

## Atlantic Climate Variability and Predictability: A CLIVAR Perspective

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### ABSTRACT

Three interrelated climate phenomena are at the center of the Climate Variability and Predictability (CLIVAR) Atlantic research: tropical Atlantic variability (TAV), the North Atlantic Oscillation (NAO), and the Atlantic meridional overturning circulation (MOC). These phenomena produce a myriad of impacts on society and the environment on seasonal, interannual, and longer time scales through variability manifest as coherent fluctuations in ocean and land temperature, rainfall, and extreme events. Improved understanding of this variability is essential for assessing the likely range of future climate fluctuations and the extent to which they may be predictable, as well as understanding the potential impact of human-induced climate change. CLIVAR is addressing these issues through prioritized and integrated plans for short-term and sustained observations, basin-scale reanalysis, and modeling and theoretical investigations of the coupled Atlantic climate system and its links to remote regions. In this paper, a brief review of the state of understanding of Atlantic climate variability and achievements to date is provided. Considerable discussion is given to future challenges related to building and sustaining observing systems, developing synthesis strategies to support understanding and attribution of observed change, understanding sources of predictability, and developing prediction systems in order to meet the scientific objectives of the CLIVAR Atlantic program.

### 1. Introduction

Time series of atmospheric, oceanic, and ecological indices describing Atlantic climate variability have been tantalizing in their suggestion of unusual, if not

unprecedented, change in recent decades. Labrador Sea Water (LSW), for instance, was fresher, colder, denser, and deeper by the early to mid-1990s than at any other time in the history of deep measurements in the region (Lazier 1995). At depths below the LSW layer, repeat hydrography has indicated a steady freshening over the past three to four decades, which likely reflects a large-scale freshening of the upper Nordic Seas (Blindheim et al. 2000) passed on via the dense northern overflows (Dickson et al. 2002). In contrast,

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recently warmer and saltier mode waters are the result of suppressed convection in the Sargasso Sea. These coordinated changes of opposite sign in the vertical density structure and heat content of the upper ocean extend well below the wind-driven layer (Dickson et al. 1996). Moreover, they seem to have contributed to a significant spinup of the baroclinic Atlantic gyre circulation, which was perhaps stronger in recent years than at any other time during the twentieth century (Curry and McCartney 2001).

These remarkable oceanographic changes have been in large part forced by multidecadal variations in the leading mode of atmospheric variability over the region: the North Atlantic Oscillation (NAO). In particular, boreal winter indices of the NAO reveal a sharp reversal from minimum index values in the late 1960s to strongly and persistently positive index values through the 1990s, corresponding to a trend toward lower (higher) atmospheric surface pressures over the subpolar (subtropical) North Atlantic. The magnitude of the recent NAO index trend is unique in the long instrumental record (Hurrell 1995; Jones et al. 2001; Cook 2003), although the past several winters have not been characterized by strongly positive NAO index conditions. Nonetheless, the long-term changes in atmospheric circulation have contributed to record surface warmth over much of the Northern Hemisphere (NH) landmass over the past decade (Hurrell 1996; Thompson et al. 2000; Rauthe and Paeth 2004).

One theory is that interactions between the oceans and atmosphere are important for understanding the recent temporal evolution of the NAO (e.g., Kushnir et al. 2002a; Czaja et al. 2003). While this remains an open issue, it is well established that changes in the tropical and subtropical distribution of sea surface temperatures (SSTs) have a controlling influence on tropical Atlantic variability (TAV), including the monsoon system of sub-Saharan Africa (e.g., Folland et al. 1986; Ward 1998; Giannini et al. 2003; Bader and Latif 2003; Hoerling et al. 2006; Lu and Delworth 2005). Here, the devastating drought from the late 1960s through the 1990s was reflected by a 35% reduction in the climatological July–September (JAS) rainfall (Hoerling et al. 2006), affecting the health and livelihood of millions of people. The accompanying multidecadal variations in Atlantic SSTs (Hurrell and Folland 2002), known as the Atlantic multidecadal oscillation (AMO), are perhaps driven by variations in the Atlantic meridional overturning circulation (MOC; Delworth and Mann 2000). Moreover, the AMO has also been linked to low-frequency boreal summer changes in rainfall and drought frequency in the continental United States (e.g., En-

field et al. 2001; Schubert et al. 2004; Sutton and Hodson 2005).

Understanding the causes of this limited sample of remarkable, if not unprecedented, changes in Atlantic climate is a central goal for Climate Variability and Predictability (CLIVAR). Moreover, clarity on these problems is a prerequisite to determining the predictability of Atlantic climate, advancing climate prediction, and understanding possible human influences on Atlantic climate change. In the following sections we briefly review advances in our knowledge of the three principal interrelated phenomena of Atlantic sector climate: the NAO, TAV, and the Atlantic MOC (Fig. 1). We also discuss the importance of these phenomena in terms of global climate variability, and we end with a review of the observing, synthesis, and prediction system challenges needed to meet the goals and objectives of CLIVAR.

## 2. North Atlantic Oscillation

The NAO is one of the most prominent and recurrent patterns of atmospheric circulation variability. It strongly influences climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic, especially during boreal winter, thus affecting society and the environment. Understanding the mechanisms that determine its structure and variability in time is, therefore, of high priority to CLIVAR, especially in the context of global climate change. The following discussion focuses on recent insights into these mechanisms. For a much more detailed description of the NAO; its relationship to the NH annular mode (e.g., Quadrelli and Wallace 2004); its impacts on the climate, economy, and ecosystems of the NH; and its relationship to other North Atlantic circulation regimes, the reader is referred to Hurrell et al. (2003).

### *a. Atmospheric processes*

There is ample evidence that most of the atmospheric circulation variability associated with the NAO arises from the internal, nonlinear dynamics of the extratropical atmosphere (Thompson et al. 2003). In particular, interactions between the time-mean flow and synoptic-time-scale transient eddies give rise to a fundamental time scale for NAO fluctuations of about 10 days (Feldstein 2000). Since such intrinsic atmospheric variability exhibits little temporal coherence on longer time scales, it is likely that month-to-month and even year-to-year changes in the phase and amplitude of the NAO will remain largely unpredictable. Moreover, observed in-

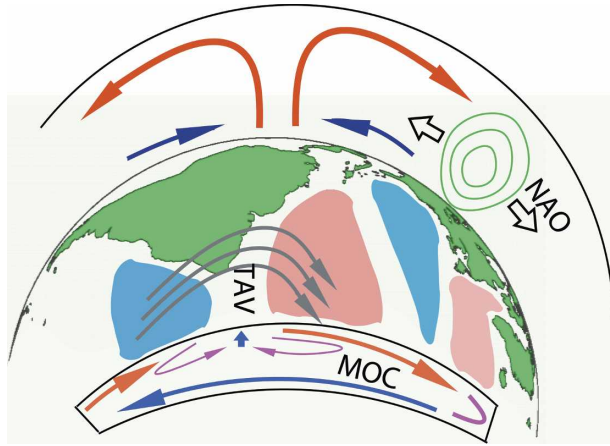


FIG. 1. Three major climate phenomena in the Atlantic sector. The NAO is associated with a meridional displacement of middle-latitude westerly winds (green contours of zonal wind velocity centered at  $40^\circ$ ). The NH tropical lobe of the SST anomaly tripole (the sign of which is associated with the negative index phase of the NAO) also is related to the second climate phenomenon, in which changes in the cross-equatorial SST gradient interact with the overlying atmosphere to produce changes in ITCZ rainfall. A warm anomaly north of the equator (which also can be induced during a warm ENSO phase) results in anomalous cross-equatorial winds (denoted by three light-gray arrows). During this phase, the ITCZ is displaced northward, producing dry conditions over the Nordeste and wet conditions over sub-Saharan Africa. Changes in the strength and position of tropical convection also may affect the position and strength of the midlatitude storm track (blue arrows) and thus the phase of the NAO. The schematic representation of the North Atlantic MOC depicts the northward transport of warm water and southward transport of newly ventilated cold water. Changes in the surface density within the subpolar gyre and subarctic basins can influence the strength of the overturning and heat transport. The high-latitude density can change as a result of anomalous advection of Arctic freshwater or changes in air–sea heat fluxes. The NAO systematically influences the strength of the MOC resulting from both effects. The tropical ocean has two additional shallow overturning cells (thin arrows) driven by Ekman transports in the trade winds zone. They can communicate surface temperature anomalies from subtropical regions to tropical upwelling zones and thus cause a delayed feedback on tropical surface temperatures. The three major climate phenomena in the Atlantic sector interact, which motivates a comprehensive investigation of Atlantic climate variability.

terannual and longer time-scale NAO fluctuations could entirely be a statistical remnant of the energetic weekly variability (Wunsch 1999; Stephenson et al. 2000). A stimulant for CLIVAR research, however, has been that this *climate noise paradigm* (Leith 1973; Madden 1976) fails to explain the enhanced interannual NAO variability observed during boreal winter over the last half of the twentieth century (Feldstein 2000, 2002; see also Thompson et al. 2000; Czaja et al. 2003), including an upward trend in indices of the NAO from

the late 1960s. Moreover, this trend is outside the 95% range of internal variability generated in multicentury integrations with different coupled climate models (Gillett et al. 2003a,b; Osborn et al. 1999; Osborn 2004; Stephenson and Pavan 2003), indicating that either the recent NAO behavior is due in part to forcing external to the coupled system, or all of the models are deficient in their ability to simulate North Atlantic interdecadal variability. Comparisons to NAO indices reconstructed from proxy data have also concluded that the recent behavior is unusual, although perhaps not unprecedented (Jones et al. 2001; Cook 2003).

At present, there is no consensus on the process or processes that are most likely responsible for the enhanced interannual variability of the NAO (Hurrell et al. 2003). One proposed source of the recent trend in the observed winter NAO index entails external forcing of the strength of the atmospheric circulation in the lower stratosphere on long time scales by reductions in stratospheric ozone and increases in greenhouse gas (GHG) concentrations (Gillett et al. 2003b). The ways by which stratospheric flow anomalies influence the troposphere, however, are not clear. Proposed mechanisms involve the effect of the stratospheric flow on the refraction of planetary waves dispersing upward from the troposphere (Chen and Robinson 1992; Hartmann et al. 2000; Shindell et al. 1999, 2001; Ambaum and Hoskins 2002), columnar adjustment consistent with a “downward control” principal (Haynes et al. 1991; Black 2002), and zonal-eddy flow feedbacks (Polvani and Kushner 2002).

#### b. The ocean’s influence

Another theory is that interactions between the oceans and atmosphere are important for understanding the recent temporal evolution of the NAO (Greatbatch 2000; Marshall et al. 2001; Wanner et al. 2001; Kushnir et al. 2002a; Czaja et al. 2003). Rodwell et al. (1999), Mehta et al. (2000), and Hoerling et al. (2001) all showed, for instance, that the phase and about 50% of the amplitude of the long-term variability in the wintertime NAO index could be recovered by forcing an atmospheric general circulation model (AGCM) with the observed time history of global SST and sea ice distributions (Fig. 2).

Interpretation of the oceanic role in affecting the phase and amplitude of the NAO hinges critically, however, on the relative influence of extratropical versus tropical SSTs. Rodwell et al. (1999), Sutton et al. (2001), and Peng et al. (2003) all demonstrated an NAO-like response to the leading pattern of SST variability over the North Atlantic, implying that the time history of NAO variability might be reconstructed from

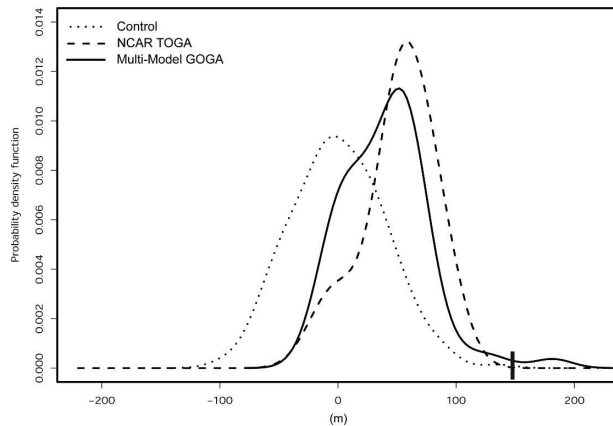


FIG. 2. Probability distribution functions (PDFs) of the January–March linear trend (1950–99) of an NAO index for a 67-member ensemble of simulations with SSTs prescribed over the world oceans Global Ocean Global Atmosphere (GOGA) across four AGCMs (solid), a 12-member ensemble of simulations with SSTs prescribed over the Tropics (TOGA) with the National Center for Atmospheric Research (NCAR) AGCM (dashed), and a long control integration with the NCAR AGCM forced by climatological annual cycles of SST and sea ice (dotted). The PDFs advance the view that the observed linear trend of  $149 \pm 42$  m (solid, vertical bar) is a combination of a strong tropically forced trend signal and an appreciable “noise” component having similar phase to the SST signal. It is worth noting that two of the SST-forced model realizations yield 50-yr trends exceeding that observed, but none do from the control integration. Adapted from Hurrell et al. (2004).

knowledge of North Atlantic SSTs alone. The ambiguity in this interpretation, though, is that the NAO itself is the dominant driver of upper-ocean thermal anomalies over the extratropical North Atlantic (e.g., Deser and Timlin 1997; Visbeck et al. 2003). Thus the level of North Atlantic climate predictability remains a controversial issue (e.g., Bretherton and Battisti 2000 versus Czaja et al. 2003; Eden and Greatbatch 2003).

Other studies indicate that ocean forcing remote from the extratropical North Atlantic could be important. Sea surface temperature variations in the tropical Atlantic, for instance, affect the strength and location of tropical Atlantic rainfall that could in turn influence the North Atlantic extratropical circulation (Xie and Tanimoto 1998; Rajagopalan et al. 1998; Venzke et al. 1999; Robertson et al. 2000; Sutton et al. 2001). Hoerling et al. (2001) and Hurrell et al. (2004) argued that the most germane analysis of North Atlantic climate variability must consider the role of forcing from the whole Tropics, not just the Atlantic sector. In particular, these studies used ensembles of experiments in which an AGCM was forced with the observed temporal evolution of SSTs over only tropical latitudes since 1950 and recovered about half the amplitude of the observed North Atlantic winter climate change (Fig. 2).

Moreover, they argued that changes in rainfall over the tropical Indo-Pacific region were of particular importance, a point further established by the multimodel idealized SST anomaly experiments of Hoerling et al. (2004; see also Miller et al. 2003; Lu et al. 2004). Sutton and Hodson (2003) also found evidence of tropical Indian Ocean forcing of the NAO on long time scales, but they concluded that over a longer time period (1871–1999) this effect was likely secondary to forcing from the North Atlantic itself. Branstator (2002) illustrated that NAO variations can be linked to a pattern of variability that circumscribes the hemisphere. This circumglobal teleconnection pattern arises from the waveguiding effect of the South Asian jet, and one potential way of exciting this pattern is through anomalies in tropical heating, especially over the tropical Indo-Pacific region. Schneider et al. (2003), in contrast, concluded that the observed trend in the boreal winter NAO index is more likely a residual of “inter-decadal time scale internal atmospheric noise.”

### c. Sea ice and land snow cover

The role of sea ice and land snow cover in affecting atmospheric variability has received very little attention, especially relative to the role of ocean anomalies. Here, too, the issue is whether changes in surface properties due to the NAO are able to modify its phase and amplitude in turn. Changes in sea ice cover in both the Labrador and Greenland Seas as well as over the Arctic are well correlated with NAO variations (Deser et al. 2000). Since changes in ice cover produce large changes in sensible and latent heat fluxes, it is reasonable to ask if there is a subsequent feedback onto the atmospheric circulation anomalies. Deser et al. (2000) suggest from observations that a local response of the atmospheric circulation to reduced sea ice cover east of Greenland in recent years is apparent. However, more recent AGCM experiments, with imposed ice cover anomalies consistent with the observed trend of diminishing (increasing) ice concentration during winter east (west) of Greenland, suggest a weak, negative feedback onto the NAO (Magnusdottir et al. 2004; Deser et al. 2004).

There is also some evidence that land processes are responsible for decadal changes in the NAO. For instance, Watanabe and Nitta (1999) found that the change toward a more positive wintertime NAO index in 1989 was accompanied by large changes in snow cover over Eurasia and North America (see also Cohen and Entekhabi 1999, 2001). Moreover, the relationship between snow cover and the NAO was even more coherent when the preceding fall snow cover was analyzed, suggesting that the atmosphere may have been forced by surface conditions over the upstream land-

mass. Support for a role of snow cover variations in modulating interannual NAO variability has also come from AGCM experiments (e.g., Watanabe and Nitta 1998; Gong et al. 2002).

The aforementioned sampling of divergent modeling results leaves many issues of land and oceanic (and furthermore tropical versus extratropical) forcing of NAO variability unanswered. Similarly, many questions remain about the role of interactions between the NAO and the lower stratosphere and its forcing by changes in atmospheric chemistry. Moreover, although the NAO is the dominant pattern of atmospheric circulation variability over the North Atlantic, it explains only a fraction of the total variance, and the presence of other recurrent circulation regimes means that most winters (including the last several) cannot be characterized by the canonical NAO pattern (e.g., Hurrell et al. 2003). Nonlinear analysis approaches, such as clustering algorithms, have also revealed interesting spatial asymmetries between the two phases of the NAO. For instance, Cassou et al. (2004) show that the positive NAO regime is shifted eastward relative to the negative NAO regime, so that its preferential excitement in recent decades explains the apparent eastward shift of the NAO pattern documented by Hilmer and Jung (2000; see also Ulbrich and Christoph 1999; Lu and Greatbatch 2002; Gillett et al. 2003b).

This new and significant understanding gained under CLIVAR has raised several important research questions, including especially how external forces might nudge the phase and amplitude of internal modes of atmospheric variability such as the NAO. Even a small amount of predictability could be useful considering the significant impact of the NAO on the climate, economy, and ecosystems of the NH.

### 3. Tropical Atlantic variability

Changes in the position and strength of the Atlantic marine intertropical convergence zone (ITCZ, sometimes referred to as AMI) are of major consequence to society on interannual to decadal time scales. The health and livelihood of millions of people, especially in the semiarid regions of northeast Brazil and sub-Saharan Africa, are particularly sensitive to interannual rainfall fluctuations associated with the intensity and position of the ITCZ. Such perturbations in the ITCZ, which are small compared to the large annual cycle, are a consequence of several factors, most notably changes in the local SSTs and atmospheric teleconnections between the tropical oceans. Moreover, land surface processes, such as the roles of soil moisture and Saharan dust, are potentially important in establishing the vari-

ability of tropical Atlantic climate. Xie and Carton (2004) provide an excellent, in-depth review of progress made over the last decade in the understanding of TAV and its predictability.

#### *a. Local modes of coupled variability*

One of the most prominent forms of associated Atlantic SST–ITCZ variability is the so-called “meridional mode” (also known as the interhemispheric or gradient mode). It is characterized by a significant shift in the rainfall distribution toward the hemisphere with anomalously warm SSTs relative to the other, accompanied by a cross-gradient atmospheric boundary layer flow in the same direction (Nobre and Shukla 1996; Chang et al. 1997; Chiang et al. 2002). This meridional displacement of the ITCZ is most pronounced during the boreal spring when the ITCZ is at its southernmost latitude and the SST gradient is flat. Observational analyses show that tropical Atlantic SST anomalies can be forced externally, most prominently by the El Niño–Southern Oscillation (ENSO) phenomenon and the NAO (e.g., Sutton et al. 2000), suggesting that the meridional mode can be interpreted largely as a tropical response to external forcing (Czaja et al. 2002; Czaja 2004). However, within several degrees latitude of the equator, the SST anomalies are associated with a surface wind response (Chang et al. 2000; Kushnir et al. 2002b; Saravanan and Chang 2004). Despite its limited influence, this feedback is important in defining the spatial and temporal characteristics of the meridional mode and its rainfall impact.

Many questions remain regarding the long-term (decadal) variability of this phenomenon, which several studies suggest is significant (e.g., Mehta 1998; Rajagopalan et al. 1998). Chang et al. (1997, 2001) suggested that the meridional mode is governed by an unstable, thermodynamic, coupled ocean–atmosphere interaction that gives rise to a quasi-oscillatory behavior on decadal time scales. Xie (1999) proposed a different coupled interaction, in which an initial heat flux–induced SST anomaly invoked an atmospheric response that enhanced the former on its equatorward side while it damped the SST anomaly on its poleward side. The time scale of this process is decadal because of the influence of the mean oceanic Ekman transport, which acts to move SST anomalies poleward. However, Kushnir et al. (2002b) concluded that the atmospheric response to SST anomalies is likely too weak to allow such a strong, oscillating coupling to occur. Thus the exact nature and cause for the apparent decadal variations of the gradient mode remain vague.

A second prominent form of coupled Atlantic SST–ITCZ variability is known as the “zonal mode” (also

referred to as the equatorial or Atlantic Niño mode). It is characterized by a less impressive shift of the ITCZ toward the equator, when the latter is anomalously warm (Zebiak 1993; Carton and Huang 1994) and the thermocline in the east is anomalously deep (Philander 1986). Typically, the zonal mode is most pronounced during boreal summer when equatorial SST anomalies often exceed  $1^{\circ}\text{C}$  during the peak of the event. In contrast to the Pacific ENSO, warm and cold events in the Atlantic are shorter, smaller in amplitude, and account for a smaller fraction of the total variance. About 14 Atlantic Niño events have occurred in the equatorial Atlantic during 1963–2003 at about 2–3-yr intervals. However, the 1974–83 decade experienced only two events compared to four in each of the other three decades. The reasons for this are unknown but may relate to changes in subduction in the tropical Atlantic, to how the Atlantic responds to the Pacific ENSO, or to interactions with decadal-to-multidecadal modes of variability, such as the AMO, within the basin.

Pronounced warm events manifest off the coast of Angola and northern Namibia tend to be connected to variability in the equatorial Atlantic in terms of both wind modulations and upper-ocean temperature, leading to the term Benguela Niño (Shannon et al. 1986). The Benguela Niño is the most prominent mode of low-frequency variability in the southeast Atlantic and has significant impacts on local fisheries and southern African rainfall (e.g., Hirst and Hastenrath 1983; Rouault et al. 2003). Interannual SST fluctuations in the Angola–Benguela Area (ABA) and the central and eastern tropical Atlantic appear to often be strongly related. Atlantic Niño and Niña events tend to peak in June–July, a few months after the largest SST anomalies in the ABA (March–April). The timing of the tropical Atlantic thermocline response to trade wind anomalies relative to the annual cycle could explain why SST anomalies in the ABA often appear to lead the equatorial Atlantic anomalies (e.g., see Reason et al. 2006).

#### *b. Remote influences on TAV*

In addition to regional coupling between SST and ITCZ variability, the ITCZ can also be directly influenced by atmospheric circulation changes during ENSO events (Hastenrath et al. 1987; Klein et al. 1999; Sutton et al. 2000; Chiang et al. 2002). El Niño leads to a suppression of the ITCZ intensity during boreal winter and early spring and is partially embedded in the meridional mode pattern. This influence can be understood in terms of the response of the global Tropics to the large perturbation in convective heating over the equatorial Pacific, which leads to a tropospheric warm-

ing and stabilization of the other tropical regions (Chiang et al. 2002).

While more has been learned about the role of such direct tropical atmospheric teleconnections in TAV, CLIVAR research is also beginning to highlight pathways through which the tropical Atlantic interacts with off-equatorial latitudes as well. One of them is via changes in the atmospheric circulation, such as the NAO, which can modify the northern trade winds (Sutton et al. 2000; Czaja et al. 2002; Melice and Servain 2003). Another involves changes in tropical SSTs and stratification due to modulation of the upper-ocean circulation, either via changes in the shallow subtropical cells (STCs) or changes in the deeper-reaching MOC.

The Atlantic STCs are shallow overturning circulations confined to the upper 500 m (Schott et al. 2004, 2005). They connect subduction zones of the subtropical ocean with upwelling zones in the Tropics, as schematically shown in Fig. 3. The subsurface STC branches carry thermocline water to the equator either in western boundary currents (after circulating across the basin in the subtropical gyres) or directly in the ocean interior. The thermocline flows supply eastward undercurrents that upwell along the equator or at the eastern boundary. The STCs are driven by poleward surface currents (largely Ekman transports), which return the upwelled waters to the subtropics (e.g., Malanotte-Rizzoli et al. 2000).

The role of STCs in low-frequency climate variability may involve two principal mechanisms. First, anomalous temperature anomalies generated at the surface in the extratropics may subduct and advect to the tropical thermocline following a subsurface pathway in which diffusion is small (Gu and Philander 1997). Second, the strength of the STCs themselves may vary and cause a change in the tropical thermocline through enhanced upwelling (Kleeman et al. 1999). Observed and modeled interannual variability seems consistent with the latter mechanism. On decadal and longer time scales, however, the ventilation of the thermocline may be important as anomalous water masses originating from the extratropics slowly fill up the thermocline, connecting both North and South Atlantic signals to the Tropics.

Various aspects of the Atlantic STCs exhibit interannual-to-decadal variability. The Ekman transport divergence between  $10^{\circ}\text{N}$  and  $10^{\circ}\text{S}$  shows variations of several Sverdrups ( $1\text{ Sv} \equiv 10^6\text{ m}^3\text{ s}^{-1}$ ) in amplitude (Schott et al. 2004), and temperature variability at thermocline levels has been documented (Zhang et al. 2003). The transfer of South Atlantic thermocline waters by North Brazil Current rings also undergoes

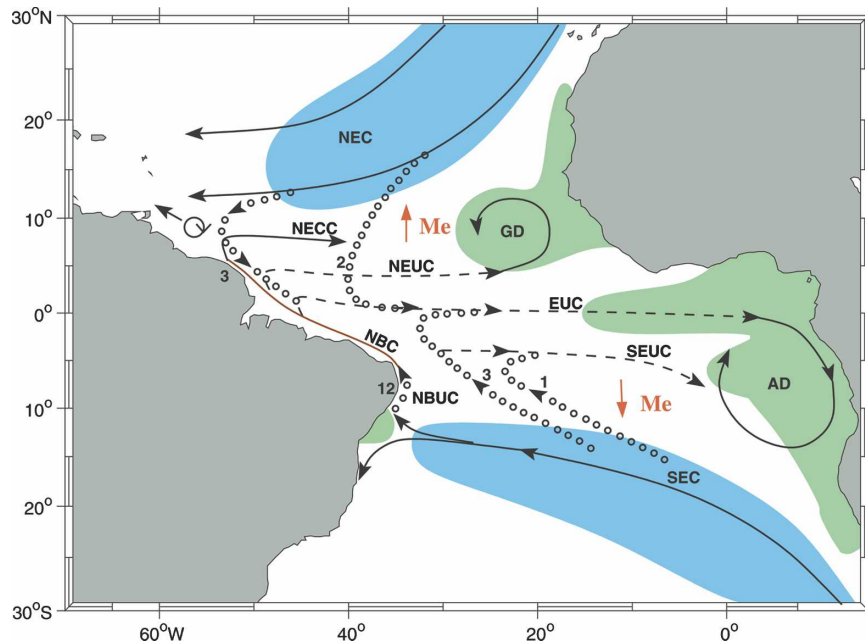


FIG. 3. Schematic representation of the Atlantic STC circulation with subduction (blue) and upwelling (green) zones that participate in the STC. Current branches participating in STC flows are the North and South Equatorial Current (NEC, SEC) and Countercurrent (NECC), Equatorial Undercurrent (EUC), North and South Equatorial Undercurrent (NEUC, SEUC), and the North Brazil Current and Undercurrent (NBC, NBOC); GD and AD are the Guinea and Angola domes. Interior equatorward thermocline pathways are dotted; transport estimates are marked for interior and western boundary pathways (from Schott et al. 2004).

longer-period variations (Goni and Johns 2003), which likely has consequences for the distribution of water masses and STC pathways.

The Atlantic MOC can also affect the tropical Atlantic circulation and climate. For example coupled model simulations (Dong and Sutton 2002) show that a significant reduction of the MOC, introduced by freshwater input to the subpolar North Atlantic, leads to important SST changes in the tropical Atlantic, resulting in the development of a dipole SST anomaly in the Tropics after about 6 yr (Fig. 4). Perhaps relatedly, changes in composition of upper-limb water masses entering the tropical zone from the south can alter the stratification in the Tropics and thus alter local air–sea coupling and the mean position and strength of the ITCZ.

On long time scales the observed basinwide changes in SST (i.e., the AMO) are believed to be associated with changes in the MOC (e.g., Manabe and Stouffer 1988; Vellinga and Wood 2002; Latif et al. 2006). These multidecadal variations in Atlantic SSTs have played a key role in driving the devastating drought that has consumed the entire sub-Saharan belt during boreal summer since the late 1960s (e.g., Folland et al. 1986; Ward 1998; Hoerling et al. 2006), although the steady warm-

ing of the Indian Ocean may have also played a role (e.g., Giannini et al. 2003; Bader and Latif 2003; Lu and Delworth 2005).

Another important aspect of the ocean's dynamical response to a change in the MOC is the so-called "equatorial buffer" (Kawase 1987; Johnson and Marshall 2002), which limits the rapid communication of MOC-related anomalies across the equator between the two hemispheres. It is likely that a change in the MOC would also substantially impact the structure of the STCs. The present pattern, in which the southern cell of the Atlantic STC is dominant over the northern cell (Fig. 3), is believed to be a direct result of the MOC, which cuts off most of the supply of thermocline waters to the equator from the northern subtropics. It has been suggested that a decrease in the MOC would lead to a greater symmetry of the cells and an increase in NH waters supplied to the equatorial undercurrent (EUC) that feeds equatorial upwelling (e.g., Fratantoni et al. 2000; Jochum and Malanotte-Rizzoli 2001; Hazeleger et al. 2003).

#### 4. Meridional overturning circulation

Variations in the Atlantic MOC appear to have some predictability (Griffies and Bryan 1997; Collins et al.

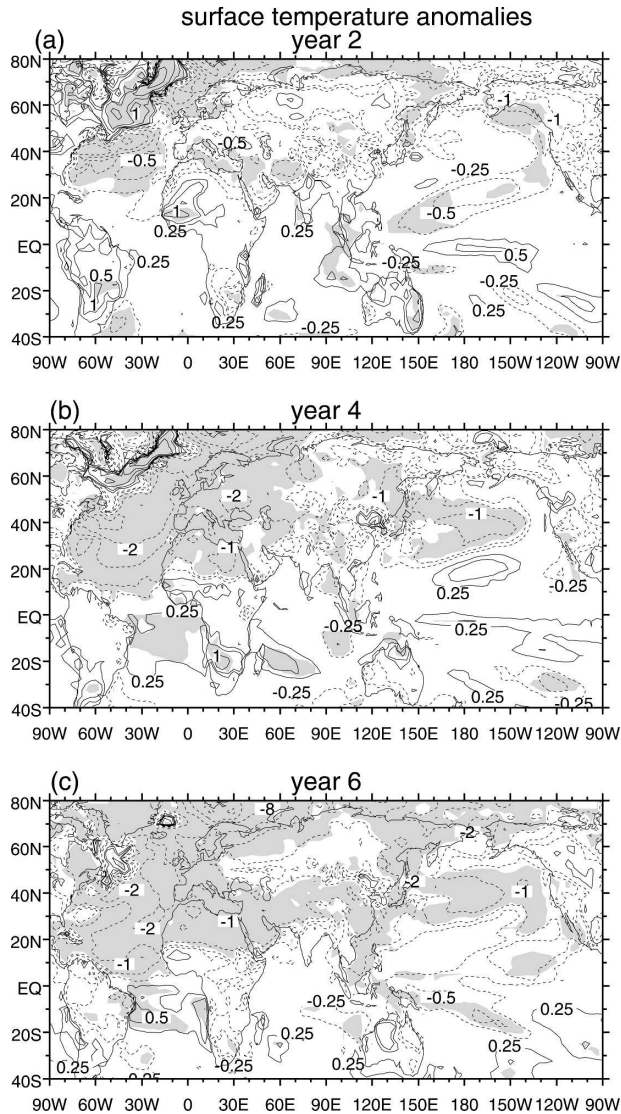


FIG. 4. Ensemble mean annual SST anomalies ( $^{\circ}\text{C}$ ) in years (a) 2, (b) 4, and (c) 6 after reduction of the MOC by a subpolar freshwater anomaly (from Dong and Sutton 2002). Shading indicates statistical significance at the 95% level.

2003), and, together with wind-forced decadal variability of the subtropical gyres (e.g., Groetzner et al. 1998), they may contribute to climate variations in the Atlantic sector on decadal to multidecadal time scales. To fully exploit this predictability, it is essential that CLIVAR scientists develop both deeper understanding of the underlying physical mechanisms and a comprehensive network of observation.

#### a. Relationship to poleward heat transport

At many latitudes the poleward heat transport in the Atlantic is closely tied to the MOC. The mechanisms

contributing to this heat transport vary on different time scales (e.g., Eden and Willebrand 2001; Dong and Sutton 2002; Visbeck et al. 2003). The directly forced surface Ekman transport with barotropic compensation gives the fastest response to atmospheric forcing, over time scales as short as several days (Visbeck et al. 2003). The barotropic horizontal gyre circulation governed by Sverdrup dynamics responds over the intraseasonal time scale. The essentially linear nature of the Ekman and Sverdrup contributions to the poleward heat transport accounts for the robustness of model estimates of seasonal (Böning et al. 2001; Jayne and Marotzke 2001) and interannual to pentadal (Beismann et al. 2002) variations in poleward heat transport. Model results suggest that changes in the thermohaline circulation dominate decadal and longer time-scale variations in heat flux (Böning et al. 1996), but with variations in wind stress curl also contributing (Dong and Sutton 2002).

#### b. Processes

The supply of North Atlantic Deep Water (NADW) that makes up the lower limb of the MOC is determined by two main contributions: the formation of LSW and the overflow of waters from the Nordic Seas.

##### 1) CONVECTION AND WATER MASS TRANSFORMATION

Surface buoyancy forcing transforms lighter waters to heavier waters at mid- to high latitudes, and this transformation takes place through seasonally modulated convection. Two rough classifications of convection sites can be defined based on their relation to the ambient circulation. Gyre convection (e.g., LSW and Greenland Sea Deep Water) typically involves annual reexposure of the preceding winter's convection product. Because these gyre pools mostly recirculate, they damp variability of surface forcing. Pathway convection also involves reexposure of the preceding winter's convection product, with a substantial buoyancy increment further increasing its density during each reexposure, so that over several seasons a long pathway displacement and a significant density change accumulate. An example of pathway convection is the progressive transformation along the pathway carrying waters from the northwestern subtropical gyre (Newfoundland Basin) to the eastern subpolar gyre (Rockall Plateau area) as well as within the Norwegian Current region.

North Atlantic convection sites exhibit significant interannual variability. In the western subpolar gyre, most of the variability is reflected in the temperature history of the LSW (Curry and McCartney 2001). Con-



vection in the Labrador Sea generally varies out of phase with convection in the Greenland Sea, and in phase with the NAO index (Dickson et al. 1996; Hurrell and Dickson 2004). Model studies indicate that NAO-related variations in the heat fluxes over the Labrador Sea induce a 2–3-yr lagged response of the MOC (Eden and Willebrand 2001; Häkkinen 1999).

## 2) OVERFLOWS

The major overflows into the North Atlantic Ocean are the Greenland–Scotland Ridge overflows and the Gulf of Cadiz overflows. Their limited spatial scales make these sites attractive for efficient monitoring, and more is known about transports at overflow sites than at most other parts of the oceans. On the other hand, the limited spatial scales (the width of the Faroe Bank Channel is <20 km) and deformation radii (<15 km for the Greenland–Scotland overflows) mean that these overflows need to be parameterized in ocean models used for climate prediction.

The exchange across the Greenland–Scotland Ridge includes roughly 5 Sv of dense overflow water and 2–3 Sv of lighter outflow water. Because of their low temperature, both components are important to the Atlantic heat budget, and because of the outflow water's low salinity it is extraordinarily important for setting conditions downstream—pulses of freshwater (including ice) outflowing through the Denmark Strait have been observed to effectively shut off formation of LSW (Lazier 1995).

Rough estimates of the average strength of the overflows can successfully be made through simple hydraulic control theory (e.g., Whitehead et al. 1974), and measurements of the velocity fields over the Greenland–Scotland Ridge indeed indicate supercritical flow in the straits (Borenäs and Lundberg 1988; Käse et al. 2003). However, supercritical flow in the straits does not translate into knowledge of the flux strength through those straits—that depends (in no simple nor fully understood manner; see the discussion by Helfrich and Pratt 2003) on upstream conditions that vary in time.

As the dense waters overflow the sill areas and begin to accelerate and descend into the North Atlantic, they entrain surrounding waters (Price and Baringer 1994). Precisely how much entrainment occurs, the location of the entrainment, and the sensitivity of the entrainment to various external parameters is a topic of ongoing investigation.

### c. Impacts

While many coupled ocean–atmosphere model integrations suggest that variations in the MOC have a sig-

nificant influence on SST, the influence on the atmosphere has been more difficult to establish (e.g., Delworth and Mann 2000; Kushnir et al. 2002a). As discussed earlier, however, coupled model experiments in which the MOC is abruptly halted show a significant tropical response (Fig. 4). These abrupt changes are rapidly communicated to the Tropics via oceanic Kelvin waves (Kawase 1987; Yang 1999; Johnson and Marshall 2002; Getzlaff et al. 2005), setting up an anomalous cross-equatorial SST gradient. This gradient leads to a shift in the ITCZ, which perturbs rainfall across the basin and in turn excites a global atmospheric response through the radiation of planetary Rossby waves (e.g., Robertson et al. 2000; Sutton et al. 2001).

On decadal and longer time scales, as previously mentioned, the so-called AMO is believed to reflect changes in the strength of the Atlantic MOC (e.g., Schlesinger and Ramankutty 1994; Delworth and Mann 2000). The AMO has been linked to winter temperatures at high latitudes (Delworth and Knutson 2000; Johannessen et al. 2003), the multidecadal drought over sub-Saharan Africa (e.g., Ward 1998), and more recently to rainfall changes over parts of the United States (e.g., Enfield et al. 2001; Sutton and Hodson 2005). The MOC has also been suggested as a plausible driver of massive, abrupt, and widespread climate changes across the NH and the globe evident from paleoclimate records (e.g., Alley et al. 2003).

### d. Climate change

Potential changes to the Atlantic MOC have been a focus of many climate studies (e.g., Cubasch et al. 2001). Most (but not all) global coupled ocean–atmosphere models project some weakening of the Atlantic MOC in response to increasing GHG concentrations, but the nature and mechanisms for the changes vary considerably from model to model.

In most models that show MOC weakening, warming and freshening of the surface waters of the North Atlantic reduce both the vertical and meridional density gradients (Dixon et al. 1999; Mikolajewicz and Voss, 2000; Thorpe et al. 2001). Other models, however, exhibit little or no weakening of the MOC, despite GHG-induced warming of the upper ocean and an enhanced hydrological cycle that increases the flow of freshwater into the Arctic and North Atlantic. Latif et al. (2000), for instance, found no change in the strength of the MOC in their coupled model as GHG concentrations increased. They postulated a stabilizing mechanism that involved a warming of the tropical eastern Pacific. This Pacific warming led to less precipitation over the Amazon and, thus, reduced river flow to the Atlantic. In turn, salinity in the tropical Atlantic increased, which

when transported poleward increased the upper-ocean density and thereby counteracted the local North Atlantic warming and freshening. Delworth and Dixon (2000) suggested another mechanism for MOC stability with future GHG changes that involved an intensification of the NAO (e.g., Gillett et al. 2003b). In their experiments, the local warming of the North Atlantic was offset by the enhanced westerly winds associated with the intensified NAO.

The range of modeling results indicates substantial uncertainty in our ability to project the response of the Atlantic climate system to increasing GHG concentrations. Banks and Wood (2002) used a coupled ocean–atmosphere model to suggest that many decades of observations would be required to detect a change in the MOC, because of the relatively small signal-to-noise ratio. Attribution of such a change is even more difficult, given the variety of modeling results.

## 5. Global connectivity

Through atmospheric teleconnections, land surface processes, and exchanges of heat, mass, and salt between the North Atlantic and the Arctic and Southern Oceans, climate variability of the Atlantic basin affects and is affected by other parts of the global climate system through complex mechanisms that are, as yet, not fully appreciated. Some potential links to remote portions of the Tropics have already been mentioned, for instance concerning forcing of the NAO from the tropical Indo-Pacific region or the role of ENSO in TAV. A thorough discussion of these aspects is beyond the scope of this article; however, the following presents a brief description of notable links to the other World Ocean basins.

### *a. Interactions with the Arctic Ocean*

Many recent studies have shown that the thermohaline exchanges between the North Atlantic and the Arctic Oceans do have climatic significance. The warm, moist southerly airflow directed along the eastern boundary of the North Atlantic under the increasingly NAO positive index conditions of recent decades has been responsible, at least in part, for driving a warmer (Dickson et al. 2000), stronger (e.g., Orvik et al. 2001), and probably narrower (Blindheim et al. 2000) flow of Atlantic water northward to the Barents Sea and into the Arctic Ocean since the 1960s (e.g., Swift et al. 1997; Carmack et al. 1997; Grotefendt et al. 1998; Karcher et al. 2003). The main fluxes of freshwater passing south from the Arctic Ocean to the North Atlantic have now been measured and appear self-consistent, with roughly

0.1 Sv passing south on either side of Greenland. It is the anticipated increase in these freshwater outflows under greenhouse gas forcing that has been implicated in model experiments with a slowdown of the MOC and associated effects on climate (e.g., Delworth and Dixon 2000; Stocker et al. 2001; Vellinga and Wood 2002). Thermohaline effects of the Great Salinity Anomaly provide a case in point (Häkkinen 1999; Haak et al. 2003).

“Switchgear” mechanisms, linked to the phase of the NAO, may impose a shared time dependence on these two main freshwater streams (Proshutinsky and Johnson 1997; McLaughlin et al. 2002; Steele et al. 2003). Decade-to-century salinity records provide clear evidence of a rapid increase in the outflow of freshwater from the Arctic to the North Atlantic over the past 3–4 decades (e.g., Dickson et al. 2002, 2003; Blindheim et al. 2000). As the main receiving volume for these northern inputs, the surface, intermediate, deep, and abyssal layers of the Labrador Sea all freshened between the mid-1960s and the mid-1990s (Lazier 1995), and this freshening has been tracked down the American seaboard to 8°N by 2000 (R. Curry 2004, personal communication).

Links to global change remain to be firmly established. While the type and scale of changes in North Atlantic Ocean salinity are consistent with an amplification of the water cycle (Curry et al. 2003), no convincing evidence has been found of a significant, concerted slowdown in the Atlantic MOC. Since high-latitude freshwater inputs from Eurasian rivers, from the melting of Arctic sea ice, and from the Greenland ice sheet are all predicted to increase during this century, however, effects on MOC overturning cannot be ruled out in the longer term.

### *b. Interactions with the Southern Ocean*

Export of NADW through the South Atlantic to other ocean basins requires a compensating northward flow through the South Atlantic and across the equator. Thus, the South Atlantic is the gateway by which the Atlantic MOC communicates with the global ocean, exchanging heat and mass with the Indian and Pacific Oceans via the Southern Ocean and around South Africa (Stramma and England 1999). These interocean links make possible the unique global reach of NADW and are believed to be of critical importance for the global thermohaline circulation and its variability (e.g., Rahmstorf and England 1997).

Waters of Pacific, Indian, Atlantic, and Southern Ocean origin merge and blend in the Argentine and Cape Basins, where large sea–air buoyancy fluxes and mixing lead to intense vertical mixing, convection, and

subduction. Numerical simulations and observations indicate that the water mass characteristics of the upper limb of the South Atlantic branch of the global thermohaline circulation is largely determined at these highly energetic eastern and western boundary regions (e.g., Donners and Drijfhout 2004).

The varying ratio between the input of warm and salty Indian Ocean waters around South Africa and relatively cool and fresh Pacific waters around South America, and the varying intensity of the water mass transformation processes in the Argentine and Cape Basins, influences the buoyancy budget and the overturning of the Atlantic on very long time scales. The characteristics of the northward upper-layer fluxes appear to depend on time and space scales set by the flow conditions around South Africa (Richardson et al. 2003) and the basin-scale South Atlantic circulation, both influencing the upper-layer waters of the North Atlantic. Since the South Atlantic circulation depends on interocean fluxes, it can be argued that uncertainties in the warm- and cold-water contributions to the upper limb of the Atlantic MOC are partly responsible for large discrepancies in current estimates of the South Atlantic meridional heat flux (Ganachaud and Wunsch, 2000; Sloyan and Rintoul 2001).

## 6. Challenges

The goals of the CLIVAR program are to improve our ability to observe, assess, attribute, and predict climate variability and change. To meet these goals three major challenges must be addressed: 1) to build, improve, and sustain a global climate observing system; 2) to develop a synthesis strategy that allows full understanding and attribution of observed change; and 3) to understand the sources of predictability and develop prediction systems.

### *a. Climate observing systems*

One of the foremost challenges facing the climate community is the design of a robust and efficient observing system that can provide the key state variables (e.g., Trenberth et al. 2002, 2006). In addition, it is crucial that process research be embedded in, and provide guidance for, the design of a sustained observing system. How should such an observing system be organized and maintained?

Within the present organizational structure of CLIVAR, observing activities are being planned in three main categories: sustained observations, process studies, and enhanced monitoring. Sustained observations are the backbone of the observing system and must provide quasi-operational fields of key variables,

including SST; atmospheric winds, temperature, water vapor, and clouds; upper-ocean temperature and salinity; surface momentum, heat, and freshwater exchanges; ocean circulation (currents); heat and water transports and budgets; and sea level and sea ice.

The measurement platforms available for these purposes include satellites, radiosondes, ships, moored surface and subsurface buoys, drifting surface buoys, and autonomous floats. Each of these platforms has its inherent strengths and weaknesses, and the ideal combination of these resources to achieve accurate fields with the needed spatial coverage and resolution to feed into climate models is a topic of utmost importance to the realization of CLIVAR goals. By definition, sustained observations are those observations acquired on a permanent basis throughout the lifetime of CLIVAR and presumably beyond. They are provided by nations and need to be coordinated through initiatives such as the Global Environmental Observing System of Systems (GEOSS).

Process studies are those observations that are required to augment the network of sustained observations to improve understanding of particular regions and/or key processes. In particular, they are intended to quantify specific processes for which present treatment in climate models is inadequate. Numerous ideas for such process studies have been put forward, and relevant examples in the Atlantic include studies of the upper-ocean heat balance to determine the roles of surface fluxes, mixing, and three-dimensional advection in the evolution of oceanic SST, especially in regions where the SST potentially affects the atmosphere; the structure and variability of the marine ITCZ; oceanic convection and water mass formation; dense overflows and mixing processes controlling the formation of deep waters; oceanic “teleconnections,” where processes remote in time or space from other regions can impact the evolution of SST; and mesoscale features and their role in large-scale ocean transports.

These studies will play a crucial role in CLIVAR and are the means by which new information will be gathered on the physical processes controlling the evolution of seasonal and interannual climate fluctuations. They will be used to test the veracity of models and, where applicable, to develop new parameterizations for unresolved physics in the models. As presently envisioned these process studies are assumed to be of relatively short duration, not to exceed several years.

Enhanced monitoring is presently the least well developed part of the overall observing system strategy, and in some sense can be viewed as representing those observations that are needed to fill important gaps between the “sustained” and “process study” categories.

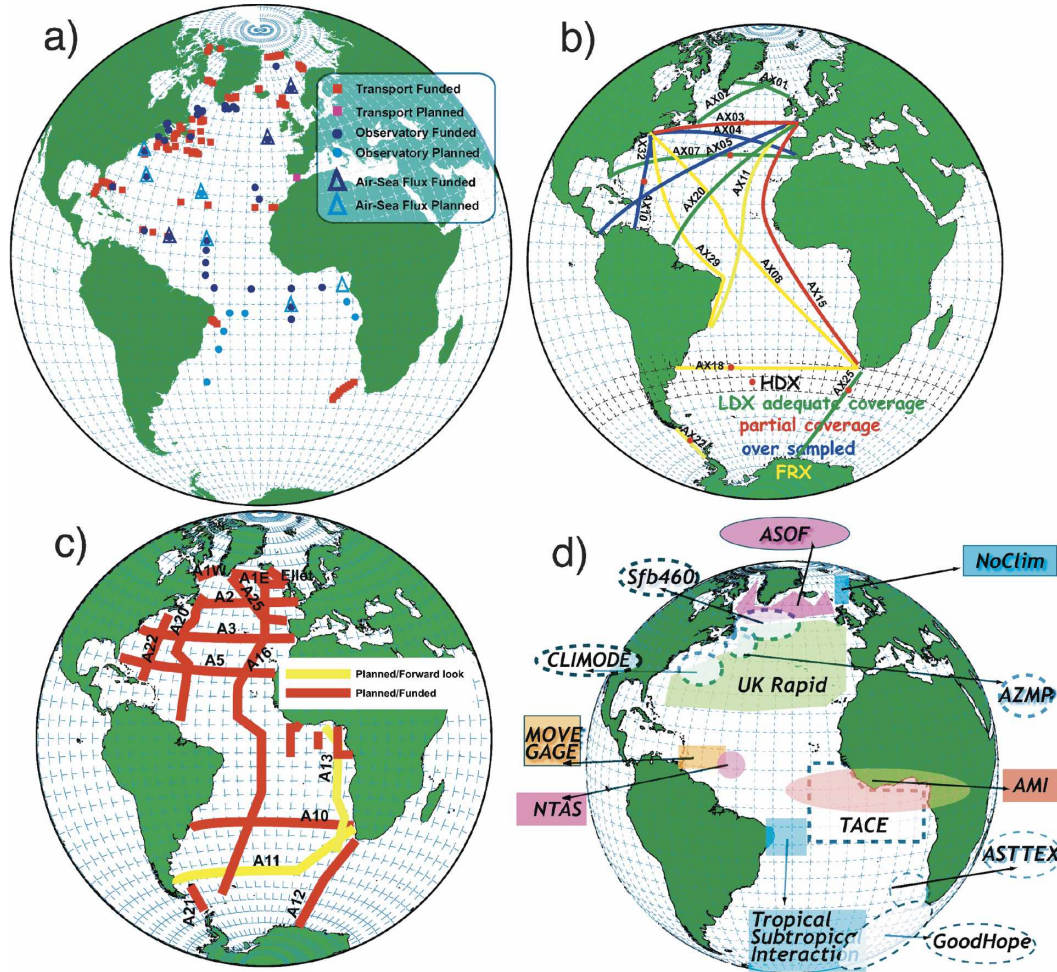


FIG. 5. Key elements of the ocean observing system relevant for CLIVAR in the Atlantic sector. (a) Time series stations are used as reference sites for air–sea fluxes, ocean stratification, and ocean transports. Others are part of the Atlantic tropical moored surface buoy array [Pilot Research Moored Array in the Tropical Atlantic (PIRATA)]. (b) Upper-ocean heat content is documented by profiling floats (ARGO; not shown) and repeat expendable bathythermograph (XBT) surveys are color coded by the frequency of the repeats. (c) Full water column changes in temperature, salinity, and chemicals such as  $\text{CO}_2$  and chlorofluorocarbons (CFCs) are documented by a network of trans-basin hydrographic sections. The repeat frequency varies from biannual in the subpolar region to once per decade for the complete network. (d) CLIVAR benefits from a collection of process studies. Some of them have a short duration of 1 or 2 yr, while others are of the enhanced monitoring type such as the German SFB460 and the U.K. Rapid Climate Change (RAPID) programs.

This dubious position is perhaps best indicated by the fact that no precise definition of “enhanced monitoring” has yet been put forth under CLIVAR. Two types of enhanced monitoring can nevertheless be envisioned: enhancements needed in either time or space to resolve features that have importance for climate modeling and forecasting; and enhancements to study processes that require more than a short-term process study to fully understand. Formulating an effective, multiagency, and multinational strategy to identify these latter processes and allocate funding for them is one of the key challenges facing the CLIVAR commu-

nity. Both of these categories may ultimately be expected to lead to transitions into the sustained observations network.

An outline of the present observing system for the Atlantic is shown in Fig. 5. It includes various observing system components that are now in place or planned for the near future. (Further details, including more on specific projects and points of contact, may be found at: <http://www.clivar.org/organization/atlantic/IMPL>.)

From a scientific standpoint, the observing system must provide the needed input to and constraints on the synthesis systems ultimately necessary for the diagnosis

of the climate system. It must also provide a suitable balance between the real-time observations needed for climate prediction and other observations needed to fully characterize the state of the climate system. The urgency to provide a capability for prediction cannot outstrip the need for adequate documentation of the present and past state of the climate. In the ocean this means a suitable allocation of resources for monitoring deep changes of temperature and salinity, below the reach of profiling floats, as well as carbon and other tracer inventories. It also means that key indices of circulation need to be measured, including shallow and deep ocean western boundary currents, exchanges between the Atlantic, Arctic, and Southern Oceans, and fluxes of heat, freshwater, and carbon across key latitudes within the basin. Over the years a continuous infusion of new technology has modernized and enhanced the CLIVAR observing capabilities. The observing systems must retain the flexibility to encourage the development and effective utilization of new technology as it becomes available, while at the same time maintaining a disciplined array of proven measurement systems in its sustained observations network.

Specific needs of CLIVAR for the Atlantic include the following:

- significant enhancements of sustained observations of the tropical Atlantic ocean, land, and troposphere; and
- implementation and sustainment of an in situ observing system for monitoring the MOC including key regions in the South Atlantic.

#### *b. Synthesis strategy*

To improve understanding of climate variability in the Atlantic sector and the accuracy of climate predictions, an important prerequisite is an optimal description of the evolving state of the coupled ocean–atmosphere–land system over an extended period. A minimum objective would be determination of optimal estimates of the time-varying circulation of the Atlantic Ocean and overlying atmosphere, including surface fluxes and land conditions, back to at least the 1950s, and at sufficiently high spatial resolution to capture most of the critical dynamical processes. This optimal description of climate variability can only be obtained through a rigorous synthesis of models and observations, both in situ and remotely sensed (e.g., Trenberth et al. 2006), although the quality of such synthesis products in historically data-sparse regions such as the South Atlantic will remain limited. While a number of analyses and reanalyses have been carried out for the global atmosphere, such activities are still very much in their

infancy for the oceans and the land. Among the benefits that a synthesis activity of this nature will provide are a dynamically consistent description of the evolving climate system state that can be used to identify and analyze patterns of climate variability; initial states, air–sea fluxes, and other parameters required as boundary conditions for climate process studies and climate predictions (e.g., Palmer et al. 2004); estimates of derived quantities such as poleward transports of heat and freshwater, and the strength of the MOC; a rigorous framework for designing and enhancing future observing systems; model predictions that can be used as proxies in data quality control; and a framework for identifying systematic model errors, optimizing model parameters, and improving model parameterizations.

A second type of synthesis is concerned with new parameterizations and generic improvements of climate models. A framework has been proposed and implemented within U.S. CLIVAR by which teams of scientists from the observational and modeling communities work together to propose, implement, and test new ways to represent unresolved processes in large-scale climate models. The use of large sets of field data and tests in several different climate models ensures input from a broad range of expertise and much faster development and validation of model improvements.

Of immediate concern for CLIVAR are the following:

- continued efforts toward improved atmospheric reanalysis;
- improvements of data assimilation systems for the Atlantic Ocean (especially the treatment of salinity); and
- development of data assimilation methods for the initialization of decadal MOC forecasts.

#### *c. Predictability and prediction systems*

Efforts to improve climate prediction are at the heart of CLIVAR. In the Tropical Ocean Global Atmosphere (TOGA) experiment, and initially in CLIVAR, much attention was focused on the problem of forecasting ENSO and its climate impacts, particularly those in the Indo-Pacific region. Forecasting the climate of the Atlantic region has just recently emerged as a high-profile activity: a number of centers have begun routinely issuing seasonal forecasts for various aspects of Atlantic climate (as yet with only moderate success). Furthermore, significant progress has been made both in identifying potentially predictable phenomena and in developing statistical and dynamical prediction systems, including useful output for probabilistic prediction from multimodel ensemble systems (Palmer et al.

2004). However, numerous challenges remain. Here we summarize some of the most important issues with regard to understanding the sources of predictability as identified at a recent (April 2004) CLIVAR Workshop on “Atlantic Predictability” (see online at <http://www.met.reading.ac.uk/courses/clivar>).

## 1) UNDERSTANDING SOURCES OF PREDICTABILITY

### (i) *Seasonal time scales*

There is evidence of seasonal climate predictability on all the continents that surround the Atlantic basin. As elsewhere on the planet this predictability arises primarily from the influence of slowly changing oceanic and land surface conditions and is generally higher in the Tropics than in the extratropics. However, many issues regarding the detailed mechanisms that govern predictability are poorly understood. Advancing understanding of these mechanisms is a key challenge.

Capitalizing on advances in ENSO prediction and extending them to the Atlantic basin is of primary importance. ENSO directly impacts the Atlantic sector, most strongly in the Tropics but also in the northern (e.g., Sutton and Hodson 2003) and southern extratropics (e.g., Reason et al. 2000; Reason and Rouault 2002; Colberg et al. 2004). The most robust features of these impacts have been characterized, but there is a need (e.g., Mathieu et al. 2004) to better understand (a) the origin of the differences between individual ENSO events and the extent of their predictability, (b) the role of Atlantic ocean conditions in modifying the direct ENSO influence (particularly in the Tropics; see below), (c) the impacts of ENSO on the South Atlantic region; and (d) decadal variability of the ENSO teleconnections to Atlantic sector climate.

Within the Atlantic, the best prospects for advancing climate prediction on seasonal-to-interannual time scales lie in the Tropics. Here the sensitivity of the climate (particularly the ITCZ-related rainfall) to boundary forcing is significant and the potential benefits to society are large. In particular, a skillful prediction of SST can yield a reliable prediction of rainfall anomalies in the semiarid regions of northeast Brazil and West Africa. The major stumbling point is the prediction of SST (Goddard and Mason 2002). Both statistical and dynamical models have difficulties, and this partly reflects an incomplete understanding of the processes that govern SST evolution.

In the tropical southeast Atlantic, there is some evidence that large warm and cold events (Benguela Niños and Niñas) may have potential predictability (Florenchie et al. 2004). These events have large subsurface expression in the equatorial region and manifest signifi-

cant SST anomalies near the Angola–Benguela frontal zone. There is evidence of a linkage between trade wind anomalies over the western equatorial Atlantic and the generation of Benguela Niños and Niñas 2–3 months later (Florenchie et al. 2003). There may also be a connection with Atlantic ENSO-like equatorial warming events (Florenchie et al. 2004). The challenge is to better understand the relationships between equatorial and Benguela events and to explain why equatorial wind modulations do not always lead to significant SST anomalies off Angola.

There is a related need for advances in understanding the basic processes that control the climate of the region. Key issues include determining the (a) interaction between the diabatic heat sources in the Congo and Amazon basins, the factors that control the strength of these heat sources, and how their interaction shapes regional climate; (b) factors that control the South Atlantic convergence zone (SACZ) and the subtropical anticyclone and their related climate impacts; and (c) controls of SST and its persistence in the tropical South Atlantic.

In the extratropical North Atlantic there is evidence from observational and model studies of some predictability of the NAO (e.g., Rodwell 2003; Palmer et al. 2004). NAO persistence is somewhat greater than that expected for a first-order autoregressive process, and in recent decades there has been significant persistence from winter to winter. The origin of this persistence is not clear although oceanic, land surface, or stratospheric influences could all play a role. There is a need to extend current modeling work to the coupled system to investigate, for example, the role of reduced thermal damping and reemergence in influencing the NAO. There is also a need for further work to understand the subtle influence of Atlantic Ocean conditions on European and North American climate in seasons other than winter (e.g., Colman and Davey 1999; Cassou et al. 2005). The influence of coastal SST is significant locally and merits further investigation. Variations in sea ice are also important locally and may have more far-reaching impacts. The predictability of sea ice and coastal SST warrants further investigation. In addition, it appears that much can be gained in seasonal-to-interannual prediction from better resolving and understanding decadal variability and trends.

The influence of land surface processes on climate predictability has for some time been identified as an important, and underresearched, issue. This is certainly true for the Atlantic sector. Soil moisture is a key variable in the hydrological cycle with a potentially large impact on, for example, intensity of droughts and heat waves. Research to better understand the role of soil

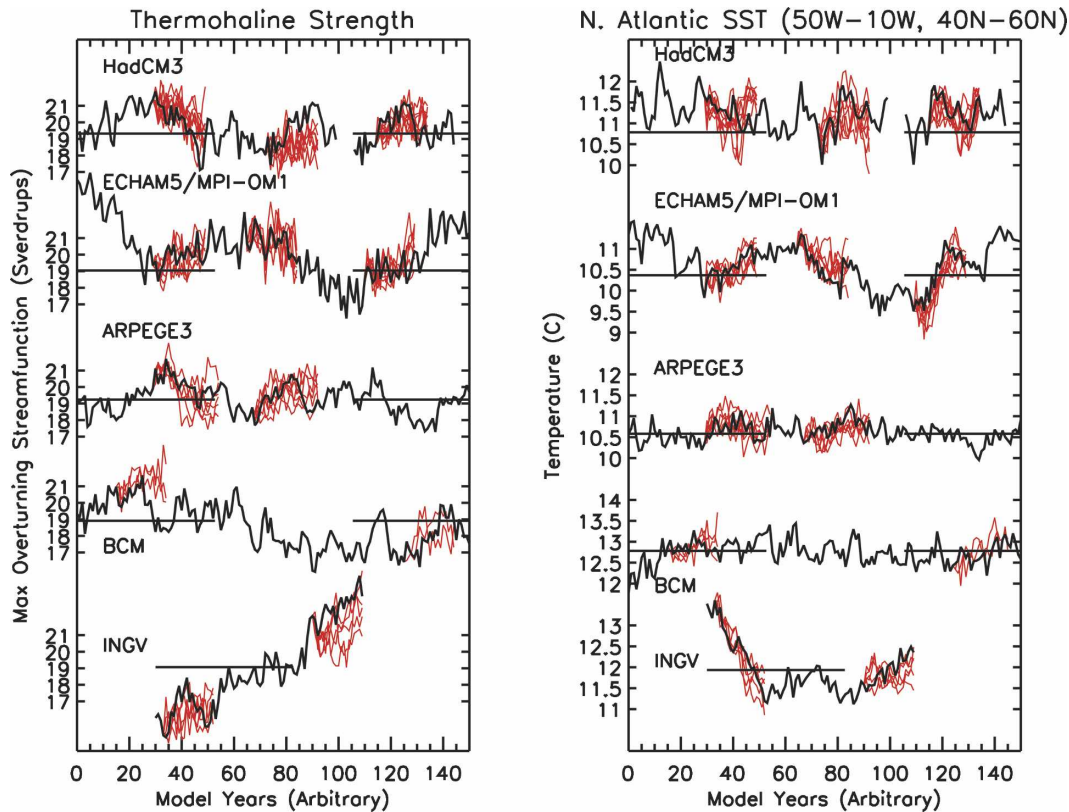


FIG. 6. The potential predictability in the strength of the MOC and SST averaged between  $40^{\circ}$ – $60^{\circ}$ N and  $50^{\circ}$ – $10^{\circ}$ W in five different coupled models. The black lines correspond to control experiments and the red lines to perfect ensemble experiments. From Collins et al. (2003).

moisture is hampered by systematic errors in models and by a lack of observational data. Other aspects of the land surface such as snow cover, snow depth, and vegetation characteristics can also influence seasonal climate, and research is needed into the predictability of these factors and their impacts. As with the oceanic influence, coupled model studies are preferable to prescribed anomaly experiments. The land surface is also an important source of aerosols in the form of Saharan dust. The impacts of dust and other aerosols on Atlantic sector climate is poorly understood, and research is required to understand and quantify these impacts and their importance for climate predictability.

CLIVAR will place emphasis on the following:

- research to better understand the fundamental ocean–atmosphere–land processes that control the climate of the tropical Atlantic region, its variability, and predictability, including the statistics of subseasonal variability; and
- development of reliable methodologies for making seasonal forecasts relevant and useful to decision makers.

### (ii) Decadal and longer time scales

There is a growing body of evidence from a variety of ocean–atmosphere model studies that the Atlantic MOC may have some predictability for lead times up to several decades. There is not consensus, however, on the extent to which these MOC variations lead to useful predictability of SSTs and any atmospheric response, although some encouraging evidence of useful predictability is beginning to emerge (Fig. 6). There is need for a much more detailed understanding of which aspects of ocean conditions most constrain the future behavior of the MOC and related aspects of climate. The roles of air–sea exchanges, convective mixing, overflows, boundary waves, and advective processes in setting the time scale and predictability of changes in the MOC have to be clarified.

Changing external forcing, whether natural or anthropogenic, also influences climate on short and long time scales and is a further source of potential predictability. Many of the issues are global, but there is a clear need to improve understanding of the factors that determine climate change at a regional scale. In the At-

lantic sector, understanding potential changes in the principal diabatic heat sources over South America and Africa, and in the North Atlantic storm track, and the consequences of such changes are natural priorities. Also important for climate prediction is the interaction between initial conditions (notably in the MOC) and the effect of changing forcing. For predictions with lead times in the range of 1–30 yr both factors are likely to be important.

The most relevant Atlantic issues for CLIVAR are as follows:

- understanding the limits of predictability of the MOC and the mechanisms that determine its predictability;
- identifying which aspects of the oceanic initial conditions most constrain the future behavior of the MOC;
- understanding how initial conditions and changing external forcings combine to determine climate evolution on decadal time scales, and (relatedly) development of suitable ensemble techniques for estimating forecast uncertainty; and
- understanding and quantifying the regional climate impacts of MOC change and the predictability of these impacts.

## 2) DEVELOPMENT OF COUPLED PREDICTION SYSTEMS

### (i) *The observing network and estimation of initial conditions*

Although the Atlantic Ocean has historically been the best observed of the world's oceans, the lack of sufficient subsurface data remains a limitation for the initialization of hindcasts used to develop and test coupled prediction systems. In addition, in spite of significant recent progress (Fig. 5), many observational gaps remain (especially in the South Atlantic) and the supply of data for the tropical Atlantic is limited relative to, for instance, the tropical Pacific. There is also a need for more atmospheric observations. In some regions, such as southern Africa and tropical South America, there has been a severe decline in the (already sparse) network of atmospheric observations, both of surface and upper-air parameters. These trends are a major concern for climate monitoring and prediction. The best use of existing data through intelligent assimilation schemes, therefore, is of utmost importance.

There are also some relatively unique challenges facing CLIVAR Atlantic. Observations and the assimilation of salinity, which plays a more important role in Atlantic than in Pacific climate, is a particular chal-

lenge. Another challenge is determining how to make best use (for decadal predictions) of data that will become available from major new projects designed to monitor the Atlantic MOC. How to best initialize the land surface in coupled models is also an aspect important for Atlantic prediction, especially on seasonal times scales.

### (ii) *Systematic model error*

The coupled models used to make seasonal and longer time-scale predictions suffer from significant biases in the Atlantic sector, and especially in the tropical Atlantic (e.g., the zonal gradient of SST on the equator frequently has the wrong sign; Davey et al. 2002). These biases cause problems for assimilation schemes and also compromise forecasts directly. Arguably there has been less attention paid to the resolution of these problems than to addressing similar problems over the Pacific Ocean. Progress in the prediction of Atlantic sector climate requires that the reduction of biases over the Atlantic be a priority. Also essential is better understanding of the physical processes that determine regional climate.

### (iii) *Generic issues*

Beyond the issues outlined above, there are many other challenges in the development of seasonal and longer-term predictions. However, these challenges are more generic rather than featuring a distinctive Atlantic perspective. These issues include how to (a) handle model uncertainty through, for example, multimodel methods; (b) meaningfully quantify probabilities (rather than merely ranges); (c) develop forecast products that provide the maximum value for specific users; (d) develop “seamless” prediction systems that provide continuous information for all lead times from days to decades (see online at <http://copes.ipsl.jussieu.fr>) and (e) establish stable funding for a climate observing system. Palmer et al. (2004) discuss the first three issues in the context of the Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER). They show that the multimodel system is a more reliable forecasting system than that based on any single model, and that output from DEMETER, suitably downscaled, is useful for probabilistic prediction of crop yield and malaria incidence.

Another outcome of DEMETER is a useful seasonal hindcast dataset. Such extended hindcasts can be used to quantify forecast skill over many realizations; to compare results (using standard metrics) from different forecasting systems, including new versions of existing



systems; and to advance understanding of the mechanisms of intraseasonal and interannual climate variability. It has been proposed that a process similar to the Intergovernmental Panel on Climate Change (IPCC) be undertaken for the regular review of progress in seasonal–decadal prediction. Such a process could be of considerable value in focusing community attention.

## 7. Summary

The international CLIVAR program has provided a nurturing framework to bring together scientists from a range of backgrounds to describe, understand, and predict many aspects of Atlantic climate variability. In this paper the discussion has centered on the main large-scale climate phenomena that involve chiefly the ocean and lower atmosphere. However, it has become clear that connections to the other parts of the globe, such as the global Tropics and high-latitude regions, as well as coupling to other atmospheric regions such as the stratosphere, have important implications for Atlantic climate variability. At the same time land surface processes and interactions with marine ecosystems are an emerging interest.

Further scientific advances during CLIVAR depend crucially on our ability to sustain basin-scale observing systems; conduct ongoing reanalysis of the ocean and atmosphere; organize process studies in climate relevant regions; and have access to and the ability to use high-resolution coupled climate models. In terms of Atlantic climate prediction, there are two overarching challenges facing the community over the next 5–10 yr. The first is fully realizing the potential of seasonal predictions for the tropical Atlantic region, where the potential skill and value is highest. The challenge is to build a climate prediction system for the tropical Atlantic region that is comparable (in terms of data coverage, model fidelity, and—subject to physical limits—forecast skill) to that in the tropical Pacific. The second overarching challenge is to take a lead in the development of systems for decadal climate prediction. The development of useful decadal climate predictions, incorporating both initial condition constraints and transient boundary forcings, is a “grand challenge” whose importance is increasingly recognized. Because of the key role played by the Atlantic Ocean in the global overturning circulation, the Atlantic climate community is naturally placed to take a lead in this area.

The full benefit for society of conquering such challenges will depend on our success in transferring the scientific advances and pilot prediction systems into global operational climate assessment and prediction activities.

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