CLIVAR Eastern Tropical Oceans Synthesis Working Group

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General Circulation Model problems simulating cold waters and widespread marine stratocumulus clouds off the southeastern tropical Pacific and Atlantic Oceans point to inadequate understanding of the processes that determine stratocumulus clouds and sea surface temperature (SST) in these regions. SST is too warm off the west coasts of South America and Africa in almost all CMIP3 coupled general circulation models. Observational process studies and monitoring in the southeastern Pacific Ocean (EPIC 2001, PACS, VOCALS 2008, and the Woods Hole Stratus Mooring) investigated clouds, surface radiative and turbulent fluxes, ocean advection, and the ocean mixed layer heat budget. In the wake of these studies, the Eastern Tropical Oceans Synthesis (ETOS) working group formed to organize scientific inquiry into the remaining questions on the southeastern Pacific climate, to apply knowledge of processes observed in the Pacific to the southeastern Atlantic, and to generate fresh hypotheses for the important processes that set clouds and SST in the southeastern Atlantic Ocean. Presently, CMIP5 model results show modest improvement in SST and cloud errors in the southeastern Pacific, yet the tropical Atlantic remains plagued with persistent errors, including the notoriously reversed zonal SST and thermocline gradient on the equator. Errors in radiatively important stratocumulus cloud contribute to SST errors, and to uncertainties in cloud feedbacks in projections of climate change.

The ETOS working group organizes and galvanizes scientific inquiry in 3 ways:

1. *Organize data sets.* ETOS has a Google Site for contributions of scientific analyses, existing in the literature or generated from recently emerging results. Many of the contributions take the form of figures that assess model performance and improvement, with an emphasis on processes that may be key to understanding the physics of SST and clouds in the southeastern tropical Atlantic and Pacific Oceans.

2. *Update on model performance.* Recently the CMIP5-generation of coupled general circulation models has become available. Results relevant to the southeaster tropical oceans from CMIP3-generation models are being reassessed in the CMIP5 models. Analyses performed previously in the eastern Pacific are being applied to the eastern Atlantic. New metrics for model errors and improvement are being developed, particularly for newly discovered mechanisms in the Atlantic Ocean.

3. *Identify further needed observations and model experiments.* Observations in eastern tropical Pacific (TAO, EPIC, PACS, Stratus buoy, and VOCALS) have led to improved climatology and process understanding (Mechoso et al. 2013). In the Atlantic the PIRATA buoys provide near-equatorial observations (e.g. 6°S, 8°E), but so far few observations are available of the southern coastal region of large SST biases, or of the region of widespread stratus clouds over the southeastern tropical Atlantic Ocean.

   European funded field campaigns have ongoing and scheduled research cruises in the PREFACE (Enhancing PREdiction oF tropical Atlantic ClimatE and its impact, 2013-

2019) and SACUS (Southwest African Coastal Upwelling System and Benguela Niños, 2013-2015, see http://www.clivar.org/sites/default/files/ATLANTIC/activities/2527/PB_TACE_further_activities.pdf) experiments. These experiments seek to improve understanding of ocean processes along the Angola-Namibia coast, with implications for improving climate models and their predictions. SACUS also focuses on Angola and Namibian boundary currents, upwelling, and their interactions. As part of PREFACE, the PIRATA buoy at 6°S, 8°E will be enhanced with additional oceanographic sensors. US agencies have an opportunity to expand the science capability of the enhanced PIRATA buoy. For example, spectral solar flux measurement from the buoy would provide continuous optical measurement of column aerosols, relating cloud conditions to biomass burning in Africa. Given the compatible sampling region, US climate research agencies could support atmospheric science objectives with research riding "piggyback" on the PREFACE and SACUS research cruises. In situ meteorological sensors and release of 6-8 radiosondes per day would complement oceanographic measurements on the European research cruises, and augment data available for honing hypotheses in advance of a US-funded field campaign. US climate science should also support model experiments that link Atlantic processes to southeastern tropical Atlantic SST errors and their connection to the equator.

Field campaigns (ONFIRE, P. Zuidema, NSF; ORACLES J. Redemann, NASA; CLARIFY, J. Haywood, UK) are being proposed to document and structure of aerosol smoke from African biomass burning, its radiative effect, and interaction with clouds. The surface radiative effect directly from aerosol is most pronounced near the coast, but cloud-aerosol interaction has implications farther out to sea. Documenting the cloud structure and surface radiative effect is also of interest to planned oceanographic field campaigns.

Hypotheses have emerged from the user-contributed web site, teleconferences, and an in-person meeting of the ETOS WG:

- Inadequate cloud radiative cooling along 20°S, mostly due to insufficient cloud amount (de Szoeke et al. 2012), contributes to warm SST errors in CMIP3 models in the southeastern Pacific. Solar radiation differences among models are only responsible for 16% of the variance of SST, and turbulence and longwave radiative heat fluxes are a negative feedback on SST anomalies, leaving room for other processes to contribute to SST errors (de Szoeke et al. 2010). The relative role of cloud forcing and cooling by ocean advection needs to be investigated in the Atlantic.
- A leading hypothesis for remaining model errors in the southeastern tropical Pacific Ocean is that ocean eddies that not resolved in climate models cool the ocean surface. Mixed layer heat budgets in models underestimate ocean cooling by 10-20 W/m^2 near the Stratus buoy at 20°S, 85°W. While ocean eddies may play an important role in the heat budget closer to the South American shore, their contribution to the surface heat budget in eddying ocean models is small at 85°W. Recent observations (Holte et al. 2013) from the Stratus buoy show that the mixed layer heat budget is balanced by mean currents and heat fluxes, eliminating the need for eddies to explain the missing cooling.

- The Equatorial Atlantic notoriously has a reversed zonal gradient of SST, a condition that is not improved in many of the CMIP5 models. The SST gradient is related to too-weak easterlies or reversed westerly zonal wind stress across the Atlantic Ocean. This error is hypothesized to be due to inadequate atmospheric moist convective heating and surface convergence in the Amazon Basin (Richter and Xie 2008, Richter 2011).
- Changes in the Atlantic meridional overturning circulation are linked to south-of-equatorial SST in the eastern Atlantic, with effects on precipitation in the West Africa monsoon (Chang et al. 2008).
- In the Atlantic Ocean, the southward Angola Current and northward Benguela Current meet at about 18°S at the Angola-Benguela Front (ABF). Large Atlantic SST errors found near and south of the ABF are correlated to simulated ABF location among models (P. Chang). The close connection between SST and ABF location errors suggest an oceanic mechanism connecting the erroneous upwelling and currents structure in models to the SST bias.
- How are the southern hemisphere cloud and SST errors related to the equator? The seasonal cycle of meridional wind across the equator influences equatorial SST at the equator (Mitchell and Wallace 1992). The seasonal cycle of wind stress on the equator is quite similar in the eastern Pacific and Atlantic Oceans. In the Pacific, models with a meridionally alternating intertropical convergence zone, which describes most contemporary “double ITCZ” errors, have two seasonal wind speed maxima on the equator, resulting in too-cold SST in the equatorial cold tongue (de Szoeke and Xie 2008). Is this mechanism responsible for model errors in the Atlantic? Does the northern African land mass influence this process?

ETOS is working on refining recommending *metrics* for model evaluation in the southeastern tropical Pacific and Atlantic.

- Cloud evaluations throughout the seasonal cycle including SST, lower tropospheric stability, cloud amount, and liquid water path in standardized regions (Klein and Hartmann 1993, Bellomo and Zuidema 2013). Model variability (e.g. spatial and seasonal variations) can be assessed against observations with Taylor (2001) diagrams.
- Climatologies of ocean surface mixed layer heat budgets at observation locations, and averaged within the Klein and Hartmann stratus regions. This approach has been effective in leveraging available observations to assess the southeastern Pacific Ocean heat budget. Ocean mixed layer heat budgets should calculated in a consistent way among models and observations (e.g. at standard depths) to eliminate vagueries from differences in the methods.
- Satellite retrievals (e.g. ISCCP, CALYPSO, MODIS) provide valuable spatially-resolved observations of SST, cloud amount, and liquid water path are useful for comparison with climate models. Satellite retrieval simulators compute radiance inline in GCMs integrations to allow direct comparison between model and satellite data. ISCCP and CALYPSO simulators are widely used, but not MODIS simulators.
- Traditional model assessments evaluate and compare biases relative to observations in model simulations run to equilibrium. ETOS also endorses another complementary analysis: to diagnose tendencies in relatively short 5-10 year climate hindcast

simulations initialized from observed conditions (Toniazzo and Woolnough 2013). Some model errors develop within days to years, and this method allows mechanisms and their time scales to be assessed from budgets in the time-evolving simulations.