Origins of the midlatitude Pacific decadal variability

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Abstract: Analysis of multiple climate simulations shows much of the midlatitude Pacific decadal variability to be composed of two simultaneously occurring elements: One is a stochastically driven, passive ocean response to the atmosphere while the other is oscillatory and represents a coupled mode of the ocean-atmosphere system. ENSO processes are not required to explain the origins of the decadal variability. The stochastic variability is driven by random variations in wind stress and heat flux associated with internal atmospheric variability but amplified by a factor of 2 by interactions with the ocean. We also found a coupled mode of the ocean-atmosphere system, characterized by a significant power spectral peak near 1 cycle/20 years in the region of the midlatitude North Pacific and Kuroshio Extension. Ocean dynamics appear to play a critical role in this coupled air/sea mode.

1. Introduction

The midlatitude, low frequency variability in and over the North Pacific is often simply referred to as the Pacific Decadal Oscillation (PDO). This is a large scale feature of climate variability that is a well documented inhabitant of the N. Pacific Basin (Latif and Barnett, 1994, 1996, hereafter LB94/LB96; Mantua et al., 1997). It is manifested by patterns of sea surface temperature (SST) and sea level pressure (SLP) that span the Pacific Basin. The PDO has been associated by the above authors, and others, with low frequency changes in weather patterns over N. America and major changes in the biota of the N. Pacific. The PDO has recently been shown to cause decadal modulation in equatorial Pacific El Niño phenomenon (Barnett et al., 1999; Pierce et al., 1999). As we shall see below, the simple characterization of all the variability in the midlatitude Pacific region as due to the PDO has led to much confusion and controversy.

In the present paper we show evidence from climate models that suggests two sources for decadal variability. One is associated with stochastic forcing and the other with a coupled mode. This latter is the only element that can accurately be referred to as the PDO.

2. Procedure

The above conclusions were obtained from general circulation models developed by the National Center for Atmospheric Research (NCAR) and the Max Planck Institute (MPI). A 200 year run was conducted with NCAR's latest atmospheric model (CCM3, run here at T42 resolution) where the atmosphere was forced solely by the seasonal cycle of global SST, a procedure that raises some potential consistency questions (Barsugli and Battisti, 1998). In this run, the observed variability is due strictly to internal processes within the CCM3. We refer to this run as ACYC (after Saravanan, 1998). A next level of sophistication was obtained from a 100 year run of the CCM3 coupled to a mixed layer ocean model (CML). This allows for local exchange of heat between the ocean and atmosphere, but is still unrealistic in that it allows no effects of ocean dynamics, e.g. advection. The third run we analyzed was the last 270 years of a 300 year simulation, the COUP run, of the NCAR Climate System Model (CSM). This fully coupled model used the identical atmospheric model (CCM3) as in the ACYC and CML runs, but also included global ocean and sea ice models that could interact with the atmosphere. The ocean model resolution varied but was typically about the same as the T42 atmosphere. The details of these models and the runs themselves are described on the NCAR CSM home page (http://www.cgd.ucar.edu/csm/).

The MPI runs are comparable to the last two NCAR simulations, with run lengths of 170 and 147 years, respectively. We refer to these as ECML for the atmosphere (T42) plus mixed layer model and ECHO2 (Frey et al, 1997; Venzke et al., 1998) for the fully coupled ocean-atmosphere run. We note that the ECHO2 run has a rather good ENSO signal (see, for example, Pierce et al., 1999) while the COUP run from NCAR does not (Meehl and Arblaster, 1997). This is likely due to the higher ocean model resolution near the equator in ECHO2 compared to COUP.

3. Analysis

We concentrated initially on the NCAR model results for the annual averaged 500 mb height field in the domain of the PDO, i.e. Asia to the western Atlantic, 60 N to 15 N. The 500 mb anomaly fields from the ACYC, CML and COUP were submitted to standard EOF analysis. The analysis was performed on both unfiltered data and data filtered to remove time scales less than 6 years associated with ENSO (ECHO2 run only). The results are basically the same in either case, so we show the results of the unfiltered analysis in order to retain full information of the power spectrum of variability. The leading EOF mode of the unfiltered data accounted for 29%, 32%, and 39% of the field variance in the ACYC, CML and COUP runs, respectively (Figure 1, upper three panels; see also Saravanan, 1998). As displayed, each EOF has been scaled by the square root of its associated eigenvalue so it has physical dimensions and all eigenvectors can be directly inter-compared. These patterns are virtually identical to each other, with pattern correlations of 0.94 or higher between all possible pairs. They are also identical to the patterns obtained in earlier studies from similar analysis of the ECHO2 simulation and the NCEP reanalysis.

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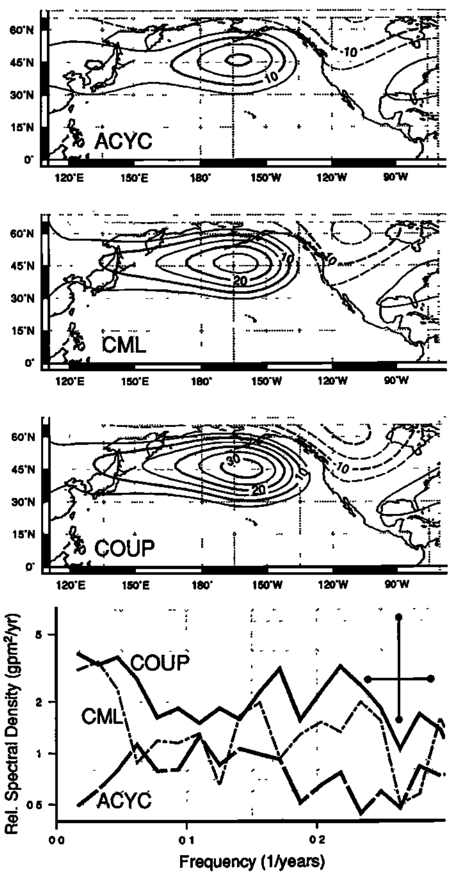

Figure 1. Leading EOF of 500 mb height anomaly (gpm) for the following experiments, starting from the top: ACYC (AGCM with specified SST); CML (AGCM with ocean mixed layer); COUP (full A/OGCM). Bottom panel: normalized spectral density of the projection of the principal components. The cross indicates bandwidth and 95% confidence interval.

The next step in the analysis was to project the 500 mb anomaly field from the ACYC and CML runs onto the leading EOF of the COUP run. The resulting time series are referred to as pseudo-principal components (PCs). The purpose of this analysis is to place all runs into a single basis set. The power spectra of the ACYC and CML pseudo-PCs are shown in Figure 1 (lower) along with the spectrum of the COUP PC.

The identical set of calculations were done on the MPI model runs. Unless noted to the contrary, they generally agree with the results found in the NCAR simulations.

4. Results

Origins Of The Midlatitude Pacific Decadal Variability

Close inspection of Figure 1 leads to the following conclusions:

1. The PDO-type variability appears in the atmosphere response in the climatologically forced (ACYC) run. This means its origin is fundamentally atmospheric, since that model allows no interaction with the ocean on interannual time scales. Note that even in this case, the pattern has some resemblance to the oft discussed Pacific North American (PNA) Pattern (e.g. Horel and Wallace, 1981), although there are some key differences also.

2. The atmospheric signal in the CCM3 coupled to a mixed layer (CML) run and COUP run are progressively more energetic. So the artificial boundary conditions in the ACYC run appreciably diminish the magnitude of the signal (Barsugli and Battisti, 1998). The signal in the COUP run is due to coupled air/sea interactions that generate positive feedbacks and a delayed negative feedback provided by slow ocean dynamics, e.g. Pierce et al. (1999). As noted above, the pattern strength in the COUP run is realistic, being nearly identical to that obtained in ECHO2 and the NCEP reanalysis. It is a factor of two less than that reported in LB94.

3. All of the model runs show ENSO processes are not the origins of the decadal variability as has been conjectured. Both the ACYC, ECML, and CML runs have no ENSO signal, yet produce realistic decadal signals. The COUP run has decadal variability in the tropical Pacific, but virtually no ENSO. Yet it also produces a very realistic signal. The ECHO2 run, although possessed of a reasonable ENSO, produces a PDO pattern that is virtually identical in magnitude to COUP and the NCEP observations. Clearly, while interactions with the tropics might further enhance the midlatitude decadal variability, they are clearly not necessary for its existence. Indeed, recent results suggest just the opposite; the midlatitude Pacific can impose decadal variability on the ENSO signals (Barnett et al., 1999; Pierce et al., 1999). The degree to which ENSO subsequently impacts the decadal signal is an open question.

4. The power spectra of the basin scale 500 mb height field principal components are statistically 'white', showing that increasing signal strength with increasing model complexity is present at almost all frequencies (Fig. 1). While the large confidence limits make energy comparisons at a specific frequency of questionable value, the fact that the energy enhancement is present at virtually all frequencies is much less likely to happen by chance.

5. There is no evidence of significant, unique spectral peaks in the power spectra of these basin scale features represented by the leading EOFs. This suggests there is no unique time scale for the variability, a result in keeping with the fundamental origin in the atmosphere. While these results hold for basin scale atmospheric features, they DO NOT hold more locally (see below). There are also theoretical reasons to believe the basin scale features may be strongly influenced, if not controlled by, ocean features of slightly lesser spatial scale (e.g. Weng and Neelin, 1998). We note the earlier analyses of LB94 did not address this possibility.

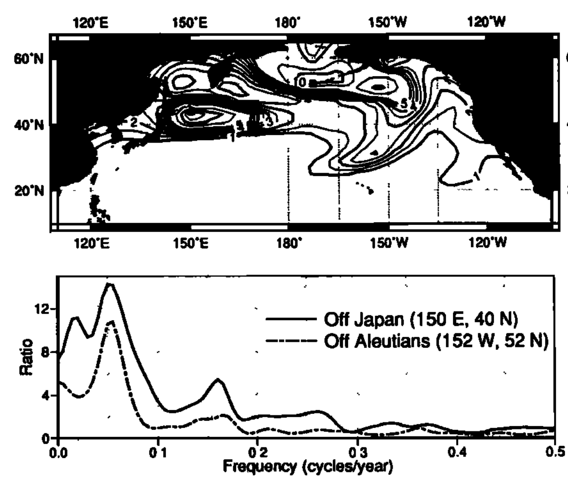

Figure 2. Top: Ratio of spectral density at a frequency of 20 years/cycle between the COUP (full O/AGCM) and CML (ocean mixed layer) runs. Contour level is 0.5 from 1.0 to 5.0, 2.5 thereafter. Lower: ratio of the spectral density, at all frequencies, off Japan and the Aleutian Islands.

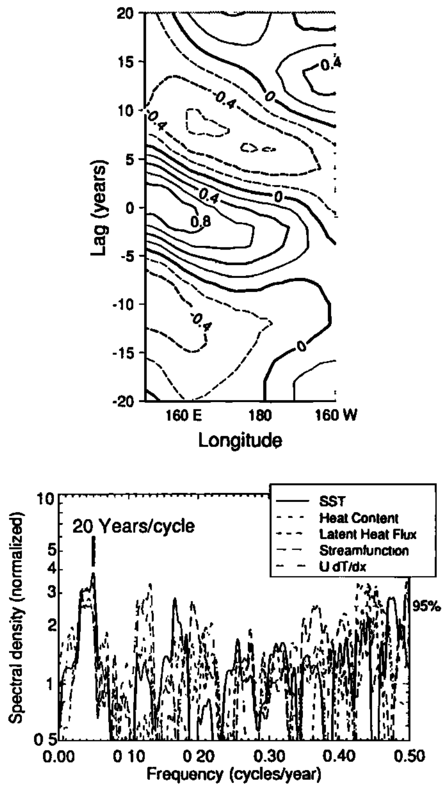

Figure 3. Lag correlation of low pass filtered Laplacian of SST at 40N, 150E with similar indices eastward along 40N to 160W (upper). Power spectra of ocean and atmospheric variables/processes at 40N, 150E showing a common peak at 1 cycle/20 years. The 95% confidence level is shown by the dashed line (lower).

Regional Characteristics

Inspection of various regional power spectra for both ocean and atmospheric variables in the fully coupled runs showed significant peaks in the midlatitude Pacific and especially the Kuroshio Extension region at a frequency of about 1 cycle/20 years. Twenty years is the circulation time scale of the model's subtropical gyre.

Figure 2 shows the ratio of spectral power for SST in the 20-year band in the COUP run to the same frequency band in the CCM3/slab ocean model run. The same signal was seen in the spectral ratios from the MPI runs. In regions where the ratio is high, the additional variability must be due to enhanced air/sea interactions in the presence of ocean dynamics since that is the only difference between the model pairs. Clearly the Kuroshio current, its extension, and the entire subtropical gyre, are deeply involved in the PDO. The variability in the Bering Sea/Gulf of Alaska is more suspect since the model has only a weak subpolar gyre and is occasionally impacted by sea ice in the former region.

Tests showed the spectral peaks do not come about from stochastic resonance (Saravanan and McWilliams, 1998), for there is no positive correlation between SSTs and net surface heat flux. As another test for purely stochastic effects, we also forced the ocean model with randomly shuffled heat and momentum flux field from the full coupled run. This 137 year long stochastically forced run showed no substantial spectral peaks near 1 cycle/20 years. We conclude that the peaks are likely the signature of dynamic ocean feedbacks of the type described in LB and more recently in Venzke et al., 1998.

The power spectral peak for SST at about 1 cycle/20 years is not a statistical fluke nor seen only in the COUP simulation. This is demonstrated in the lower panel of Figure 3 which shows the power spectra of other ocean (heat content, stream function/transport and zonal heat advection) and atmospheric (latent heat flux) variables off Japan for the ECHO2 model. The upper panel shows the time lagged correlation of the Laplacian of SST off Japan, to be discussed below, with increasing eastward longitude. The 20 year time scale is obvious in all the analyses.

Feedback Processes

The key question is to determine if there is a feedback between the ocean and atmosphere that will allow an oscillatory coupled ocean-atmosphere mode, one that can rightfully be referred to as the PDO. We note that Weng and Neelin (1998) and Munnich et al. (1998) offer a simple theoretical description of such a mode in the presence of strong stochastic forcing such as described above.

We demonstrated the feedback processes as follows: The wind stress curl pattern associated with the 20 year spectral peak in Basin-wide oceanic stream function was isolated in the ECHO2 control run by regression analysis. The strongest relation between the two was nearly simultaneous. It is this wind pattern that must be driven by the ocean if there is to be an oscillatory coupled mode. We shall refer to this curl pattern simply as $\hat{\tau}$.

The next step was to force the ECHAM4 atmospheric GCM (AGCM, Roeckner et al., 1996), the same as used in ECHO2, with specified SST fields that correspond to the two extremes of the PDO; one extreme corresponding to a warmer than normal Kuroshio extension region, while the other extreme has SST of opposite sign in this region. These SST forcing fields, defined only above 20N, were taken from the results of LB94, but were nearly identical to those produced by COUP or ECHO2 and seen in nature. A twelve realization ensemble of AGCM runs was computed for each of the extreme PDO forcing fields, a total of 2 ensembles and 24 runs.

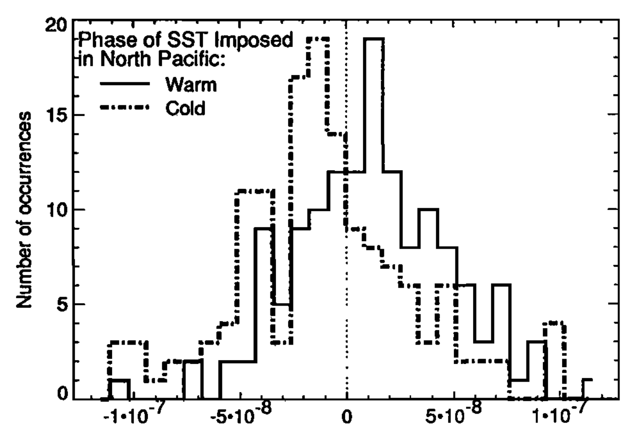

Figure 4. Results from the ECHAM4 AGCM forced with the PDO SST anomalies specified north of 20N only. Shown is the projection of the full wind stress curl field onto the PDO wind stress curl pattern $\hat{\tau}$ (described in text) stratified by the pattern of anomalous SSTs imposed as a lower boundary condition to the AGCM. Solid line: warm central north Pacific, surrounded by cold anomalies. Broken line: cold central north Pacific, surrounded by warm anomalies. A k/s test shows the two distributions are statistically distinct at a confidence level of 99%.

The wind stress curl fields from each AGCM ensemble were projected onto the $\hat{\tau}$ pattern and the distribution function of the projection weights computed (Figure 4). It was found that the two distribution functions are different from each other at the 0.01 level. Further, the centroid of the distributions change sign with change in the PDO polarity. These facts establish the response of the atmosphere to oceanic circulation changes. So there is a coupling between the ocean and atmosphere and its sign depends on the state of the PDO in the ocean. The sense of the coupling is such as to force an oscillation as described below.

Physics of the PDO

The models suggest it is the slow changes in meridional gradient, actually the Laplacian, of SST that exerts a torque on the atmosphere thereby altering the curl of the wind stress (Fig. 3, upper), an idea first proposed by Barnett and White (1972). The anomalous curl so generated, acts to change the gyre circulation and set in motion, through advection and simple geostrophic adjustment, generation of an anomalous SST field with opposite signed Laplacian. This change, once it has become large enough in magnitude and eastward extent (Fig. 3, upper) induces the opposite signed curl pattern and the entire process oscillates. In principle, this is the type of physical scenario envisioned in LB94/96. It is important to note that this set of physics places a heavy burden on the ocean model in simulations of the PDO. Changes in spatial resolution, etc. are apt to affect the simulated general circulation and so give different results than reported here.

The physics that determines the time scale is the subject of intense research. There are at least two possibilities. The circulation time of the gyre is about 20 years and sophisticated statistical analysis shows signals propagating completely around the gyre in this interval. These signals may trigger successive oscillations. Alternatively, the several year adjustment time of the ocean to changes in the windstress curl plus the advection time scale needed to add/subtract heat over a large enough area in the Kuroshio extension to affect the Laplacian and subsequently, the atmosphere, also is about 10 years (1/2 cycle). We plan to report in a future note which of these physical scenarios sets the time scale for the PDO.

In any event, the existence of a significant 20 year spectral peak in two different coupled global climate models provides evidence in support of the idea that there is a coupled ocean/atmosphere mode of decadal variability. This mode is seen most strongly in the Kuroshio extension region of the Pacific but also over much of the Basin above 30 N. This is in addition to the basin-wide variability forced stochastically by the atmosphere, which has no preferred period. We suggest that studies which do not carefully separate out these two mechanisms will find conflicting mixtures of physics responsible for Pacific decadal variability. In principal, only the coupled mode described above ought to be referred to as the Pacific Decadal Oscillation, since the stochastic variability is simply the passive ocean response to atmospheric forcing.

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