

Suppressant effect of instantaneous CO₂ doubling on global precipitation

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Abstract

The global precipitation in rich CO₂ climate increases with temperature rise as revealed in many former studies, while CO₂ stand-alone causes to decrease of rainfall through modulation of the heat and moisture balances in the surface and the atmosphere. In the present study, the energy balances that are responsible for the suppression of rainfall were quantitatively investigated based on seven GCMs in which instantaneous doubling of CO₂ experiments were conducted. Radiative heating induced by CO₂ doubling warmed both the atmosphere and the surface, while the amount of the surface heating was smaller relative to that of the atmosphere. Consequently, the attenuated heating at the surface resulted in weakening of evaporation on the surface, which could explain the decrease of rainfall. As for the heat budget of the atmosphere, the attenuated heating was balanced with the less condensation heating, implicating radiative adjustment was a key element for the rainfall decrease.

Key words: global warming, water cycle, atmospheric energy balance

1. Introduction

Projection of change in hydrological cycle with global warming is one of the fundamental issues for our lives. By use of general circulation models (GCMs), it is well known that the water cycle becomes intensified in accordance with surface warming in the future (Meehl *et al.* 2007a). Under doubling CO₂ (hereafter, 2xCO₂) atmosphere, intensified radiative forcing heats the surface, which acts to increase latent heat flux and decrease sensible heat flux (Gregory and Webb 2008). Increased latent heat flux supplies more water vapor to the atmosphere and causes intensification of precipitation. Hence, the rate of increase against the temperature rise is projected to only 1~2% K⁻¹ in precipitation, which is smaller comparing to the rate of increase in atmospheric water vapor 7~8% K⁻¹ (e.g. Allen and Ingram 2002; Trenberth *et al.* 2003; Held and Soden 2006; Vecchi and Soden 2007; Sun *et al.* 2007; Stephence and Ellis 2008). This difference of increasing rates

between the atmospheric water vapor and the precipitation lead to a decreasing of precipitation efficiency with global warming over the Asian monsoon region in rainy season (Douville *et al.* 2002; Ueda 2009). In terms of heat budget of the atmosphere in the tropics, Sugi *et al.* (2002) revealed that the less increasing rate of precipitation is closely related with weakening of atmospheric circulation.

Meanwhile, several studies have revealed that 2xCO₂ alone causes to decrease the global precipitation (Yang *et al.* 2003; Lambert and Webb 2008). From the perspective of tropospheric energy budget, the change in global condensation heating accompanied by precipitation balances with the change in radiative cooling (e.g. Mitchell *et al.* 1987; Boer 1993; Allen and Ingram 2002; Stephens and Ellis 2008). It should be noted that the increasing of atmospheric CO₂ plays an important role in controlling the atmospheric radiation, referred to as "overlap effect" (Sugi and Yoshimura 2004). Water vapor absorbs infrared radiation emitted by increased CO₂ in the lower troposphere, which causes to decrease radiative cooling (Ohring and Joseph 1978; Sugi and Yoshimura 2004). In terms of the atmospheric energy balance, the attenuated radiative cooling should be balanced with weakening of condensation heating, which can explain the physical mechanisms for the aforementioned smaller increasing rate of rainfall in comparison with that of water vapor (Sugi 2008). Lambert and Webb (2008) investigated the rate of enhancement of the global precipitation due to the surface warming, while the radiative regulation by increased CO₂ is not assessed quantitatively.

It has been also pointed out that the precipitation change balances with the alteration in the surface energy budget (e.g. Boer 1993; Vecchi and Soden 2007). The intensification of evaporation in relation to the change in the surface energy balance is necessary for the increase of precipitation in the future. Richter and Xie (2008) examined the cause of a small precipitation change in rich CO₂ climate from a surface evaporation perspective. Surface relative humidity increases in accordance with the global warming, while decrease of surface wind speed in combination with more stable vertical stratification cause to decrease rate of surface evaporation and ensuing slight precipitation increase.

There have been a number of studies that focused on the increase in precipitation accompanied with the atmospheric temperature rise (e.g. LeTreut and McAvaney 2000; Cubasch *et al.* 2001), while the suppressant due

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to increasing CO₂ is not investigated quantitatively. In addition, the causes of global precipitation change have been examined by either atmosphere or surface energy balance. Therefore, the aim of the present paper is to evaluate the constraint effect of 2xCO₂ on global precipitation and propose an integrated view of the surface and atmospheric energy balance based on the multi model analysis.

2. Data and method

We used control and instantaneous doubling of CO₂ experiment in GCMs coupled with slab ocean (mixing layer only) archived by the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi model dataset (Meehl *et al.* 2007b). Instantaneous doubling of CO₂ concentration in the atmosphere causes to increase temperature abruptly, then climate system reaches a new equilibrium state in ~20 years (Gregory *et al.* 2004, Lambert and Webb 2008). The analyses were performed by ensemble mean of seven models which contain their transient terms (Table 1).

Global precipitation P increases gradually with the surface temperature rise, while it decreases just after the atmospheric CO₂ doubles instantaneously through the alteration of radiative balance (Yang *et al.* 2003). These slow and abrupt changes can be decomposed by tropospheric energy budget conservation (Allen and Ingram 2002) during the transit term in the instantaneous 2xCO₂ experiment (Lambert and Webb 2008), which is written as

$$l\Delta P \approx \alpha\Delta T + \Delta R \quad (1)$$

where $l\Delta P$ represents condensational heating, $\alpha\Delta T$ represents radiative cooling which depends on temperature rise ΔT , ΔR represents radiative perturbation by the instantaneous 2xCO₂ which is independent of temperature change. This separating method can be applied to other energy fluxes under the instantaneous 2xCO₂ experiment (Gregory *et al.* 2004). Any radiative fluxes change abruptly (ΔR) just after the doubling of atmospheric CO₂ concentration, and increase/decrease gradually with the

surface temperature change ($\alpha\Delta T$). In this study, we focus on the abrupt change ΔR on the energy balance just after the 2xCO₂, hereafter, referred to as ‘‘radiative effect of 2xCO₂’’, calculated by ordinary least squares regression against the surface temperature perturbation ΔT .

Long-term mean for the perturbation of surface heat balance in the globe can be written as

$$\Delta Q_{sfc} = -\Delta R_{sfc} - \Delta H - l\Delta E \quad (2)$$

where ΔR_{sfc} is net surface radiation, ΔH , $l\Delta E$ is sensible and latent heat flux (positive upward). ΔQ_{sfc} is net surface heating, the value 0 corresponds with steady state and positive (negative) value means temperature rise (fall) with the surface heating (cooling). As for the atmosphere, the change of heat balance can be expressed as

$$\Delta Q_{atm} = \Delta H + l\Delta P + \Delta R_{top} + \Delta R_{sfc} \quad (3)$$

where ΔQ_{atm} is net atmospheric heating, $l\Delta P$ is condensation heating, ΔR_{top} is net radiation (positive downward) at top of the atmosphere (TOA). All of these fluxes implicate atmospheric heating (cooling) for positive (negative) values.

3. Results

3.1 Surface heat balance

Figure 1 shows the changes in surface energy fluxes during their transient terms against the temperature rise ΔT in accordance with instantaneous doubling of CO₂ concentration. They evolved towards a steady state under 2xCO₂ atmosphere over 20 years with surface warming. In other words, the surface temperature rose up to 3.5 K roughly corresponded to 20 years. Analogous to Eq. (1), y-intercepts ($\Delta T = 0$ K) of each flux show the radiative effect of 2xCO₂. We defined positive energy flux perturbations as heat gain of the atmosphere. Because land/ocean have large thermal inertia, which initially require a large amount of surface heating ΔQ_{sfc} (3.25 W m⁻² at y-intercept). Therefore, ΔQ_{sfc} reached x-intercept in the 20 years, implying a new equilibrium of the heat balance between the surface and the atmosphere.

Heat balances at the time of y-intercept ($\Delta T = 0$ K) and steady state ($\Delta T = 3.5$ K) exhibited quite different features. The latent heat flux decreased ($l\Delta E$, -1.79 W m⁻²) and warmed up the surface notably at the y-intercept, which was the result of the change of the energy balance due to the radiative effect of 2xCO₂. The net surface radiation (ΔQ_{sfc}) changed only a little (-1.07 W m⁻²) just after the atmospheric CO₂ concentration doubles. As mentioned before, a large amount of energy is consumed to heat the land/ocean. In other words, the heat loss at the surface

Table 1. The models used in this study.

Model	Country
CGCM3.1(T47)	Canada
CGCM3.1(T63)	Canada
CSIRO-Mk3.0	Australia
GFDL-CM2.0	USA
MIROC3.2(medres)	Japan
MRI-CGCM2.3.2	Japan
UKMO-HadGEM1	UK

Table 2. Radiative effect of 2xCO₂ on each energy flux (W m⁻²) at the surface. Each rank is global / land / ocean surface area averaged multimodel ensemble mean. Parentheses are land / ocean contribution rate per unit area (%) to the global mean.

	ΔR_{sfc}	ΔH	$l\Delta E$	ΔQ_{sfc}
globe	-1.07	-0.39	-1.79	3.25
land	-0.58 (54)	0.33 (-85)	-0.27 (15)	0.61 (19)
ocean	-1.28 (117)	-0.70 (179)	-2.44 (136)	4.38 (135)

should be reduced to keep the heat budget constant. This can be found as negative values of latent heat flux prior to the temperature increase ~ 1 K. After temperature rise, downward longwave radiation and sensible heat from the warmed atmosphere increased and succeeding intensified evaporation induced cooling of the surface.

The changes due to 2xCO₂ on the surface energy flux averaged over the land and the ocean are shown in Table 2. As discussed above, the change in the latent heat flux ($l\Delta E$) just after the doubling of CO₂ acted as the most dominant factor for the surface heating rather than the net radiation (ΔR_{sfc}) and the sensible heat flux (ΔH) over the globe. In the case of changes over the land, values were much less (15%, 19%, 54% in $l\Delta E$, ΔQ_{sfc} , ΔR_{sfc}) than those over the globe (almost contrary in the case of ΔH , -85%). Overall, the rates of the contribution to the global change over the ocean were greater than those over the land, ranging from 117% to 179%. These features suggested that the radiative effects of 2xCO₂ over the globe were attributed to the ocean adjustments, corresponding with the surface evaporation constraint in the warmer climate (Richter and Xie 2008).

3.2 Atmospheric heat balance

Atmospheric energy balance also changed with the surface temperature rise in 2xCO₂ climate (Figure 2). The radiative effect of 2xCO₂, appeared in y-intercept, caused to increase net radiation (ΔR_{top}) at the TOA considerably (3.60 W m⁻²), indicating strong radiative forcing. As the air temperature rose, the resultant enhanced downward radiation tended to be balanced with increasing upward radiation from the warmer atmosphere. Toward a steady state, the ΔR_{top} decreased gradually reaching 0 W m⁻² when the air temperature increase came to ~ 3.5 K. Because of less heat capacity of atmosphere in comparison with that in the surface, the small amount of heating (ΔQ_{atm} , 0.26 W m⁻² at $\Delta T = 0$ K) could warm the atmosphere that was responsible for the equilibrium temperature around 3.5 K.

Atmosphere was heated by the latent heat release through the condensation process ($l\Delta P$). Figures 1 and 2

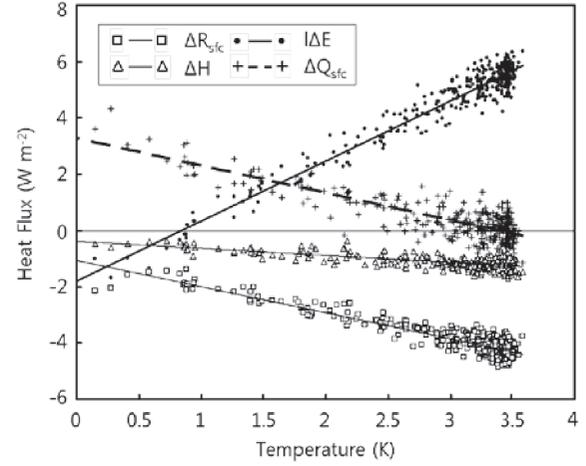


Fig. 1. Scatter diagram of surface energy fluxes change (W m⁻²) against surface air temperature change (K) on 2xCO₂ experiment relative to control experiment (multimodel ensemble mean). ΔR_{sfc} : net surface radiation, ΔH : sensible heat flux, $l\Delta E$: latent heat flux. Each flux represents positive (negative) upward (downward). ΔQ_{sfc} : net surface heating. 12-month low-pass filter is applied.

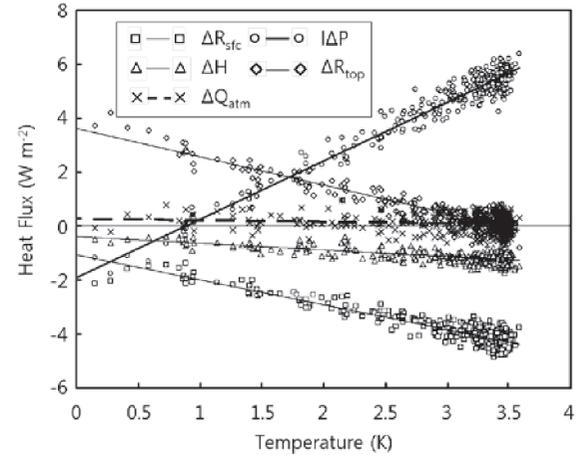


Fig. 2. Same as Fig. 1, but for the change of the atmospheric energy fluxes (W m⁻²). $l\Delta P$: condensation heating, ΔR_{top} : net radiation at the TOA. Each flux represents positive (negative) atmospheric heating (cooling). ΔQ_{atm} : net atmospheric heating.

revealed that the change in global and long term (monthly) mean precipitation synchronized with evaporation change. Condensation heating was suppressed initially (-1.88 W m⁻² at $\Delta T = 0$ K) then increased with temperature rise (positive at $\Delta T > \sim 1$ K). Atmospheric radiative cooling is attenuated by the increase of CO₂ concentration, occurring not only over the tropics but also over the globe (Sugi and Yoshimura 2004). The net surface radiation ΔR_{sfc} changed a little (-1.07 W m⁻²) although the ΔR_{top} increased significantly because the radiative cooling in the

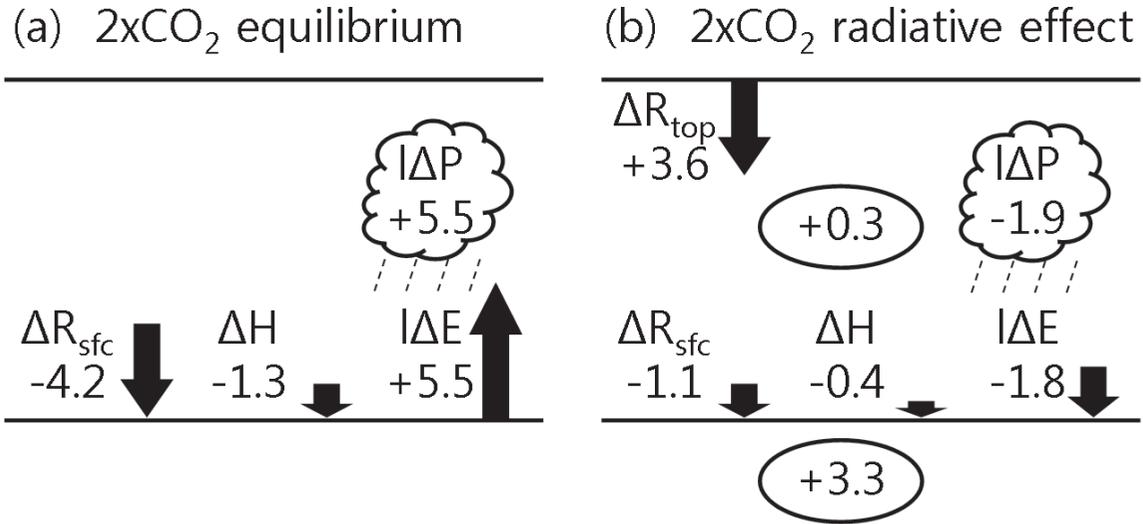


Fig. 3. Schematic diagram of energy flux changes on (a) steady state under $2x\text{CO}_2$ and (b) radiative effect of $2x\text{CO}_2$ in seven models ensemble mean (W m^{-2}). Values in center and bottom circles in (b) represent net atmospheric and surface heating.

atmosphere was weakened due to the “overlap effect” of CO_2 and water vapor absorption bands. A small amount of ΔQ_{atm} (0.26 W m^{-2}) relative to ΔQ_{sfc} was attributed to the decrease of condensation heating ($I\Delta P$) that was counterbalanced with the reduced radiative cooling ($-\Delta R_{\text{top}} - \Delta R_{\text{sfc}}$) in the atmosphere.

4. Summary and discussion

This study investigated the radiative effect of $2x\text{CO}_2$ on global precipitation from the surface and the atmospheric heat balance perspective based on the instantaneous doubling of CO_2 experiments by use of the GCMs coupled with slab ocean model. The instantaneous $2x\text{CO}_2$ caused to decrease both evaporation and precipitation through the alteration of the energy fluxes in the surface and the atmosphere. The change at the $2x\text{CO}_2$ steady state and the radiative effect of $2x\text{CO}_2$ on the surface and atmospheric heat balance is summarized in Figure 3. While the net radiation at the TOA balanced under the $2x\text{CO}_2$ equilibrium, the instantaneous $2x\text{CO}_2$ intensified the net radiation at the TOA significantly. This intensified radiative heating was almost restored in the surface because the land/ocean has larger thermal inertia relative to the atmosphere. If we consider the “overlap effect” of water vapor and CO_2 , the change in the net surface radiation decreased remarkably. To conserve the surface and atmospheric energy balance, both the latent heat flux and the condensation heating decreased considerably. As for the energy balance in the atmosphere, the reduction of global precipitation could be interpreted as the weakening of the atmospheric radiative cooling due to the “overlap effect” and ensuing reduction of condensation heating.

The radiative effects of $2x\text{CO}_2$ were found as robust

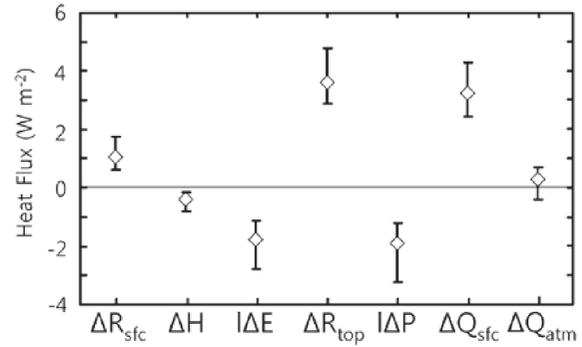


Fig. 4. Radiative effect of $2x\text{CO}_2$ on each energy flux and heating (W m^{-2}). Open squares represent multi-model ensemble means and ranges of error bars correspond with minimum-maximum values among each model’s 95% confidence intervals.

changes among the models. Figure 4 shows multi-model ensemble means and maximum ranges of every model’s 95% confidence intervals of $2x\text{CO}_2$ -induced radiative effects on each heat flux over the globe. Although the intermodel variances on each heat flux were discernible, the magnitudes of signals were dominant, showing significant consistency in the alterations on the energy fluxes by the radiative effect of $2x\text{CO}_2$.

This study diagnosed the change of global energy balance and water cycle in response to $2x\text{CO}_2$ perturbation in terms of heat and moisture budget of the surface and the atmosphere. It should be noted here that this study considered the heat balance in the atmosphere only by the energy exchange on surface and TOA. It is required to investigate the change in radiative cooling and condensation heating at each layer of atmosphere in

future works. In addition, the difference in the surface heat balance between the land and the ocean has been not investigated in detail yet. Recently, the physical explanation about the constraint of the surface evaporation over the ocean was proposed in view of atmospheric adjustment by means of a standard bulk formula (Richter and Xie 2008). Thus further studies of the regional and temporal difference and the controlling mechanisms of the changes in energy balances from various kinds of perspectives (e.g. surface water and energy balances on any kinds of soil and vegetation types, latitudinal and land/ocean differences) are needed to get more understanding of the changes in the hydrological cycle of the surface and the atmosphere with the perturbation of atmospheric CO₂ concentration.

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