J5.4 EFFECTS OF PRECIPITATION ON THE TROPICAL WESTERN PACIFIC OCEAN USING A COUPLED SINGLE-COLUMN MODEL

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1. INTRODUCTION

The importance of salinity variability on the thermodynamics and dynamics of the upper ocean has gained an increased appreciation in the last few years. Much of this interest was initiated by the recognition of the barrier layer feature in the tropical Pacific. During the Western Equatorial Pacific Ocean Circulation Study (WEPOCS) Lindstrom et al. (1987) and Lukas and Lindstrom (1991) found a shallow (30 m) surface mixed layer whose depth was determined by the salinity stratification; the isothermal layer was deeper than the isohaline layer. The stable salinity-stratified region at the bottom of the surface mixed layer was called the barrier layer by Godfrey and Lindstrom (1989). This layer was perceived to be an inhibitor of entrainment cooling due to its stability. The existence of the barrier layer has been associated with heavy rainfall and moderate winds (e.g., Anderson et al. 1996) and with the westward subduction of high-salinity water in the South Equatorial Current under the low-salinity water to the west (e.g., Lukas and Lindstrom 1991, Shinoda and Lukas 1995).

A number of studies have focused on the role of the December westerly wind burst in affecting the salinity of the upper tropical Pacific (Smyth et al. 1996, Anderson et al. 1996, Feng et al. 1998). Freshwater lenses that occurred during the TOGA COARE IOP have also been studied (Tomczak, 1995, Wijesekera et al. 1999), as have the dynamics of surface fronts associated with the freshwater lenses (Soloviev and Lukas, 1997). Ocean mixed layer models have been used to understand the extent to which precipitation in the tropical Pacific affects the upper ocean (Anderson et al. 1996, You 1998; Li et al. 1998). In these cases, simulations with varying amounts of precipitation relative to the observed value have been performed, and the resultant SST difference examined. Over the four-month IOP, differences in SST even with significant changes in the precipitation amounts tend to be small (< ~ 0.2 °C). Thus the role of the surface salinity variability and resultant barrier layers on controlling the sea surface temperature in the western Pacific, at least over short time scales, is still in question. However, given that these investigations used an ocean mixed layer model solely, no information as to any amplifying effects that may occur as the atmosphere responds to small changes in the SST have been examined.

This study uses as coupled single-column atmosphere/ocean model (Clayson and Chen, 2002) as a basis for examining possible feedbacks that could enhance the oceanic response to precipitation. A single-column model provides a computationally inexpensive method for evaluating the feedbacks between the ocean and atmosphere. The model is however limited in its uses. A single-column model cannot reproduce feedbacks with large-scale dynamic systems; however, the effects of large-scale dynamics can be included within the model with judicious advection forcing. The model however can, to the extent which it reproduces the physical system adequately, provide information about local variability in the atmosphere-ocean state due to the effects of precipitation on the ocean.

2. MODEL AND DATA DESCRIPTION

The model used in this work consists of a coupled atmosphere/ocean single column model, as described in Clayson and Chen (2002). Additional simulations for comparison use the ocean mixed layer model in stand alone mode.

a. Ocean mixed layer model

The ocean component of the coupled model consists of the one-dimensional ocean model described by Kantha and Clayson (1994). This model uses second moment turbulence closure, and includes improved parameterizations of the pressure covariance terms that have been developed based on large eddy simulations. Penetration of shortwave radiation into the upper ocean is modeled following Morel and Antoine (1994) with multiple spectral bands. Treatment of the shear instability-induced mixing in the strongly stratified region below the oceanic mixed layer is induced following Large et al. (1994). The model includes the skin surface temperature parameterization developed by Wick (1995), modified by Schluessel et al. (1997) to include the effects of precipitation and the diurnal thermocline. Parameterizations for Langmuir circulation and wave breaking effects have also been included. The ocean mixed layer model has been evaluated over many time scales and in many locations (e.g. Kantha and Clayson 1994, Webster et al. 1996). The vertical resolution of the ocean model is 1 m; temporal resolution is 15 min. The profiles of temperature, salinity, and currents used to initialize the model are described in the following section.

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b. Atmospheric model

The atmospheric component of the model used for this study is the single column version of the NCAR Community Climate Model (CCM3; Kiehl et al. 1996) known as SCCM 1.2. The SCCM 1.2 contains physical paramaterizations that are identical to those used in the full scale CCM3. The SCM has 18 vertical levels, with a rigid lid at 2.917 mb. The model uses a time step of 15 minutes. The atmospheric boundary layer parameterization uses the nonlocal scheme described by Holtslag and Boville (1993). This scheme determines an eddy-diffusivity profile based on a diagnosed boundary-layer height (following Vogelezang and Holtslag, 1996) and a turbulent velocity scale. It also includes nonlocal vertical transport effects for heat and moisture, and a direct coupling to the parameterization of deep and shallow convection.

The convection scheme used in SCCM 1.2 is the Zhang-McFarlane convection scheme (Zhang and McFarlane, 1995). The cloud fraction in CCM3 is based on the Slingo (1987) algorithm as modified by Hack et al. (1993). As described in Clayson and Chen (2002), we have modified the SCCM 1.2 by replacing the Slingo scheme with the Tiedtke (1993) parameterization for cloud amount, and was shown to provide greatly improved simulations of cloud parameters during the TOGA COARE IOP. Cloud optical properties are now calculated as a function of the cloud water path and the effective cloud droplet radius.

The SCCM is forced using data from the TOGA COARE Intensive Flux Array (IFA) region. Since the model is one-dimensional, large-scale vertical and horizontal advection must be specified from an existing data set. For our simulations advection data is obtained from the data analysis of Lin and Johnson (1996), as described below.

c. Coupled model

In the coupled model, the atmospheric model provides the near-surface horizontal wind speeds, air mixing ratio, air temperature, precipitation rate, and downwelling shortwave and longwave radiation to the ocean at each timestep. These values, combined with the sea surface (skin) temperature previously determined by the ocean model, are used as inputs to a turbulent flux model (described in Clayson et al. 1996). The modeled turbulent fluxes drive the evolution of the ocean mixed layer. In response to the surface fluxes, the ocean model determines a new profile of temperature, salinity, and horizontal velocity. The newly determined SST is used to provide the atmosphere model with an updated surface moisture and latent heat flux, sensible heat flux, and upwelling longwave radiation flux.

3. OBSERVATIONAL DATA

Observational data used in this study is from the TOGA COARE Intensive Flux Array (approximately from 4°S to 2°N and 150 to 160°E) during the Intensive Observation Period (IOP) (November 1992 through February 1993). A complete description of this data set is given by Godfrey et al. (1998). Observational data is used to initialize the model and force the model at the horizontal boundaries. Details of the individual data sets used in this study are described below.

a. IMET buoy data

Profiles of ocean temperature, salinity, and currents were obtained from the WHOI mooring buoy data during the TOGA COARE IOP located at 1°45'S, 156°E (Weller and Anderson, 1996). The instrumentation on the mooring line of the buoy contained 11 temperature recorders, 18 conductivity and temperature recorders, eight current and temperature recorders, and an Acoustic Doppler Current Profiler (ADCP) (Anderson et al. 1996). The uppermost temperature measurement was obtained at a depth of 0.45 m, and the uppermost salinity measurement was at 2.0 m.

b. Atmospheric advective tendencies

The data set used for providing the horizontal and vertical advective tendencies for the atmospheric component of the SCM is from the analysis of Lin and Johnson (1996). This data set uses all available rawinsonde and satellite IR data collected within the IFA region. Data from research vessels and the IMET buoy are also used within this analysis. The data is available during the four month IOP at 6-h intervals with a vertical resolution of 25 hPa. The analysis includes vertical profiles of the horizontal advective fluxes of temperature and moisture, vertical and horizontal velocities, and temperature and moisture profiles.

c. Ocean advective tendencies

The horizontal and vertical advection of heat and salt are calculated from the results of a three-dimensional ocean model. The model is the University of Colorado version (CUPOM) of the Princeton sigma-coordinate, free surface, 3D ocean model (Blumberg and Mellor, 1987) configured for the tropical Pacific ocean (Clayson, 1995), which uses the mixed layer model described above.

d. Comparison of coupled model with observations

An extensive comparison of the coupled model with various in situ and satellite observations is presented in Clayson and Chen (2002). The coupled model is able to successfully reproduce variations in cloud parameters and surface fluxes; the model also overestimates the latent and sensible heat fluxes compared to observations.

The overestimation is most likely due to errors in the atmospheric surface layer temperature and specific humidity. The sea surface temperatures produced by the model are reasonable. The mean bias in sea surface temperature as compared to buoy data is 0 °C; the maximum deviation from the observed temperature is 0.4 °C.

4. EFFECTS OF PRECIPITATION

The model simulations presented here are similar to previous studies in that for comparison to the original model simulations the precipitation at the surface is set to zero. Results using the ocean mixed layer model with precipitation are shown in Figure 1. For clarity just the difference in sea surface (skin) temperature between the model simulation with rain and without rain is shown. Differences in sea surface temperatures between the simulations are very small, with little long-term temperature bias. This consistency between simulations also applies to the upper ocean temperatures, as shown in Figure 2. These results are comparable to simulations performed by other researchers using one-dimensional ocean models. It should be noted that all simulations used the same advection fields; differences in spatial variability in precipitation and resulting sea surface temperatures would most likely combine to alter advection. However, within the confines of a single-column model we can only test local influences.

Coupled model simulations of sea surface temperature using the precipitation field as generated by the model and with a surface precipitation value set to zero are shown in Figure 3. Differences are much stronger between the coupled model simulations. The most significant period of difference is from day 372 to 385 (corresponding to 6 – 19 January). During this time the coupled model with precipitation is significantly warmer than the model without precipitation. This occurs at the end of the westerly wind burst that occurred in late 1992, and is during the period of the IOP dominated by squalls (Anderson et al. 1996). It does not occur during the westerly wind burst, when the precipitation values were at their maximum for a sustained period of time (see for example Figure 4). The westerly wind burst at the end of 1992 is also marked by elevated latent and sensible heat fluxes (Figure 5), which was also the period with the highest average differences in the surface turbulent fluxes between the simulations. These differences in surface turbulent fluxes do not seem however to significantly affect the SST, which instead is most affected after this time period when the average difference between the surface outgoing fluxes is considerably lower. Finally, the westerly wind burst is also the period with the strongest differences in solar radiation between the two simulations (Figure 6).

The upper ocean temperature profiles which lead to the differences in sea surface temperatures are shown in Figure 7. Unlike the case of the ocean-only model simulations, strong differences in temperature profiles are seen, especially during the period of 6 – 19 January. During this particular time, the simulation with the precipitation feedback switched on trapped the heat in a much shallower mixed layer, while the simulation without the precipitation feedback distributed the heat over a deeper mixed layer. This difference is due to the effect of the stronger stable stratification for the case with precipitation, which reduces the depth of mixing within the ocean, causing an increased sea surface temperature. It should be noted that in the period of 1 – 5 January the precipitation in the model with precipitation feedbacks is enhanced, which further promotes stable stratification and reduced mixing as the wind speeds decrease. Beginning roughly day 283 (16 January) the simulation with precipitation feedback begins to cool compared to the simulation without precipitation feedback; this occurs in conjunction with increased latent and sensible heat flux. As the winds remain constant between the simulations, the increase in latent and sensible heat flux is due to changes in the ocean surface temperature and atmospheric near-surface state. These changes are due to the increased sea surface temperature, and thus during this period this is a negative feedback between the precipitation and sea surface temperature, as solar radiation also decreases in the simulation with precipitation feedbacks.

5. SUMMARY

A single-column coupled model was used to evaluate the response of the tropical Pacific to rainfall. A series of simulations using the ocean stand-alone part of the coupled model were compared with results using the coupled model. For both models, a simulation with precipitation from the original coupled model was determined; simulations were then performed with the precipitation at the ocean surface set to zero. Differences between the precipitation/no precipitation case in the ocean stand-alone model were small; differences were much more exaggerated in the coupled model. An initial analysis showed that the differences in the coupled model were not due to differences in shortwave radiation but differences in surface latent heat flux between the two simulations were observed. As noted in the Introduction, the single-column model cannot reproduce feedbacks that may occur through non-local gradients in ocean temperature or salinity or atmospheric dynamics. Thus the variability occurring in the model when no precipitation is coming in through the ocean surface presents an incomplete picture. However, the results can be used to demonstrate that although sea surface temperature variability is small when considering the ocean in isolation, feedbacks to the atmosphere can amplify this ocean response as evidenced by the more significant change in sea surface temperature from the coupled model with no surface precipitation than in the stand-alone ocean model with no precipitation. A further discussion of the feedback mechanisms involved will be shown in the presentation.

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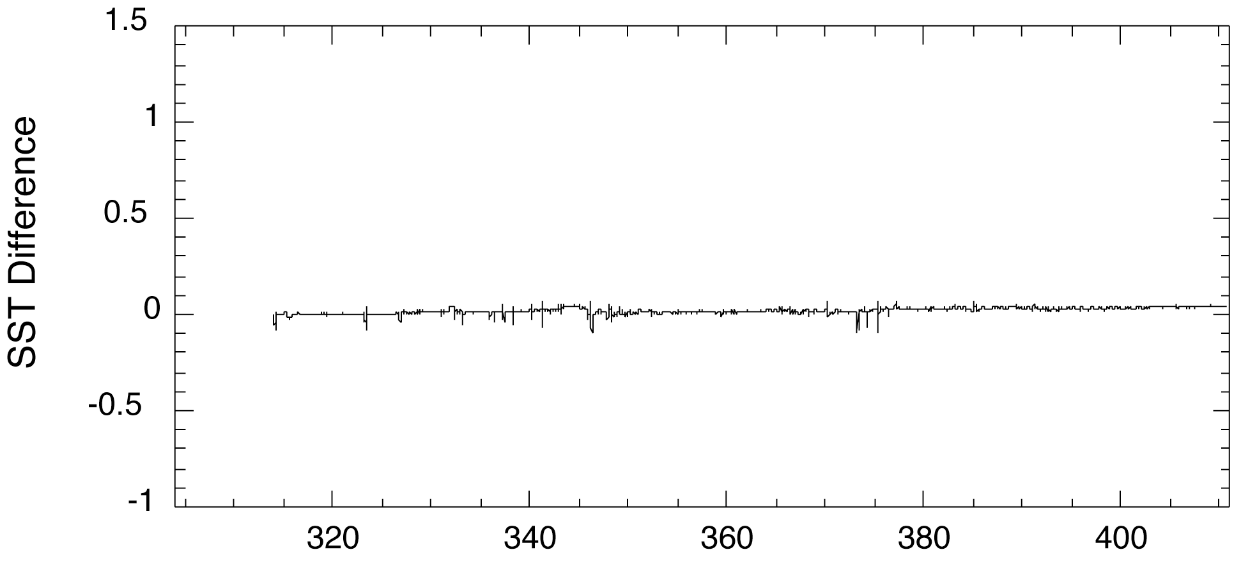

Figure 1. Sea surface temperature differences with ocean-only model between simulations with and without precipitation.

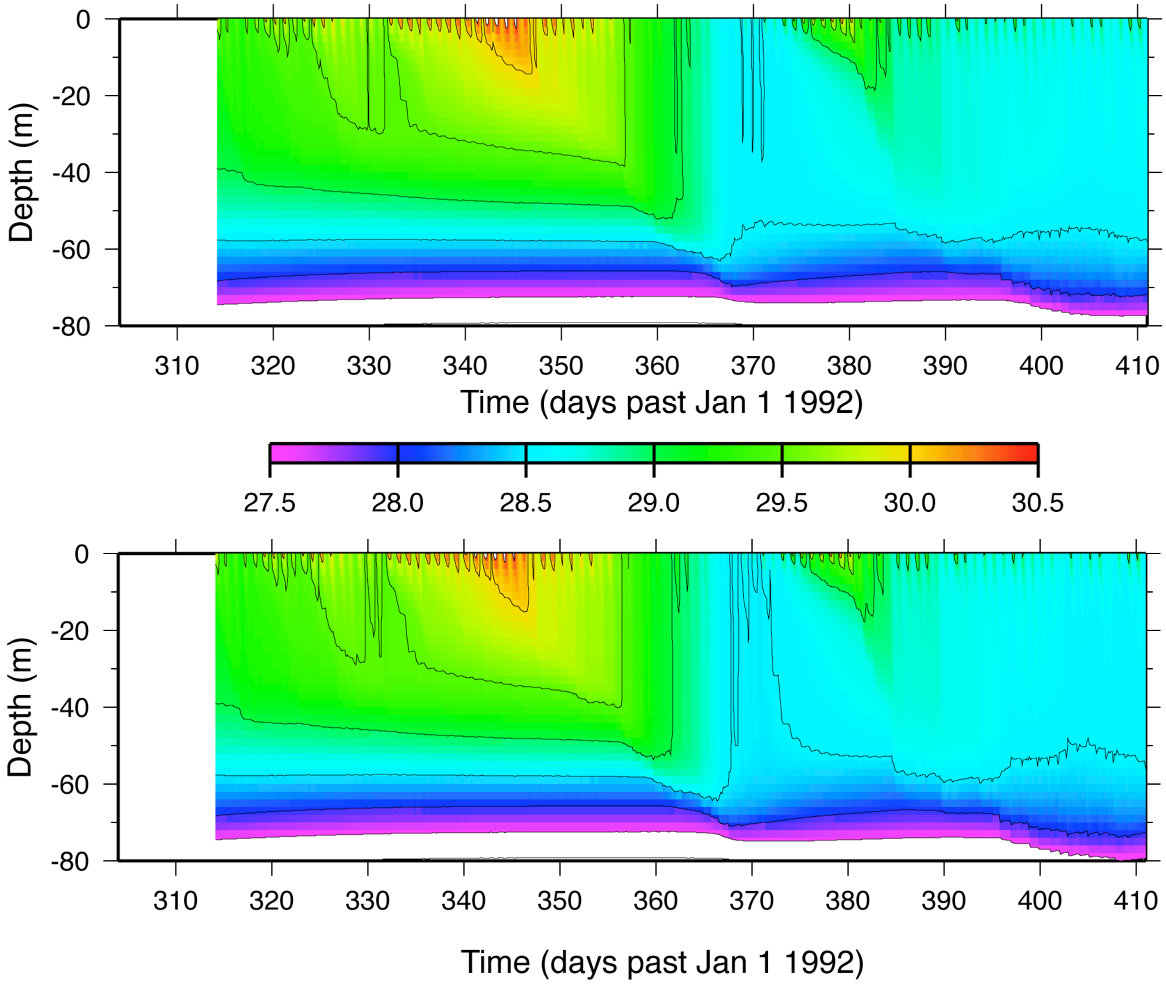

Figure 2. Upper ocean temperatures ocean-only model simulations with (top panel) and without (bottom panel) precipitation.

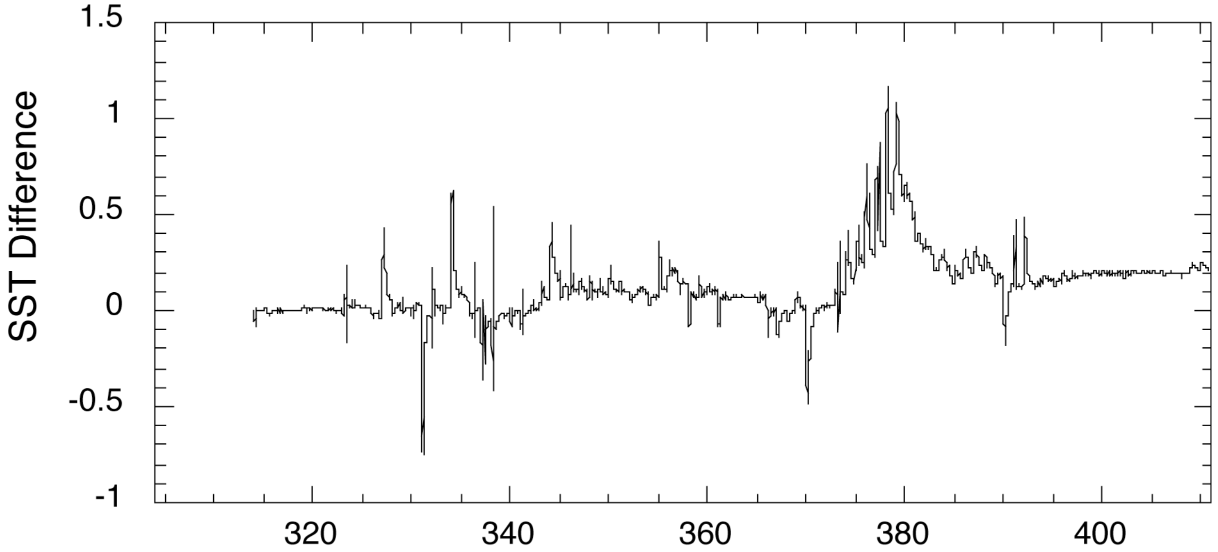

Figure 3. Sea surface temperature differences with coupled model between simulations with and without precipitation. Positive differences indicate the simulation with precipitation feedback is warmer.

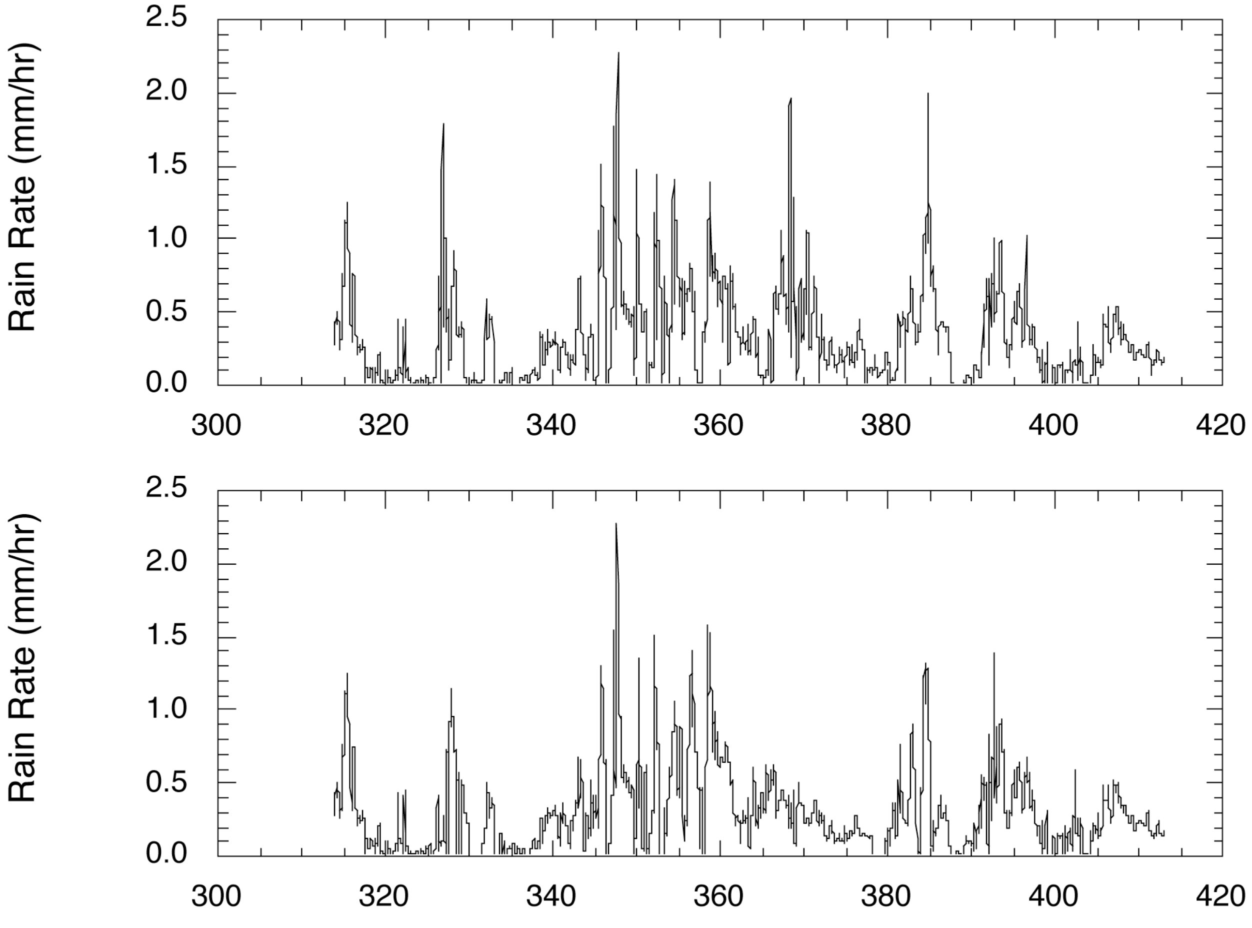

Figure 4. Differences in rain rates with coupled model between simulations with (top panel) and without (bottom panel) precipitation feedback.

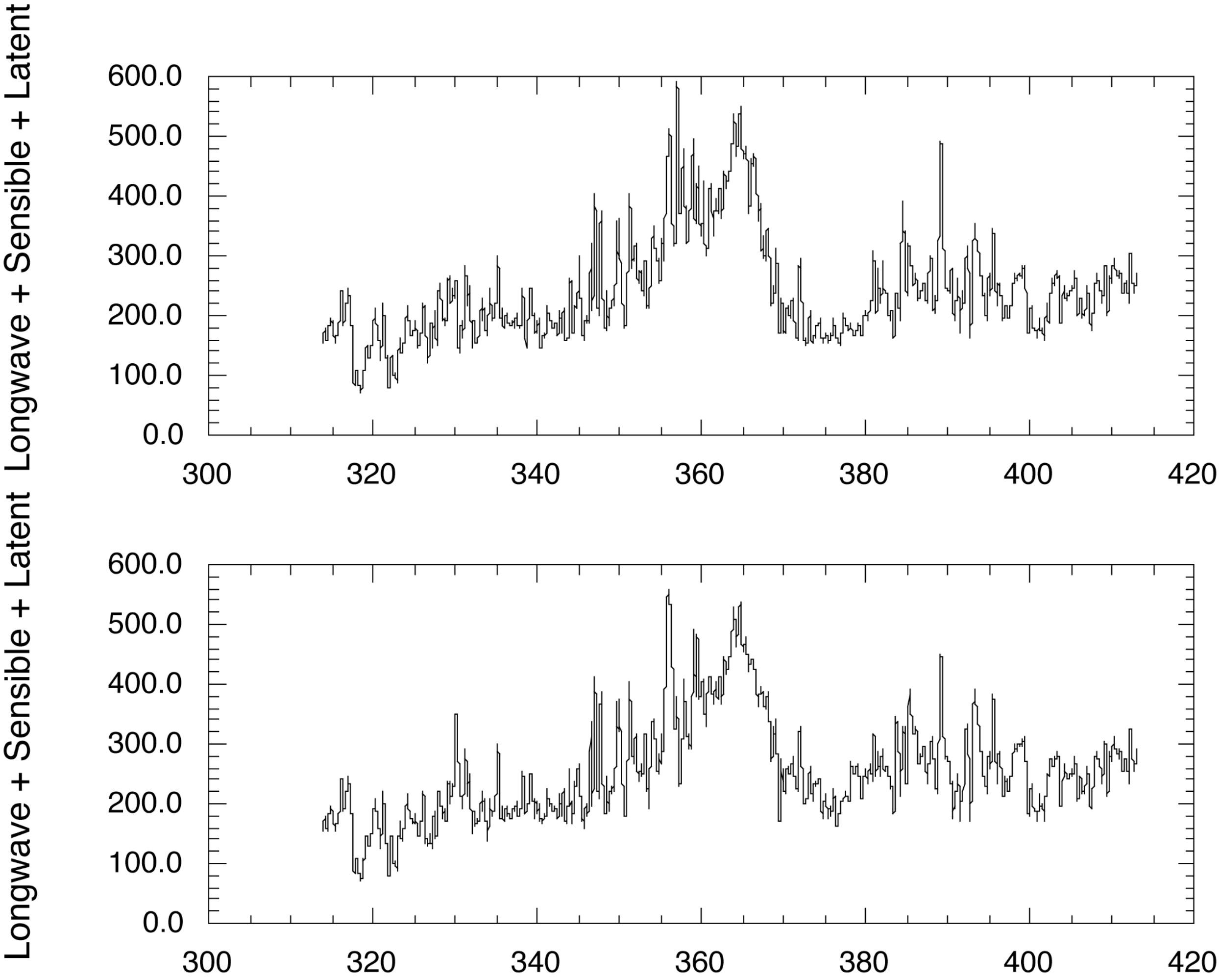

Figure 5. Differences in turbulent and longwave fluxes with coupled model between simulations without (top panel) and with (bottom panel) precipitation feedback.

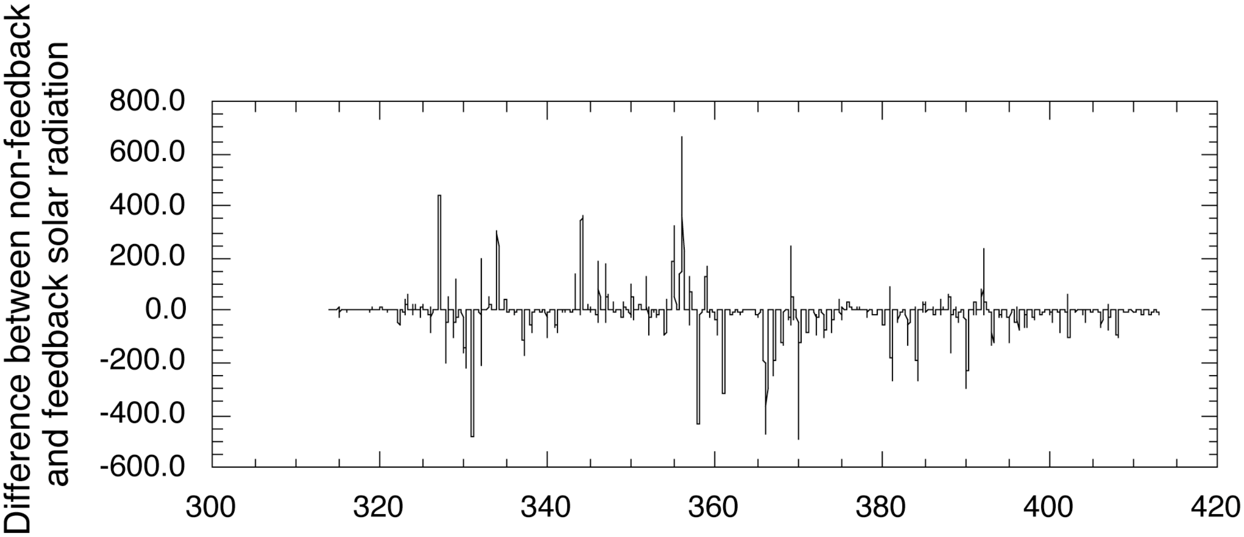

Figure 6. Difference in surface solar radiation flux with coupled model between simulations with and without precipitation feedback.

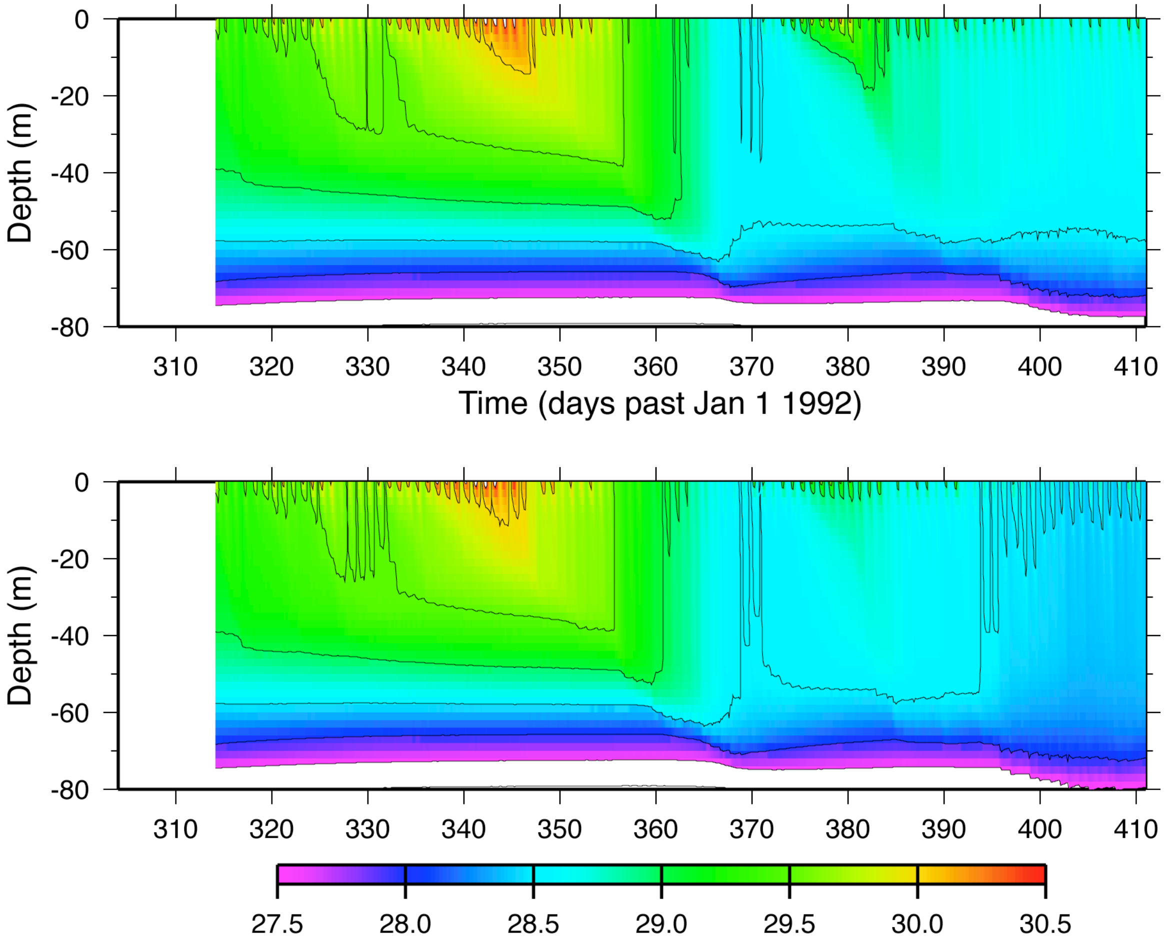

Figure 7. Upper ocean temperature differences with coupled model between simulations with (top panel) and without (bottom panel) precipitation feedback.