

Why is there a short-term increase in global precipitation in response to diminished CO₂ forcing?

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[1] Recently, it was found that a reduction in atmospheric CO₂ concentration leads to a temporary increase in global precipitation. We use the Hadley Center coupled atmosphere-ocean model, HadCM3L, to demonstrate that this precipitation increase is a consequence of precipitation sensitivity to changes in atmospheric CO₂ concentrations through fast tropospheric adjustment processes. Slow ocean cooling explains the longer-term decrease in precipitation. Increased CO₂ tends to suppress evaporation/precipitation whereas increased temperatures tend to increase evaporation/precipitation. When the enhanced CO₂ forcing is removed, global precipitation increases temporarily, but this increase is not observed when a similar negative radiative forcing is applied as a reduction of solar intensity. Therefore, transient precipitation increase following a reduction in CO₂-radiative forcing is a consequence of the specific character of CO₂ forcing and is not a general feature associated with decreases in radiative forcing. **Citation:** Cao, L., G. Bala, and K. Caldeira (2011), Why is there a short-term increase in global precipitation in response to diminished CO₂ forcing?, *Geophys. Res. Lett.*, 38, L06703, doi:10.1029/2011GL046713.

1. Introduction

[2] The global hydrological cycle is an important component of the climate system. Changes in the hydrological cycle and associated extreme events could have profound effects on the ecosystems and our society [Meehl *et al.*, 2007]. Recently, it was shown that in response to a reduction in atmospheric CO₂ concentrations, global mean precipitation increases temporarily for several decades before it starts to decrease [Wu *et al.*, 2010]. As a result, two different precipitation states are observed at two different CO₂ levels with the same global mean temperature. Wu *et al.* [2010] referred to this precipitation behavior as ‘precipitation hysteresis’ and attributed it to the accumulated heat storage in the ocean.

[3] Here we revisit the issue of short-term precipitation increase following a reduction in CO₂ forcing by simulating transient climate change in response to imposed changes in CO₂ and solar forcing. Our results show that the temporary increase in precipitation following a reduction in atmospheric CO₂ content is due to the specific feature

of CO₂-radiative forcing and not a general character associated with the decrease in radiative forcing.

2. Method

2.1. Model

[4] We used the UK Met Office Hadley Center coupled Atmosphere-Ocean-General Circulation Model (AOGCM), HadCM3L [Cox *et al.*, 2000]. HadCM3L has a resolution of 3.75 degree longitude and 2.5 degree latitude for both the atmosphere and ocean. It has 19 levels in the atmosphere and 20 levels in the ocean. The model version we used here does not use ocean flux correction and has Iceland removed from the land-sea mask [Lunt *et al.*, 2007]. The land component is represented by the MOSES II land surface scheme [Essery and Clark, 2003]. In this study, neither the land nor ocean carbon cycle component was included.

2.2. Simulations

[5] Using the HadCM3L model, we simulated several thousand model years under a constant atmospheric CO₂ concentration of 280 ppm and a solar constant of 1365 W m⁻² to reach a quasi-equilibrium state for pre-industrial climate. Starting from this pre-industrial initial condition, three transient simulations were performed as described in the following:

[6] 1. *CO₂ step*, Step-function 4 × CO₂ simulation: In this simulation, atmospheric CO₂ was instantaneously quadrupled to 1120 ppm and the model was integrated for 70 years. After this 70-year period, atmospheric CO₂ was returned to the pre-industrial level instantaneously and the model was integrated for additional 150 years.

[7] 2. *Solar step*, Step-function solar intensity change simulation: In this simulation, the amount of solar energy received at the top of the Earth’s atmosphere (represented as the solar constant in the model) was instantaneously increased from its control value of 1365 W m⁻² by 4.54% to 1427 W m⁻² and the model is integrated with this increased solar intensity for 70 years. After this period, the solar intensity was returned to the control value instantaneously and the model was integrated for additional 150 years. The 4.54% increase in solar intensity was chosen so that the increase in global mean surface temperature was approximately the same as that in the simulation with 4 × CO₂.

[8] 3. *CO₂ ramp*, Gradual CO₂ change simulation: In this simulation, the model was forced with the 2% annual increase in atmospheric CO₂ until it reaches 4 × CO₂ level after 70 years. Then, the model was forced with the 2% annual decrease in atmospheric CO₂ until atmospheric CO₂ returns to its pre-industrial level after 70 years. Afterwards the model was integrated with the pre-industrial CO₂ level for additional 150 years.

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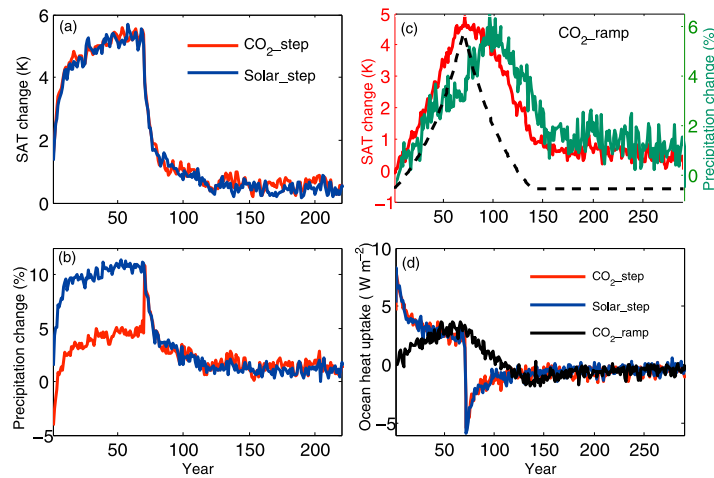


Figure 1. Temporal evolution of climate change from HadCM3L simulations: global and annual mean changes in (a) surface air temperature (SAT) and (b) precipitation from the simulation with step-function changes in atmospheric CO_2 (CO_2_step) and solar intensity (Solar_step); (c) global and annual mean changes in SAT (red line), precipitation (green line), and prescribed atmospheric CO_2 concentrations (black line) from the simulation with 2% annual change in atmospheric CO_2 (CO_2_ramp); (d) global and annual mean ocean heat uptake from the simulations of CO_2_step , Solar_step , and CO_2_ramp . The ocean heat uptake was calculated from the time-series of annual mean ocean heat content by integrating ocean temperature downward from the ocean surface to the bottom of the ocean. A reduction in atmospheric CO_2 concentration leads to a short-term increase in global precipitation but this increase is not observed for the simulation where similar negative radiative forcing is applied as a reduction of solar intensity. The different response of precipitation occurs despite the fact that the change of ocean heat uptake is nearly the same in response to the change of CO_2 and solar forcings.

[9] In addition, a 290-year control simulation with the pre-industrial CO_2 concentration of 280 ppm and the default solar constant of 1365 W m^{-2} was performed. All results presented below are the changes relative to this control simulation. We first present results from the CO_2_step and Solar_step simulations, and then present results from the CO_2_ramp simulation.

3. Results and Discussion

3.1. Climate Response to Step-Function Changes in CO_2 and Solar Forcing

3.1.1. Time Series of Transient Climate Response

[10] Figures 1a and 1b show changes in global and annual mean surface air temperature and precipitation in the simulations of CO_2_step and Solar_step . Despite the nearly same temperature change in these two simulations, precipitation changes are quite different. Averaged over the last 20 years of the first 70-year simulation segment, the difference in global mean surface temperature between the CO_2_step (5.33°C) and Solar_step (5.25°C) simulations is only 0.08°C (1.5%). However, the corresponding precipitation increase is 10.8% in the Solar_step simulation, compared to a much smaller 4.7% increase in the CO_2_step simulation. The sudden removal of the enhanced CO_2 forcing (and return to $1 \times \text{CO}_2$ forcing) causes the global mean precipitation to increase by 5.1% from year 70 to year 71, and it takes about ten years for global mean precipitation to return to its level before the removal of the enhanced CO_2 forcing (Figure 1b, red line). In contrast, in response to a sudden removal of enhanced solar forcing, precipitation decreases immediately (Figure 1b, blue line). As discussed below, the different behaviors of precipitation response to CO_2 and solar forcing are explained by differing sensitivity of precipitation to changes in the two forcings.

3.1.2. Sensitivity of Precipitation to Changes in Temperature and CO_2 /Solar Forcing

[11] As discussed in previous studies [e.g., *Allen and Ingram, 2002; Gregory and Webb, 2008; Bala et al., 2009; Andrews et al., 2009; Andrews et al., 2010; Andrews and Forster, 2010*], precipitation response to imposed forcings can be decomposed into two parts: (1) a ‘fast’ response component referring to the change of precipitation associated with the fast adjustment of the stratosphere and troposphere in response to the external forcing; this ‘fast’ adjustment occurs on timescales of weeks to months before significant changes in global and annual mean surface temperature occur. (2) A ‘slow’ response component referring to the change of precipitation associated with slowly-evolving surface temperatures; the timescale of this ‘slow’ response is governed by the timescale of surface temperature change that is often measured in years (but note that the atmosphere responds rapidly to slowly changing surface temperatures).

[12] From the energy-constraint point of view, the fast response resolves the radiative imbalance between the top of the atmosphere (TOA) and surface caused by a forcing agent [*Gregory and Webb, 2008; Bala et al., 2009; Andrews et al., 2009*]. In response to an increase in atmospheric CO_2 , instantaneous radiative forcing at the surface is much smaller than that at the TOA because CO_2 absorbs and emits longwave radiation in the atmosphere [*Hansen et al., 1997*]. Since the atmosphere has a relatively small heat capacity, it cannot store heat and the radiative imbalance between the surface and TOA must be eliminated on a timescale of a few weeks. Reduction in latent heat flux into the atmosphere and thus reduction in precipitation plays a major role in eliminating the forcing difference between the surface and TOA. However, the detailed dynamic processes, such as changes in vertical stability and lapse rate, by which the fast response

Table 1. Regression Coefficients for Predicting Changes in Global and Annual Mean Precipitation From Changes in Atmospheric CO₂, Surface Temperature, and Solar Intensity^a

	Years of Simulation Results Used	Equation Used	% Precipitation Change per % Increase in Solar Intensity	% Precipitation Change per CO ₂ Doubling	% Precipitation Change per Degree of Warming
<i>CO₂_step</i>	1 to 220	equation (2)		-4.16 ± 0.15	2.48 ± 0.06
<i>Solar_step</i>	1 to 220	equation (3)	-0.34 ± 0.08		2.40 ± 0.08
<i>CO₂_ramp</i>	1 to 290	equation (2)		-4.16 ± 0.26	2.64 ± 0.10
<i>CO₂_step_up</i>	1 to 70	equation (1)		-3.50 ± 0.28 ^b	2.20 ± 0.11
<i>CO₂_step_down</i>	71 to 220	equation (1)		-3.42 ± 0.28 ^b	2.69 ± 0.12
<i>Solar_step_up</i>	1 to 70	equation (1)	0.10 ± 0.17 ^c		1.97 ± 0.16
<i>Solar_step_down</i>	71 to 220	equation (1)	0.12 ± 0.17 ^c		2.62 ± 0.12

^aUncertainties are represented by one standard error from the regression.

^bPercent precipitation change per CO₂ doubling for *CO₂_step_up* and *CO₂_step_down* is inferred from the fast response of *CO₂_step_up* (-6.99 ± 0.55%) and *CO₂_step_down* (-6.84 ± 0.56%) phase of the CO₂ quadrupling simulation *CO₂_step*.

^cPercent precipitation change per % increase in solar intensity for *Solar_step_up* and *Solar_step_down* is inferred from the fast response of *Solar_step_up* (0.47 ± 0.76%) and *Solar_step_down* (0.53 ± 0.77%) phase of the 4.5% enhanced solar intensity simulation *Solar_step*.

evolves, merit further studies. The slow response occurs as a result of the change in surface temperature, which is directly controlled by the imbalance in surface energy fluxes and the effective heat capacity of the surface. Many feedbacks in the climate system (e.g., water vapor, lapse rate, and ice-albedo feedbacks) are associated with the surface temperature changes. The fast and slow components of precipitation response represent the sensitivity of precipitation to the change in external forcing (e.g., CO₂ forcing, solar forcing) and surface temperature, respectively.

[13] We diagnosed the sensitivity of precipitation to the change in atmospheric CO₂ ('fast response') and surface air temperature ('slow response') using the linear regression method adopted by previous studies [e.g., Gregory and Webb, 2008; Bala et al., 2009; Andrews et al., 2009], but with extensions. We calculated linear regressions of change in precipitation (%) per degree of warming using data from (a) the first 70 years with enhanced CO₂ and solar intensity levels (referred to as *CO₂_step_up* and *Solar_step_up* in Table 1), and (b) the subsequent 150 years with control CO₂ and control solar intensity levels (referred to as *CO₂_step_down* and *Solar_step_down* in Table 1). For these regressions involving only one value of CO₂ or solar forcing the slope yields the sensitivity of precipitation to temperature change, and the intercept yields the fast response (equation (1)). Using the entire 220-year simulation results from *CO₂_step* and *Solar_step* that involve more than one value of CO₂ or solar forcing, we applied multivariate regression to determine the sensitivity of precipitation to the change in atmospheric CO₂ concentration, the change in solar intensity, and the change in global mean surface air temperature (equations (2) and (3)). These regressions are represented mathematically by the following equations:

$$\Delta P = \Delta P_{\text{fast}} + \beta \Delta T \quad (1)$$

$$\Delta P = \alpha_{\text{CO}_2} \log_2 \left(\frac{\text{CO}_2}{280.0} \right) + \beta \Delta T \quad (2)$$

$$\Delta P = \alpha_S \Delta S + \beta \Delta T \quad (3)$$

In the above equations, ΔP is the change in global and annual mean precipitation in percent; ΔT is the change in global and annual mean surface air temperature in Kelvin; ΔS is the change in solar intensity in percent. ΔP_{fast}

represents the fast response of precipitation (%). α_{CO_2} and α_S represent the precipitation sensitivity to a doubling of atmospheric CO₂ and one percent change in solar forcing, respectively, and β represents the precipitation sensitivity to the change in surface temperature. Additional discussion of the multivariate regression approach is given in the auxiliary material (Figure S1).¹

[14] As diagnosed from the linear regressions, precipitation sensitivity to the increase of CO₂ forcing is negative, whereas the precipitation sensitivity to the increase of solar forcing is nearly zero (Table 1). As discussed in previous studies [e.g., Gregory and Webb, 2008; Andrews et al., 2009; Bala et al., 2009], the decrease in precipitation following increased CO₂ forcing is a result of the reduced latent heat flux to the atmosphere that is needed to resolve the radiative imbalance between TOA and surface. The fast precipitation adjustment is much smaller in response to the solar forcing, consistent with the fact that the radiative imbalance between TOA and surface is much smaller for the solar forcing than the CO₂ forcing [Hansen et al., 1997]. In all cases, the precipitation sensitivity to temperature change is similar (Table 1). These results are consistent with previous studies [e.g., Andrews et al., 2009; Bala et al., 2009] and explain why for comparable temperature change, precipitation increases much more in response to solar forcing than to CO₂ forcing (Figures 1a and 1b). Likewise, the sudden increase of precipitation in response to the removal of enhanced CO₂ forcing (Figure 1b, red line) is explained by the fast adjustment to the decrease of CO₂ forcing, which tends to increase precipitation.

3.1.3. Why Do Precipitation States Differ at the Same Temperature?

[15] Figure 2 shows the change in global and annual mean precipitation as a function of the change in global and annual mean surface air temperature for the 220-year *CO₂_step* and *Solar_step* simulations. In the simulation of *CO₂_step* (Figure 2a) for a given temperature state two different precipitation states are observed with one cluster of points (red dots) representing the warming phase with 4 × CO₂ and the other cluster of points (blue dots) representing the cooling phase with 1 × CO₂. In comparison, the difference in precipitation between the warming and cooling phase in the *Solar_step* simulation is much less pronounced

¹Auxiliary materials are available in the HTML. doi:10.1029/2011GL046713.

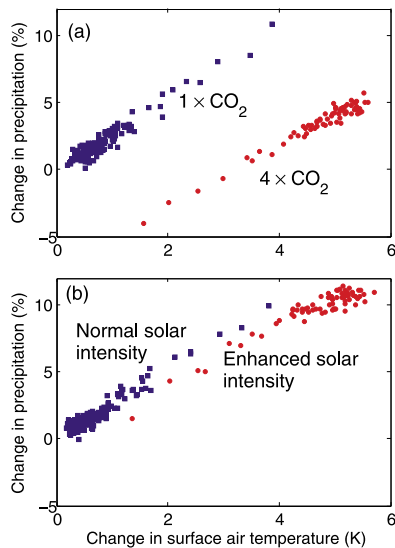


Figure 2. HadCM3L-simulated changes in global and annual mean precipitation as a function of changes in global and annual mean surface air temperature for (a) CO_2_step and (b) $Solar_step$ simulations. The red dots represent the first 70-year simulation period with enhanced CO_2 or solar forcing, and the blue dots represent the following 150-year simulation period when the enhanced CO_2 or solar forcing is removed. At constant temperature, changes in CO_2 have a much larger effect on precipitation than changes in solar intensity with similar radiative forcing.

(Figure 2b). Wu *et al.* [2010] observed similar precipitation behavior in response to gradual changes of CO_2 concentrations in their HadCM3 simulations, and attributed this behavior to the accumulated heat storage in the ocean.

[16] As shown in Figure 1d the temporal evolution of ocean heat uptake is almost indistinguishable between the CO_2_step and $Solar_step$ simulation, though the precipitation response is quite different between these two simulations. Thus, ocean heat uptake and storage alone cannot explain the different behaviors of precipitation change. A full explanation involves the sensitivity of precipitation to atmospheric CO_2 . In the case of CO_2_step simulation (Figure 2a), any given state with the same temperature corresponds to two different CO_2 concentrations: one with $4 \times CO_2$ (red dots) and the other with $1 \times CO_2$ (blue dots). As a result of the fast adjustment to CO_2 forcing, for the same temperature change differing atmospheric CO_2 concentrations lead to different states of precipitation. Since the precipitation sensitivity to the change in solar forcing is much weaker, the difference in precipitation between the warming and cooling phase is much smaller in the $Solar_step$ simulation (Figure 2b).

3.2. Climate Response to Gradual Changes of CO_2 Forcing

[17] As shown in Figure 1c, in the CO_2_ramp simulation both temperature and precipitation increase in response to the increase in CO_2 concentrations. As atmospheric CO_2 decreases, surface temperature decreases immediately, but global precipitation continues to increase and remains at the enhanced level for several decades before it starts to decrease. Starting from the $4 \times CO_2$ level, each incremental

decrease in CO_2 forcing induces an increase in precipitation through fast tropospheric adjustment. During the first few decades following CO_2 decrease, precipitation increases as a consequence of its sensitivity to the change in atmospheric CO_2 , but later the effect of surface cooling dominates and precipitation starts to decrease.

[18] Multivariate regression (equation (2)) was applied to the CO_2_ramp simulation to obtain the sensitivity of precipitation to changes in atmospheric CO_2 concentration and temperature. The regressed sensitivity to temperature is similar between the CO_2_ramp and CO_2_step simulation (Table 1). The regressed sensitivity to atmospheric CO_2 is also similar between the CO_2_ramp and CO_2_step simulations with -4.2% precipitation change per atmospheric CO_2 doubling (Table 1). These results suggest that the sensitivity of precipitation change to CO_2 and temperature forcing is a robust feature that is independent of the CO_2 change scenario.

[19] For the CO_2_ramp simulation there are two different states of temperature and precipitation at one atmospheric CO_2 concentration (Figures 3a and 3c). This behavior of temperature and precipitation change as a function of atmospheric CO_2 concentration is a direct result of the ocean thermal inertia. After atmospheric CO_2 starts to decrease, the ocean continues to take up heat, but at a slower rate, for about 40 years (black line of Figure 1d). This diminished rate of ocean heat uptake slows the rate of decrease in surface air temperature, i.e., the rate of temperature change during the period when CO_2 ramps down is lower than that during the period when CO_2 is ramped up (red line of Figure 1c). Therefore, ocean thermal inertia leads to the possibility of two temperature or precipitation states for a single atmospheric CO_2 content, with the two temperature or precipitation states differing in their ocean heat contents (Figure 3b).

[20] However, the lag of precipitation change behind temperature change is caused by the precipitation sensitivity to the change in atmospheric CO_2 . As shown in Figure 3d, two different precipitation states are observed for a single temperature with the two precipitation states corresponding to two different CO_2 concentrations. We have not performed a parallel simulation with gradual changes in the solar intensity ($Solar_ramp$). Nevertheless, from the comparison of CO_2_step and $Solar_step$ simulations, it is reasonable to expect that in the $Solar_ramp$ simulation there will be two states of temperature and precipitation for a given solar intensity, but at constant temperature changes in solar intensity would have a much smaller effect on precipitation than changes in atmospheric CO_2 with similar radiative forcing.

4. Summary and Conclusions

[21] We have performed idealized simulations with step-function changes in CO_2 and solar forcing to elucidate principal mechanisms associated with precipitation change and external forcings. We have used idealized scenarios and focused our analysis on the global-mean values. We do not suggest that sudden changes in external forcings represent realistic possibilities for the future, but they are idealized mathematical functions designed to illustrate the fundamental physics that would be operative even at lower rates of radiative forcing changes.

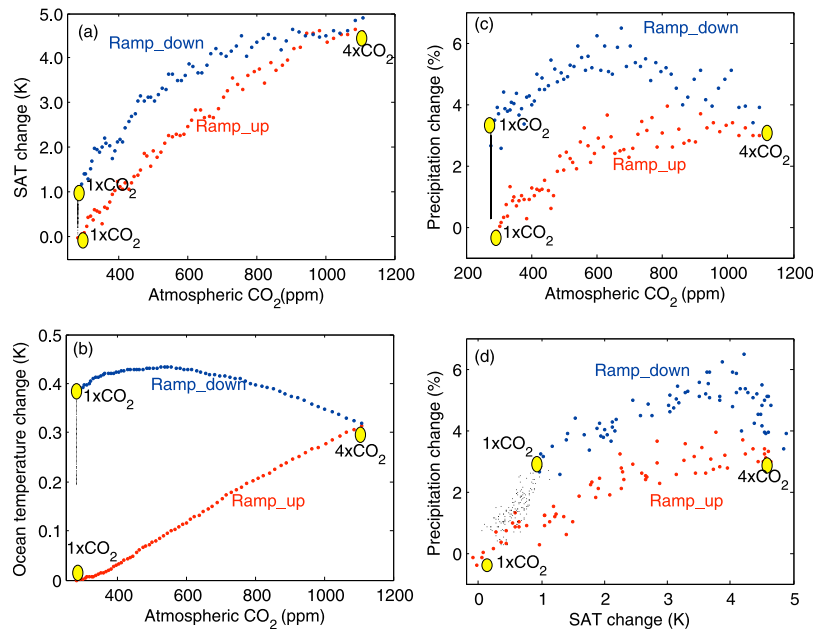


Figure 3. HadCM3L results from the simulation with 2% annual change in atmospheric CO_2 (CO_2 ramp): (a) global and annual mean changes in surface air temperature (SAT) as a function of atmospheric CO_2 ; (b) global and annual mean changes in ocean temperature as a function of atmospheric CO_2 (the ocean temperature change is the change in ocean temperature that is averaged from the ocean surface to the bottom of the ocean); (c) global and annual mean changes in precipitation as a function of atmospheric CO_2 ; (d) global and annual mean changes in precipitation as a function of global and annual mean changes in SAT. Red dots represent the first 70-year simulation phase with 2% annual CO_2 increase (*ramp_up*) and time moves forward from the lower left to the upper right. Blue dots represent the subsequent 70-year period with 2% annual CO_2 decrease (*ramp_down*) and time moves forward from the upper right to the lower left. The simulation states when atmospheric CO_2 reaches $1 \times \text{CO}_2$ and $4 \times \text{CO}_2$ concentrations are marked with yellow circles. Due to the ocean thermal inertia one atmospheric CO_2 state corresponds to two different states of temperature and precipitation, and due to the precipitation sensitivity to atmospheric CO_2 content, one temperature state corresponds to two different precipitation states.

[22] Our results show that the increase in precipitation following a reduction in atmospheric CO_2 content is caused by the specific character of CO_2 -radiative forcing. An analysis from the surface energy balance perspective further demonstrates that it is the specific feature of CO_2 -radiative forcing, but not ocean heat uptake, that is responsible for the specific behavior of precipitation response to CO_2 forcing (refer to auxiliary material and Figure S2 for a detailed analysis). Reductions in precipitation associated with slow cooling of the ocean eventually overwhelms the CO_2 effect, and thus after a few decades there are net reductions in precipitation. As a result of the ocean thermal inertia, changes in temperature lag behind the change in atmospheric CO_2 . However, it is primarily the sensitivity of precipitation to the change in CO_2 forcing that explains the temporary precipitation increase in response to reduced CO_2 forcing. Due to the sensitivity of the climate system to CO_2 forcing, different CO_2 states at the same global mean temperature would have different amounts of precipitation. This is not the case for solar forcing since precipitation is much less sensitive to the change in solar forcing. This point is demonstrated clearly by the different response of global precipitation to CO_2 and solar forcing despite the fact that ocean heat uptake is nearly the same in response to these two forcings. The response of precipitation to temperature

changes is nearly the same regardless of the nature of the radiative forcing change. Thus, the ‘fast’ response to radiative forcing changes depends on the character of the radiative forcing; the response to temperature changes is similar, regardless of the specific radiative forcing causing the temperature change.

[23] The temporary increase in precipitation in response to a reduction in CO_2 forcing has important implications for understanding the effects of inadvertent climate change as well as effects of atmospheric CO_2 mitigation. To a first approximation, atmospheric CO_2 increases would be the inverse of atmospheric CO_2 decreases, and thus in response to emissions of CO_2 , on the global mean basis we would expect to see a short-term decrease in global precipitation and, as the Earth surface warms, a long-term increase in precipitation. Furthermore, it may take much longer to mitigate precipitation change via removal of atmospheric CO_2 than to mitigate temperature change. In the CO_2 ramp simulation when atmospheric CO_2 starts to decrease from its peak level of $4 \times \text{CO}_2$, global mean precipitation keeps increasing for about 30 years before it starts to decline; it takes 50 years for the global mean surface temperature to decrease to its $2 \times \text{CO}_2$ level, whereas it takes 78 years for the global mean precipitation to decrease to its $2 \times \text{CO}_2$ level (Figure 1c). We conclude that, at the same global mean temperature,

climate would be drier as atmospheric CO₂ increasing than it would be while CO₂ is decreasing due to the dependence of precipitation on atmospheric CO₂ concentrations.

[24] **Acknowledgments.** The authors and the editor thank the two reviewers for their assistance in evaluating this paper.

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