The 1997–1999 abrupt change of the upper ocean temperature in the north central Pacific

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[1] The abrupt warming of the north central Pacific Ocean from 1997 to 1999 is studied using an ocean data assimilation product. During this period, the average mixed-layer temperature in the region of 170–210°E, 25–40°N rises by 1.8 K. The major contributors to the warming are surface heat flux (1.3 K), geostrophic advection (0.7 K), and entrainment (0.7 K). For the geostrophic advection, the contributions by the zonal, meridional, and vertical components are 0.4, −0.1 and 0.3 K, respectively. Mixing and meridional Ekman advection have cooling effect. The significance of the geostrophic advection indicates the importance of ocean dynamics in controlling the abrupt warming tendency during the 1997–99 period and the inadequacy of a slab mixed-layer model in simulating such warming tendency. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4572 Oceanography: Physical: Upper ocean processes; 4255 Oceanography: General: Numerical modeling. **Citation:** Kim, S.-B., T. Lee, and I. Fukumori (2004), The 1997–1999 abrupt change of the upper ocean temperature in the north central Pacific, *Geophys. Res. Lett.*, *31*, L22304, doi:10.1029/2004GL021142.

1. Introduction

[2] Understanding the decadal variability of the North Pacific is important because of its impact on the regional and global climate, fisheries and ecosystem. A well-known climate shift associated with the phase change of Pacific decadal variability occurred in the mid 1970s [*Miller et al.*, 1994; *Deser and Blackmon*, 1995; *Yasuda and Hanawa*, 1997]. In 1997–99, the North Pacific experiences an abrupt warming and simultaneous variations in the ecosystem [*Peterson and Schwing*, 2003], signifying yet another possible phase change of Pacific decadal variability. For both the 1997–99 event and the previous phase shifts (e.g., in the mid 1970s), the largest change in sea surface temperature (SST) occurs in the north central Pacific (NCP) [*Latif and Barnett*, 1994; *Yasuda and Hanawa*, 1997; *Peterson and Schwing*, 2003]. We therefore focus on this region.

[3] The mechanisms controlling the SST change in the NCP on the interannual or longer time-scales are not well understood [*Miller et al.*, 2003]. In particular, estimates of geostrophic advection are not adequately addressed. For example, surface heat flux and Ekman advection are reported to drive the 1970s decadal SST shift in the NCP [*Miller et al.*, 1994; *Deser and Blackmon*, 1995; *Yasuda and Hanawa*, 1997; *Nakamura et al.*, 1997], but the role of ocean geostrophic advection has not been discussed. In a coupled general circulation model (GCM) study, *Pierce et al.* [2001] and *Schneider et al.* [2002] conclude that the decadal-scale heat budget within the top 20-m layer in the NCP is balanced between Ekman advection and vertical mixing. The large contribution by the vertical mixing is probably because the 20-m layer lies within a mixed layer (ML). It is not clear whether such a conclusion would remain valid were the full ML considered.

[4] This study presents a ML temperature balance analysis for the NCP by directly resolving ocean dynamics. The investigation is made for the period of 1997–2000. The relative contributions of oceanic advection, entrainment, mixing and surface heat flux are quantified. The analysis result may have implications to the SST changes associated with the phase shift of Pacific decadal variability.

2. General Circulation Model Solutions

[5] Model results used for this investigation are obtained from a data assimilation product of Estimating the Climate and Circulation of the Ocean (ECCO, http://www.ecco-group.org, see also *Stammer et al.* [2002]). The model used is the parallel version of the primitive-equation Massachusetts Institute of Technology (MIT) Ocean GCM [*Marshall et al.*, 1997]. The spatial domain is nearly global (75°S–75°N). The model has a uniform resolution of 1° × 1° in the study region. There are 46 vertical levels with layer thickness of 10 m in the upper 150 m and 21 layers above 300 m. The model employs two advanced mixing schemes: the K-profile parameterization vertical mixing [*Large et al.*, 1994] and the Gent-McWilliams isopycnal mixing [*Gent and McWilliams*, 1990]. The model is forced by National Centers for Environmental Prediction (NCEP) reanalysis products (12-hourly wind stress, daily diabatic air-sea fluxes) with the time-means replaced by those of the Comprehensive Ocean-Atmosphere Data Set fluxes [*da Silva et al.*, 1994]. In addition to this imposed heat flux, model SST is relaxed to NCEP's SST analysis. The model was first spun up for 10 years from rest using climatological temperature and salinity [*Boyer and Levitus*, 1998] forced by seasonal climatological forcings averaged from 1980 to 1997. An approximate Kalman filter and smoother [*Fukumori*, 2002] are used to assimilate anomalies of sea level and subsurface temperature obtained from the TOPEX/Poseidon (T/P) altimeter and the Global Telecommunication System (GTS) (D. Behringer, personal communication, 2002), respectively. An earlier version of this system can be found in work by *Fukumori et al.* [1999].

[6] The NCP defined here is the area bounded by 170–210°E, 25–40°N, chosen as the region in the North Pacific where the interannual change in SST is the largest over the

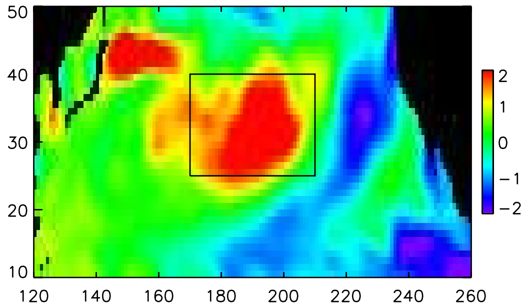

Figure 1. Change in the yearly mean SST (in K) of the ECCO model from 1997 to 2000, after 5° by 5° smoothing. The rectangle shows the study area (170–210°E, 25–40°N).

4 years (Figure 1). Reynolds SST also shows the largest change in the same area. This is the region of several previous studies as well [e.g., *Latif and Barnett*, 1996; *Schneider et al.*, 2002]. The ML is defined diagnostically from the GCM output fields, such that at the ML depth the density is larger by 0.125 kg m^{-3} than that at 5 m. The isothermal layer depths derived from expendable bathythermograph (XBT) observations and the model compare reasonably well with each other (Figure 2a), demonstrating the fidelity of the model estimates. The comparison is performed south of 35°N to avoid temperature inversion at northern latitudes. The apparent "noisiness" of the time series is because the comparison is made at the XBT's irregular sampling location and time. On average, the model's ML depth is too shallow by 10–20 m. This may be due to the mixing coefficient in the model being too small.

3. Temperature Budget

[7] The ML temperature balance can be written as

$$\frac{\partial[T]}{\partial t} = \left[\frac{1}{\rho C_p}\frac{\partial q}{\partial z}\right] - [\nabla \bullet (\mathbf{v}T)] - [\nabla \bullet (\kappa \nabla T)] - \frac{1}{h}\Delta T\frac{\partial h}{\partial t}, \quad (1)$$

where the square brackets represent the depth average within the ML. T is the temperature, q the sum of the radiative and turbulent diffusive heat fluxes in the vertical direction, ρC_p the density times specific heat of sea water, $\mathbf{v} = (u, v, w)$ the three-dimensional velocity including both geostrophic and ageostrophic components, $\nabla \equiv (\partial/\partial x, \partial/\partial y, \partial/\partial z)$, κ the diffusivity in three dimensions, and h the ML depth. ΔT is the difference between ML temperature and the temperature of entrained water. Equation (1) is further averaged horizontally to produce the volume-mean quantities, after carefully assessing the effect of the spatially varying ML depth. The terms on the rhs of Equation (1) denote surface heat flux, advection, mixing and entrainment respectively. Entrainment includes the horizontal advection across a sloping ML base and vertical velocity [*Moisan and Niiler*, 1998]. Here the two advective contributions are included as parts of the horizontal and vertical advection in Equation (1) respectively. We treat them separately from $\partial h/\partial t$ because they are driven by different mechanisms. A prerequisite of budget analysis is budget closure, namely the sum of the budget components matching actual temperature change. This requirement, however, is often unsatisfied as noted by *Qiu* [2002, Figure 16]. Our analysis is characterized by the closure of the ML temperature budget, allowed by retaining all the terms of the model.

[8] The ML temperature in the NCP rises by 1.8K during the 1997–99 period (Figure 3a and Table 1). The rise in the Reynolds SST for the same period is 1.9K. To quantify the

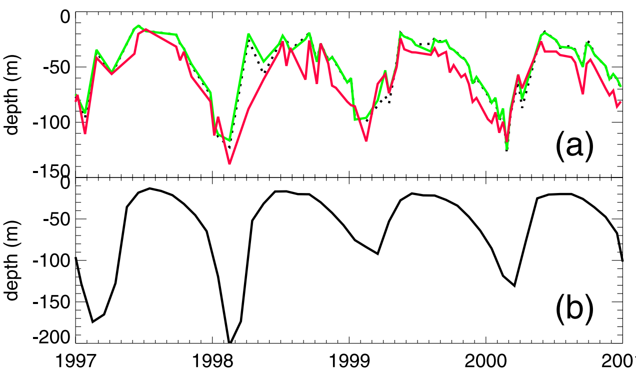

Figure 2. (a) Verifying the model isothermal layer depth (ILD, green) over 190–210°E, 25–35°N by comparing with XBT ILD (red). The ILD (MLD) is determined such that the temperature (density) at the layer base is lower (larger) than the 5-m value by 0.5 K ($0.125\sigma_0$). The model MLD is shown in black dot. (b) Domain-mean MLD from the model.

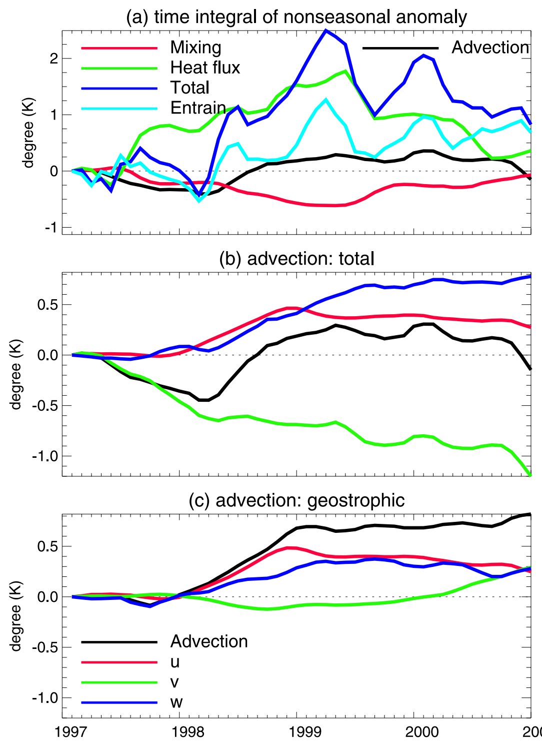

Figure 3. ML temperature budget over the NCP. (a) Time integral of the interannual anomaly of the budget components. (b) Decomposition of the total advection into zonal, meridional, and vertical components. (c) Contributions of geostrophic current to the total advection and its three directional components. The same labels apply to Figures 3b and 3c.

Table 1. Temperature Budget[a]

	Averaged From Jan. 1997 Until 1999	Averaged From Jan. 1997 Until 2000
Mixed layer temperature	1.77	1.28
Surface heat flux	1.31	0.58
Advection by geostrophic current	0.73	0.68
zonal (u)	0.41	0.32
meridional (v)	−0.06	0.14
vertical (w)	0.34	0.27
Entrainment	0.72	0.68
Mixing	−0.46	−0.21

[a]The cumulative contribution by the interannual trend of each budget component, as shown in Figure 3, is averaged over the year indicated in the table. Units in K.

interannual changes, we removed the mean monthly tendencies averaged over 11 years from 1993 to 2003. During this period, the linear trend in the ML temperature is very small, favoring the analysis of interannual anomaly. In the presence of a linear trend, the interannual variation may appear somewhat distorted [e.g., *Vivier et al.*, 2002, Figure 16]. We further applied a three-month running mean to the tendencies and integrated these results in time for analysis, which are shown in Figure 3. The major contributors to the warming are surface heat flux, advection and entrainment. The surface heat flux contributes to the warming most significantly in 1997, but in 1998 its impact is secondary and from 1999 it is the dominant cooling mechanism. The advective warming and entrainment persist until 1999 while the surface flux begins cooling.

[9] To illustrate the nature of the advective warming, we have decomposed it into zonal, meridional and vertical components (Figure 3b). The decomposition is based on the 'external flux' form [*Lee et al.*, 2004], where the zonal component, for example, is given by integrating $u_b \times (T_b - T_r)$ at zonal boundaries, where u_b and T_b are the quantities at the boundaries and the reference, T_r, is the domain mean temperature. The advective tendencies are further decomposed into geostrophic (Figure 3c) and ageostrophic contributions (differences between Figures 3b and 3c). The contribution by zonal advection is dominated by the zonal geostrophic current. The dominance of the geostrophic component over the ageostrophic is not surprising since the NCP features the zonally flowing Kuroshio Extension (KE) and the North Pacific Current. The meridional component is mostly ageostrophic, associated primarily with Ekman advection. From 1998 the Trades (the westerlies) intensify at the southern (northern) boundary of our domain [*Peterson and Schwing*, 2003], reducing (increasing) the southward Ekman transport of cold water that warms (cools) the NCP. The consequent cancellation of the Ekman warming and cooling keeps the meridional component small from 1998 onwards. About half of the warming by vertical advection is geostrophic. The vertical geostrophic velocity at depth z is given as [*Pedlosky*, 1996]

$$\nabla \times (\tau/\rho f) - \beta/f \int_z^0 v_g dz,$$

where τ is the wind stress, f the Coriolis parameter, $\beta = \partial f/\partial y$ and v_g the meridional geostrophic velocity. Vertical advective warming is determined not only by the negative anomaly in the wind stress curl around 1998 [*Qiu*, 2003; *Peterson and Schwing*, 2003] but also by the changes in associated temperature difference across the ML base.

[10] The entrainment warming around January 1999 and 2000 is due to reduced deepening of a ML (Figure 2b) as a result of weaker wind and weaker surface cooling than normal (as in the KE during the same period [*Vivier et al.*, 2002]). Similarly, reduced shoaling in spring 1999 and 2000 leads to less warming than normal by detrainment (unlike bulk formulation, detrainment warms the ML because of the vertical gradient in ML temperature). But spring of 1998 experiences the transition from a deep to shallow ML (Figure 2b), producing larger detrainment and greater warming than normal. The nonseasonal variation in ΔT contributes also to the anomalous entrainment.

[11] Mixing cools the ML up to 1998 and warms the ML from 1999. The variability of mixing shows strong negative correlation with the surface heat flux variability (Figure 3a). We find this mixing is dominated by its vertical component that may be expressed as $-\kappa_z \partial T/\partial z/h$ after depth-averaging within the ML. Anomalous warming (cooling) by the surface heat flux increases (decreases) the vertical stability, $\partial T/\partial z$, leading to cooling (warming) tendency by the mixing.

4. Discussion

[12] The most significant finding from the budget analysis in Figure 3 is the importance of the advective warming by the zonal and vertical components. Table 1 shows the cumulative tendencies of various budget terms (as plotted in Figure 3) from 1997 to 1999 and to 2000. The zonal and vertical geostrophic advection contributes 0.4 and 0.3 K of the warming respectively from 1997 to 1999. They together account for as much net warming as the entrainment or half the surface heat flux does. These results indicate that the ocean dynamics play a significant role in the 1997–99 warming. In comparison, the NCP SST shift in the mid 1970s is reported to be driven by atmospheric processes, namely the meridional Ekman advection and surface heat flux [*Yasuda and Hanawa*, 1997; *Nakamura et al.*, 1997]. In these studies, however, zonal and vertical advection, and entrainment are not determined directly. *Miller et al.* [1994] emphasize atmospheric processes after finding that horizontal advection, surface heat flux and entrainment were the main mechanisms for the 1970s cooling. It is not clear whether geostrophic advection also plays a role in the NCP SST shift in the mid 1970s.

[13] Some previous GCM studies report that the ocean's role is secondary in decadal-scale NCP temperature balance, and that the meridional Ekman advection, vertical mixing and surface heat flux are dominant. In these GCM studies, however, the temperature balance analysis is performed for the top layers with a fixed depth (20-m by *Pierce et al.* [2001] and *Schneider et al.* [2002], or 50-m by *Wu and Liu* [2003]). Temporal and spatial variation of ML depth was not considered. When it is considered we find that a wintertime ML (typically 100m or thicker) is deeper than a wintertime Ekman layer (approximately 35m thick, based on *Pond and Pickard* [1983]). Also Ekman flow is surface-enhanced. Therefore the temperature budget within the 20-m layer will be dominated by Ekman advection. Moreover, a 20-m layer being the upper part of the ML means that vertical mixing would be very important because

it is needed to distribute the surface heating through the entire ML (noted also by *Pierce et al.* [2001]). In fact, mixing and surface heat flux are indeed dominant with present model results when the top 20-m layer is considered (not shown). However, the relative importance of geostrophic advection becomes more prominent when the entire ML is analyzed.

[14] Often a slab ocean model coupled to an atmospheric GCM is used to study the midlatitude SST variability. In employing the slab model lies an assumption that the ocean responds passively to atmospheric forcing without the involvement of ocean dynamics such as horizontal geostrophic and vertical advection, and entrainment. *Deser et al.* [2003] report that parameterizing entrainment through a variable-depth ML better represents the winter-time SST variability, which suggests the positive role of including ocean dynamics. Additionally here we have found that the zonal and vertical geostrophic advection is important for the 1997–99 warming event. To the extent that this event reflects a phase switch of Pacific decadal variability, ocean dynamics cannot be ignored in studying such variability.

[15] The advective warming by the zonal geostrophic current is not small for the 1997–99 period. Moreover, the warming persists until the end of 2000 (Figure 3c and Table 1). Further analysis shows that about 0.3K of the warming is contributed by the time-varying part of the zonal geostrophic current as opposed to changes in advected temperature itself. The time-varying current averaged along the western boundary of the NCP shows the same interannual variation as that observed by *Qiu* [2003]. Furthermore he found that the strength of the zonal current oscillates with a 12-yr period, responding to Rossby waves initially generated by a wind stress curl anomaly in the northeastern Pacific. Thus the warming by the time-varying zonal current suggests that the delayed response of ocean circulation to wind stress curl may be one of the important elements defining a decadal phase shift in SST. The suggestion is consistent with *Latif and Barnett*'s [1994] theory that the midlatitude decadal oscillation is maintained by such delayed response of ocean circulation.

5. Summary

[16] This study shows that ocean geostrophic advection, in addition to surface heat flux and entrainment, is an important cause of the abrupt warming in the north central Pacific between 1997 and 1999. The geostrophic warming is contributed mostly by the zonal and vertical components. The significance of the zonal and vertical advection implies that ocean dynamics play a crucial role in the warming. To the extent that this event is part of a decadal variability, our finding differs from past studies where atmospheric processes, namely surface heat flux and meridional Ekman advection, drive decadal variability in the north central Pacific. To fully account for these advective processes and entrainment, it is necessary to analyze the ocean temperature budget down to the bottom of the mixed layer rather than a fixed-depth slab layer or a surface layer.

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