GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.5, PAGES 615-618, MARCH 1, 1999

Interdecadal interactions between the tropics and midlatitudes in the Pacific basin

Tim P. Barnett and David W. Pierce
Climate Research Division, Scripps Institution of Oceanography, La Jolla, California

Mojib Latif and Dietmar Dommenget
Max Planck Institute for Meteorology, Hamburg, Germany

R. Saravanan
National Center for Atmospheric Research, Boulder, Colorado

Abstract. Analysis of global climate model simulations and observations suggest decadal, midlatitude changes in and over the North Pacific cause decadal modulation of the El Niño-Southern Oscillation. This coupling between the two geographic regions is via atmospheric, not oceanographic, teleconnections. In essence, large scale changes in the circulation of the atmosphere over the Pacific Basin, while largest in midlatitudes, have a significant projection onto the wind field overlying the equatorial regions. These low frequency wind changes precondition the mean state of the thermocline in the equatorial ocean to produce prolonged periods of enhanced or reduced ENSO activity. The midlatitude variability that drives equatorial impacts is of stochastic origin and, although the magnitude of the signal is enhanced by ocean processes, likely unpredictable.

1. Introduction

There is currently considerable scientific interest and debate about the manner in which decadal climate changes (time scales of order 10 years or longer) in the tropical/equatorial Pacific interact with similar time scale changes in the midlatitude Pacific. These changes manifest themselves as modulations of the ENSO (El Niño-Southern Oscillation) in the tropics, e.g. the persistent warming of the tropical water temperatures in the first half of the 1990s (Trenberth and Hurrell, 1994; Trenberth and Hoar, 1996; Gu and Philander, 1997) and concomitant drought in such places as Australia (e.g. Morrissey and Graham, 1995). In the midlatitudes of the N. Pacific, the changes are apparent not only in sea surface temperature over virtually the entire N. Pacific (e.g. Latif and Barnett, 1994, 1996), but in low frequency modulations of phytoplankton (Venrick et al., 1987) and fish populations (Mantua et al., 1997), as well as periods of extended above/below normal rainfall over the United States (Latif and Barnett, 1994, 1996). The key questions we address here are the degree to which the midlatitude and tropical climate changes (ENSO) interact and the principal direction of information flow in this interaction on decadal time scales.

Paper number 1999GL900042.
0094-8276/99/1999GL900042$05.00

2. The Nature of the Decadal Variability in the Midlatitude Pacific

Recent modelling work has demonstrated that decadal variability in the N. Pacific has at least two components (Barnett et al., 1999)

The large basin scale patterns of variability are stochastically forced by the atmosphere (Tett and Barnett, 1999). We shall refer to this as the stochastic mode (cf. Hasselmann, 1976). The accompanying spectra of atmospheric variables are white, while the ocean variables have a red spectrum.

The second element of the midlatitude decadal change is associated with a deterministically forced coupled mode of the Pacific ocean-atmosphere system, the Pacific Decadal Oscillation (PDO). This involves feedbacks between the gyral heat transport, the resulting variations in meridional gradients of SST, and the response of the wind stress curl to these SST changes—much as envisioned in Latif and Barnett (1994, 1996). It is responsible for a highly prominent peak in the power spectra of many ocean and atmosphere variables in the western Pacific at a frequency of 1 cycle/20 years. The time scale is set by the advection time of the gyre and Rossby wave travel times. However, these mechanics are not entirely understood, nor is the manner in which the stochastic and deterministic modes interact.

3. Procedure

We have investigated the direction of information flow between the tropics and midlatitudes at decadal time scales with the help of ECHO-2, a 147-year control run of a sophisticated coupled general circulation model (CGCM) of the global climate system from the Max Planck Institute for Meteorology in Hamburg (Frey et al., 1997; Venzke et al., 1999; Pierce et al., 1999). The model has full state-of-the-science physics, except it has no active sea ice component and instead uses restoring to observed ocean conditions poleward of 60°. Its resolution is approximately 50 km in the equatorial ocean increasing to 280 km above 20°. It produces a credible, though slightly weak ENSO signal and mimics well both the strength and patterns of the decadal variability in the N. Pacific (e.g. Pierce et al., 1999; Barnett et al., 1999; Venzke et al., 1999).

Additionally, we have used two runs of full physics atmospheric models joined to simplified mixed layer oceans: a CCM3 atmosphere/mixed layer ocean run of 100 years (Kiehl et al., 1996), and an ECHAM3 atmosphere/mixed layer ocean run of 170 years (Dommenget, personal communication, 1998). These mixed layer runs lack any ENSO variability, but they both replicate well the large scale pattern and signal strength of the Pacific decadal variability (Barnett et al., 1999; Pierce et al., 1999). This allows us to exclude the possibility that ENSO variability teleconnected to the midlatitudes causes the results shown below. Unless otherwise noted, all time series have been filtered to eliminate variations with time scales less than 10 years, so that the focus of the results is on decadal changes, e.g. the 20-year spectral peak of the PDO. We have also analyzed 47 years of observed data to verify that the results in the models are realistic with regard to features they represent.

4. Analysis and Results

The clue to the mechanism that couples the tropics and midlatitudes at decadal time scales shows up in time series of model SST in the central N. Pacific (32°N, 172°W) and at the equator in the heart of the El Niño signal (160°W) (Fig. 1). With the equatorial SST plotted with the reversed sign, the illustration shows the two time series in close harmony, such that when the N. Pacific is warm the equatorial regions are cool and vice versa. The maximum simultaneous correlation is -0.63. The same computation from the observations gives a correlation of -0.68. These results lead to the conclusion that, since the strongest relation is contemporaneous, the connection is via the atmosphere, not the ocean.

The nature of the connection was determined by investigating the relation between SST fields and changes in the surface wind stress, here taken to be represented by the zonal stress. Shown in Fig. 2 are the results of a canonical correlation analysis performed on yearly averaged data from the 147 years of the ECHO-2 data, both mixed layer ocean runs, and 47 years of observed data. Canonical correlation analysis (CCA) sits at the apex of the regression techniques and is used here to find the most strongly correlated coexisting patterns in the wind/SST data sets (cf. Barnett and Preisendorfer, 1988). The domain of the analysis is from 60°N to 40°S and 120°E to 90°W. The familiar SST pattern that goes with the midlatitude decadal variability in the N. Pacific (Latif and Barnett, 1994, 1996; Mantua, 1997; Tett and Barnett, 1999) turns out to be the most important predictor for all the models and the observations (Fig. 2, left column). Note that while this pattern has some signal in the equatorial zone, it is definitely not the pattern associated with ENSO, which has a strong maximum within 5° of the equator between the dateline and the coast of South America.

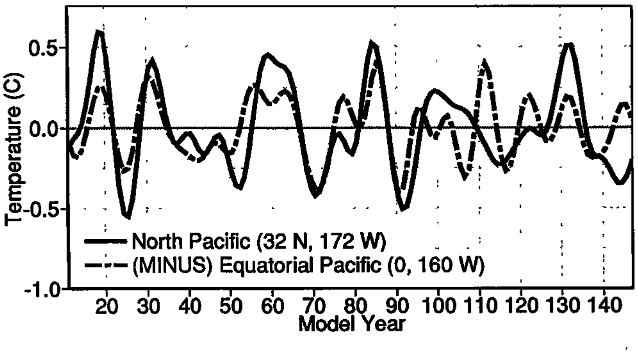

Figure 1. Time series of central N. Pacific sea surface temperatures (solid) and equatorial sea surface temperature (dashed; shown inverted) for the ECHO2 model. The correlation between the two original series is -0.63.

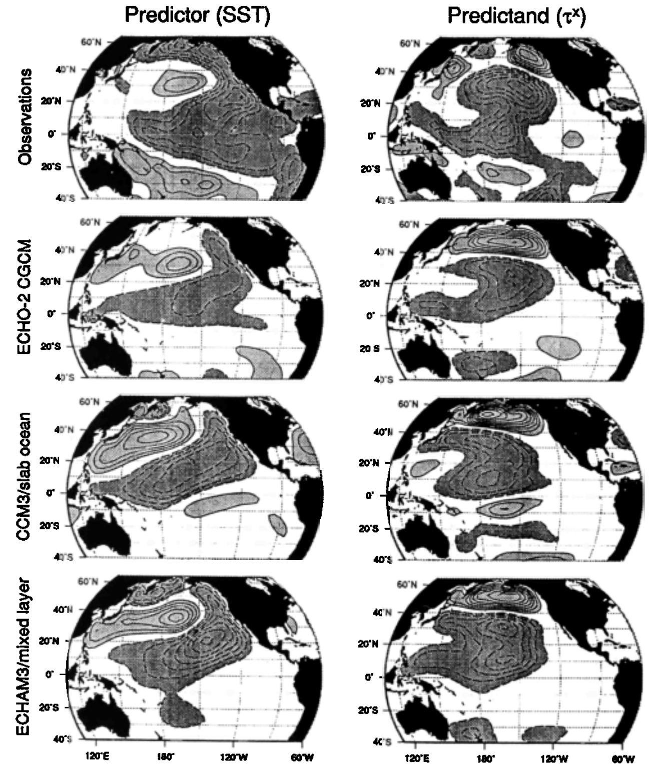

Figure 2. Canonical correlation analysis of sea surface temperature and zonal wind stress. Left column panels show the pattern of SST that predicts zonal wind stress (right column). From top to bottom the rows are: (1) Observations (2) ECHO-2 full physics GCM (3) CCM3 atmosphere coupled to a slab ocean model (4) ECHAM3 atmosphere coupled to a fixed mixed layer ocean model. Contour interval is 0.05 C for the left column (SST); 1.0×10^{-3} N m^{-2} for the right column (τ^x). Negative contours are dashed. The zero contour is omitted.

The pattern of wind stress associated with the decadal SST patterns is shown in the right column of Fig. 2. As expected, the strongest signals are in the N. Pacific. However, the alteration of the zonal wind stress in association with the N. Pacific SST has a substantial signal over the central and western equatorial Pacific. This is just the region where changes in zonal stress have substantial impacts on and lead to the ocean component of ENSO (e.g. Philander, 1990). In both the observations and models, the decadal wind stress variance accounted for by this mode in the equatorial wave guide region is 40-60%.

ENSO variability teleconnected to the midlatitudes cannot cause the large midlatitude response since the mixed layer simulations, which completely lack an ENSO signal, show the same signal as the full CGCM. These simulations also lack the PDO as described above, for they have no gyres to key the interactions required for the PDO. These results alone seem to confirm that it is the stochastic component of midlatitude Pacific decadal climate variability that imposes itself on the tropical Pacific and not the other way around.

The above results suggest the PDO, by itself, has little impact on the tropics. This conclusion was checked with numerical experiments using the Pacific decadal SST signature (from Latif and Barnett, 1994) above 20°N to force ECHAM4 (Roeckner et al., 1996), the same atmospheric general circulation model (AGCM) used in ECHO2. Two 12-member ensembles of year long runs were made; each ensemble had the same pattern of decadal SST change but opposite polarity, one a 'warm' phase when the Kuroshio Extension region has above normal temperatures, and the other a corresponding 'cold' phase. The difference of the wind stress curl pattern between the two ensembles is shown in Fig. 3 (upper). This curl pattern is associated with the ocean-dynamic part of the 20-year variability in ECHO2 (Barnett et al., 1999). The monthly wind fields for the two ensembles were then projected onto this pattern. The resulting histograms for the imposed 'warm' and 'cold' SST conditions, Fig. 3 (middle), are significantly different at over 95% confidence using a Kolmolgrov-Smirnoff test, so the wind field in the AGCM does respond differently at opposite phases of the SST pattern such as shown in Fig. 2 (left). ECHAM4 produces a signal that looks quite realistic and agrees well in magnitude with that derived from the NCEP reanalysis.

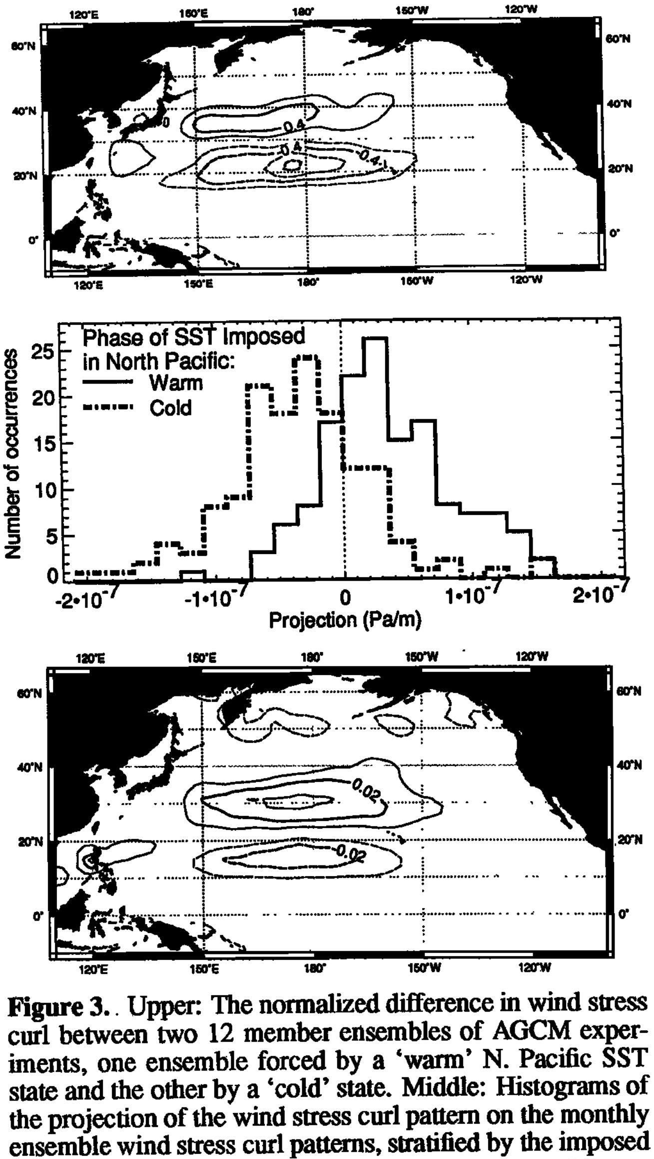

Figure 3.. Upper: The normalized difference in wind stress curl between two 12 member ensembles of AGCM experiments, one ensemble forced by a 'warm' N. Pacific SST state and the other by a 'cold' state. Middle: Histograms of the projection of the wind stress curl pattern on the monthly ensemble wind stress curl patterns, stratified by the imposed SST condition. The distributions are significantly different at the 99% level, showing the wind stress curl field over the Pacific responds to the differing SSTs associated with the PDO. Units are such that scaling the pattern by the histogram bin gives Pa m^{-1}. Lower: As in upper panel but for zonal wind stress (N m^{-2}), for direct comparison with the right column of Fig. 2.

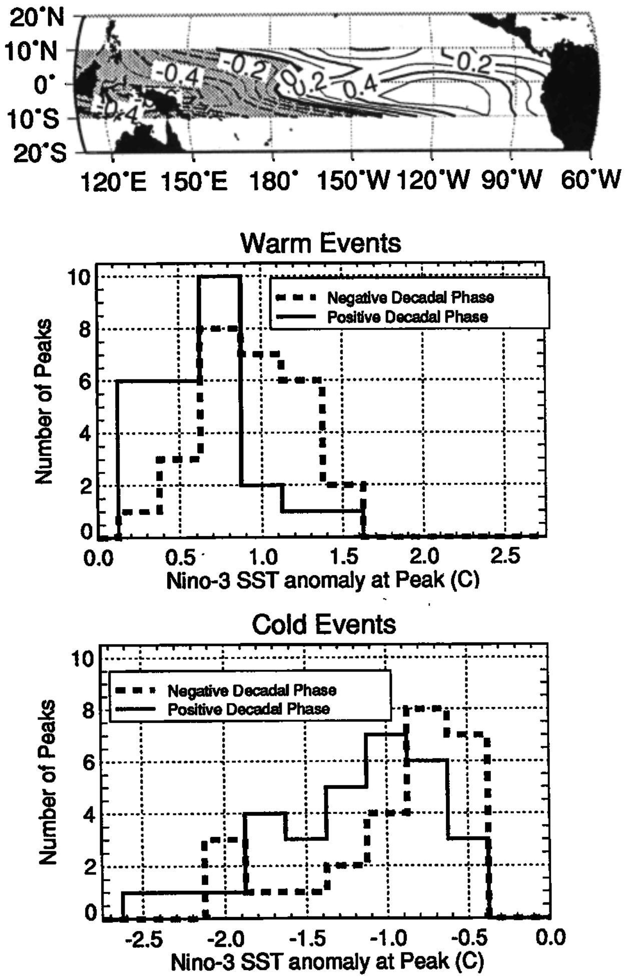

Figure 4. Upper: Correlation between decadal changes in depth of the 20 C isotherm and an index of the Pacific Decadal Oscillation defined by the leading principal component of the N. Pacific SST field. Lower: Histograms of El Niño/La Niña strength under warm/cold conditions in the central N. Pacific. Both panels are constructed from the 147 year ECHO2 control run.

Comparing the wind field illustrations in Fig. 3 (lower panel) and Fig. 2 (right column) leaves no doubt they are *not* the same. Hence, the PDO does invoke an atmospheric response, but it is confined to the midlatitudes, so does not impact ENSO directly. Space does not permit further discussion of important questions such as the impact that the interaction between the PDO and stochastic mode, e.g. Weng and Neelin (1998), might have on this conclusion.

Given that the stochastic mode of midlatitude variability can project a wind signal onto the equator that represents 40-60% of the decadal variability, it is natural to wonder if this is large enough to induce significant changes in the coupled model's equatorial ocean thermal structure. The correlation between an index of decadal SST variations in the central N. Pacific and the low frequency variations in depth of the 20 C isotherm in the near equatorial zone, commonly taken as an index of ENSO variations in the ocean, is shown in Fig. 4 (upper). The strong bimodal character is basically the well known spatial ENSO signal in the interior ocean.

Recent work (Kirtman and Schopf, 1998) shows that a modulation in the slope of the main equatorial thermocline, such as illustrated in Fig. 4, leads directly to modulation of the ENSO process. Analysis of the CGCM results does indeed show the probability distribution of ENSO magnitudes to be significantly different depending on the phase of the main decadal SST pattern in the N. Pacific (e.g. Fig. 4, lower and Pierce et al., 1999). It seems clear that the processes discussed above offer one possible explanation for at least part of the low frequency modulation of ENSO at decadal time scales by stochastically driven, low frequency variations in the midlatitude N. Pacific climate system.

The overview that emerges from these results suggests that decadal variability in the midlatitude N. Pacific is an important driver of the decadal variability of the tropical Pacific. The physics of the midlatitude decadal variability, which is partially stochastic and partly deterministic, are presented elsewhere (Latif and Barnett, 1994, 1996; Tett and Barnett, 1999; Barnett et al., 1999). Suffice to say, they do not rely directly on tropical Pacific processes. Effectively, the decadal changes in the general circulation over the N. Pacific reach far enough equatorward to alter the zonal stress in the central equatorial Pacific. These low frequency wind changes precondition the mean state of the thermocline in the equatorial ocean to produce prolonged periods of enhanced or reduced ENSO activity. The wind stress variations can be viewed as a spatial expansion/contraction and modulation in strength of the Northeast Trade Wind System that are associated with major changes in the circulation over the Pacific.

In closing, we need to stress again that other factors, e.g. interaction between the Asian monsoon and ENSO, need to be investigated more fully in order to see what other regional climate changes might impact ENSO variability on decadal time scales.

Acknowledgments. The authors gratefully acknowledge support from the Department of Energy's CHAMMP Program (DE-FG03-91-ER61215), the National Science Foundation (NSF ATM-93-14495), Department of Energy grant DE-FG03-98ER62505, the Scripps Institution of Oceanography, the Max Planck Institute for Meteorology, and the European Union's SYNTEX Programme. The model simulations were done at the Climate Simulation Laboratory (CSL) at NCAR. We especially appreciated the help provided by CSL personnel. NCAR is sponsored by the National Science Foundation. Additional model calculations were done at Deutsches Klimarechenzentrum (DKRZ) in Hamburg and at the Scripps Institution of Oceanography. Niklas Schneider and Art Miller provided useful critique of an early version of this manuscript. Two anonymous reviewers provided invaluable suggestions for manuscript improvement.

References

Barnett, T. P., D. W. Pierce, R. Saravanan, N. Schneider, D. Dommenget, and M. Latif, Origins of the midlatitude Pacific decadal variability, Geophys. Res. Lett., 1999, submitted.

Frey, H., M. Latif, and T. Stockdale, The coupled GCM ECHO-2. Part I: The tropical Pacific, *Mon. Wea. Rev.*, *125*, 703-720, 1997.

Gu, D. and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchanges between the tropics and extra tropics. *Science*, *275*, 805-807, 1997.

Hasselmann, K., Stochastic climate models. Part I, Theory, *Tellus*, *28*, 473-485, 1976.

Kiehl, J. T., B. Boville, B. Briegleb, J. Hack, P. Rasch, and D. Williamson, Description of the NCAR Community Climate Model (CCM3). *NCAR Technical Note NCAR/TN-20+STR*, Boulder, CO, 1996.

Kirtman, B. P., and P. S. Schopf, Decadal variability in ENSO predictability and prediction. *J. Clim.*, *11*, 2804-2822, 1998.

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

Latif, M. and T. P. Barnett, Decadal climate variability over the North Pacific and North America: Dynamics and predictability. *J. Clim.*, *9*, 2407-2423, 1996.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Met. Soc.*, *78*, 1069-1079, 1997.

Morrissey, M. L. and N. E. Graham, Recent trends in rain gauge precipitation measurements from the tropical Pacific: Evidence for an enhanced hydrologic cycle. *Bull. Am. Met. Soc.*, *77*, 1207-1219, 1995.

Pierce, D. W., T. P. Barnett, and M. Latif, Connections between the tropics and midlatitudes on Decadal Time Scales. *J. Clim.*, 1999, submitted.

Philander, S. G. H., *El Niño, La Niña, and the Southern Oscillation*, 293 pp, Academic Press, 1990.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dumenil, M. Esch, M. Giogetta, U. Schlese, and U. Schulzweida, The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Max Planck Institute Rep. No. 218*. Available from MPI, Bundestrasse 55, D-20146 Hamburg, Germany, 1996.

Tett, S. and T. P. Barnett, North Pacific Decadal Variability in a coupled AOGCM: Description and Mechanisms. *J. Clim.*, 1999, submitted.

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

Trenberth, K. E. and T. J. Hoar, The 1990-1995 El Nino-Southern Oscillation event: The longest on record. *Geophysical Res. Letters*, *23*, 57-60, 1996.

Venrick, E. L., J. A. McGowan, D. R. Cayan, and T. L. Hayward, Climate and Chlorophyll *a*: Long-term trends in the central North Pacific Ocean, *Science*, *238*, 70-72, 1987.

Venzke, S., M. Latif and A. Villwock, The coupled GCM ECHO-2. Part II: Indian Ocean response to ENSO. *J. Clim.*, 1999, submitted.

Weng, W. J., and J. D. Neelin, On the role of ocean-atmosphere interaction in midlatitude interdecadal variability. *Geophys. Res., Let.*, *25*, 167-170, 1998.

T. P. Barnett and D. W. Pierce, Climate Research Division, Scripps Institution of Oceanography, La Jolla, CA 92093. (e-mail: tbarnett@ucsd.edu; dpierce@ucsd.edu)

D. Dommenget and M. Latif, Max Planck for Meteorology, Bundestrasse 55, D-20146 Hamburg, Germany. (e-mail: dommenget@dkrz.de, latif@dkrz.de)

R. Saravanan, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307. (e-mail: svn@ncar.ucar.edu)

(Received September 1, 1998; revised November 5, 1998; accepted December 29, 1998.)