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# Effects of doubled CO<sub>2</sub> on tropical sea surface temperatures (SSTs) for onset of deep convection and maximum SST: Simulations based inferences

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[1] A primary concern of CO<sub>2</sub>-induced warming is the associated rise of tropical (10S-10N) sea-surface temperatures (SSTs). GISS Model-E was used to produce two sets of simulations—one with the present-day and one with doubled CO<sub>2</sub> in the atmosphere. The intrinsic usefulness of model guidance in the tropics was confirmed when the model simulated realistic convective coupling between SSTs and atmospheric soundings and that the simulated-data correlations between SSTs and 300 hPa moist-static energies were similar to the observed. Model predicted SST limits for (i) the onset of deep convection and (ii) maximum SST, increased in the doubled CO<sub>2</sub> environment. Changes in cloud heights, cloud frequencies, and cloud mass-fractions showed that convective-cloud changes increased the SSTs, while warmer mixed-layer of the doubled CO<sub>2</sub> contained ~10% more water vapor; clearly that would be conducive to more intense storms and hurricanes. **Citation:** Sud, Y. C., G. K. Walker, Y. P. Zhou, G. A. Schmidt, K.-M. Lau, and R. F. Cahalan (2008), Effects of doubled CO<sub>2</sub> on tropical sea surface temperatures (SSTs) for onset of deep convection and maximum SST: Simulations based inferences, *Geophys. Res. Lett.*, 35, L12707, doi:10.1029/2008GL033872.

## 1. Introduction

[2] Two features of present-day tropical SSTs are well-established. First, the highest observed SST does not exceed 30–31°C [e.g., Waliser and Graham, 1993] and second, towering cumulus clouds emerge suddenly at around 28°C SST [Gadgil et al., 1984; Graham and Barnett, 1987; Zhang, 1993]. Some highly cited explanations for the upper limit of the SST are as follows. Newell [1979] suggested evaporative cooling that increases with the SST also limits it. Ramanathan and Collins [1991] suggested that clouds following onset of deep convection reduce the solar irradiation into the ocean to provide a thermostat-like control. Several scientists [e.g., Wallace, 1992; Fu et al., 1992; Lau et al., 1994; Clement et al., 1996] argued that the R-C explanation was

simplistic and many other contributory processes were ignored. Using the TOGA-COARE data, Sud et al. [1999] identified “downdraft cooling” to be the key missing element of the thermostat regulation, as well as provided a physical basis for the onset of deep convection at 28°C.

[3] Singer and Avery [2006] referred to the Sud et al. [1999] and argued that tropical SSTs can not warm beyond 30–31°C, even for doubled CO<sub>2</sub> (hereafter 2xCO<sub>2</sub>) atmosphere. However, Sud et al. [1999] did not imply that the 28°C for the onset of deep convection and the 30–31°C as the limiting SST are rigid constraints. On the contrary, Sud et al. had argued that outside of tropics, deep convection occurs at temperatures far below 28°C. In their data analysis, Kleypas et al. [2008] found relatively small SST increase in the tropics and attributed it to cooling by thermostat referring to it as a “mysterious thermostat”. We submit, one cannot evaluate these inferences without examining the realism of key processes that influence tropical SSTs and how the above two SST limits adjust to a 2xCO<sub>2</sub> environment and how dire can be its consequences. The coupling between saturation moist static energy (SMSE) at convective detrainment-level  $h_t$  { $h_t = c_p T + gz + Lq^*$ , where standard symbols for enthalpy  $c_p T$ , potential energy  $gz$ , and latent energy  $Lq^*$  are employed} and cloud base MSE  $h_b$  help to estimate the cloud-buoyancy energy that a cloud in ascent conserves, but for its reduction by entrainment/detrainment of ambient/in-cloud air. In addition, such an analysis also gives the maximum attainable SSTs [Sud et al., 1999]. In the rest of this paper we describe a) the model and simulation experiments in Section 2, b) the key results with verification in Section 3, and c) a brief discussion of several findings and resulting consequences in Section 4.

## 2. GISS Model-E simulations

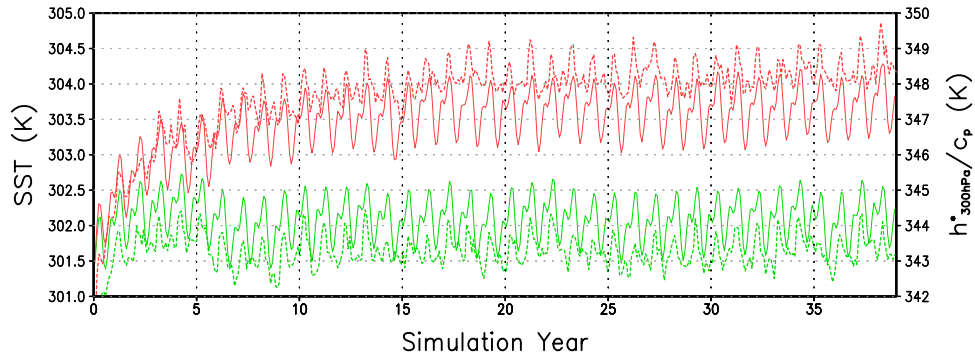
[4] GISS Model-E (GISS-E) was chosen for the proposed investigation. It employs 4° lat. x 5° long. x 20-sigma levels in the vertical. GISS-E [Schmidt et al., 2006] has fully interactive land, a multilayer ocean, and dynamical atmosphere with parameterized physics. Its current cloud-scheme is from Del Genio et al. [1996]. The code and accompanying forcing datasets can be downloaded from the GISS website: <http://www.giss.nasa.gov/tools/modelE>. The model was run at GISS for 380-years till its land, ocean, and atmosphere attained quasi-equilibrium with present-day CO<sub>2</sub>. This was reconfirmed by running the model for forty

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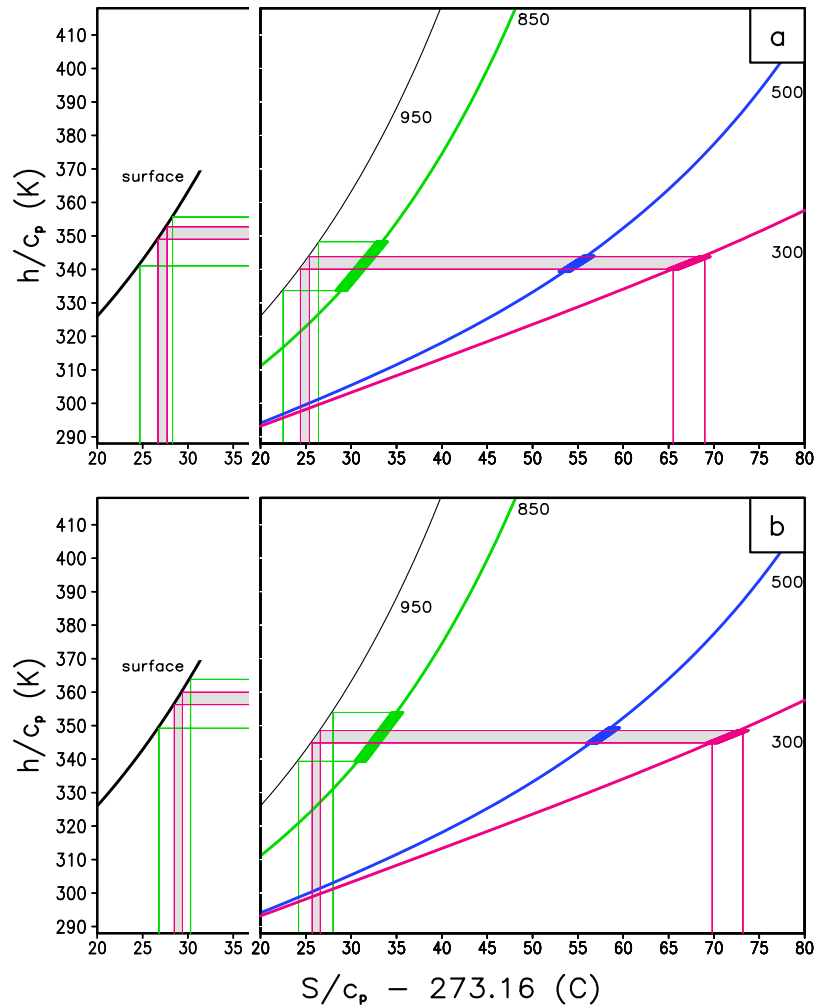
**Figure 1.** Four lines show time-evolution of SST and  $h_{300}^*$  (averaged for 10S-10N) for the present-day and 2xCO<sub>2</sub> simulations. Solid (dashed) lines correspond to SST ( $h_{300}^*$ ). Initial time and annual-mean values for both fields are taken as datum.

more years as a baseline simulation. Thereafter, another parallel simulation with 2xCO<sub>2</sub> was made.

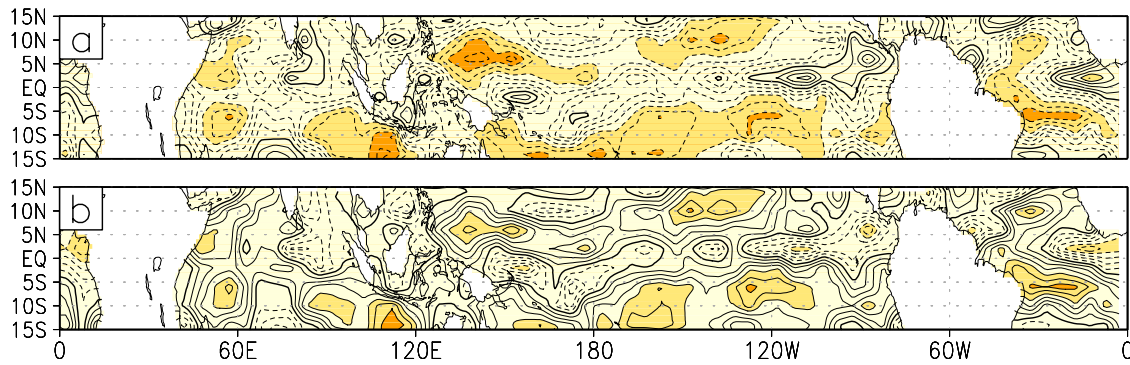
### 3. Data Analysis

[5] A coupled model takes many centuries to attain full equilibrium, but the mixed-layer of GISS-E achieved quasi-

equilibrium between the atmosphere and ocean mixed-layer in a much shorter period. The last 20 years of the 40-years integration were sufficient for examining the SST-dependant convective coupling with the atmosphere. Figure 1 shows that GISS-E maintains drift-free tropical (10S-10N) as well as global (not shown) SSTs over the integration period. The two wavy lines show several annual cycles of SST and



**Figure 2.** Tropical (10S-10N) 300hPa SMSE and SST in (a) 1xCO<sub>2</sub> and (b) 2xCO<sub>2</sub> cases. Ambient  $\Delta S_{t300}/c_p$  corresponds to SMSE as  $\Delta h_{t300}/c_p$ . Conserving SMSE in cloud ascent yields  $\Delta h_b/c_p = \Delta h_{t300}/c_p$ ; left panels have  $\Delta S_{surf}/c_p$  (SST range) with corrections in  $h_{t300}$  due to PBL and CCWF.



**Figure 3.** Correlations between (a) SST and cloud top pressures and (b) SST and cloud mass fraction for 2x CO<sub>2</sub> minus 1x CO<sub>2</sub> using 12 month running means. Contour interval is 0.1 with solid (dashed) lines for positive (negative) values; clear, light, medium, and dark shades cover <0.4, 0.4–0.6, 0.6–0.8, >0.8 range.

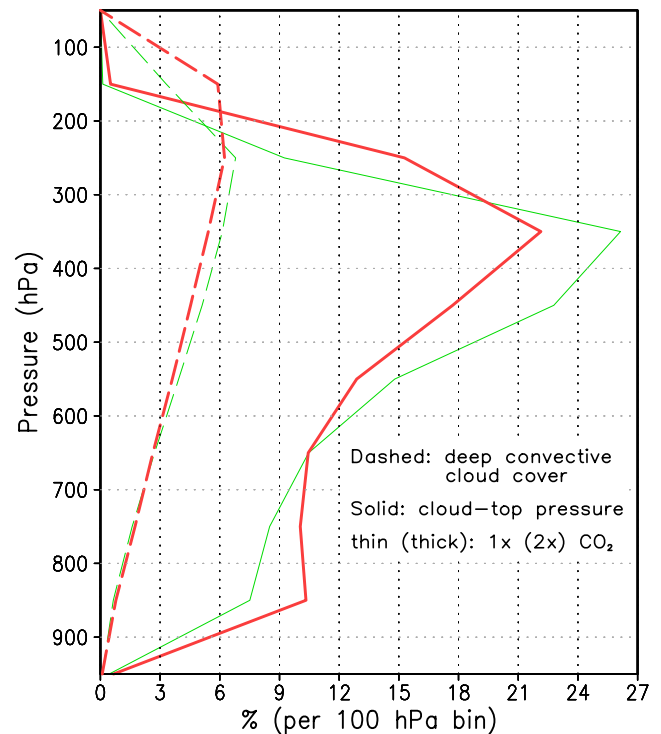
300 hPa  $h_i$  (hereafter  $h_{i300}$ ). On doubling the CO<sub>2</sub>, the tropical-mean SST started to rise in unison with  $h_{i300}$ . This is seen as second set of lines bifurcating upwards from the control case. Following Sud *et al.* [1999], Figure 2 shows that one can easily obtain the minimum SST needed to support clouds detraining at 300hPa. Introducing ambient dry static energy as  $S/c_p$  (°C) and SMSE as  $h/c_p$  (°K) for cloudy air, we get cloud base  $h_b \equiv h_{i300}$ , if the cloud is non-entraining that conserves  $h$ . For ambient  $\Delta S/c_p$ , (shown as bold riders at each pressure level), we obtain  $\Delta h/c_p \equiv \Delta h_{i300}/c_p$ . With appropriate allowance for boundary-layer contribution (MSE differences between sea-surface and cloud base levels) plus  $h$  loss in cloud ascent often defined by Critical Cloud Work Function (CCWF), we obtain somewhat larger  $h/c_p$  but with the same  $\Delta h/c_p$  (left panels). This in turn gives larger surface  $S/c_p$  (or SST), but with same  $\Delta S/c_p$  (or SST range). Thusly inferred SST increase is  $\sim 1.5^\circ\text{C}$  for 2xCO<sub>2</sub> minus 1xCO<sub>2</sub> *vis-à-vis* the simulated value of  $1.53^\circ\text{C}$ . The minimum SST for the onset of shallow clouds (850hPa detraining) is smaller, but its  $\Delta S/c_p$  is much larger due to the verticality of  $S/c_p$  at 850hPa. Accordingly, the atmosphere can generate shallow clouds if the cloud-base air-mass is nearly saturated before the onset of moist convection [Sud and Walker, 2003]. The simulated and the analyzed observations data [Uppala *et al.*, 2005] were used to determine how well GISS-E captures the observed correlations between  $h_{i300}$  and SSTs. The patterns of correlations were similar to the observed (not shown), which implies realistic SST- $h_{i300}$  coupling.

[6] Figure 3a shows the correlation between 2xCO<sub>2</sub> minus present-day 1xCO<sub>2</sub> cloud top pressures (CTPs) and cloud mass-fractions with the SSTs. Preponderance of negative correlations imply that cumulus clouds reach higher levels in 2xCO<sub>2</sub> atmosphere, which accords with Lindzen *et al.* [2001], while larger cloud fractions above 300 hPa, inferred from positive correlation with SSTs (Figure 3b) does not; however, the clouds between 650–300hPa did reduce (Figure 4). Total cloudiness for the entire column-atmosphere also reduced marginally. Indeed, larger  $h_b$  of 2xCO<sub>2</sub> simulation enabled convection to reach higher and the accompanying subsidence warming reduced cloud-detrainment into layers just below. The energy budget showed more shortwave ( $3.5 \text{ Wm}^{-2}$ ) and longwave ( $4.0 \text{ Wm}^{-2}$ ) absorbed by the ocean. This was almost entirely balanced by more evaporation. At the top of the atmosphere (TOA), there was virtually no change in the net

incoming SW(outgoing LW) radiations for clear sky conditions, but each was larger by  $\sim 4.0$  ( $\sim 0.5$ )  $\text{Wm}^{-2}$  for 2xCO<sub>2</sub> simulation for all sky conditions. The total radiative cooling of the atmosphere was  $4.0 \text{ Wm}^{-2}$ ; and of this only  $1.5 \text{ Wm}^{-2}$  was mitigated by rainfall increase. The rest was primarily advection from land regions. Our rationale for trusting the GISS-E guidance is as follows.

#### 4. Discussion

[7] All numerical models have limitations due to coarseness of resolution and parameterized sub-grid scale processes; hence all unverifiable model guidance(s) must be evaluated for realism of the key interactions affecting the results.



**Figure 4.** Cloud top pressure (solid) and convective-cloud frequency (dashed) binned by 100 hPa intervals. Plots for present-day (doubled) CO<sub>2</sub> runs are shown by thin (thick) lines.



GISS-E simulated convective coupling verified well against the observed; moreover, the correlations between SST and  $h_{t300}$  were also similar to the observed. This confirmed model's ability to simulate tropical convection-SST coupling reasonably. The model predicts an increase of both 28°C SST for the onset of deep convection and 30–31°C as its upper limit. Accordingly, *Singer and Avery* [2006] and *Kleypas et al.* [2008] projections of present-day limits of maximum SSTs are potentially invalid for a doubled CO<sub>2</sub> atmosphere.

[8] Cloud detrainment heights and mass-fluxes are governed by condensation heating deficits [*Larson and Hartmann*, 2003], which force cloud detrainment-level SMSEs to align with the cloud base SMSE. It is true for observations [*Sud et al.*, 1999] and is evidenced in GISS-E simulations. Hence the cloud influences on net incoming SW and outgoing LW at the top of the atmosphere are far more complex than the *Lindzen et al.* [2001] postulate(s). Despite lack of a state-of-the-art cloud-aerosol-precipitation microphysics for inferring cloud optical thickness, we argue that GISS-E model approximations would largely, if not entirely, cancel out in the anomaly minus control mode of analysis. Moreover, GISS-E simulations are well within the limits of several observations-data analyses [e.g., *Lindzen et al.*, 2001; *Fu et al.*, 2002; *Hartmann and Michelsen*, 2002; *Lin et al.*, 2002; *Spencer et al.*, 2007]. Clearly, SST-cloud couplings are difficult to discern directly from observations because instantaneous clouds are affected by circulation dynamics more than the local SSTs.

[9] In doubled CO<sub>2</sub> simulation, only about 10% of increased TOA solar irradiation warmed the atmosphere directly. There was an accompanying increase of net SW and LW radiation into the ocean and that in turn increased the ocean-evaporation, whereas the precipitation was virtually unchanged. Indeed, there was compensating low-level horizontal divergence of water vapor. Even if the OLR aloft had increased, the model would have used up the diverging evaporation to bolster the condensation heating through clouds ascending to appropriate detrainment levels, but that did not happen. Instead, the model simulated a warmer boundary-layer with more water vapor and shallow clouds. Both of them are conducive to increased warm rain [*Lau and Wu*, 2003] as well as more intense precipitation in emerging tropical storms and/or hurricanes, a topic of extensive data analysis [e.g., *Emanuel*, 2005; *Lau and Wu*, 2007] and active debate. Overall, GISS-E guidance of CO<sub>2</sub> caused tropical (10S–10N) SST warming is fundamentally correct and the present-day SST-limits for both (i) the onset of moist convection and (ii) SST maximum in the tropics are bound to rise.

[10] **Acknowledgments.** GISS and GSFC modeling research is supported by NASA HQ. We used GISS ModelE simulations to infer the relationship between atmospheric temperatures and SSTs in a 2XCO<sub>2</sub> environments.

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