Climate Response to the Physiological Forcing of Carbon Dioxide in Radiative-Convective Equilibrium: An Idealized Study

Timothy W. Cronin, Kerry A. Emanuel, Ronald G. Prinn

Program in Atmospheres, Oceans, and Climate, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge 02139

Introduction

• Elevated CO_2 → reduced stomatal conductance and transpiration over land surfaces – "**physiological forcing**" (Figure 1)

• Roughly 0.4 K warming of surface air over land for a doubling of CO_2 (Table 1)

• Potentially 20-30 % of total 2 x CO_2 warming, regionally (Cao et al., 2010)

• Can we constrain the magnitude of this important component of climate change with theory and simple models?

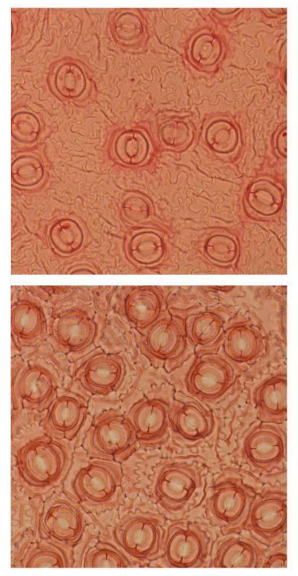

Figure 1 – Lammertsma et al. (2011) found declining stomatal conductance in leaf specimens from Florida tree species.

Top panel: contemporary plant leaf
Bottom panel: leaf of same species just a few decades ago
Image from:
[www.sciencedaily.com/releases/2011/03/110303111624.htm]

Theory (1)

• Extending Betts and Chiu (2010), we identify the warming mechanism as an **increase in the equilibrium depth of the mixed layer (ML)** (Figure 2)

• Based on Betts and Chiu (2010) and Takahashi (2009), we use the ML temperature equation:

$$[1] \quad \mathrm{H} = c_p Q_{ML} P_{ML}/g$$

• Change in the pressure depth and temperature of the ML are related by lapse rate differences:

$$[2] \quad \delta\mathrm{H} = \delta T_A \rho_M c_p Q_{ML}/(\Gamma_d - \Gamma_m)$$

• This diagnostic relationship between changes in sensible heat flux and changes in surface air temperature can be compared roughly with results from GCM studies (Table 1)

• Order-of-magnitude estimation: $\delta T_A/\delta\mathrm{H} \approx 0.25$ K/(W m^{-2})

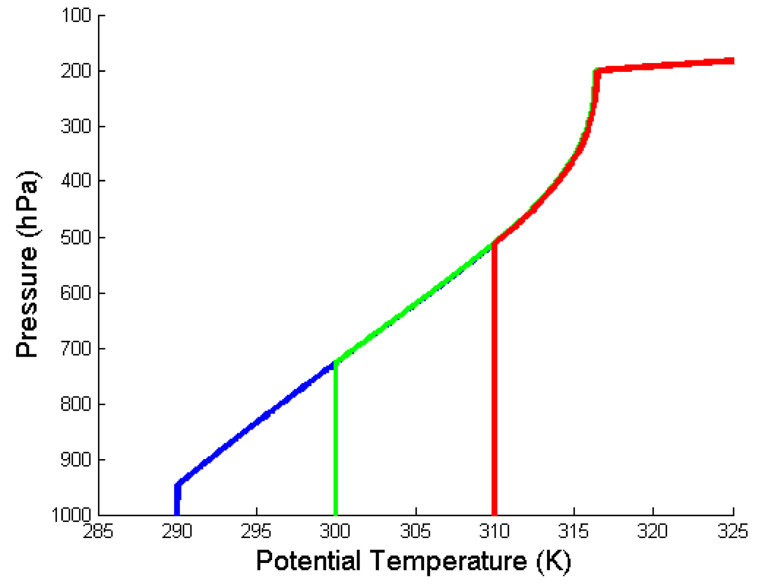

Figure 2 – Schematic of equilibrium warming mechanism. Under elevated CO_2, reduced evapotranspiration results in a larger sensible heat flux, which can balance the larger radiative cooling of a deeper, warmer ML.

Experimental Design

• 2-column RC model (Abbot and Emanuel, 2007), (Figure 3)

• Run for different evaporative fraction β [0-1] over land as in Molnar and Emanuel (1999)

• Surface enthalpy fluxes based on bulk formulae:

$$[3] \quad \mathrm{H} = \rho_0 c_p c_D |\boldsymbol{v}| (T_s - T_A)$$

$$[4] \quad \mathrm{E} = \rho_0 L_v c_D |\boldsymbol{v}| \beta (q_s{}^* - q_A)$$

• Equivalent to "big-leaf" surface fluxes with: $c_D|\boldsymbol{v}| = g_A$ and $\beta = \frac{g_c}{g_A + g_c}$

• Can relate changes in canopy conductance to changes in evaporative fraction using $\delta(\ln\beta) = \frac{g_A}{g_A+g_c}\delta(\ln g_c)$

• Vary solar constant S_0 [1000,1025,1050] W m^{-2} and column width [1000,2000,4000] km

• Equatorial location, perpetual equinox ($F_\downarrow = S_0/\pi$), no diurnal cycle or cloud-radiation interactions, ocean and land albedo and c_D set equal

• Land-ocean surface air temperature contrast: $\Delta T_A = T_{A,land} - T_{A,ocean}$

• Land-ocean surface skin temperature contrast: $\Delta T_S = T_{S,land} - T_{S,ocean}$

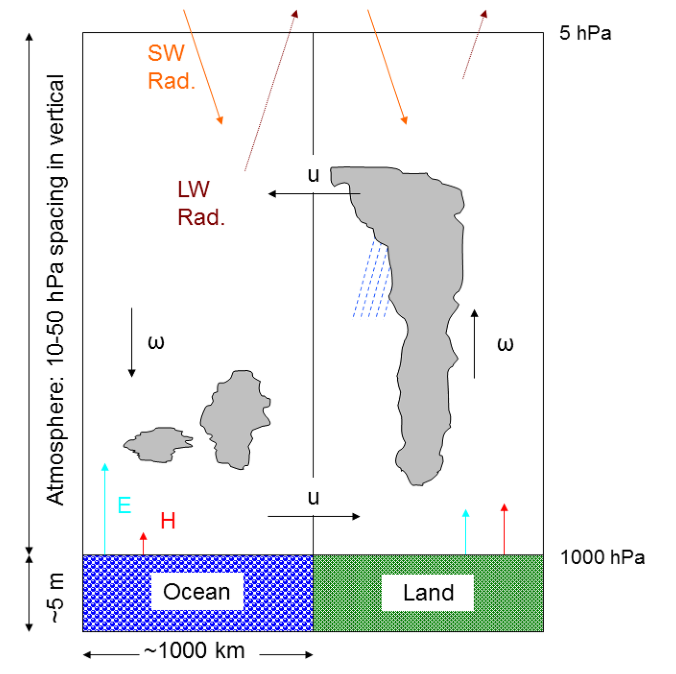

Figure 3 – Schematic of 2-column RC model. Sophisticated treatment of radiation and convection, dynamics based on prognostic vorticity equations in direction orthogonal to domain. Mixed land/ocean domain allows for calculation of land-ocean contrasts and comparison to eqns. [5] and [6].

Theory (2)

- Surface energy balance and convective neutrality (see theory sheet) give an approximate analytic expression for the dependence of ML temperature on β:

$$[5] \quad T_A(\beta) - T_A(\beta_{ref}) = -\frac{E_{ref}}{\beta_{ref}\,E^*}\ln\left(\frac{F^* + E^*\beta}{F^* + E^*\beta_{ref}}\right)$$

- Parameters F* and E* (units: W m^{-2} K^{-1}) govern shape of curve described by [5] and are based on thermodynamics and land surface properties
- Surface skin temperature changes are related by the multiplicative factor $(1+\gamma)$ to [5] (γ is order 1):

$$[6] \quad T_S(\beta) - T_S(\beta_{ref}) = -\frac{(1+\gamma)E_{ref}}{\beta_{ref}\,E^*}\ln\left(\frac{F^* + E^*\beta}{F^* + E^*\beta_{ref}}\right)$$

- For $\beta_{ref} = 1$ we denote the LHS of eqns. [5] and [6] as ΔT_A and ΔT_S, respectively, to compare to model simulations
- For $E^*\beta >> F^*$, $T_A(\beta)$ is simply logarithmic

Table 1

Study	δT_{PF}(K)	$\frac{\delta T_{PF}}{\delta T_{+CO_2}}$ (%)	δH (W/m^2)	δT_A(K, eqn [2])
Sellers et al. (1996)	0.2	7	~	~
Cox et al. (1999)	0.39	11	~	~
Notaro et al. (2007)	0.4	15	~	~
Boucher et al. (2009)	0.52	13	1.91	0.48
Cao et al. (2009)	0.12	5	0.15	0.04
Cao et al. (2010)	0.47	14	2.11	0.53

Summary of studies on warming due to physiological forcing. Warming due to physiological forcing (δT_{PF}) is given in both absolute and percent terms. Sensible heat flux changes have only been reported in recent studies. The last column gives a warming estimate using δH of recent studies and my eqn. [2].

Land – Ocean Surface Temperature Contrasts

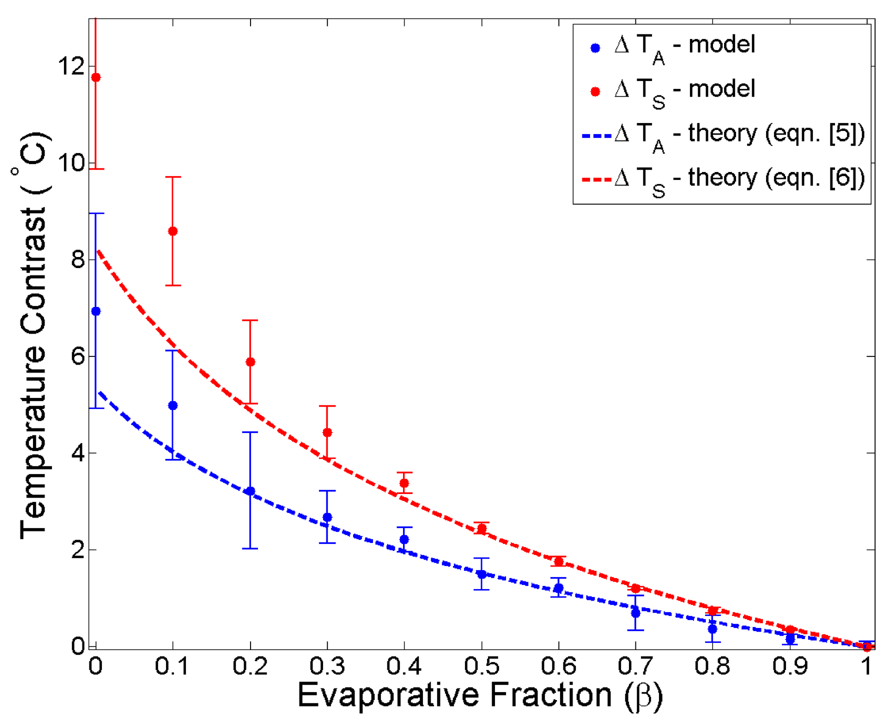

Figure 4 – Comparison of model and theory. Model results are the mean of nine 2-column runs (3 values each of column width and S_0); error bars are 1-σ. Theory is eqns. [5] and [6] expanded about β_{ref}= 1, using E_{ref}= 140 W m^{-2}, F^*= 8.4 W m^{-2} K^{-1}, E^*= 51.7 W m^{-2} K^{-1}, and γ= 0.55.

- Model and theory agree fairly well (even away from β_{ref})
- Low-β deviations expected due to nature of expansion and neglect of other factors (e.g. advection)
- δT_A~ 0.27 K for a 10% reduction in β, so long as $E^*\beta >> F^*$ (scale of warming similar for a broad range of land surface parameters)
- Limitation: Only valid for large, homogeneous, tropical land areas; compensatory increase in soil evaporation neglected
- Limitation: Impacts of β on land+ocean mean T_A unclear
- Limitation: Lack of clouds; could incorporate cloud effects into theory by including an additional term in F^*

Precipitation and Circulation

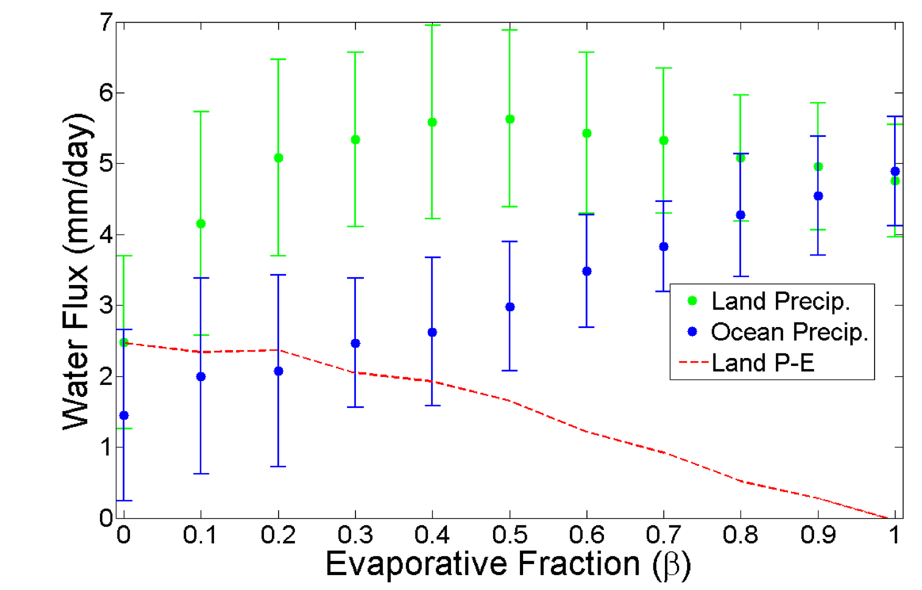

Figure 5 – Model results for precipitation over land and ocean columns (values and error bars as in Fig. 4; error bars on land P-E line omitted for clarity)

• Decreasing β→ Stronger mean circulation with ascent (not shown) and enhanced precipitation over warmer land

• Decreasing β→ Increasing P-E over land: would expect strongly negative soil moisture-precipitation feedback with inclusion of interactive soil moisture

• Limitation: Fuller theory (in development) needs to take mean overturning circulation into account

• Limitation: Diurnal cycle may have nontrivial impacts on land-ocean hydrology (and temperature) contrast

Conclusions

• We have successfully developed a theory to constrain the magnitude of the land-ocean warming contrast due to physiological forcing in a moist-neutral atmosphere

• The diagnostic relationship [2] and Table 1 suggest that future GCM studies should report δH values

• Our results have numerous limitations, but hopefully provide a building block for analyzing results of GCM studies of surface warming due to physiological forcing

• Potential future work: impacts of clouds and mean circulation (models and theory), diurnal cycle and interactive soil moisture (models)

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