Fast versus Slow Response in Climate Change: Implications for the Global Hydrological Cycle

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Abstract

Recent studies have shown that changes in global mean precipitation are larger for solar forcing than for CO_2 forcing of similar magnitude. In this paper, we use an atmospheric general circulation model to show that the differences originate from differing fast responses of the climate system. We estimate the adjusted radiative forcing and fast response using Hansen's "fixed SST forcing" method. Total climate system response is calculated using mixed layer simulations using the same model. Our analysis shows that the hydrologic sensitivity, defined as the change in global mean precipitation per unit warming, is the same for the two forcings when the fast responses are excluded from the definition of hydrologic sensitivity, suggesting that the slow response (feedback) of the hydrological cycle is independent of the forcing mechanism. Based on our results, we recommend that the fast and slow response be compared separately in multi-model intercomparisons to discover and understand robust responses in hydrologic cycle. The significance of this study to geoengineering is discussed.

1. **Introduction**

Recent studies [*Allen and Ingram*, 2002; *Bala et al.*, 2008] have been shown that the hydrologic sensitivity, defined as the percentage change in global-mean precipitation per degree is larger for solar forcing than for CO_2 forcing. Differences between CO_2 and solar radiative forcing of the troposphere [*Allen and Ingram*, 2002], and radiative forcing at the surface [*Bala et al.*, 2008] have been invoked to reconcile the differences in hydrologic sensitivity. Rapid adjustment of the troposphere in the solar case which reduces the effective radiative forcing by about 25 %, and the absence of this adjustment for CO_2 case have been also cited as the primary reason for the differing hydrological sensitivity [*Lambert and Faull*, 2007].

Recent investigations [*Andrews and Forster*, 2008; *Gregory and Webb*, 2008] reveal that CO_2 increase also causes significant rapid tropospheric adjustment leading to changes in cloud, water vapour, ice and snow, and reduction in effective radiative forcing. There are indications that tropospheric adjustment to CO_2 may be responsible for some of the model spread in equilibrium climate sensitivity and could affect time-dependent climate projections [*Gregory and Webb*, 2008]. It has also been shown that the cloud feedback, defined as the part of the change that evolves with changes in global- and annual-mean surface temperature (ΔT), is small and most of the cloud changes are fast adjustments.

A question then naturally arises whether the differences in rapid adjustments are responsible for the apparent difference in hydrologic sensitivity between CO_2 and Solar forcings. For instantaneous doubling of CO_2, the fast response involves reduction in surface evaporation and hence precipitation [*Gregory and Webb*, 2008; *Yang et al.*,

2003]. This is because radiative forcing at the surface caused instantaneously by doubling of CO_2 is much smaller than that at the TOA [*Bala et al.*, 2008; *Collins et al.*, 2006a; *Hansen et al.*, 1997]. Since the atmosphere has a relatively small heat capacity, it cannot store heat and the forcing differences between the surface and TAO must be eliminated on a time scale of few months. Therefore, non-radiative fluxes at the surface undergo rapid changes such that the net forcing at the surface and TOA are the same after the fast adjustment. A reduction in latent heat flux to the atmosphere (evaporation at the surface) and hence precipitation is a major part of this adjustment as shown in this study; reducing the later heat release in the troposphere (via precipitation process) helps to alleviate the CO_2-heating gradient in the vertical. In the case of solar forcing, the gradient of the instantaneous radiative forcing in the vertical is much smaller [*Hansen et al.*, 1997] and therefore, the reduction in latent heat flux and precipitation are expected to be small for the fast adjustment in this case.

For equilibrium climate change experiments using slab-ocean models forced by instantaneous radiative forcings, the simulated climate change actually represents the total climate change which is the sum of responses from both fast and slow responses. The fast response refers to the adjustment of the stratosphere, troposphere and the land surface before any ΔT occurs. Fast adjustment in radiative fluxes is also referred to as the adjusted radiative forcing. The response that depends on ΔT is called the slow response or feedback and is usually represented as change in the specific variable per unit ΔT.

The fast response of any climate variable can be estimated by regressing that variable against ΔT in instantaneous forcing experiments using climate models [*Gregory et al.*, 2004]; the intercept for $\Delta T=0$ gives an estimate of the fast response. It can also be

estimated by running a climate model with prescribed sea surface temperature (SST) and sea ice concentration [*Hansen et al.*, 2005]: by comparing simulations with and without the forcing, one can estimate the fast response. This method is referred to as Hansen's "fixed SST forcing". The limitation of this method is that there will be a small climate change (ΔT is of the order of a few tenths of a degree) resulting from a change in land surface temperature. This limitation can be removed by also fixing the land surface temperatures [*Shine et al.*, 2003] which is technically more difficult to do in a GCM. The slow response of any climate variable is usually obtained from the slope of the regression line for that variable in the regression method [*Gregory et al.*, 2004]: the fixed SST forcing method cannot give the slow response.

In this study, we estimate both the fast and slow response to CO_2 and Solar forcing in a climate model. The main goal is to show that the differences noted in the total response of the hydrological cycle arise from differences in the fast adjustments in the two cases. We further demonstrate that the slow response of the hydrological cycle which is a response to ΔT is about the same and is independent of the forcing mechanism.

2. Model and Experiments

We use the Community Atmosphere Model (CAM3.1) [*Collins et al.*, 2006b] to investigate the differing response of hydrological cycle to CO_2 and solar forcings. The horizontal resolution of the model is 2° in latitude and 2.5^o in longitude. There are 26 levels in the vertical. Two configurations for representing ocean and sea ice are employed: 1) prescribed sea surface temperatures (SST) and sea ice concentrations for estimating the fast adjustment, 2) a simple slab ocean-thermodynamic sea configuration for simulating the total response and hence for deriving the slow response. We performed

three experiments using the first configuration with prescribed climotological SST and sea ice: 1) “Climo” simulation with an atmospheric CO_2 concentration of 355 ppmv (CO_2 level corresponding to year 1990) and a “solar constant” of 1370 Wm^{-2}, 2) “2xCO2-climo” is similar to Climo but with the CO_2 concentration doubled to 710 ppmv, 3) “Solar-climo” is also similar to the Climo simulation but the solar constant is increased by 1.8% so that solar forcing is approximately close to the CO_2 forcing in the 2xCO2-climo case. Each of these prescribed SST simulations started on 1 September and lasted for 30 years and 4 months. The first four months are discarded when we assess climate statistics. These three experiments constitute the “fixed SST forcing” [*Hansen et al.*, 2005] method in our study to estimate the fast response of the climate system. Three additional experiments are performed using the second configuration with a slab ocean-thermodynamic sea ice model coupled to the same atmosphere model: 4) “Control”, 5) “2xCO2” and 6) “Solar” simulations with forcings as prescribed in the Climo, 2xCO2-climo, and Solar-climo cases, respectively. Each simulation lasts for 50 years, and the last 30 years are used for calculating climate statistics. The drift in global- and annual-mean surface temperature in the 30-year segment used for the analysis is of the order of $1x10^{-4}$ K. The first 20 years which is the time taken by the slab ocean model to reach equilibrium are discarded. Total response (slow plus fast response) of the climate system to CO_2 and solar forcings are calculated using these three experiments. We derive the slow response by subtracting the fast response (estimated by the fixed SST method) from the total response.

3. Results

3.1 Estimation of adjusted forcing and fast response

The changes in global- and annual-mean values of key climate variables in 2xCO2-climo and Solar-climo relative to the Climo case are shown in Table 1. These changes (adjusted radiative forcing and fast adjustments of non-radiative fluxes) could be also estimated using Gregory's regression method [*Gregory et al.*, 2004] applied to the slab-ocean experiments forced by instantaneous radiative forcings. However, the "best" result of the regression method depends on the optimal number of years used in the analysis and hence uncertainty could be large. Specifically, the error in the estimation of intercept (fast response) could be large because there are few points near the intercept. The advantage of Hansen's "fixed SST forcing" method is that the adjusted forcing and fast adjustments can be evaluated to arbitrary precision by running a long enough experiment. The spatial patterns of fast adjustment are also directly available in the fixed SST method. Therefore, we use the fixed SST forcing method for estimating the fast adjustment in our study. It has been shown that there is good agreement between the fixed SST method and regression analysis when the later is used with the first 10 years of simulation [*Hansen et al.*, 2005]. In general, the regression method tends to give more negative and less positive forcings [*Gregory and Webb*, 2008] and the differences are statistically significant at the 5 % level in many cases. The comparison of regression and fixed SST methods is not the focus of this study and hence we do not perform a comprehensive assessment of the methods here.

The fast adjustment leads to a land surface warming of 0.37 and 0.24 K in the 2xCO2-climo and Solar-climo cases, respectively (Table 1). After the fast adjustment, the surface and TOA (Top of the atmosphere) radiative forcing are the same since atmosphere does not store heat on time scales of more than a few months. While the TOA forcing is purely radiative, surface forcing consists of both radiative and non-radiative fluxes. Since the radiative components at the surface differ from that at TOA [*Bala et al.*, 2008], changes in non-radiative fluxes (latent and sensible heat fluxes) are expected so that the net climate forcings are equal at the surface and TOA. The latent heat flux decreases in both the cases but the decreases are larger by about 1 Wm^{-2} in the 2xCO2-climo case compared to the Solar-climo case. Correspondingly, precipitation decreases in both the cases with larger decreases in the 2xCO2-climo case. The larger decrease in 2xCO2-climo is related to strong vertical gradient in longwave absorption by elevated CO_2 with stronger absorption in the upper troposphere and weaker absorption in the lower troposphere [*Bala et al.*, 2008; *Collins et al.*, 2006a; *Hansen et al.*, 1997]. This vertical gradient in long wave forcing can be seen from Table 1 which shows that the adjusted surface longwave forcing is about 1.7 Wm^{-2} lower than the forcing at TOA in the 2xCO2-climo case. The fast adjustments are also slightly different for the column precipitable water (Table 1). The adjustments in sensible heat fluxes are much smaller compared to that in latent heat fluxes.

The spatial distribution of adjustment in surface temperature, evaporation, precipitation and precipitable water are shown in Fig. 1. The adjustment patterns are strikingly similar in the two cases but the magnitudes are enhanced in the 2xCO2-climo case for the surface temperature, evaporation and precipitation. Surface temperature over

land and sea ice increases by more than 1°C in some locations (Fig.1). A general decrease in precipitation and evaporation over the oceans and increases over land can be seen. Regional changes in evaporation and precipitation are of the order of 10%. Regional water vapor changes are of the order of 5 % with more positive changes in the Solar-climo case over the oceans.

Vertical distribution of the fast adjustments in temperature shows stratospheric cooling in the 2xCO2 case and a slight warming in the Solar case (Fig. 2). These differences are related to enhanced longwave cooling in the stratosphere by elevated CO_2 in the 2xCO2-climo case and enhanced shortwave absorption by stratospheric Ozone in the Solar-climo case. We notice larger changes in specific humidity in the Solar-climo case than in the 2xCO2-climo case which we believe is related to the warming in the stratosphere in the Solar-climo case. The pattern of fast adjustments in clouds in the troposphere is similar in the two cases (Fig. 2) with mostly decreases in the troposphere which is in good agreement with other studies [*Andrews and Forster*, 2008; *Gregory and Webb*, 2008]. The cloud adjustment patterns resemble the relative humidity adjustments, suggesting that the fast adjustments in cloudiness are associated with relative humidity changes in this model.

3.2 Total and slow responses

Global- and annual-mean changes in 2xCO2 and Solar relative to the Control are listed in Table 2. The surface temperature warms by 2.26 and 1.98 K in the 2xCO2 and Solar cases, respectively. Land-mean warming is more than the ocean-mean warming in agreement with literature [*IPCC 2007*, 2007]. Global-mean precipitation changes are 4.4 and 5.3 %, respectively, and hence the hydrologic sensitivity as defined by the percentage

change in precipitation per unit warming is 1.9 and 2.7 % per K, respectively. This sensitivity is the total sensitivity that includes both the slow and fast responses [*Allen and Ingram*, 2002; *Bala et al.*, 2008; *Held and Soden*, 2006; *Wentz et al.*, 2007]. This gives an impression that the hydrological sensitivity of the climate system strongly depends on the forcing mechanism. However, as we will show the hydrological sensitivity is almost independent of the forcing mechanism if we consider only the slow response, and fast response is excluded from climate change but included as part of the radiative forcing.

To obtain the sensitivity due to slow response, we need to subtract the changes due to fast response estimated in the previous section. Consider a climate variable x whose total change is Δx_{tot} as simulated in the slab-ocean experiments. This total response can be decomposed into

$$\Delta x_{tot} = \Delta x_f + \Delta x_s \text{ ---------- } (1)$$

where Δx_f and Δx_s are the fast and slow response components, respectively. The slow response is, therefore, obtained by subtracting the fast response (simulated in the fixed SST experiments) from the total response simulated in the slab-ocean experiments. We separate the surface temperature response in a manner similar to (1):

$$\Delta T_{tot} = \Delta T_f + \Delta T_s \text{ ---------- } (2)$$

The fast response in temperature (which is confined to land) is only about 5-7 % of the total response in our study (Tables 1 and 2). However, the fast response in precipitation is about 40 % of the total response in the 2xCO2 case. Therefore, the separation of the fast and slow responses becomes important when we investigate the response of hydrological cycle to climate forcings. The sensitivity of x, λ_x is usually defined as

$$\lambda_x = \Delta x_{tot} / \Delta T_{tot} \text{ ---------- } (3)$$

If we modify the definition of sensitivity so that it refers only to the slower response component, we have

$\lambda_x = (\Delta x_{tot} - \Delta x_f)/(\Delta T_{tot} - \Delta T_f)$ -------- (4)

This definition basically represents the slope of the regression line in the Gregory's regression method [*Gregory et al.*, 2004]. The slow response of the various components of the climate system is listed in Table 3. The climate sensitivity, defined as the ratio of slow response in temperature to adjusted TOA radiative forcing (Table 1), is almost independent of forcing mechanism [*Hansen et al.*, 1997]: it differs between the two cases by only 10%. The responses of TOA clear-sky, and cloudy-sky components of shortwave and longwave fluxes and surface longwave responses also differ by 10 %. The surface shortwave radiative response is the only component that differs by a larger 20%. The precipitation sensitivity is similar in the two cases when the fast response is excluded (Table 3). The slow response hydrologic sensitivity of 3 % per unit warming is in good agreement with previous estimates of 3.4 % /K obtained from an intercomparison of multiple slab-ocean models [*Allen and Ingram*, 2002]. The sensitivities of water vapor (precipitable water), sensible heat and latent heat fluxes are also nearly the same when the fast response is excluded (Table 2).

The regression method for estimating the fast adjustment and slow response [*Gregory et al.*, 2004] is shown in Fig. 3. According to this method, the intercept of linear regression of any climate variable against the change in global- and annual-mean surface temperature gives the fast adjustment and the slow response (or feedback) is provided by the slope. Fig. 3 shows that the slow response of TOA and surface fluxes, precipitation and water vapor (as represented by the slopes of the regression lines) are similar for

climate change induced by both CO_2 and solar forcings, suggesting that the slow responses are the same. The intercepts are markedly different for TOA net longwave and shortwave fluxes mainly because the radiative forcings are in different wavelengths; in longwave for the 2xCO2 case and shortwave for the Solar case. Differing fast adjustments also partly contribute to the difference in intercepts of radiative fluxes. However, fast adjustment is the sole driver for the differing intercepts in latent and sensible heat fluxes, precipitation and precipitable water.

It is instructive to note that the intercepts (Fig. 3) which represent the adjusted radiative forcings and fast adjustments differ significantly from the estimates (Table 1) given by the fixed SST method. In general, we find that the regression method tends to give more negative and less positive forcings compared to fixed SST method, in agreement with an earlier study [*Gregory and Webb*, 2008]. For instance, the TOA net radiative forcings from the regression method are 2.54 and 2.73 Wm^{-2} for the 2xCO2 and Solar cases but are 3.37 and 3.54 Wm^{-2} from the fixed SST method. The sign of fast adjustments in precipitation and evaporation is negative (a positive surface forcing) in the fixed SST method and positive (a negative surface forcing) in the regression method.

It is also interesting to note that the climate sensitivity as given by the regression method is identical for the 2xCO2 and Solar cases (Fig. 3; slope of the regression lines of TOA and surface net fluxes) since the regressed lines overlap. However, our estimate of climate sensitivity (Table 3) by subtracting the fast response from total response shows differences of the order of 10 % between these two cases. This indicates significant differences between the fixed SST method and regression method in agreement with an earlier study [*Gregory and Webb*, 2008].

The spatial pattern of the ratio of the magnitude of fast response to the magnitude of the slow response shows that the fast response in land surface temperatures in some regions can be as high as 50 % of the slow response (Fig. 4). This ratio is obtained by dividing the magnitude of the fast adjustment shown in Fig.1 by the slow response which is obtained from (2). High fractional values over ocean and land areas are obtained for evaporation and precipitation, suggesting larger fraction for fast response in the hydrological cycle. The pattern for precipitable water is similar to the surface temperature, indicating very strong control of temperature on the water vapor field.

Discussion

In this study, we have investigated the fast response of climate system to CO_2 and solar forcings in detail. The fast response at the surface involves a reduction in evaporation for both the forcings which is mirrored as a reduction in precipitation. Therefore, instantaneous radiative forcing itself induces a response on a timescale of a few months to a year before the global- and annual-mean surface temperature changes. Since this fast response is almost 40 % of the total response for a few key variables like precipitation in the CO_2-forcing case, it becomes important to separate the fast response from slow response that truly represents the feedbacks in the climate system. When the fast response component is subtracted from the total response, we are able to derive the slow response component. We find that this slow response or feedback is the same for CO_2 and solar forcing for the hydrological cycle.

Modeling and observational studies have estimated that the hydrologic sensitivity for CO_2 forcing is about 2 %/K [*Adler et al.*, 2008; *Bala et al.*, 2008; *Held and Soden*, 2006]. However, as we have discussed before, this value represents the total response of

the hydrologic cycle and is an underestimate of true hydrologic response because of the inclusion of the fast response. The slow response has higher value: ~ 3°C/K as discussed in this paper and 3.4^{o}K/C in an intercomparison of slab-ocean models [*Allen and Ingram*, 2002]. Because the fast response could be as high as 40% of the total response and could vary among models, we recommend that the fast and slow response be compared separately when multi-model intercomparisons are made. Such separation may help us to reveal and understand robust responses in hydrologic cycle.

Climate modeling studies have indicated that CO_2-fertilization reduces surface evaporation via increased "water efficiency" and hence can lead to surface warming and affect surface hydrology [*Betts et al.*, 2007; *Gedney et al.*, 2006; *Levis et al.*, 1999; 2000; *Matthews and Caldeira*, 2007; *Sellers et al.*, 1996]. Therefore, it is possible that part of the reduction in surface evaporation in our study is due to CO_2-fertilization of plants in the land model. To quantify this, we performed two additional experiments (one with prescribed SST and another with slab-ocean model) where the effects of increased CO_2 levels are seen by the land model but not by the radiative transfer model of the atmosphere. Mean global and land warming in these experiments are of the order of 0.01 K and mean global and land latent heat flux changes by 0.002 and 0.17 Wm^{-2}: changes that are one or two orders of magnitude smaller than the fast radiative adjustments investigated in this paper. Therefore, the fast hydrological adjustments discussed in this modeling study are primarily driven by radiative forcing. It should be, however, noted that there is uncertainty in the quantification of the climate effects of CO_2-fertiliation: while our modeling study finds negligible effect, another modeling study [*Betts et al.*,

2007] simulated a CO_2-fertilization effect that is of the same order of magnitude as the fast adjustments simulated in this study.

A recent modeling study on sunshade geoengineering shows that insolation reductions sufficient to offset global-scale temperature increases lead to a decrease in global mean precipitation [*Bala et al.*, 2008]. This study concluded that solar forcing is more effective in driving changes in global mean evaporation than is CO_2 forcing of a similar magnitude and implied that an alteration in solar forcing might offset temperature changes or hydrological changes from greenhouse warming, but could not cancel both at once. Similar conclusions on reduced hydrological cycle in geo-engineered climate have been reached by other modeling studies on geoengineering [*Lunt et al.*, 2008; *Matthews and Caldeira*, 2007; *Rasch et al.*, 2008; *Robock et al.*, 2008]. Our investigation in this paper provide insights into the cause for the differing hydrological changes between 2xCO2 and Solar forcings and concludes that the differing fast responses in the hydrological cycle are main cause for the differing hydrologic sensitivity.

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Table 1 Adjusted radiative forcing and fast response of non-radiative variables in the 2xCO2-climo and Solar-climo cases.

Variable	2xCO2-climo	Solar-climo
TOA[a] clear-sky longwave radiative forcing† (Wm^{-2})	3.71±0.15*	-0.37±0.15
TOA cloudy-sky longwave radiative forcing (Wm^{-2})	-0.68±0.11	-0.15±0.11
TOA longwave radiative forcing[b] (Wm^{-2})	3.03±0.15	-0.52±0.20
TOA clear-sky shortwave radiative forcing (Wm^{-2})	0.16±0.11	5.45±0.10
TOA cloudy-sky shortwave radiative forcing (Wm^{-2})	0.18±0.20	-1.39±0.25
TOA shortwave radiative forcing[c] (Wm^{-2})	0.34±0.21	4.06±0.28
'Adjusted TOA radiative forcing"[d] (Wm^{-2})	3.37±0.21	3.54±0.20
Precipitation (%)	-1.8±0.18	-0.7±0.20
Precipitable water (%)	0.7±0.36	1.3±0.30
Surface shortwave forcing[e] (Wm^{-2})	0.22±0.22	2.49±0.30
Surface sensible heat forcing (Wm^{-2})	-0.33±0.13	-0.04±0.10
Surface latent heat forcing(Wm^{-2})	-1.46±0.17	-0.52±0.18
Surface longwave forcing[f] (Wm^{-2})	-1.34±0.14	-0.49±0.21
Adjusted surface forcing[g](Wm^{-2})	3.35±0.24	3.54±0.24
Land surface temperature change (K)	0.37±0.18	0.24±0.16
Global-mean surface temperature change (K)	0.17±0.08	0.11±0.07

[a] Top of the atmosphere
[†]Downward fluxes provide positive forcing both at the surface and TOA
*The uncertainty for each variable is ± 1 standard deviation estimated from a sample of 30 annual means.
[b]TOA longwave radiative forcing is the sum of rows 2 and 3.
[c]TOA shortwave radiative forcing is the sum of rows 5 and 6.
[d]Adjusted TOA radiative forcing is the sum of rows 4 and 7.
[e]Incident minus reflected shortwave radiation at the surface.

[f]Upward minus downward longwave radiation at the surface.
[g]Adjusted surface radiative forcing is obtained by subtracting rows 12, 13 and 14 from 11. Note that the surface forcing and TOA radiative forcing are the same after tropospheric adjustment since the atmosphere cannot store heat on time scales of more than a few months.

Table 2 Total Climate response in 2xCO2 and Solar cases

Variable	2xCO2	Solar
Global-mean surface temperature (K)	2.26±0.36*	1.98±0.28
Land mean surface temperature (K)	2.50±0.36	2.15±0.29
Ocean mean surface temperature (K)	2.09±0.36	1.86±0.29
Global-mean precipitation (%)	4.39±0.43	5.32±0.42
Global-mean precipitable water (%)	15.27±1.17	15.37±1.04

*The uncertainty for each variable is ± 1 standard deviation estimated from a sample of 30 annual means.

Table 3 Slow climate response in 2xCO2 and Solar cases

Variable	2xCO2	Solar
Global-mean surface temperature (K)	2.09	1.87
Climate sensitivity (K/Wm^{-2})	0.62	0.53
TOA clear-sky longwave ($Wm^{-2}K^{-1}$)	-1.93	-2.01
TOA cloudy-sky longwave ($Wm^{-2}K^{-1}$)	0.23	0.17
TOA longwave ($Wm^{-2}K^{-1}$)	-1.70	-1.84
TOA clear-sky shortwave ($Wm^{-2}K^{-1}$)	0.84	0.78
TOA cloudy-sky shortwave ($Wm^{-2}K^{-1}$)	-0.68	-0.77
TOA shortwave ($Wm^{-2}K^{-1}$)	0.16	0.01
TOA net flux ($Wm^{-2}K^{-1}$)	-1.54	-1.83
Surface net shortwave ($Wm^{-2}K^{-1}$)	-0.55	-0.77
Surface net longwave ($Wm^{-2}K^{-1}$)	-1.00	-1.10
Hydrologic sensitivity (%/K; total response)*	3.0 (1.94)	3.2 (2.69)
Precipitable water sensitivity (%/K; total response)	7.0 (6.8)	7.5 (7.8)
Surface sensible heat flux ($Wm^{-2}K^{-1}$; total response)	-0.37(-0.35)	-0.35(-0.49)
Surface latent heat flux ($Wm^{-2}K^{-1}$; total response)	2.41 (1.58)	2.59 (2.19)

*Values in brackets show the total response that includes the fast adjustments.

Figure Captions

Fig. 1 Fast adjustments in annual-mean surface temperature, latent heat flux (evaporation), precipitation, and precipitable water (column integrated water vapor) in the 2xCO2-climo and Solar-climo cases. The hatching indicates regions where the changes are significant at the 1% level. Significance level is estimated using a Student-t test with a sample of 30 annual means. For surface temperatures, fast adjustments can occur only over land and sea ice since sea surface temperature and sea ice concentration are prescribed. The spatial patterns of fast adjustments are similar in both cases but the magnitudes are different (Table 1): adjustments in surface temperature, latent heat flux and precipitation are larger for the 2xCO2-climo case but precipitable water adjustment is larger in the Solar-climo case.

Fig. 2 Fast adjustments in zonal-mean temperature, specific humidity, relative humidity and cloud fraction in the 2xCO2-climo and Solar-climo cases. The hatching indicates regions where the changes are significant at the 1% level. Significance level is estimated using a Student-t test with a sample of 30 annual means. To avoid errors due to interpolation, we did not perform any interpolation in the vertical and hence the vertical axis shown is the model's hybrid sigma coordinate. In general, the spatial patterns of adjustments are similar in both the cases with some exceptions: the stratosphere is colder in the 2xCO2-climo case while the Solar-climo shows a slight warming there, specific humidity increases everywhere in Solar-climo but it shows both increases and decreases in the 2xCO2-climo case. The patterns of fast adjustments in relative humidity and clouds resemble each other, suggesting that cloud changes are associated with relative humidity changes.

Fig. 3 Linear regression of TOA net longwave, shortwave, net radiative fluxes, surface net fluxes, surface latent and sensible heat fluxes, precipitation, and precipitable water against the global- and annual-mean surface temperature changes in the 2xCO2 (stars and solid line) and Solar cases (circles and dashed line). The intercepts give estimates of the fast responses and the slopes yield the slow responses of the climate variables climate change. We can infer that the slow responses of all the variables shown are similar for

climate change induced by both CO_2 and solar forcings. However, the intercepts are markedly different. In the case of radiative fluxes in the top panels, the differences are mainly caused by radiative forcings which act in different wavelengths; in longwave for the $2xCO_2$ case and shortwave for the Solar case. Differing fast adjustments also partly contribute to the difference in the intercepts of radiative fluxes. However, differing fast adjustment is the sole driver for the differing intercepts for latent and sensible heat fluxes, precipitation and precipitable water.

Fig. 4 Ratio of the magnitude of fast adjustment to the magnitude of slow adjustment for climate changes in 2xCO2 and Solar cases. The hatching indicates regions where the fast adjustments are significant at the 1% level. Significance level is estimated using a Student-t test with a sample of 30 annual means. There are regions where this fraction exceeds 0.5, suggesting that the magnitude of fast response is half the slow response in those regions. While fast adjustments in temperature and precipitable water are mostly confined to land areas, both land and oceanic areas show large fast adjustments in evaporation and precipitation.

Fig. 1

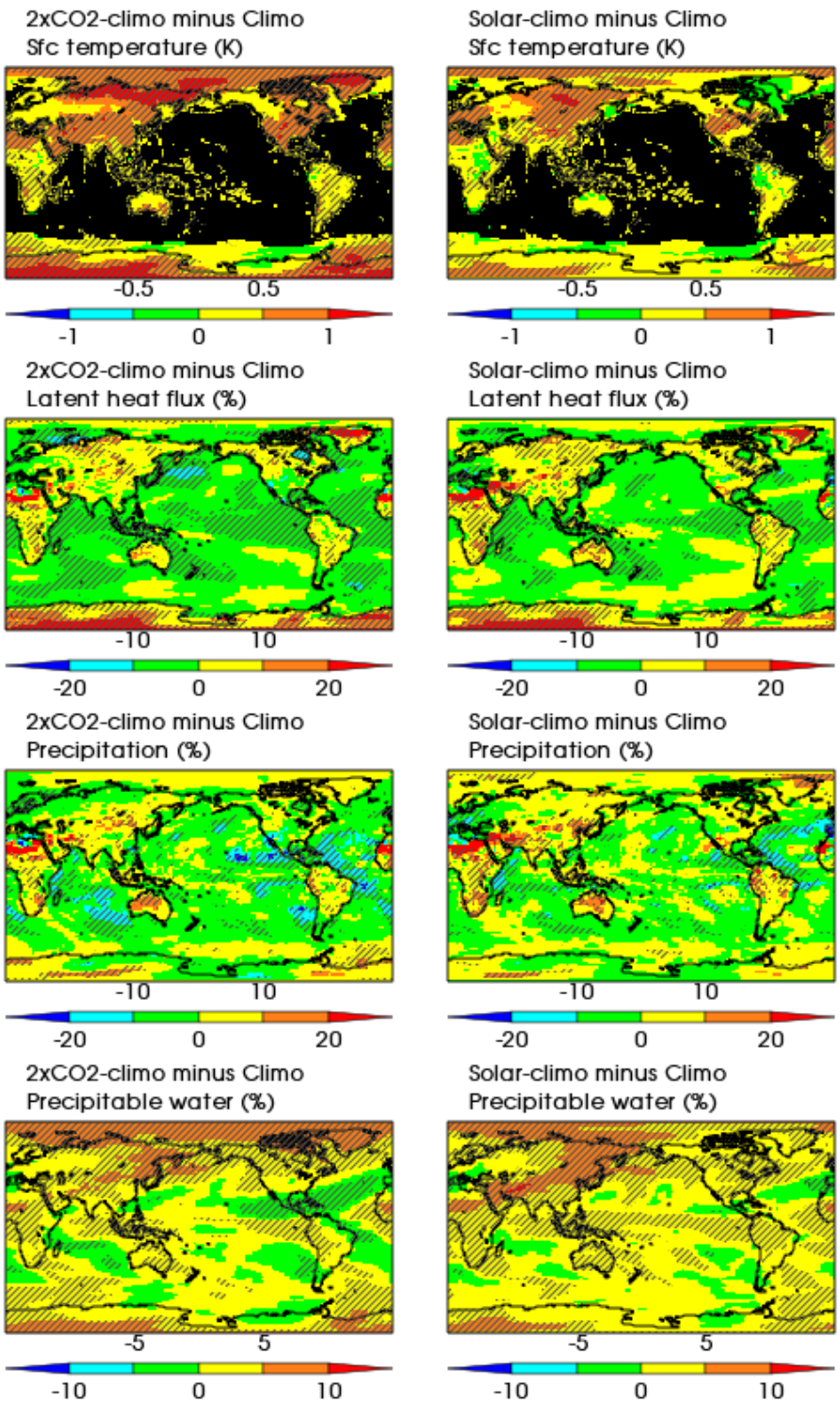

2xCO2-climo minus Climo
Sfc temperature (K)
-0.5
0.5
-1
0
1
Solar-climo minus Climo
Sfc temperature (K)
-0.5
0.5
-1
0
1
2xCO2-climo minus Climo
Latent heat flux (%)
-10
10
-20
0
20
Solar-climo minus Climo
Latent heat flux (%)
-10
10
-20
0
20
2xCO2-climo minus Climo
Precipitation (%)
-10
10
-20
0
20
Solar-climo minus Climo
Precipitation (%)
-10
10
-20
0
20
2xCO2-climo minus Climo
Precipitable water (%)
-5
5
-10
0
10
Solar-climo minus Climo
Precipitable water (%)
-5
5
-10
0
10

Fig. 2

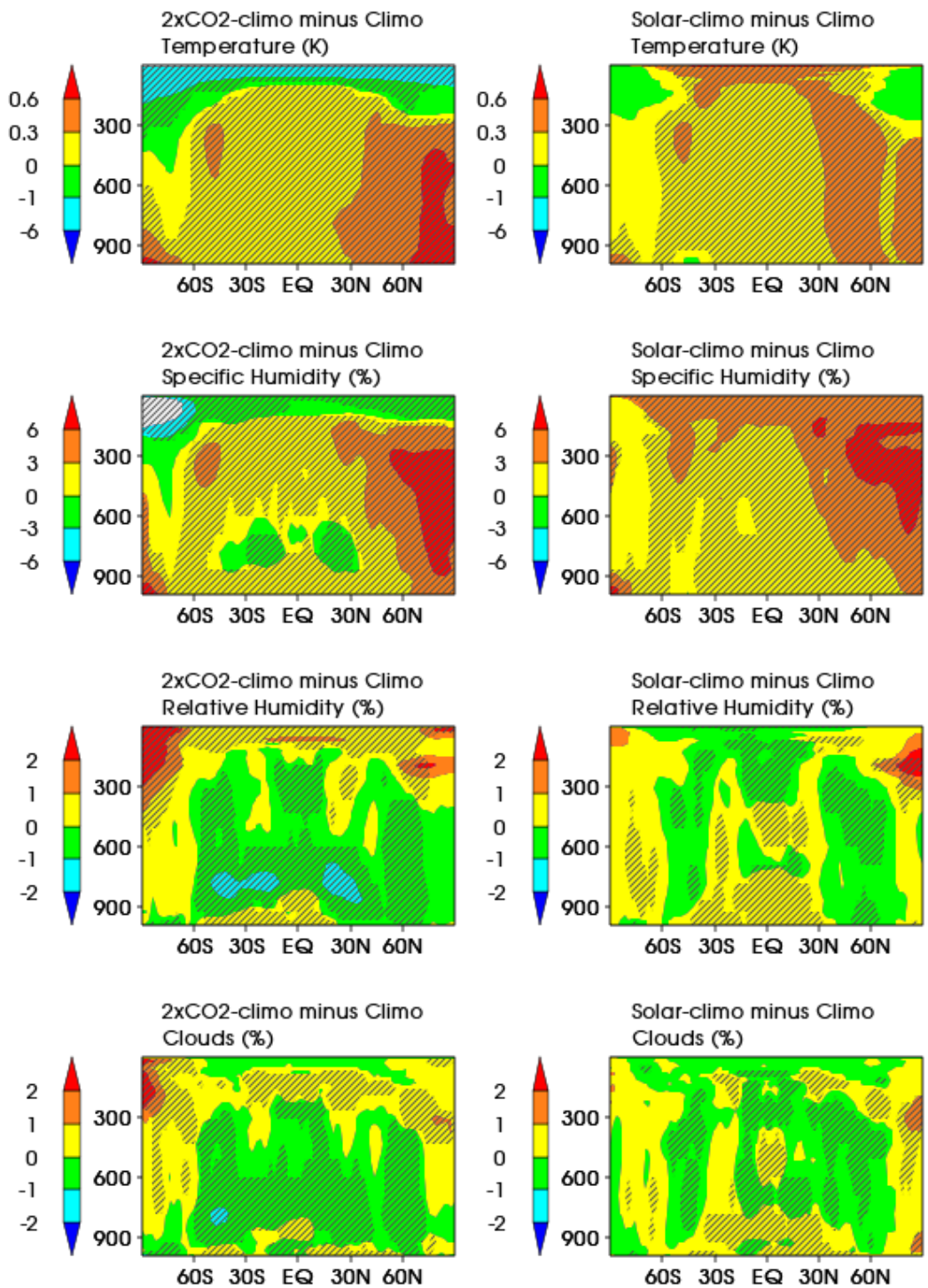

2xCO2-climo minus Climo
Temperature (K)
0.6
0.3
0
-1
-6
300
600
900
60S 30S EQ 30N 60N
Solar-climo minus Climo
Temperature (K)
0.6
0.3
0
-1
-6
300
600
900
60S 30S EQ 30N 60N
2xCO2-climo minus Climo
Specific Humidity (%)
6
3
0
-3
-6
300
600
900
60S 30S EQ 30N 60N
Solar-climo minus Climo
Specific Humidity (%)
6
3
0
-3
-6
300
600
900
60S 30S EQ 30N 60N
2xCO2-climo minus Climo
Relative Humidity (%)
2
1
0
-1
-2
300
600
900
60S 30S EQ 30N 60N
Solar-climo minus Climo
Relative Humidity (%)
2
1
0
-1
-2
300
600
900
60S 30S EQ 30N 60N
2xCO2-climo minus Climo
Clouds (%)
2
1
0
-1
-2
300
600
900
60S 30S EQ 30N 60N
Solar-climo minus Climo
Clouds (%)
2
1
0
-1
-2
300
600
900
60S 30S EQ 30N 60N

Fig. 3

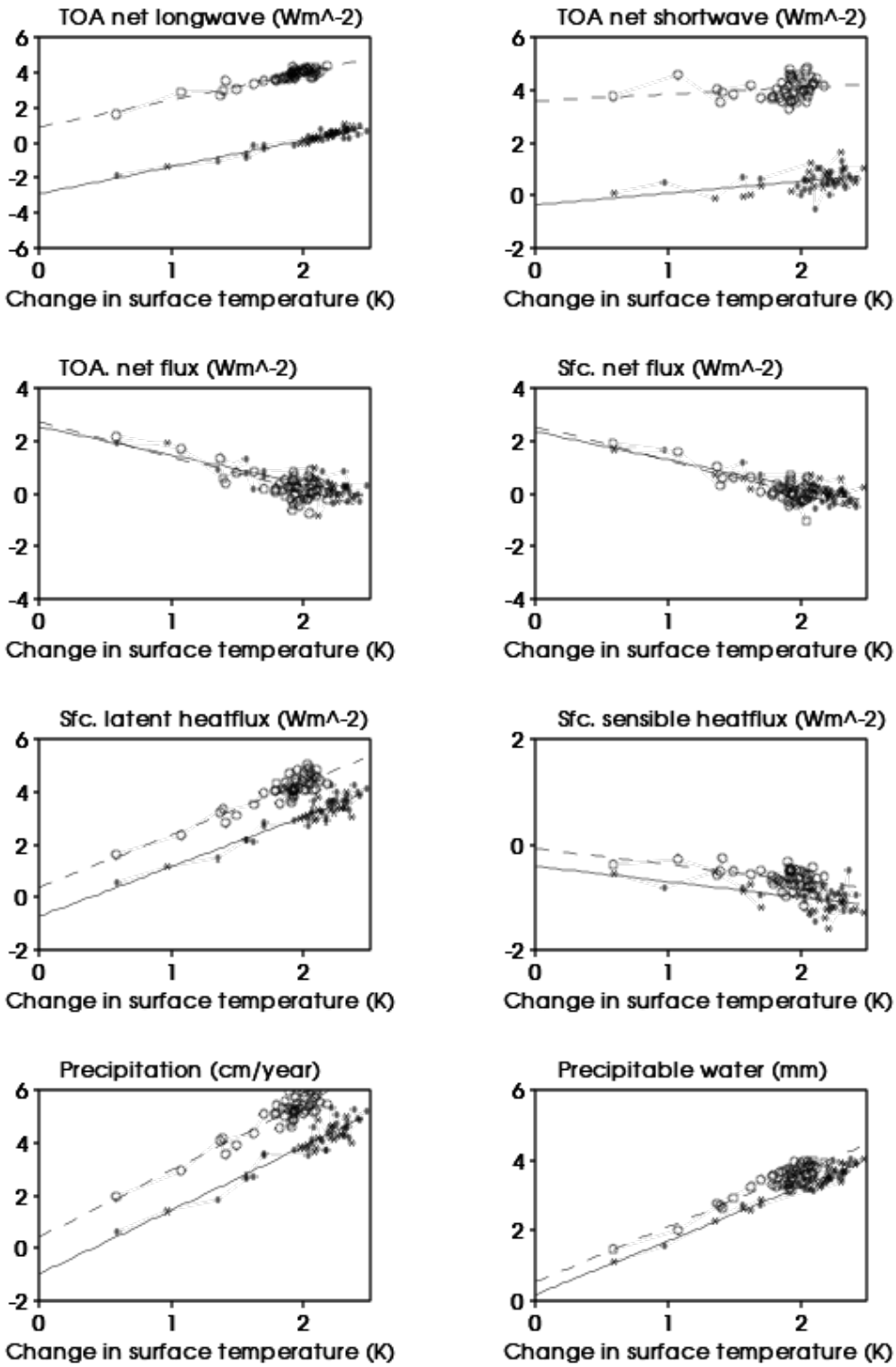
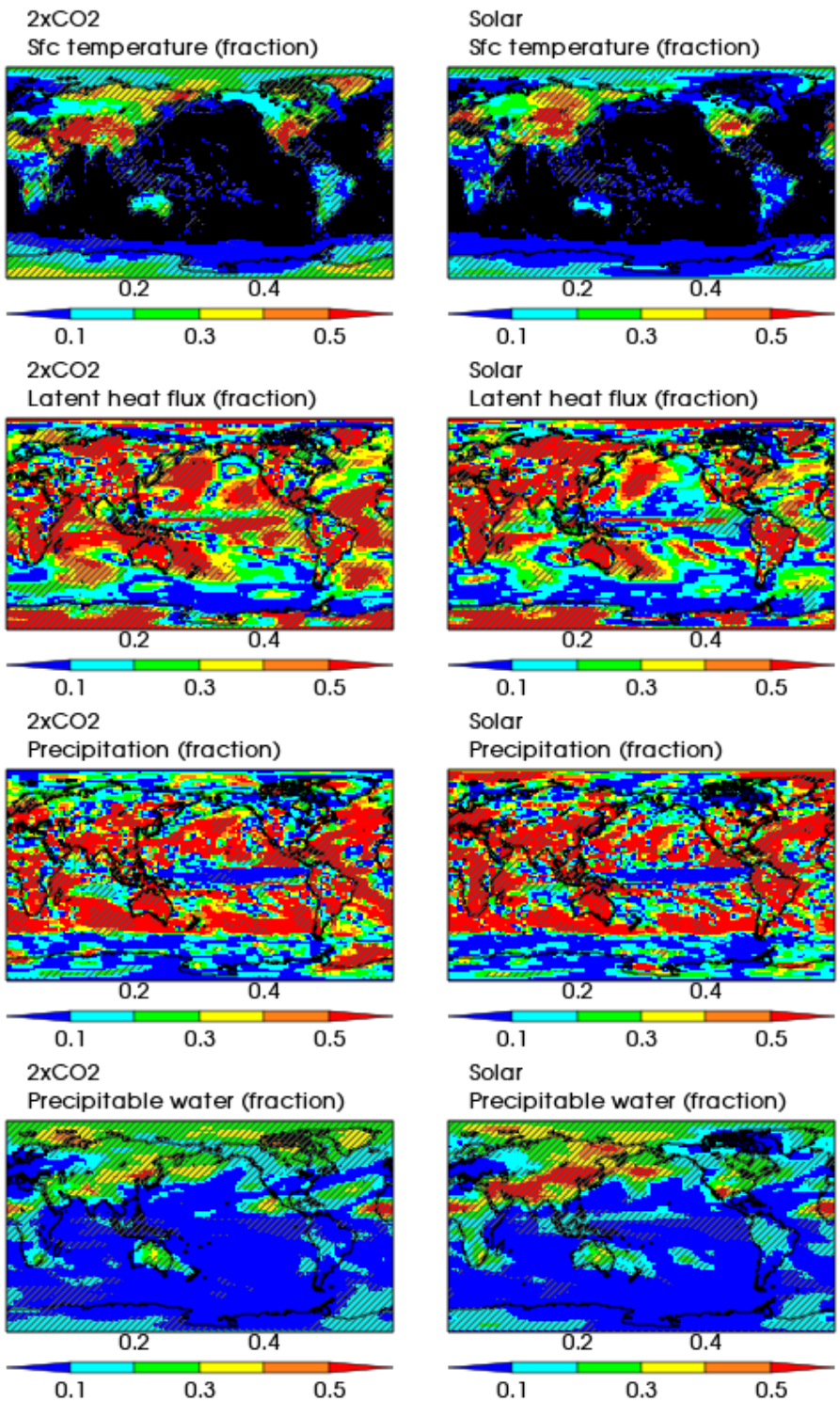

TOA net longwave (Wm^-2)
TOA net shortwave (Wm^-2)
TOA. net flux (Wm^-2)
Sfc. net flux (Wm^-2)
Sfc. latent heatflux (Wm^-2)
Sfc. sensible heatflux (Wm^-2)
Precipitation (cm/year)
Precipitable water (mm)
Change in surface temperature (K)

Fig. 4


2xCO2
Sfc temperature (fraction)
0.2
0.4
0.1
0.3
0.5
Solar
Sfc temperature (fraction)
0.2
0.4
0.1
0.3
0.5
2xCO2
Latent heat flux (fraction)
0.2
0.4
0.1
0.3
0.5
Solar
Latent heat flux (fraction)
0.2
0.4
0.1
0.3
0.5
2xCO2
Precipitation (fraction)
0.2
0.4
0.1
0.3
0.5
Solar
Precipitation (fraction)
0.2
0.4
0.1
0.3
0.5
2xCO2
Precipitable water (fraction)
0.2
0.4
0.1
0.3
0.5
Solar
Precipitable water (fraction)
0.2
0.4
0.1
0.3
0.5