Dynamics and Thermodynamics of the North Pacific Ocean

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Observations from the TOPEX/POSEIDON (T/P) radar altimeter, along with other observations and meteorological products, were used to examine the relationship between ocean dynamics and thermodynamics in the Pacific Ocean. We have addressed the following general scientific questions:

Understanding oceanic heat storage and transport. To what extent are heat content anomalies due to lateral (ocean) fluxes?

Impact of subsurface water on the upper ocean heat budget. How do subsurface temperature anomalies affect the heat budget?

Thermodynamic and dynamic responses. To what extent are SSH variations best explained by surface fluxes or by thermocline motion?

1 Recent progress

Much of our work this year was in modeling the upper ocean heat budget in the western boundary current regions of the North Pacific. A related second topic was explaining the damping of Rossby waves in the tropical Pacific, in conjunction with work on the OVWST.

Heat Budget of the KE region

The KE region has the largest variability both in subsurface and surface temperature at interannual timescales in the extratropical North Pacific, and has the largest heat exchanges with the atmosphere, making it a key region for interannual-to-interdecadal climate variability in the North Pacific. Substantial interannual changes in the southern recirculation gyre of the Kuroshio in the T/P SSH field are suggestive of important variations in heat content and possibly subtropical mode water (STMW) formation.

To understand the impact of ocean dynamics (specifically horizontal fluxes) on the SST and heat content variability, postdoctoral investigator Frédéric Vivier used a three-dimensional model of the upper ocean, developed in volume finite elements, based on previous efforts by Qiu and Kelly (1993) and Kelly and Qiu (1995a,b). The surface geostrophic

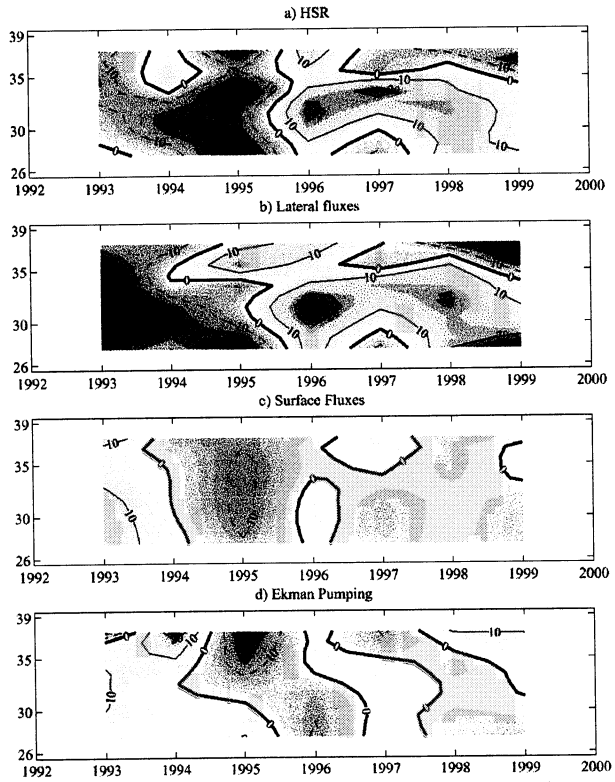

Figure 1: Zonal average of the nonseasonal terms of the vertically integrated heat budget. (a) heat storage rate, (b) lateral fluxes, (c) surface fluxes, and (d) Ekman pumping [thermocline heave].

velocity field is specified from T/P altimeter measurements, ensuring a realistic representation of the Kuroshio Extension (both in strength and location), where OGCMs frequently encounter difficulties.

An analysis of the upper ocean heat storage rate (Figure 1) shows the contribution of lateral fluxes (mostly advection) on interannual time scales. In particular, the transition between the contracted southern recirculation gyre and the elongated gyre is associated with an increase in heat storage, owing to the convergence of heat transport by the geostrophic circulation. In addition, during periods of an elongated gyre, the waters below the mixed layer are warmer and vertical entrainment is less efficient in exporting the heat out of the mixed layer.

Dr. Vivier recently returned to LODYC in Paris with a position funded by CNRS.

A similar analysis for the North Atlantic was begun on this grant and is being continued, funded by NSF, by graduate student Shenfu Dong.

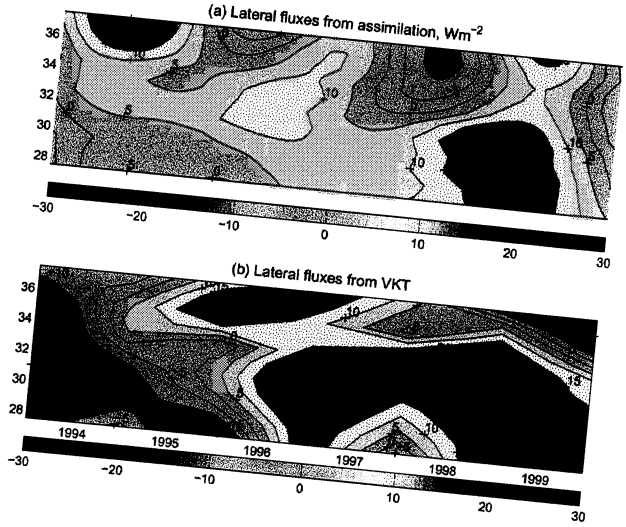

Figure 2: Zonal average of the nonseasonal lateral fluxes from the one-dimensional heat budget and from Vivier et al. (2002).

Inferring lateral fluxes in the KE region: 1970-2000

To extend the results of the detailed analysis of Vivier et al. to a longer period, Kelly has developed a simple one-dimensional heat budget from which advection is inferred and is applying this method to the North Pacific over a 30-year period. Starting with the climatological mixed layer depth (MLD), SST is assimilated using a linearized Kalman filter. The MLD is adjusted to allow for seasonal and interannual anomalies, and assimilating surface and subsurface temperatures (from JEDAC), the residual is interpreted in terms of lateral ocean fluxes (advection plus diffusion).

The analysis shows good agreement between the lateral flux estimates from this simple model (Figure 2a) and those from the more sophisticated model (Figure 2b), justifying the use of the model to infer the heat budget over the last 30 years. Comparing the contributions of surface fluxes and lateral fluxes with the heat storage rate (HSR), it appears that the relative importance of these terms is largely time-scale dependent (Figure 3). For monthly anomalies, the surface fluxes are more highly correlated with the HSR than are the lateral fluxes, although both terms are important. However, for interannual variations, lateral fluxes are more important than surface fluxes in determining the heat content of the ocean.

Finally, the 31-year record was used to test whether the ocean state has any predictive skill for climate forecasting. SST, even with the fluctuations with periods longer than 1 year removed, has no skill in predicting surface fluxes. However, oceanic heat content anomalies have a skill of 20% (of the anomaly variance) in predicting surface flux anomalies up to one year in advance. This result is consistent with the idea that the persistence of climate variations is associated with the ocean's heat storage in western boundary current regions.

Explaining damped Rossby waves using scatterometer winds

The use of scatterometer winds to force a simple circulation model in the tropical Pacific

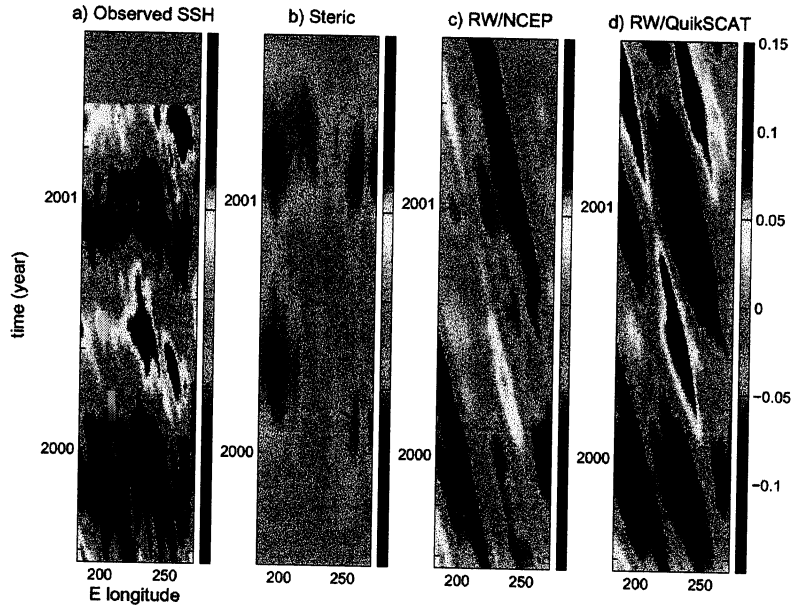

Figure 4: Sea surface height anomalies using the simple model. (a) Observed SSH anomalies from the T/P altimeter, (b) thermal expansion anomalies from NCEP heat fluxes. Expected SSH response from Rossby wave model for (c) NCEP and (d) QuikSCAT wind stress curl. Units are meters.

in press, *J. Phys. Oceanogr.*, jointly funded with NSF.

Vivier, F., K. A. Kelly, L. Thompson. Heat budget in the Kuroshio Extension region: 1993-1999, in press, *J. Phys. Oceanogr.*, 2002.

Dong, S., and K. A. Kelly, The seasonal and interannual variations in the geostrophic currents in the Mid-Atlantic Bight, revised for *J. Geophys. Res. - Oceans*, 2002, jointly funded with ONR.

Dong, S. and K.A. Kelly, Heat budget in the Gulf Stream region: the importance of heat advection and storage, submitted to *J. Phys. Oceanogr.*, jointly funded with NSF.

Kelly, K. A., and L. Thompson, Scatterometer winds explain damped Rossby waves, in press, *Geophys. Res. Lett.*, jointly funded with OVWST.

Kelly, K.A., The Relationship Between Heat Transport Convergence and Surface Fluxes in the Western North Pacific: 1970–2000, to be submitted to *Journal of Climate.*

3 Abstracts and Presentations: 2001-2002

"Satellite Microwave Observations of the Global Ocean," with Dudley Chelton, "WOCE and Beyond," San Antonio, November, 2002.

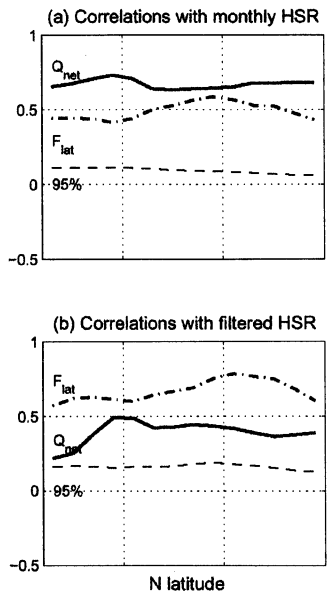

Figure 3: Correlations of the heat storage rate with net surface heat fluxes (solid line) and with lateral fluxes (dashed) for (a) the monthly values and (b) after lowpass filtering the terms to eliminate fluctuations with periods shorter than 1 year.

has explained a phenomenon observed in the late 1970s, but never satisfactorily explained previously. Westward propagating waves in the North Pacific Ocean are overwhelmed by a zonally coherent response in the latitude band 10–16°N, as observed in sea surface height (SSH) anomalies from the T/P altimeter (Figure 4a). The apparent lack of wave propagation in this region has also been observed in anomalies in the oceanic thermocline. Our previous efforts had been directed at isolating mechanisms to damp the Rossby wave.

SSH anomalies from a simple model of wave propagation, forced with two different wind products, is compared with the SSH expected from the seasonal heating cycle (Figure 4b)to understand the processes responsible for the coherent annual period signal. Based on three different flux products seasonal heating cycle is out-of-phase and too small to be responsible for the observed annual cycle in SSH. Comparisons of wind-forced SSH forced by NCEP reanalysis winds (Figure 4c) and by winds from the QuikSCAT/SeaWinds scatterometer demonstrate that the observed SSH variations reflect the dominant local Ekman pumping response to zonally coherent wind stress that is produced only by the scatterometer fields (Figure 4d). Rossby waves do propagate westward, but the magnitude of the free wave is smaller than the locally forced response. The wind stress variations are associated with the annual migration of the Intertropical Convergence Zone, which is not reproduced well by the NCEP analysis.

2 Published Articles and Submitted Manuscripts

Thompson, L., K. A. Kelly, D. Darr, and R. Hallberg, 2002. Buoyancy and mixed-layer effects on the sea surface height response in an isopycnal model of the North Pacific,

"Ocean circulation and climate studies using satellite data," Ocean 500 seminar series, University of Washington, November, 2002.

"A Better Understanding of Tropical Ocean Circulation Using Improved Wind Fields," OSU, Corvallis, October, 2002 LODYC, Paris, France, June, 2002

Vivier, F., "Heat budget in the Kuroshio Extension region: 1993-1999," EGS meeting, Nice France, April 2002.

"Improved Rossby wave modeling with scat winds," Regional workshop on scatterometer winds, Seattle, February, 2002

Kelly, K.A., "Understanding of tropical Rossby wave dynamics with improved wind fields," Ocean Sciences Meeting, Honolulu, Hawaii, February 2002.

Kelly, K.A.,"Heat budget in the Kuroshio Extension region: 1993-1999," Ocean Sciences Meeting, Honolulu, Hawaii, February 2002.

Kelly, K.A., "Interannual-to-Decadal Variations in SST and Upper Ocean Heat Budget in the Western North Pacific," Fall AGU Meeting, San Francisco, Dec., 2001.

Kelly, K.A.,"A better understanding of tropical ocean circulation using improved wind fields," Woods Hole Oceanographic Institution, Woods Hole, September, 2001.

Vivier, F., "Heat budget in the Kuroshio Extension region: 1993-1999," School of Oceanography, University of Washington, June 2001.

Kelly, K.A., "Interannual-to-Decadal Variations in SST and Upper Ocean Heat Budget in the Western North Pacific," Western Pacific Geophysics Meeting, Tokyo, June, 2001.