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A mechanism for generating ENSO decadal variability

Richard Kleeman
Bureau of Meteorology Research Centre, Melbourne, Australia

Julian P. McCreary, Jr.
International Pacific Research Center, University of Hawaii, Honolulu, Hawaii

Barry A. Klinger
Oceanographic Center, Nova Southeastern University, Dania, Florida

Abstract. A coupled ocean-atmosphere model of the Pacific basin is used to illustrate a mechanism by which El Niño and the Southern Oscillation (ENSO) may be modulated on decadal time scales. For reasonable choices of model parameters, solutions exhibit two types of oscillation, an ENSO-like interannual mode and a decadal one. The decadal mode affects the equatorial zone by means of an oceanic teleconnection that involves transport variations of the North Pacific Subtropical Cell. Since almost half of the cool, thermocline water that upwells in the eastern equatorial Pacific participates in this cell, these variations significantly alter the extent of the cold tongue, and hence provide an efficient mechanism for modulating ENSO.

1. Introduction

Decadal variations in the El Niño/Southern Oscillation (ENSO) phenomenon have been extensively documented in recent years [*Trenberth and Hurrell*, 1994; *Graham*, 1994; *Kleeman et al.*, 1996; *Latif et al.*, 1997]. At the same time, decadal variability in the North Pacific midlatitudes has attracted much attention [*Trenberth and Hurrell*, 1994; *Mann and Park*, 1996; *Nakamura et al.*, 1997; *Nakamura and Yamagata*, 1999]. Indeed, ENSO decadal variability appears to be related to the midlatitude variability [*Latif et al.*, 1997; *Kleeman and Power*, 1999], suggesting that the tropics and midlatitudes are linked at decadal time scales.

Neither the nature nor location of the mechanisms that cause Pacific decadal variability have yet been identified. Some modeling studies indicate it is generated in midlatitudes [*Latif and Barnett*, 1994, 1996; *Xu et al.*, 1998], whereas others suggest it has a tropical origin [*Knutson and Manabe*, 1998; *Yukimoto et al.*, submitted manuscript, *J. Geophys. Res.*, 1998]. *Nakamura et al.* [1997] and *Nakamura and Yamagata* [1999] provide observational support that there are (at least) two modes of Pacific decadal variability: one confined to the North Pacific with sea-surface temperature (SST) anomalies centered on the Subarctic Front, and another extending throughout the tropics in both hemispheres with large SST anomalies near the Subtropical Front.

Two processes have been proposed to explain the midlatitude-tropical linkage. *Gu and Philander* [1997] hypothesized an *oceanic* teleconnection, in which midlatitude temperature anomalies are advected to the equator within the subsurface branch of the North Pacific Subtropical Cell (STC). This cell is a shallow, meridional overturning circulation in which water flows out of the tropics in the surface layer, subducts in the North Pacific subtropical gyre, returns to the tropics within the thermocline, and upwells in the eastern equatorial ocean. Recently, *Barnett et al.* [1999] concluded that an *atmospheric* teleconnection accounts for the ENSO decadal variability in their coupled solution; specifically, decadal wind anomalies generated at midlatitudes extend far enough into the tropics to force the ocean circulation there.

In this paper, we report on solutions to a coupled model of intermediate complexity that is confined to the Pacific basin. For reasonable parameter choices, solutions develop two dynamically distinct oscillations: an ENSO-like interannual signal and a decadal one. The decadal oscillation is carried into the tropics by variations in the transport of the surface branch of the North Pacific STC, an oceanic teleconnection quite different from the one proposed by *Gu and Philander* [1997].

2. Model

The ocean component of the coupled system is essentially the $3\frac{1}{2}$-layer model used by *Lu et al.* [1998], except that layer temperatures are allowed to vary. A useful model property is that the strength of its STCs is determined by the meridional-transport divergence ΔM_1 across latitudes $y_{ds} = 23°$S and $y_{dn} = 23°$N, equatorward of which subduction is suppressed [*McCreary and Lu*, 1994]. Moreover, ΔM_1 results almost entirely from the Ekman-transport divergence across y_{dn} and

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y_{ds}, so that STC strength is set primarily by the zonal wind stress at these latitudes. Thus, the model contains an explicit process by which *subtropical* winds affect the amount of thermocline (layer-2) water that upwells along the equator.

In a preliminary step, the ocean model is spun up to equilibrium in response to the annual-mean winds of *Hellerman and Rosenstein* [1983] and is relaxed to the annual-mean SST of *Reynolds and Smith* [1994]. This equilibrium solution provides the background state to which anomalies of model SST, T_1', and wind stress discussed next are referenced.

The atmospheric component consists of two parts. The first part generates wind-stress anomalies from T_1', using joint modes of variability (SVDs) between observed SST and wind-stress anomalies determined from GISST [*Parker et al.*, 1995] and COADS wind-stress [*da Silva et al.*, 1994] data. At each time step of the integration, T_1' is decomposed into a spectrum of SVDs, and the wind-stress anomaly field associated with the SVDs is then used to force the ocean. The second part generates latent-heat anomalies based on wind-speed anomalies derived from the wind stresses calculated in the first part [*Kleeman and Power*, 1995].

The first and third SVDs (SVD1 and SVD3, respectively) are critical modes, responsible for the interannual and decadal variability present in solutions: The decadal (interannual) oscillation is absent when SVD3 (SVD1) is removed from the model atmosphere. The spatial structure of SVD1 exhibits the familiar equatorial wind-stress response to interannual SST variations, together with a remotely forced teleconnection to the northern midlatitudes. Figure 1 displays the spatial structure of SVD3, showing both its SST (contours) and wind-stress (arrows) patterns. It accounts for almost all of the zonal-wind variability generated by the atmospheric model in the subtropical North Pacific, and for this reason it strongly affects the ocean model's northern STC. An SST/wind stress pattern like SVD3 is involved in the generation of decadal variations in coupled GCMs [*Latif and Barnett*, 1994, 1996; *Yukimoto et al.*, submitted manuscript, *J. Geophys. Res.*, 1998], and develops in an AGCM forced by a prescribed SST anomaly [*Latif and Barnett*, 1996].

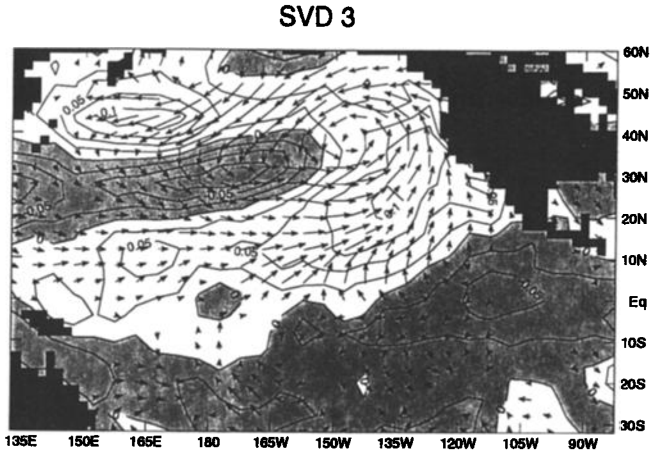

Figure 1. Spatial structures of SST and wind-stress anomalies associated with SVD3. Units are dimensionless. Negative values are shaded.

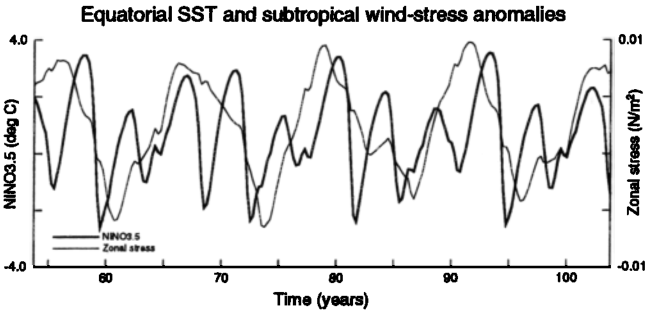

Figure 2. Time series of SST anomalies in the NINO3.5 region (thick curve) and subtropical zonal wind-stress anomalies (thin curve) for the main run.

One difficulty inherent in a statistical atmosphere like ours is that it can confuse cause and effect, since the atmosphere *always* responds to the SST patterns associated with SVDs, rather than vice versa. Another is that it can introduce unrealistic, basin-scale atmospheric teleconnections. It is a useful property, then, that oscillations in our solutions are caused by SVD1 and SVD3, both of which describe linkages supported by dynamical models.

3. Results

Figure 2 illustrates the time dependence of a solution to a complete version of the above model (our "main-run" solution), displaying time series of T_1' in the NINO3.5 region (180°E–120°W, 5°S–5°N) and zonal-wind-stress anomalies in the subtropics (135°E–120°W, 20°N–25°N). The response consists of two independent signals: an interannual oscillation with a period of 4.4 years, and a decadal one with a period of 11.9 years. The clear impression is that the decadal modulation of equatorial SST coincides with the decadal variation in the subtropical wind stress.

Figure 3 illustrates the spatial structure of decadal fluctuations in T_1' during its warm-tropical phase, determined by regressing T_1' against the subtropical wind-stress index in Figure 2. The solution reproduces the pattern of observed decadal variability reasonably well [*Latif et al.*, 1997; *Nakamura and Yamagata*, 1999], except that its response is stronger in the central, equatorial ocean. A similar pattern also occurs in the *Latif and Barnett* [1994, 1996] solution, and both solutions exhibit a clockwise rotation of heat-content anomalies in the North Pacific (not shown). These striking similarities suggest that their decadal oscillation and ours share a common dynamics.

Figure 4 shows T_1' in the NINO3.5 region (T, thick curve), total transport across y_{dn} (M_1, thin curve), and

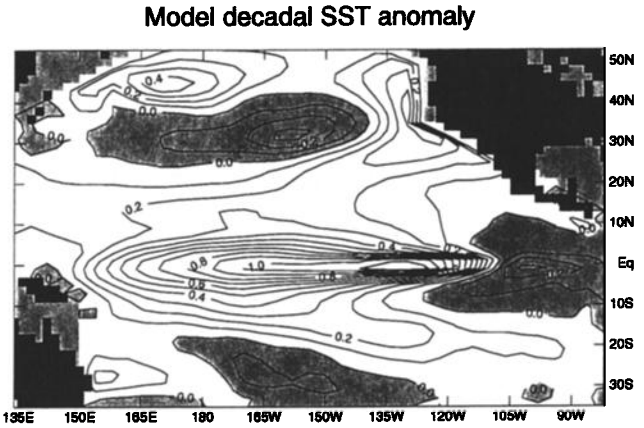

Figure 3. Spatial structure of the decadal oscillation for the main run. Values correspond to a local change in model SST (°C) when the wind-stress index increases by one standard deviation. Negative values are shaded.

equatorial upwelling ($\mathcal{W}$, dashed curve), each curve low-pass filtered to highlight the decadal signal. Curves $\mathcal{T}$ and $\mathcal{W}$ are clearly inversely related, indicating that the equatorial SST anomalies result largely from changes in the amount of cool water that upwells into layer 1. Indeed, variations in the *temperature* of the upwelled layer-2 water are small (~ 0.1°C) and cannot account for $\mathcal{T}$, so that the *Gu and Philander* [1997] advective process is not the cause of $\mathcal{T}$ in our solution. Curves $\mathcal{W}$ and M_1 almost overlap, supporting the idea that the equatorial upwelling anomaly is determined by the amount of layer-1 water that flows out of the tropics across y_{dn}. These close relationships indicate that subtropical wind variability causes the solution's decadal SST variability through its effect on the amount of layer-1 water that is drained from the tropics. This conclusion is supported by several of the test solutions reported next.

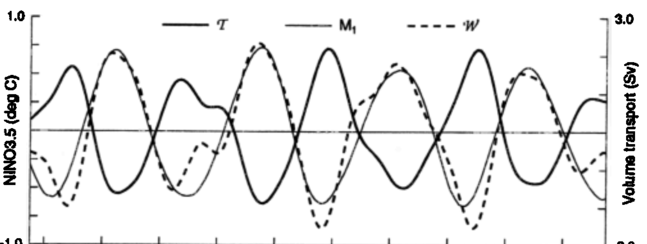

Figure 4. Time series of SST anomalies in the NINO3.5 region ($\mathcal{T}$, thick curve), total transport across y_{dn} (M_1, thin curve), and upwelling into layer 1 between 0.5°S and 0.5°N ($\mathcal{W}$, dashed curve). To suppress interannual variability, all series have been low-pass filtered using a Gaussian mask with a full width at half maximum of 4 years.

4. Mechanisms

As might be expected, the interannual oscillation is absent in a test solution with coupling suppressed from 10°S to 10°N (the "decadal" solution). The decadal signal remains, however, and it closely resembles the one in the main run, indicating that its origin lies outside the tropics. To locate its generation region more precisely, we obtained three additional test solutions without coupling in: *1)* midlatitudes ($y > 35$°N); *2)* the northwestern ocean ($x < 175$°W, $y > 25$°N); and *3)* the northeastern ocean ($x > 175$°W, $y > 25$°N). Decadal oscillations remained in tests 1 and 2 but not in test 3. These results point toward the northeastern, subtropical Pacific as being a key region of ocean-atmosphere interaction for the main run's decadal signal, a result consistent with *Nakamura and Yamagata's* [1999] analysis of their second mode.

For the decadal solution, we also correlated T_1' with various terms q_i in the T_1' equation at time lags of zero and $P/4$, where P is the oscillation period. These correlations measure the positive and delayed-negative feedbacks associated with each q_i, respectively. The zero-lag correlations indicate that the primary positive-feedback mechanism is anomalous latent heating due to wind-speed variations, Q_w', in the northeastern Pacific. Indeed, there is no oscillation in a test solution without Q_w', confirming the importance of this process. The $P/4$-lag correlations suggest that the primary delayed-negative feedbacks are anomalous horizontal advection in the subtropics and vertical mixing by convective overturning north of 35°N in the central Pacific. A likely cause of the delay is the westward propagation of Rossby waves, generated by wind curl associated with the SVD3 wind-stress vortex in the northeastern ocean (Figure 1); however, we were unable to demonstrate this property conclusively because of difficulties with separating locally and remotely driven flows.

5. Summary and conclusions

In this paper, we report solutions to an intermediate coupled model that can develop both interannual and decadal oscillations. Positive feedback for the decadal oscillation is provided by latent-heat flux anomalies in the northeastern subtropics due to wind-speed variations. Delayed negative feedback arises from anomalous horizontal advection and convective overturning.

The decadal oscillation affects equatorial SST by altering the amount of surface water that is drained from the northern tropics, which is the driving force of the North Pacific STC. As such, this mechanism is similar to, but fundamentally different, from the *Gu and Philander* [1997] mechanism. In both studies, decadal SST variability in the tropics is generated by heat-transport anomalies associated with variations in the North Pacific STC; however, in our model these anomalies are generated by *transport* changes in primarily the *upper* branch of the STC, whereas in the *Gu and Philan-*

der [1997] hypothesis they are caused by *temperature* changes in the *lower* branch induced by midlatitude surface heat-flux anomalies.

The simplicity of the coupled model is an advantage, enabling us to identify readily key dynamical processes and coupling regions. It is also a limitation in that other significant processes, such as the background annual cycle and realistic mixed-layer physics, are neglected. Additionally, because one part of the model atmosphere is based upon empirical correlations, the system allows only a limited exploration of atmospheric dynamics. We are currently extending the model to overcome these shortcomings.

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R. Kleeman, Bureau of Meteorology Research Centre, G.P.O. Box 1289K, Melbourne 3001, Australia. (e-mail: rzk@bom.gov.au)

J. P. McCreary, International Pacific Research Center, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822. (e-mail: jay@soest.hawaii.edu)

B. A. Klinger, Oceanographic Center, Nova Southeastern University, 8000 N. Ocean Dr., Dania, FL 33004. (e-mail: klinger@ocean.nova.edu)

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