LARGE-SCALE VERSUS EDDY EFFECTS CONTROLLING THE INTERANNUAL VARIATION OF MIXED LAYER TEMPERATURE OVER THE NINO3 REGION

Seung-Bum Kim*, Tong Lee**, and Ichiro Fukumori**

*Remote Sensing Systems, USA, kim@remss.com
**Jet Propulsion Lab/California Institute Technology, USA

ABSTRACT: Processes controlling the interannual variation of mixed layer temperature (MLT) averaged over the NINO3 domain (150-90°W, 5°N-5°S) are studied using an ocean data assimilation product that covers the period of 1993 to 2003. Advective tendencies are estimated here as the temperature fluxes through the domain's boundaries, with the boundary temperature referenced to the domain-averaged temperature to remove the dependence on temperature scale. The overall balance is such that surface heat flux opposes the MLT change but horizontal advection and subsurface processes assist the change. The zonal advective tendency is caused primarily by large-scale advection of warm-pool water through the western boundary of the domain. The meridional advective tendency is contributed mostly by Ekman current advecting large-scale temperature anomalies though the southern boundary of the domain. Unlike many previous studies, we explicitly evaluate the subsurface processes that consist of vertical mixing and entrainment. In particular, a rigorous method to estimate entrainment allows an exact budget closure. The vertical mixing across the mixed layer (ML) base has a contribution in phase with the MLT change. The entrainment tendency due to temporal change in ML depth is negligible comparing to other subsurface processes. The entrainment tendency by vertical advection across the ML base is dominated by large-scale changes in wind-driven upwelling and temperature of upwelling water. Tropical instability waves (TIWs) result in smaller-scale vertical advection that warms the domain during La Niña cooling events. When the advective tendencies are evaluated by spatially averaging the conventional local advective tendencies of temperature, the apparent effects of currents with spatial scales smaller than the domain (such as TIWs) become very important as they redistribute heat within the NINO3 domain. However, such internal redistribution of heat does not represent external processes that control the domain-averaged MLT.

KEY WORDS: ENSO, climate variability, mixed layer, heat budget.

1. INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is a major mode of interannual climate variability in the tropical Pacific that has worldwide climatic and socio-economic impact. El Niño and La Niña are the oceanic components of ENSO. The oceanic mixed layer (ML) plays a critical role in the evolution of these events. The mechanism of the mixed layer temperature (MLT) variation is very complicated. The present study examines processes governing the interannual variation of MLT in the eastern equatorial Pacific.

The interannual MLT balance at several Tropical Atmosphere-Ocean (TAO) mooring locations has been examined by Wang and McPhaden (2001, hereafter WM01). These studies concern local heat budgets at a few equatorial mooring locations as opposed to a balance over the larger equatorial domain pertinent to ENSO. The anomalous warming associated with El Niño/La Niña events typically spans thousands of kilometers zonally and hundreds of kilometers meridionally on both sides of the equator. Because of smaller-scale processes such as tropical instability waves (TIW), it is by no means clear that local MLT balance is representative of the balance for large-scale heat content (or averaged temperature) of the eastern equatorial Pacific.

In this paper we study the processes controlling the MLT in the NINO3 region by directly evaluating zonal, meridional, and vertical advective contributions for the mixed layer. We adopt two newly-developed methods to facilitate the study, namely the evaluation of the external advection of heat using the *modified boundary-flux* form (Lee *et al.* 2004) and a scheme to formally close the MLT budget (Kim *et al.* 2006). Our analysis is performed for the period of 1993-2003 that encompasses three El Niño/La Niña events (1994-95, 1997-99, and 2002-03). By analyzing the three events we examine how advective tendencies generally contribute to the MLT balance.

2. OCEAN GCM PRODUCTS

The analysis fields and temperature budget output used for this investigation are obtained from a data assimilation product of ECCO (Estimating the Circulation and Climate of the Ocean, http://www.ecco-group.org). The model used is the parallel version of the primitive-equation Massachusetts Institute of Technology (MIT) Ocean GCM. The spatial domain is nearly global (80°S–80°N). Horizontal grid spacing is 1° globally except within 20° of the equator, in which meridional grid spacing is gradually reduced to 0.3° within 10° of the equator. There are 46 vertical levels with layer thickness of 10m in the upper 150m and 21 layers above 300m. The model employs two advanced mixing schemes: the K-profile parameterization vertical mixing (KPP) and the Gent-McWilliams isopycnal mixing (GM). The model is forced by National Centers for Environmental Prediction (NCEP) reanalysis products (12-hourly wind stress, daily heat and freshwater air-sea fluxes) with the time-means replaced by those of the Comprehensive Ocean-Atmosphere Data Set fluxes. In addition to this imposed heat flux, model sea surface temperature (SST) is relaxed to NCEP's SST analysis with a time scale of 1-2 months. The model was first spun up for 10 years from rest using climatological temperature and salinity 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 of subsurface temperature obtained from the TOPEX/Poseidon (T/P) altimeter and the Global Telecommunication System (GTS), respectively. The resultant analysis fields are consistent with the physics of the GCM such that the property budgets (heat, salt, and momentum) are closed.

The ML is determined diagnostically from the GCM output fields such that the density at the ML depth is larger than that at 5m (model's surface level) by 0.125 kg m^{-3}. The density offset corresponds to a 0.5K temperature difference between sea surface and ML base at 35p.s.u. and 20°C, which is a commonly-used criterion for the ML in the tropics (*e.g.*, Hayes *et al.* 1991; WM01). The isothermal layer depths derived from expendable bathythermograph (XBT) observations and the model compare reasonably well with each other (Fig. 1a), demonstrating the fidelity of the model estimates. On average, the model's isothermal layer depth is too shallow by 6m. This may be due to the mixing coefficient in the model being too small. The smaller range of temporal variability may also be due to an underestimate in the variability in wind. The most noticeable change in the ML depth is the shoaling during the La Niña in 1998 (Fig. 1b).

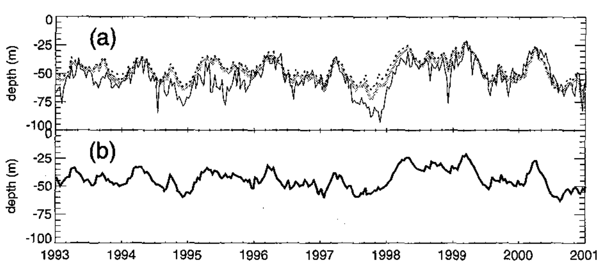

Fig. 1. (a) Comparison of the model isothermal layer depth (ILD, thick grey) over the NINO3 area with XBT ILD (thin black) at the locations where XBTs are available. The model's mixed layer depth (MLD) is shown in black dots. The ILD (MLD) is determined such that the temperature (density) at the layer base is lower (larger) than the 5-m value by 0.5K ($0.125\sigma_\theta$). (b) Domain-mean MLD from the model with even spatial sampling. All the depths are given every 10days.

3. MIXED LAYER HEAT BALANCE MECHANISM

The equation describing the balance of the spatially-averaged MLT change can be given as (Kim *et al.* 2006):

$$\frac{d\langle T\rangle}{dt}=\left\langle \frac{1}{\rho C_p}\frac{\partial q}{\partial z}\right\rangle+\langle\nabla_z(\kappa\nabla_z T)\rangle_{z=0}-\{u_\perp(T-T_r)\}_{ML}$$
$$+subsurface+\langle ML\ mixing\rangle$$
$$subsurface=\left\langle \Delta T\frac{\partial h}{\partial t}\right\rangle-\{u_\perp(T-T_r)\}_{induct}-\{w(T-T_r)\}+\langle\nabla_z(\kappa\nabla_z T)\rangle_{z=-h}$$
$$\Delta T=\langle T\rangle-T_{-h}$$

where the angled bracket represents the volume-weighted average over the NINO3 ML and the brace indicates an integral over ML boundary surfaces after dividing by ML volume. Variables T, h, ρ, and κ are temperature, ML depth, density, and vertical diffusivity, respectively. q is penetrative solar flux, and C_p is specific heat of sea water. $u_\perp$ and w are the velocities normal to ML boundaries in horizontal and vertical directions, respectively, and $\nabla_z=\partial/\partial z$. ΔT is the temperature difference between ML water and entrained water. The subscript r denotes a reference. Specifically, $T_r \equiv \langle T\rangle$ and is the volume-averaged MLT over the NINO3 region at time t that permits assessing advective contributions from independent directions (Lee *et al.* 2004). The advective tendencies formulated above is called the *modified boundary-flux* form (Lee *et al.* 2004). The subscripts *ML* and *induct* denote respectively the advective tendencies across lateral boundaries within the ML and between the ML and the thermocline (lateral induction).

The components of the rhs of Eq. 1a define the tendencies by surface heat flux, advection by horizontal currents, subsurface processes, and *ML mixing*, respectively. The subsurface processes are divided into entrainment heat advection and vertical mixing (Eq. 1b). The entrainment heat advection consists of temporal ML depth variation ($\Delta T\partial h/\partial t$), lateral induction, and vertical advection ($-\{w(T-T_r)\}$). The vertical mixing, $\langle\nabla_z(\kappa\nabla_z T)\rangle$, may be expanded as $\iint(\kappa\nabla_z T(z=0) - \kappa\nabla_z T(z=-h))dxdy/V$ with V denoting the ML volume. The first term is the surface boundary condition and is the sum of outgoing longwave, sensible and latent heat fluxes ($\langle\nabla_z(\kappa\nabla_z T)\rangle_{z=0}$). The second term is the vertical mixing at the ML base ($\langle\nabla_z(\kappa\nabla_z T)\rangle_{z=-h}$).

Surface heat flux cools the ocean during the three El Niños (late 1994, 1997-98, and 2002, Fig. 2a). The opposite happens during the La Niña events. This damping effect of surface heat flux is consistent with the finding of WM01. The GM mixing, which includes horizontal mixing, and the KPP nonlocal mixing are relatively small (Fig. 2a; these two terms are shown together as *ML mixing*).

The warming and cooling by zonal advection during the El Niños and La Niñas (Fig. 2b), respectively, agree with conventional understanding, *i.e.*, eastward intrusion of warm-pool water during an El Niño and westward retreat during a La Niña (Picaut *et al.* 1997). The zonal advection contributes about a 3K warming during the 1997-98 El Niño to the MLT balance. Its magnitude is comparable to the total MLT change during the event. Thus the zonal advection is one of the important factors of the NINO3 MLT changes. The meridional advective tendency is also in phase with the MLT tendency.

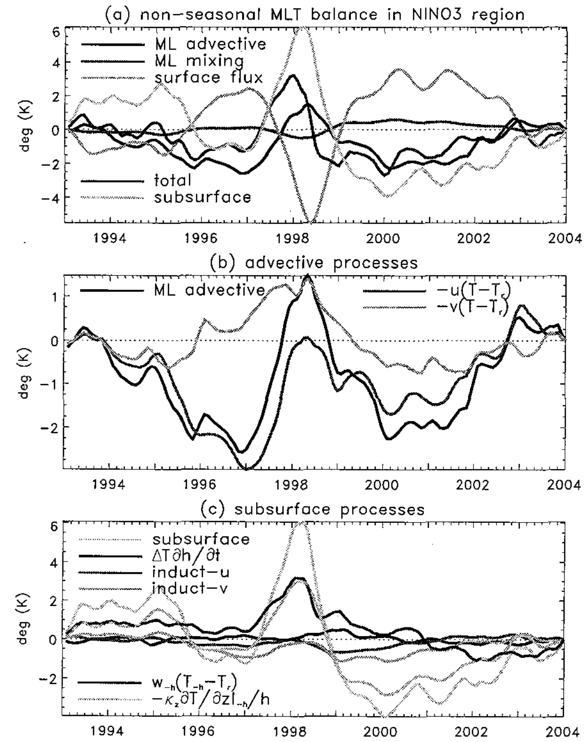

Fig. 2. Non-seasonal MLT balance over the NINO3 area: (a) overall balance, (b) advective processes within a ML, and (c) subsurface processes. Each curve is a time-integral of the component of the non-seasonal MLT tendency, defined in Eq. 1. The advective tendencies are computed using the modified boundary-flux form. See Eq. 1 for notations. The time series are smoothed with 3-point (90 days) running mean.

We now discuss subsurface processes (Fig. 2c). Vertical advective tendency through the ML base, $w_{-h}(T_{-h}-T_r)$, has the same phase as the MLT variations. Analyzing the 1997-99 El Niño/La Niña, both interannual changes in wind-driven upwelling rate (w_{-h}) and temperature difference across the ML base ($T_{-h}-T_r$) contribute to the vertical advective tendency. During the El Niño, the upwelling weakens in response to waning trade wind, and depressed thermocline raises the temperature of upwelling thermocline water (T_{-h}) more than the rise of the domain mean temperature (T_r). The opposite happens during the La Niñas. Vertical mixing produces warming tendency during the El Niños, and vice versa during the La Niñas. As the thermocline deepens in the cold tongue region during the El Niños, the vertical temperature gradient decreases, and the vertical mixing at the ML base, -$\kappa\partial T/\partial z|_{z=-h}/h$, produces an anomalous warming. Generally the vertical mixing tendency has the same phase as the MLT tendency (Fig. 2c).

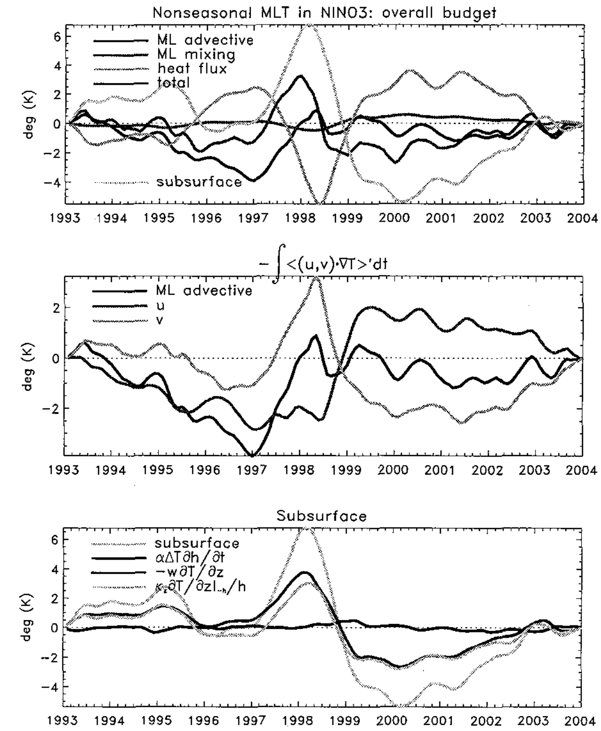

Fig. 3. The same as Fig. 2 except that the advective tendencies are determined using the local-advection form ($(u,v,w)\bullet\nabla T$).

Let us compare the local-advective tendency with the modified boundary-flux tendency for the 1997-99 El Niño/La Niña, to examine if the former can represent the external heat source/sink represented by the latter. Spatial average of local zonal advective tendency does not describe the warming process caused by the eastward advection of warm-pool water towards the cold-tongue region during the 1997 El Niño and vice versa during the La Niña. The failure arises because the local advection quantifies the internal redistribution of heat by eddies (Fig. 4; Lee *et al.* 2004). In the meridional direction, local advective tendency varies by about 5K during the 1997-99 El Niño/La Niña (Fig. 3b, solid green curve), significantly larger than the external contribution of about 2K (Fig. 2b). Local vertical advective tendency contributes to the MLT change by about 6K during the 1997-99 El Niño/La Niña (Fig. 3c), which is larger than about 3K contribution by the external vertical heat exchange (Fig. 2c). The difference arises most notably because the local advection lacks the 4K external warming effect by the eddies during the La Niña.

The comparison of the advective tendencies between local-advection and modified boundary-flux methods indicates that, for all three directions, the spatial average of the local temperature advection cannot be interpreted as external processes that control the temporal change of the NINO3 MLT. The comparison also suggests that currents with scales smaller than the NINO3 domain such as the eddies and the low-frequency sub-domain-scale currents are very important in redistributing heat within the NINO3 domain. Yet such internal redistribution is not very helpful in understanding the interannual variation of the NINO3 volume-mean MLT. Our finding with regard to the difference between the modified boundary-flux and the local-advection approaches has implications not only to the NINO3 region, but to many other areas as well (*e.g.*, mid-latitude regions that have eddies within).

Our findings about the advective mechanism of the NINO3 MLT balance differ from Vialard *et al.* (2001). They concluded that surface heat flux, subsurface processes, and eddies (TIWs) are three major terms controlling interannual changes in spatial-mean MLT (their Fig. 11d). Although our local balance analysis would have led to a similar conclusion (our Fig. 3), our boundary-flux approach has shown that surface heat flux, subsurface processes, and large-scale horizontal advection are the main contributors (Fig. 2a). TIWs significantly influence only the vertical advective contribution to the MLT change, yet they are secondary to the effect of the large-scale upwelling.

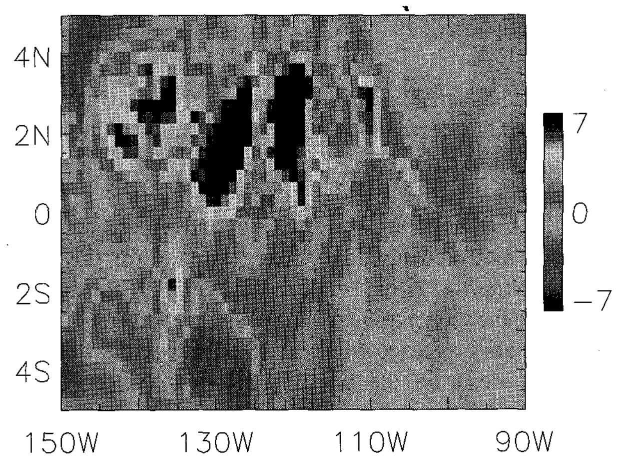

Fig. 4. Simulated zonal advective tendency evaluated with the local-advection form ($-u\partial T/\partial x$) in December 1998, after depth-averaging within a ML. Units in degrees K/month.

4. CONCLUSIONS

Processes controlling the interannual variation of mixed layer temperature (MLT) averaged over the NINO3 domain (150-90°W, 5°N-5°S) are studied using an ocean data assimilation product that covers the period of 1993 to 2003. All the balance terms are important in the MLT budget except the entrainment due to lateral induction and temporal variation in ML depth. All three advective tendencies are caused primarily by large-scale and low-frequency processes, and they assist the NINO3 MLT change. When the advective tendencies are evaluated by spatially averaging the conventional local advective tendencies of temperature, the apparent effects of currents with spatial scales smaller than the domain (such as TIWs) become very important as they redistribute heat within the NINO3 domain. As a result, for example, the averaged zonal advective tendency counteracts rather than assists the NINO3 MLT change. However, such internal redistribution of heat does not represent external processes that control the domain-averaged MLT.

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