15B.1 AN IDEALIZED WALKER MODEL COUPLED TO AN OCEAN MIXED LAYER

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1. INTRODUCTION

Recently, a class of simplified tropical climate models based on the Quasi-Equilibrium Tropical Circulation Model (QTCM) of Neelin and Zeng (Neelin and Zeng 2000) has been constructed to explore feedbacks between clouds, radiation, sea surface temperature (SST) and the large scale divergent circulation. The QTCM is based on the observation that a significant portion of the tropical mean climate and variability can be explained with a barotropic and one baroclinic vertical mode. These modes are prescribed *a priori* and projected on the non-linear primitive equations; the resulting equations are then vertically integrated leaving a two dimensional model.

The QTCM is then further reduced to a one dimensional, irrotational depiction of the east-west Walker circulation and coupled to an ocean mixed layer. The Weak Temperature Gradient (WTG) approximation of Sobel et al. (2001) is applied. Here we consider radiative feedbacks of two cloud types, high convective anvils and low non-precipitating stratus. These are parameterized as linear functions of model variables. We present cloud feedbacks on the mean and CO_2-enhanced Walker circulation.

2. MODEL EQUATIONS

The model variables are separated as the sum of a horizontally constant radiative-convective equilibrium state (RCE) denoted with a subscripted 0 and a perturbation:

$$\begin{aligned}
\tilde{T}(p,t) &= T_0(p) + a(p)T(t) \\
\tilde{q}(x,p,t) &= q_0(p) + b(p)q(x,t) \\
\tilde{u}(x,p,t) &= V(p)u(x,t) \\
\tilde{\omega}(x,p,t) &= \Omega(p)\omega(x,t) \\
\tilde{T}_s(x,t) &= T_{s0} + T_s(x,t)
\end{aligned}$$

T is temperature, q moisture, u and ω the winds and T_s the surface (ocean) temperature. All thermodynamic quantities are expressed in equivalent energy units (J kg^{-1}). The signs of the basis functions V and Ω are chosen so that the direction of u is that of the upper tropospheric x-wind component and $\omega > 0$ represents upward motion everywhere in the column.

The model equations of Sobel (2003) are used, except for the radiative heating terms which are modified as follows:

$$\begin{aligned}
R &= R^{clr} + R^{cld} + \Delta R(x) \\
S &= S^{clr} + S^{cld} + \Delta S(x) \\
R^{clr} &= R_0^{clr} + \epsilon_R^q q + \epsilon_R^T T + \epsilon_R^{T_s} T_s = R_0^{clr} + R'^{clr} \\
S^{clr} &= S_0^{clr} + +\epsilon_S^q q + \epsilon_S^T T + \epsilon_S^{T_s} T_s = S_0^{clr} + S'^{clr}
\end{aligned}$$

R is the sum of the net atmospheric radiative flux divergence and the mean lateral dry static energy export ΔR out of the domain. S is the sum of the net surface heating due to radiation and ocean transport $[\Delta S(x)]$. $\Delta R(x)$ is prescribed to be horizontally uniform, and $\Delta S(x)$ is taken to vary linearly across the domain. The ϵ's are linearization coefficients computed from a numerical radiative transfer model (Chou and Neelin 1996). If q and T_s are conceived as functions of T, one can linearize $R'^{clr} - S'^{clr} \approx c(x)T(p_s)$, where $T(p_s)$ is the surface air temperature. The domain mean of c dictates the climate sensitivity. If $\delta q \sim \delta T$ and $\delta T_s \sim \delta T(p_s)$ for some climate perturbation, the QTCM coefficients give $c = 2.3$ W m^{-2} K^{-1} or a warming of 1.7 K for 4 W m^{-2} of greenhouse gas forcing.

We include two cloud types, deep convective clouds and stratus clouds:

$$\begin{aligned}
R^{cld} &= -r_1 P + [1 - H(P)] r_2 LTS \\
S^{cld} &= -r_1 P - [1 - H(P)] r_2 LTS
\end{aligned}$$

H is the Heaviside function. Deep convective cloud radiative forcing (CRF) is assumed proportional to large scale precipitation, P, and stratus CRF assumed proportional to lower tropospheric stability, LTS. Observations give $r_1 \approx 0.175$ (Bretherton and Sobel 2002) and $r_2 \approx 3.5$ (Klein and Hartmann 1993). Prescribed greenhouse gas forcing GHG can be incorporated into the clear sky fluxes.

The steady state, domain integrated moist static energy equation reduces to $\int (S - R)\, dx = 0$. Invoking RCE energy balance, this reduces to

$$\overline{GHG} = R'^{clr} - S'^{clr} + \overline{LOW} \qquad (1)$$

with $\overline{LOW}$ the domain averaged stratus CRF (over bar denotes domain mean). In the absence of any imposed greenhouse forcing, this cooling must be compensated for by decreased clear sky cooling (lower T).

Other differences from Sobel's (2003) study are the use of a horizontally uniform gross moist stability M in the convective area and a longer convective relaxation time scale, $\tau_c = 16$ h.

3. MODEL SOLUTIONS AND ANALYSIS

Fig. 1 examines high cloud feedbacks by comparing

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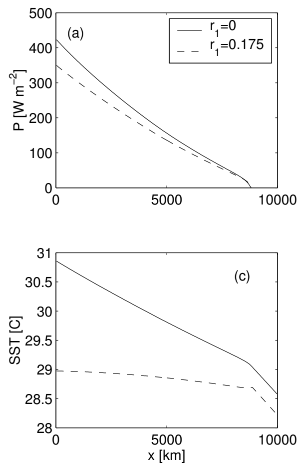

Figure 1: Model output of (a) precipitation, [W m^{-2}], (b) column water vapor path [mm], (c) SST [C], and (d) evaporation [W m^{-2}] for the case with no clouds (solid) and strictly high clouds (dashed).

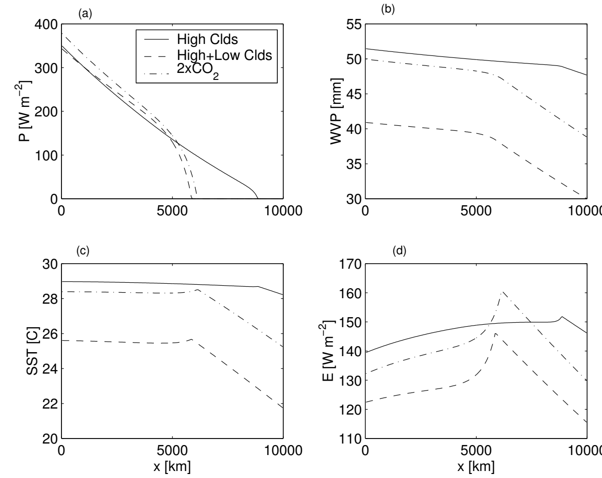

Figure 2: Same as Fig 1 except for high clouds only (solid), both high and low clouds (dashed) and 2xCO_2 sensitivity (dotted).

cases with and without the radiative effects of convective anvils, while suppressing any stratus CRF. As the high clouds have zero net top of the atmosphere (TOA) radiative forcing their presence does not change the convective area fraction. They do however block significant shortwave and decrease $\overline{S}$; the surface energy budget then dictates the evaporation $\overline{E}$ must decrease a corresponding amount. Less $\overline{E}$ implies less precipitation, $\overline{P}$. Convective heating balances radiative cooling, so $\overline{R'^{clr}}$ decreases and T lowers. Suppressed horizontal gradients in E translate to flattened SST gradients.

Fig. 2 shows the model response when low clouds are added. The enhanced radiative cooling decreases T. The convective area fraction is driven primarily by two things: the effective gradient in moist static energy flux, $S - R$, across the domain, and the gross moist stability M. Low clouds locally cool the cold pool and decrease $S - R$. Energy balance requires a corresponding increase in $S - R$ in the warm pool and the horizontal gradient is effectively increased. The circulation strengthens, the cold pool widens, more clouds are produced and the system further cools.

In the 2xCO_2 sensitivity also shown in Fig. 2, a uniform 4 W m^{-2} radiative warming was added to the atmosphere and results in an increase of domain averated T of 2.6 K. The low clouds are found to have a positive feedback on the surface warming. The domain averaged stratus CRF decreases by 2 W m^{-2} from the control run to the 2xCO_2 run. This warming is due to two effects: a decrease in cold pool LTS, and a increase in the convective area fraction. Moreover, the effective value of $\overline{c}$ decreases to 2.15 W m^{-2} K^{-1} due primarily to larger increases in tropospheric water vapor. Without low clouds (not shown), this effect is absent, $\overline{c}$ remains 2.3 W m^{-2} K^{-1}, and the temperature only increases 1.7 K.

4. CONCLUSION

We have created a conceptual model of the divergent tropical circulation and its interaction with clouds, SST and other climatic variables of interest. Model shortcomings - primarily the neglect of the rotational atmospheric circulation and highly truncated vertical structure - are exchanged for clarity. It is our hope that the conclusions of simple models such as this will provide testable hypotheses for more sophisticated models and observations.

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