6.1 THE RESPONSE OF THE OCEAN TO DECADAL VARIABILITY IN ATMOSPHERIC FORCING: WIND VERSUS THERMAL FORCING

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1. INTRODUCTION

The response of the ocean to decadal variability in atmospheric forcing is primarily mediated by two modes of variability of the thermocline (Liu, 1999). The first mode is similar to the first baroclinic mode in a resting ocean and has westward phase propagation, while the second mode has similar vertical structure to the second barolinic mode, but follows an "advective" pathway, the flow field of the mid-thermocline. Liu (1999) has identified the first mode as primarily forced by Ekman pumping, while the second mode is primarily forced by diabatic processes, specifically by heating anomalies. In this study we use a vertical modal decomposition of a North Pacific model simulation to investigate the amplitudes and spatial structure of the first and second baroclinic modes and their respective forcing fields.

2. NUMERICAL MODEL

The model used for this study is the Hallberg Isopycnal Model (Ladd and Thompson, 2000; Thompson et al. 2001). It is configured with 16 layers in the vertical including a Kraus-Turner bulk mixed layer and a variable density buffer layer. The model domain is 20°S to 60°N, 126°E to 76°W and a horizontal resolution of 2 degrees. Mixed layer densities and isopycnal layer thicknesses were initialized with sea surface densities and layer thicknesses calculated from climatological September temperature and salinity values. After an initial 30 year spin-up using climatological forcing, the model is forced at the surface with daily linear interpolations of monthly heat fluxes and climatological freshwater flux forcing. (converted to density fluxes) and surface winds from January 1965 to December 1993. There is also a weak relaxation of mixed-layer densities to observed values.

3. VERTICAL MODAL DECOMPOSITION

To understand the dynamic response of the model ocean to variability to atmospheric forcing, we use a vertical modal decomposition of density structure (interface displacements). Dynamic vertical modes form a complete set that can describe any perturbations to the system. We follow the procedure of Thompson et al (2001) where an analysis of the seasonal cycle of thermocline displacement was performed. Here, we use the mean winter time stratification field and use the winter anomalies of the density field.

Casting the vertical structure equation onto layers allows the eigenvalue problem to be solved independently at each location. Then, the interface deviations can be decomposed into the vertical modes. Killworth et al (1997) show that as long as the mean flow is smaller than the phase speed, the vertical structure is little changed by the presence of the mean flow, although the phase speed can be strongly modified. We find that the first baroclinic mode structure is little effected by the presence of the mean flow, while the second baroclinic mode is quantitatively, but not qualitatively change (not shown).

Using the vertical modal structure (with the mean flow set to zero), the interface deviations can be decomposed into vertical modes. The phase speeds do depend strongly on the presence of the mean flow The phase lines derived from phase speeds with non-zero mean flow show good agreement with anomaly propagation from the vertical model decomposition (Figure 1) when the change in the phase speed with longitude is taken into account. It is clear that the vertical modal decomposition separates out different dynamical signals as each mode shows distinctly different propagation speeds.

The spatial structure of the amplitude of each of the modes shows a consistent picture (Figure 2). The first baroclinic shows east-west asymmetry, possibly owing to the effects of topographic coupling, but relatively uniform amplitude with latitude. However, the second mode shows a distinct pattern that is related to its propagation characteristics. It appears to be forced by diabatic pumping at the eastern end of the Kuroshio Extension and then proceeds to propagate towards the western boundary which it reaches at about 20N. At low latitudes (10N and equatorward), Ekman pumping dominates the forcing.

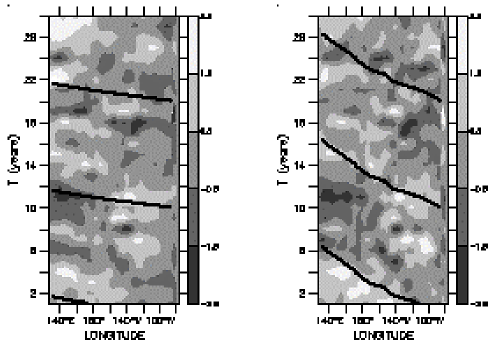
4. FORCING OF THE BAROCLINIC MODES

To identify how each of these modes are forced, we proceed with the linear analysis and use the quasi-geostrophic potential vorticity equation. Each of vertical mode is forced under quasi-geostrophic theory either by Ekman pumping or by diabatic forcing. Given the normalized vertical structure of each mode, the forcing of each mode can be found by multiplying the potential vorticity equation by the vertical structure and integrating. The first baroclinic mode is primarily forced by Ekman pumping with a significant contribution from diabatic forcing in the western part of the Kuroshio Extension (Figure 3). The second baroclinic mode is primarily forced by diabatic pumping at mid to high latitudes, with Ekman pumping more important in the tropics. There is no local maximum in the eastern subtropics as depicted in the idealized runs of Liu (1999).

5. CONCLUSIONS

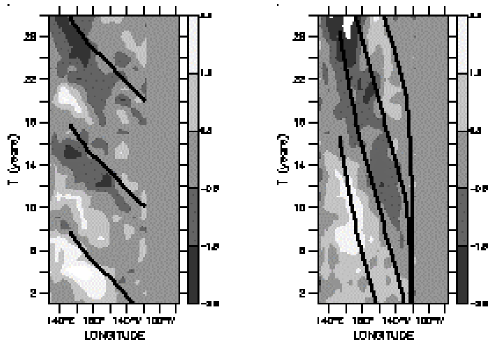
A vertical modal analysis is done of the density deviations in an ocean general circulation model of the North Pacific driven by decadal variability in atmospheric forcing. The different dynamic vertical modes show varying propagation characteristics, with the first baroclinic mode exhibiting consistent westward propagation at latitudes south of 40N, while the higher baroclinic modes show westward phase propagation at low latitudes, but propagate eastward at higher latitudes. The change in direction occurs at lower latitudes for successively higher vertical modes. The propagation characteristics of each mode can be understood by the inclusion of the mean flow in the quasi-geostrophic potential vorticity equation.

Projection of the Ekman pumping and diapycnal fluxes in the potential vorticity equation for each dynamic vertical mode shows the importance of Ekman pumping throughout the North Pacific. Diabatic pumping, or that associated with thermal forcing, is important in the Kuroshio Extension, and much less so further to the south. The spatial distribution of the forcing is consistent with the structure of the energy in the baroclinic modes. The first baroclinic mode energy increases poleward, while the second baroclinic mode has a band of positive energy emanating westward from the eastward end of the Kuroshio Extension and ends at the western boundary at 20N.



9N Mode 1

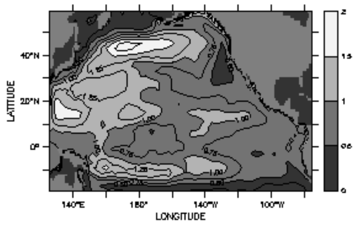
9N Mode 2



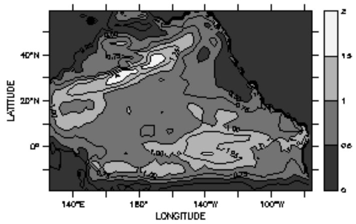
29N Mode 1

29N Mode 2

Figure 1. Time longitude plots of the first and second baroclinic modes. Overlain are phase lines derived from phase speeds with non zero mean flow.

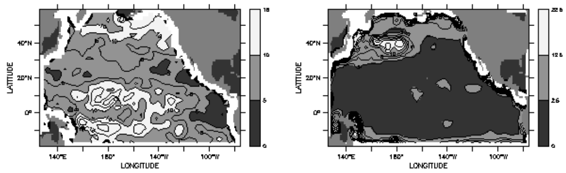


Mode 1 energy



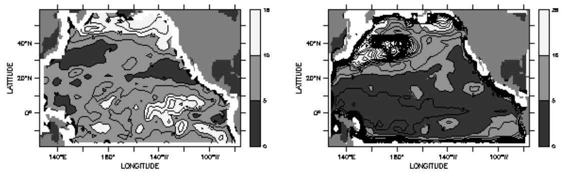
Mode 2 energy

Figure 2. RMS amplitude of the first and second baroclinic modes from the yearly anomalies.



First mode Ekman pumping

First mode Diabatic Pumping



Second mode Ekman Pumping

Second mode Diabatic Pumping

Figure 3. RMS amplitude of the forcing from Ekman and diabatic pumping.

6. REFERENCES

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