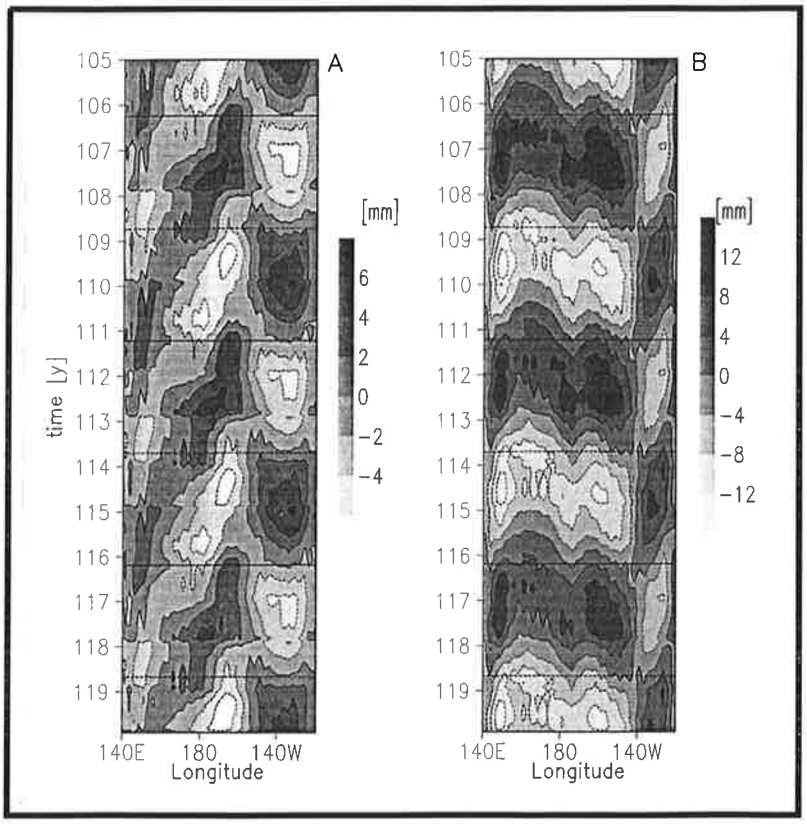
Max-Planck-Institut für Meteorologie

REPORT No. 187



A MECHANISM FOR DECADAL CLIMATE VARIABILITY

by

MOJIB LATIF • ANSELM GROETZNER • MATTHIAS MÜNNICH
ERNST MAIER-REIMER • STEPHAN VENZKE • TIMOTHY P. BARNETT

HAMBURG, January 1996

AUTHORS:

Mojib Latif
Anselm Groetzner
Matthias Münnich
Ernst Maier-Reimer
Stephan Venzke

Max-Planck-Institut
für Meteorologie

Timothy P. Barnett

Climate Research Division
Scripps Institution of Oceanography
La Jolla
Ca. 92093-0224
U.S.A.

MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE
BUNDESSTRASSE 55
D-20146 Hamburg
F.R. GERMANY

Tel.: +49-(0)40-4 11 73-0
Telefax: +49-(0)40-4 11 73-298
E-Mail: <name> @ dkrz.de

REPb 187

ISSN 0937-1060

A Mechanism for Decadal Climate Variability

M. Latif, A. Groetzner, M. Münnich, E. Maier-Reimer, S. Venzke, T. P.Barnett*)

Max-Planck-Institut für Meteorologie
Bundesstraße 55
D-20146 Hamburg, Germany

*)Climate Research Division
Scripps Institution of Oceanography
La Jolla, Ca. 92093-0224, U. S. A.

Prepared for the proceedings of the NATO winter school on "Decadal variability" held in Les Houches, February 1995.

ISSN 0937-1060

Abstract

We describe in this paper a mechanism for decadal climate variability that can lead to decadal climate cycles in the North Pacific and North Atlantic Oceans. A hierarchy of numerical models and observations are used to understand the fundamental dynamics of these decadal cycles. They are generated by large-scale ocean-atmosphere interactions in mid-latitudes and must be regarded as inherently coupled modes. The memory of the coupled system, however, resides in the ocean and is associated with slow changes in the subtropical ocean gyres.

When, for instance, the subtropical ocean gyre is anomalously strong, more warm tropical waters are transported poleward by the western boundary current and its extension, leading to a positive SST anomaly in mid-latitudes. The atmospheric response to this SST anomaly involves a weakened storm track and the associated changes at the air-sea interface reinforce the initial SST anomaly, so that ocean and atmosphere act as a positive feedback system. The atmospheric response, however, consists also of a wind stress curl anomaly which spins down the subtropical ocean gyre, thereby reducing the poleward heat transport and the initial SST anomaly. The ocean adjusts with some time lag to the change in the wind stress curl, and it is this transient ocean response that allows continuous oscillations. The existence of such decadal cycles provides the basis of long-range climate forecasting at decadal time scales.

1. Introduction

The study of decadal climate variability is not only of scientific but also of enormous social and economical interest. Civilization can cope with extreme climate variations that last briefly, say a particularly severe winter. Climate variations with time scales of centuries are beyond a single human's or even a single political system's lifetime and so elicit little but intellectual interest. But the impact of variations in a key climate variable, say precipitation, that last a decade can generally not be avoided by society, e.g. the extended droughts in California, Australia, or the Sahel.

We concentrate in this paper on the decadal variability in the North Pacific and North Atlantic Oceans and describe one particular mechanism that explains many of the aspects of the decadal variability observed in these regions. Different competing hypotheses to explain the decadal variability observed in the North Pacific were put forward. Both Trenberth and Hurrell (1994) and Graham (1994) argue that the decadal variations in the North Pacific are forced by changes in the equatorial Pacific sea surface temperature (SST) and subsequent changes in the atmospheric circulation over the North Pacific. However, both studies disagree about the nature of the decadal variability. While Graham (1994) and some other studies (e. g. Nitta and Yamada (1989)) explain the changes in the mid-1970s as a discrete "shift", Trenberth and Hurrel (1994) view the decadal variability as more oscillatory.

A completely different hypothesis was offered by Jacobs et al. (1994). They argue that the recent decadal variation in the North Pacific is caused by planetary waves which were excited during the strong 1982/1983 El Niño/Southern Oscillation (ENSO) warm extreme (see Philander (1990) for a comprehensive review on ENSO). The planetary waves propagate slowly westward across the Pacific basin at off-equatorial latitudes and interact eventually with the Kuroshio current, leading lo large-scale SST anomalies in the North Pacific and associated changes in the overlying atmosphere. Jiang et al. (1995) attribute low-frequency climate variability in mid-latitudes to the chaotic nature of the ocean that allows, for instance, multiple equilibria of the wind-driven ocean circulation.

The observations show pronounced decadal variability in the North Atlantic also (e. g. Kushnir (1994)). Most studies attribute the decadal variability in the Atlantic to variations of the thermohaline circulation (e. g. Yang and Neelin (1993), Delworth et al. (1993), Weisse et al. (1994)). Such variations are forced by density anomalies at the sea surface which modify the pattern and strength of oceanic convection, which in turn leads to large-scale variations in the oceanic general cicrulation.

Here, we propose an alternative hypothesis for the generation of decadal variability in both the North Pacific and North Atlantic Oceans which involves variations in the wind-driven ocean circulation. Our hypothesis is based on unstable large-scale ocean-atmosphere interactions in mid-latitudes leading to climate cycles in these regions. The possibility of unstable ocean-atmosphere interactions in mid-latitudes on seasonal and longer time scales was originally hypothesized by Namias (for the North Pacific) in a series of papers (e.g. Namias, 1959, and 1969) and by Bjerknes (1964) (for the North Atlantic). Namias argued that SST anomalies in the North Pacific can change the transient activity in the atmosphere, which in turn changes the mean westerly flow reinforcing the initial SST anomalies. The paper by Bjerknes is interesting, since it postulates a climate cycle with a period of about 10 years in the Atlantic which involves interactions of the westwind regime and the subtropical ocean gyre. As we shall see below, the "early" ideas of both Namias' and Bjerknes' apply remarkably well to the decadal climate variability observed in both oceans.

The decadal variability is studied by means of a hierarchy of numerical models and a mechanism is postulated for the generation of decadal variability in mid-latitudes. We describe in section 3 a decadal mode in the North Pacific from observations and as simulated in a multi-decadal integration with a coupled ocean-atmosphere general circulation model which is described in section 2. A preliminary description of this mode and the physics responsible for it were given by Latif and Barnett (1994). Suffice to say, it has many of the features of the decadal variability observed in the North Pacific. The results of uncoupled experiments with the individual model components are also shown in section 3. These uncoupled experiments were performed, in order to get more insight into the nature of the atmospheric response to mid-latitudinal SST anomalies and the ocean adjustment to decadal wind stress variations, which are both crucial parts of our mechanism. We describe the results of a simple coupled ocean-atmosphere model which retains the essential physics of the decadal cycles in section 4. Section 5 deals with the decadal variability in the North Atlantic, as simulated by our coupled ocean-atmosphere general circulation model. The paper is concluded with a summary and discussion of our major findings in section 6.

2. Coupled ocean-atmosphere general circulation model and observational data

2.1. Coupled model

The coupled general circulation model (CGCM) and its behaviour with respect to climate drift and interannual variability during the first twenty years of a 125-year integration are described in Latif et al. (1994). Overall, the model drift is relatively small and the CGCM simulates well the decadal variabiliy in the North Pacific, as shown in Latif and Barnett (1994) and Latif and Barnett (1996). As will be shown below, the CGCM succesfully reproduces also some fundamental aspects of the decadal variability in the North Atlantic.

The atmospheric component of our coupled GCM "ECHO" is ECHAM-3, the Hamburg version of the European Centre operational weather forecasting model. The model is described in detail in two reports (Roeckner et al., 1992; DKRZ, 1992). ECHAM-3 is a global low-order spectral model with a triangular truncation at wavenumber 42 (T42). The nonlinear terms and the parameterized physical processes are calculated on a 128 x 64 Gaussian grid which yields a horizontal resolution of about 2.8^o x 2.8^o. There are 19 levels in the vertical which are defined on σ-surfaces in the lower troposphere and on p-surfaces in the upper troposphere and in the stratosphere.

The ocean model is "HOPE" (Hamburg Ocean Model in Primitive Equations) which is based on primitive equations (see Latif et al., 1994 and references therein). Its domain is global and we use realistic bottom topography. The meridional resolution is variable, with 0.5^o within the region 10^oN to 10^oS. The resolution decreases poleward to match the T42-resolution of the atmosphere model. The zonal resolution is constant and also matches the atmospheric model resolution. Vertically, there are 20 irregularly spaced levels, with ten levels within the upper 300 m. Since we have not yet included a sea-ice model in HOPE, the SSTs and sea surface salinities are relaxed to

Levitus (1982) climatology poleward of 60°, using Newtonian formulations with time constants of about 2 and 40 days, respectively, for the upper layer thickness of 20 meters. The vertical mixing is based on a Richardson-number dependent formulation and a simple mixed layer scheme to represent the effects of wind stirring (see Latif et al. (1994) for details).

The two models were coupled without flux correction. They interact over all three oceans in the region 60°N - 60°S. The ocean model is forced by the surface wind stress, the heat flux, and the freshwater flux simulated by the atmosphere model, which in turn is forced by the SST simulated by the ocean model. The coupling is synchronous, with an exchange of information every two hours. The coupled GCM is forced by seasonally varying insolation. The coupled integration started at 1 January and continued for 125 years.

2.2. Observational data

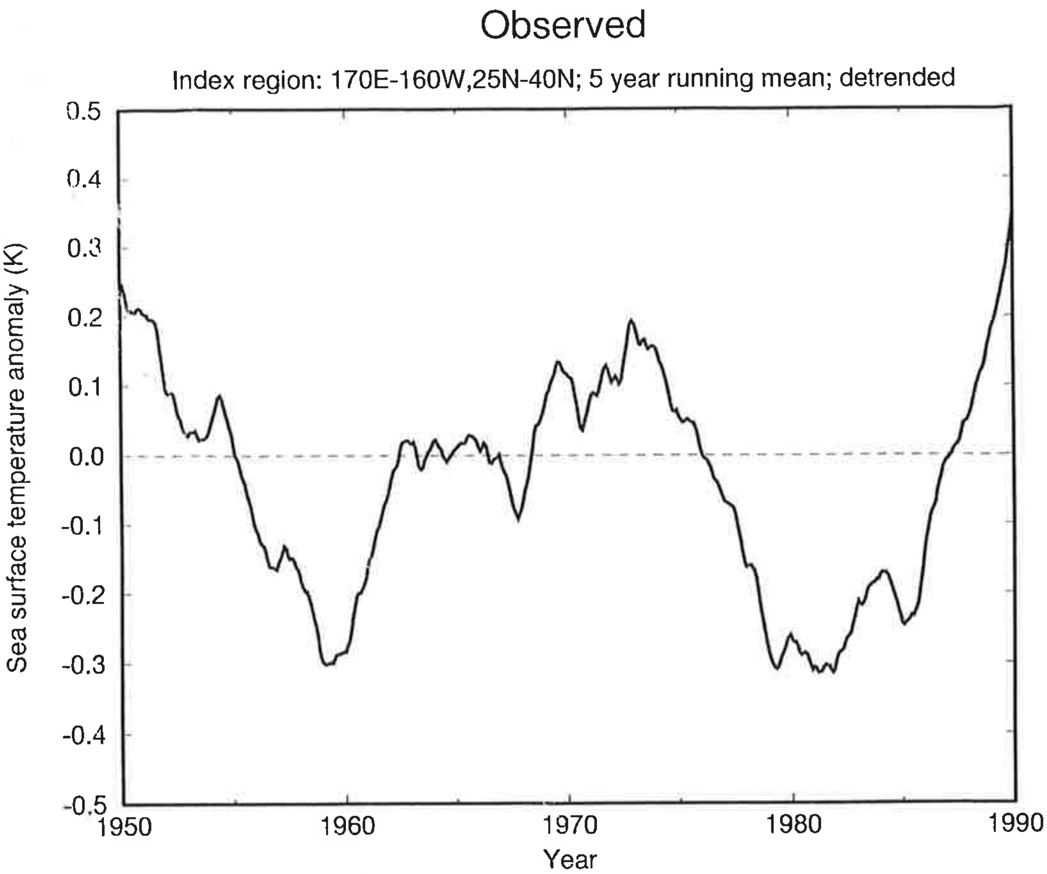
Various observational data sets will be used to describe the decadal variability observed. A short description of these data is given below. The data were available at monthly intervals. Sea surface temperature (SST) data were obtained from the SST data set of the British Meteorological Office (UKMO) which is referred to as the "GISST" data set, covering the period 1949-1991, and 700 hPa height data were provided by the Climate Analysis Center. The latter were available for the Northern Hemisphere and the period 1950-1991. Near surface air temperature over North America was obtained from an update of the Climate Research Unit (CRU) product (Jones et al. (1986)). This record will be used back to 1866. Inspection of the individual monthly maps for the era showed a surprising amount of information in the regions wherein the North Pacific decadal mode, that we shall discuss in the next section, has maximum variance. So we have some confidence in the results for the whole period 1866-1992. Rainfall, in gridded field format, was also provided courtesy of the CRU (cf Hulme and Jones (1993)). Comparison of these data with the US divisional data and individual data suggest they are valid in the main areas of interest back to 1900. We show additionally subsurface temperature measurements of the North Atlantic which are described by Levitus et al. (1994).

3. The decadal variability in the North Pacific

3.1 Observations

In order to describe the decadal variability in the North Pacific, we performed a correlation analysis of low-pass filtered SST and 700 hPa height anomalies observed during the period 1950 to 1990. The correlation analysis was performed as follows: First, the observations were detrended and smoothed with a five year running mean filter. We then defined a SST index by averaging the SST anomalies over the region 25°N-40°N and 170°E-160°W (Fig. 1a). This particular region was chosen because it is located in the region of maximum decadal variability. Finally, we computed locally the correlation coefficients of the SST index with the low-pass filtered SST and 700 hPa anomalies.

The decadal variability is clearly seen in the North Pacific SST index time series, with minima around the years 1960 and 1980 and maxima around the years 1950, 1970, and 1990. Although the time period considered is definitely too short to estimate a reliable period for the decadal variability, there is, a)



b)

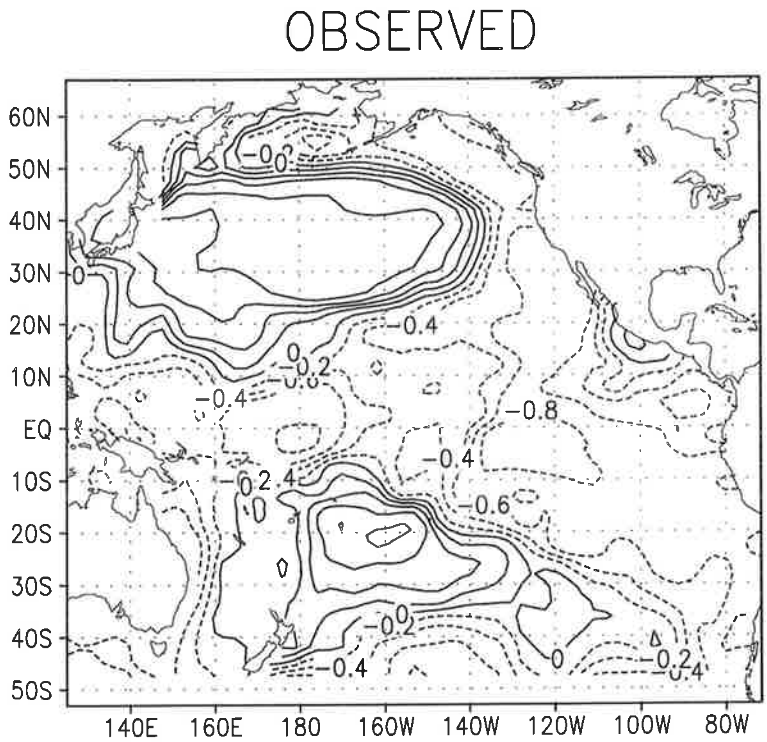
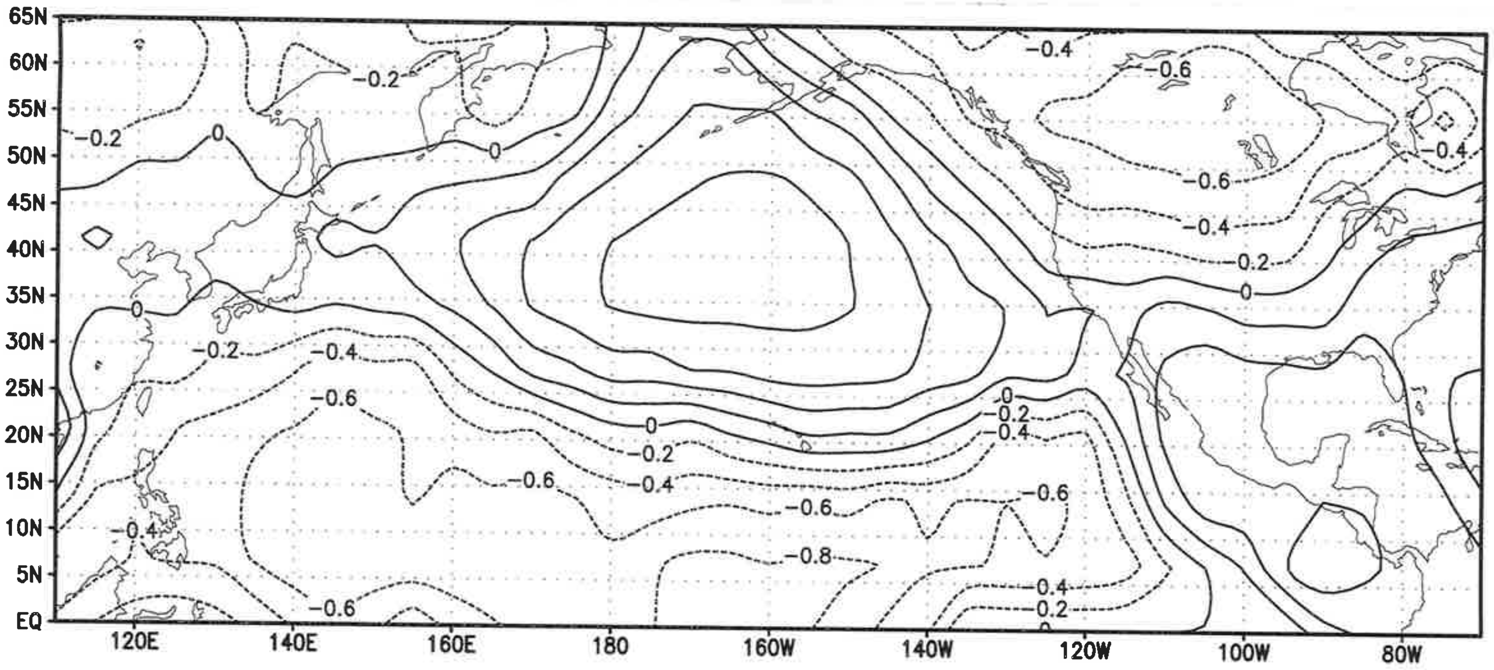


Figure 1: Observed low-pass filtered (retaining variability on time scales longer than 5 years) SST anomalies averaged over the North Pacific (25°N-45°N, 170°E-160°W) for the period 1950-1990, as derived from the GISST data set. b) Spatial distribution of correlation coefficients of the index time series shown in (a) and SST anomalies in the Pacific. c) Spatial distribution of correlation coefficients of the index time series shown in (a) and 700 hPa height anomalies over the Pacific and North America.

c) correlation of 700 hPa height anomalies with North Pacific SST index

Observed

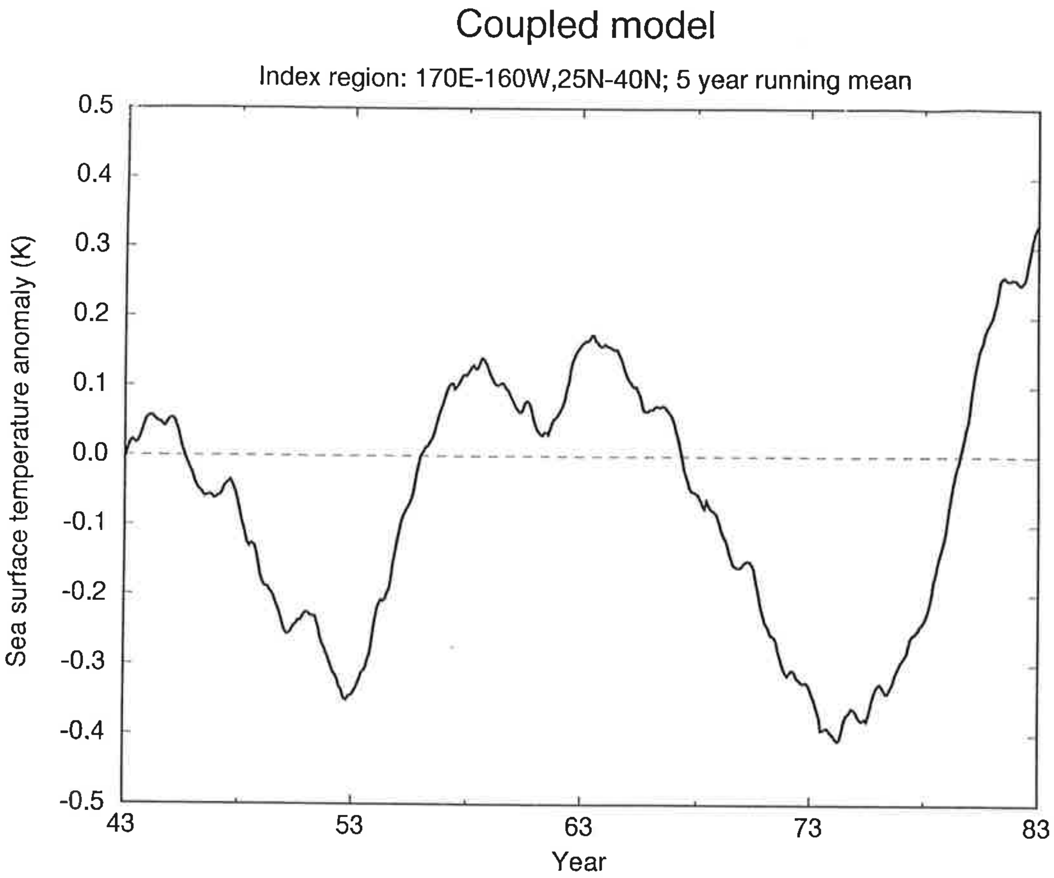


however, some evidence of a 20-year time scale. The results of the correlation analysis are shown in Figs. 1b, and 1c. The dominant SST anomaly in the North Pacific is positive (by definition) and surrounded by negative anomalies (Fig. 1b), a result that was found also by Trenberth and Hurrell (1994). These features are statistically highly significant. The SST anomaly pattern shows a remarkable symmetry about the equator, with equatorial Pacific SST anomalies of opposite sign and SST anomalies of the same sign in the Southern Hemisphere relative to the main anomaly in the North Pacific.

The anomalous atmospheric circulation, as expressed by the 700 hPa height anomaly field (Fig. 1c), is dominated by the reverse of the "Pacific-North-American" (PNA) pattern which is an eigenmode of the atmosphere and also excited during extremes of the El Niño/Southern Oscillation (ENSO) phenomenon (Horel and Wallace (1981)). Anomalous high pressure is found over the North Pacific, which was also noted by Trenberth and Hurrell (1994). A negative height anomaly is centered over Canada and a positive height anomaly over the southern part of the United States and Central America. The anomalies associated with the PNA pattern are statistically highly significant, with explained variances relative to the low-pass filtered height anomalies of about 90% in the center of the Aleutian anomaly and about 60% in the centers further downstream.

3.2 Coupled general circulation model simulation

The corresponding results for the coupled general circulation model are shown in Fig. 2. We have chosen a model period that begins in year 43 and extends to year 83 for the correlation analysis. This time period shows a very similar a)



b)

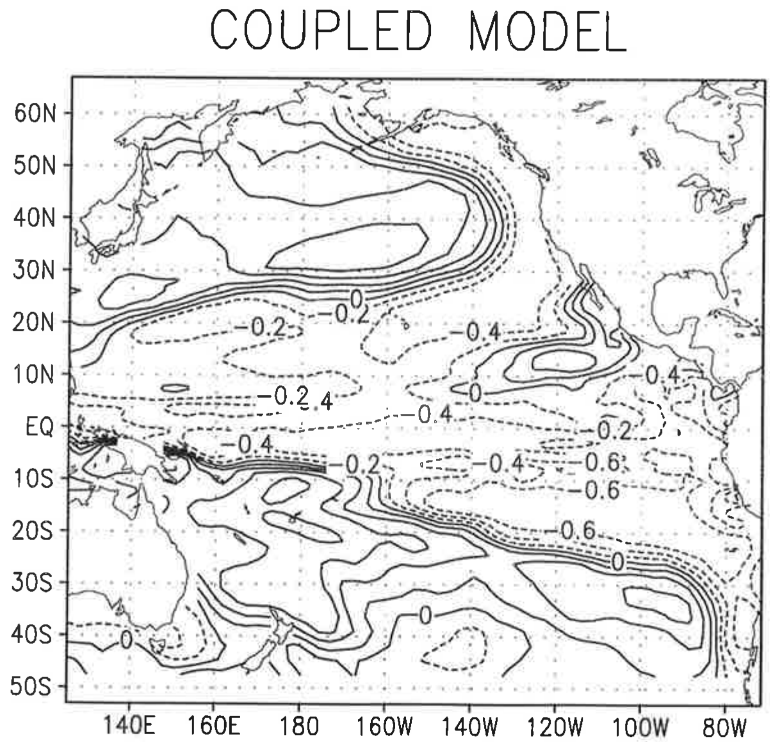
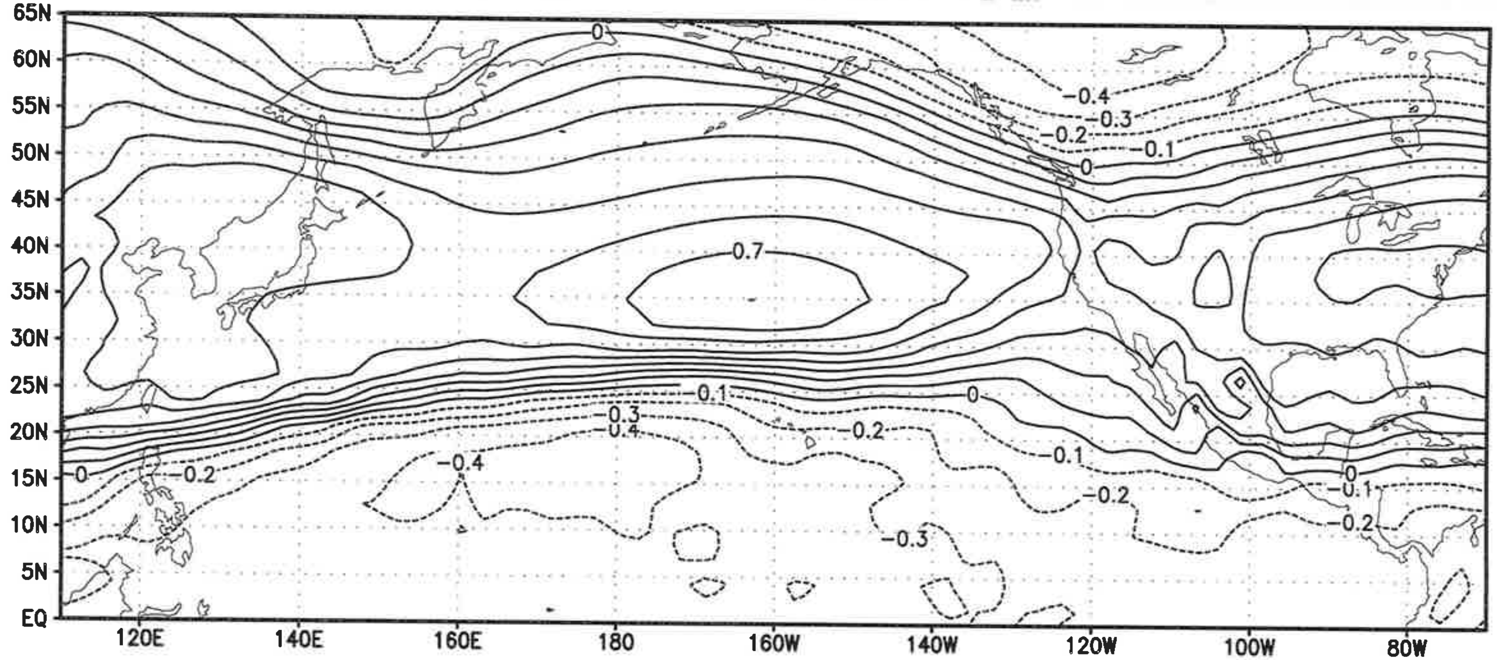


Figure 2: a) With the CGCM simulated low-pass filtered (retaining variability with time scales longer than 5 years) SST anomalies averaged over the North Pacific (25°N-45°N, 170°E-160°W) for the model years 43-83. b) Spatial distribution of correlation coefficients of the index time series shown in (a) and SST anomalies in the Pacific. c) Spatial distribution of correlation coefficients of the index time series shown in (a) and 500 hPa height anomalies over the Pacific and North America.

c) correlation of 500 hPa height anomalies with North Pacific SST index

Coupled model



time behaviour in North Pacific SST as the observations during the period 1950-1990 (compare Fig. 2a with Fig. 1a). Overall, the coupled model results are consistent with the observations. The associated SST correlation pattern as derived from the CGCM (Fig. 2b) shows the main positive anomaly in the North Pacific which is surrounded by negative anomalies. The symmetry about the equator is also found in the coupled model simulation. The negative equatorial anomaly, however, is less pronounced than in the observations.

We use the 500-hPa field to describe the changes in the large-scale atmospheric circulation in the coupled simulation. Since the changes in the height field are equivalent barotropic, the model results (Fig. 2c) can be compared directly to the observations (Fig. 1c), although they are presented at a different vertical level. The atmospheric response in the coupled model is also characterized by the reverse of the PNA pattern, but the changes are systematically too zonal relative to the observations. The fundamental spatial phase relationship between the North Pacific SST and height anomaly fields, however, are very similar: anomalously warm SSTs are accompanied by anomalously high pressure over the North Pacific and thus a weakened Aleutian low.

Thus, we believe that our CGCM simulates reasonably well the decadal variations observed in the North Pacific, so that we can use it to investigate the dynamics of the decadal variability in more detail. This is not possible with the available observations which are too sparce and not homogeneous. To elucidate the mechanism producing the decadal variations in SST, we investigated the characteristic evolution of upper ocean heat content anomalies, as defined by the vertically averaged temperatures over the upper 500 meters of the water column via a complex empirical orthogonal function

(CEOF) analysis (Barnett (1983)). Before the CEOF analysis, the heat content data were smoothed with a low-pass filter that retained variability at time scales longer than 3 years (further details can be found in Latif and Barnett (1994)).

The leading CEOF mode, accounting for about one third of the variance in the filtered heat content data, has a period of about 20 years. Anomalies in upper ocean heat content reconstructed from this leading CEOF mode (Fig. 3) are displayed at intervals of about two and a half years. When the SST anomalies are fully developed and in a stage corresponding to that shown in Fig. 2b (Θ=0) the main heat content anomaly is positive and covers the majority of the western and central Pacific. A negative anomaly extends to the southwest from North America and increases in area and strength as it approaches the tropics. With time, through one-half of a cycle, the large anomalies rotate around the Pacific in a clockwise fashion reminiscent of the general gyral circulation. Thereafter, the whole sequence of events is repeated, but with reversed signs, and that completes one full cycle.

This evolution is characteristic of the transient response of a midlatitude ocean to a variable wind stress, as described in many theoretical and modeling papers (e. g. Anderson and Gill (1975), Anderson et al. (1979), Gill (1983)). The response is mostly baroclinic at climate time scales longer than several months and involves the propagation of long, relatively fast planetary waves with westward group velocity and their reflection into short, relatively slow planetary waves with eastward group velocity. However, the mean horizontal currents will affect the wave propagation. The net effect of this wave propagation is to modify the strength of the subtropical gyre circulation. In particular, resultant fluctuations in poleward transport of warm tropical

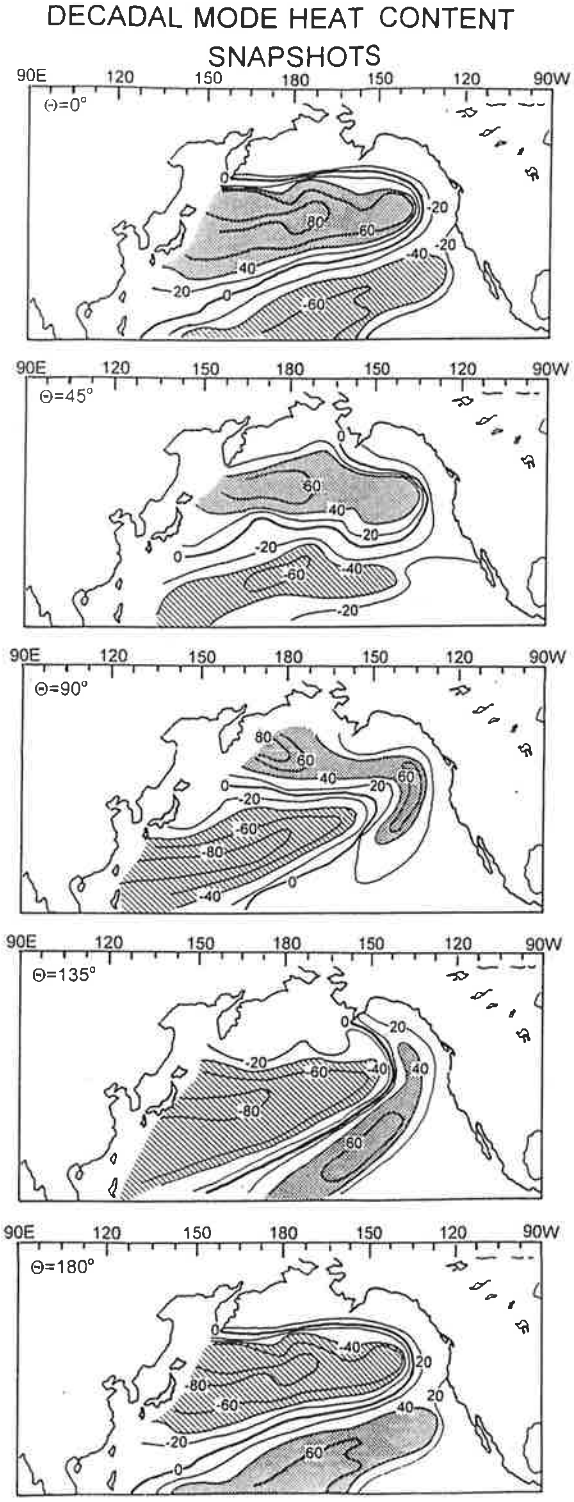


Figure 3 : Reconstruction of anomalous heat content (^{o}Cm) simulated by the CGCM from the leading CEOF mode. The individual panels show the heat content anomalies at different stages of the decadal cycle, approximately 2.5 years apart from each other.

waters by the western boundary current lead to the generation of SST anomalies along the path of the Kuroshio and its extension. The spin-up time of the subtropical gyre is several years to a decade or even longer, which accounts for the decadal time scale of the mode under discussion.

3.3 Atmospheric response experiments

The remaining task is to explain the oscillatory nature of this mode. Our hypothesis is that it arises from an instability of the coupled ocean-atmosphere system in the North Pacific. The characteristic SST anomaly pattern exhibits a strong meridional gradient which either reduces or enhances the meridional SST gradient normally found in the central Pacific. Suppose the coupled system is in its reduced meridional SST gradient state shown in Fig. 2b. It has been suggested by Palmer and Sun (1985) that such a distribution of SST would result in a northward shift of the baroclinic eddy activity in the atmosphere, leading to a weakened Aleutian Low, and subsequently reduced westerly winds over the mid-latitudes ocean. Indeed, the model results show that a reduced meridional SST gradient goes along with anomalous high pressure over the entire North Pacific (Figs. 2b and 2c).

To further investigate the nature of the atmospheric response to the anomalous SST pattern, we forced the atmospheric component of our coupled model in a stand-alone integration by a SST pattern similar to that shown in Fig. 2b. The integration was done in a perpetual January mode and an ensemble of 12 January integrations was performed. The atmospheric response is highly significant and shows the expected result: anomalous high pressure over the North Pacific (Fig. 4a). We note, however, that the mean response becomes much weaker when

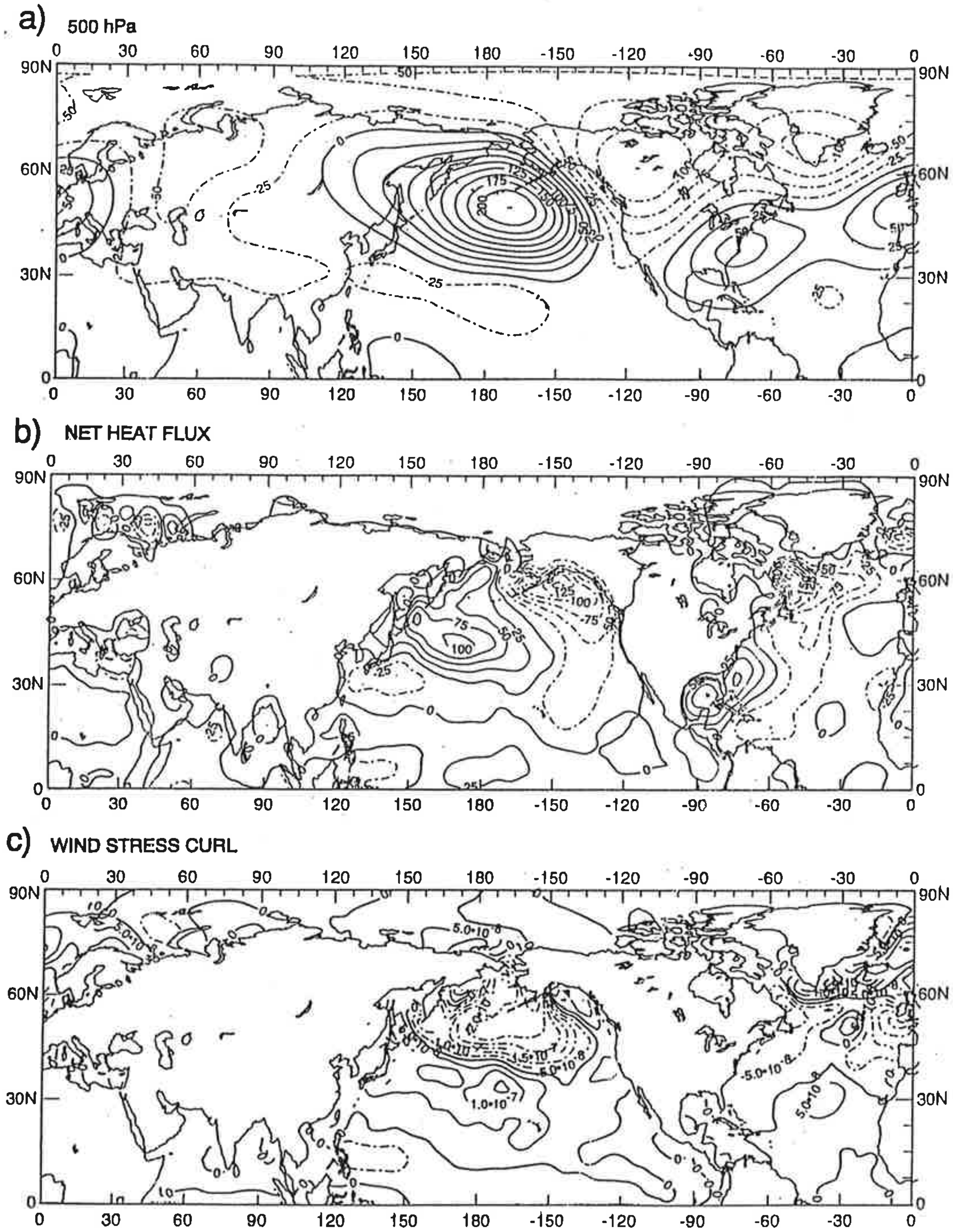


Figure 4: Atmospheric response to a mid-latitudinal SST anomaly. The upper panel shows the response in the 500 hPa field (gpm), the middle panel shows that of the net surface heat flux (W/m^2), while the lower panel shows that of the wind stress curl (Pa/m). The mean fields shown in the panels were obtained by averaging the results of a 12 member ensemble of 30-day perpertual January integrations using the same SST forcing. Please note that the response weakens considerably when the ensemble size is increased.

the ensemble size is increased, but the response pattern remains virtually unchanged (Latif and Barnett (1996)). The response pattern is the weak Aleutian-low extreme of the "Pacific North American" (PNA) mode. The response shown in Fig. 4 arose from an atmospheric model simulation in which tropical SSTs were near their climatological norms, that is the tropics played a minor role in the result. This was confirmed by an additional integration in which SST anomalies south of 25^{o}N were entirely neglected.

The associated changes in the net surface heat flux (Fig. 4b) are such that they tend to reinforce the SST anomalies over the western North Pacific. Heat is anomalously pumped into the ocean in most of the region where it is already warm and vice versa (compare Fig. 2b with Fig. 4b). Changes in the latent and sensible heat fluxes contribute most to the net surface heat flux anomaly. Furthermore, because the westerlies are weakened over the warm SST anomaly, the mean wind speed is reduced, leading to reduced mixing in the ocean, which tends also to strengthen the initial SST anomaly (Miller et al. (1994)). Thus, ocean and atmosphere form a positive feedback system capable of amplifying an initial disturbance, giving rise to instability of the coupled system. The growth is eventually equilibrated by nonlinear processes and the phase switching mechanism described below.

The changes in the wind stress curl (Fig. 4c) force characteristic changes in the ocean, eventually reducing the strength of the subtropical gyre and enhancing meridional SST gradients. The ocean has a memory to past changes in the wind stress and is not in equilibrium with the atmosphere, as described below. It is this transient response of the ocean to imposed wind stress, expressed in terms of planetary wave propagation illustrated in Fig. 3, that provides a mechanism to switch from one phase of the decadal mode to another and, hence, enables the coupled system to oscillate. The oscillation can become easily irregular in the presence of high frequency weather fluctuations. Elements of these ideas were put forward some decades ago (Namias (1959 and 1969), (Bjerknes (1964), White and Barnett (1972)).

3.4 Oceanic response experiments

As described above, a crucial part of the mechanism for the generation of decadal climate variability in the North Pacific is the transient response of the ocean circulation to low-frequency wind stress variations. In order to obtain more insight into the oceanic adjustment, we conducted a series of "ocean-only" integrations in which we forced a coarse-resolution version (3.5^{o}x 3.5^{o}) of our oceanic general circulation model (OGCM) HOPE by prescribed low-frequency periodic wind stress variations. The spatial wind stress pattern by which we forced our OGCM was derived from the stand-alone integrations with our atmosphere model (section 3.3) and is shown in Fig. 5, and the time evolution was assumed to be sinusoidal.

We discuss here two cases in which the forcing period amounts to five years and twenty years, respectively. As can be seen clearly in Fig. 6 showing the time evolution of the sea level anomalies along two particular latitudes bands, the ocean is not in equilibrium with the wind stress forcing at a period of five years. Consistent with planetary wave propagation, slow westward phase propagation can be seen between 20^{o}N and 30^{o}N (Fig. 6a), while the response further to the north is more stationary in character (Fig. 6b). Similar results are obtained for a forcing period of ten years (not shown). The ocean approaches an equilibrium response for forcing periods longer than

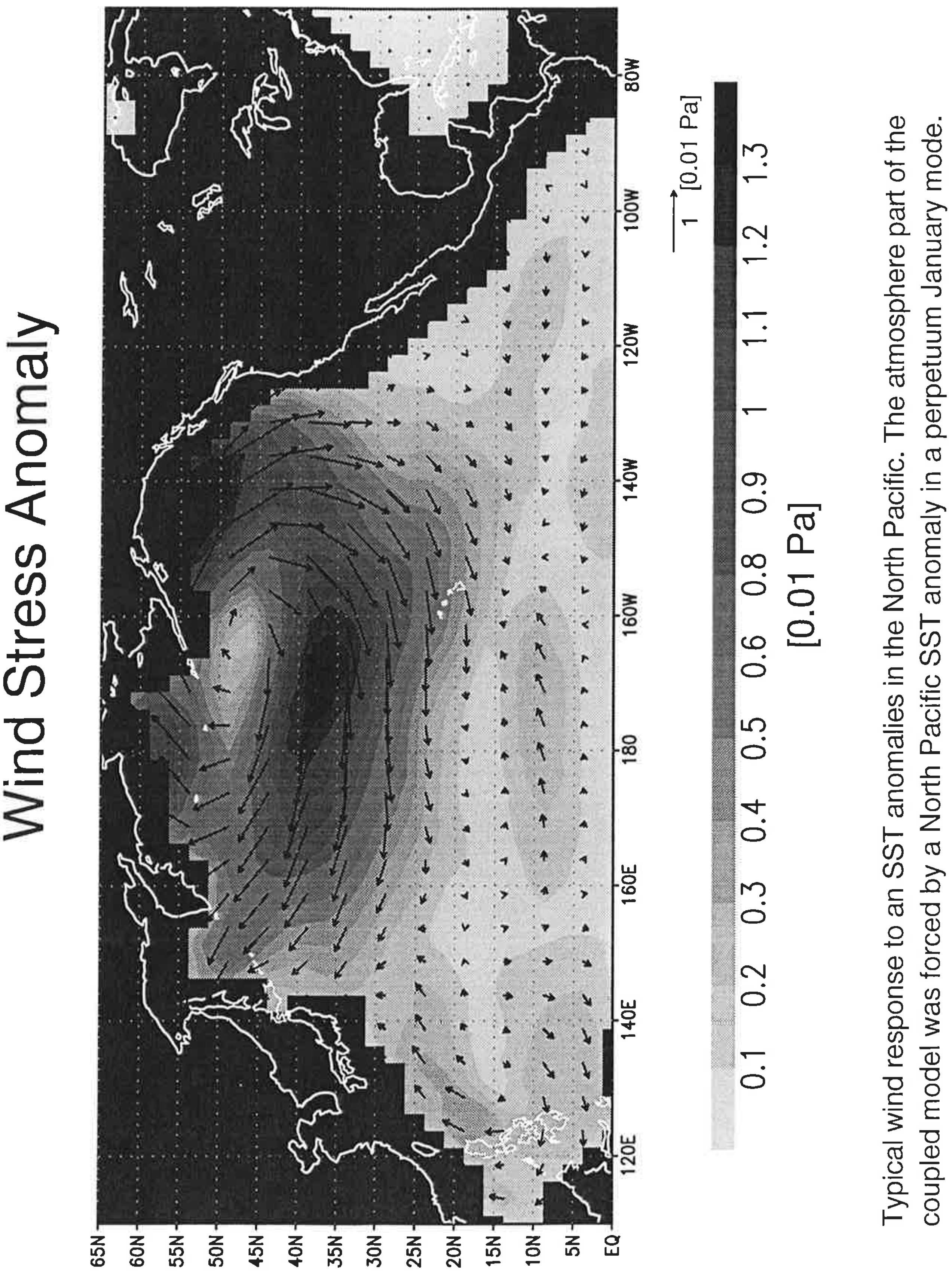


Figure 5: Wind stress anomaly (Pa) used in the periodic forcing experiments with our OGCM.

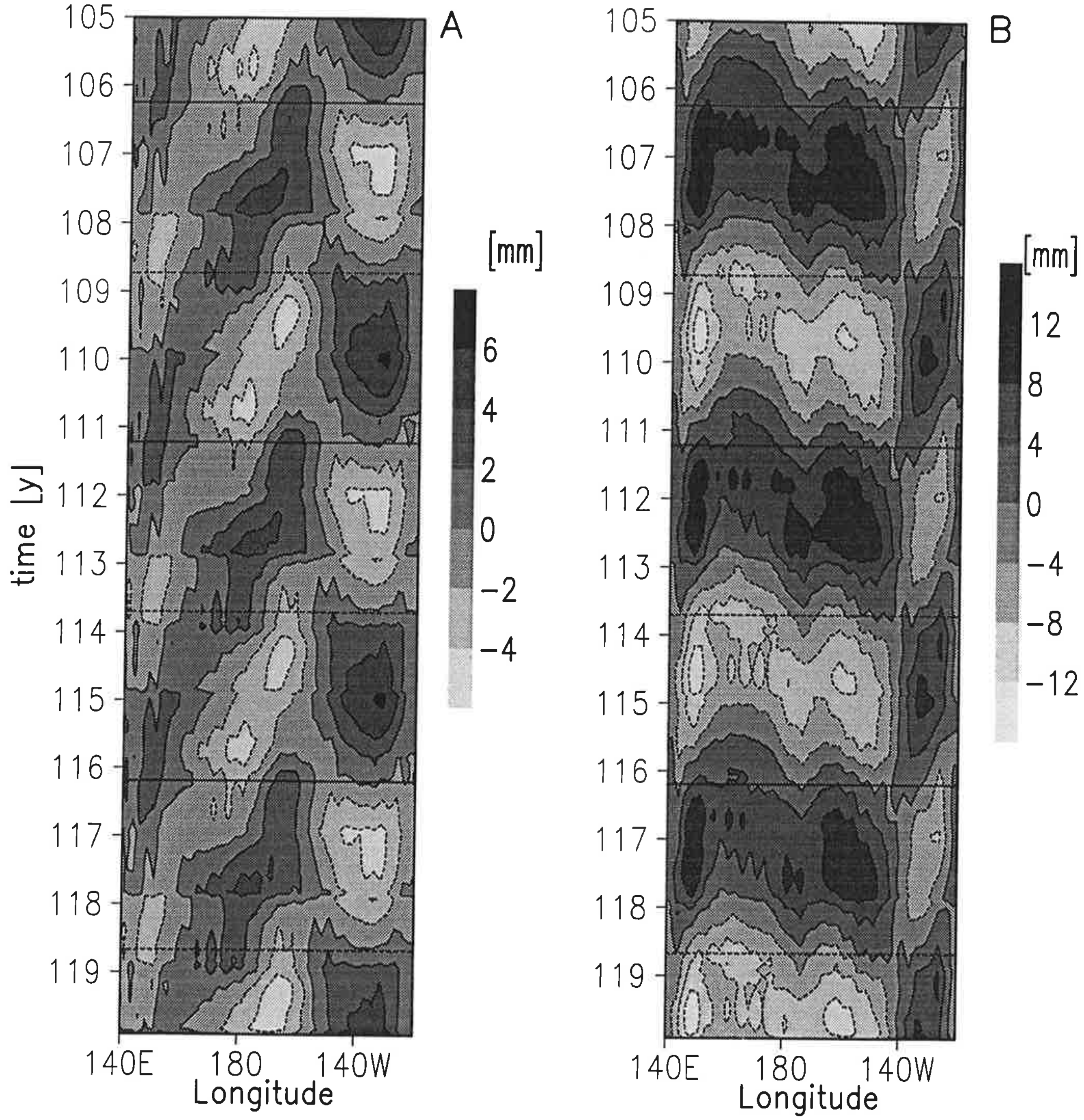


Figure 6: Hovmoeller diagrams of sea level anomalies (mm) averaged over the region 20°N-30°N (left) and 35°N-45°N (right) for a forcing period of 5 years. Rigdes (troughs) of the wind stress anomaly are indicated by solid (dashed) horizontal lines.

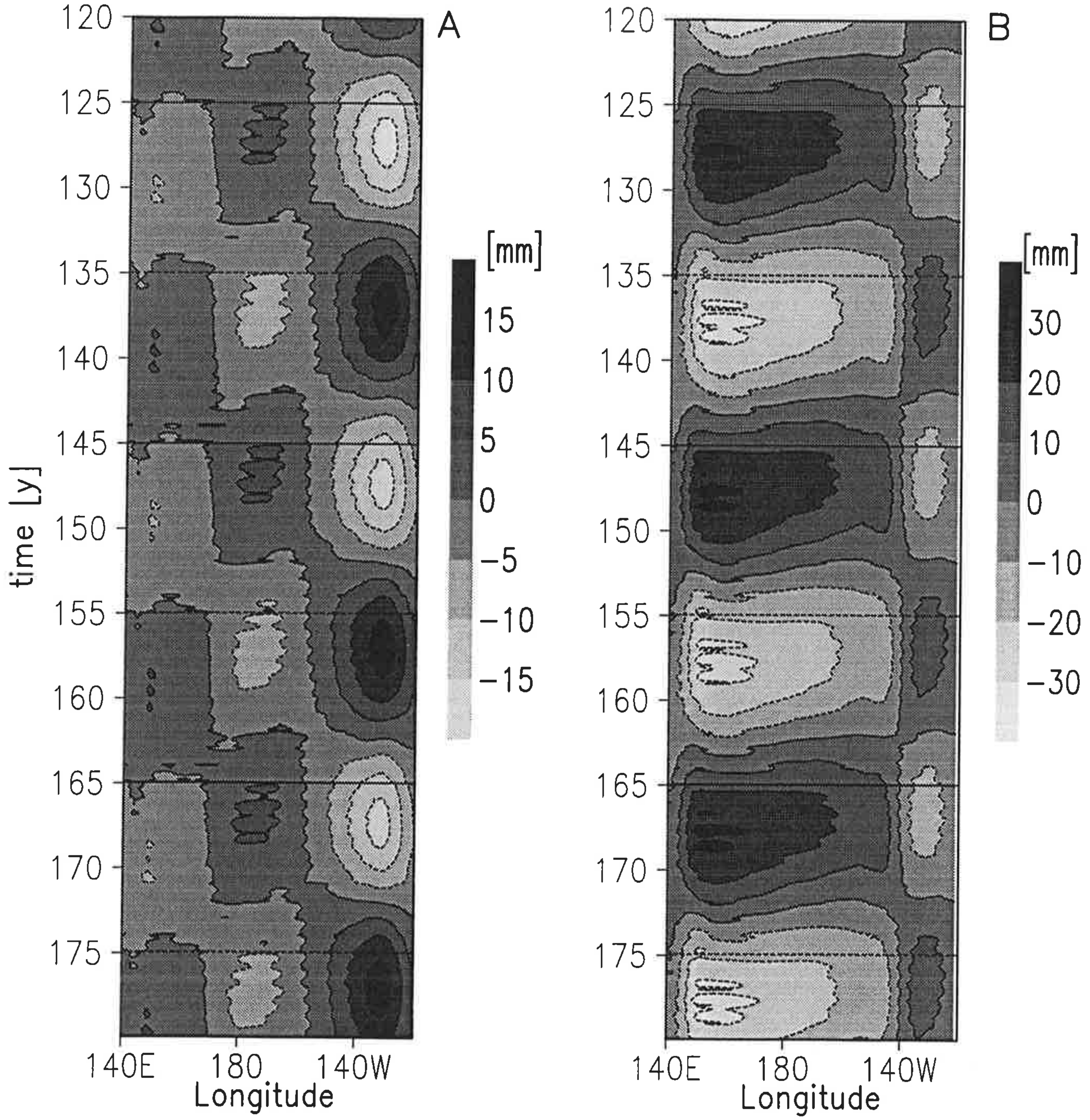


Figure 7: Hovmoeller diagrams of sea level anomalies (mm) averaged over the region 20°N-30°N (left) and 35°N-45°N (right) for a forcing period of 20 years. Rigdes (troughs) of the wind stress anomaly are indicated by solid (dashed) horizontal lines.

about twenty years. This is demonstrated in Fig. 7 which shows the case for a forcing period of exactly twenty years. No phase propagation is seen at this period, neither in the subtropics (Fig. 7a) nor in the mid-latitudes (Fig. 7b). Thus, our ocean-only experiments with low-frequency periodic wind stress forcing support fully the picture that the ocean has a sufficiently long memory to enable decadal oscillations. The precise period of the decadal oscillations, however, will not only depend on the wave transit times but also on the nature of the ocean-atmosphere interactions.

4. Simple coupled model

In summary, both our CGCM results and the uncoupled atmospheric and oceanic experiments support the picture that the decadal mode arises from unstable ocean-atmosphere interactions over the North Pacific, so that the mode is best described as an inherently coupled air-sea mode. The memory of the coupled system resides in the ocean, while the atmosphere responds passively to the slowly varying boundary conditions. It is interesting to note that this paradigm for the generation of the decadal variability over the North Pacific is similar to that for the ENSO phenomenon in the tropical Pacific (e.g. Schopf and Suarez (1988), Neelin et al. (1994)).

It is therefore tempting to construct a simple ocean-atmosphere model that retains the essential physics of the decadal variability, as described above. The ocean dynamics is described according to Anderson and Gill (1975) who studied the spin-up problem of a stratified ocean. The relevant equations are the linearized shallow water equations for a particular vertical mode in the quasi-geostrophic approximation, combined into a single equation for the streamfunction ψ:

$$(\psi_{xx} + \psi_{yy} - (f^2/c^2)\cdot\psi)_t + \beta\cdot\psi_x = -(1/H)\cdot\text{curl } \underline{\tau} + \nu\cdot\psi_{xxxx} \qquad (1)$$

Subscripts denote partial derivitaves. Some friction is added in (1) for numerical reasons. The special form of the friction is chosen to account for the existence of western boundary currents. Boundary conditions are ψ=const.=0 along boundaries. The parameters $f=2\cdot\omega\cdot\sin\varphi$, β, c, H, and ν denote the Coriolis parameter and its variation with latitude, the speed of the vertical mode considered and a measure of its degree of forcing, and the eddy viscosity, respectively. The surface wind stress vector devided by the reference density is denoted by $\underline{\tau}$, but we consider its zonal component τ^x only in our simple coupled model. Thus, the wind stress curl is given by the meridional derivative of τ^x:

$$\text{curl } \underline{\tau} = -(\partial\tau^x/\partial y) \qquad (2)$$

The (mean) forcing curl $\bar{\underline{\tau}}$ for our ocean model is assumed to be of the form $A\cdot\sin(2\pi y/B)$, with B the meridional extent of the basin. This is a reasonable approximation of the real westwind regime in mid-latitudes, leading to a double-gyre circulation which can be identified with the subtropical and subpolar gyres.

The coupling with the atmosphere is respresented in a rather crude way and by wind stress only. Consistent with the scenario developed above, we assume that the atmosphere has no internal dynamics and responds passively to the oceanic changes. Since our ocean model carries no sea surface temperature, we parameterize the SST variations in terms of the strength of the western boundary current which is taken to be proportional to the streamfunction difference across the two gyres near the eastern boundary. The actual wind stress curl is given by:

$$\text{curl } \underline{\tau} = \alpha \cdot g(q) \cdot \text{curl } \bar{\underline{\tau}}, \qquad q = [(\partial\psi/\partial y)_W / (\partial\bar{\psi}/\partial y)_W] \qquad (3)$$

Bars denote in (3) quantities that were derived from the steady state solution of the uncoupled system. The subscript "W" indicates that the pressure gradients are computed near the western boundary. The coupling strength is given by the parameter α. In order to describe the non-linear equilibration of the growth, we assume a function $g(q)$ proportinal to $[q/(1 + \gamma \cdot |q|)]$, with γ a parameter controling the degree of the non-linearity.

The equations are solved numerically on a 2^o x 2^o grid. Preliminary results indicate that such a simple coupled model oscillates at decadal time scales at sufficiently high values of the coupling strength α. An example is shown in Fig. 8 which shows the normalized streamfunction anomaly in the center of the subtropical gyre as function of longitude and time for a rectangular basin that extends 50^o in the meridional and 100^o in zonal direction. The other parameters are given in the caption of Fig. 8. Although the oscillation is weakly damped for the set of parameters chosen, a clear periodicity of the order of 30 years can be readily seen. Thus, the results of our simple coupled model support our hypothesis that decadal variability in mid-latitudes can originate from unstable air-sea interactions in mid-latitudes themselves. A complete investigation of the sensitivity of our simple coupled model is underway and will be described by Münnich et al. (in preparation).

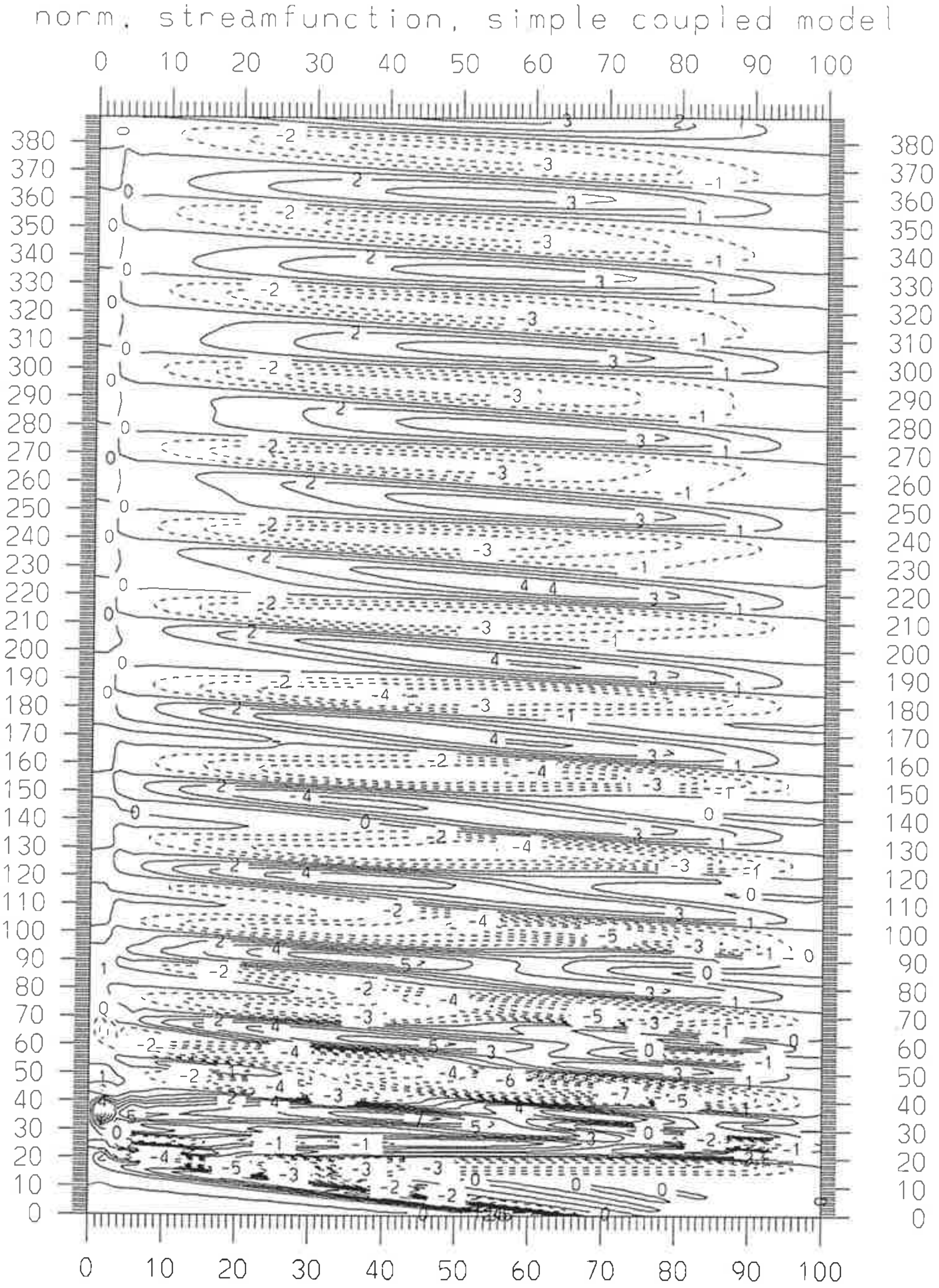


Figure 8: Hovmoeller diagram of normalized pressure anomalies in the center of the subtropical gyre in a multi-century integration with the simple coupled ocean-atmosphere model. Parameters are: c=2.6 m/s, $\nu=3\cdot10^3 m^2/s$, $\gamma=0$, $\alpha=40$. The basin size is 100^o in the zonal direction and 50^o in the meridional direction. A Gaussian disturbance in the eastern quarter of the basin was introduced at time t=0.

5. The decadal variability in the North Atlantic

The type of decadal variability described above can exist in principal also in the North Atlantic. Indeed, observations show some evidence of a decadal cycle in the North Atlantic. This is shown in Fig. 9 which displays observations of subsurface temperature anomalies in the North Atlantic at 125 m depth (Levitus et al. (1994)). The subsurface temperature measurements show some remarkable oscillatory behaviour during the last few decades, with a period of the order of about 15 years. However, the observational record is certainly much too short, in order to prove the existence of a decadal climate cycle in the North Atlantic.

We investigated therefore additionally the variability simulated by our coupled ocean-atmosphere general circulation model "ECHO" in the multi-decadal integration described above. In order to derive the major modes of ocean-atmosphere co-variability, we performed a Canonical Correlation Analysis (CCA, see Barnett and Preisendorfer (1987)) between low-pass filtered simulated North Atlantic SST and 500 hPa height anomalies. The coupled run shows a rather stable decadal cycle in the North Atlantic, as can be inferred from the time series of the leading CCA mode (Fig. 10a). The canonical correlation amounts to about 0.9, and the period of the decadal variations is of the order of 17 years, which is consistent with the observations of Levitus et al. (1994) shown in Fig. 9.

The corresponding SST anomaly pattern (Fig. 10b) shows a positive anomaly along the path of the (model) Gulf stream in the western and central part of

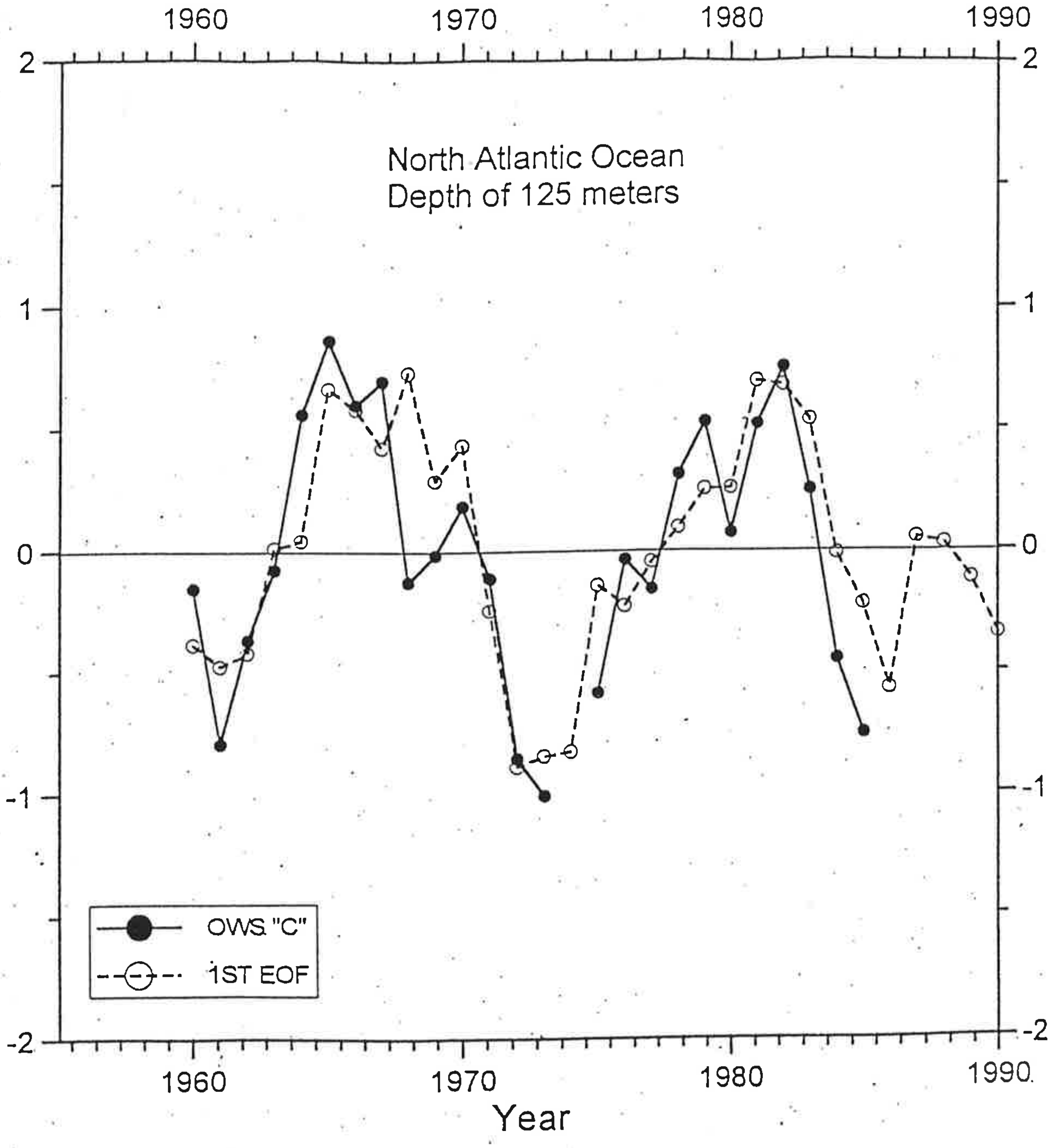


Figure 9: Time series of subsurface temperature anomalies at 125 m measured at weather ship "C" (35.5°W, 52.5°N) and time series of the first EOF (multiplied by -1) of North Atlantic temperature anomalies at the same depth. After Levitus et al. (1994).

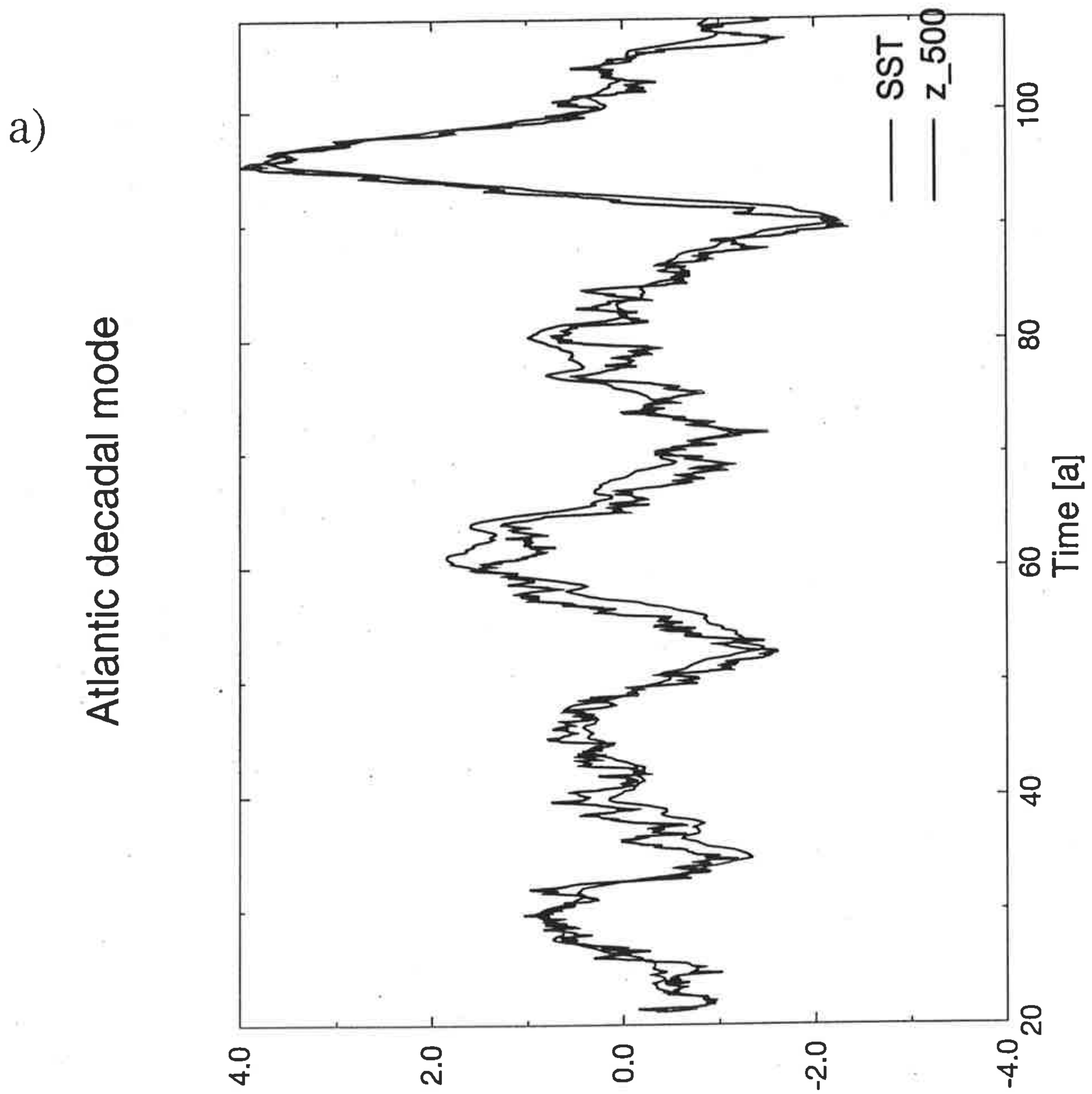
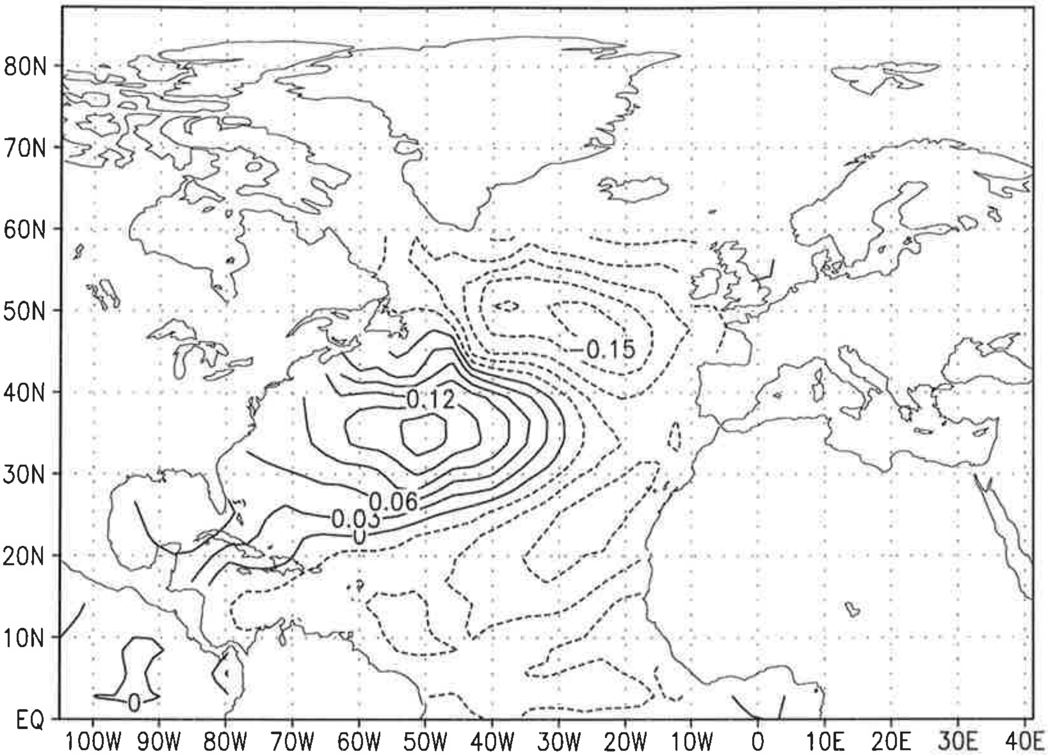


Figure 10: Canonical Correlation Analysis (CCA) of low-pass filtered (retaining variability with time scales longer than 5 years) North Atlantic SST and 500 hPa height anomalies simulated by the CGCM. The SST and height anomalies were projected onto the first five EOFs prior to the analysis. a) canonical time series, b) canonical SST (predictor), and c) canonical 500 hPa height (predictand) pattern. The units in (b) and (c) are ^{o}C and gpm, respectively, and the values are representative of a one-standard deviation change.

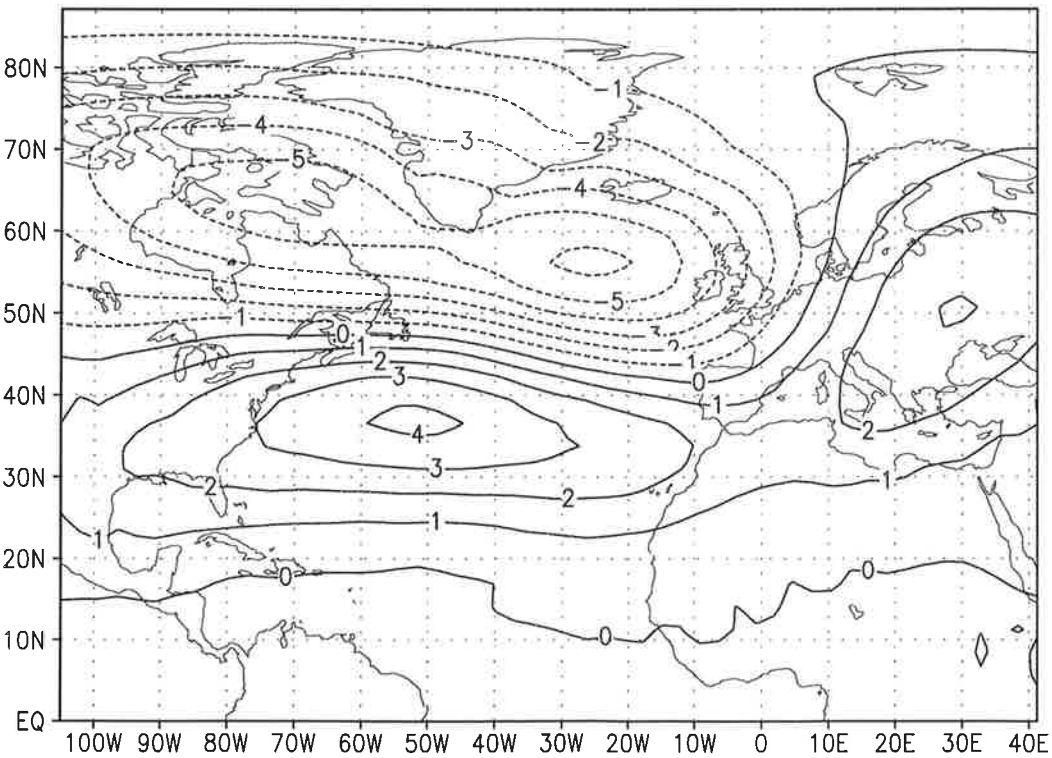
b)

Atlantic mode : SST



c)

Atlantic mode : z500



the basin centered near $35^{o}N$ which is surrounded by negative anomalies. Fortunately, the center of the negative SST anomaly in the northeast coincides approximately with the location of weather ship "C", so that the observations shown by Levitus et al. (1994) can be regarded as a good index of the decadal mode. Overall, the characteristics of the decadal mode simulated in the North Atlantic are very similar to that in the Pacific (Figs. 1 and 2), with anomalously high pressure over anomalously warm SST (Fig. 10c).

The anomalous height pattern bears some resemblence to the North Atlantic Oscillation (NAO, see e. g. van Loon and Rodgers (1978)) which is (like the PNA) an eigenmode of the atmospheric circulation and characterized by a dipole pattern, with opposite changes in the Iceland low and Azores high. The centers of action, however, are displaced equatorward by about 10^{o} in the coupled model simulation. All major features in the canonical SST and 500 hPa height fields are statistically highly significant, with explained variances up to 60% relative to the low-pass filtered values.

The mechanism behind the decadal variability in the North Atlantic is similar to that for the North Pacific (see section 3). The variations in heat content or subsurface temperature are qualitatively similar to those found in the Pacific (Fig. 3) and show basically the same propagation characteristics (not shown). Thus, we belive that the decadal variability in the North Atlantic is generated by the same mechanism as its counterpart in the North Pacific. This would imply that the period of the North Atlantic mode is about half the period of the North Pacific mode, since the basin size of the North Atlantic is about half the basin size of the North Pacific. Our results indicate, however, that the time scales of the two oscillations are very close to each other. The reasons for this are still under investigation.

6. Summary and discussion

A hierarchy of numerical models was used to understand the decadal variability observed in the Northern Hemisphere, and we propose a mechanism for its generation. Our results suggest that a considerable part of the decadal variability in both the North Pacific and North Atlantic can be attributed to cycles with periods of approximately 15 to 20 years. The decadal modes originate from unstable ocean-atmosphere interactions and must therefore be regarded as inherently coupled phenomena. The existence of such cycles implies the potential for long-range climate forecasting at decadal time scales over North America and Europe.

The scenario for the generation of the decadal mode is similar to that developed by Bjerknes (1964) for the Atlantic Ocean. According to this picture, the memory of the coupled system resides in the ocean. The ocean adjusts slowly to past variations in the surface wind stress field, and these slow variations in the wind-driven ocean circulation are crucial in setting the time scale of the decadal mode. Wave and advective processes are both found to be important in the ocean adjustment. The wave adjustment, however, appears to be the dominant process, as discussed by Latif and Barnett (1996). The atmosphere responds passively to the changes in the lower boundary conditions. However, since the decadal mode is an inherently coupled phenomenon, the feedback of the atmosphere onto the ocean is a crucial part of the dynamics of the decadal mode.

Our results are in conflict with several previous studies, since we found the tropics played a minor role for the generation of the decadal mode. The studies of Trenberth and Hurrell (1994) and Graham (1994) argue basically that low-frequency changes in tropical Pacific SST introduce the signal into the North Pacific through a changed atmospheric circulation. Jacobs et al. (1994) argues also that decadal variability in the North Pacific is forced by the tropics, but through the ocean by the propagation of planetary waves in the aftermath of strong ENSO extremes, such as the 1982/1983 warm event. We did not find much evidence for an active role of the tropics in the generation of the decadal mode in the North Pacific. Our view of an independent mid-latitudinal mode is supported by the findings of Robertson (1996). He investigated a multi-century integration with another CGCM and found a similar mode in the North Pacific to that described here. However, the integration Robertson (1996) analyzed shows virtually no ENSO-type variability in the tropical Pacific so that some of the proposed tropical forcing mechanisms cannot operate in that integration.

Another point of controversy which might originate from our study is the question of whether the atmosphere is sensitive to mid-latitudinal SST anomalies. Our results suggest indeed that mid-latitudinal SST anomalies force a significant atmospheric response, as implied by the early study of Palmer and Sun (1985). Further, we were able to reproduce the dominant atmospheric response pattern found in the coupled integration and observations by forcing our atmosphere model in a stand-alone mode by the characteristic North Pacific SST pattern of the decadal mode. We speculate that changes in the surface baroclinicity and resultant changes in the transient activity are crucial in establishing the time-mean response. If correct, this would imply that

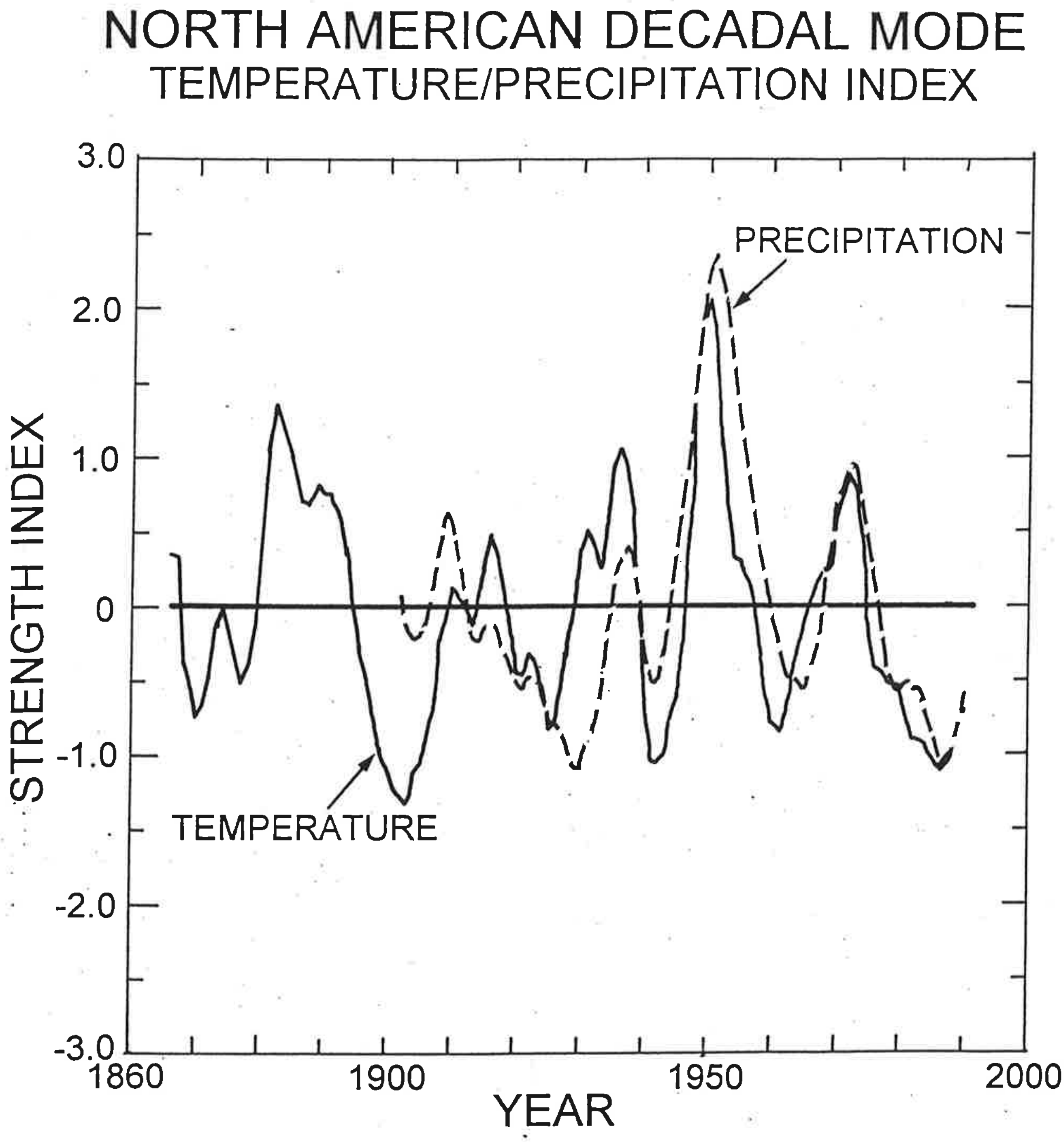


Figure 11: Normalized near surface temperature and rainfall indices of the North Pacific decadal mode, as derived from observations over North America (details can be found in Latif and Barnett (1996)).

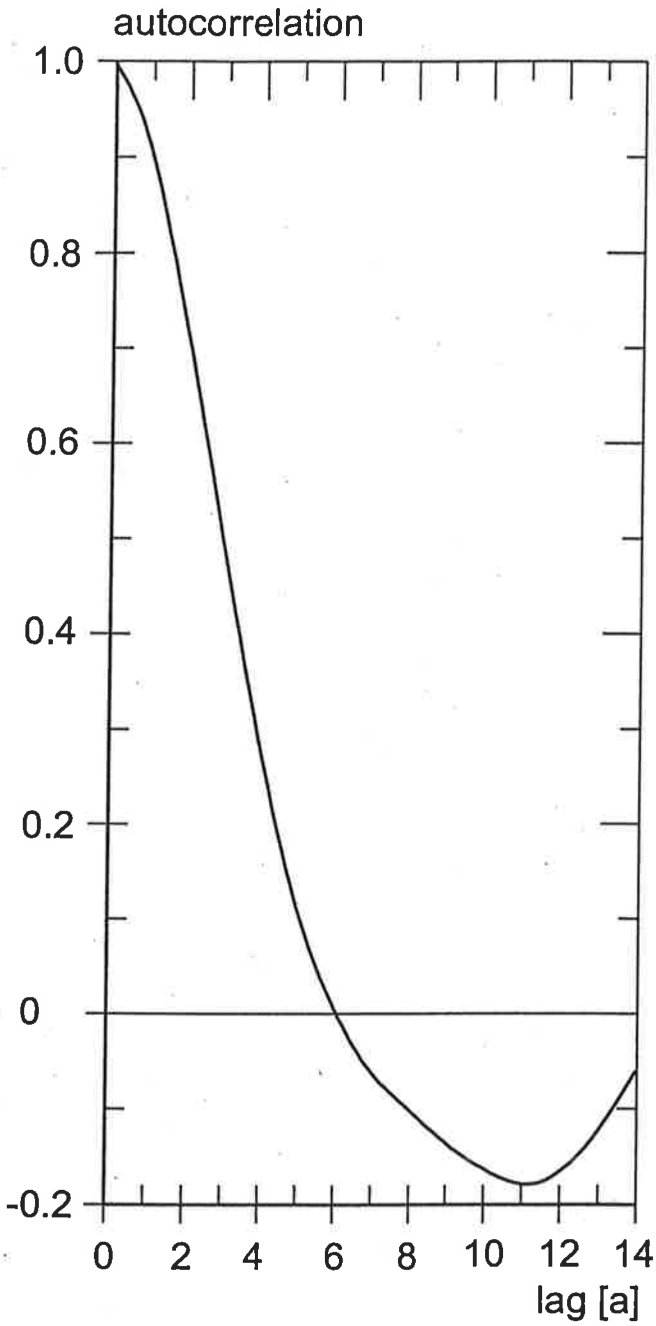


Figure 12: Autocorrelation function of the near surface temperature index of the North Pacific decadal mode (shown in Fig. 11).

atmosphere models need to simulate the eddy activity rather well when they are used in a coupled model to study decadal variability. This would require quite high resolution for climate integrations, at least of the order of the T-42 resolution we used in our coupled integration.

Finally, we would like to discuss critically the predictability of the decadal modes. Our results suggest that their predictability is probably less than that of ENSO, for example, if one measures the predictability limits in terms of fractions of the cycle period. This can be inferred from Fig. 12 showing the autocorrelation function of an index time series of the North Pacific decadal mode (Fig. 11), as derived from observations (see Latif and Barnett (1996) for details). Although the structure of the autocorrelation function shows some weak evidence for a periodicity of approximately 20 years, the minimum correlation at lead times of about 10 years are insignificant and of the order of -0.2 only. This suggests that the predictability of the decadal mode is considerably less than one-half cycle. In contrast, the autocorrelation functions of typical ENSO indices show significant correlations at lead times of the order of about two years, which corresponds to approximately half an ENSO cycle (e.g. Wright, 1985). Thus, the decadal mode is strongly damped and the internal "noise" in the coupled ocean-atmosphere system will limit its predictability considerably.

Acknowledgement

We would like to thank Drs. D. Cayan, C. Frankignoul, P. Müller, W. White, and E. Zorita for many fruitful discussions. We thank Drs. T. Stockdale, J. Wolff, and G. Burgers for helping in the development of the coupled general circulation model. We thank the Theoretical Applications Division of the Los Alamos National Laboratory for making most of the computer time available for the CGCM run, Dr. D. Poling for tending the run and managing the extensive output files, and Dr. C. Keller for facilitating the cooperation on the CGCM project. In addition, we thank M. Junge, J. Ritchie, T. Tubbs, and M. Tyree for providing computational assistance. This work was supported in part by the National Science Foundation under grant NSFATM 9314495, the U.S. Department of Energy's CHAMP program under grant DE-FG03-91ER61215 (T.P.B.), NOAA via the Lamont/SIO Consortium program (M. M.), the German Climate Computer Centre (DKRZ), the European Community under grants EV5V-CT92-0121 and EV5V-CT94-0538, and the Bundesminister für Forschung und Technologie under grant 07VKV01/1 (M.L.).

References

Anderson, D.L.T. and A.E. Gill, 1975: Spin-up of a stratified ocean with application to upwelling. Deep-Sea Research, 22, 583-596.

Anderson, D.L.T., K. Bryan, A.E. Gill, and R.C. Pacanowski, 1979: The transient response of the North Atlantic - some model studies. J. Geophys. Res., 84, 4795-4815.

Barnett, T. P., 1983: Interaction of the Monsoon and Pacific trade wind system at interannual time scales. Part I: The equatorial zone. Mon. Wea. Rev., 111, 756-773.

Barnett, T. P. and R. Preisendorfer, 1987: Origins and levels of monthly forecast skill for United States surface air temperatures determined by canonical correlation analysis. Mon. Wea. Rev., 115, 1825-1850.

Bjerknes, J., 1964: Atlantic Air-Sea Interaction. Adv. in Geophys., 10, 1-82.

Brankovic, C., T.N. Palmer, and L. Ferranti, 1994: Predictability of seasonal atmospheric variations. J. Climate, 7, 217-237.

Delworth, T., S. Manabe, and R.J. Stouffer, 1993: Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. J. Climate, 6, 1993-2011.

DKRZ, 1992: The ECHAM-3 atmospheric general circulation model. Edited by Deutsches Klimarechenzentrum Modellbetreuungsgruppe. Technical report no. 6.

Available from: DKRZ, Bundesstr. 55, D-20146 Hamburg, Germany.

Gill, A,. 1982: Atmosphere-Ocean Dynamics. Academic Press, New York.

Graham, N.E., 1994: Decadal-scale climate variability in the 1970's and 1980's: Observations and model results. Clim. Dyn., 10, 135-162.

Horel, H.D. and J.M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. Mon. Wea. Rev., 109, 813-829.

Hulme, M. and P.D. Jones, 1993: A historical monthly precipitation dataset for global land areas: Applications for climate monitoring and climate model evaluation. pp. A/14-A/17, in Analysis methods of precipitation on a global scale, Report of a GEWEX Workshop, 14-17 September, 1992, Koblenz, Germany, WMO-TD-No. 558, Geneva.

Jacobs, G.A., H.E. Hurlbert, J.C. Kindle, E.J. Metzger, J.L. Mitchell, W.J. Teague, and A.J. Wallcraft, 1994: Decade-scale trans-Pacific propagation and warming effects of an El Niño anomaly. Nature, 370, 360-363.

Jiang, S., F.-F. Jin, and M. Ghil, 1995: Multiple equilibria, periodic and aperiodic solutions in a wind-driven, double-gyre, shallow-water model. J. Phys. Oceanogr., submitted.

Jones, P.D., R.S. Bradley, H.F. Diaz, P.M. Kelly, T.M.L. Wigley, 1986: Northern Hemisphere surface air temperature variations: 1851-1984. J. Clim. Appl. Met., 25, 161-179.

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

Latif, M. and T.P. Barnett, 1994: Causes of decadal climate variability over the North Pacific and North America. Science, 266, 634-637.

Latif, M. and T. P. Barnett, 1996: Decadal variability over the North Pacific and North America: Dynamics and predictability. J. Climate, accepted.

Latif, M., T. Stockdale, J.O. Wolff, B. Burgers, E. Maier-Reimer, M.M. Junge, K. Arpe, and L. Bengtsson, 1994: Climatology and variability in the ECHO coupled GCM. Tellus, 46A, 351-366.

Levitus, S., T. P. Boyer, and J. Antonov, 1994: World ocean atlas 1994. Volume 5: Interannual variability of upper ocean thermal structure. U. S. Department of Commerce, NOAA, Washington D. C.

Miller, A.J., D.C. Cayan, T.P. Barnett, N.E. Graham, and J.M. Oberhuber, 1994: Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. Clim. Dyn., 9, 287-302.

Namias, J., 1959: Recent seasonal interactions between North Pacific waters and the overlying atmospheric circulation. J. Geophys. Res., 64, 631-646.

Namias, J., 1969: Seasonal interactions between the North Pacific and the atmosphere during the 1960s. Mon. Wea. Rev., 97, 173-192.

Neelin, J. D., M. Latif, and F.-F. Jin, 1994: Dynamics of coupled ocean-atmosphere models: The tropical problem. Annu. Rev. Fluid. Mech., 26, 617-659.

Nitta, T. and S. Yamada, 1989: Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation. J.Meteor. Soc. Japan, 67, 375-383.

Palmer, T.N. and Z. Sun, 1985: A modelling and observational study of the relationship between sea surface temperature in the northwest Atlantic and the atmospheric general circulation. Quart. J.R. Meteorol. Soc., 111,947-975.

Philander, S. G. H., 1990: El Niño, La Niña, and the Southern Oscillation. Academic Press, San Diego, Ca. 92101.

Robertson, A.W., 1996: Interdecadal variability over the North Pacific in a multi-century climate simulation. Climate Dynamics, in press.

Roeckner, E., K. Arpe, L. Bengtsson, S. Brinkop, L. Dümenil, M. Esch, E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R. Sausen, U. Schlese, S. Schubert, and M. Windelband, 1992: Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution. Report-No. 93, October, 1992, 171 pp. Available from Max-Planck-Institut für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany.

Schopf, P. S. and M. J. Suarez, 1988: Vacillations in a coupled ocean-atmosphere model. J. Atmos. Sci., 45, 549-566.

Trenberth, K.E. and J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. Clim. Dyn., 9, 303-319.

van Loon, H. and J. G. Rodgers, 1978: The seasaw in winter temperatures between Greenland and Northern Europe. Part I: General description. Mon. Wea. Rev., 106, 296-310.

Weisse, R. and U. Mikolajewicz, 1994: Decadal variability of the North Atlantic in ocean general circulation model. J. Geophys. Res., 99, 12.411-12.421.

White, W.B. and T.P. Barnett, 1972: A servomechanism in the ocean/atmosphere system of the mid-latitude North Pacific. J. Phys. Oceanogr., 2(4), 372-381.

Wright, P.B., 1984: Relationships between indices of the Southern Oscillation. Mon. Wea. Rev., 112, 1913-1919.

Yang, J. and J. D. Neelin, 1993: Sea-ice interactions with the thermohaline circulation. Geophys. Res. Letters, 20, 217-220.