particularly at the eastern mooring sites during 2009 compared to 2010. In 2010, the ACT was anomalously weak; while in 2009 the ACT was normal (or slightly cooler than normal). Unfortunately, the experiment did not sample a strong Atlantic Niño event.

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Three other talks presented new results regarding equatorial deep jets (EDJ). These jets, that are characterized by small vertical wavelength, downward phase and upward energy propagation and an oscillation period of about 4.5 years, were recently observed at the equatorial 23°W mooring site (Fig. 2) and analyzed with respect to their possible effect on SST and climate in the tropical Atlantic region (Brandt et al. 2011). Ascani (2012) presented idealized simulations for the generation of EDJ as well as latitudinally alternating zonal jets (Equatorial Intermediate Current System, EICS). Both current systems are found to originate from intraseasonal fluctuations generated by the instabilities of the tropical wind-forced, near-surface current system. The analysis of the meridional and vertical structure of EDJ using observations, reduced gravity modeling and theory were presented by Didwischus (2012) and Greatbatch (2012). Greatbatch (2012) were able to explain the increased meridional width of the EDJ compared to inviscid theory by isopycnal mixing of momentum.

The large number of research cruises in the Gulf of Guinea was used by Bourlès (2012) to draw a new summary of the circulation and its variability in the northern part of the Gulf. A special focus was on the Guinea current system, including an eastward flowing undercurrent under the Guinea current that is fed by salty subtropical waters.

## Summary and Outlook

TACE has provided important contributions to the understanding of the seasonal to interannual circulation of the tropical Atlantic, the interannual ACT variability, and the role of various processes in climate model biases. Using a large number of new observations performed during TACE, the seasonal mixed layer heat budget along the equator could finally be closed and interannual circulation variability could be observed and related to different climate patterns. Following the increasing importance of multidisciplinary research in the tropical Atlantic for predicting climate, ocean-atmosphere $pCO_2$ sensors have been installed on two PIRATA sites since 2006 (6°S, 10°W and 8°N, 38°W), and shipboard underway $pCO_2$ measurements and/or sea water sampling for the measurement of the $CO_2$ system have been performed in the tropical Atlantic as part of the PIRATA cruises since 2006. Oxygen sensors were also included at two PIRATA sites (23°W, 4°N and 11.5°N). These time series are being used to investigate physical-biogeochemical interactions - an important aspect of ongoing tropical Atlantic climate research.

Several open questions remain after TACE:

- What are the contributions of different processes (e.g. diapycnal mixing, equatorial wave processes) to interannual variations in the mixed layer heat budget?
- What is the role of internal ocean variability in setting up large –scale ocean atmosphere interactions?
- Is there a need for a better representation of small meridional and vertical scale flow features (like EDJ and EICS) or shelf and near-coastal processes in coupled climate models?

One important outcome from TACE was the investigation of many different factors that contribute to climate model SST biases. State-of-the art climate simulations still show strong biases in the tropical Atlantic climate system, which limits climate predictability in the region. The largest SST bias is found in the Benguela upwelling region (Fig. 3). Hypotheses for the cause of this bias that involve ocean dynamics include possible misrepresentation of the connectivity between equatorial and coastal upwelling regions in climate models. The advective water transport from the equator to the Benguela region, as well as wave processes along the equatorial and coastal wave-guide are of particular importance. Unrealistic stratification or wave processes in conjunction with unrealistic local forcing in the coastal upwelling region could lead to too warm SST in the eastern tropical Atlantic. However, atmospheric processes (atmospheric convection, cloud processes) may also contribute. With the end of TACE, the focus of ongoing research programs is shifting more toward the tropical Southeast Atlantic, which is presently a region of exceptional low ocean data availability. This new focus has led to the establishment of the US CLIVAR Eastern Tropical Oceans Synthesis Working Group (http://www.usclivar.org/working-groups/etos) that is aimed at enhancing cooperation between groups focusing on the different tropical oceans, and between observationalists/modelers and ocean/atmospheric scientists, to gain a better understanding of the key oceanic, atmospheric, and coupled processes occurring in this region.

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