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The roles of vertical mixing, solar radiation, and wind stress in a model simulation of the sea surface temperature seasonal cycle in the tropical Pacific Ocean

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Abstract. The climatological seasonal cycle of sea surface temperature (SST) in the tropical Pacific is simulated using a newly developed upper ocean model. The roles of vertical mixing, solar radiation, and wind stress are investigated in a hierarchy of numerical experiments with various combinations of vertical mixing algorithms and surface-forcing products. It is found that the large SST annual cycle in the eastern equatorial Pacific is, to a large extent, controlled by the annually varying mixed layer depth which, in turn, is mainly determined by the competing effects of solar radiation and wind forcing. With the application of our hybrid vertical mixing scheme the model-simulated SST annual cycle is much improved in both amplitude and phase as compared to the case of a constant mixed layer depth. Beside the strong effects on vertical mixing, solar radiation is the primary heating term in the surface layer heat budget, and wind forcing influences SST by driving oceanic advective processes that redistribute heat in the upper ocean. For example, the SST seasonal cycle in the western equatorial Pacific basically follows the semiannual variation of solar heating, and the cycle in the central equatorial region is significantly affected by the zonal advective heat flux associated with the seasonally reversing South Equatorial Current. It has been shown in our experiments that the amount of heat flux modification needed to eliminate the annual mean SST errors in the model is, on average, no larger than the annual mean uncertainties among the various surface flux products used in this study. Whereas a bias correction is needed to account for remaining uncertainties in the annual mean heat flux, this study demonstrates that with proper treatment of mixed layer physics and realistic forcing functions the seasonal variability of SST is capable of being simulated successfully in response to external forcing without relying on a relaxation or damping formulation for the dominant surface heat flux contributions.

1. Introduction

In recent years, climate studies have been focusing on the interannual variability of the coupled tropical ocean and global atmosphere system, especially the El Niño–Southern Oscillation (ENSO) phenomenon. Less attention has been paid to the seasonal cycle upon which ENSO is superimposed. Since the seasonal cycle is itself a large signal and ENSO is apparently phase locked to it, improved knowledge of the processes that determine the characteristics of the seasonal cycle is essential to our ability to understand and eventually predict short-term climate change. Although a class of coupled models has been very successful at predicting the onset of ENSO events by specifying the mean seasonal cycle of sea surface temperature (SST) [e.g., *Zebiak and Cane*, 1987], future refinements to coupled models may require an internally evolving seasonal SST variability that is free of climate drift and with realistic phase and amplitude. In this study we attempt to simulate the SST seasonal cycle in the tropical Pacific Ocean using a newly developed upper ocean model and try to identify the important processes that are responsible for the seasonal variability.

Plate 1 shows the *Levitus* [1982] climatological SST for the tropical Pacific Ocean. The top panel is the annual mean, the middle panel is the standard deviation of the monthly mean from the annual mean, and the bottom panel is the seasonal variation of the monthly mean anomalies averaged from 5°S to 5°N. The annual mean SST is characterized by a vast warm pool in the west, a cold tongue in the east, and a warm spot off the coast of Mexico. The standard deviation is small in the warm pool but rather large in the cold tongue with a maximum off the coast of South America. Similarly, the equatorial seasonal cycle has large zonal variations with a weak semiannual cycle in the west, a strong annual cycle in

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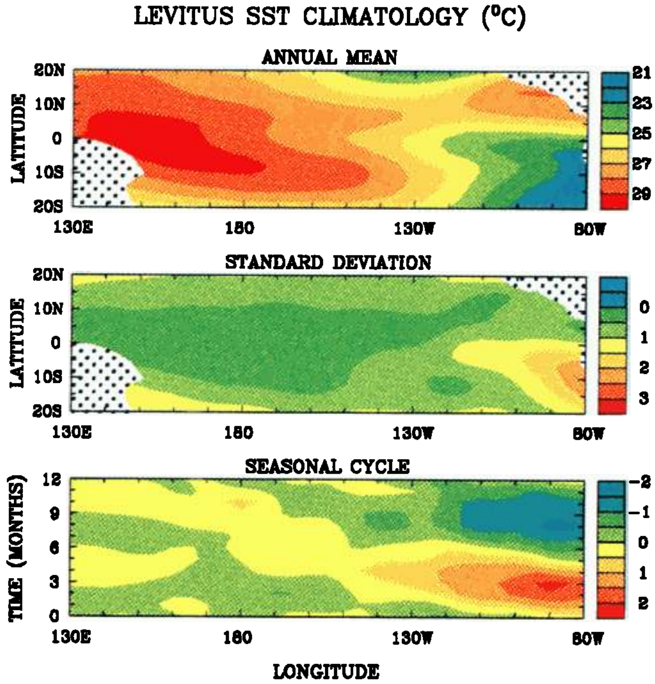

Plate 1. Levitus sea surface temperature (SST) climatology for the tropical Pacific, (top) annual mean, (middle) standard deviation, and (bottom) time–longitude contours of SST anomaly averaged from 5°S to 5°N. Contour intervals are 1°C in top panel and 0.5°C in the other two panels.

the east, and a westward phase propagation in between. It has been recognized that the semiannual cycle of SST in the western equatorial Pacific basically follows the seasonal migration of the sun, while the large SST annual cycle in the eastern equatorial Pacific is strongly tied to the dynamic processes in the upper ocean [e.g., *Gordon and Corry*, 1991].

Present tropical ocean models, ranging from the simple reduced gravity models [e.g., *Busalacchi and O'Brien*, 1980] to the more sophisticated general circulation models (GCMs) [e.g., *Philander et al.*, 1987], are capable of simulating the wind-driven seasonal variations of the equatorial thermocline and surface currents, but there remains difficulty in reproducing the externally forced seasonal cycle of SST. The early reduced gravity models did not, of course, contain active thermodynamics and thus related SST variations to thermocline fluctuations. This certainly is an oversimplification because the changes of SST are not necessarily associated with those of thermocline depth on seasonal timescales. Even in regions such as the eastern tropical Pacific, where the thermocline is close to the surface, the SST variability is influenced in a nonlinear manner by the contrasting response of mixed-layer temperatures during entrainment versus detrainment episodes. The GCMs, with explicit treatment of thermodynamics, have also had difficulty in simulating the SST seasonal cycle satisfactorily without relaxing the model SST back to climatology or imposing air temperature and humidity in heat flux parameterizations. For example, *Giese and Cayan* [1993] have shown that the SST seasonal cycle in the equatorial Pacific predicted by their GCM is not even close to that observed if air temperature is not specified in the latent heat flux formula.

Since, in reality, air temperature and humidity closely follow SST and not the other way around, specifying these quantities in heat flux parameterization is tantamount to a priori imposing the desired SST [*Seager et al.*, 1988] and implies that the atmosphere has an infinite heat capacity. In order to relax this constraint, *Seager et al.* [1988] introduced a modified heat flux formulation which did not have to specify air temperature and humidity as atmospheric inputs. Their ocean model was a reduced gravity model with the addition of a constant depth mixed layer in which a temperature equation was formed. The model SST was very sensitive to the special treatment of the entrainment at the base of the mixed layer. This model was able to simulate the general features of the tropical Pacific SST variability, but the seasonal cycle was phase lagged as compared to observations. *Seager and Blumenthal* [1994] further improved the model by using satellite-derived solar radiative forcing, but the problem with the seasonal cycle remained. It is likely that this model is too simple to handle mixed layer variability because of the fixed mixed layer depth and the assumed relation between the temperature of entrained water and the depth of the thermocline.

Generally speaking, there are two possible causes for the poor simulations of the SST seasonal cycle in the present tropical ocean models, inaccurate model forcing and incomplete model physics. Because of the sparsity of observational data, inaccurate atmospheric forcing has always been a problem for large-scale ocean models and is a favored excuse for poor model performance. Uncertainties in the forcing data are sometimes so large that the differences between model results and observations can be explained away by errors in the forcing. This led *Blumenthal and Cane* [1989] to conclude that in the tropical Pacific it is impossible to identify model deficiencies unambiguously, and further advances in SST simulation have to await improved forcing data. Recently some satellite-derived products of wind stress and solar radiation have become available, and these products have relatively dense space–time coverage as compared with conventional data sets. These new satellite-derived forcing data should impact our ability to simulate SST.

The main challenge faced by modelers, however, is to improve model physics so that important physical processes are not missing or mistreated in their models. Several previous studies have attempted to determine the physical processes that dominate the surface layer heat balance in the eastern equatorial Pacific, where the SST seasonal cycle is largest. For example, *Wyrtki* [1981] suggested a balance among surface heat flux, zonal advection, and upwelling; *Enfield* [1986] identified upwelling and associated meridional advection as dominant terms in the heat budget; *Philander et al.* [1987] emphasized the importance of zonal advection by attributing the spring warming of SST to the warm surge from the west; and *Seager et al.* [1988] explained the SST seasonal cycle mainly in terms of the variations of upwelling and thermocline depth associated with zonal wind fluctuations. Because of the lack of observational data and the inadequacy of ocean models, the role of vertical turbulent mixing in influencing the SST seasonal cycle has barely been investigated. This is arguably an important gap to fill, and there is still room for improvement in vertical mixing parameterization.

Here we take up the tasks of improving model physics by introducing a new hybrid vertical mixing scheme and of evaluating the impact of uncertainties in atmospheric forcing by driving the model with several different products of solar radiation and wind stress, including satellite-derived data sets. Specifically, we seek to answer the following questions: (1) For a given atmospheric forcing, can we improve the SST seasonal cycle simulation in the tropical Pacific by improving the vertical mixing parameterization? (2) If the answer to the first question is yes, then how does vertical mixing affect the SST seasonal cycle? (3) What are the effects of solar radiation and wind stress on SST variability? (4) How sensitive are model SST simulations, including the seasonal cycle and annual mean, to the uncertainties in the surface fluxes? In the next section we briefly describe the model used in this study. The various data sets of solar radiation and wind stress are compared in section 3. Then the model results are presented in section 4, followed by discussion and conclusion in section 5.

2. Model Description

The ocean circulation model used in this study is the three-dimensional, reduced gravity, primitive equation model of *Gent and Cane* [1989], which was specifically designed for the upper tropical ocean. The model allows for a stretched horizontal grid and uses the Lorenz N cycle scheme for time integration and the order 8 Shapiro filter for horizontal smoothing. A novel feature of this model is its flexible vertical coordinate. The model ocean is vertically divided into a specified number of layers. The uppermost layer represents the mixed layer, and the layers below are chosen according to a sigma coordinate. Thus the thicknesses of all the layers are allowed to change, but the ratio of each sigma layer to the total water column below the mixed layer is fixed to its prescribed value. Once the mixed layer depth is predicted (based upon the mixing scheme described below), the thicknesses of the remaining layers are calculated diagnostically. The real advantage of such a vertical coordinate is its computational efficiency. The vertical resolution is fine exactly where it is needed, right below the mixed layer and in the thermocline where shear-produced turbulence is active. This overcomes one of the disadvantages of the level models which need high resolution over the entire range of the mixed layer variation.

One important component of our modified version of the circulation model used here is the hybrid vertical mixing scheme recently developed and implemented by *Chen et al.* [1994]. This scheme incorporates physics of the widely used *Kraus-Turner* [1967] type mixed layer model and the *Price et al.* [1986] dynamical instability model. By combining the advantages of those two models, the hybrid scheme simulates the three major physical processes of oceanic vertical turbulent mixing in a computationally efficient manner. The mixed layer entrainment and detrainment are related to the atmospheric forcing using a bulk mixed layer model; the shear flow instability is accounted for by a partial mixing controlled by the gradient Richardson number; and the free convection in the thermocline is simulated by an instant adjustment. The hybrid scheme has been applied to both one- and three-dimensional ocean models [*Chen et al.*, 1994]. It returns good results both within and below the surface mixed layer, as well as on and off the equator. As compared with some commonly used mixing schemes, the hybrid scheme behaves more reasonably in both idealized experiments and realistic simulations. Equipped with this vertical mixing scheme, the *Gent and Cane* [1989] model becomes quite suitable for the present study. It overcomes two limitations of the *Seager et al.* [1988] model, i.e., the constant mixed layer and the ad hoc assumption on the temperature of entrained water.

Another important model component we should describe here is the formulation of surface heat fluxes. As mentioned earlier, it is not logical to specify air temperature and humidity in heat flux parameterization if SST is to be predicted as an externally forced variable. We adopt the heat flux formulation of *Seager et al.* [1988] which requires only cloud cover and wind speed as atmospheric input. Except in the case where satellite-derived solar radiation is directly given, the downward solar radiation is calculated using *Reed*'s [1977] formula which depends on cloud cover, latitude, and time of year. The latent heat flux is computed using the standard bulk formula with the assumption that the air humidity is a fixed proportion of the saturation humidity evaluated at the model SST. The long wave and sensible fluxes are combined into a simple cooling that is proportional to the model SST. Thus the net surface heat flux Q is

$$Q = (1 - A)(1 - a_c C + a_\theta \theta) Q_0 - \rho_0 C_E L|\mathbf{u}|(1 - \delta) q_s - \alpha(T_s - T^*)$$

where A is the albedo (0.06); C, the cloud cover; θ, the solar altitude; Q_0, the clear sky flux; and q_s, the saturation humidity evaluated at the sea surface temperature T_s. The wind speed $|\mathbf{u}|$ has a minimum value of 4 m/s to account for the effect of high-frequency winds. The adjustable parameters a_c, a_θ, δ, α, and T^* are taken to be 0.75, 0.002, 0.78, 1.667 W/°Cm^2 and −3°C, respectively. These values are close to the optimal estimates of *Blumenthal and Cane* [1989]. The same heat flux formulation was successfully used by *Gent* [1991] in the original *Gent and Cane* [1989] model to study the heat budget in the western tropical Pacific. Instead of the annual mean cloud cover used by Gent, we use seasonally varying cloud data in the solar radiation formula. For most of the experiments described in this paper the solar radiation is allowed to penetrate below the surface in the form $I(z) = \gamma I(0)e^{-z/h_\gamma}$ with $\gamma = 0.33$ and $h_\gamma = 17m$.

The model ocean extends from 120°E to 70°W and from 30°S to 30°N with realistic but simplified land boundaries. The horizontal grid is stretched in such a way that the meridional grid spacing is about 0.3° near the equator and 1° at 20°N and 20°S; the zonal grid spacing is about 0.3° near the eastern and western boundaries and 1° in the middle of the ocean. There are nine layers in the vertical. The first layer is the surface mixed layer with a variable depth predicted by the mixed layer model, and the other eight layers are scaled according to a sigma coordinate with sigma values 0.0286, 0.0429, 0.0714, 0.14, 0.14, 0.14, 0.14, 0.28. Thus relatively high resolution is always achieved right below the mixed layer. The average depth of the modeled upper ocean is about 400 m. For a mixed layer of 50 m the layer right below is 10 m and the deepest layer is 100 m. The model ocean is initially at rest, and the initial temperature fields and layer thicknesses are calculated from the Levitus data with the 10°C isotherm chosen as the model base. The horizontal boundary conditions are no slip and no heat flux. To minimize the artificial effect of the northern and southern boundaries, the model temperature is gradually relaxed back to the

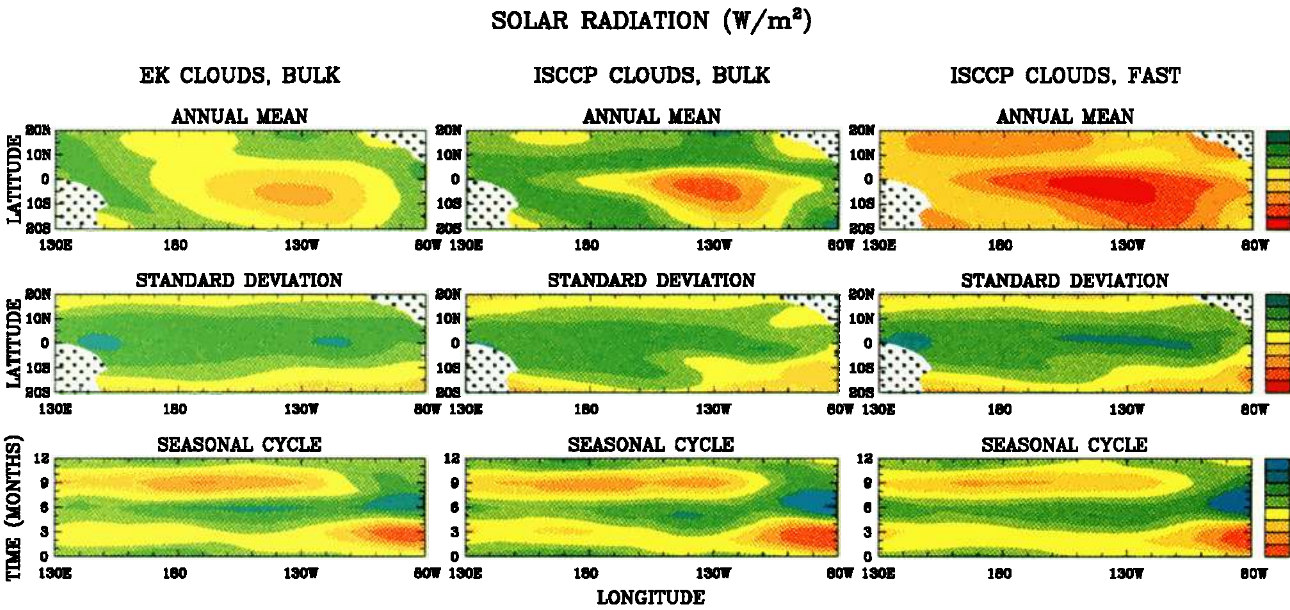

Plate 2. Three products of solar radiation, (left) bulk formula with *Esbensen and Kushnir* [1981] (EK) cloud cover, (middle) bulk formula with International Satellite Cloud Climatology (ISCCP) cloud cover, and (right) ISCCP radiation using FAST scheme. See text for details. Contour intervals are 20 W/m^2 in top panel and 10 W/m^2 in the other two panels.

seasonally varying Levitus climatology within 10° of the northern and southern boundaries.

3. Atmospheric Forcing

Monthly climatological surface heat flux and wind stress are used to force the model since our emphasis in this study is the climatological seasonal cycle rather than interannual variability. For consistency the forcing products are interpolated to a 2° × 2° common grid, although the original data sets have different spatial resolution. Our heat flux formulation is such that the solar radiation is not only a function of latitude and time, but also is strongly dependent on cloud cover; the latent heat flux has a pattern similar to that of wind speed; and the long wave and sensible heat fluxes are proportional to the model SST. Among the four components of the surface heat flux we focus our attention on the downward solar radiation which is the only truly external component. The various products of solar radiation and wind stress used for this study are described in this section.

3.1. Solar Radiation

Three different products of solar radiation were chosen. The first was computed using the bulk formula in our model with the monthly climatological cloud cover from *Esbensen and Kushnir* [1981] (hereinafter referred to as EK). The second was obtained using the same formula but with the cloud cover fraction from the International Satellite Cloud Climatology Project (ISCCP) [*Rossow and Schiffer*, 1991]. The third was the ISCCP solar radiation calculated using the FAST scheme of *Bishop and Rossow* [1991]. The last two products are not independent of each other since they share the same ISCCP cloud data. The difference is that the latter is a simplified treatment of the radiative transfer scheme used to process the ISCCP data that makes use of many other atmospheric parameters, in addition to the cloud cover, in deriving the solar irradiance.

The three products of solar radiation are shown in Plate 2 for the tropical Pacific. As in Plate 1, the plots of annual mean, standard deviation, and equatorial seasonal cycle are used. The annual mean fields of the three products have similar patterns with a maximum to the south of the equator, but the details and magnitudes are quite different. The solar radiation using EK clouds is much smoother than that using ISCCP clouds, and the ISCCP radiation with FAST scheme is, on average, 40–60 W/m^2 greater than the other two products. This latter difference is much larger than the errors of the ISCCP radiation claimed by *Bishop and Rossow* [1991]. The three standard deviation maps are rather similar, with a minimum along the equator and a gradual poleward increase, although, again, the EK radiation has less small-scale structure. The equatorial seasonal cycle of solar radiation anomaly is characterized by a prominent semiannual signal in all three cases because the sun crosses the equator twice a year. However, in the far eastern part of the ocean the seasonal variations are much stronger than elsewhere and the maximum in September disappears. This is because there is an annual cycle in the cloud cover in that region.

It is worth noting that the temporally varying cloud fraction has a very significant effect on the surface irradiance. Without the modulating effects of clouds the annual mean radiation would be symmetric about the equator, the equatorial seasonal cycle would be semiannual everywhere, and there would be no zonal variations in both the mean and the seasonal cycle. Therefore it is not realistic to treat solar radiation only as a function of latitude [e.g., *Philander et al.*, 1987] or to use a time-independent cloud cover in the formula of solar radiation [e.g., *Gent*, 1991]. By comparing

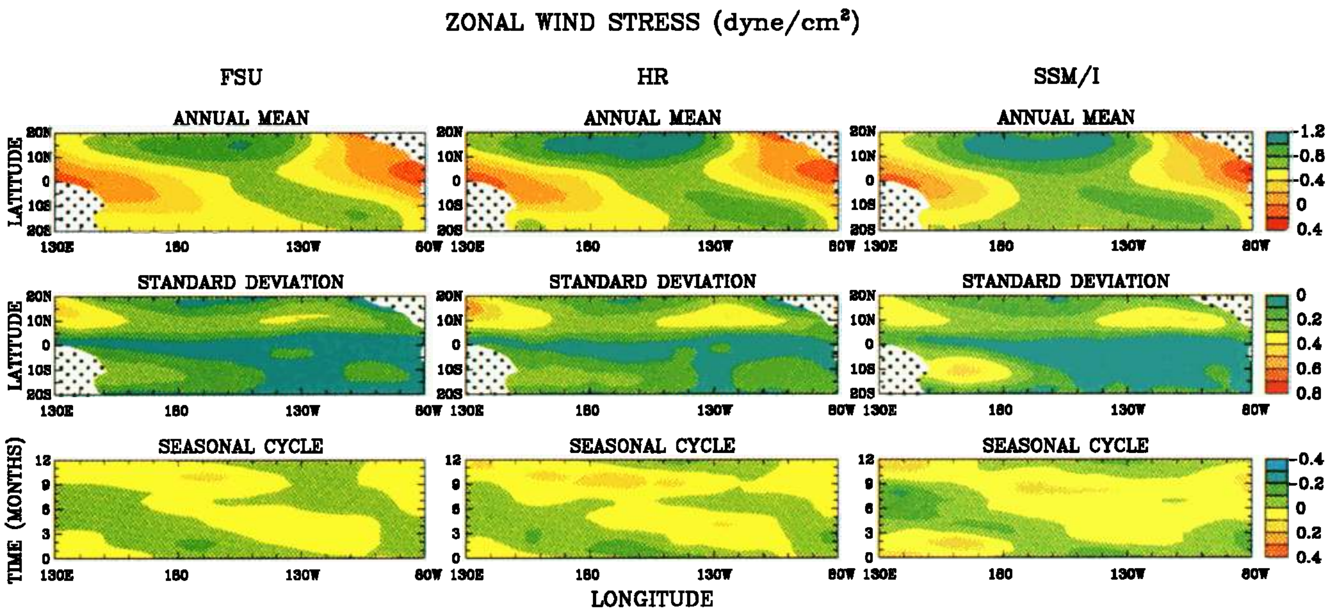

Plate 3. Zonal wind stress from three products, (left) Florida State University (FSU), (middle) *Hellerman and Rosenstein* [1983] (HR), and (right) special sensor microwave imager (SSM/I) based data. Contour intervals are 0.2 dyne/cm^2 in the top panel and 0.1 dyne/cm^2 in the other two panels. See text for details.

the equatorial seasonal cycle of solar radiation to that of the Levitus SST (Plate 1, bottom), one would suspect that the large seasonal variation of radiation in the eastern Pacific might influence the strong SST annual cycle there. Another point worth noting is that the three radiation products have similar seasonal cycles, although their annual mean fields have quite different magnitudes. This implies that the different short wave radiation data sets may produce rather different annual mean SST fields, but they may not differ much from one another in their effect on the SST seasonal cycle.

3.2. Wind Stress

Three different products of wind stress are used in this study. The first is the monthly climatology of the Florida State University (FSU) analysis of shipboard observations [*Goldenberg and O'Brien*, 1981]. The second is the monthly climatological wind stress of *Hellerman and Rosenstein* [1983] (hereinafter referred to as HR). The third is the satellite-derived wind stress based on the special sensor microwave imager (SSM/I) observations of surface wind speed [*Atlas et al.*, 1991]. The SSM/I wind speed is assigned a direction by utilizing a variational analysis that incorporates the wind data from the European Centre for Medium-Range Weather Forecasts as well as conventional ship and buoy observations. The monthly "climatology" of the SSM/I-based wind stress is constructed from 3 years of data (July 1987 to June 1990). A constant drag coefficient of 1.5×10^{-3} and a constant air density of 1.2 kg/m^3 were used in calculating wind stress for all products. No attempt has been made to reconcile their differences by tuning the drag coefficient.

The three wind stress products are shown in Plates 3 (zonal component) and 4 (meridional component). In general, the three products are quite similar in both spatial distribution and temporal variability. The annual mean wind stress is strong under the northeast and southwest trades but weak in the western equatorial Pacific and off the coast of Mexico. The standard deviations have maxima in a zonal band in the northern hemisphere and in two regions in the west separated by the equator, indicating the seasonal excursions of the Intertropical Convergence Zone and the monsoon circulation. The equatorial seasonal variations of the two wind stress components are quite different, although both are dominated by an annual cycle. The seasonal variation of the zonal wind stress is weak and has a westward phase propagation, while that of the meridional wind stress is much stronger and has little phase change along the equator. The major difference among the three wind stress products is that the trade winds are stronger in the HR- and the SSM/I-based products than in the FSU data.

Surface wind stress is the primary driving force for the tropical ocean. It not only sets up the large-scale ocean circulation, but it also plays an important role in the upper ocean thermodynamics. The effect on the surface layer heat budget is threefold. First, wind-driven currents can cause both horizontal and vertical advective heat fluxes, especially in coastal and equatorial regions where cold water can upwell to the surface owing to divergent Ekman transport. Second, the latent heat flux, which is usually a significant component of the surface heat flux, is, to a large extent, controlled by the magnitude of wind. Finally, the vertical turbulent mixing of heat may result from the mechanical stirring by wind and from the shear instability associated with wind-driven currents. Thus the SST seasonal cycle is definitely related to the seasonal variability of winds. The wind stress annual cycle may result in an annual signal in horizontal advection, upwelling, latent heat loss, and vertical mixing. These competing processes, along with the semiannual solar heating, are possible causes for the SST seasonal cycle.

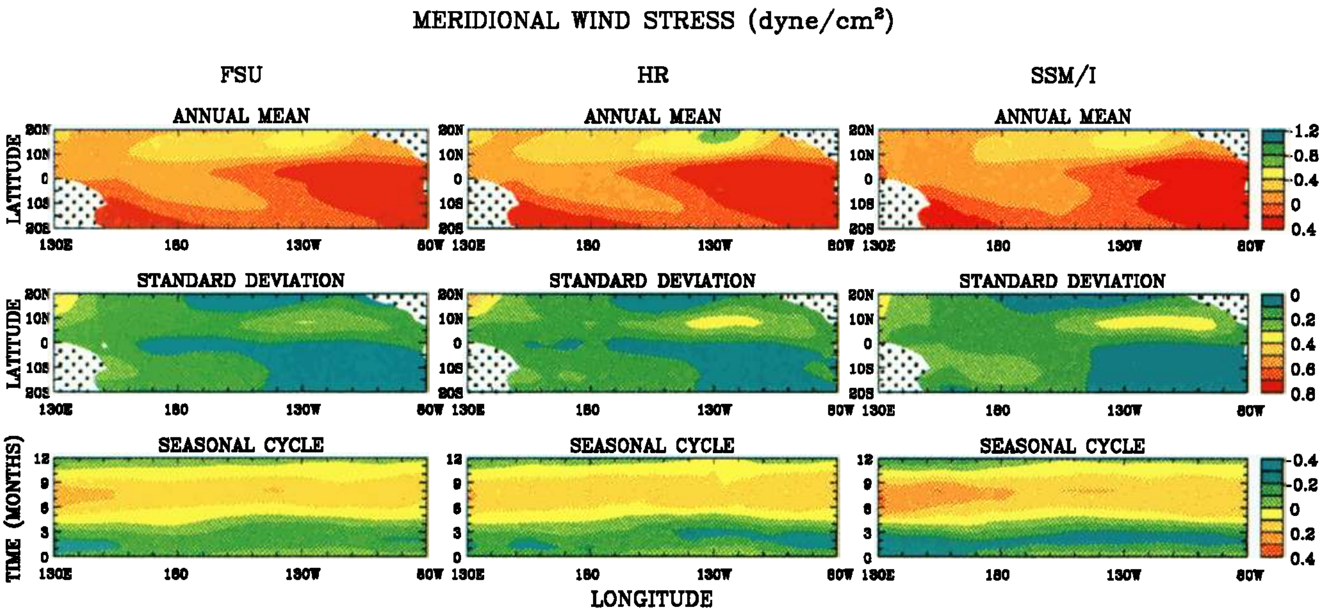

Plate 4. The same as Figure 3, except for meridional component of wind stress.

4. Model Results

A total of eight experiments using various forcing sets and vertical mixing schemes are presented in this section. In each experiment the tropical Pacific model was run for 10 years and a mean "climatological" seasonal cycle was obtained using the last 5 years of model output. Consistent with the Levitus data and the atmospheric forcing data, the model variables were averaged to form monthly mean fields. The SST simulation is our sole focus in this paper; the mixed layer depth and heat budget will be analyzed to aid in interpreting the SST results.

4.1. The Role of Vertical Mixing

Two experiments with different vertical mixing schemes were performed to investigate the role of vertical turbulent mixing in influencing the SST variability. The first adopted the mixing scheme used by *Gent* [1991]; a 50-m constant depth mixed layer plus a simple Richardson number dependent algorithm for interior mixing. The second applied our hybrid vertical mixing scheme which allows a variable mixed layer in both space and time. The FSU wind stress and the solar radiation with the EK cloud cover were used in both experiments.

The SST simulation from the model with constant mixed layer depth is depicted in Plate 5a. The same plot format is used here as in Plate 1, except the top panel is now the difference between the annual mean model and Levitus SST fields. The annual mean model SST is too cold in the central equatorial Pacific and in the west from 10°N to 20°N, while it is too warm from 10°S to 20°S and off the coast of Mexico. Unlike the Levitus data (Plate 1), the model SST does not have large standard deviations in the cold tongue and off the coast of South America. The semiannual cycle of the model SST in the western equatorial Pacific is similar to that observed, but the annual cycle in the eastern equatorial Pacific is much too weak and phase lagged by about 2 months as compared with the Levitus climatology.

Plate 5b shows the model simulated SST when using our hybrid vertical mixing scheme. The annual mean SST errors in this case are quite similar to those in the previous case, although the hybrid scheme helps to reduce slightly the error in the central equatorial region and under the core of the southeast trade winds. However, the SST time variability in this case is considerably different from that in the case with constant mixed layer depth, especially in the east. The hybrid scheme gives rise to an SST annual cycle in the eastern equatorial Pacific that has comparable amplitude and phase to observations. The improved SST annual cycle is also evident in the map of standard deviation which now has relatively large values, though not as large as those in the Levitus data, in the eastern equatorial and coastal regions.

Why is the SST seasonal cycle so sensitive to the vertical mixing parameterization in the eastern equatorial Pacific? This is because there are large seasonal fluctuations in the strength of turbulent mixing in response to the seasonally varying atmospheric forcing, which must be accounted for in order to simulate SST correctly. Plate 6 displays the distribution and variability of the mixed layer depth in the case with the hybrid mixing scheme. The annual mean depths are larger than 80 m under the trade winds but less than 20 m in the cold tongue. In the eastern equatorial Pacific there is a prominent annual cycle of the mixed layer depth in close correspondence with that of SST. In spring the mixed layer depth is shallow owing to weak winds and strong solar radiation, and the SST is warm because the strong heat input is confined to a relatively shallow surface layer. In fall the mixed layer depth is deep owing to strong winds and weak solar radiation and the SST is cool because the weak heat input is now distributed in a rather deep mixed layer. At present there are no reliable observations of the mixed layer depth seasonal variation in the eastern Pacific. A crude estimate of the mixed layer depth from the Levitus climatology does show an annual cycle in this region, in phase with that in the model.

Generally speaking, vertical mixing affects the SST seasonal cycle not only by changing the depth over which the

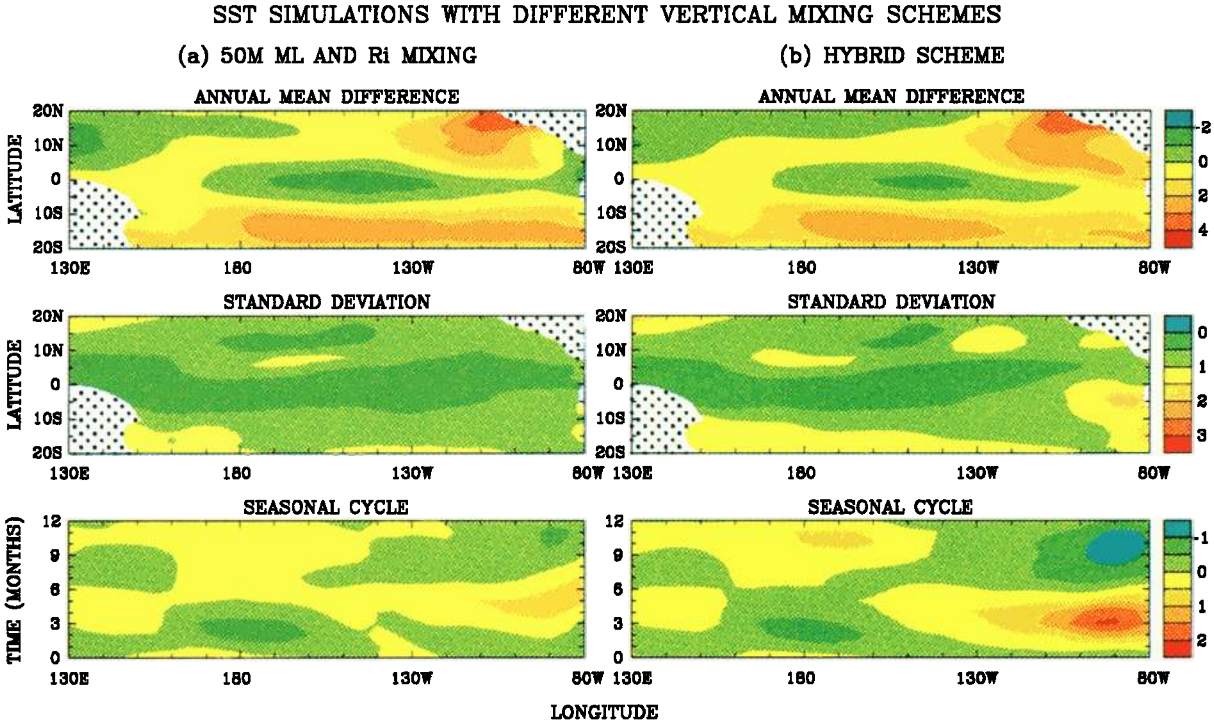

Plate 5. SST simulations with two different vertical mixing schemes, (a) a 50-m mixed layer plus Richardson number dependent mixing [*Gent*, 1991] and (b) the hybrid mixing scheme [*Chen et al.*, 1994]. Top panel shows the annual mean difference between model SST and Levitus climatology; middle panel, the standard deviation; and bottom panel, the seasonal cycle of equatorial SST anomaly. Contour intervals are 1°C in the top panel and 0.5°C in the other two panels.

surface heat flux is distributed, but also through entrainment and diffusion at the base of the surface mixed layer. We will demonstrate later that in the eastern equatorial Pacific, although entrainment and diffusion are significant cooling processes in late spring and early fall when the mixed layer deepens, the most important effect of vertical mixing on the SST seasonal cycle is through the annual variation of the mixed layer depth. Because the hybrid mixing scheme is capable of simulating the mixed layer variability, it is superior to the scheme with a constant depth mixed layer in modeling the SST annual cycle in the eastern equatorial Pacific. In the case with a 50-m mixed layer depth the SST annual cycle actually represents the annual variation of the surface layer heat content which lags the total heat flux variation by 90° and is much less than the mean heat content. In the case with the hybrid scheme, although the heat content still does not change much, a large SST annual cycle results from the mixed layer depth variation which is in phase with the surface forcing and is twice as large as the mean depth.

Thus an important measure of the effect of vertical mixing on the SST seasonal cycle is the relative magnitude of the seasonal mixed layer depth variation to the annual mean depth. In regions where the mean mixed layer depth is relatively large the mixing-produced SST variation is usually small. This explains why the large seasonal variations of the mixed layer depth under the trade winds are not reflected in the SST field. This also partly explains why the semiannual variation of the mixed layer depth in the western equatorial Pacific does not contribute much to the SST variations there. Another reason for the relatively small SST variability in that region is the weaker surface heating as compared with that in the east. It seems likely that the SST seasonal cycle is locally driven in both the western and eastern equatorial Pacific. In the west it follows the semiannual cycle of the sun, and in the east it is controlled by the annual cycle of the mixed layer depth which, in turn, is determined by the combined effect of solar radiation and wind stress.

4.2. The Role of Solar Radiation

Three experiments using the three different products of solar radiative forcing described in section 2 were carried out to assess the effects of solar radiation and its uncertainty on model SST simulations. In all three experiments the vertical turbulent mixing was parameterized using our hybrid mixing scheme and the wind stress forcing was the FSU monthly climatology. The SST simulation from one of these experiments, in which the EK cloud data were used in calculating solar radiation, has already been described in section 4.1. where the role of vertical mixing is emphasized (Plate 5b). The SST simulations from the other two experiments are depicted in Plates 7a and 7b, respectively.

The annual mean SST fields from the three experiments are very different, but the differences are expected; the stronger the mean solar radiation, the warmer the mean SST. The major SST errors found in the case with the EK cloud cover (Plate 5b) still remain in the case with the ISCCP cloud cover (Plate 7a). However, the SST simulation in the latter case is worse in the north, but better in the south and in the central equatorial regions, consistent with the differences in the solar radiation products (see Plate 2). The annual mean SST in the case of the ISCCP radiation using the FAST scheme is much warmer everywhere because the mean solar radiation

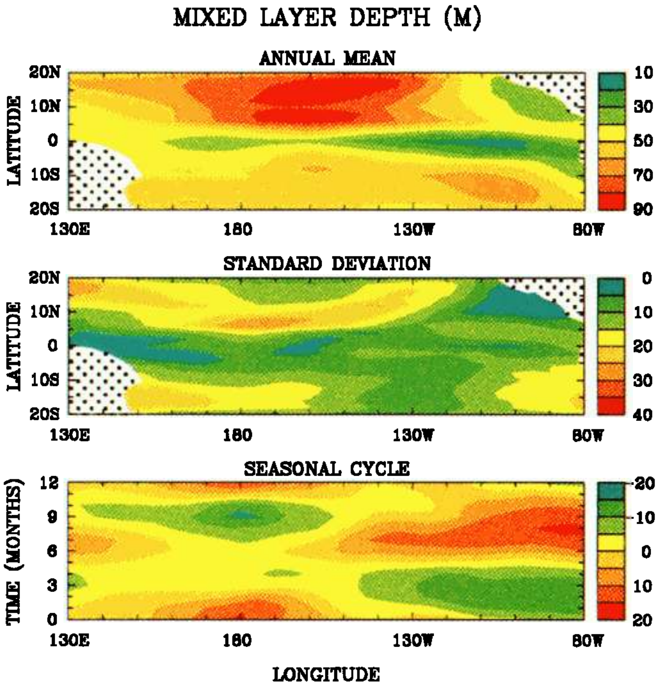

Plate 6. Mixed layer depth corresponding to the SST simulation in Plate 5b. Contour intervals are 10 m in the top panel and 5 m in the other two panels.

in this case is much larger than in the other two cases. The standard deviations and the equatorial seasonal variations in the three cases are quite similar, although the annual cycle in the east is a little stronger in the two cases using the satellite-derived cloud data. This confirms our earlier speculation that the uncertainties in the solar radiation data result in large uncertainties in annual mean SST simulations but have relatively small effect on the seasonal cycle.

Solar radiation directly heats the water in the upper ocean and indirectly influences SST by stabilizing the upper ocean and thus weakening the vertical turbulent mixing of heat. Therefore the seasonal variation of solar radiation can produce a seasonal cycle not only in the heat input to the ocean, but also in the mixed layer depth over which the heat input is uniformly distributed. In the western equatorial Pacific the direct heating is the major effect of solar radiation on the SST variability because the SST semiannual cycle there follows the solar heating variation (with an expected lag of 90°) and is not sensitive to vertical mixing parameterization (see Plate 5). In the eastern equatorial Pacific, however, the effect of solar radiation on the mixed layer depth is also important, and the prominent SST annual cycle there is largely determined by the annual variation of the mixed layer depth, as discussed earlier.

When winds are weak and solar radiation is strong, the model-simulated mixed layer depth can be as shallow as a few meters and a significant part of the solar radiation can penetrate below the mixed layer. An additional experiment, which is similar to the experiment described in Plate 7a, except solar radiation is totally confined to the mixed layer, was performed to test the sensitivity of the SST simulation to the penetrative radiation (Plate 8). The annual mean SST errors are larger in this case than in Plate 7a, especially in the regions where model SST is too warm. The seasonal SST variations are also too strong, mainly because of the overheating in spring. The penetrative radiation is indeed important for SST simulation; it should be included in the model to keep the SST from becoming too warm under strong solar heating and weak wind conditions.

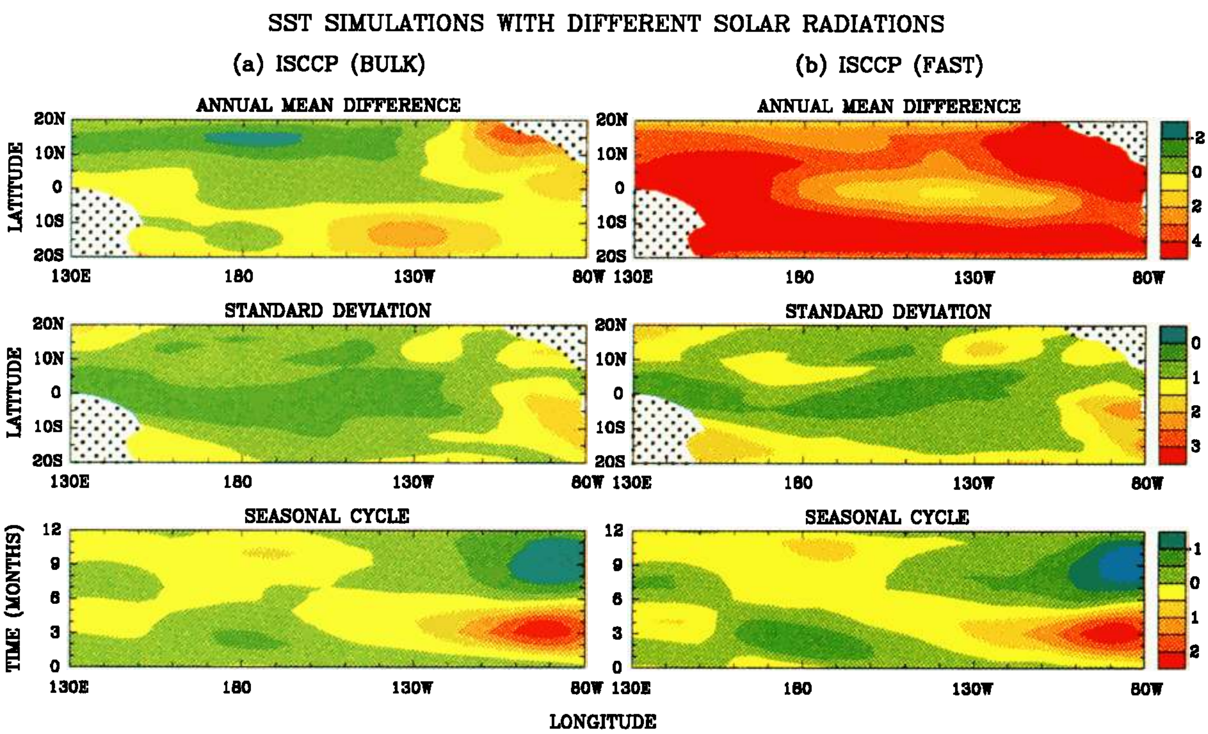

Plate 7. The same as Plate 5b, except using different solar radiations, (a) bulk formula with ISCCP cloud cover and (b) ISCCP radiation using FAST scheme.

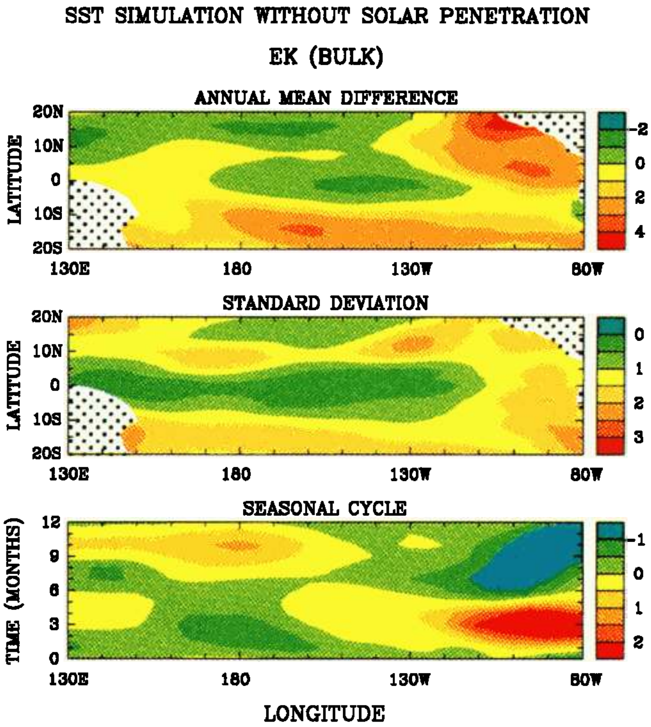

Plate 8. The same as Plate 7a, except no penetrative solar radiation.

4.3. The Role of Wind Stress

Although wind stress does not appear in the thermodynamic equation, it has tremendous influence on SST because of its effect on the advective and diffusive processes that redistribute heat in the upper ocean. We have already mentioned several times the important role of wind forcing in influencing SST variability through its control of the mixed layer depth. For instance, the large annual cycle of SST in the eastern equatorial cold tongue owes its existence to the annually fluctuating mixed layer depth which is, to a large extent, controlled by the annual variation of wind. The generally shallow mixed layer in that region, which is necessary for the large SST variability, is also a consequence of wind forcing; the wind-driven upwelling cools SST and reduces sensible and latent heat fluxes, resulting in a large net surface heat flux which limits mixed layer deepening.

To further demonstrate the effect of wind forcing on advective and latent heat fluxes, Plate 9 shows the distribution and variability of these fluxes in the tropical Pacific corresponding to the SST simulation depicted in Plate 7a. The annual mean latent heat flux generally follows the pattern of wind speed with large values under the trade winds. An exception is in the eastern equatorial cold tongue where the minimum is mainly due to the upwelled cold water. On the other hand, the annual mean field of the total mixed layer advective heat flux, which is the sum of zonal, meridional, and vertical advection, has a pattern closely related to the wind-driven equatorial surface currents. The maximum advective cooling is found in the eastern central equatorial region where both the upwelling and the zonal advection associated with the South Equatorial Current are most intense. The standard deviation maps of the two heat fluxes are also quite different; the latent heat flux has large variations under the trades and monsoons, while the advective heat flux varies significantly in regions of known strong circulation.

The most interesting feature in the equatorial seasonal cycle of both heat fluxes is the westward phase propagation in the central equatorial Pacific. We have explained the SST

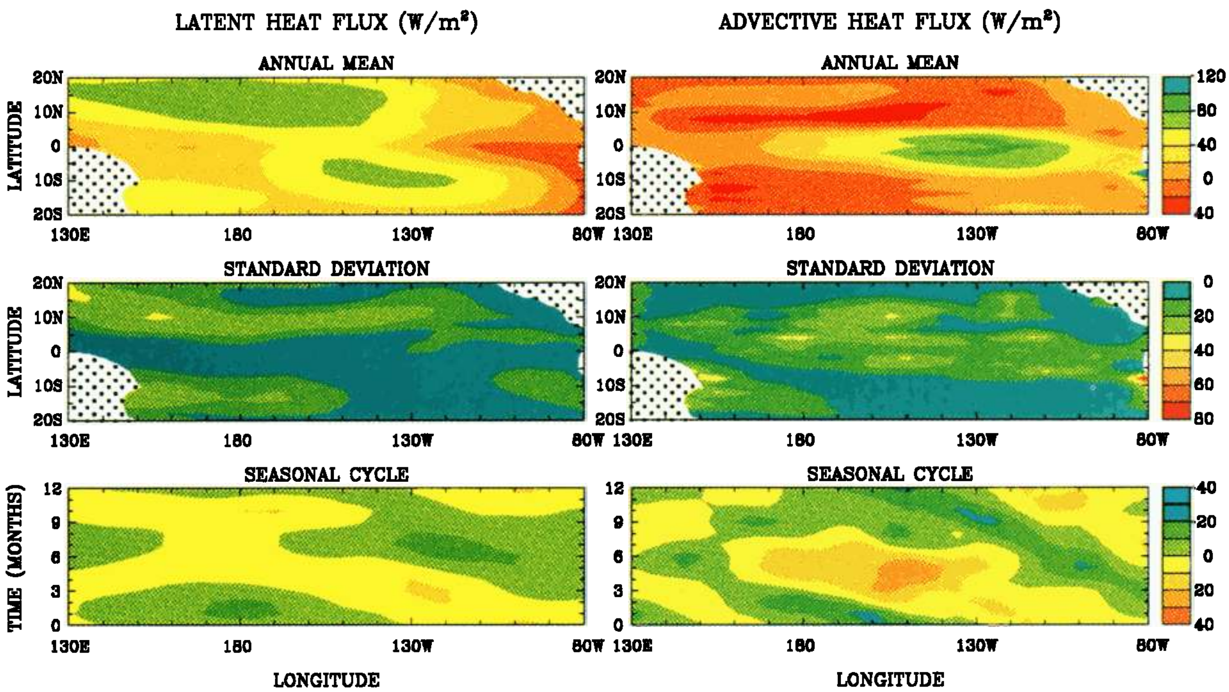

Plate 9. (left) Latent heat flux and (right) total mixed layer advective heat flux corresponding to the SST simulation in Plate 7a. For convenience a constant 140 W/m^2 is added to the annual mean latent heat flux. Contour intervals are 20 W/m^2 in the top panel and 10 W/m^2 in the other two panels.

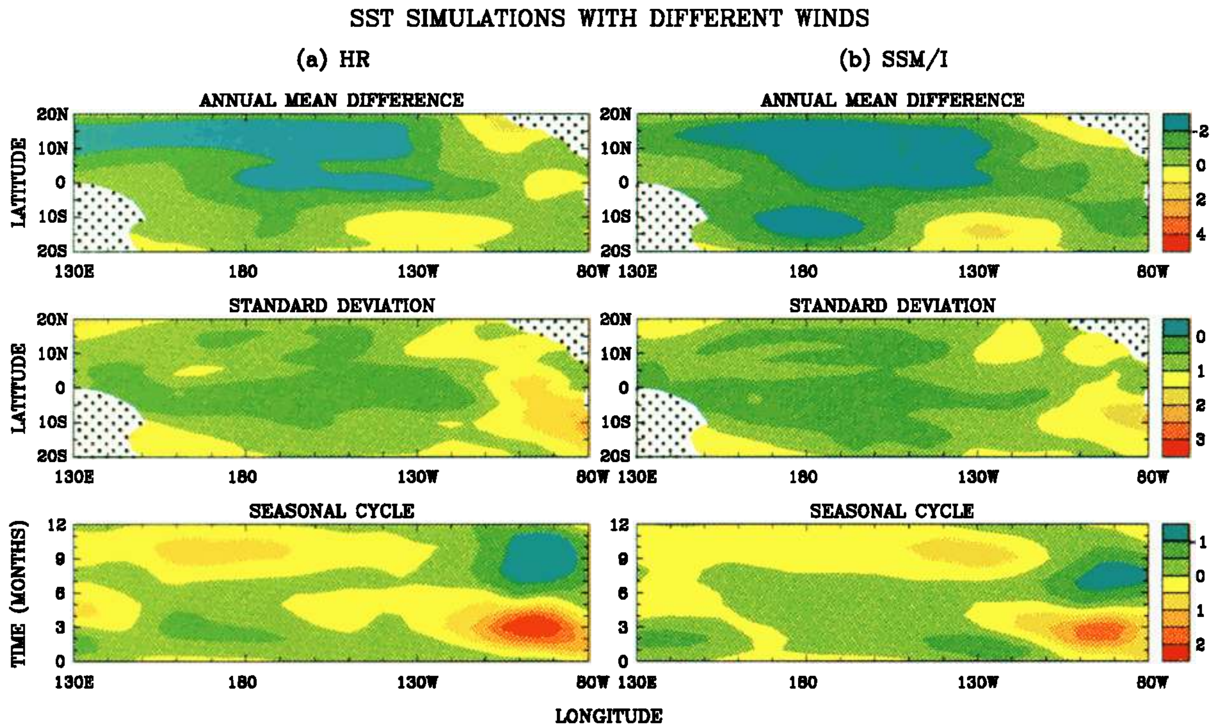

Plate 10. The same as Plate 7a, except using different wind forcing, (a) *Hellerman and Rosenstein* [1983] and (b) SSM/I-based wind stress.

semiannual cycle in the west in terms of the seasonal variation of solar radiation and have attributed the annual cycle in the east to the mixed layer variability. The westward phase propagation of the SST anomaly in the central part of the ocean results from the advective and latent heat flux anomalies induced by the westward propagating anomaly in the zonal wind stress (see Plate 3). The small zonal wind stress anomaly can produce significant anomalies in latent cooling, equatorial upwelling, meridional advection, and zonal advection. The anomaly in the latent heat flux is less than that in the total advective heat flux. The three components of the advective flux have been checked to determine which has the largest westward propagating signal. It turns out that the anomalous zonal advection contributes most to the SST anomaly in the central equatorial Pacific, especially in spring when the SST increases owing to the zonal heat flux associated with the reversed surface current.

In order to evaluate the effect of uncertainties in the wind stress data, we compare three experiments using the three different wind products described in section 2. One of these experiments is the one shown in Plate 7a where FSU climatological wind stress was applied. The SST simulations from the other two experiments in which HR and SSM/I wind products were used are displayed in Plates 10a and 10b, respectively. In all three cases the solar radiation was calculated using the bulk formula and the ISCCP cloud cover data and the vertical mixing was parameterized using the hybrid scheme. The same SST error pattern is found in all cases, but the annual mean SST is cooler everywhere when the HR and the SSM/I winds are used because these winds are stronger than the FSU wind. There are some differences in the SST seasonal variations. Consistent with the corresponding zonal wind stress, the SST anomaly in the central equatorial Pacific has a distinct semiannual cycle in the case of the HR wind and has no clear phase propagation in the case of the SSM/I wind. Nevertheless, the large SST annual cycle in the eastern equatorial Pacific is present in all cases, although the cooling starts too early in the case of the SSM/I wind, owing to the earlier intensification of the southeast trades at the equator.

4.4. The Mixed Layer Heat Budget

The mixed layer heat budget in the equatorial Pacific was calculated as a function of time to further investigate the contributions of various processes to the SST seasonal variability. The heat balance is written as an equation for SST change rather than for the mixed layer heat storage rate so that the effect of each heat flux term on SST can be directly assessed. Thus the equation for SST change is

$$T_t = Q_S + Q_D + Q_U + Q_W,$$

where T_t is the rate of SST change; Q_S, the net surface heat flux divided by the mixed layer depth; Q_D, the sum of the vertical mixing and horizontal diffusion; Q_U, the zonal advection; and Q_W, the sum of the vertical and meridional advection. The latter two advection components are put together because oftentimes they both represent the cooling effect of the equatorial upwelling. The heat loss from the mixed layer due to penetrative radiation is subtracted from the surface heat flux. The five terms in the above equation are computed for the case corresponding to the SST simulation in Plate 7a. The area-averaged seasonal variations of these terms are shown in Figure 1 for the western (130°E–160°E, 5°S–5°N), central (140°W–170°W, 5°S–5°N), and eastern (80°W–110°W, 5°S–5°N) equatorial Pacific Ocean, respectively. For reference the corresponding SST and mixed

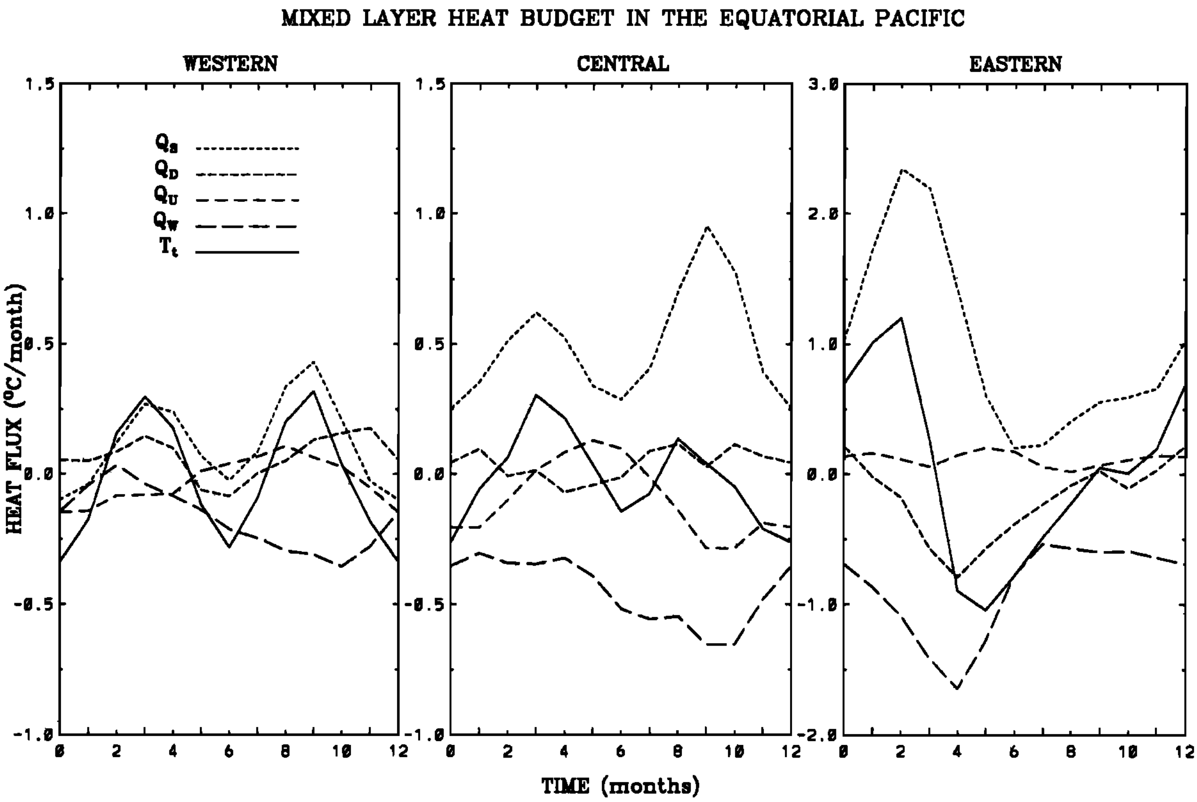

Figure 1. Area-averaged mixed layer heat budget corresponding to the SST simulation in Plate 7a for western (130°E–160°E, 5°S–5°N), central (140°W–170°W, 5°S–5°N), and eastern (80°W–110°W, 5°S–5°N) equatorial Pacific Ocean.

layer depth are displayed in Figure 2 against those from the case with constant depth mixed layer.

In the eastern equatorial Pacific all terms in the heat budget are important, except zonal advection which is small throughout the year. The surface heating is, on average, balanced by the oceanic cooling due to upwelling and vertical mixing, but the heating is largest in February–March, while the maximum cooling occurs in April. Looking at the size of the mixing term, one might think that the vertical turbulent mixing is not as important as we have argued. The subtlety involved is that the vertical mixing term includes only the direct cooling effect of entrainment and diffusion but not the indirect and most important effect through the variation of the mixed layer depth. The influence of the seasonal mixed layer depth fluctuation manifests in the heating term which is an order of magnitude larger in February than in July. This is also evident in Figure 2 where the large annual fluctuation of SST in the east corresponds closely to that of the mixed layer depth.

The huge annual cycle in the heating rate is partly caused by the variation in surface heat flux, but it is mostly due to the fact that in spring the heat flux heats up a shallow mixed layer, while in fall it acts on a rather deep mixed layer. For example, when the mixed layer depth is fixed, although the surface heat flux is more or less the same, the SST annual cycle is weak and phase lagged (Figure 2). Also, because of the large mixed layer variability, the cooling effect of upwelling and vertical mixing is larger in spring, although the strongest winds are found in fall. Unlike the heating, however, the oceanic cooling does depend on wind-generated motions. Thus the maximum cooling occurs in April when winds start to pick up and the mixed layer is still relatively shallow, thereby lagging the heating maximum by 1 month. This phase shift is partly responsible for the large variation in the rate of SST change.

In the central equatorial Pacific the surface heating, the upwelling and associated meridional advection, and the zonal advection are important contributors to the SST seasonal variability. The diffusion term is generally small, partly because the cooling due to vertical mixing is compensated by the heating effect of meridional mixing. The zonal advection has a large annual cycle. It is a cooling term during most of the year because the South Equatorial Current brings cool water westward, but it becomes a warming term in late spring and early summer when the surface current reverses direction. The upwelling and associated meridional advection are now largest in fall, in accordance with the strong winds, and the mixed layer depth is no longer a limiting factor. The rate of SST change has a semiannual cycle different from that in the surface heating. For example, the maximum SST warming in spring is much larger than that in fall, while the opposite is true for the surface heating. This characteristic is consistent with the westward phase propagation of SST anomalies. The zonal advection plays an important role in increasing the SST warming in spring and reducing it in fall.

In the western equatorial Pacific the rate of SST change follows closely the semiannual cycle of the surface heating, as expected from earlier results (see Plates 2 and 7). There are significant seasonal variations in advective and diffusive

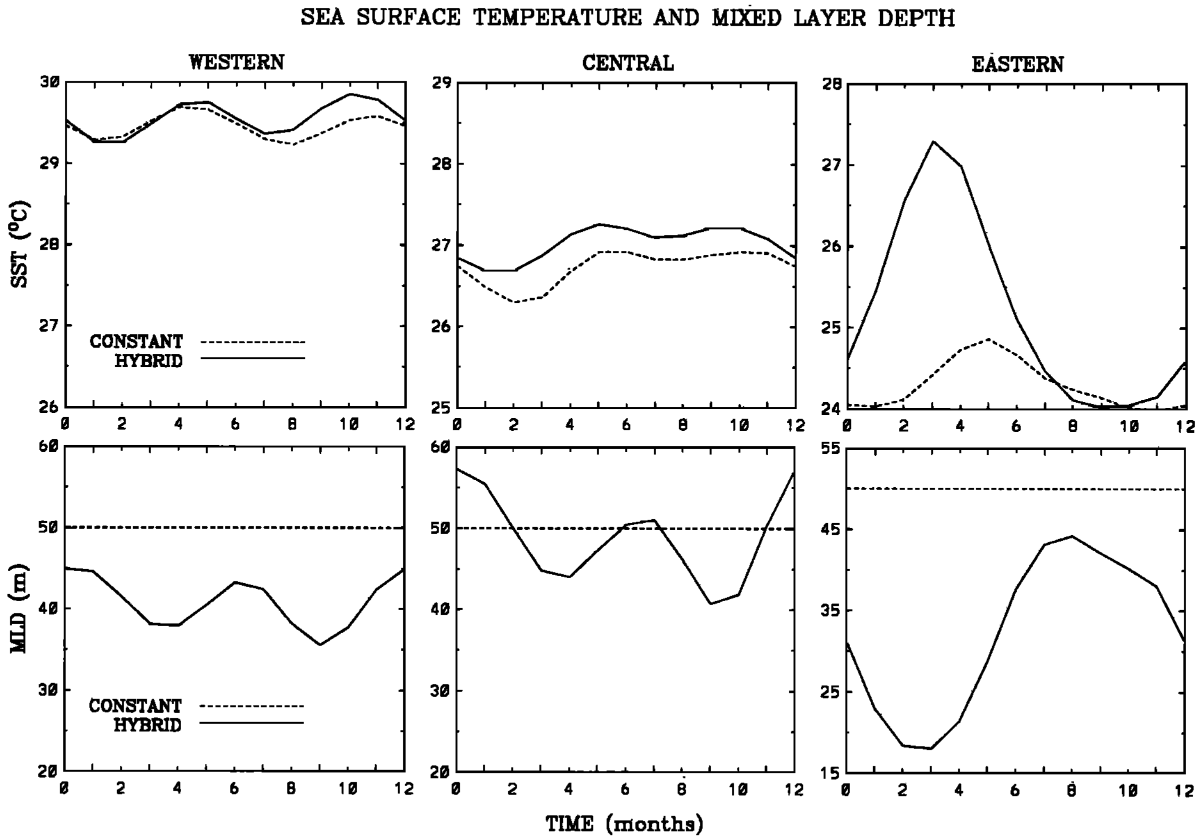

Figure 2. Area-averaged sea surface temperature and mixed layer depth for western, central, and eastern equatorial Pacific Ocean. Two cases with different mixing schemes are compared.

terms, but the net effect of these terms is generally small in this region. The effect of vertical mixing on SST variability is not important in either the western or the central equatorial Pacific, partly because the mixed layer depth variation is not large enough compared to the mean depth (Figure 2). Thus the choice of vertical mixing scheme in simulating the SST seasonal cycle is less crucial in these regions than in the eastern equatorial Pacific.

4.5. A Remark on Annual Mean SST

It is apparent that none of the experiments described above produces the correct annual mean SST, although the seasonal cycle is well simulated as long as the hybrid vertical mixing scheme is used. In contrast to the seasonal cycle, the annual mean SST simulation is very sensitive to the uncertainties in the mean surface fluxes but not to the parameterization of vertical mixing. It is not likely that the annual mean will be improved by further refinement of the vertical mixing scheme; nor is it probable to overcome the systematic errors in annual mean SST simulations by tuning the exchange coefficients in the forcing functions. For example, the model-simulated mean SST is usually too cold under the northeast trades but too warm under the southeast trades. This problem cannot be solved by changing the drag coefficient for wind stress because a larger (smaller) coefficient will make the simulation even worse in the north (south), while making it better in the south (north). However, tuning the drag coefficient may reduce the differences among the annual mean SST simulations using different wind stress data since the annual mean winds of the three products differ mainly in magnitude (see Plate 3). Generally speaking, the uncertainty in wind forcing data is less than that in solar radiation (cloud cover); the large errors in annual mean SST simulations are more likely to be a result of inaccurate surface heating.

It is useful to estimate how much heat flux modification is needed to bring the model-simulated annual mean SST close to observed climatology. To do so, a model run was performed in which a *Haney* [1971] type feedback term was added to the heat flux formula to relax the model SST back to the Levitus climatology. The relaxation coefficient was 40 W/m^2/°C, and the FSU winds and the ISCCP clouds were used for model forcing. The heat flux arising from the feedback term was averaged to form an annual mean which was then used to modify the annual mean (but not the seasonal anomaly) of the solar radiation with ISCCP clouds. We performed an additional experiment using the modified solar radiative forcing, and the SST simulation is displayed in Plate 11. Comparing with the Levitus climatology in Plate 1, one can see that both the annual mean and the seasonal cycle are now well simulated. Nevertheless, the SST standard deviation is still underestimated off the coast of South America, probably because coastal upwelling variability is too weak in the model [*Seager and Blumenthal*, 1994].

Plate 12 shows the modified annual mean solar radiation and the differences between different pairs of radiation products. The modified radiation has a similar pattern as the original one. The difference between the two, which is the heat flux modification needed to relax SST back to climatology, has average magnitude less than 20 W/m^2, although larger values are found in some areas. In fact, this amount of heat flux error can also arise from other heat flux components, although we have arbitrarily chosen to modify short wave radiation for convenience. All we can say is that the model needs more net heat input in the central equatorial region and under the northeast trades but less under the southeast trades and off the coast of Mexico. The required modification is, on average, no larger than the difference between any two solar radiation products used in this study, nor is it larger than the typical differences (O(50 W/m^2)) among various net surface heat flux products [e.g., *Niiler*, 1981]. Thus uncertainties in presently available heat flux data are too large to allow confident simulation of annual mean SST. Further improvement has to await more accurate or validated forcing data.

5. Discussion and Conclusions

A major finding of this study is that vertical mixing plays an important role in generating the large SST annual cycle in the eastern equatorial Pacific, and, consequently, the model simulation of the SST annual cycle depends crucially on the vertical mixing parameterization. Vertical mixing influences SST not only by entraining cold water into the surface mixed layer, but also by changing the mixed layer depth over which the surface heat flux is uniformly distributed. The latter proves to be more important in the eastern equatorial Pacific. Thus being able to simulate the annual fluctuation of the mixed layer depth is the minimal requirement for a suitable mixing scheme in this region. The failure of some tropical ocean models and coupled models in simulating the SST seasonal cycle is likely due, in part, to inadequate treatment of vertical mixing. With the application of our hybrid vertical mixing scheme the model SST annual cycle in the eastern equatorial Pacific is much improved in both amplitude and phase. Away from the eastern equatorial cold tongue, SST variability is less affected by vertical mixing, mainly because the mean mixed layer depth is deeper and the ratio of depth variation to the mean is smaller.

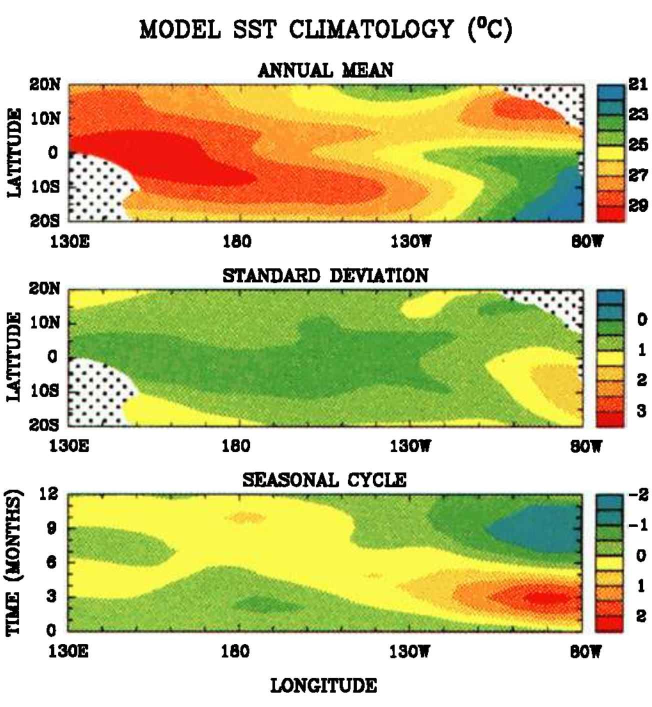

Plate 11. The same as Plate 7a, except using a modified solar radiation. See text for details.

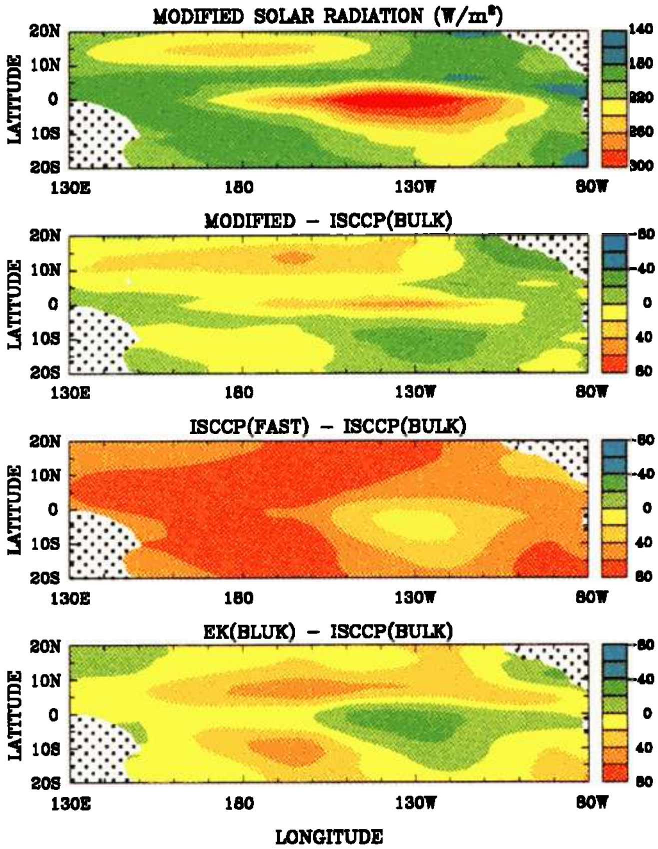

Plate 12. Modified solar radiation and differences between different pairs of solar radiation products. Contour intervals are 20 W/m^2. See text for details.

The mixed layer depth is largely determined by the competing effects of solar radiation and wind forcing. Solar radiation prohibits vertical mixing by increasing stratification in the upper ocean, while wind forcing generates turbulent mixing by direct stirring and shear instability associated with wind-driven currents. In the eastern equatorial Pacific the mixed layer shallowing in spring is due to strong solar heating and weak winds, and the mixed layer deepening in fall is caused by the dominance of strong winds over weak solar radiation. However, controlling the mixed layer depth is not the only role played by solar radiation and wind forcing. Solar radiation is always a large heating term in the upper tropical ocean heat budget. The SST in the western equatorial Pacific basically follows the semiannual cycle of solar heating. Wind forcing has even more diversity in influencing SST variability. Besides its strong effect on vertical mixing, wind forcing influences oceanic advective processes that redistribute heat in the upper ocean. The SST cooling caused by upwelling and related meridional advection is significant throughout the equatorial Pacific, and the SST seasonal cycle in the central equatorial region is strongly affected by the zonal advective heat flux associated with the seasonally reversing South Equatorial Current.

Uncertainties in atmospheric forcing have been hindering ocean modeling for many years. The situation with SST simulation is particularly discouraging because the uncertainty in surface heat flux can easily result in SST errors of a few degrees which are intolerable for any practical purpose. It has been demonstrated in our experiments that the amount of heat flux modification needed to eliminate the annual mean SST errors in the model is, on average, no larger than the differences among the three solar radiation products used in this study. The implication is that any attempt to attribute the annual mean SST errors to model deficiencies will be in vain until the uncertainty in surface heat flux is greatly reduced. For example, it is possible that underestimating meridional diffusion is the reason for the SST overcooling in the central equatorial Pacific, as suggested by *Enfield* [1986], but one cannot be sure of this because the errors in surface heat flux can cause SST deviations of the same magnitude. However, the results of this study are considerably more encouraging for the seasonal variability. Fortunately, uncertainties in the seasonal variation of atmospheric forcing are much smaller than in the annual mean. The large SST annual cycle in the eastern equatorial Pacific is relatively insensitive to the choice of forcing sets. It is this insensitivity that allows us to identify unambiguously the role of vertical mixing in controlling the SST annual cycle in that region.

One purpose of this research was to test the applicability of the new satellite-derived forcing products in tropical ocean models. The SSM/I-based wind stress data have similar distribution patterns as the FSU and HR products but have somewhat different magnitude and seasonal variability. These similarities and differences are reflected in SST simulations. Considering the fact that only 3 years of SSM/I data are available for building the "climatology," the differences are actually less than expected. The real advantage of the satellite-derived wind stress product is its relatively dense space–time coverage, which we did not make use of in this study. Since its large-scale similarity with conventional wind products is now established [*Busalacchi et al.*, 1993], the high-resolution SSM/I-based wind product will be used in a follow-up study to explore the effect of high-frequency winds. The satellite-derived solar radiation products also have desirable attributes, such as the sharp maximum in the central equatorial Pacific where the oceanic cooling is most intense. However, neither of the ISCCP products represents an overall improvement over the EK product in terms of the seasonal SST simulation. For studies of interannual SST variability the consistent data coverage of ISCCP products may prove advantageous over the sparse surface estimates. The ISCCP solar radiation obtained using the FAST scheme seems too large to produce reasonable annual mean SST in our model. In order to make use of this solar radiation product, we may have to take out a constant amount of excess heat and adopt a more realistic formula for long wave and sensible heat fluxes, as suggested by *Seager and Blumenthal* [1994].

In summary, we have simulated the climatological SST seasonal cycle in the tropical Pacific using a newly developed upper ocean model. The roles of vertical mixing, solar radiation, and wind stress were investigated in a hierarchy of numerical experiments with various combinations of vertical mixing schemes and surface-forcing products. Our major conclusion is that the SST seasonal cycle can be well simulated by improving vertical mixing parameterization, but the annual mean SST cannot be confidently reproduced until more accurate forcing data become available. The next step is to apply the model to a realistic multiyear simulation to investigate the interaction between the seasonal cycle and interannual variability and to take full advantage of the satellite-derived forcing data.

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