AGU PUBLICATIONS

Journal of Advances in Modeling Earth Systems

Supporting Information for

Sea Surface Temperature Contrast in Tropical World: Part 1 Mean State

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Introduction

We provide here text and figures that could not be fit into the main text. These show several key things. S1) Forcing warming with insolation or CO2 produces similar changes because the climate is dominated by the water vapor response to SST. S2) Solar absorption by water vapor is important for the shortwave cloud radiative effect, and albedo. S3) 1D RCE modeling shows the importance of Ozone in warming the top of the well mixed layer. Also the top-heavy radiative cooling profile with warming occurs even if the relative humidity is uniform. S4) The relative humidity in the upper troposphere does change the temperature of the top of the well-mixed layer a little. Less RH means a warmer temperature for the reduction in radiative cooling rate. S5) Doubling the vertical resolution of the GCM makes the climate about 3K cooler for the same insolation. This is because the boundary layer inversion is better resolved and more low cloud albedo results. Once this is accounted for, however, the key model behaviors occur in similar places in SST space. S7) Returns to the question of relative humidity, ozone and CO_2 forcing on the vertical distribution of clouds in the GCM. Change in the profile of cloud amount is similar whether the warming is forced by insolation increases on CO_2 increases.

Text S1. Forcing with CO_2 or Insolation.

The basic responses of Tropic-World to warming are fairly insensitive to the method of forcing, whether insolation increases or CO_2 increases. To illustrate this we have done a series of experiments in which the insolation is set and then the CO_2 is increased by a factor of 2 or 4. Figure S1 shows that the SST dependence of the temperature contrasts, the greenhouse effect, precipitation, subsiding fraction, relative humidity and planetary albedo are relatively insensitive to whether the warming is caused by insolation or CO_2 increase.

Text S2. Solar absorption by water vapor

As the climate warms the relative humidity in the rising and subsiding regions stays approximately constant as a function of temperature, but the specific humidity increases a great deal. This means that the absorption of solar radiation by water vapor increases. Figure S2 shows the solar heating rate as a function of pressure for the subsiding region for average and clear conditions.

In the region between 250 and 150hPa the shortwave heating rate increases about 0.5K/day in going from the C342 case to the C390 case. How much energy does this represent? We can integrate the heating rate in degrees per second through mass to obtain an energy rate using equation (3). Using a heating rate of 1K/day across a pressure depth of 100 hPa we obtain an energy rate of ~12 Wm^{-2}. An albedo change of 1% gives and energy rate of ~4 Wm^{-2}, if the insolation is 400 Wm^{-2}. So the increases in shortwave absorption by water vapor shown in Figure S2 give an absorption increase that is sufficient to cancel small albedo increases associated with low cloud water increases in the control series of experiments.

Text S3. 1-D RCE without ozone

Figure S3A shows the 1-D RCE calculations in which the ozone is specified to be a small value. Compare to Figure 12 in the main text for the case with ozone. Note that the temperature where the lapse rate falls to 8K/km above the maximum lapse rate is a nearly constant 200K independent of surface temperature. This is compared to about 210K with ozone (Figure 12), and the transition value increases slightly with surface temperature because the transition level moves higher into the atmosphere with warming and into the increasing ozone.

Figure S3B is the also for low ozone, but the relative humidity was set to a constant value of 50%, independent of pressure. In this case the transition to lower lapse rates also occurs near 200K, while the cold point temperature drops as low as 185K.

Text S4. Relative Humidity and FAT

Figure S7 indicates that ozone contributes significantly to the warming of cloud top and reduction of cloud fraction when the surface warms and forces convection upward into the region where ozone heating is more substantial and causes a reduction in lapse rate. This is different from the results of Bony et al(2016), who stated that their reduction in cloud fraction was not dependent on ozone, and argued for a mechanism involving the dependence of static stability on pressure. In our experiments ozone is important, but even with small ozone values the cloud top temperature increases with surface warming. Zelinka and Hartmann(2010) and Bony et al. (2016) have suggested that the warming and suppression of cloud fraction with warming results from a pressure effect on static stability. If the top of the convecting layer is sufficiently cold, the lapse rate should approach the dry adiabatic if convection is balanced by emission from water vapor, as shown in Figure S3c and in cloud-resolving simulations in which water vapor is the only radiatively active gas (Harrop and Hartmann 2012, Hartmann et al. 2019). The moist lapse rate where the saturation vapor pressure is higher does have a dependence on pressure as well as temperature, however, because the saturation specific humidity at a fixed temperature increases with decreasing pressure. With this in mind we offer an alternative explanation for why the cloud tops get slightly warmer even when ozone is not present. For the TW simulations, one possible reason could be that the relative humidity near the top of the troposphere decreases with surface warming (Figure 9 in the paper). From Equation 14 we see that the relative humidity enters both in the emission and the transmission parts of the cooling to space approximation. If the RH decreases with warming, the clear-sky radiative cooling will weaken with it. This will shift the peak of the radiatively-driven divergence downward to warmer temperatures and cause the cloud top temperature to warm. Thus from the basic FAT theory mechanism we expect that the cooling from water vapor will weaken at a fixed temperature if the relative humidity is reduced in the upper troposphere (Harrop and Hartmann, 2012) and that this will lead to warming of the cloud top temperature.

To test the role of the relative humidity on cooling rate in the upper troposphere of the subsiding region we undertake some additional RCE experiments with our one-dimensional model. To simply model the relative humidity changes in Figure 9 we adjust the value of the relative humidity maximum at the top of the convecting layer. Figure S4 shows that reducing the peak relative humidity at the top of the convecting layer from 80% to 40% makes the temperature of the upper convective heating maximum warmer by 5K. This is about half of the warming of cloud top seen in Figure S7a (see below), but much smaller than the 20K warming associated with fixed ozone. Equation 14 indicates that the relative humidity enters in two places in determining the cooling rate. The emission is linear in the relative humidity, and so should decrease substantially, but the lower relative humidity also means that the transmission of that radiation to space will become more efficient with lower relative humidity, so these two effects partially cancel. Cloud resolving model simulations (Kuang and Bretherton 2004, Hartmann et al. 2019) and simulations with single column convective parameterizations (Hartmann and Berry2017) indicate that convective overshoot is important near the top of the convective layer, which may make the rate of destabilization below the level of neutral buoyancy important for the cloud fraction at cloud top. Thus in a more realistic simulation we might expect the average cloud top position to be more sensitive to the radiative destabilization rate immediately below the level of neutral buoyancy than in our 1-D simulation. In that case drying out of the upper troposphere with warming may provide a plausible mechanism for the warming of cloud tops and the decrease in high cloud fraction in the TW simulations shown here.

The relative humidity at the top of the troposphere declines with warming in the control simulations. From Equation 14 in the main text we see that relative humidity enters in both the emission and the transmission terms of the cool-to-space approximation. To make a quantitative estimate of the effect of such changes on the convective heating structure we apply the relative humidity structures shown in Figure S4b. In order to remove temperature effects and isolate the relative humidity effects, the insolation was adjusted to give the same surface temperature as the relative humidity was changed. The ozone is set to a very small value. The temperature and heating rate solutions for these cases are shown in Figure S4a,c,d. While the temperature profile changes very little because of the assumption of a moist adiabatic lapse rate, the convective heating rate and lapse rate kink shift to warmer temperatures by about 5K.

Text S5. Vertical Resolution

In this work we started with the 24-level version of AM2.1 that was used for CMIP5. We added 8 layers in the upper troposphere and stratosphere to better accommodate the high SST experiments we conducted, but did not change the resolution in the boundary layer so as not to de-tune the boundary layer cloud parameterizations. This produced simulations with relatively weak low cloud feedbacks. To test the sensitivity to this choice we also did simulations in which the resolution was doubled to 64 vertical levels. This resulted in a cooler mean climate, but if we adjust the insolation to produce a mean SST comparable to the 32-level experiments, the climate and its sensitivity to SST changes is similar to the 32-level experiments.

Figure S5A shows the corresponding plot to Figure 3 in the text, except that the 64-layer solutions for four values of insolation are superimposed as open symbols. The SST difference, Rnet differene and GHE are remarkably similar as functions of global mean SST, but for the same insolation the 64-level version is about 3K cooler than the 32-layer version. The SST contrast increases up to 309K and then declines. The greenhouse effect (GHE) is unchanged as a function of SST.

The reason for this can be seem in Figure 5B, which shows the cloud radiative effects as a function mean SST. The net cloud radiative effect (NCRE) is 10-15 Wm^{-2} more negative in the 64-level case, because the shortwave cloud radiative effect is more negative.

Figure 5C shows that the precipitation and its apportionment between convective and large-scale parameterizations does not depend strongly on resolution, but is a robust function of SST. The estimated inversion strength (EIS) and lower tropospheric stability (LTS) are both increased in the 64-level version compared to the 32-level version. Higher vertical resolution allows sharper gradients to be maintained and this increases the inversion strength and the amount of low cloud reflectivity for a given global mean SST value. The changes in the ice cloud are much more modest than the low-level clouds (not shown), so the majority of the sensitivity to vertical resolution is in the boundary layer where the inversion is present. This is not surprising.

Text S6. Stratospheric Ozone GCM Experiments

Harrop and Hartmann(2012) performed experiments with a cloud resolving model to show that ozone heating could cause cloud tops to warm as the SST is increased, because warming raises the clouds to regions where ozone heating becomes important if ozone is specified as a fixed function of pressure. In an atmosphere whose only radiatively active gas is water vapor, the model cloud tops remained at the same temperature as the SST was increased, in agreement with the FAT theory (Hartmann and Larson, 2002) We performed experiments in TW in which we reduced the ozone to a small value. Because of the important greenhouse effect of ozone, however, this causes the climate to cool, so in addition we did another set of experiments in which the ozone was reduced, but the global mean SST was maintained at the same value as in the control experiment by applying a small heating to the slab ocean model at every location. Figure S7a shows that the presence of ozone causes the top edge of the cloud to be around 10K warmer, especially for the warmest cases. The sensitivity of the cloud top temperature to surface temperature is also increased when ozone is included. Figure S7b shows that the decrease in cloud fraction and increase of cloud top temperature also occurs when the climate is warmed with CO_2 when ozone is fixed.

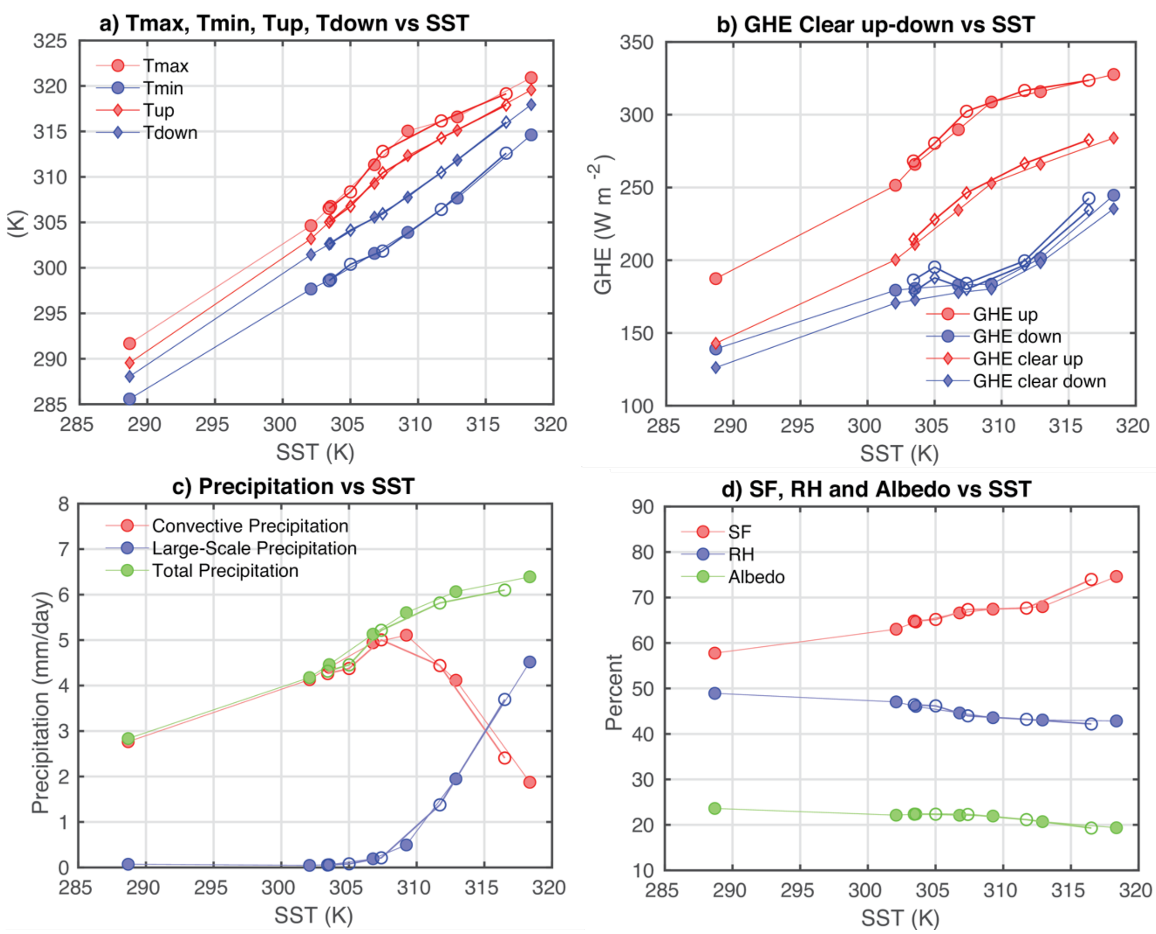

Figure S1. a) Tmax, Tmin, Tup, and Tdown, b) All-sky and clear-sky greenhouse effect in the rising and subsiding regions, c) Total, convective and large-scale precipitation and d) subsiding fraction (SF), mass-averaged relative humidity (RH) and global albedo. Closed circles represent the control simulations forced by insolation increases. Open circles are experiments where the SST was increased by increasing the CO_2 concentration.

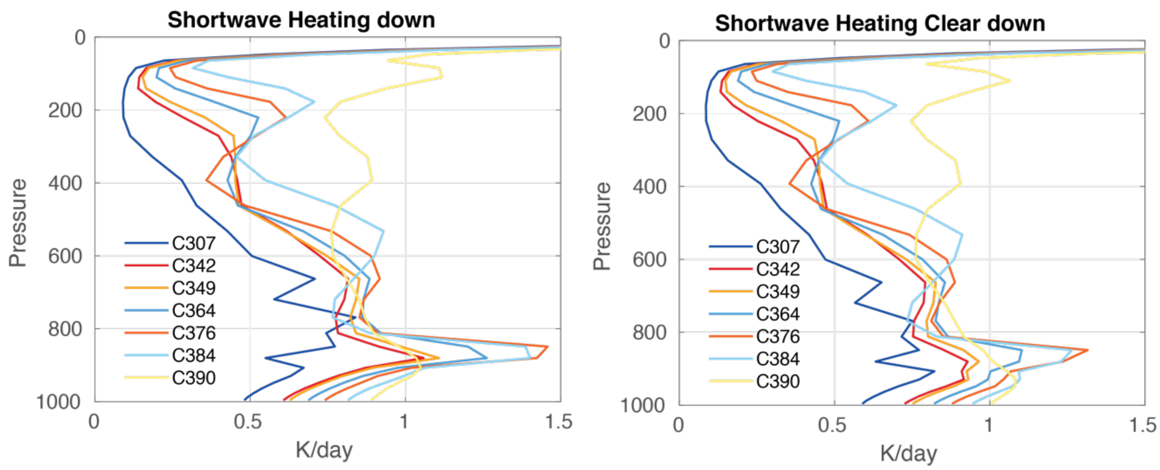

Figure S2. Shortwave radiative heating rate in the subsiding region as a function of pressure for the control cases.

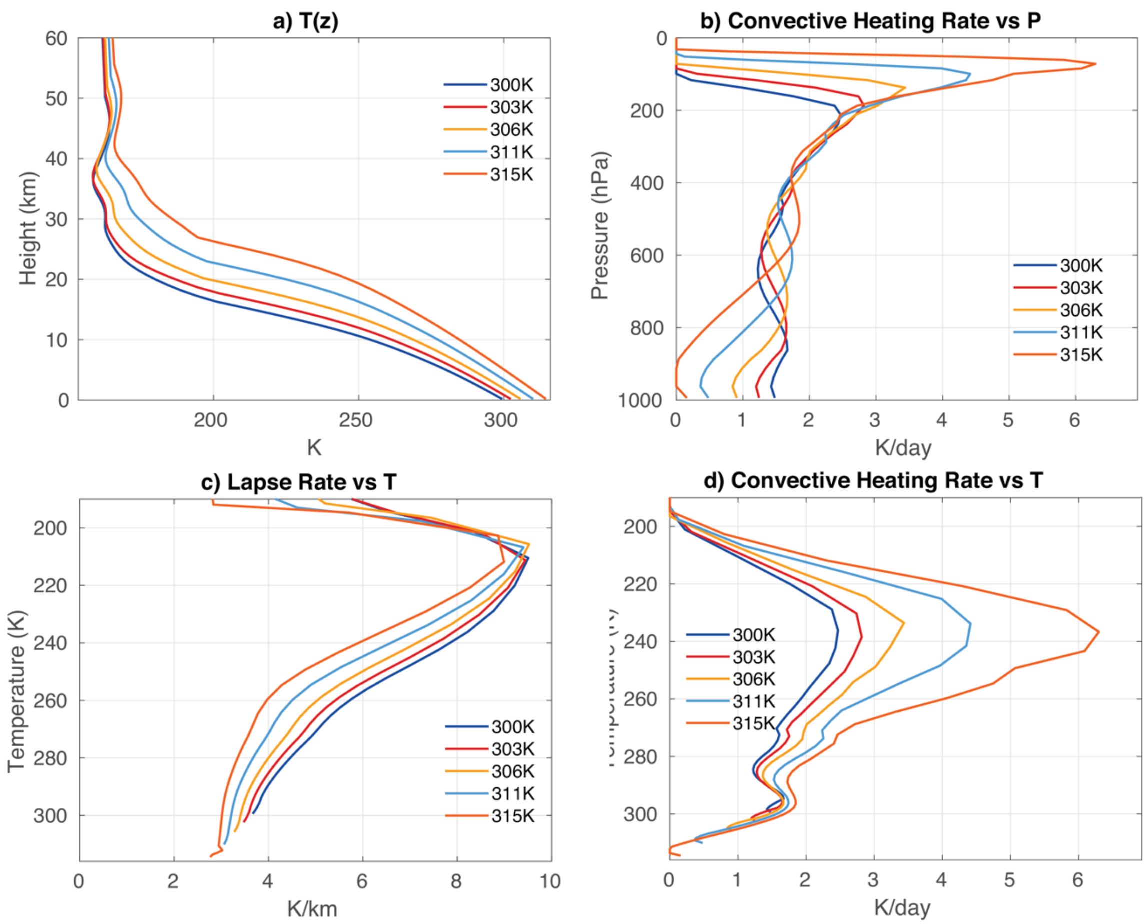

Figure S3A. Same as Fig. 10 in the main text, except for the case in which the ozone is fixed to the climatological tropical profile as a function of pressure, but multiplied by 10^{-6} so as to create a no-ozone case.

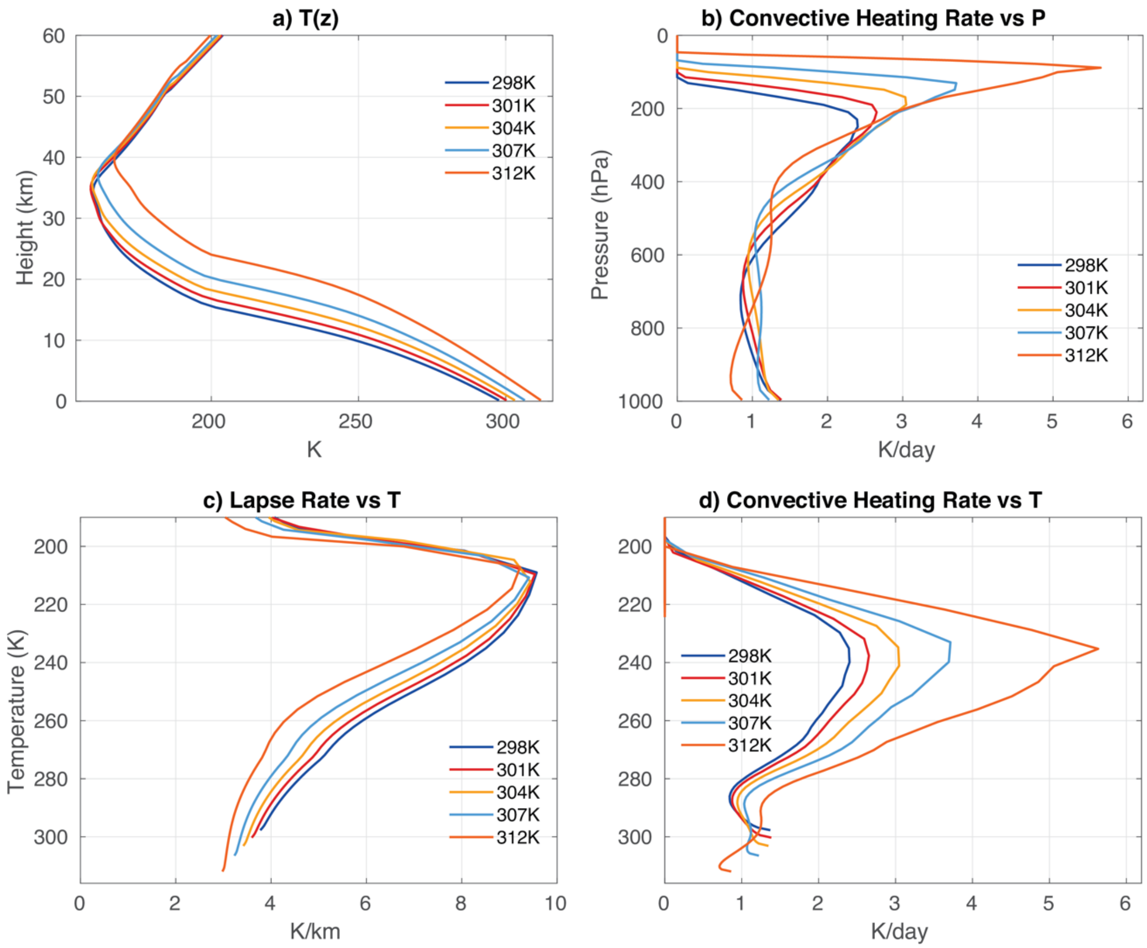

Figure S3B. Same as Fig. S3A except the relative humidity has been set to a uniform 50%. Insolation values have been increased to make the surface temperature fall in a similar range.

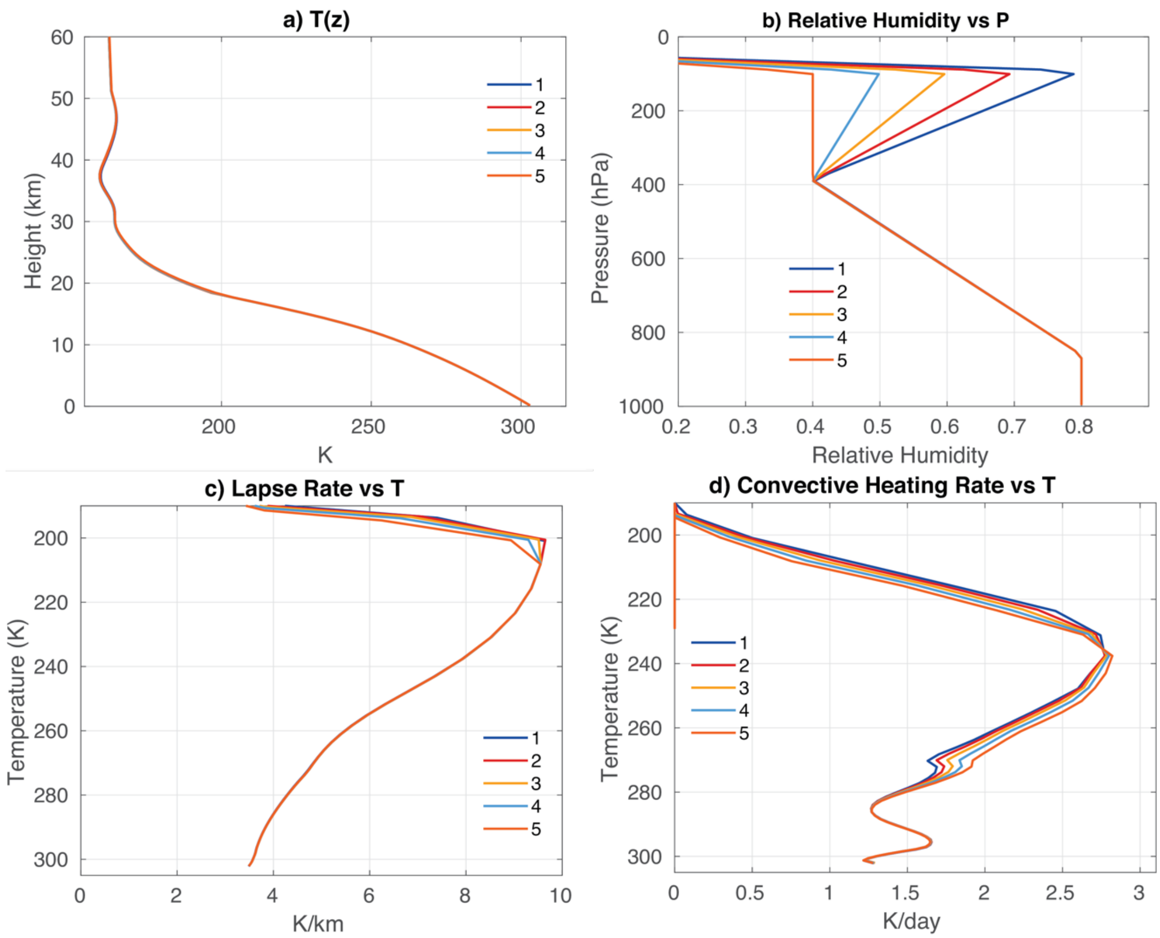

Figure S4A. a) Temperature versus height, b) relative humidity versus pressure, c) lapse rate versus temperature and d) convective heating rate versus temperature for cases meant to study the effect of upper tropospheric humidity on the temperature at which the convective heating rate peaks for 1-D RCE calculations to test the sensitivity of the convective heating to relative humidity.

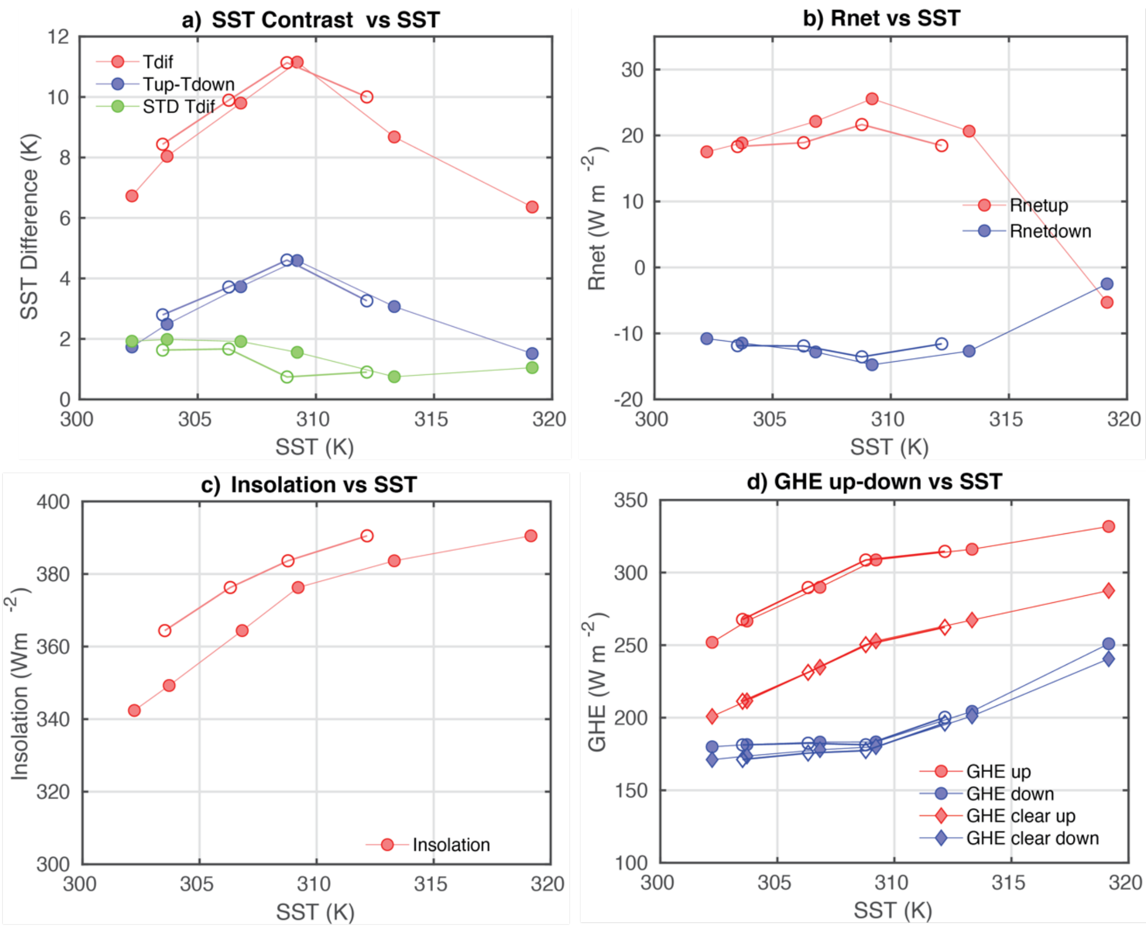

Figure 5A Same as Figure 3 in the text, except that the results of the 64-level model with doubled vertical resolution are superimposed as open symbols.

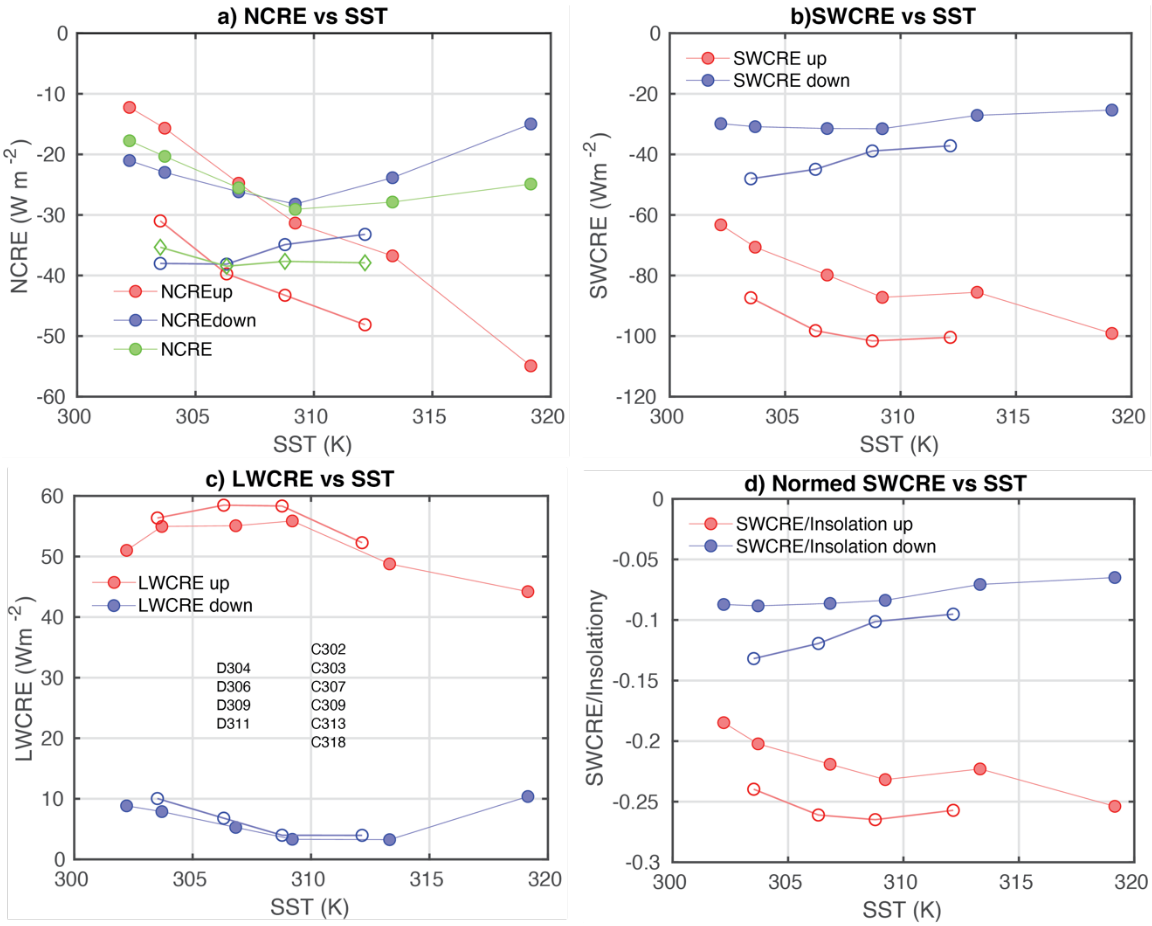

Figure 5B. Cloud radiative effects as functions of global mean SST for the 32-level version (solid) and the 64-level version (open).

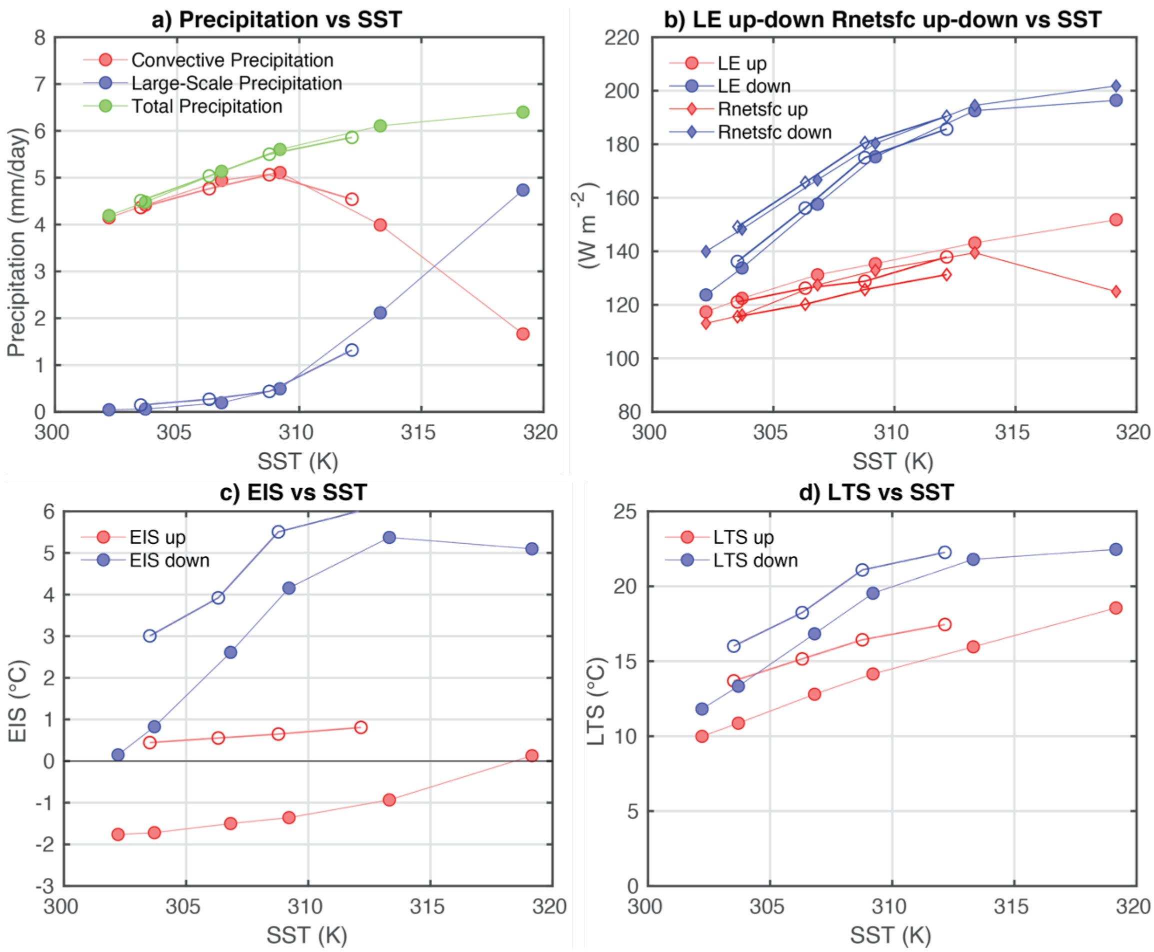

Figure 5C. Same as Figure 5 in the text, except that the 64-level solutions are shown as open symbols.

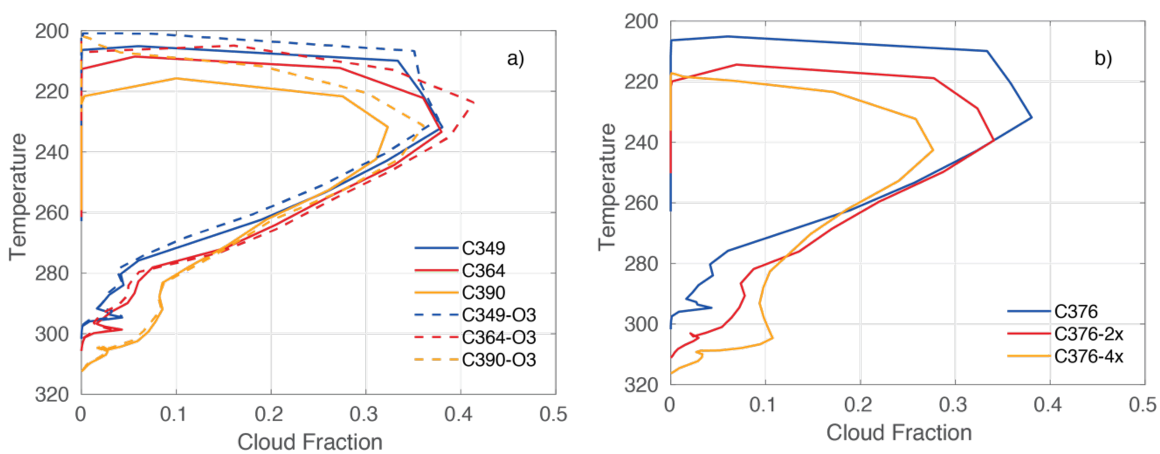

Figure S6. Cloud fraction plotted against temperature as the vertical coordinate. a) cases C303(C349), C307(C364) and C318(C390) with tropical ozone profile (solid), and cases with the same mean SST, but with tropical ozone times 10^{-6} (dashed). b) for case C309(C376) but with 1X, 2X and 4X CO_2 concentration and tropical ozone.

End of Supplementary Information