# Observed and simulated multidecadal variability in the Northern Hemishphere

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## Abstract

Analyses of proxy-based reconstructions of surface temperatures during the past 330 years show the existence of a distinct oscillatory mode of variability with an approximate time scale of 70 years. This variability is also seen in instrumental records, although the oscillatory nature of the variability is difficult to assess due to the short length of the instrumental record. The spatial pattern of this variability is hemispheric or perhaps even global in scale, but with particular emphasis on the Atlantic region. Independent analyses of multicentury integrations of two versions of the GFDL coupled atmosphere-ocean model also show the existence of distinct multidecadal variability in the North Atlantic region which resembles the observed pattern. The model variability involves fluctuations in the intensity of the thermohaline circulation in the North Atlantic. It is the intent of this paper to provide a direct comparison of the observed variability to that simulated in a coupled ocean-atmosphere model, making use of both existing instrumental analyses and newly available proxy-based multi-century surface temperature estimates.

The analyses demonstrate a substantial agreement between the simulated and observed patterns of multidecadal variability in sea surface temperature(SST) over the North Atlantic.

There is much less agreement between the model and observations for sea level pressure. Seasonal analyses of the variability demonstrate that for both the model and observations SST appears to be the primary carrier of the multidecadal signal.

# 1 Introduction

Understanding the internal, unforced variability of the climate system on decadal and longer timescales is of substantial importance to society. Not only does a proper understanding of such variability have significant implications for long-range climate forecasting and societal decision making, but it is precisely these timescales on which anthropogenic impacts on climate are likely to be expressed (Santer et al.,1995). A proper understanding of the internal variability of the coupled ocean-atmosphere system that might be expected in the absence of exogenous climate forcings (both human-induced and naturally occurring, such as variations in volcanic activity or solar irradiance) is critical for the problem of anthropogenic signal detection. Furthering our understanding of such variability is clearly a key focus of current climate research.

The simplest paradigm for interpreting climate variability describes the coupled ocean-atmosphere system as a first-order Markov process (red noise) in which we expect enhanced internal climate variability at progressively longer timescales due to the thermal inertia of the ocean and the associated ‘reddening” of the stochastic climate spectrum (Hasselmann, 1976). Such a model does not predict the existence of peaks in the climate spectrum. While much of the climate system can be explained by this paradigm, there are notable departures from such a model. The El Niño-Southern Oscillation is one well known phenomenon that leads to greater variability (on interannual, roughly 3-7 year timescales) than would be expected from such a simple conceptual model. Moreover, there appears to be greater variability in the instrumental record than would be expected from simple red (or even “coloured”) noise on both decadal timescales (broadly speaking, 10-20 years–see e.g., Mann and Park, 1994;1996 and the numerous references therein), and multidecadal timescales (broadly, 30-70 years–see e.g. Folland et al 1984;1986; Schlesinger and Ramankutty, 1994; Mann and Park, 1994; Mann and Park, 1996; Minobe,1999). In studying the latter, multidecadal variability, however, we are near the limit of what inferences the instrumental climate record can provide. Proxy data can be analyzed for a longer-term perspective on multidecadal and century-scale climate variability (e.g., Stocker and Mysak, 1992; Mann et al, 1995; Minobe, 1997), but that perspective has in the past been hampered by limitations in the spatial extent and reliability of the underlying proxy data. Verifiable proxy-based climate reconstructions are, however, now available (Mann et al, 1998), and more robust empirical insight into long-term multidecadal climate variability seems possible (see also Mann, 1999).

A complementary approach to such empirical analyses is the use of numerical models of the Earth's climate system. The analysis of extended integrations of such models offers the possibility of detailed analysis of not only the characteristics of model generated variability but also the underlying physics and potential predictability. An additional benefit of the use of numerical models is the ability to separate a forced signal from internal variability through the use of suitably designed experiments. With only a single realization of the observed climate record this decomposition is problematic. However, there is no guarantee that models can accurately simulate fluctuations in the real climate system.

A combined approach comparing observational (both instrumental and proxy-based) and model-based results is therefore highly desirable. Observational analyses provide a powerful constraint on the credibility of model solutions, while the model analyses have the potential to address the underlying physics governing the climate system. In this paper, our goal is to provide a direct comparison of observed and simulated multidecadal-to-centennial timescale variability evident in the Northern Hemisphere in instrumental observational studies (Deser and Blackmon, 1993; Kushnir, 1994; Mann and Park, 1994; Schlesinger and Ramankutty, 1994; Mann and Park, 1996), longer term proxy climate data (Stocker and Mysak, 1992; Mann et al, 1995) and coupled ocean-atmosphere model integrations (Delworth et al, 1993; Delworth et al, 1997; Timmermann et al, 1998). We make use of recent model-based results, and the proxy-based reconstructions of surface temperature patterns during the past few centuries recently estimated by Mann et al (1998–henceforth "MBH98") for a more robust, long-term model-data comparison than previously possible. Both the North Atlantic characteristics, and possible larger-scale influences, are investigated.

# 2 Description of Observational Data and Model

## 2.1 Instrumental and Proxy-based Observations

We make direct use of results from recent analyses of instrumental temperature and sea level pressure data to compare with the results obtained in this study. The instrumental analyses are complemented by global surface temperature reconstructions based on "multiproxy" networks of annual resolution proxy climate indicators (dendroclimatic, ice core, varved sediment, coral, and historical indicators, combined with the few available long instrumental records). The temperature reconstructions (MBH98) are based on the annual-mean calibration of such multiproxy networks against the dominant patterns of variation or "eigenvectors"of the $20^th$ century global surface (land air and sea surface) temperature data, and have demonstrated reconstructive skill in cross-validation with pre-$20^th$ century instrumental temperature data. The reconstructions provide estimates of surface air and sea surface temperature over large regions of the globe, based on reconstructions of a lower-dimensional eigenvector-space representation of the global surface temperature field. ENSO-related patterns are discussed elsewhere (Mann et al, 1999a), as are implications for the North Atlantic Oscillation and middle east climate (Mann, 1999), and Northern Hemisphere mean temperatures over the past millennium (Mann et al, 1999b). The reconstructed temperature patterns are also available interactively (Mann et al, 1999c). While the largest-scale variations (e.g., Northern Hemisphere mean temperature, most closely related to the principal Empirical Orthogonal Function or "EOF" of the instrumental global temperature data) are skillfully resolvable back to AD 1400, the degree of resolved spatial variance decreases with the decreasing number of reconstructed eigenvectors back in time. The pattern most relevant for describing multidecadal North Atlantic variability, as discussed later, is determined only back to 1650. The limited variance resolved in these reconstructions at the smallest spatial scales of the proxy-based reconstructions under examination limits a detailed comparison of simulated and observed multidecadal variability. Nonetheless, broad comparison of the spatiotemporal characteristics of modeled and estimated climate variations are possible based on several centuries of data with these reconstructions.

## 2.2 Model output

The primary model output to be used comes from an extended control integration of a coupled ocean-atmosphere model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) described in detail by Manabe et al. (1991;1992). The coupled model is global in domain, with realistic geography consistent with resolution. The model is forced with a seasonal cycle of insolation at the top of the atmosphere. The atmospheric component numerically integrates the primitive equations of motion using a semi-spectral technique in which the variables are represented by a set of spherical harmonics and by corresponding grid points with a spacing of approximatey $7.5^o$ longitude and $4.5^o$ latitude. There are nine unevenly spaced levels in the vertical. The oceanic component of the model uses a finite difference technique with twelve unevenly spaced levels in the vertical, and a horizontal resolution of approximately $3.7^o$ longitude and $3.7^o$ latitude. The model atmosphere and ocean interact through fluxes of heat, water, and momentum at the air-sea interface. In order to reduce climate drift, adjustments to the model-calculated heat and water fluxes are applied at the air-sea interface. These flux adjustments are derived from preliminary integrations of the separate atmospheric and oceanic components [see Manabe et al. (1991)

for details]. A simple thermodynamic sea-ice model is used, in which the ice moves with the ocean currents.

Preliminary results will also be presented from a 1000 year integration of a recently developed higher resolution version of the model described above. This model (referred to as the R30 coupled model) has approximately twice the horizontal resolution as the R15 model, and a 50in vertical resolution. Both models employ similar physics.

# 3 Analyses of the Instrumental Record

While the length of the instrumental record (100-150 years) is too short for a definitive description of multidecadal variability, recent analyses of the instrumental record do provide some intriguing insights. More than a decade ago, Folland et al (1984) noted the existence of a distinct multidecadal timescale variation in global SST and marine air temperatures, and later related it to a pattern of pronounced interhemispheric SST contrasts in the Atlantic with strong connections to Sahel drought (Folland et al, 1986), and possible associations with the El Nino phenomenon. Subsequently Deser and Blackmon (1993) confirmed the existence of similar multidecadal variability in a variety of climate fields in the North Atlantic, and argued for the existence of a cold period in the North Atlantic from about 1900-1930 and a warm period from about 1940-1970. Kushnir (1994; hereafter referred to as K94) analyzed time series of SST spanning the period 1900-1987 over the North Atlantic, and demonstrated that there exists a coherent pattern of SST and associated cold-season half year SLP variations on multidecadal timescales. Cold conditions prevailed around 1920 and in the 1970s to 1980s, while warm conditions prevailed from approximately 1930 to 1960. The spatial patterns of the SST and SLP anomalies span the North Atlantic (see Figs. 5 and 6 of K94), with the largest SST anomalies between approximately $35^o$N and $70^o$N. The SLP pattern associated with a positive SST anomaly has an anomalous low pressure center in the central North Atlantic at about $45^o$N, with positive anomalies poleward of $60^o$N. It was speculated in K94 that the observed SLP pattern may be a response to the SST anomaly pattern. The K94 pattern is somewhat different than the NAO atmospheric signal which is clearly seen on the decadal time scale (e.g., Lamb and Peppler, 1987; Hurrell, 1995).

The analysis of K94 was consistent with a coincident study of global-scale temperature signals by Mann and Park (1994–henceforth, MP94) which demonstrated a significant multidecadal secular variation in the global temperature record from 1890-1989, largely orthogonal to the principal (global warming) secular variation, but nonetheless statistically significant in its own right. The analysis of MP94 was based on a multivariate frequency-domain method which identifies coherent oscillatory and secular modes of variation ("MTM-SVD"–see the review by Mann and Park, 1999–henceforth "MP99"), and is quite independent of the compositing approach used by K94. MP94 identified apparent larger-scale features of the signal, including opposite sign temperature variations in the south Atlantic (reminiscent of the interhemispheric/Sahel drought-related SST pattern of Folland et al, 1986), and significant amplitude variability in parts of the Pacific basin. The pattern nonetheless emphasized the North Atlantic region, and exhibited the "warm-cold-warm" North Atlantic sequence during the 20th century described by K94, Deser and Blackmon (1993), and Folland et al (1986). While MP94 noted that this signal resembled a single cycle of a multidecadal oscillation, they emphasized that a true oscillatory signal on this timescale could not be confidently distinguished from a significant secular variation based on a century of data. In an indepenent study, Schkesinger and Ramankutty (1994) argued that a multidecadal (65-70 year period) signal could indeed be isolated in the global mean instrumental temperature record based on analyses of the nearly 150 year-long IPCC estimated global temperature record (1854-1992).

The MP94 analysis was confirmed and further expanded upon in MP96, which used the same method as MP94 to analyze joint fields of SLP and surface temperature in the Northern Hemisphere from 1899-1993, identifying the same multidecadal variation as MP94. That analysis separately analyzed the cold and warm half-year seasonal expressions of the signal, confirming the relationship between SST and SLP identified by K94 during the cold season. Significant impacts on Eurasian cold-season temperatures were inferred as a response to large circulation variations during the cold season over the North Atlantic. The separate cold- and warm-season analyses demonstrated that SST, but *not* SLP, anomalies were seasonally-persistent, suggesting that SST acts as the "carrier" of the signal.

Kushnir et al. (1997) and Tourre et al. (1999) further extended these analyses through the use of a longer instrumental data set based on the Kaplan et al (1998) statistical reanalysis of SLP and temperature data in the Atlantic region back to 1856. The analysis employed the MTM-SVD technique used by MP94 and MP96, using data long enough to at least marginally resolve a multidecadal oscillatory spatiotemporal signal from secular variability. The authors isolated a spectral peak in the multivariate data fields just resolvable from the secular band (periods longer than about 70 years in that analysis). The spatial SST and SLP patterns associated with this approximately 52 year signal (Fig. 1, adapted from Kushnir et al, 1997) is consistent in large part with the features of multidecadal variability in the Atlantic discussed above, involving high-amplitude variability over much of the North Atlantic. The evolving SST and SLP patterns resembled, at certain phases, those in MP96 and K94. The sequence of panels in Fig. 1 denote the temporal evolution of the pattern at a spacing of approximately 4.3 years. Beginning at phase 0 (defined arbitrarily) in Fig. 1, positive SST anomalies are seen in the central North Atlantic. Positive SLP anomalies are seen in the subtropical North Atlantic, with negative SLP anomalies at higher latitudes of the North Atlantic (this situation resembles a positive phase of the North Atlantic Oscillation). The fact that positive SST anomalies underlie the enhanced westerlies (as inferred from the anomalous SLP gradients) implies that the positive SST anomalies are not being maintained by surface heat flux anomalies induced by wind speed changes, since the anomalous winds should enhance the anomalous westerlies and the air-sea heat flux, thereby leading to a cooling of the oceanic surface layer. As we move forward in time to phase 90 (approximately 13 years later), the region of positive SST anomalies expands to encompass the entire North Atlantic, extending to 20$^o$S. This corresponds to the time of maximum positive SST anomalies in the North Atlantic. There is a distinct shift of the SLP anomalies, such that negative SLP anomalies overlie the positive SST anomalies in the eastern and central North Atlantic, with positive SLP anomalies over the northwest Atlantic.

The Kushnir et al (1997) findings were independently confirmed by Allan et al (1999) based on both MTM-SVD and extended EOF analyses of an independent set of global statistical SST and SLP reanalyses (see Allan et al, 1996) over the world oceans from 1871-1995. The Kushnir et al (1997) and Allan et al (1999) analyses emphasize a subtlety to the multidecadal climate variability that has been obscured in past studies. These latter studies support the existence of a continuously evolving signal, and no analysis of standing patterns of variability can isolate such a signal in its entirety. In the context of this evidence from the extended instrumental record, previous analyses by Folland et al (1986), Deser and Blackmon (1993), K94, MP94, and MP96, might best be interpreted as having described varying combinations of two orthogonal standing patterns which are in quadrature. The combination of these patterns describes a true multidecadal oscillatory signal with a 50-80 year timescale.

The above analyses seem to demonstrate overwhelming evidence for a significant multidecadal variation in the climate system during the past 100 to 150 years, centered in the North Atlantic, but with some degree of global expression. The short nature of these instrumental analyses, however, calls into question whether or not a true multidecadal oscillatory signal can be argued for.

# 4 Comparison of observed and simulated multidecadal variability

## 4.1 Analyses using the instrumental record

The Kushnir et al. (1998) and Tourre et al. (1999) analyses of the instrumental record can be explicitly compared with analyses of output from millennial-scale integrations of the GFDL coupled ocean-atmosphere model. Previous analyses have demonstrated (Delworth et al., 1993; hereafter referred to as DMS93) that there exists distinct multidecadal variability in this coupled model. The simulated variability involves the thermohaline circulation (THC) in the North Atlantic, has a timescale of approximately 40-80 years, and is associated with SST variations resembling the observed multidecadal SST variations seen in the instrumental record (see Fig. 6 of DMS93 for an explicit comparison). For a more complete discussion of this variability and its mechanism, see DMS93 and Delworth et al. (1997).

In order to make an explicit comparison with the analyses of Kushnir (1997), an MTM-SVD analysis of the combined fields of annual mean SST and SLP is computed for 1000 years of the model output. The spatial domain is similar to that shown in Fig. 1, extending from $45^o$S to $80^o$N in the Atlantic. The local fractional variance spectrum (LFV - see MP99 for details) from that analysis, shown in Fig. 2a, reveals a clear and significant peak with a time scale of approximately 56 years, similar to the peak in the observed spectrum at 52 years (not shown).

In order to compare the spatial patterns of the observed and simulated multidecadal variability, we can reconstruct the temporal evolution of the spatial pattern associated with the 56 year peak in the model spectrum; this is shown in Fig. 2b. Since the signal is cyclical, the beginning phase (defined by phase=$0^o$) is arbitrary. We choose to start at the phase of the cycle where SSTs anomalies over most of the central and northern North Atlantic are positive and increasing. This corresponds to a period preceding the maximum THC in the North Atlantic. This choice is also made to facilitate comparison with the instrumental analyses in Fig. 1, such that a given phase for the model variability corresponds approximately to the same phase for the observational analysis. The phase evolution shown follows one half of a roughly 56 year cycle, with each $30^o$ phase increment corresponding to approximately 4.6 years.

Starting at phase 0, the model has positive SST anomalies in the central and northeastern North Atlantic and Greenland Sea. The simulated SLP pattern has negative values to the southeast of Greenland, with positive values in the west central North Atlantic and central to northern Europe. The general feature of negative SLP anomalies at higher latitudes with positive SLP anomalies in the middle latitudes is in qualitative agreement with the instrumental analyses shown in Fig. 1. The simulated positive SST anomalies extend further north than the observed anomalies, which are concentrated in the central North Atlantic (Fig. 1). The SLP pattern for both the observations and the model bears some similarity to a positive phase of the NAO. The model SLP distribution at higher latitudes of the North Atlantic is consistent with anomalous southerly flow over the Greenland Sea (the observational analyses hint at this, but their limited spatial extent precludes a more definitive statement). Additional analyses (not shown; see Delworth et al., 1997) have shown that the simulated East Greenland Current is anomalously weak at this period, thereby reducing the export of relatively cold, fresh water from the Arctic into parts of the North Atlantic. This reduction contributes to the enhancement of the THC by reducing the freshwater transport into the convective regions of the model North Atlantic, thereby effectively increasing near-surface salinity, density, convection, and the THC.

As we proceed forward in the cycle through phases 30 and 60, we see increasing positive temperature anomalies in the North Atlantic. The model pattern amplifies, with distinct maxima in the SST anomaly pattern in both the central North Atlantic and southern Greenland Sea. This tendency for two maxima in SST anomalies in the North Atlantic and Greenland Sea is also seen in the instrumental analyses at phase 30 and 60, although the limited spatial extent of the observations limits the analysis to the southern parts of the Greenland Sea. The largest SST anomalies in the model associated with the multidecadal signal are largely confined to the region north of $20^o$N, whereas in the observations appreciable SST anomalies extend to $20^o$S.

While there is relatively good agreement between simulated and observed temperature at these phases, the SLP fields show distinct differences. The instrumental analyses indicate that the region of negative SLP anomalies appears to move southward with increasing phase, such that by phases 90 and 120 the negative SLP anomalies are centered to the east of the positive SST anomalies at approximately $40^o$N. In contrast, for the model the negative SLP anomalies remain fixed in place off the southeast coast of Greenland, and resemble the positive phase of the NAO.

As we move past phase 90 to phase 120 the simulated and observed SST anomalies begin to weaken. During this period the model THC reaches its maximum, and then begins to weaken, leading to the reduction in SSTs. The weakening of the simulated THC is related to the presence of an anomalous anticyclonic gyre in the upper 1000 m. of the central North Atlantic. The effect of this gyre circulation, induced by positive thermal anomalies associated with the enhanced THC, is to reduce the transport of salt into the convective regions, thereby reducing near-surface density, convection, and the THC (see DMS93). The anomalous model SLP field is still characterized by a north-south pattern, but the amplitudes of the anomalies are somewhat weaker, and the positive SLP anomalies have shifted to the east. The observed SST anomalies reach a peak at phase 90 and decrease thereafter.

As we proceed onward in the model cycle to Phase 180 (not shown, but corresponds to Phase 0 with signs reversed for both SST and SLP) we see the appearance of negative SST anomalies in the North Atlantic, with maximum amplitudes at high latitudes. This is associated with a continued weakening of the THC. Note also that by Phase 180 there are positive SLP anomalies over Greenland, with negative SLP anomalies over the central North Atlantic and northern Europe. At this phase there are anomalous northerly winds over the Greenland Sea, associated with an enhanced East Greenland Current and enhanced transport of relatively cold, fresh water out of the Arctic (see Delworth et al., 1997). This process further weakens the THC by reducing the near-surface density in the convective region. Consistent with the above discussion there is good agreement between the simulated and observed variability

Associated with this phase in the model is a developing cyclonic gyre in the upper 1000 m. of the central North Atlantic, related to the cold water associated with the weakened THC and reduced northward heat transport. This cyclonic gyre effectively enhances the transport of salt into the convective regions of the model North Atlantic, thereby sowing the seeds for increased near-surface density, enhanced convection, and a return to a stronger THC over the North Atlantic at a later phase. The intensity of this gyre lags the intensity of the THC by approximately 10 years, thereby contributing to the multidecadal time scale of the oscillation.

It is important to note that while both the simulated and observed SLP anomalies described above bear a resemblance to the NAO at some phases, the full temporal and spatial evolution is more complex than can be described by a single standing pattern. For example, the simulated SLP patterns at both Phase 0 and Phase 90 would project positively onto the NAO, and yet Phase 0 has substantial meridional flow over the Greenland Sea which is not present at Phase 0. Such differences could be very important in modulating the exchange of heat and fresh water between the Arctic and North Atlantic.

## 4.2 Analyses using the proxy-based reconstruction of surface temperature

The comparison above of the simulated multidecadal variability to the results of instrumental analyses is quite intriguing, but the relative shortness of the instrumental record makes it difficult to draw firm conclusions about multidecadal variability. Indeed, only longer, multiple century empirical records of climate variability can address whether such variations have a distinct timescale and to see how robust they are in time. Using such data, Mann et al. (1995) confirmed that a significant multidecadal signal was evident in globally-distributed long-term proxy data over several centuries, and the variability had gross spatial features similar to those in the instrumental data. For example, the signal was shown to emphasize the North Atlantic region, and to have larger-scale influences over the Pacific and North American region. The influence of the signal in these latter regions was confirmed subsequently in an independent analysis by Minobe (1997).

In this section we provide an explicit comparison of the multidecadal variability revealed in the comprehensive set of multiproxy-based global temperature reconstructions described in section 2.1 and the GFDL coupled model. MBH98 noted that the multidecadal North Atlantic variation in the instrumental record described by K94, MP94, MP96, Tourre et al, 1999 and others, is largely expressed by the 5th ranked eigenvector of the twentieth century global surface temperature data. It is noteworthy that the expression of the NAO is primarily expressed in an independent (3rd) eigenvector (see MBH98; Mann, 1999), and exhibits decidedly muted multidecadal variability in comparison. The fifth eigenvector has substantial loadings in the vicinity of the Atlantic basin, and is in general reminiscent of a particular phase of the multidecadal signal established in the instrumental record (i.e., one of the snapshots of the Kushnir et al, 1997 pattern. Though two in-quadrature patterns are required to describe the true multidecadal oscillatory signal (the 4th eigenvector appears to describe much of the in-quadrature pattern during the 20th century), and the 5th eigenvector almost certainly represents a mixing of the multidecadal signal with unrelated higher-frequency variability, the reconstruction of the 5th eigenvector is available relatively far back in time (AD 1650) making the analysis of its associated reconstructed principle component (RPC) a particularly useful approach to analyzing the robustness of the 20th century signal back in time. This history is shown in Fig. 3a. Note the clear variations on multidecadal time scales throughout the record, dominated by 50-90 year timescale variability. Indeed, the cold and warm periods identified above in the K94 and other observational studies are readily seen during the 20th century, but continued cold-warm alterations are clearly evident before the 20th century. The temporal characteristics of this time series are quantified through a spectral analysis (based on the robust confidence testing approach of Mann and Lees, 1996) also shown in Fig. 3b. Note the highly significant peak in the 50-100 year band, distinct from secular variability, associated with a persistent multidecadal timescale of variability in the estimated history of the pattern described by the 5th eigenvector. The multidecadal peak is essentially unaltered if the 20th century variations are excluded from the analysis (see Fig. 3b), demonstrating that the signal is not unique to the 20th century, but is indeed robust over several centuries. Because the paleoreconstruction approach of MBH98 does not build any a priori frequency-domain information from the 20th century calibration period into the pre-20th century reconstructions, the latter indications of a multidecadal climate signal are truly independent from any inferences from the instrumental record. These results are consistent with Stocker and Mysak (1992) who demonstrate the existence of distinct multidecadal to centennial variability in a variety of proxy data.

In order to explicitly compare the observed and simulated multidecadal variability, we applied the MTM-SVD approach (described above) to both the proxy-based global surface temperature patterns from 1650-1980 and to 1000 years of model SST. (For the observations, note that prior to 1650 the lack of resolution of the key fifth eigenvector, as discussed above in these reconstructions, limits the resolved spatial variance in the temperature pattern reconstructions in the regions of interest). The model analyses are conducted over the Atlantic from $45^o$S to $80^o$N, and over the Indian and Pacific oceans from the Equator to $60^o$N. While the choice of this domain is motivated by the results of previous studies, the sensitivity of the results presented below to the domain of analysis has been evaluated and found to be small. The analyses of the reconstructed data cover approximately the same domain, but have large regions of missing data due to limitations in the reconstruction.

The "local fractional variance" spectrum (see MP98) for both the observations and model are shown in Fig. 4. The analysis reveals a highly significant peak obtained from the MTM-SVD analysis centered near 70 year period for the observations and at approximately 56 years for the model. In both cases the spectral peak exceeds some measures of statistical significance. For the model output the spectral peak becomes much stronger if the domain of analysis is limited to the North Atlantic basin. Separate analyses (not shown) have confirmed that this peak in the model spectrum is strongly related to the above described mode of variability of the model thermohaline circulation. Additional analyses using surface air temperature for all model grid points north of 20S have revealed similar multidecadal variability (results not shown).

The temporal evolution of the patterns of variability associated with the above spectral peaks may be reconstructed (see MP98). These patterns are shown in Fig. 5a for the observational data over oceanic regions. While the loss of spatial variance in the reconstructed patterns for the observations limits any detailed regional inferences, the signal clearly exhibits an evolving spatial pattern (Figure 5a) during a typical cycle which shares in large part the characteristics of the multidecadal signal described above in the instrumental temperature data. The analysis of this extended proxy-reconstructed surface temperature dataset thus points to the existence of a narrowband pattern of variability which has a dominant timescale of approximately 70 years, and which spatially emphasizes the Atlantic and adjoining continental regions.

In order to facilitate the comparison with both the proxy analysis and previously published instrumental analyses, the MTM-SVD analysis was also applied to the joint field of model SST and SLP; the domain of analysis for SLP extends from the Equator to 90$^o$N. Since the spectrum and reconstructed spatial patterns of simulated SST from the joint SST/SLP analysis were extremely similar to those from the MTM-SVD analysis of SST alone (comparison not shown), we have displayed in Fig. 5b the reconstructed pattern of SST and SLP from the joint analysis. In this manner, the SST pattern may be compared explicitly to the proxy temperature reconstruction in Fig. 5a, while the SLP pattern may be compared to previously published results (Mann,1996).

Since the signal is cyclical, the beginning phase (defined by phase=0$^o$) is arbitrary. We choose to start at a smiliar phase of the cycle as in Fig. 1, where SSTs anomalies over large regions of the North Atlantic are positive and increasing. The SST pattern at phase 0 for the model (Fig. 5b) compares reasonably well over the North Atlantic to the corresponding analyses from the multiproxy reconstruction of temperature (see Fig. 5a). In both the model and observations there are positive SST anomalies in the Greenland Sea/northeastern North Atlantic and the central North Atlantic, with a region of negative SST anomalies in the subtropical North Atlantic. There are positive SST anomalies in the eastern south Atlantic in the observational analyses, while the simulated SST anomalies over this region are relatively small.

Over the Pacific the model has positive SST anomalies in the northwestern part of the basin; the proxy analysis has positive anomalies in the northern and northeastern parts of the basin.

As we proceed forward in the cycle to phase 90, we see the largest positive temperature anomalies in the model North Atlantic. During this period the model THC reaches its maximum, and then begins to weaken, leading to an eventual reduction in simulated SST. The temperature anomalies for the proxy reconstruction (Fig. 5a) are also maximum at approximately phase 60-90, but their spatial structure is more uniform in the North Atlantic than the simulated pattern. The positive SST anomalies over the South Atlantic in the reconstructions weaken substantially, and become negative by phase 90. The model has some tendency towards negative SST anomalies over the South Atlantic at this time, but the amplitudes are relatively small.

Over the Pacific both the model and the observations show substantial positive temperature anomalies; for the model the largest values are in the west central North Pacific, whereas the observed values are more homogeneous and cover the northern and eastern sectors of the North Pacific.

There are also positive SLP anomalies over the central North Pacific for the model at this phase. The positive SST anomalies in the western Pacific are generally in the vicinity of anomalous southerly winds (as inferred from the SLP anomalies). The physical significance of the relationship between the North Atlantic and North Pacific variablity in this model is not clear. As will be discussed later, however, Timmermann et al. (1998) postulate an explicit dynamical link between North Atlantic THC multidecadal variations and North Pacific SST and SLP variations based on analyses of an independent coupled model integration. Such a link may depend, however, on the reponse of the atmosphere to extratropical SST anomalies. It is likely, however, that the link between the North Atlantic and Pacific SLP anomalies is via the atmosphere.

In summary, a direct comparison of the spatial patterns of the simulated and proxy-reconstructed observed multidecadal variability has demonstrated some degree of resemblance between the two, with the largest resemblance in the North Atlantic, which is the primary region of the model's multidecadal variability. However, notable differences in the details and amplitudes of the patterns are also clear. For example, the region of large positive SST anomalies over the Atlantic extends much further south in the proxy reconstructions than in the model - this is consistent with the previously discussed comparison of the model variability to the instrumental analyses.

# 5 Additional characteristics of the simulated multidecadal variability in the GFDL coupled model

## 5.1 Seasonal dependence

It is important to separately examine and compare the cold and warm-season signatures of the model-produced and observed multidecadal signal. Separate analyses of the simulated multidecadal variability using only winter (DJF) and summer (JJA) data are shown in Figure 6 (only one phase is shown from each season, corresponding approximately to phase 30-60 from Fig. 5b). It is clear that the SST signal is seasonally invariant. This is consistent with the observational analyses (MP96, see Fig. 5), and supports the notion that the upper ocean is the primary carrier of this multidecadal signal. However, the winter and summer SLP patterns are quite different. Over the North Atlantic, the winter SLP signal has a larger amplitude than the summer signal, and thus dominates the annual mean analyses presented above. At this phase, the winter season is characterized by a pattern that has some resemblance to the NAO. There is also a smaller positive SLP anomaly in the Pacific.

During the summer the simulated SLP pattern resembles the observed analyses of MP96 (see Fig. 5c) over the North Atlantic, with anomalously low pressure overlying the positive SST anomaly in the central North Atlantic. The summer signal in SLP is approximately 1/3 the amplitude of the winter signal.

We regard the very robust and seasonally-persistent expression of the signal in the SST field as the most meaningful surface diagnostic of the dynamics of the signal, related to the underlying oceanic thermohaline circulation dynamics which appear to govern the signal (see DMS93). The precise SLP patterns (and the seasonal details of them) depend on the sensitivity of the overlying atmosphere to extratropical SST anomalies. Such considerations are discussed in more detail later.

## 5.2 Vertical structure

In order to explore the vertical structure in the atmosphere of this mode of variability, additional MTM-SVD analyses were performed on the joint fields of SST, 850 Mb geopotential height, and 500 Mb geopotential height from the model (the domain of analysis is described in the figure caption). Analyses were performed separately on DJF and JJA mean data, and the results are shown in Figure 7. The phases displayed correspond approximately to Phase 30-60 in Fig. 5b (as can be inferred from the SST pattern shown in the top panels of Fig. 7). The DJF results (Fig. 7a) show a north-south gradient in anomalous geopotential height over the North Atlantic at both 850 Mb and 500 MB, with an approximately 50% increase in amplitude between the two levels. Over the Pacific the spatial pattern of the anomalous geopotential heights is similarly invariant with height, and there is a similar increase of amplitude with height. Thus, one could describe the DJF atmospheric anomaly structure as equivalent barotropic, similar in this respect to the observed Arctic Oscillation (Thompson and Wallace,1998).

The results from JJA are somewhat different. As described in the previous section the amplitudes of the atmospheric anomalies in JJA are considerably weaker than in DJF, with a rather different spatial structure. There is some tendency of the anomalies to amplify with height.

## 5.3 Ocean-atmosphere coupling

A key issue is whether the simulated THC multidecadal variability is due to a coupled air-sea mode of variability, or whether it is due to internal oceanic variability. For our purposes we regard a coupled mode as variability arising from a process in which the large-scale state of the ocean (SST) strongly influences the large-scale state of the atmosphere, which in turn feeds back coherently upon the state of the ocean. A clear example of this type of variability is the El-Nino-Southern Oscillation (ENSO) in the tropical Pacific. DMS93, along with Griffies and Tziperman (1995), speculated that the multidecadal THC variability was primarily due to internal oceanic variability stimulated by stochastic surface fluxes. Delworth and Greatbatch (2000) have run a number of experiments using only the ocean component of the coupled model. They demonstrate that the variability in the GFDL model can be excited by surface flux forcing which is stochastic in time, thereby suggesting that the variability is principally due to the excitation of an internal oceanic mode. In fact, given the very weak response of the atmospheric model used in DMS93 to mid-latitude SST anomalies (see Kushnir and Held, 1996) it would be surprising if a coupled air-sea mode in the mid-latitudes could be supported in this model. Further, Delworth and Greatbatch (2000) show that surface heat fluxes (rather than momentum or fresh water) are the dominant fluxes in exciting this variability.

The MTM-SVD analysis further reinforces the notion of an oceanic "carrier" of the multidecadal signal. A separate analysis of the SLP and geopotential fields alone (not shown) yields no statistically significant peak in the multidecadal period range of interest. In contrast, analyses of both the SST field alone, and joint SST/atmospheric fields, show a consistent significant multidecadal signal. Moreoever, the SLP fields associated with the signal do show a consistent though seasonally-specific relationship with the SST field, and the SLP expression of the signal cannot be dismissed as random. The sum of these results is thus best interpreted as indicating an oceanic signal, any particular phase of which favours the projection of a particular resonant pattern from an essentially white-noise atmospheric background, the magnitude of which is weak enough relative to noise levels that the signal can not be clearly detected in the atmospheric fields alone.

# 6 Results from additional coupled models

In order to assess the dependence on resolution of the simulated multidecadal variability, an MTM-SVD analysis was conducted using recent results from a 1000 year integration of the GFDL R30 coupled model. Shown in Fig. 8 is the SST spectrum computed from model years 301-1000 using a domain in the North Atlantic from the Equator to $80^o$N. There is a very clear peak on time scales which are similar to the peak in the R15 model, thereby demonstrating similar variability in two models of quite different resolution - but similar physics.

The presence of multidecadal THC variability is not unique to the GFDL coupled model. Timmermann et al. (1998) have demonstrated that a distinct mode of multidecadal variability of the THC exists in the ECHAM-3 coupled model at the Max Planck Institute. In an extended control integration of that model they report variations of the THC with an approximate time scale of 30-35 years (distinctly shorter than in the GFDL model). The mechanism for their variations depends on two-way interactions between the atmosphere and the ocean. The spatial patterns of SST, SSS, and SLP anomalies associated with this variability bear a strong resemblance to the GFDL model results (for example, compare Fig. 14 of Timmermann et al., 1998, to Figs. 6 and 20 of DMS93). There are also some differences; Timmermann et al. (1998) report a large-scale response of the atmosphere to thermohaline-related SST variations in the Atlantic which encompasses the entire Pacific/North American sector, whereby coupled ocean-atmosphere processes in the North Pacific take on, at least, a secondary role. The latter connection is intriguing in that it is consistent with studies (MP94; Mann et al, 1995; MP96; Minobe, 1997) which argue for a detectable multidecadal signal in the North Pacific. Kushnir and Held (1996) note, however, that the GFDL low-resolution coupled model, in contrast to the MPI coupled model, exhibits little evidence of sensitivity of the overlying atmosphere to mid-latitude SST anomalies. This distinction probably explains why a much larger-scale resonant barotropic response to North Atlantic SST is observed in the MPI multidecadal signal, but not in DMS93. Kushnir and Held (1996) question the robustness of the barotropic responses exhibited in the MPI coupled model, and point out that the matter of which response is physically correct is not yet resolved. In spite of these differences in atmospheric sensitivity, however, the agreement in SST and SLP between the two models is quite good.

An additional extended integration of a coupled model in which there is substantial THC variability on multidecadal time scales is reported by Capotondi and Holland (1998). They show that in a 300 year integration of the NCAR Climate System Model (CSM) there are distinct variations in the intensity of the THC with a 30 to 50 year time scale, along with associated spatial patterns of SST and SSS anomalies which resemble the GFDL results. Their conclusion is tempered, however, by the relatively short integration.

Recent analyses (Vellinga and Wood, 1999) of the Hadley Centre HADCM3 model show pronounced multidecadal variability in volume transport across a section south of Greenland. These results are of particular importance because of the relatively higher resolution of that model.

The above results suggest, at a minimum, that the existence of distinct multidecadal time scales of variability in the North Atlantic is not unique to the GFDL coupled model. Such multidecadal variability is particularly relevant in light of model projections of future reductions in the intensity of the THC due to increasing concentrations of greenhouse gases in the atmosphere (Manabe and Stouffer,1994; Haywood et al, 1997; Wood et al.,1999; Dixon et al., 1999).

# 7 Summary and Discussion

The purpose of this paper has been to compare results from analyses of both the instrumental and proxy climate record with the output from extended integrations of coupled ocean-atmosphere models. We wish to see to what degree recently documented multidecadal variability in the North Atlantic agrees with simulated multidecadal variability in coupled ocean-atmosphere models.

Recent analyses of both the instrumental record and an extended record derived from multiproxy data have shown a distinct pattern of multidecadal variability encompassing the North Atlantic region. The instrumental record has revealed basin-wide patterns of SST changes associated with large-scale SLP anomalies. An extended multiproxy record representing surface temperature has shown that such multidecadal variability has been present in the climate system over the last 300 years.

Several recent extended integrations of coupled ocean-atmosphere models have been shown to contain multidecadal variations of the thermohaline circulation in the North Atlantic. Associated with these variations are large-scale anomaly patterns of sea surface temperature (SST) and sea level pressure (SLP) which resemble the results from observational analyses. However, there is an apparent phase difference between the SLP patterns for the observations and the models.

One of the principal issues with regard to climate variability on these time scales involves the relative interactions between the oceanic circulation and the atmosphere at mid-latitudes. The work of Timmermann et al. (1998) suggests that a relatively strong response of the atmosphere to extratropical SST anomalies gives rise to a coupled mode of variability encompassing both the thermohaline circulation in the North Atlantic and the North Atlantic Oscillation. The work of Delworth et. al. (1993) and Delworth and Greatbatch (1999), however, suggests that such multidecadal variability in the THC can arise as an oceanic response to stochastic surface flux forcing. In reality both processes can be operating. It is thus of paramount importance to increase our theoretical understanding of the atmospheric response to SST anomalies at mid-latitudes.

A fruitful path towards improving our understanding of decadal to centennial climate variability lies in close comparisons between observed and simulated climate variations. The analyses presented in this paper are a step along this path. While the models used in this study have fairly coarse resolution and simplified physics, they nonetheless successfully simulate many aspects of the Earth's climate. In addition, these same properties allow multiple extended integrations with available computing resources. There are also substantial limitations with regard to the instrumental and proxy data, including limitations in both spatial and temporal coverage. Thus, it is clearly desirable to improve both the models and the available data in order to further our understanding of this topic.


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# Figure Captions

Fig. 1 Reconstruction of the approximately 52 year signal in SST and SLP from Kushnir et al. (1997). The color shading denotes SST (units are $^o$C) while the contours depict SLP (units are mb). Each panel is separated in time by approximately 4.3 years. See Kushnir et al. (1997) and Tourre et al. (1999) for details of the analysis.

Fig. 2 (a) MTM-SVD LFV spectrum for joint analysis of the model Atlantic SST and SLP fields (45$^o$S to 80$^o$N) in 1000 year integration of the GFDL coupled model. (b) Spatial pattern of model SST and SLP fields associated with the peak at approximately 56 years in (a). One half of the full evolution of an approximately 56 year cycle is shown in 6 equally spaced increments (approximately 4.7 years apart). The color shading denotes SST (units are $^o$C) while the contours depict SLP (units are mb). The second half of the cycle (not shown) corresponds to the 6 panels shown, but with signs reversed for both SST and SLP.

Fig. 3 Reconstructed principal component (RPC) of Eigenvector #5 from Mann et al. (1998) describing the long-term variations in the dominant surface temperature pattern associated with multidecadal North Atlantic climate variability (refer to Mann et al. (1998) for spatial pattern of this eigenvector).
(a) time-domain signal from 1650-1980 (updated with instrumental PC values after 1980)
(b) Multitaper Spectrum of the RPC with median red noise background and confidence intervals (90,95,99%–dashed curves) estimated by the method of Mann and Lees (1996).

Fig. 4 (a) MTM-SVD multivariate local fractional variance (LFV) spectrum of proxy-reconstructed surface temperature patterns (1650-1980) showing highly significant peak centered near 70 year period. Shown by horizontal dashed lines are the median, 90%, 95%, and 99% confidence levels for significance relative to the null hypothesis of coloured noise. (b) MTM-SVD LFV spectrum for joint analysis of the model SST and SLP fields. The domain of analysis for SLP extends from the Equator to 90$^o$N; for SST the domain extends in the Atlantic from 45$^o$S to 80$^o$N, and in the Indian and Pacific oceans from the Equator to 60$^o$N.

Fig. 5 (a) Spatial pattern of the multidecadal signal in proxy-reconstructed temperature identified in Fig. 4(a). Shown here is one half of an approximately 70 year cycle in 6 equally spaced increments (roughly 6 years apart). The other half of the cycle (not shown) would correspond to the same 6 panels, but with signs reversed (and adding 180$^o$ to the indicated phases). Temperatures are colour shaded with the indicated scale, with units of $^o$C). (b)

Spatial pattern of multidecadal signal in model SST and SLP. Shown here is one half of an approximately 56 year cycle in 6 equally spaced increments (roughly 4.7 years apart). The other half of the cycle (not shown) would correspond to the same 6 panels, but with signs reversed (and adding $180^o$ to the indicated phases). Temperatures are colour shaded with the indicated scale, with units of $^o$C); SLP is indicated by the contours (units are mb), with dashed contours indicating negative values.

Fig. 6 Spatial pattern of multidecadal signal in model SST and SLP fields based on seasonal mean analyses (same domain of analysis as described for Fig. 5b). The phase shown corresponds approximately to phase 0 from Fig. 5b.
Top panel: DJF analysis
Bottom panel: JJA analysis

Fig. 7 Spatial pattern of multidecadal signal from a joint analysis of annual mean SST, 850 mb geopotential height and 500 mb geopotential height. The domain of analysis for SST is idential to that described in Fig. 5(b), while the domain for geopotential heights extends from $20^o$N to $90^o$N. The phase shown corresponds approximately to phase 0 from Fig. 5(b). This analysis indicates the vertical structure in the atmosphere associated with the multidecadal variability.
(a) Analysis using DJF data.
(b) Analysis using JJA data.

Fig. 8 MTM-SVD LFV spectrum for SST from the R30 coupled model. The domain of analysis extended in the Atlantic from the Equator to $80^o$N. The analysis used 700 years of annual mean data from the model.