Decadal to Centennial Variability of the Atlantic From Observations and Models

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Some aspects of multidecadal Atlantic climate variability, and its impact on regional and hemispheric scale climate, are reviewed. Observational analyses have documented distinct patterns of Atlantic variability with decadal (8-12 years) and multidecadal (30-80 years) time scales. Numerical models have succeeded in capturing some aspects of this observed variability, but much work remains to understand the mechanisms of the observed variability. The impacts of the variability—particularly on the multidecadal time scale—are striking, including modulation of African and Indian summer monsoon rainfall, summer climate over North America and Europe, and a potential influence on Atlantic hurricane activity. Some of the observed variability, particularly in recent decades, is likely influenced by changing radiative forcings, of both anthropogenic and natural origin. This poses an important challenge for the detection, attribution and prediction of climate change.

1. INTRODUCTION

Recent research has shown that decadal to centennial scale variability of the Atlantic Ocean has a crucial impact on climate over large regions of the Northern Hemisphere. As will be discussed more completely below, Atlantic multidecadal temperature fluctuations have been linked to changes in Atlantic hurricane activity, drought over the Sahel, Indian summer monsoon rains, summer climate conditions over North America and Europe, and the characteristics of El Niño-Southern Oscillation (ENSO) variability. For any program of research on climate, obtaining an improved understanding of the characteristics and mechanisms of Atlantic variability, and its global scale influences, is of high priority. Indeed, this is one of the key foci in the International Climate Variability and Predictability (CLIVAR) program.

In this review, we first provide a synthesis of observational studies of decadal to centennial variability of the Atlantic, starting with analyses based on instrumental records, and complementing that with analyses based on proxy reconstructions of Atlantic variability. Our focus is on basin-wide patterns, and we will not discuss variability more confined to the Tropical Atlantic [see, for example, *Xie and Carton*, 2004]. Several patterns of Atlantic variability can be seen on different timescales. A dominant pattern emerges on the multidecadal timescale (30-80 years), with anomalies of one sign spanning the North Atlantic from the Equator to 60°N. This type of variability is the focus of this paper. On the interannual to decadal scale, a distinctive "tripolar" pattern exists in the North Atlantic. This pattern appears to be the result of atmospherically induced heat flux anomalies acting on the oceanic mixed layer. Next, we will review

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the observed impacts that Atlantic multidecadal variability has on regional and hemispheric scale climate. Subsequent to that, we will examine how well a variety of computer models can reproduce the observed variability, and summarize the insights those models offer on the mechanisms of the observed variability. We next discuss interactions between changing radiative forcing agents, from anthropogenic and natural sources, and Atlantic variability. Finally, we have a brief discussion of the potential predictability of Atlantic variability, and pathways to evaluate and realize that predictability.

2. DOMINANT CHARACTERISTICS OF OBSERVED VARIABILITY

One of the challenges of quantifying Atlantic decadal to centennial variability has been the relatively short length of the instrumental record with respect to the timescales of variability being examined. Instrumental records typically extend back to the middle of the 19th century, making it very difficult to assess variability with timescales much longer than a decade. Thus, a crucial component of the study of Atlantic variability has been the complementary analysis of instrumental records—somewhat short in duration, but of relatively high accuracy—and proxy reconstructions of past climate variability. We will synthesize some results from studies using both the instrumental and proxy records.

2.1. Analyses Based on Instrumental Records

Dominant patterns of variability have emerged from analyses of SST variability over the Atlantic. We illustrate these by showing the results of an empirical orthogonal function (EOF) analysis of annual mean SST data for the period 1870-2005 over the region in the Atlantic from the Equator to 60°N [the SST data were obtained from the HADISST data set, *Rayner et al*., 2003]. EOF analysis decomposes a data set into patterns that maximally explain the variance. A linear trend has been removed from each spatial location prior to the EOF analysis (the effects of this on the EOF decomposition are discussed below). Shown in Plate 1a is the dominant pattern of SST variability, explaining 39.3% of the spatially integrated variance. This pattern is characterized by anomalies of one sign across the North Atlantic, with largest amplitude in the subpolar gyre. The timescale associated with this pattern is multidecadal, as shown by the EOF time series in Plate 2a and its spectrum in Plate 2b. This multidecadal variability was noted in the pioneering paper of *Folland* [1986]. Since that original analysis, a number of other studies have examined datasets containing observed SST records, with the datasets generally starting in the middle 19th or early 20th. *Kushnir* [1994] clearly delineated the oceanic and atmospheric components of this multidecadal variability. His analysis shows that the multidecadal SST pattern is associated with a distinctive sea level pressure (SLP) pattern characterized by anomalously low SLP over the central and east central North Atlantic. Analyses by *Mann and Park* [1994, 1996], *Schlesinger and Ramankutty* [1994], *Enfield and Mestas-Nunez* [1999], *Mizoguchi et al*. [1999], and *Delworth and Mann* [2000] further established the existence of this multidecadal pattern of variability in the Atlantic. This has subsequently [*Kerr*, 2000] been termed the Atlantic Multidecadal Oscillation (AMO; a warm phase of the AMO indicates positive SST anomalies in the North Atlantic). This dominant pattern of multidecadal variability in the Atlantic, and its climatic relevance, is the focus of this paper. As discussed below, most hypotheses for the origins of the AMO invoke fluctuations of the Meridional Overturning Circulation (MOC).

An EOF analysis was also conducted on data that had not been detrended. The dominant EOF has a spectrum very similar to that for the detrended case. The spatial pattern of the EOF, however, has a less structured pattern, consistent with contributions from a somewhat homogeneous background trend. The time series of this EOF is similar to the detrended case, with the exception of a trend component. These analyses suggest that the existence of a distinctive dominant pattern of multidecadal variability is not an artifact of removing a linear trend. From these analyses, however, we are unable to infer whether this multidecadal variability is due to external forcing or internal variability.

The second and third patterns of variability from the EOF analysis of the detrended data are shown in Plates 1b and 1c, and are characterized by more structured patterns with SST anomalies of opposing signs. The second EOF is reminiscent of the “tripole” pattern of Atlantic SST variability [see, for example, *Wallace and Jiang*, 1987, or *Wallace et al*., 1990]. Anomalies of one sign stretch eastward from the Labrador Sea across the Atlantic, and from off the African coast southwestward to the southern Caribbean, while opposite signed anomalies extend eastward from the east coast of North America. On the interannual time scale, this pattern is mainly a result of atmospheric forcing of the ocean [*Cayan*, 1992; *Battisti et al*., 1995]. Positive or negative phases of the North Atlantic Oscillation [NAO; *Hurrell*, 1995] modulate the surface turbulent heat fluxes over the Atlantic. A positive phase of the NAO is associated with anomalously strong westerly winds over the subpolar gyre, leading to enhanced ocean to atmosphere heat fluxes. The third EOF resembles the decadal pattern of variability reported by *Deser and Blackmon* [1993] and *Tourre et al*. [1999]. Aspects of the second and third EOFs may be associated with propagating SST anomalies [*Tourre et al*., 1999; *Sutton and Allen*, 1997; *Hansen and Bezdek*, 1996]. The EOF analysis applied here is somewhat

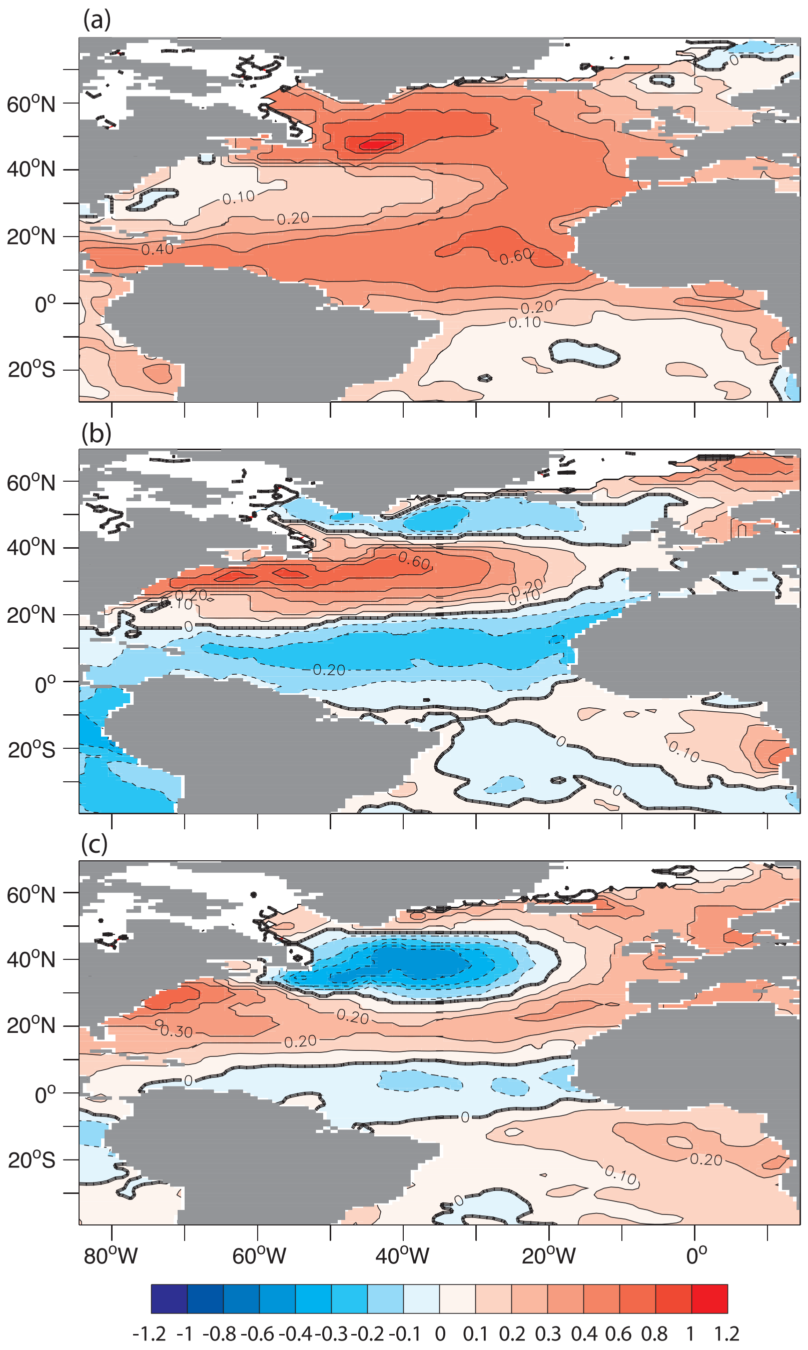

Plate 1. Output from an EOF analysis of observed annual mean SST over the period 1870-2005. SST data are from HADISST1 (*Rayner et al*., 2003). EOF analysis was conducted over the domain 0°N to 60°N in the Atlantic. The values plotted at each grid point are the linear regression of the original SST time series on the standard deviation of the EOF time series, and then multiplied by 2 (thereby yielding a map corresponding to SST anomalies associated with a two standard deviation fluctuation of this EOF). Units are K. Contour intervals are 0.1 between -0.4 and 0.4, and 0.2 otherwise. (a) First EOF, explaining 39.3% of the spatially integrated variance. (b) Second EOF, explaining 14.6% of the spatially integrated variance. (c) Third EOF, explaining 10.3% of the spatially integrated variance.

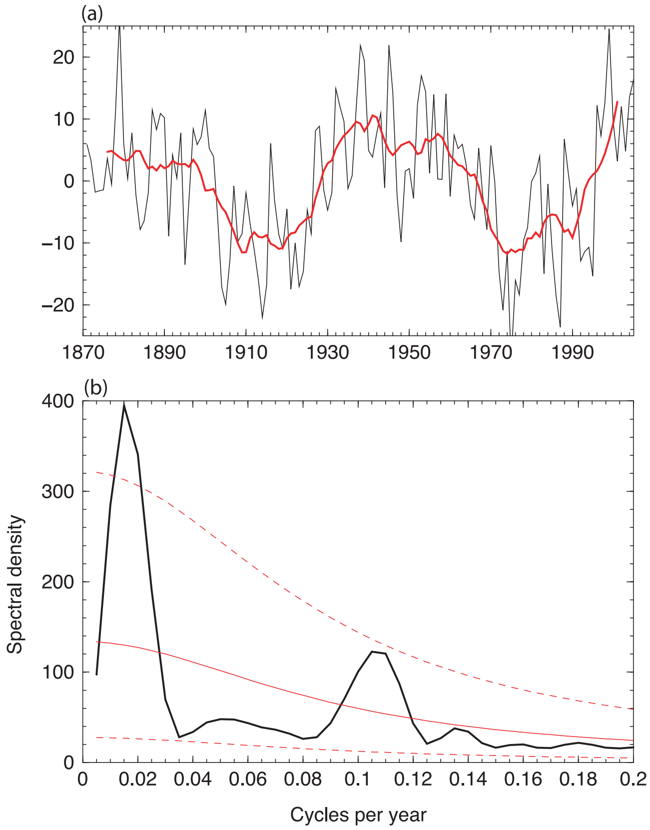

Plate 2. (a) Dimensionless time series associated with the first EOF of SST shown in Plate 1. (b) Spectrum of the time series in (a). Units along the *x*-axis are cycles per year. The solid black line denotes the spectral estimates, the solid red line is a the spectrum of a first-order Markov process (red noise) derived from the time series, and the dashed lines are the 95% confidence limits about that red noise spectrum.

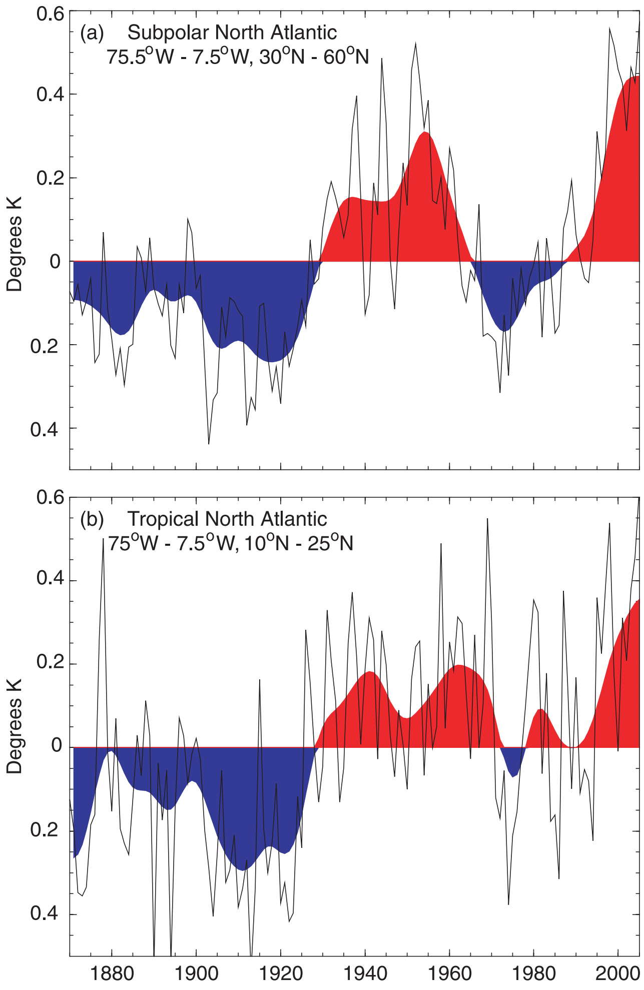

Plate 3. Time series of observed annual mean SST. The thin black curve denotes annual means, color shading denotes low pass filtered data. The response function of the filter is 0.5 at 15 years, thereby effectively removing timescales shorter than 15 years. The minimum slope method (*Mann*, 2004) was used within five years of the ends of the time series. (a) Subpolar North Atlantic. (b) Tropical North Atlantic (75°W-7.5°W,10°N-25°N).

limited, in that it is not designed to pick out propagating patterns. Other statistical analyses yield patterns that differ in their details from this, but there is generally one pattern reflecting the direct influence of surface heat flux anomalies on the ocean mixed layer, and another that captures decadal scale propagating features. On decadal scales, modeling studies [for example, *Grotzner et al*., 1998] have suggested a significant role for coupled ocean-atmosphere interactions, leading to modulation of the NAO. As stated above, however, the focus of this paper is the multidecadal signal described above, that is mainly captured by the leading EOF.

Time series of annual mean SST averaged over the subpolar and tropical North Atlantic are shown in Plate 3. These are the regions with largest amplitudes in the first EOF shown above. Multidecadal variability is clear in each time series, with somewhat larger amplitude in the subpolar regions. A longer-term warming trend is also clear. The fluctuations in the subpolar and tropical regions are largely in phase.

2.2. Analysis Based on Proxy Reconstructions

The length of the instrumental record (~150 years) is too short to draw firm conclusions on the robustness of the AMO, although the spectral analysis (Plate 2b) of the instrumental record hints at enhanced variability on the multidecadal time scale. Analyses of multi-century reconstructions of climate have been conducted that demonstrate that something like the AMO has been operating in the Atlantic climate system for at least the last several centuries.

Mann et al. [1995, 1998] present analyses based on a multiproxy reconstruction of temperature variability over the Northern Hemisphere. The multiproxy reconstruction utilizes a network of annual resolution climate indicators—tree rings, ice cores, varved sediment, coral, historical indicators—combined with the few available long instrumental records. The analyses document the temporal and spatial evolution of a pattern of variability with enhanced variance on the 50-100 year timescale. The pattern is hemispheric in scale, but with largest amplitude in the North Atlantic sector. *Delworth and Mann* [2000] compare this pattern of observed variability to the temporal and spatial evolution of a pattern of multidecadal variability simulated in a coupled climate model, and show good correspondence between the two. In the model, the variability is generated by multidecadal fluctuations of the MOC [*Delworth et al*., 1993]. For both the proxy reconstructions and the model, the Atlantic multidecadal variability was coherent with multidecadal fluctuations in the North Pacific. Many of the features seen in the proxy reconstruction are in agreement with analyses based on the instrumental record, thus lending support to the robustness of the multidecadal variability.

Shabalova and Weber [1999] present analyses from a variety of proxy indicators primarily over Europe and North America. Some of the records are greater than 900 years in length. Their analyses suggest the presence of a distinct multidecadal [60-80 years] pattern of temperature variability, with largest expression over Western Europe and eastern North America.

Gray et al. [2004] present an AMO index for the period 1567-1990 derived from a set of twelve tree-ring records in the southern United States, northern and southern Europe, and the Middle East. This index is reproduced in Plate 4. Their results suggest that the AMO has persisted for several centuries, and that the characteristics seen in the 20th century were present in past centuries. Their wavelet analysis [see Plate 3 of *Gray et al*., 2004] is consistent with enhanced variance on multidecadal time scales, but no sharply defined time scale.

Additional studies with proxy climate indicators in the vicinity of the Atlantic contain multidecadal fluctuations that could be associated with large-scale SST changes. For example, *Cronin et al*. [2000] note salinity oscillations in Chesapeake Bay with a timescale of approximately 60-70 years; they relate these fluctuations to large-scale droughts over eastern North America. This association of Atlantic multidecadal temperature fluctuations with North American drought is consistent with other analyses of the instrumental record [*Enfield et al*., 2001; *McCabe et al*., 2004]. Such proxy studies provide a crucial background against which to evaluate variability seen in the instrumental record, and more work along these lines is urgently needed. In particular, the relationship between Atlantic temperature fluctuations and climate anomalies over continental regions may have a substantial seasonal dependence [*Sutton and Hodson*, 2007], thereby posing an additional challenge for proxy reconstructions.

The above analyses of various proxy reconstructions of climate variability, extending several centuries into the past, demonstrate that the multidecadal variability seen in the instrumental record is not purely a feature of the last 150 years, but has occurred for the last several centuries. The important feature is not the presence of a distinct spectral peak, but rather the tendency in a variety of climate indicators for enhanced variability on the multidecadal time scale. An important issue, discussed later, is the degree to which changing radiative forcing over the last century has interacted with this (apparently) natural pattern of Atlantic multidecadal variability.

3. IMPACTS OF ATLANTIC VARIABILITY

A crucial question is whether this dominant pattern of SST variability has a significant impact on climate. Modeling studies in which the impact of this SST pattern on the atmosphere can be unambiguously investigated are extremely

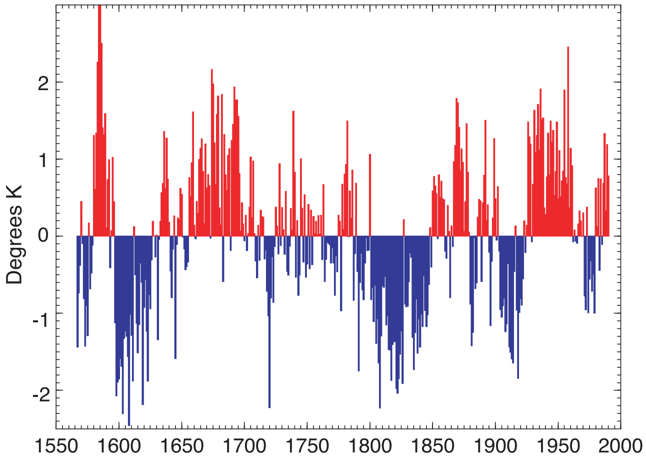

Plate 4. Index of AMO as reconstructed by *Gray et al*. (2004). Units are K.

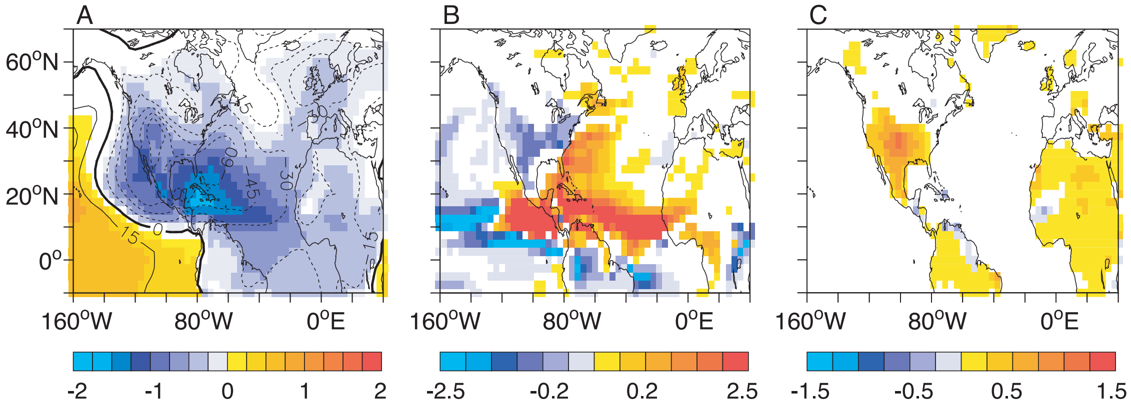

Plate 5. Adapted from *Sutton and Hodson* (2005). These panels show the simulated response of various fields to an idealized AMO SST anomaly using the HADAM3 atmosphere general circulation model. Results are time-means for the Aug-Oct. period. (a) Sea level pressure, units are Pa, with an interval of 15 Pa. (b) Precipitation, units are mm day^{-1}. (c) Surface air temperature, units are K.

useful. Several different experimental methodologies have been utilized, as described in detail below. They all indicate a significant impact of Atlantic changes on regional to global scale climate.

3.1. Studies With Atmosphere-Only Models

The recent work of *Sutton and Hodson* [2005] provides a clear assessment of the impact of the AMO. They used an atmosphere model (HADAM3, the atmospheric component of the coupled climate model HADCM3; see *Gordon et al*., 2000] to investigate the impact of AMO-like SST fluctuations during Northern Hemisphere summer. In their study, they prescribe a pattern of SST anomalies in the North Atlantic corresponding to a warm phase of the AMO. We reproduce some of their results here as Plate 5, showing the Aug-Oct (ASO) response of SLP, precipitation, and surface air temperature to an idealized AMO-like pattern of SST forcing. Their results show a clear response over the Atlantic, North America, and Western Europe. Over the Atlantic a broad area of low pressure develops, extending westward into the Caribbean and southern United States. This is similar to the observational results of *Kushnir* [1994]. The pressure anomaly pattern denotes weakened easterly trade winds, potentially reinforcing the positive SST anomalies in the tropical North Atlantic Ocean by reducing the latent heat flux. Precipitation is generally enhanced over the warmer Atlantic waters, and is reduced over a broad expanse of the United States. The summer temperature response is clear, with substantial warming over the United States and Mexico, with weaker warming over Western Europe. These responses demonstrate a robust and significant impact of Atlantic multidecadal temperature fluctuations on large-scale climate. However, a study such as this with prescribed SST changes cannot address the issue of what causes the observed SST fluctuations.

3.2. Studies With Atmosphere Models Coupled to a Mixed Layer Ocean

In studies with atmosphere-only models, SST anomalies are prescribed. This effectively implies an infinite heat capacity of the ocean, and can distort air-sea interactions. An atmospherically generated heat flux anomaly has no effect on SSTs, thereby distorting aspects of the air-sea coupling. An alternate technique is to couple the atmosphere model to a mixed layer model of the ocean, consisting of a 50m slab of water. The slab mixed layer interacts with the atmosphere via exchanges of heat. In order to simulate SSTs close to observed in the absence of explicit heat transport by ocean currents, a climatological heat flux adjustment is added at each oceanic grid point; this is designed to mimic the effects of oceanic heat flux convergence and the exchange of heat between the oceanic mixed layer and the deep ocean. The heat flux adjustment is calculated from a spinup integration in which simulated SSTs are relaxed back to observed SSTs with some restoring time scale (50 days in the case of the experiments discussed below). The heat flux adjustment is calculated as the average heat flux used to restore SSTs towards the observations. When run with the heat flux adjustments, the model simulates SSTs close to those observed.

For the idealized experiments described here, we use the atmospheric component of the GFDL CM2.1 coupled model [*Delworth et al*., 2006] coupled to a 50m slab ocean. We describe here a new experiment whose principal findings are consistent with *Sutton and Hodson* [2005]. A perturbation experiment is conducted by altering the heat flux adjustment term, which in turn alters the SST and air-sea heat flux. Specifically, we add spatially uniform positive heat flux adjustments over the subpolar North Atlantic (30°N-60°N). The spatial integral of the anomalous heating is 0.2×10^{15} W. This is roughly equivalent to a 15-20% increase in the observed Atlantic Ocean heat transport. A small cooling is applied uniformly over the rest of the global ocean so that no net heat flux is added to the climate system. This experiment is designed to assess the atmospheric response to an idealized, substantially enhanced oceanic heat flux convergence. SSTs are not prescribed, but adjust as part of the coupled system in response to the artificially enhanced oceanic heat flux convergence.

The responses in surface air temperature, SLP, precipitation, and the vertical shear of the zonal wind are shown in Plate 6 for the months of August-October (these are representative of the warm season response, and these particular months are of most relevance for tropical storm activity). There is a marked warming over the subpolar gyre, consistent with the heat flux adjustment term. There is additional warming over the tropical Atlantic. In the mixed layer formulation employed here, there is no heat transport by ocean currents, and the temperature changes can arise only through atmospheric teleconnections. The temperature response bears some resemblance to the dominant pattern of observed Atlantic SST variability, shown in Plate 1a. The SLP decrease (~1.8 hPa) in the subtropical North Atlantic is somewhat larger than the observational results displayed in Plate 5 from *Sutton and Hodson* [2005]. The negative SLP anomaly over the central Atlantic is consistent with weakened northeasterly trade winds in the tropical Atlantic, leading to a warming of the ocean mixed layer. The importance of latent heat flux anomalies in the tropical Atlantic is well established (see, for example, *Carton et al*., 1996]. There is an increase of precipitation over the tropical Atlantic, the Sahel, and parts of western India, consistent with a northward movement of the Intertropical Convergence Zone (ITCZ). There is a substan-

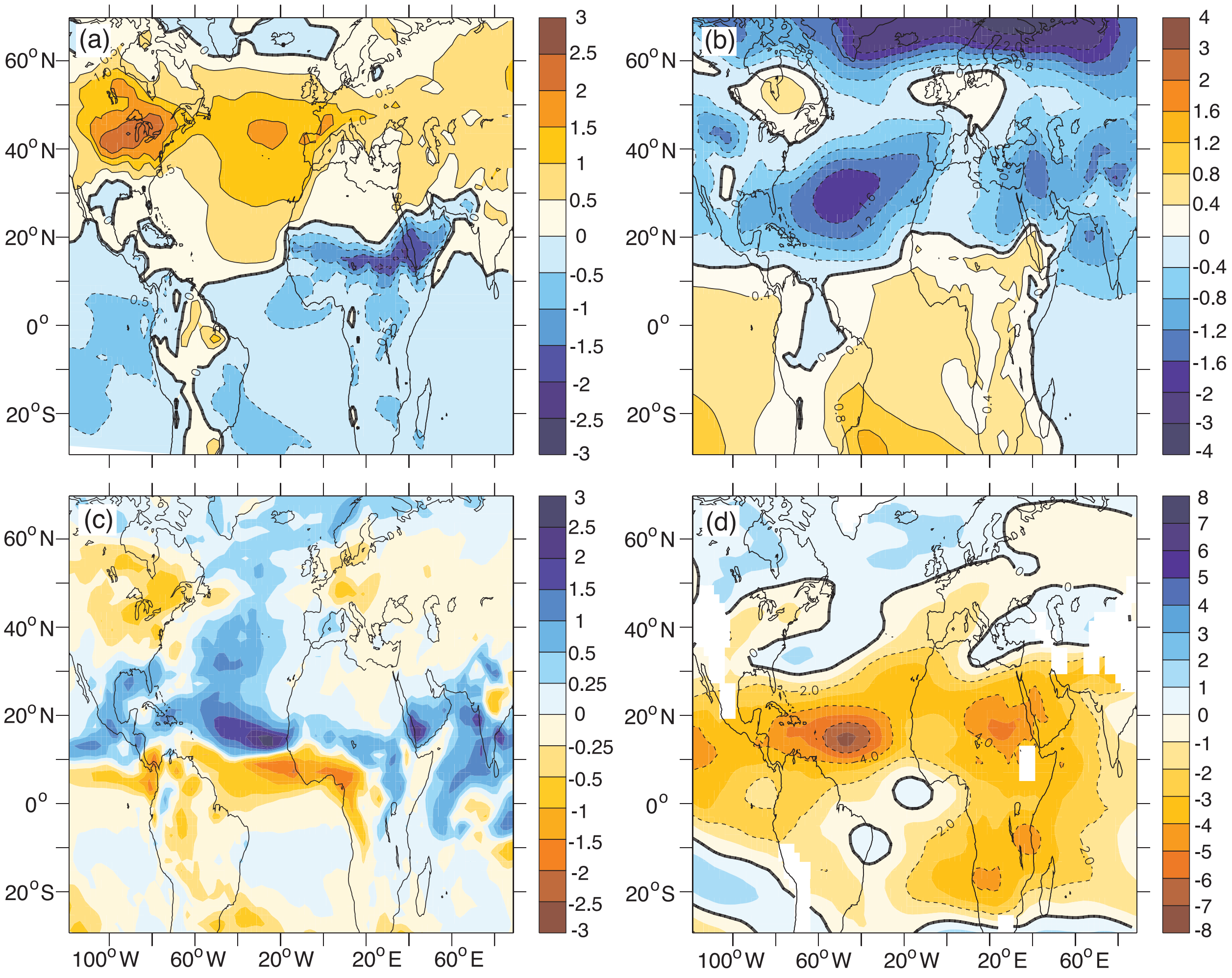

Plate 6. Response of GFDL AM2.1 climate model (atmosphere model coupled to mixed layer ocean) to imposed oceanic heating over the extratropical North Atlantic. The total heating is 0.2×10^{15} W, and is applied uniformly over the region 30°N to 60°N, from North America to Europe. The panels show the 40 year time-mean differences, expressed as the simulation with enhanced ocean heating minus the control simulation. Results are shown for August-October time-means, noting the relevance of that season for Atlantic hurricanes. (a) Near-surface air temperature (units are K), (b) SLP (units are hPa), (c) precipitation (units are mm day^{-1}), (d) vertical shear of the zonal wind, computed as the zonal component of the wind at 200 hPa minus the zonal component of the wind at 850 hPa. Units are m s^{-1}. Negative values indicate a reduction in shear in response to the extratropical ocean heating.

tial reduction (up to 7 m s^{-1}) of the vertical shear of the zonal wind over the tropical Atlantic, especially in the zonal band from approximately 10°N-20°N. This latter feature is crucial for tropical storms [*Goldenberg et al*., 2001].

This idealized experiment shows the impact of a spatially uniform heating of the Atlantic slab ocean on atmospheric circulation and regional climate. The resultant SST anomalies are not a precise replication of the AMO pattern, but demonstrate the substantial impact that changes in Atlantic Ocean heat transport could have on climate. The idealized heating was large in order to elicit a clear response; the resultant atmospheric changes are somewhat larger than observed. Many of these changes are consistent with observed changes [*Zhang and Delworth*, 2006]. As will be shown below (section 3.3.3), experiments with spatial patterns of heating that are designed to more faithfully replicate the AMO's spatial pattern of SST anomalies yield similar atmospheric responses. It is important to note that heating in the subpolar gyre is able to exert a significant impact on the atmosphere in the tropical and subtropical Atlantic.

These results are consistent with the work of *Chiang and Bitz* [2005], who demonstrated the impact of high latitude cooling (the imposition of ice sheets) on the marine ITCZ. Their modeled response to the imposition of ice sheets is a widespread cooling of the Northern Hemisphere, and a southward migration of the ITCZ (these results mirror the response to an imposed North Atlantic heating shown above). *Chiang and Bitz* [2005] clearly show how atmospheric processes, including feedbacks with the ocean mixed layer and impacts on tropical trade winds, translate the initial imposition of ice sheets into a planetary scale response. *Dahl et al*. [2005] and *Broccoli et al*. [2006] have also explored the influence of higher latitudes on the tropics in general, and the tropical Atlantic in particular.

3.3. Studies With Coupled Ocean-Atmosphere Models

A more comprehensive picture of the impact of AMO-like SST fluctuations on climate can be obtained using coupled ocean-atmosphere models, in which the ocean circulation is also free to evolve. However, it requires a somewhat different experimental design, since, by the nature of the model, SSTs are free to evolve. Several experimental designs have been used to probe the relationship between AMO-like SST fluctuations and climate.

3.3.1. Extended control integrations. Analyses of extended control integrations of coupled models have proven extremely useful in assess the associations between simulated AMO-like fluctuations and larger-scale climate. For example, *Knight et al*. [2006] has analyzed a 1400-year control integration of HADCM3, and demonstrates very coherent links between simulated AMO-like fluctuations and large-scale climate anomalies across the Northern Hemisphere. They note a clear relationship between AMO-like SST fluctuations and surface air temperature over North America and Eurasia, atmospheric circulation changes, including modulation of the vertical shear of the zonal wind in the tropical Atlantic, and large-scale changes in rainfall. Analyses of such experiments [see also *Delworth et al*., 1993, and *Jungclaus et al*., 2005] show clear connections between simulated AMO-like SST fluctuations, and large-scale climate anomalies, but they are not able to firmly establish a causal relation. The experiments described in the following sections are designed to explicitly probe the role of AMO-like SST fluctuations in forcing large-scale climate anomalies.

3.3.2. Freshwater forcing experiments. Numerous experiments have been performed in which large amounts of fresh water are applied to the North Atlantic Ocean in a coupled climate model [*Stouffer et al*., 2006]. The model response is typically a weakening or shutoff of the model's North Atlantic thermohaline circulation after a decade or two of persistent freshening, leading to a large-scale cooling of the North Atlantic (and a weaker warming of the South Atlantic). The model response can be viewed as an extreme cold phase of the AMO, and is characterized by a near-global scale response [*Vellinga and Wood*, 2002; *Zhang and Delworth*, 2005]. Shown in Plate 7 (reproduced from Zhang and Delworth, 2005] are the global-scale precipitation changes in response to a near-shutdown of the Atlantic MOC, which resembles a cold-phase of the AMO. In the Atlantic, there is a southward shift of the ITCZ and associated rainfall, leading to increased aridity over the Caribbean, the Sahel in Africa, and the Indian subcontinent, and increased rainfall over Northeastern Brazil. There are also strong responses over the Indian and Pacific basins. In the extratropical North Pacific there is a significant cooling (not shown), associated both with changes in the wind stress patterns and the advection of colder air off the Eurasian continent. For the remote response in the Indian and Pacific, *Zhang and Delworth* [2005] show that air-sea interactions in these regions are crucial for the response. These global scale responses may be viewed as an analogue for an extreme negative (cold) phase of the AMO. The simulated global-scale responses as simulated in *Zhang and Delworth* [2005] are consistent with the global-scale synchronization of abrupt climate change as indicated by observations from paleo indicators [see, for example, *Peterson et al*., 2000; *Wang et al*., 2001, 2004].

3.3.3. Initial impulse experiments. In this type of experiment [*Dong and Sutton*, 2002], a large salinity anomaly is instantaneously inserted into the model North Atlantic.

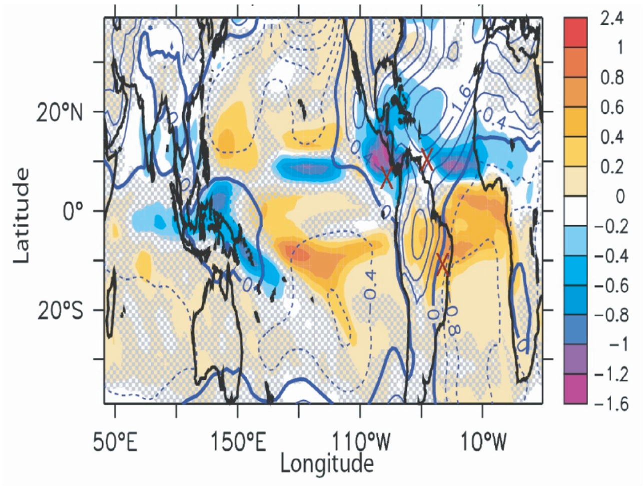

Plate 7. Simulated annual mean precipitation (color shading) and sea level pressure (contours) simulated in response to a near-shutdown of the Atlantic thermohaline circulation [adapted from *Zhang and Delworth*, 2005]. Units for precipitation are mm day^{-1}, and units for pressure are hPa (dashed contour lines indicate negative values). These changes are consistent with the global synchronization of abrupt climate changes as indicated by paleo records (the Xs mark the locations) of precipitation at the Cariaco Basin [*Peterson et al.*, 2000], northeastern Brazil [*Wang et al.*, 2004], and the northeastern tropical Pacific [*Benway et al.*, 2004]

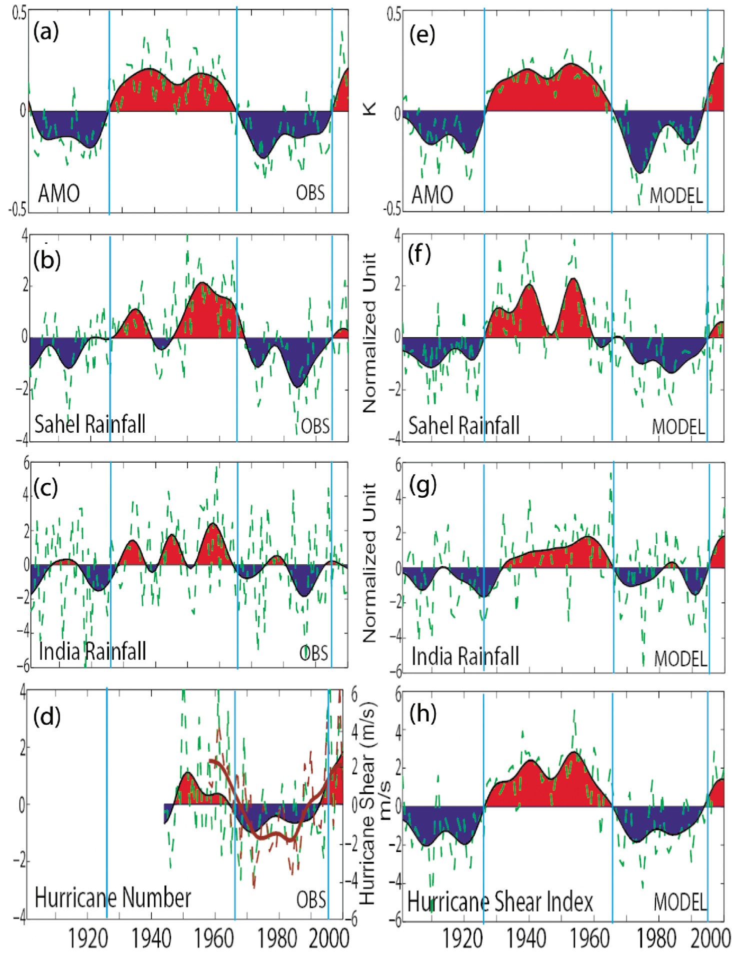

Plate 8. Left column: Various observed quantities with an apparent association with the AMO. Right column: Simulated responses of various quantities to AMO-like fluctuations in the Atlantic ocean from a hybrid coupled model [adapted from *Zhang and Delworth*, 2006]. The responses are computed as the mean of a 10 member ensemble of experiments in which AMO-like temperature fluctuations are induced in the slab ocean component of a coupled model over the Atlantic ocean by perturbing the ocean heat flux convergence [see *Zhang and Delworth*, 2006, for details]. This technique induces an SST anomaly pattern that resembles the observed AMO-like SST fluctuations in the Atlantic, and allows the rest of the climate system to evolve in response to those anomalies. Dashed green lines are unfiltered values, while the color-shaded values denote low pass filtered values. Vertical blue lines denote transitions between warm and cold phases of the AMO. (a) and (e) Annual mean SST averaged over the North Atlantic. Units are K. The resemblance of the simulated curve to the observed curve is a validation of the experimental design. (b) and (f) Rainfall anomalies over the Sahel (20°W-40°E,10°N-20°N) averaged over the months of June, July, August and September (JJAS). (c) and (g) JJAS rainfall over West Central India (65°E-80°E,15°N-25°N). (d) Green dashed lines and color shading indicate the number of major Atlantic Hurricanes from the HURDAT data set, with no bias-type correction as recommended by *Landsea* [2005]. The brown lines denote the vertical shear of the zonal wind (multiplied by -1) as derived from the ERA-40 reanalysis, calculated as the difference in the zonal wind between 850 and 200 hPa over the south-central part of the main development region for tropical storms (10°N-14°N,70°W-20°W), units are m s^{-1}; dashed brown line is unfiltered data, solid line is filtered data. (h) Vertical shear of the simulated zonal wind (multiplied by -1), calculated as in (d).

Dong and Sutton [2002] apply a negative salinity anomaly of 2 PSU, and study the transient adjustment of the Atlantic circulation. This forcing substantially weakens North Atlantic deep-water formation, leading to a decrease of the MOC and associated heat transport, and inducing a cold phase of the AMO. The propagation of the signal from the high latitudes to lower latitudes involves both atmospheric processes and oceanic wave processes, as highlighted by both *Dong and Sutton* [2002] and *Johnson and Marshall* [2002]. *Dong and Sutton* [2002] show that the SST response in the Atlantic has the characteristics of a cold phase of the AMO, and this in turn induces a southward shift of the Atlantic ITCZ, and associated southward migration of rainfall over the Atlantic (similar to the water-hosing experiments described above). A crucial result is that the AMO-like SST changes have a strong impact on the tropical atmosphere, which can efficiently communicate this signal to the global atmosphere, thereby generating impacts over the Pacific and Indian sectors.

3.3.4. Hybrid coupled model experiments. In this type of experiment, the Atlantic portion of a fully coupled ocean-atmosphere model is replaced with a slab ocean (similar to that described in section 3.2). Outside of the Atlantic, the model has a fully dynamic ocean component, with buffers at the northern and southern boundaries of the Atlantic where temperature and salinity are relaxed back to model climatology. These buffers prevent the generation of spurious signals that could propagate away from the Atlantic.

In the Atlantic a pattern of heat flux anomalies is applied that has the spatial structure of the AMO, and is modulated in time in a manner analogous to the observed AMO over the course of the 20th century [see *Zhang and Delworth*, 2006, for additional details]. Using this technique, *Zhang and Delworth* [2006] demonstrate that many features of observed multidecadal climate variability in the 20th century may be interpreted, at least partially, as a response to the AMO. As shown in Plate 8 [reproduced from *Zhang and Delworth*, 2006], a warm phase of the AMO leads to increases in Sahelian and Indian monsoonal rainfall, as well as reductions in the vertical shear of the zonal wind in the tropical Atlantic region important for tropical storm development. Thus, the AMO creates large-scale atmospheric circulation anomalies that would be favorable for enhanced tropical storm activity. A positive AMO also leads to anomalously warm summer conditions over North America and Western Europe (not shown), and contributes to multidecadal fluctuations of hemispheric temperature [*Zhang et al*., 2007]. This experimental design allows a more precise control over Atlantic SST anomalies than in sections 3.3.1 and 3.3.2, while allowing air-sea interactions in the Indo-Pacific sector to progress normally.

3.4. Synthesis

The modeling studies cited above demonstrate that multidecadal fluctuations of Atlantic SST—the so-called AMO—have a substantial impact on climate fluctuations over a large portion of the globe. In addition, these experiments have shown that ocean heat flux anomalies, even when confined to the extratropics of the North Atlantic, can have significant impacts on tropical temperatures and atmospheric circulation that are of relevance for tropical storms.

In addition to the impact on time-mean climate, *Dong et al*. [2006] demonstrate that the AMO can modify the characteristics of interannual variability in the Pacific. This is accomplished via atmospheric teleconnections patterns, in which changes originating in the Atlantic alter the base state properties of the Pacific that determine the nature of the ENSO, primarily by altering the trade wind characteristics and resultant changes in the thermocline structure. Their results suggest a warm phase of the AMO leads to a weakening of ENSO variability. *Timmermann et al*. [2005] also suggest that large changes to the Atlantic MOC can modulate the characteristics of ENSO, but they propose a mechanism whereby the communication of a signal from the Atlantic to the tropical Pacific is via oceanic wave processes. They suggest that a weakening of the Atlantic MOC leads to a deepening of the tropical Pacific thermocline, and a weakening of ENSO.

In addition to the modeling studies cited above, substantial observational evidence exists documenting a linkage between the Atlantic multidecadal variability and tropical climate. The study of *Black et al*. [1999] using Caribbean sediment records suggests that trade winds are more intense over the Cariaco Basin and the Atlantic ITCZ shifts southwards when the North Atlantic is colder than average. This supports the robust link between intensification of tropical North Atlantic trade winds, the southward shift of the Atlantic ITCZ, and cooling in the northern North Atlantic. Such observational records support the modeling results that the AMO is linked to other tropical climate variability (such as rainfall over the Sahel and northeastern Brazil) in a fundamental way. The high-resolution records in the Cariaco Basin reveal the same level of low frequency variability over the past 825 years as seen in the 20th century.

Given the above results, two important questions arise: (1) What is the source of these AMO-like SST fluctuations, and (b) Are these fluctuations predictable?

4. INSIGHTS ON MECHANISMS OF ATLANTIC VARIABILITY FROM MODELS

The modeling and observational studies described in the previous sections have identified the impact that AMO-like fluctuations have on the global climate system. These impacts were deduced from various modeling experiments, in which AMO-like SST perturbations were induced via several techniques. Several key questions remain: What is the mechanism by which AMO-like fluctuations are generated in nature? Are the AMO fluctuations a part of the spectrum of internal variability of the coupled climate system? Are they a response to external forcing, such as the changing anthropogenic forcing in the 20th century from increasing greenhouse gases and aerosols? Are they a combination of the two?

Given the constraints on observational data, one method for investigating mechanisms of AMO-like variability has been the analysis of extended integrations of ocean-only models, or coupled ocean-atmosphere models. For example, the early studies of *Weaver and Sarachik* [1991) and *Greatbatch and Zhang* [1995] describe mechanisms for decadal variability isolated within the context of ocean-only models. *Te Raa and Dijkstra* [2002] used an ocean-only model to identify the modes of variability that may contribute to interdecadal variability. Their analyses reveal the presence of an oscillatory mode in the ocean under conditions of sufficiently low horizontal mixing, which they discuss in terms of a Hopf bifurcation. Crucial to the mechanism are westward propagating temperature anomalies that interact with the thermohaline circulation. *Huck et al*. [2001] also present detailed analyses of the mechanism of thermohaline circulation interdecadal variability in box models and three-dimensional models, and demonstrate that interdecadal variability is "…a robust geostrophic feature whose amplitude is mainly controlled by the horizontal diffusivity." In these studies, oceanic processes drive the interdecadal variability.

The use of coupled ocean-atmosphere models provides a potentially more complete representation of the climate system. The control integrations of coupled models use constant, prescribed levels of insolation and atmospheric trace gases and aerosols. Thus, any variability in such integrations arises because of interactions with the coupled climate system. The output from these simulations may be interpreted as a representation of internal variability of the coupled system. Several such modeling studies have shown that AMO-like fluctuations can arise as part of the spectrum of internal variability, independent of anthropogenic forcing. These studies suggest that the AMO is at least partially a result of fluctuations of the Atlantic MOC and associated fluctuations in heat transport. A strong (weak) MOC leads to a warm (cold) phase of the AMO. Several different hypotheses on the mechanisms of the MOC fluctuations have been proposed.

Using the GFDL R15 coupled model, *Delworth et al*. [1993] documented clear multidecadal variability of the simulated MOC that led to AMO-like SST fluctuations in the Atlantic, characterized by a multidecadal timescale. They suggested that the fluctuations arose as the oceanic response to essentially stochastic atmospheric flux forcing, thereby exciting a damped internal mode of oceanic variability. This explanation was supported by additional experimentation in *Delworth and Greatbatch* [2000], in which the oceanic component of the R15 coupled model was forced with flux anomalies from the coupled model that had the same spatial structure as the coupled model, but were random in time. Phase lags between the transports of salt and heat contributed to the oscillatory nature of the fluctuations. The timescale in the simulated variability appeared to depend on interactions between horizontal and vertical transports of heat and salt, but the precise physics governing the timescale are not clear. *Eden and Jung* [2001] also pointed out the importance of surface fluxes in driving MOC fluctuations. They forced an ocean-only model with estimates of the surface flux forcing related to the NAO over the period 1865-1997, and found that multidecadal heat flux anomalies associated with the NAO drove multidecadal fluctuations of the MOC, producing SST fluctuations that resembled the AMO. This supports the importance of flux anomalies in driving the MOC fluctuations, but makes no statement on potential feedbacks to the atmosphere.

In an independent coupled climate model, *Timmermann et al*. [1998] demonstrated a mode of MOC variability that was very similar to the *Delworth et al*. [1993] variability, but postulated a different mechanism. They suggested that air-sea coupling was essential to the oscillation. A specific pattern of SST fluctuations gave rise to an atmospheric response. This atmospheric response generated a pattern of water flux forcing that led to a reversal of the phase of the oscillation by modifying upper ocean vertical stratification and convection.

Vellinga and Wu [2004] analyzed a long control integration of HADCM3, and found a near-centennial timescale of Atlantic MOC variability. They also suggested that air-sea coupling was essential to their mode of variability. A strong MOC (associated with a warm North Atlantic) led to a more northerly position of the ITCZ; this in turn led to greater fresh water input to the tropical North Atlantic. This fresh water pulse took several decades to propagate to the subpolar gyre, where it inhibits deep-water formation, thereby weakening the MOC and leading to a cold North Atlantic. *Knight et al*. [2005, 2006] further delineated the climatic impacts of this AMO-like SST variability.

Jungclaus et al. [2005] used the ECHAM5 coupled climate model to show the presence of strong multidecadal variability in their control simulation with a timescale of 70-80 years. Their postulated mechanism involves an interplay and phase delays between the strength of the MOC and the associated heat and salinity transports. Of particular importance in their mechanism is the exchange of fresh water between the Arctic and the subpolar North Atlantic, in which a build-up and release of fresh water by the Arctic is crucial. The release of fresh water from the Arctic into the Greenland and Labrador

Seas inhibits oceanic convection and weakens their model MOC. Their mechanism is somewhat similar to *Delworth et al*. [1993, 1997], in that they see a damped oceanic mode, continuously excited by stochastic atmospheric noise. This has some similarity to the results of *Holland et al*. [2001]. The impact of fresh water releases on the MOC has also been shown by *Zhang and Vallis* [2006]. In their study, releases of fresh water into the North Atlantic, such as that observed with great Salinity Anomaly type events, generate a clear response in Labrador Sea convection, the deep western boundary current, the position of the Gulf Stream, and sea surface temperature. These studies point to the crucial role that freshwater anomalies, particularly from the Arctic, can play in Atlantic decadal and multidecadal variability.

The above papers are a representative cross section of theoretical work on decadal and longer scale variability of the MOC and its impact on Atlantic variability. They provide strong support for the hypothesis that interdecadal fluctuations of the MOC can be an integral part of the spectrum of internal climate variability. However, the variety of timescales present in the simulations, as well as differences among the proposed mechanisms, suggests that much work is needed to more fully understand the dynamics of multidecadal Atlantic variability. In particular, both the development of improved climate models and the close comparison of such models with improved and sustained oceanic observations are necessary for improving our understanding.

One important point to note is that the observed tropical SST multidecadal fluctuations are nearly as large as the observed subpolar multidecadal fluctuations (see Plate 3). However, for most of the coupled model results the tropical fluctuations are considerably smaller than the subpolar fluctuations. This difference is a particularly important point when considering the potential influence of Atlantic multidecadal variability in tropical circulation in general, and on tropical storms in particular [*Mann and Emanuel*, 2006]. This difference may be a result of model deficiencies, or a symptom of external forcing of the observed tropical North Atlantic, independent of natural variability. The resolution of such issues is a crucial research challenge.

5. ATLANTIC VARIABILITY AND CLIMATE CHANGE

The studies discussed in the previous section provide model-based support to the hypothesis that multidecadal fluctuations of the MOC are an integral part of the spectrum of internal climate variability, and yield AMO-like patterns of SST variability in the Atlantic. During recent decades, however, increasing emissions of various atmospheric pollutants have altered the Earth's radiative balance, causing patterns of surface temperature change. Two possible impacts of this are: (1) the changing radiative forcing influences the temporal variability of the MOC, and (2) the response of surface temperature to the radiative forcing changes has a spatial and temporal pattern which resembles the AMO, thereby making it difficult to ascertain the relative contributions of MOC fluctuations and anthropogenic forcings to recently observed temperature changes in the Atlantic.

Addressing the first possibility is largely outside the scope of this review. However, we note that research has shown that a positive phase of the NAO tends to strengthen the MOC. Some work [*Shindell et al*., 1999; *Hoerling et al*., 2004] has suggested that anthropogenic forcing favors a more positive phase of the NAO, thereby influencing the MOC. Greenhouse gas-induced warming also leads to a reduction of Arctic sea ice and associated freshening of the upper ocean, potentially weakening the MOC. The observational results of *Bryden et al*. [2005] suggest a possible weakening of the MOC, although major uncertainties remain in both the observational estimates of ocean circulation changes and their attribution to physical factors. The results of *Schott et al*. [2006] do not support such a basinwide slowdown. In addition, *Delworth and Dixon* [2006] have used numerical experiments to show that increasing greenhouse gases and sulfate aerosols can have significant—and opposing—influences on the MOC in the 20th century. While increasing greenhouse gases tend to weaken the MOC, increasing aerosols may strengthen the MOC. Two effects of the aerosols are involved: (a) by cooling the higher latitudes of the Northern Hemisphere, the upper ocean cools and becomes denser, leading to enhanced convection and overturning; (b) at the same time, increased aerosols reduce total evaporation and the transport of water vapor to higher latitudes, thereby reducing the inflow of fresh water to the Arctic/North Atlantic system, increasing salinity and upper ocean density, and increasing the MOC. In addition, observational evidence of significant changes in dust exported from Africa could have important implications for North Atlantic climate (P. Ginoux, personal communication). Thus, the temporal evolution of radiative forcing (both natural and anthropogenic) in the 20th century could plausibly have influenced the temporal evolution of the MOC.

The second possibility is that the direct effect of radiative forcing changes induces a pattern of Atlantic temperature change that resembles the AMO. Simulations of 20th century climate using state of the art climate models forced with estimates of radiative forcing agents over the 20th century [see, for example, *Knutson et al*., 2006, and *Santer et al*., 2006] provide some perspective on this question. In these simulations, we can compare directly an estimate of forced climate change over the Atlantic with observed changes. It is clear from such studies [see, for example, Figure 10 of *Knutson et al*.] that there is a very substantial forced component to the century-scale warming in the Atlantic, with a multidecadal component to the forced warming. *Biasutti and Giannini* [2006] show that the combination of increasing greenhouse gases and aerosol concentrations can induce a pattern of late 20th century SST anomalies that has some resemblance to the AMO. This is consistent with earlier work by *Rotstayn and Lohmann* [2002] on the role of aerosols in producing cooling in the Northern Hemisphere relative to the Southern Hemisphere, leading to a southward displacement of the ITCZ and Sahelian drought.

However, the forced signal of 20th century temperature change is unable to completely characterize the amplitude and spatial structure of the fluctuations over the last 50 years in the Atlantic. This implies that either (a) the model's response to the forcing is incorrect, (b) the estimates of the forcing are incorrect, (c) internal variability plays some significant role in the warming, or (d) some combination of these reasons.

Of particular interest is better understanding the reasons for the recent warming in the tropical Atlantic in light of its hypothesized link to enhanced hurricane activity. Recently two studies [*Mann and Emanuel*, 2006; *Trenberth and Shea*, 2006] have attempted to estimate forced and internal variability components of Atlantic temperature change by using observed near-global scale temperature changes as an estimate of the forced component of Atlantic change. These studies focused in particular on the issue of tropical North Atlantic SST fluctuations of relevance for hurricanes, and the extent to which such fluctuations arise from natural variability or forced climate change.

Recognizing the inherent difficulties in trying to estimate a forced response based purely on observations, we adopt a similar approach. We use two methods to provide some perspective on the relative roles of forced climate change and internal variability, and the sensitivity of any such decomposition to the method used. We focus on SSTs over the Main Development Region (MDR) for tropical storms, here defined as 6°N-18°N, 60°W-20°W, as used by *Mann and Emanuel* [2006].

In both approaches, observations are used to estimate the forced response of tropical Atlantic SSTs to changing radiative forcing. The internal variability component is estimated as the remainder when subtracting the estimated forced response from the observed time series of SST. The difference between the methods lies in the definition of the forced response. All data have been low-pass filtered prior to analysis.

In Plate 9 we first show (top panel) the time series of SST averaged over the Indian and Pacific oceans (black line) and averaged over a subset of the tropical North Atlantic (red line, area defined in caption). In the first method, referred to as Method A, the forced SST variations in the tropical North Atlantic are estimated by using a two component statistical model, similar to that used in *Mann and Emanuel* [2006]. The first component of the statistical model is an estimate of the global forced signal, constructed as the mean SST over the Indian and Pacific oceans (this differs slightly from the methodology used in *Mann and Emanuel*, 2006, but does not fundamentally alter the conclusions). The second component of the statistical model is an estimate of aerosol effects, adapted from *Crowley* [2000]. Regressing the time series of observed Atlantic SST (averaged over the MDR) on the two components of the statistical model provides an estimate of the forced component of Atlantic change; the residual is an estimate of the internal variability, and is plotted in the bottom panel of Plate 9 (blue curve).

In Method B, the forced component is defined as the average SST change over the Indian and Pacific oceans. The internal variability component is then estimated as the remainder when subtracting the MDR SST from the forced component; this internal variability estimate is plotted in the lower panel of Plate 9 as the green line.

These results highlight the difficulties in decomposing the observations into forced and internal variability components. It is clear that there is a very significant global-scale forced signal (as defined here, shown by the black line in the top panel). However, the estimates of the internal variability component (as defined by the differing techniques, and shown in the bottom panel) differ substantially. For Method B (green line), the residual is of comparable amplitude to the forced signal over the period 1980-2005, suggesting a substantial role for internal variability of the climate system. Method A suggests a much smaller role for internal variability. In both cases, the forced climate change signal is apparent in the tropical Atlantic; what is more problematic is quantifying the role of internal variability in the late 20th century.

One caveat is that the estimate of the forced response may have serious deficiencies, in that regional forcing (from aerosols, for example) could be playing a larger role in the Atlantic than in the mean over the Indian and Pacific oceans. If this were the case, the relative fraction of the signal that is forced could be larger. However, the climatic effects of aerosols have significant uncertainties.

6. DISCUSSION AND KEY CHALLENGES

Decadal to centennial North Atlantic Ocean surface temperatures are characterized by two dominant types of variability: on the interannual to decadal scale, structured patterns of SST anomalies with opposing signs are seen. A tripolar pattern is seen as the direct response of the ocean mixed layer to the pattern of surface heat flux anomalies associated with the NAO. An additional pattern is characterized by out of phase anomalies between the Labrador Sea and the regions off the east coast of North America. On multidecadal

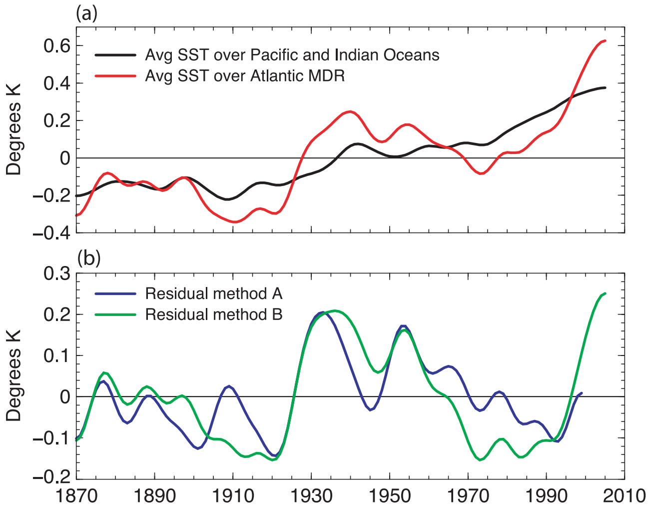

Plate 9. (a) Time series of Aug-Oct SST, derived from HADISST [*Rayner et al*., 2003], updated through 2005. The red curve indicates observed time series averaged over the region 6°N-18°N,60°W-20°W [one definition of the main development region (MDR) for Atlantic tropical storms, as used by *Mann and Emanuel*, 2006]. The black curve denotes SST averaged over the domain 30°E-100°W, 60°S-60°N (ie, most of the global ocean excluding the Atlantic). (b) The blue and green curves represent estimates of the non-forced component of the MDR SST time series for ASO, computed as residuals using differing techniques as described in the text (blue is Method A, green is Method B). Note that data for Method B end in 2000. All data (top and bottom panels) are low pass filtered prior to plotting. Smoothing within five years of the end points uses the minimum slope technique [*Mann*, 2004] for smoothing time series near their boundaries.

time scales a more homogeneous pattern is seen, with anomalies of one sign spanning the entire North Atlantic. This pattern is referred to as the AMO.

A variety of recent studies have shown that AMO-related SST fluctuations induce substantial climate fluctuations over neighboring continental regions, including Africa, North and South America, Western Europe, and the Indian subcontinent. We have focused analyses on the Northern Hemisphere warm season, when the impacts of Atlantic temperature fluctuations on larger-scale climate appear to be strongest. A warm phase of the Atlantic induces a northward shift of the ITCZ, associated with enhanced summer rainfall over India, the Sahel region of Africa, and the Caribbean. Associated with this is a substantial reduction of vertical shear of the zonal wind in the main development region for Atlantic tropical storms, thereby potentially leading to enhanced tropical storm activity. The warm Atlantic also leads to positive temperature anomalies over North America and Western Europe, with some evidence of reduced rainfall over the United States.

One hypothesis for the origin of the AMO is that fluctuations in the MOC generate AMO-like SST fluctuations. Consistent with that possibility, several independent numerical climate models produce internal variability similar to the observed AMO, and these fluctuations are associated with variations in the intensity of the MOC. However, detailed analyses of the various models do not yield the same mechanism underlying each. In some models, strong two-way coupling with the atmosphere is essential. Atmospheric changes in response to one phase of the multidecadal variability create conditions that lead—with a time delay, typically associated with oceanic processes—to a phase reversal. In other models, the atmosphere appears to serve primarily as a source of flux forcing of the ocean, stimulating inherent modes of oceanic MOC variability. An additional possibility is that the multidecadal SST fluctuations are simply a manifestation of a red noise process.

A crucial issue is assessing the degree to which the observed variability is associated with internal variability of the climate system, generated through interactions of the coupled ocean-atmosphere-land system, or a response to changing radiative forcing associated with either natural influences (solar irradiance changes or volcanic activity) or anthropogenic sources. One example of why such topics are vitally important is the question of why Atlantic hurricanes increased from the 1970s to the post-1995 period. If the dominant influence is internal variability [*Goldenberg et al*., 2001], then the future would eventually bring a return to reduced levels of hurricane activity. However, if the warming is predominantly due to anthropogenic forcing [*Mann and Emanuel*, 2006], the future prospects for Atlantic hurricanes appear daunting. Another such example is the pronounced warming of the Northern Hemisphere in the early part of the 20th century. *Delworth and Knutson* [2000] and *Johannessen et al*. [2004] suggest that internal variability of the coupled climate system involving changes in ocean circulation may have contributed significantly to this warming. In addition, *Zhang et al*. [2007] demonstrate how AMO-like SST variations can contribute to hemispheric scale temperature fluctuations, such as the early 20th century warming, the pause in hemispheric scale warming in the mid 20th century, and the late 20th century rapid warming.

This topic highlights a critical issue in climate change projections: on timescales of one to two decades, is there predictability in the system based on the initial conditions? Accurate predictions of such variability, even a few years in advance, could be useful, especially in light of the impacts discussed in section 3. Several studies have previously examined the issue of decadal predictability in the Atlantic in light of multidecadal fluctuations of the MOC [see, for example, *Griffies and Bryan*, 1997; *Pohlmann et al*., 2004; *Latif et al*., 2006]. In particular, *Latif et al*. [2006, 2007] provide an up to date assessment of understanding of Atlantic decadal predictability. Several coupled climate models show clear evidence of decadal scale predictability of the MOC, although the level of predictability appears to depend on the initial conditions. With regard to such decadal scale predictability, several major issues are: (1) the degree to which any decadal predictability of the ocean's MOC translates into appreciable atmospheric impacts, particularly over continental regions, (2) the capability of current coupled ocean-atmosphere models to correctly represent the physical processes that are important for the variability and predictability, and (3) the availability of adequate observational systems and associated data assimilation systems that would be required to successfully initialize coupled models for the prediction of decadal scale fluctuations.

Can climate models that are suitably initialized with the observed state of the climate system produce more accurate decadal-scale projections of climate variability and change than models that do not take into account such information? If the answer to this question is yes, then improved understanding of the dynamics of internal variability of the climate system may help to resolve issues of climate change detection and attribution, such as the potential role of internal variability in the recent warming of the tropical Atlantic.

In order to make progress to address some of these issues, it is vital to develop the capability to (a) accurately observe in real time the state of the Atlantic, and (b) use that information to make predictions of the future evolution of the Atlantic based on state of the art numerical models combined with data assimilation techniques.

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