Scientific Understanding of the Atlantic Basin Climate System – A Mid-CLIVAR Perspective

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1. Introduction

The US CLIVAR (Climate Variability and Prediction) Program, now in its eighth year, was designed to investigate the season-to-season, year-to-year, and decade-to-decade fluctuations in the climate. These climate variations influence nearly all spheres of human activity: our clothing, shelter, and energy needs; our ability to grow crops and raise livestock for food and fiber; and our safety from a wide range of natural hazards. Thus, while CLIVAR has a broad focus on understanding the mechanisms of climate variability, it also has a pragmatic focus on climate prediction, particularly of those climate fluctuations that affect humans and their livelihoods.

Much, or even most, of climate variability on these inter-seasonal to interdecadal timescales involves interactions between the atmosphere and the oceans. The autonomous behavior of the atmosphere dominates shorter timescales, while interactions with ice sheets and glaciers, changes in the gross properties of the land surface, and astronomical forcing are likely important on much longer timescales. While land surface-atmosphere and cryosphere-atmosphere interactions are probably of some importance on timescales of interest to CLIVAR, its primary focus has been on interactions between the atmosphere and the oceans.

At its midpoint, CLIVAR is undergoing a transition from identifying phenomena and determining their underlying mechanisms, towards using this knowledge to make probabilistic climate predictions on seasonal time scales and longer, and towards accurately assessing climate-related risks and probabilities. During its first half, as CLIVAR sought to identify and understand the key relevant phenomena and processes of atmosphere-ocean interaction, the science was organized around regions of the globe, in particular, around specific ocean basins. For the Atlantic basin, a small number of key phenomena were identified: coupled atmosphere-ocean variability in the tropical Atlantic, the North Atlantic Oscillation, and the large-scale meridional overturning circulation. Thus, the business of the US CLIVAR program in the Atlantic (Atlantic CLIVAR, for short) can largely be summed up with three acronyms, TAV (Tropical Atlantic Variability), NAO (North Atlantic Oscillation), and MOC (Meridional Overturning Circulation). To these three acronyms we must add one more, ENSO (El Niño – Southern Oscillation), for while ENSO originates in the tropical Pacific Ocean, it strongly influences the Atlantic basin, especially in the tropics. It is, in fact, the complex interplay between externally forced variability, especially from ENSO, and that generated by internal processes that makes Atlantic-basin climate an especially challenging subject of study.

Building on what has been learned during its nominal first half, US CLIVAR is moving in its second eight years towards a globally integrated approach to climate observations, climate model development, and climate prediction. This is a good time, then, to assess what has been learned about Atlantic basin climate processes and variability during the first eight years of US CLIVAR research in the Atlantic. This assessment is based on a meeting, sponsored by the US CLIVAR Office, held at the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami in January 2005. The remainder of this essay builds on the scientific results presented at this meeting to assess our current understanding of the coupled atmosphere-ocean system in the Atlantic basin, as it relates to climate variability and prediction.

A fundamental problem in climate science is distinguishing climate variability that originates from or is reinforced by atmosphere-ocean coupling within a basin from variability that represents the largely passive response of the ocean to atmospheric signals arising either remotely – e.g. from ENSO – or from the chaotic internal dynamics of the atmosphere. This is particularly a conundrum in the Atlantic basin, which has no coupled mode as robust or as dominant as ENSO. Where in the Atlantic is local atmosphere-ocean coupling "important" ? From a pragmatic standpoint, where must the mutual interactions between the atmosphere and ocean be included in models if they are to capture most of the observed variability? R. Saravanan, the keynote speaker, addressed this question. He pointed out that the answer depends on the region and the timescale of the variability under consideration, and he showed a table (Table 1) that offers a convenient framework for much of our subsequent discussion.

	Climatology	Seasonal to Interannual	Decadal to Centennial
Tropics	Large Cold-tongue feedbacks?	Moderate Gradient mode Atlantic "Niño" West African monsoon	Moderate Sahel rainfall trend Subtropical cells
Midlatitudes	Moderate Thermohaline circulation Sea ice	Small Response to tropical forcing?	Moderate Thermohaline circulation?

Table 1. Importance of local air-sea coupling to Atlantic climate variability in different regions and on different timescales, with relevant phenomena listed. After presentation by R. Saravanan.

The next section of this report describes the state of science in the tropical Atlantic, focusing on the influences from ENSO, local coupling between the atmosphere and the ocean (the top middle box of Table 1), and the challenges posed in obtaining realistic numerical simulations of the mean climate in this complex region (top left box of Table 1). Section 3 addresses the situation in the extratropical Atlantic. Here we focus on the prospects for predictability, both from weak local air-sea coupling (bottom middle box of Table 1) and from tropical influences. In section 4 we turn our attention to longer time-scale phenomena. These arise as an ocean-dynamics-filtered response to variations in the North Atlantic Oscillation (NAO), with the possibility (bottom right box of Table 1) that variations in the meridional overturning circulation (MOC) feed back to influence the NAO. The final section discusses some leading challenges for future research. Among these are the difficulties in producing a realistic climate and climate variability in coupled models of the tropical Atlantic, the issue of potentially important interactions, especially in the tropics, with terrestrial processes, and the problem of predicting how the Atlantic basin climate, and especially the MOC, will respond to anthropogenic global warming. In this paper we emphasize presentations at the conference, which will be cited using the first and last names of the lead author, without a year of publication. Some examples of published work are included for context. These are cited in the conventional manner.

2. The Tropical Atlantic

a. ENSO influences

Dynamical (model) assessment of remote influences on tropical Atlantic SST indicates that the Pacific contributes mainly to the interannual variability, while the extratropical Atlantic contributes mainly to decadal variability (Zhengyu Liu). Our understanding of the mechanism by which ENSO influences the tropical Atlantic has increased significantly during recent years, but a consensus has yet to be reached regarding the strength of a tropical pathway relative to an extratropical pathway. The tropical pathway, through an atmospheric tropical wave response to El Niño, results in a pan-tropical tropospheric warming and changes to atmospheric stability and subsidence patterns (Chiang and Sobel 2002; Neelin and Su 2005). This teleconnection is rapid, and the equatorial Atlantic thermocline is particularly sensitive to enhanced surface easterlies along the equator during the early stages of an El Niño event in May–June when the thermocline shoals seasonally in the equatorial east Atlantic. At this time, oceanic Kelvin waves generated by anomalous easterlies in the western equatorial Atlantic can cause an upwelling signal in the Atlantic cold tongue region (Mathias Munnich). Since the peak of ENSO is coincident with the seasonal cold tongue in the Pacific in boreal fall, the cold Atlantic SST anomalies can appear (deceptively) to anticipate the El Niño event. One may speculate that this difference in phasing is partly responsible for the intermittent nature of the equatorial association; only ENSO events that begin early enough will result in an SST anomaly (of the opposite sign) in the Gulf of Guinea.

Off the equator, tropical Atlantic SSTs show a lagged warming in response to an El Niño event. This warming is largely confined to regions of convection, i.e. north of the equator, where the boundary layer is closely tied to the free troposphere (Chiang and Sobel 2002); it is mediated by local air-sea coupling, occurring at a time lag of several months where the mixed layer is deep over the tropical North Atlantic. Over the tropical South Atlantic, the impacts are small. Responses that are more meridionally symmetric, however, are seen in coupled models that simulate a double ITCZ in the Atlantic, as for example in Zhengyu Liu's model.

The extratropical Rossby wave response to ENSO affects the tropical Atlantic through the Tropical Northern Hemisphere (TNH) pattern in the northern hemisphere during an El Niño event and the Pacific South American (PSA) pattern in the southern hemisphere. The teleconnection is strongest in the northern hemisphere because ENSO peaks during boreal winter, and due to continental asymmetries: the TNH has a pole centered over Florida that weakens the NE trades in the later stages of boreal winter, influencing SSTs through changes in surface heat fluxes. El Niños that persist well into boreal spring typically, but not always, result in large Western Hemisphere warm pools (David Enfield). The PSA is strongest during October–December, but its effects are mostly confined to southeastern South America and the South Atlantic Convergence Zone, perhaps extending to the Angola-Benguela frontal area (Christopher Reason). The impact of the PSA on the tropical South Atlantic appears relatively small; again, probably due in part to the absence of local climatological convection. These extratropical-wave teleconnections are less robust than the tropical one, because of the large internal variability of the midlatitude atmosphere.

Variability in the Atlantic equatorial cold tongue displays decadally varying influences from ENSO, though the dominant signal is for La Niña to favor Atlantic Niños, especially when El Niño is strong in boreal spring (Yochanan Kushnir). Strong El Niños apparently tend to produce positive equatorial Atlantic heat-content anomalies 18 months later (Noel Keenlyside). Warm conditions in the tropical Pacific increase vertical shear in the atmosphere over the North Tropical Atlantic, suppressing the formation of tropical cyclones, despite the warming of Atlantic SSTs (Anatha Aiyyer).

b. Local air-sea coupling

Local air-sea coupling over the tropical Atlantic has been well described in terms of a meridional mode and a zonal mode (e.g. Chiang *et al.* 2002). The former peaks in March–May when meridional SST gradient are weak, and it involves wind-evaporation-SST (WES) feedbacks; it leads to intrinsic Atlantic variability and can significantly amplify the response to ENSO and the NAO over the tropical North Atlantic, particularly if pre-existing Atlantic SST gradients are conducive (Giannini et al. 2004; Huei-Ping Huang). The zonal mode is the Atlantic's highly damped cousin of ENSO, involving the Bjerknes as well as WES feedback mechanisms.

Ocean GCM simulations forced with observed winds, with and without heat fluxes, indicate that SST variability is largely heat-flux driven over the tropical North Atlantic, while the wind forcing is important over the tropical South Atlantic, apparently mostly through local Ekman dynamics (Fig. 2, Howard Seidel).

A secondary seasonal cooling over the equatorial Atlantic in November–December is associated with a seasonal strengthening of surface easterlies, generated by heating contrasts between the South American Monsoon system in the southwest, and the relatively cool Sahara dessert in the northeast. Equatorial thermocline shoaling leads to a secondary maximum in "zonal mode-type" variability during November–January, that appears related to Benguela Niños and the subsequent meridional mode during March–May (Yuko Okumura).

The effects of both the meridional mode and of ENSO contribute to rainfall variability over Northeast Brazil, and there is a weak tendency for these influences to be "concordant", in that Pacific warm events coincide with warm conditions in the North tropical Atlantic, suppressing Nordeste rainfall (Giannini et al. 2004; Huei-Ping Huang).

c. *Modeling challenges*

Statistical and dynamical models for SST prediction at seasonal lags have comparable skill over the tropical Atlantic. Over the tropical North Atlantic, both methods are relatively successful, and can beat the skill of persistence hindcasts. Over the equatorial and tropical South Atlantic, statistical methods such as the inverse model (Lisa Goddard showing results of Dmitri Kondrashov) are still superior to coupled GCM hindcasts. Near the equator, there is some skill in current coupled GCM hindcasts in the first two months, but the margin over persistence is modest (Tim Stockdale). Over the tropical South Atlantic, coupled model skill is worse than persistence. There is some evidence that the DEMETER multi-model ensemble is of benefit along the equator in June–August (from May), but the impact of averaging over several models is modest (Lisa Goddard). Atmospheric GCM ensemble hindcasts of Sahel July–September rainfall made using persisted SST anomalies from June show high skill, once the GCM hindcasts have been calibrated using model output statistics (MOS) corrections (Ousmane Ndiaye). Skill decreases markedly, however, when May SST anomalies are used.

Coupled GCMs are still unable to represent correctly the mean seasonal cycle, and often show an Atlantic ITCZ that migrates seasonally across the equator (e.g. results from the National Center for Environmental Prediction Climate Forecast System shown by Philip Arkin and Jim Carton). The seasonal cold tongue fails to develop properly over the eastern equatorial Atlantic in boreal spring, and this is associated with poor simulation of the zonal mode (Bohua Huang). Thus, coupled model errors in simulating leading modes of TAV are often closely coupled to their errors in simulating the mean climate, and there is good reason to expect that correcting the mean climate will improve the simulation of variability (Bohua Huang). Errors in the mean state of the equatorial thermocline translate into errors in equatorial variability, because upwelling tends to be displaced too far west (DeWitt 2005). This appears to be one reason why coupled model hindcasts do not show enough intra-ensemble spread in SST over the eastern equatorial Atlantic: mean upwelling is too weak, so that wind-induced thermocline changes are not communicated to the surface (Tim Stockdale). This has repercussions for the effectiveness of ocean data assimilation; in that constraining the subsurface ocean state in the equatorial Atlantic may be largely irrelevant if the signal is not properly upwelled to the surface (Tim Stockdale).

The sources of the mean biases in coupled ocean-atmosphere GCMs are still poorly understood. The proximity to tropical continents is a large factor over the Atlantic sector, as compared to the Pacific. It is well known that atmospheric GCMs have difficulties in representing convection over land, especially the Amazon. Strong Amazonian rain events are found to exert a lagged impact on winds and SST over the tropical Atlantic in observed data (Rong Fu). Atmospheric GCMs show biases in the location of maritime convection, which is overly tied to SST in the models, and not sensitive enough to low-level convergence; they thus tend to wrongly position convection in longitude (Michela Biasutti). The subtropical anticyclone over the South Atlantic is a key feature associated with the SE trade winds the seasonal cold tongue. Experiments with flux correction indicate the importance of the momentum fluxes, and, by inference, upwelling, in the Gulf of Guinea and along the Angolan coast (Bohua Huang). Tropical instability waves are an important observed feature of the equatorial Atlantic. Studies with eddy-resolving ocean GCMs demonstrate that these mesoscale eddies play an important role in transporting heat, and that the climatological east-west gradient of SST can be substantially improved by resolving them (Ragu Murtugudde), while interannual variability is enhanced (Paula Malanotte-Rizzoli; Markus Jochum). Data from the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) (Semyon Grodsky) and satellite-derived surface currents (Robert Helber) provide important means to validate these model results.

3. Middle latitudes and the NAO

If the overall picture of tropical Atlantic studies is that there is potential predictability on seasonal to interannual time scales that could be tapped given better coupled models, this picture is nearly reversed in middle and high latitudes. There are no glaring or fundamental deficiencies in the ability of our models to simulate the main features of observed variability, but, at the same time, it appears there is, at best, modest predictability on seasonal-to-interannual timescales. The relative ease of simulation, may, in fact, arise from the same source as the poor predictability: the predominately one-way local coupling between the atmosphere and the ocean (bottom-middle box of Table 1.) The atmosphere, whose long timescale variations are dominated by the North Atlantic Oscillation (NAO), influences the upper ocean locally through air-sea fluxes of sensible and latent heat and Ekman transports and remotely through changes in the wind-driven gyres. It appears that the former explain most of the variability in the sea-surface temperature (SST), while the latter make important contributions to changes in upper-ocean heat content (Bin Zhao). There is robust interannual variability in the wind-driven geostrophic advection of heat, giving rise to these robust changes in heat content and contributing to variability in air-sea fluxes (Kathryn Kelly). The contribution of these heat content variations to atmospheric predictability remains uncertain.

From an atmospheric perspective, the seasonal-to-interannual prediction problem can be encapsulated in our ability, or lack thereof, to predict the NAO index. Because the NAO is a robust intrinsic mode of variability within the atmosphere, associated with changes in the position of the North Atlantic jet and stormtrack, it has strong variability on atmospheric timescales and is subject to the intrinsic unpredictability of the midlatitude atmosphere. On subseasonal timescales, the NAO does, however, display a "shoulder" in its persistence at lags of three to four weeks (Yochanan Kushnir). This shoulder, and its implied enhanced intraseasonal predictability, may derive from the long memory and downward influence of the stratospheric polar vortex (Mark Baldwin).

The situation is decidedly murkier, however, on interannual timescales. There appears to be a winter-to-winter influence from the quasi-biennial oscillation (QBO) of the equatorial stratosphere, conveyed through the influence of the QBO on the stratospheric polar vortex (Holton and Tan 1980) and then downward to the troposphere. Yet the QBO should reduce the year-to-year persistence of the NAO, while there is, in fact, more interannual persistence than is readily explained by the creation of mixed-layer heat content anomalies during one cold season, their preservation beneath the shallow summer thermocline, and their reemergence as SST anomalies during the following winter (Yochanan Kushnir). The source of this apparently additional interannual persistence is not clear. One possibility is that it derives from signals forced by remote SST anomalies. For example, the NAO responds to SST anomalies in the tropical Atlantic, and it is possible that local atmosphere ocean coupling in the extratropics is sufficient to enhance this response and preserve it well into the winter (Shiling Peng). On seasonal timescales, the extratropical ocean response, in SST, to the NAO includes influences from heat fluxes and from anomalous Ekman transports, and these tend to be mutually reinforcing in midlatitudes (Shiling Peng). The result is that the atmospheric NAO and the dominant SST pattern with which it is associated, the SST "tripole", comprise a coupled system, in which the weak atmospheric response to the local SST is enhanced, somewhat, by atmospheric eddy dynamics that tend to reinforce the NAO (Linlin Pan). Still, this coupling is weak, in the face of very strong and chaotic variability of the extratropical atmosphere, as is the potential influence of remote SST signals. Thus, it is estimated that no more than 20% of the interannual variability of the seasonally averaged NAO index is predictable (Yochanan Kushnir).

4. Long timescale changes in the Atlantic basin and the role of the Meridional Overturning Circulation

As mentioned in the preceding section, the North Atlantic Oscillation strongly influences the upper ocean through changes to both the air-sea buoyancy fluxes and wind forcing. Surface property fields and the wind-driven currents are markedly affected by this decadal variability. In this section, the extent to which NAO influences the properties and pathways of the intermediate and deep ocean are explored. By creating variability in those waters that constitute the overturning circulation, the potential arises for a long-term feedback mechanism. Essentially, the question as to whether or not there is air-sea coupling on multi-decadal and centennial time scales (bottom right box of Table 1) hinges on the sensitivity of the ocean's thermohaline circulation to NAO and, in turn, on the ocean's memory of this variability over very long time scales and on the strength and nature of feedbacks of the ocean onto the atmosphere. Observational evidence for the first of these is discussed in this section, as are modeling efforts that have been directed toward assessing the role of ocean-atmosphere coupling in the generation of long-term North Atlantic variability. While these studies do not clarify the role of the thermohaline circulation in creating this coupling, they do point to the role of ocean dynamics in affecting the atmospheric variability.

a. Thermohaline response to NAO

The Atlantic overturning circulation is largely characterized by its volume transport and associated poleward heat flux, which is an important component of the global poleward heat flux. Variability in the volume transport of the MOC, therefore, has strong climate implications. Using repeat hydrographic cross-sections at 48N, Lorbacher and Koltermann (2000) found a strong correlation between the NAO and the meridional overturning rate. In an effort to improve on the direct method used in this study, a method that relies on an unknown reference level, box inverse methods have been used to incorporate information from air sea fluxes and hydrography (Rick Lumpkin). These model results show that the variability of Labrador Sea Water transport across the 48N sections driven by local forcing is significantly and positively correlated with the NAO. Variations in the transport of the deeper waters, however, while large compared to the time-mean, are not significant, due to considerable uncertainty in the year-to-year estimates of export. (Rick Lumpkin) Finally, no significant interannual variation in the net overturning resulted from the box model inversion.

A measure of the variability in the upper limb of the meridional overturning circulation is available from cable measurements made across the Florida Straits since 1982 (Chris Meinen). Applying a two-year running mean to a time series of the NAO and the heat transport across the Straits shows the two to be negatively correlated (Fig. 4), but only 12% of the total variance is contained in those frequencies. Whether the negative correlation is related to the dynamics of the wind-driven or thermohaline flow remains unclear.

In addition to transport changes, there is evidence that the NAO may affect the pathways of the deep and intermediate waters. Chlorofluorocarbon (CFC) data document an inside passage that provides an alternate pathway from the Deep Western Boundary Current for transporting climate anomalies and newly ventilated deep waters from the subpolar regions into the subtropical interior (Rana Fine). North Atlantic variations of this inside passage transport may depend on the NAO. Finally, although volume-averaged property changes have been suggested to be consistent with global climate change, the spatial pattern of salinity and temperature changes in the North Atlantic intermediate and deep waters suggest strong top to bottom influence of the NAO over the past fifty years (Susan Lozier).

A study of Atlantic Ocean climate variability simulated by the HYbrid Coordinate Ocean Model (HYCOM), designed to determine how the simulated basin responds to NAO-related atmospheric forcing, shows that the response changes as a function of the time scale of the forcing (George Halliwell, Visbeck *et al.* 2003). Of particular interest is that

NAO forcing at sub-decadal periods produces a tripole SST anomaly, yet at longer, quasi-decadal periods, there is evidence for a strong thermohaline response. At interdecadal periods a direct wind-driven anomalous gyre response is not detectable; instead the thermohaline ocean response is completely dominant.

b. Ocean feedback

Evidence from observations (Czaja and Marshall 2001) and model simulations (Lixin Wu) suggests that two dominant modes characterize North Atlantic variability: the interannual to decadal tripole and the decadal to multidecadal monopole (Deser and Blackmon 1993; Kushnir 1994). These studies show a coherent decadal variation between the ocean and the atmosphere. Recent modeling efforts have been directed toward assessing the role of ocean-atmosphere coupling in the generation of this North Atlantic decadal variability. In a series of coupled ocean-atmosphere simulations, air-sea coupling has been systematically modified to test its impact on the North Atlantic decadal variability (Lixin Wu). These modeling experiments suggest that ocean-atmosphere coupling is vital to the maintenance of the North Atlantic decadal oscillation at selected timescales. The coupling in the North Atlantic is characterized by a robust NAO-like atmospheric response to the SST tripole anomaly, which tends to intensify the SST anomaly and meanwhile also provides a delayed negative feedback, which is associated with the adjustment of the subtropical gyre to the anomalous wind stress curl in the subtropical Atlantic. (Lixin Wu)

In another modeling study to assess the impact of the ocean on the NAO, a simplified atmospheric model coupled to a slab ocean mixed layer was employed (Fabio D'Andrea). The interaction of the NAO with the wind-driven ocean was found to damp the NAO spectrum at very low frequencies, but since the observed spectrum on the NAO is not characterized by a decrease of power, it is suggested that perhaps the MOC maintains the energy at low frequencies. An assessment of the spatial pattern of the surface fields linked to the MOC is crucial to understanding this possible linkage, as are coupled modeling experiments that can isolate the contribution of the MOC to the ocean-atmosphere coupling on decadal and centennial scales.

5. Future challenges

It is a truism that scientific research invariably yields more questions than answers. As US CLIVAR goes forward, however, it is perhaps appropriate to focus on those among the many interesting and challenging open questions for which answers are likely to yield the greatest tangible benefits in improved predictions of the climate system and better understanding of its predictability. Perhaps first among these is the striking situation in the tropical Atlantic, where there are strong indications of untapped predictability of the coupled atmosphere-ocean system if only our coupled models were capable of simulating the observed climate. In fact, the striking incapability of the models in this region was brought up at the very start of our meeting. In his introduction to the conference Walter Robinson suggested that the ever-improving verisimilitude of coupled models was a strong motivation for holding such a meeting. Moments later R. Saravanan, in his keynote presentation, pointed out this is decidedly *not* the case for the tropical Atlantic!

Effort is and should be applied to rectifying these serious model biases. At the same time, it may be worth asking how well we can predict on seasonal to interannual time scales without waiting for improved coupled models, relying, at least for the time being, upon statistical dynamical approaches, hybrid forecasting systems, and anomaly or flux-corrected models.

A possibly related challenge in the tropical Atlantic, one that may bear significantly on the prediction of rainfall over the land (the quantity with greatest significance for people), as well as on the overall behavior of the coupled system, is to quantify and accurately model the many ways the "standard" parts of the climate system – the atmosphere and the ocean, – interact with the land surface. Africa provides the upwind boundary condition for the tropical Atlantic, and there is strong evidence that this is an active boundary. African easterly waves are important organizers of precipitation and cyclogenesis across the tropical Atlantic, and their initiation depends on conditions, especially convection, over Africa (Kerry Cook). More exotically, a case can be made that African dust is an integral component of the tropical Atlantic climate system. Dust loadings over the tropical Atlantic are linked to Sahelian drought (Fig. 5 - Joseph Prospero), and may have predictable influences on the Atlantic marine intertropical convergence zone (ITCZ) (Chidong Zhang). Because the generation of dust depends on wind and precipitation over the land, if this influence is important it is not simple.

As we look further out into decadal time scales, anthropogenic climate change becomes a key issue for our projections and forecasts. Beyond the simple question of how much and how fast will Earth warm, three important climate processes are potentially vulnerable to the influences of global warming, and all have significant influences on Atlantic-basin climate:

1) How will the frequency and nature of El Niños change as climate warms?
2) How will stratospheric polar vortex respond to changes in tropospheric climate and directly to changes in the composition of the atmosphere, both greenhouse gases and ozone?
3) How will the meridional overturning circulation (MOC) change, and how will these changes be manifested throughout the climate system?

The research of Atlantic CLIVAR has shown that 1 and 2 are very important for Atlantic climate, but Atlantic-focused researchers look primarily to others for the answers. The third question, however, is central to the Atlantic sector climate science. Work on the MOC described in the previous section, provides a framework for ongoing monitoring of the MOC and for interpreting changes and trends should they be observed. Moreover, it is known, from paleoclimatic records that the MOC underwent substantial fluctuations in intensity and structure in the past (Jean Lynch-Stieglitz). Refined and more detailed proxy records are beginning to reveal how these past MOC changes affected other aspects of Atlantic climate, such as the position of the marine ITCZ – such studies can provide important clues as to the implications of possible future MOC changes induced by global warming.

One goes to a conference hoping to hear of one dramatic breakthrough that transforms our understanding of some aspect of the climate system, or, even better, leads to a striking advance in our predictive ability. As should be clear from this report, there is, no single dominant feature or process in the climate of the Atlantic basin, but rather a fascinating and challenging web of links and interactions. Researchers in Atlantic climate confront a system in which changing trace gases in the stratosphere may, through the influence of the polar vortex on the NAO, the influence of the NAO on the MOC, and the influence of the MOC on tropical climate, affect rainfall over South America. Thus, rather than single breakthroughs, we seek a continuous advance in our understanding accompanied by refinements in our models. With such steady progress, we hope to arrive, eight years hence, with a qualitatively improved ability to provide useful forecasts for the millions of people who live under the influence of the Atlantic climate system.

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Chiang, J.C.H., and A.H. Sobel, 2002: Tropical tropospheric temperature variations caused by ENSO and their influence on the remote tropical climate. *J. Climate*, **15**, 2616-2631.

Chiang, J.C.H., Y. Kushnir, and A. Giannini, 2002: Deconstructing Atlantic ITCZ variability: influence of the local cross-equatorial SST gradient, and remote forcing from the eastern equatorial Pacific. *J. Geophys. Res.*, **107(D1)**, 10.1029/2000JD000307.

Czaja, A. and J. Marshall, 2001: Observations of atmosphere-ocean coupling in the North Atlantic. *Quart. J. Roy. Meteor. Soc.*, 127, 1893-1916

Deser, C., and M. L. Blackmon, 1993: Surface climate variations over the North Atlantic Ocean during winter: 1900–1989. *J. Climate*, **6**, 1743–1753.

DeWitt, D. G., 2005: Diagnosis of the Tropical Atlantic near equatorial SST bias in a directly coupled atmosphere-ocean general circulation model. *Geophys. Res. Lett.,* **32**, L01703,doi:10.1029/2004GLO21707.

Giannini, A., R. Saravanan, and P. Chang, 2004: The preconditioning role of Tropical Atlantic Variability in the development of the ENSO teleconnection: implications for the prediction of Nordeste rainfall. *Climate Dynamics*, **22**, 839-855.

Holton, J. R. and H. C. Tan, 1980: The Influence of the equatorial quasi-biennial oscillation on the global circulation at 50 Mb. *J. Atmos. Sci.*, **37**, 2200-2208.

Kushnir, Y., 1994: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Climate*, **7**, 141–157.

Lorbacher, K. and K. P. Koltermann, 2000: Subinertial variability of transport estimates across 48°N in the North Atlantic, International *WOCE Newsletter*, **40**, ISSN 1029-1725.

Neelin, J. D., and H. Su, 2005: Moist teleconnection mechanisms for the tropical South American and Atlantic sector. *J. Climate*, in press.

Visbeck, M., E. P. Chassignet, R. G. Curry, T. L. Delworth, R. R. Dickson, and G. Krahman, 2003: The ocean's response to North Atlantic oscillation variability, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, James G. Hurrell, Yochanan Kushnir, Geir Ottersen, and Martin Visbeck, eds. American Geophysical Union, 279 pp.

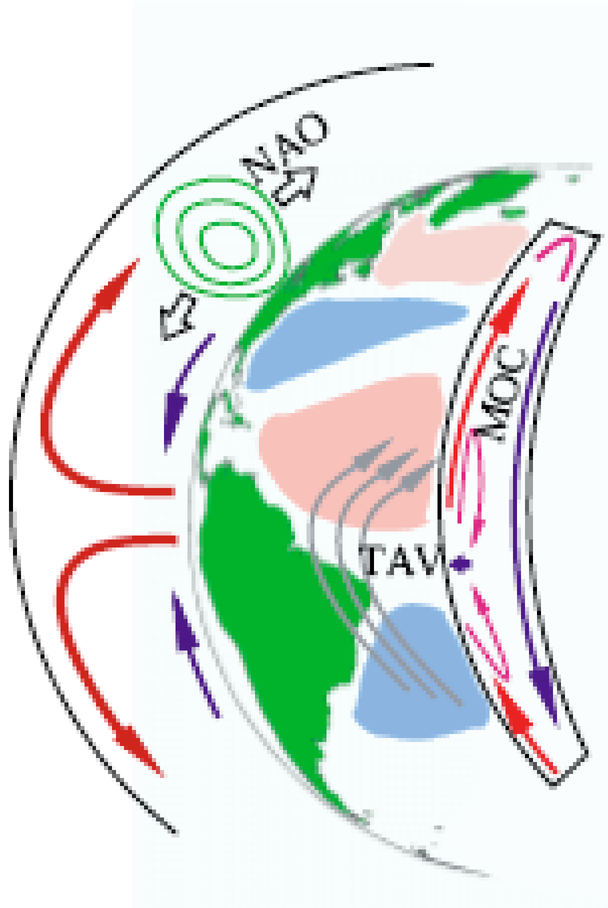

Figure 1. The three major interacting phenomena of climate variability in the Atlantic basin (from the US CLIVAR Implementation Plan – 2000). The curvy arrows depict circulations in the atmosphere and the ocean. The contours in the atmosphere indicate the zonal winds of the North Atlantic jet, with the open arrows indicating its shifts in position associated with the NAO. The colored regions in the ocean depict patterns of SST variability. Not depicted are important influences from the tropical Pacific and potentially important influences from the stratosphere and from Africa.

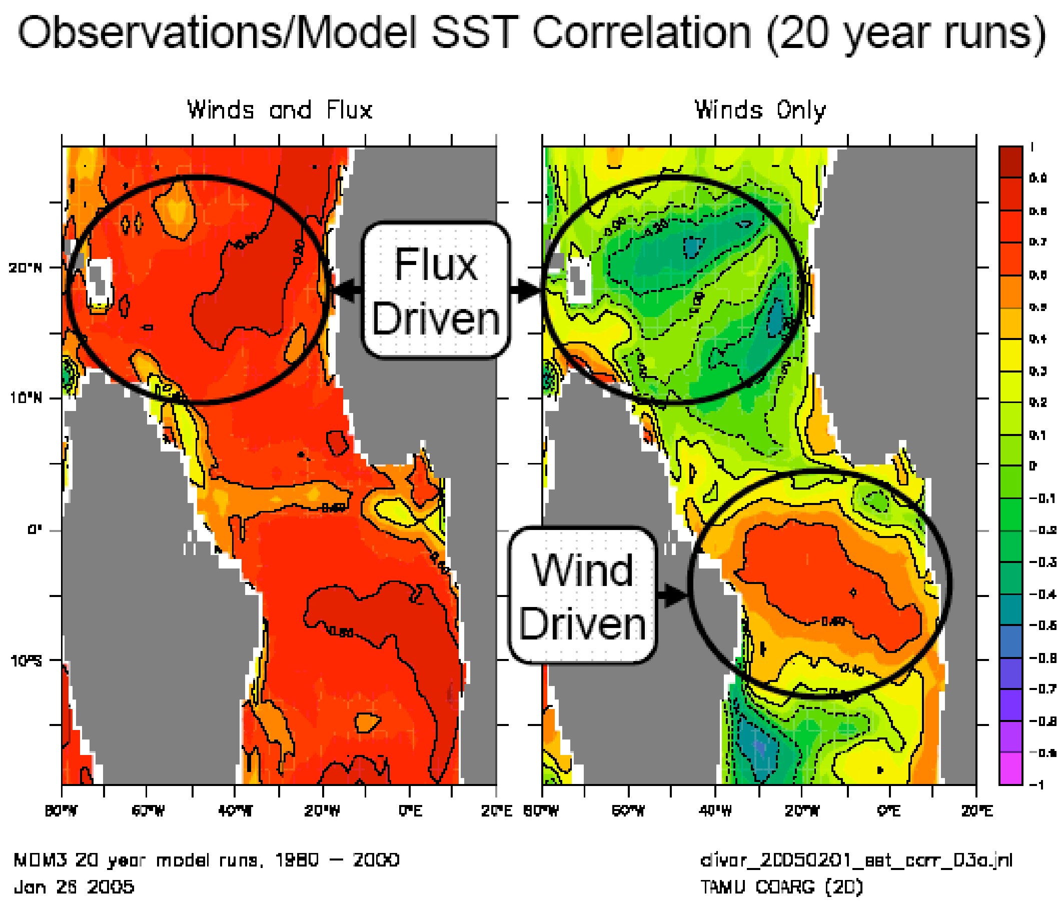

Figure 2. Correlations between observed and modeled SSTs. The modeled SSTs are from an ocean general circulation model, driven by atmospheric observations. The left-hand panel shows the results when the model is forced with observed surface heat fluxes and winds, while the right-hand panel is the result when the model is forced only with observed winds. (Howard Seidel)

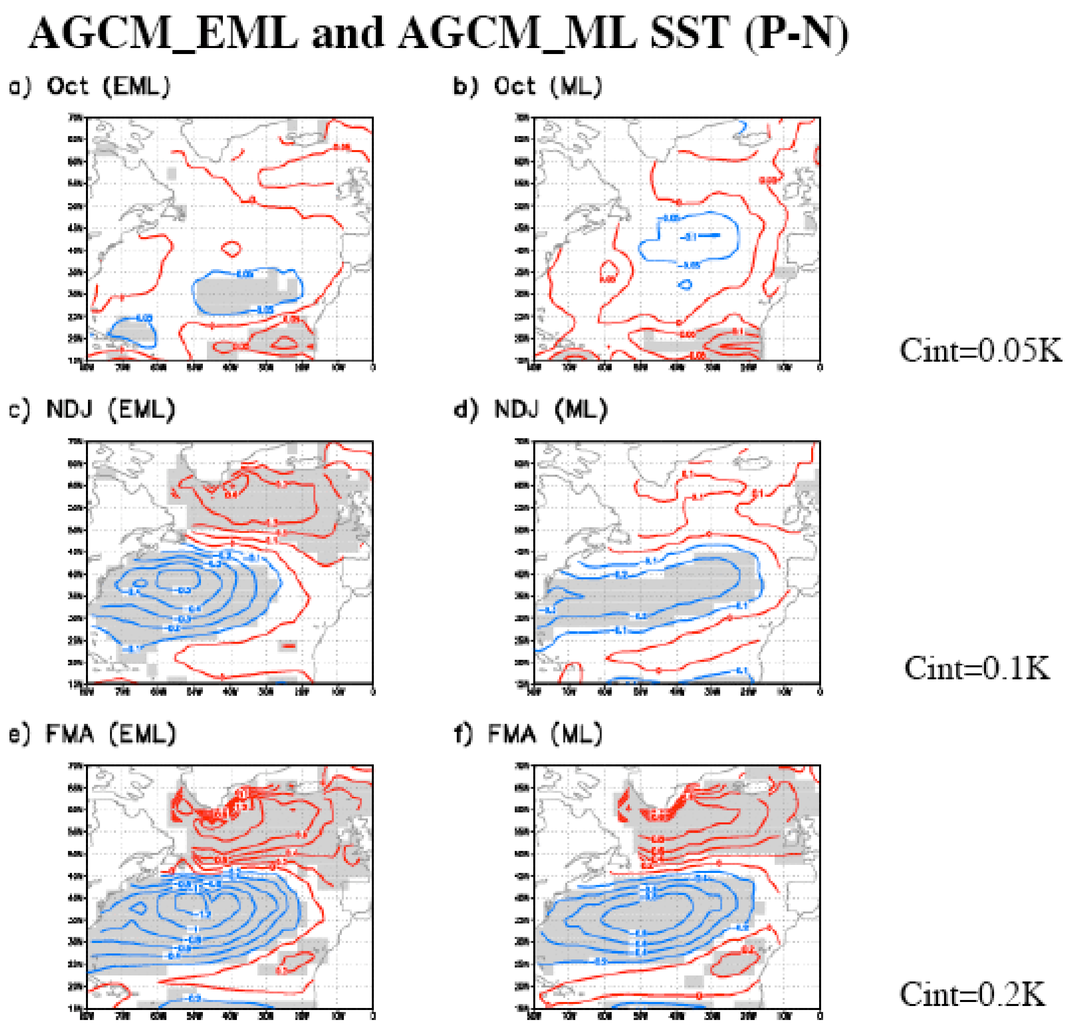

Figure 3. Response, in extratropical Atlantic SST, to a tropical Atlantic SST anomaly, from large ensembles of atmospheric general circulation model runs, coupled to a mixed-layer ocean (left) and a mixed-layer ocean including Ekman transports (right). The Ekman transports accelerated the oceans response to the signal communication via the "atmospheric bridge," and feed back on the atmosphere to create a stronger NAO response earlier in the winter (Shiling Peng)

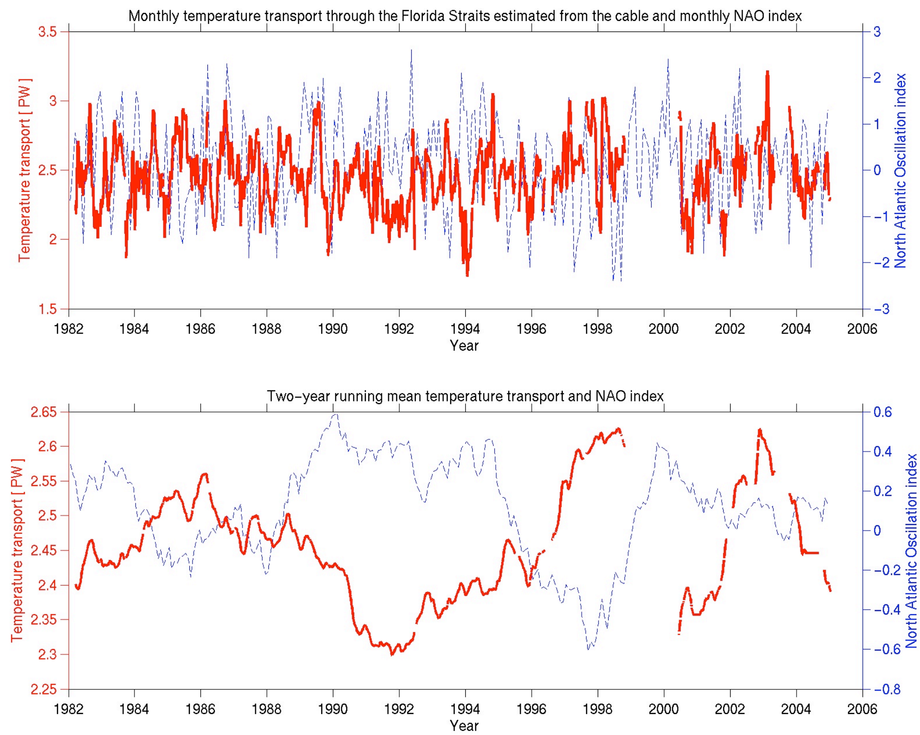

Figure 4. Upper panel: Monthly mean temperature transport across the Florida Straits (red), estimated from cable measurements from the Florida Current Monitoring Program, and the North Atlantic Oscillation Index (blue). Lower panel: Same time series as in the upper panel, but calculated with a two-year running mean. (Chris Meinen)

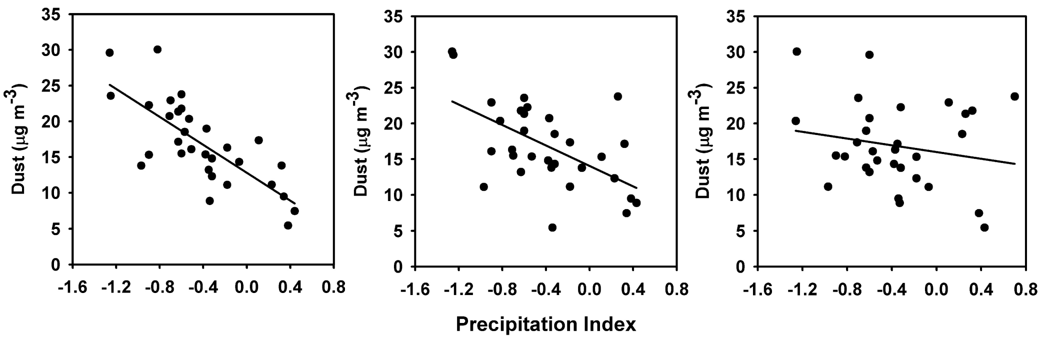

Figure 5: Scatter plots of Barbados May-September mean dust loads against the Soudano-Sahel Precipitation Index (SSPI) updated and normalized to the period 1941-2001. A: Dust plotted against prior year SSPI. B: Dust against current year SSPI. C: Dust against following year SSPI. Units: dust concentration, g m-3; SSPI: normalized departures (standard deviations) from the long-term mean. The scatter plot of dust against the following year SSPI suggests that the correlations are not spurious. A similar series of scatter plots of winter mean dust concentrations against the SSPI yields no significant correlations. (Joseph Prospero)