A new approach to improved SST anomaly simulations using altimeter data: Parameterizing entrainment temperature from sea level

Rong-Hua Zhang, Antonio J. Busalacchi, Raghuram G. Murtugudde, Eric C. Hackert, and Joaquim Ballabrera-Poy

Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park, Maryland, USA

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[1] Observed Topex/Poseidon/Jason-1 (T/P/J) altimeter sea level (SL) data are used to improve an empirical parameterization of the temperature of subsurface water entrained into the mixed layer (T_e). An inverse modeling method is first adopted to estimate T_e from a SST anomaly (SSTA) equation using observed SST and simulated upper ocean currents from an intermediate ocean model (IOM). An empirical relationship between anomalies of T_e (estimated) and SL (observed) from T/P/J altimeter is then constructed by utilizing a singular value decomposition (SVD) of their covariance. As compared with SSTA simulations using modeled SL data, the use of T/P/J SL data allows observed information about dynamic ocean adjustments to be built directly into the empirical T_e model being used to parameterize the thermocline effect on SSTAs. The improved T_e model leads to better SSTA simulations in the tropical Pacific. Cross validation is made to examine the sensitivity of the SSTA simulations to the period chosen for training the T_e model. The proposed approach provides a new way to more effectively use T/P/J altimeter data in climate studies. *INDEX TERMS:* 4522 Oceanography: Physical: El Niño; 4215 Oceanography: General: Climate and interannual variability (3309); 4504 Oceanography: Physical: Air/sea interactions (0312); 9355 Information Related to Geographic Region: Pacific Ocean; 4231 Oceanography: General: Equatorial oceanography. **Citation:** Zhang, R.-H., A. J. Busalacchi, R. G. Murtugudde, E. C. Hackert, and J. Ballabrera-Poy (2004), A new approach to improved SST anomaly simulations using altimeter data: Parameterizing entrainment temperature from sea level, *Geophys. Res. Lett.*, *31*, L10304, doi:10.1029/2003GL019237.

1. Introduction

[2] Simulations of SST anomalies (SSTAs) in the equatorial Pacific Ocean still remain a problem area for climate studies, with relatively large systematic errors in various ocean models [e.g., *Chen et al.*, 2000; *Latif et al.*, 2001]. It has been known that subsurface processes (e.g., entrainment and mixing) are very important in controlling interannual SST variability in the equatorial Pacific [e.g., *Zebiak and Cane*, 1987; ZC87 hereafter; *Wang and McPhaden*, 2000]; their realistic parameterizations, therefore, are crucial to the SSTA simulations in ocean models. As such, an empirical procedure has been developed to parameterize T_e for better SSTA simulations [*Zhang et al.*, 2003]. This has been successfully tested in an intermediate ocean model (IOM), developed by *Keenlyside and Kleeman* [2002], KK02 hereafter. The model was found to simulate well the interannual SST variability, particularly in the central equatorial Pacific.

[3] Previously, sea level (SL) anomalies were taken from a model simulation forced by observed atmospheric winds and used to construct the empirical T_e model [*Zhang et al.*, 2003]. The model SL obviously has systematic errors which can distort the T_e model and further degrade SSTA simulations. The advance of space-based observations [e.g., *Busalacchi*, 1997] provides an unprecedented basin-wide coverage of data over the ocean. In particular, SL data from satellite observations have considerable potential in data assimilation schemes supporting climate studies [e.g., *Ji et al.*, 2000; *Chen et al.*, 2000]. Here we propose a new way to use T/P/J SL data for improving an empirical parameterization of T_e, the process that significantly affects SST variability in the tropical Pacific and remains a problem area for realistic SSTA simulations in ocean models.

2. Descriptions of an Empirical T_e Model and IOM

[4] The governing equation determining the evolution of interannual SST variability in the surface mixed layer can be written as [e.g., *Keenlyside*, 2001]:

$$\begin{aligned}\frac{\partial T'}{\partial t} =& -u'\frac{\partial \overline{T}}{\partial x} - (\bar{u}+u')\frac{\partial T'}{\partial x} - v'\frac{\partial \overline{T}}{\partial y} - (\bar{v}+v')\frac{\partial T'}{\partial y} \\ & - \{(\overline{w}+w')M(-\overline{w}-w') - \overline{w}M(-\overline{w})\}\frac{(\overline{T}_e - \overline{T})}{H} \\ & - (\overline{w}+w')M(-\overline{w}-w')\frac{(T'_e - T')}{H} - \alpha T' + \frac{\kappa_h}{H}\nabla_h \\ & \cdot (H\nabla_h T') + \frac{2\kappa_v}{H(H+H_2)}(T'_e - T')\end{aligned}$$

Here, T' and T_e' are anomalies of SST and the temperature of subsurface water entrained into the mixed layer; H is the depth of the mixed layer; H_2 is a constant (125 meter); M(x) is the Heaviside function; and other variables are conventional. As expressed, the local rate of SST change (tendency) is controlled by horizontal advection, entrainment (the M(x) terms), anomalous heat flux parameterized as thermal damping since surface heat fluxes are generally a negative feedback on interannual SSTAs [e.g., *Wang and McPhaden*, 2000], horizontal diffusion and vertical mixing, respectively. Note that T_e is associated with two vertical processes: entrainment across the base of the mixed layer and mixing between the surface mixed layer and subsurface layer. The function M(x) accounts for the fact that SSTAs are affected by vertical advection only when subsurface

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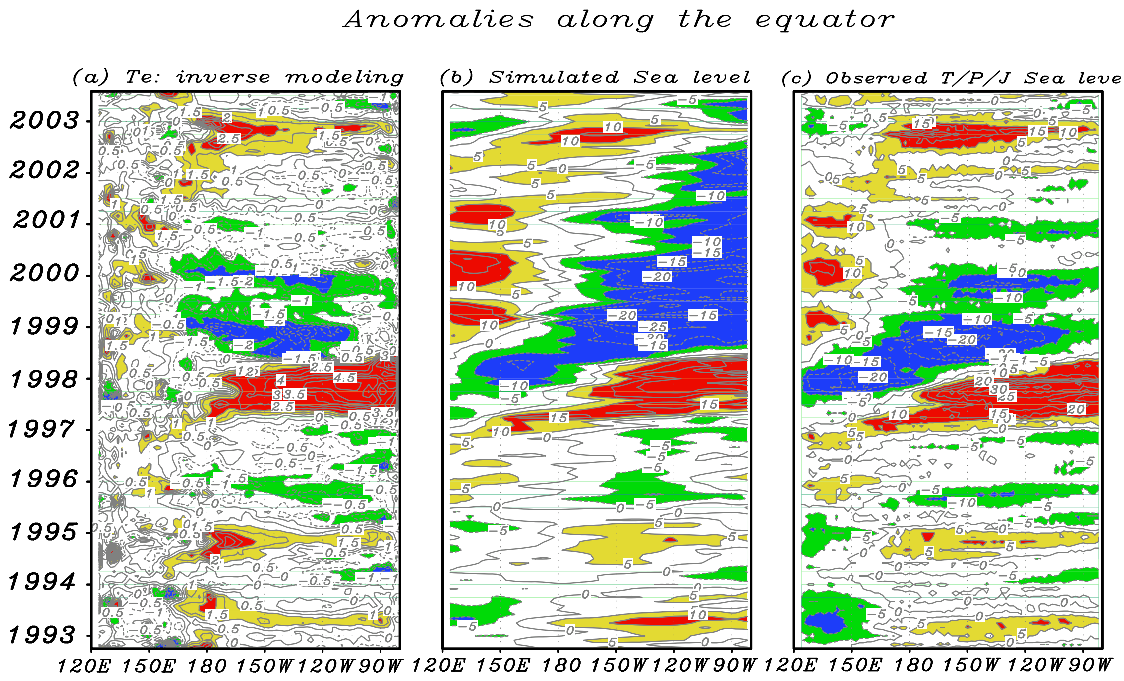

Figure 1. Anomalies along the equator during period Oct. 1992–Sep. 2003 of T_e estimated from the inverse modeling (a), SL simulated from an ocean model (b) and observed from T/P/J altimeter (c). The contour interval 0.5°C in (a), and is 5 cm in (b) and (c).

water is entrained into the mixed layer; but SSTAs can always be influenced by subsurface temperature variability through vertical mixing (the last term).

[5] One crucial component with the SSTA model is the determination of T_e. Since this variable is not precisely defined, *Zhang et al.* [2003] proposed an empirical procedure to parameterize T_e in terms of other variables available from a dynamic ocean model (e.g., sea level). Since the SST tendency on the left side can be estimated from observational data, it is possible to determine T_e anomalies by inverting the SSTA equation from observed and model-produced data. Then, making use of the fact that variations in SL are well correlated with the thermocline displacements which are a major source for subsurface temperature variability over the equatorial Pacific, an empirical relation between T_e and SL anomalies can be developed to parameterize T_e from SL. The SSTA model is embedded into an IOM which is an extension of the *McCreary* [1981] baroclinic modal model to include varying stratification and partial nonlinearity effects [KK02]. The model is able to realistically simulate the mean upper-ocean equatorial circulation and its variability.

3. A SSTA Simulation in the IOM

[6] An integration is carried out to examine the performance of the model's SSTA simulations, forced by the latest FSU wind from January 1978 to September 2003 [*Bourassa et al.*, 2001; see website at http//:www.fsu.edu]. Interannual wind anomalies are calculated relative to its mean climatology from 1974 to 2001. The dynamical ocean model calculates upper ocean current and pressure fields, and SL anomalies.

[7] Using model outputs from the FSU run (mean & anomaly currents) and observed SST [*Reynolds et al.*, 2002], T_e anomalies are estimated by inverting the SSTA equation for the period 1978–2003. Figure 1a illustrates the estimated T_e anomalies along the equator for the period 1992–2003. Although the field is "noisy", particularly in the western Pacific where the variability is weak, large interannual anomalies can be clearly seen in association with El Niño and La Niña events.

[8] Next, a SVD analysis is performed using the model's SL data from the interannual run (Figure 1b) and the T_e anomalies estimated (Figure 1a) for the period October 1992 –September 2003 (a total of 11 years of data). The SVD technique allows the relationship of spatial structure between SL and T_e variability to be constructed, which can be used to parameterize T_e in terms of SL anomalies. With five SVD modes included, this technique can very well reconstruct the original interannual variability of T_e from the model SL anomalies.

[9] Finally, the prescribed climatology of mean currents from the model and thermal fields from observations, and the calculated anomaly fields (currents and T_e) are all passed to the SSTA model to determine its space-time evolution. With this empirical T_e parameterization, SSTA simulations are significantly improved in the tropical Pacific, as compared with those using other local T_e schemes [e.g., ZC87; *Keenlyside*, 2001]. Model performance is evaluated in terms of correlation and root mean square (RMS) error between modeled and observed SSTAs (Figure 2). Correlation values exceeding 0.80 cover a broad region over the central and eastern equatorial Pacific. High correlation regions are also evident in the far western Pacific. However, largest RMS errors are located in the eastern basin and exceed 1.5°C (Figure 2b).

[10] Note that we have utilized the model SL to construct the empirical model to parameterize T_e for use in the SSTA model. Indeed, the ocean dynamical adjustments have a strong influence on interannual SST variability in the

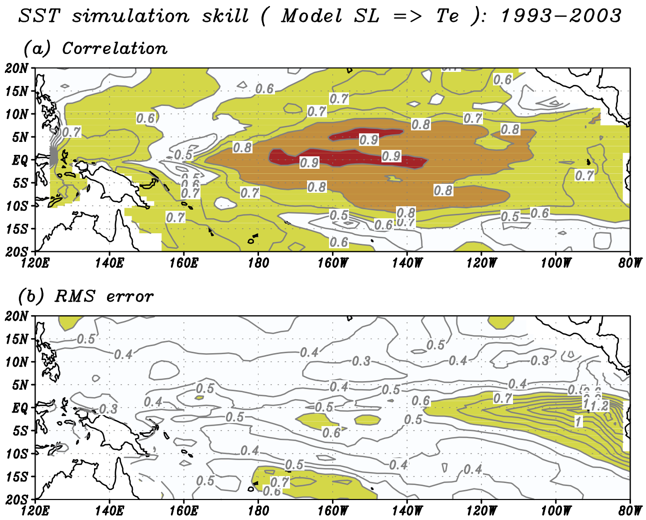

Figure 2. Correlation and RMS error between observed and simulated SSTAs during the period 1993–2003 using the model's SL-based T_e model. The time series at each point have been smoothed by a five-month running mean filter before calculating the statistics. The contour interval is 0.1.

equatorial Pacific and, as expected, variations in SL and SST are well correlated over the equatorial Pacific. This is illustrated in Figure 3a. However, model SL can have systematic errors due to erroneous atmospheric forcing and/or model physics. As compared with SL anomalies from T/P/J altimeter (Figure 1c), errors in the simulated SL (Figure 1b) are clearly evident, such as the anomaly amplitudes particularly in the eastern equatorial Pacific. As a result, the model considerably underestimates the correlation between SST and SL in the eastern equatorial Pacific, as compared with the corresponding correlation between observed SST and SL from T/P/J altimeter

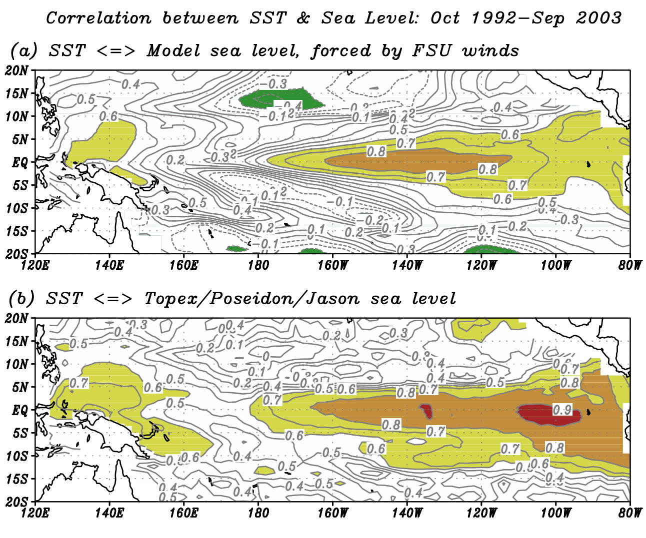

Figure 3. Correlation during the period 1992–2003 between SSTAs observed and SL anomalies simulated from the IOM (a) and observed from T/P/J altimeter (b), respectively. The contour interval is 0.1.

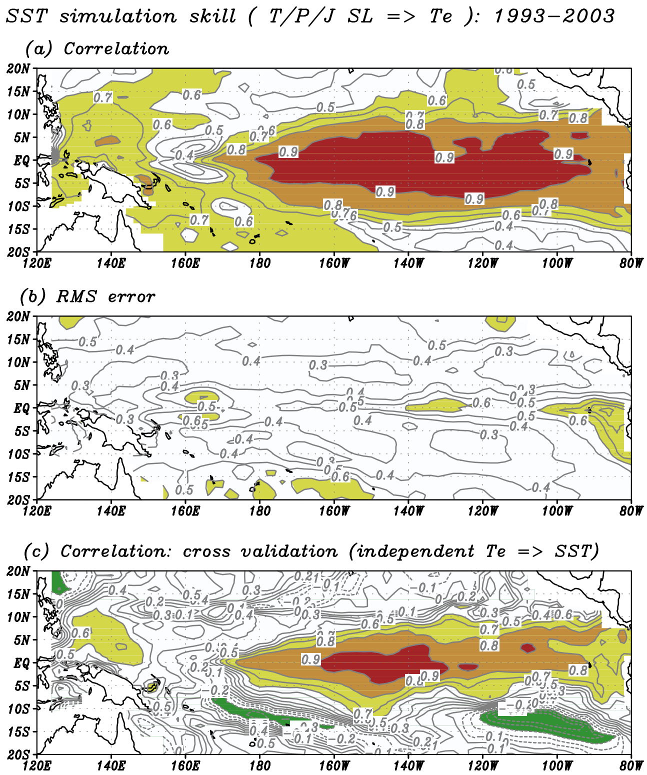

Figure 4. (a)–(b): The same as in Figure 2 but for using the T/P/J SL-based T_e model; (c) the same as in (a) but for a T_e model independently constructed during the period 1993–1998 and 1999–2003, respectively.

(Figure 3b). So the use of model's SL data in constructing the T_e model could potentially distort the T_e -SL relationship and thus degrade the SSTA simulations.

4. An Improved SSTA Simulation Using T/P/J Sea Level Data

[11] Using observed T/P/J SL data can significantly enhance the SL-SST correlation in the eastern equatorial Pacific (Figure 3b). Thus, a SVD analysis is performed between the T/P/J SL data (Figure 1c) and the T_e anomalies estimated (Figure 1a) for the period October 1992–September 2003; the constructed T_e model is then used for SSTA simulations.

[12] The T/P/J altimeter data have made a significant improvement in the SSTA simulations over the equatorial Pacific, with the largest gain in the east. The qualitative assessment is shown in Figures 4a–4b for the anomaly correlation and RMS error for the period 1992–2003. In the SSTA simulations using T/P/J SL-based T_e model, correlation values exceeding 0.80 extend all the way from the central basin to the coastal region of South America (Figure 4a), compared to those using the model SL (Figure 2a). A significant reduction in RMS errors is also noticed in the eastern equatorial Pacific, with the RMS errors all below 1°C in the tropical Pacific (Figure 4b).

[13] Next, we examine if the skill for SSTA simulations is strongly sensitive to the data period selected for constructing the T_e model and for its independent application. The period (1992–2003) is divided into two sub-periods 1992–

1998 and 1999–2003, from which two T_e^{92-98} and T_e^{99-03} models are separately constructed and are then cross-used to simulate SSTAs independently for the two periods (i.e., the T_e^{92-98} model is used for the period 1999–2003 and the T_e^{99-03} model for the period 1992–1998). Correlation between the simulated and observed SSTAs is calculated for the total period 1992–2003 (Figure 4c).

[14] As expected, the correlation values for the independent case (Figure 4c) are lower than those for the dependent case (Figure 4a). This degradation in skill of SSTA simulations most likely reflects the removal of artificial skill inherent to the empirical procedure to construct the T_e model. Nevertheless, the correlation is still quite high, with the values over 0.7 covering a broad area in the central and eastern equatorial basin. In particular, the correlation does not drop significantly over much of the central and eastern equatorial Pacific.

[15] Note that the cross validation experiment we present above is the strictest test of the T_e parameterization scheme possible, and the results obtained during the independent case (Figure 4c) present the worst case in the skill of SSTA simulations. Encouragingly, in the equatorial region, the skill of SSTA simulations using independent SL data from T/P/J altimeter (Figure 4c) is still higher than that using the dependent model's SL data (Figure 2a), and much higher than that using the independent model's SL data (figures not shown). Thus, the observed altimeter SL has clear advantage over model SL for better empirical T_e parameterization to improve SSTA simulations.

5. Conclusions

[16] We propose a new way to use observed T/P/J altimeter SL data for improving SSTA simulations in the equatorial Pacific. This is accomplished by using observed SL data to build an empirical T_e model for better parameterization of subsurface thermal effects, not as input in a data assimilation scheme. This approach is tested and demonstrated in an intermediate ocean model for improved SSTA simulations. The improved SSTA simulations using T/P/J observations are promising for better El Niño simulation and prediction in an intermediate coupled model [*Zhang et al.*, 2003]. Retrospective El Niño predictions and real-time forecasts with this improved T_e model, constrained by T/P/J SL data, will be conducted. Moreover, this approach may also have merit in more comprehensive ocean general circulation models where uncertainties in the parameterization of vertical mixing and entrainment continue to lower SSTA simulation skill.

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J. Ballabrera-Poy, A. J. Busalacchi, E. C. Hackert, R. G. Murtugudde, and R.-H. Zhang, Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park, MD, USA. (rzhang@essic.umd.edu)