Supplemental Online Material to “Climate response to changes in atmospheric carbon dioxide and solar irradiance on the time scale of days to weeks”

Long Cao¹, Govindasamy Bala², Ken Caldeira³

¹Department of Earth Sciences, ZheJiang University, HangZhou, ZheJiang, 310027, China, P.R.
²Divecha Center for Climate Change & Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, 560012, India
³Department of Global Ecology, Carnegie Institution, Stanford, CA, 94305, USA

Supplemental text:

S1. Climate model and simulations

We used the UK Met Office Hadley Center global climate model, HadCM3L (Cox et al., 2000). HadCM3L is an atmosphere-ocean coupled general circulation model (AOGCM). It has a horizontal resolution of 3.75 degree longitude and 2.5 degree latitude for both the atmosphere and ocean, and a vertical resolution of 19 levels in the atmosphere and 20 levels in the ocean. The land component is represented by the MOSES II land surface scheme with process-based representation of energy and moisture balance at land surface (Essery and Clark, 2003). Canopy conductance, which represents the bulk effect of stomatal opening on the exchange of water vapor and CO₂, responds directly to atmospheric CO₂ concentrations in such a way that increasing level of atmospheric CO₂ decreases the rate of canopy conductance (Cox et al., 1999).

A quasi-equilibrium pre-industrial climate state was obtained from a 3000 model-year HadCM3L simulation under a constant atmospheric CO₂ concentration of 280 ppm. Starting from this quasi-equilibrium state four sets of perturbation simulations were performed: 1) A quadrupling of atmospheric CO₂ from 280 to 1120 ppm that is applied to the calculation of atmospheric radiation (4×CO₂_RAD); 2) A quadrupling of atmospheric CO₂ from 280 to 1120
ppm that is applied to the calculation of plant stomatal conductance (4×CO₂_PHY); 3) A quadrupling of atmospheric CO₂ from 280 to 1120 ppm that is applied to the calculation of both atmospheric radiation and stomatal conductance (4×CO₂); 4) A 4% increase in solar constant (4% Solar). In addition, a set of control simulation with atmospheric CO₂ of 280 ppm and a default solar constant of 1365 W m⁻² was conducted. We analyze results from perturbation runs relative to the mean of the control simulation.

To remove the effect of seasonal cycle, for each set of the above simulations twelve runs were conducted with each run starting from the first day of each month of the year. Similar experiments with monthly mean results were performed by Doutriaux-Boucher et al. (2009). To further increase the signal-to-noise ratio, three-member ensemble simulations were performed for each of the twelve runs; each member of the ensemble was initialized from the same day of different years of the 3000-year quasi-equilibrium simulation. In this way, thirty six simulations (three member ensemble for each of the twelve runs starting from the first day of each month of the year) were performed for each set of run, and altogether 180 (5×36) simulations were performed. Each simulation lasted for one month with daily-mean output saved. By averaging the results over the three-member ensemble of twelve runs the effect of seasonal cycle is removed. All results are presented in terms of the change in perturbation simulations relative to the control simulation.

To further examine climate response beyond one month, a set of five-year ensemble simulations with monthly-mean output involving the step-function quadrupling of atmospheric CO₂ or 4% increase in solar constant were performed. Similar to the runs with daily-mean output, for each forcing scenario twelve simulations were performed with each simulation starting from the first day of each month of the year. Results are then averaged over the twelve simulations so that the
effect of seasonal cycle is removed. In addition, a set of 1000-year simulations involving the step-function quadrupling of CO₂ or 4% increase in solar constant were performed, and the yearly-mean results from these simulations are used in the analysis.

References:

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Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature, 408, 184–187.

Doutriaux-Boucher, M., M. J. Webb, J. M. Gregory, and O. Boucher (2009), Carbon dioxide induced stomatal closure increases radiative forcing via a rapid reduction in low cloud, Geophys. Res. Lett., 36, L02703, doi:10.1029/2008GL036273.

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S2. A note on linear regression

We perform linear regression of global mean precipitation change against global mean surface temperature change (Fig. 1) and linear regression of land/ocean mean precipitation change against global mean surface temperature change (Fig. S1). The regressions shown in Fig. 1 and Fig. S1 are done using annual mean data at two different time resolutions: 1) 60 annual means at the monthly resolution that are obtained by averaging twelve 5-year runs starting from different months of the year; 2) 15 annual means at the yearly resolution that are obtained from the first 15 years of the 1000-year simulation. We also perform linear regression using the data at either monthly or yearly resolution. Table S1 provides numerical values of regressed fast precipitation response (vertical-axis intercept of the regression of Fig. 1 and Fig. S1) using the data at monthly resolution, yearly resolution, and the combined data at both the monthly and yearly resolution.
Supplemental figures

Figure S1: Left panels: HadCM3L-simulated change in land-mean (a) and ocean-mean (c) change in precipitation against change in global mean surface temperature for the simulation involving a quadrupling of atmospheric CO$_2$ (black) and simulation involving a 4% increase in solar irradiance (red). Results are shown at the daily (square, day 1 to day 30), monthly (circle, month 1 to month 60), and yearly (plus sign, year 1 to year 15) resolutions. Results at the monthly resolution are obtained by averaging twelve 5-year runs starting from different months of the year, and results at the yearly resolution are obtained from the first 15 years of the 1000-year simulations. Black and red lines are linear regression to the data at monthly and yearly resolutions as described in the SOM. (b) Daily evolution of land-mean (b) and ocean-mean (d) precipitation change in response to a quadrupling of atmospheric CO$_2$ (thick black line) and 4% increase in solar irradiance (thick red line) plotted with regressed fast precipitation response (thin black line for 4×CO$_2$ and thin red line for 4% increase in solar irradiance) as determined from the vertical-axis intercept in the linear regression shown in panel (a). Shaded bands represent the 95% confidence interval for the regressed fast precipitation response. A version of global mean results is shown in Fig. 1.
Figure S2: HadCM3L-simulated daily changes in global mean temperature for the simulation involving a quadrupling of atmospheric CO₂ (4×CO₂, thick black lines), a quadrupling of atmospheric CO₂ but with only CO₂-radiative effect included (4×CO₂_RAD, thin black lines), and 4% increase in solar irradiance (4% Solar, thick red lines). Shown are (a) surface temperature change relative to the mean of the control simulation, (b) fractional surface temperature change relative to the near-equilibrium warming (Here near-equilibrium warming is estimated by the warming averaged over the last 100-year results of the 1000-year simulations), and (c) differences between temperature change at 850mb and the surface (temperature change at 850 mb minus temperature change at the surface) (c). The dashed lines represent inter-daily variability (2σ) calculated from the standard deviation of the control simulation. A version with land-mean and ocean-mean change is shown in Fig. 2.
Figure S3: HadCM3L-simulated changes in low cloudiness, clear-sky shortwave flux, cloud shortwave flux, and latent heat flux (All fluxes are defined as positive down) for the simulation involving a quadrupling of atmospheric CO\textsubscript{2} (4×CO\textsubscript{2}, thick black lines), a quadrupling of atmospheric CO\textsubscript{2} but with only CO\textsubscript{2}-radiative effect included (4×CO\textsubscript{2}_RAD, thin black lines), and 4% increase in solar irradiance (4×Solar, thick red lines). All results are relative to the control simulation. Upper, middle, and lower panels are land-mean, ocean-mean, and global-mean results respectively. The dashed lines represent inter-daily variability (2ơ) calculated from the standard deviation of the control simulation.
Figure S4: HadCM3L-simulated changes in global mean vertical profile of temperature at day one, two, five, and thirty for the simulation involving a quadrupling of atmospheric CO₂ (4×CO₂, thick black lines), a quadrupling of atmospheric CO₂ but with only CO₂-radiative effect included (4×CO₂_RAD, thin black lines), and 4% increase in solar irradiance (4% Solar, thick red lines). All results are relative to the control simulation. A version with land-mean and ocean-mean change is shown in Fig. 3.
**Figure S5**: HadCM3L-simulated changes in global mean boundary layer moisture flux export, near-surface specific humidity, near-surface relative humidity, and near-surface specific humidity deficit (surface saturation specific humidity minus near-surface specific humidity) for the simulation involving a quadrupling of atmospheric CO$_2$ (4×CO$_2$, thick black lines), a quadrupling of atmospheric CO$_2$ but with only CO$_2$-radiative effect included (4×CO$_2$ _RAD, thin black lines), and 4% increase in solar irradiance (4×Solar, thick red lines). All results are relative to the control simulation. The dashed lines represent inter-daily variability (2ơ) calculated from the standard deviation of the control simulation. A version with land-mean and ocean-mean change is shown in Fig. 4.
Figure S6: HadCM3L-simulated daily changes in global mean evaporation, precipitation, and precipitation minus evaporation for simulation involving a quadrupling of atmospheric CO₂ (4×CO₂, thick black lines), a quadrupling of atmospheric CO₂ but with only CO₂-radiative effect included (4×CO₂_RAD, thin black lines), and 4% increase in solar irradiance (4% Solar, thick red lines). All results are relative to the control simulation. The dashed lines represent inter-daily variability (2ơ) calculated from the standard deviation of the control simulation. A version with land-mean and ocean-mean change is shown in Fig. 5.
Figure S7: HadCM3L-simulated geographical pattern of changes in surface temperature, evaporation, precipitation, and precipitation minus evaporation averaged over day five in response to a quadrupling of atmospheric CO₂ and 4% increase in solar irradiance. All results are relative to the control simulation. Hatched regions are where changes are statistically significant at the 5% level using Student t test.
Figure S8: HadCM3L-simulated zonal land-mean (top two panels) and zonal ocean-mean (bottom two panels) changes in surface temperature, evaporation, precipitation, and precipitation minus evaporation averaged over day five in response to a quadrupling of atmospheric CO₂ and 4% increase in solar irradiance. All results are relative to the control simulation. Hatched regions are where changes are statistically significant at the 5% level using Student t test.
Figure S9: A schematic illustration of HadCM3L-simulated global mean climate change at day five in response to a quadrupling of atmospheric CO$_2$ and a 4% increase in solar irradiance. Arrows represent the direction of change in boundary layer moisture flux with the upward arrow indicating an increase in moisture flux out of the boundary layer and the downward arrow indicating a decrease in moisture flux out of the boundary layer. A version with land-mean and ocean-mean results is given in Fig. 6.
Table S1: Regressed fast response of precipitation change (m yr\(^{-1}\)) based on annual-mean data at monthly resolution, annual-mean data at yearly resolution, and the combination of annual-mean data at both monthly and yearly resolution for the simulations involving a quadrupling of atmospheric CO\(_2\) (4×CO\(_2\)) and 4% increase in solar irradiance (4% solar). Uncertainty is represented by one standard error from the regression.

|                  | 4×CO\(_2\)                      | 4% solar                     |
|------------------|---------------------------------|------------------------------|
|                  | Monthly data (year 1 to 5)      | Yearly data (year 1 to 15)   | Combined monthly and yearly data | Monthly data (year 1 to 5) | Yearly data (year 1 to 15) | Combined monthly and yearly data |
| Global-mean      | -0.0838±0.0038                  | -0.0669±0.0104               | -0.0757±0.0038                 | -0.0018±0.0105              | -0.0398±0.0101               | -0.0078±0.0043                 |
| Land-mean        | -0.0247±0.0195                  | -0.0028±0.0463               | -0.0109±0.0139                 | 0.0425±0.0192                | 0.0873±0.0445                 | 0.0698±0.0155                 |
| Ocean-mean       | -0.1079±0.0074                  | -0.0897±0.0118               | -0.1018±0.0377                 | -0.0436±0.0062               | -0.0297±0.0096               | -0.0394±0.0043                |
Table S2: HadCM3L-simulated change in climate variables averaged over day five for the simulation involving the combined radiative and physiological effect of quadrupling of atmospheric CO₂ (4×CO₂); the radiative effect of quadrupling of atmospheric CO₂ (4×CO₂_RAD); physiological effect of quadrupling of atmospheric CO₂ (4×CO₂_PHY); and a 4% increase in solar irradiance (4% Solar). All results are relative to the mean of the control simulation. Uncertainty is represented by one standard error calculated from ensemble simulations.

|                                | 4×CO₂         | 4×CO₂_RAD     | 4×CO₂_PHY     | 4% Solar      |
|--------------------------------|---------------|---------------|---------------|---------------|
|                                | Land-mean     | Ocean-mean    | Land-mean     | Ocean-mean    | Land-mean     | Ocean-mean    | Land-mean     | Ocean-mean    |
| Surface temperature (K)        | 1.39±0.03     | 0.05±0.01     | 0.59±0.04     | 0.05±0.01     | 0.72±0.04     | 0.00±0.00     | 0.46±0.04     | 0.03±0.01     |
| 850 mb temperature (K)         | 1.03±0.02     | 0.34±0.02     | 0.43±0.02     | 0.25±0.02     | 0.53±0.01     | 0.05±0.01     | 0.32±0.02     | 0.10±0.01     |
| Evaporation (m yr⁻¹)           | -0.11±0.00    | -0.03±0.00    | 0.01±0.00     | -0.03±0.00    | -0.12±0.00    | 0.01±0.00     | 0.02±0.00     | 0.01±0.00     |
| Precipitation (m yr⁻¹)         | -0.03±0.01    | -0.07±0.00    | 0.02±0.01     | -0.04±0.00    | -0.04±0.01    | -0.02±0.00    | 0.04±0.01     | -0.01±0.00    |
| Precipitation minus evaporation | 0.08±0.00     | -0.04±0.00    | 0.01±0.00     | -0.02±0.00    | 0.08±0.01     | -0.03±0.00    | 0.02±0.01     | -0.03±0.00    |
| Near-surface specific humidity (g kg⁻¹) | -0.39±0.02    | 0.09±0.00     | 0.12±0.02     | 0.09±0.00     | -0.48±0.02    | -0.01±0.00    | 0.08±0.02     | 0.03±0.00     |
| Near-surface relative humidity (×100) | -5.98±0.08   | 0.15±0.02     | -0.51±0.08    | 0.16±0.03     | -5.27±0.12    | -0.06±0.04    | -0.52±0.07    | 0.01±0.03     |
| Low cloud                      | -0.02±0.01    | -0.00±0.00    | -0.00±0.00    | -0.00±0.00    | -0.01±0.01    | -0.00±0.00    | 0.00±0.00     | 0.00±0.00     |
Table S3: The same as Table S2, but for global mean values.

|                                | 4×CO₂   | 4×CO₂_RAD | 4×CO₂_PHY | 4% Solar |
|--------------------------------|---------|-----------|-----------|----------|
| Surface temperature (K)        | 0.44±0.01 | 0.20±0.01 | 0.21±0.01 | 0.16±0.02 |
| 850 mb temperature (K)         | 0.53±0.02 | 0.29±0.02 | 0.18±0.01 | 0.16±0.01 |
| Evaporation (m yr⁻¹)           | -0.05±0.00 | -0.02±0.00 | -0.03±0.00 | 0.01±0.00 |
| Precipitation (m yr⁻¹)         | -0.06±0.00 | -0.03±0.00 | -0.02±0.00 | -0.00±0.00 |
| Precipitation minus evaporation (m yr⁻¹) | -0.00±0.00 | -0.01±0.00 | 0.00±0.00 | 0.01±0.00 |
| Near-surface specific humidity (g kg⁻¹) | -0.05±0.00 | 0.10±0.00 | -0.15±0.00 | 0.04±0.00 |
| Near-surface relative humidity (×100) | -1.63±0.00 | -0.03±0.00 | -1.57±0.03 | -0.14±0.02 |
| Low cloud                      | -0.01±0.01 | -0.00±0.00 | -0.00±0.01 | -0.00±0.00 |
Table S4: Changes in HadCM3L-simulated radiative and turbulent fluxes averaged at day five for the simulation involving the combined radiative and physiological effect of quadrupling of atmospheric CO\(_2\) (4×CO\(_2\)); the radiative effect of quadrupling of atmospheric CO\(_2\) (4×CO\(_2\)_RAD); physiological effect of quadrupling of atmospheric CO\(_2\) (4×CO\(_2\)_PHY); and a 4\% increase in solar irradiance (4\% Solar). All results are relative to the mean of the control simulation. Uncertainly is represented by one standard error calculated from ensemble simulations.

|                   | 4×CO\(_2\) | 4×CO\(_2\)_RAD | 4×CO\(_2\)_PHY | 4% Solar |
|-------------------|------------|----------------|----------------|----------|
|                   | Land-mean  | Ocean-mean     | Land-mean      | Ocean-mean| Land-mean | Ocean-mean |
| Top-of-atmosphere (W m\(^{-2}\), positive downward) |            |                |                |          |
| Shortwave         | 3.95±0.06  | 1.71±0.11      | 0.83±0.01      | 1.27±0.11 | 2.98±0.01 | 0.12±0.12 | 8.39±0.02 | 10.38±0.11 |
| Longwave          | 4.06±0.17  | 4.87±0.05      | 5.44±0.18      | 5.21±0.08 | -1.17±0.18| -0.38±0.10| 0.05±0.17 | -0.62±0.11 |
|                   |            |                |                |          |
| Surface (W m\(^{-2}\), positive downward) |            |                |                |          |
| Shortwave         | 3.55±0.03  | 0.89±0.13      | -0.25±0.04     | 0.36±0.14| 3.67±0.02 | 0.22±0.15 | 5.59±0.03 | 7.63±0.13 |
| Longwave          | -2.23±0.03 | 2.20±0.11      | 2.45±0.08      | 2.38±0.11| -4.51±0.10| -0.23±0.01| -1.01±0.07| -0.03±0.11 |
| Sensible heat     | -8.14±0.14 | 0.76±0.02      | -0.43±0.16     | 0.73±0.03| -7.32±0.16| -0.17±0.03| -2.37±0.14| -0.03±0.03 |
| Latent heat       | 8.80±0.08  | 2.46±0.30      | -0.91±0.11     | 2.25±0.40| 9.32±0.12 | -0.86±0.38| -1.49±0.10| -0.51±0.40 |
Table S5: The same as Table S4, but for global mean values.

|                  | 4×CO₂  | 4×CO₂_RAD | 4×CO₂_PHY | 4% Solar |
|------------------|--------|-----------|-----------|----------|
| Top-of-atmosphere (W m⁻², positive downward) |        |           |           |          |
| Shortwave        | 2.36±0.08 | 1.15±0.08 | 0.95±0.09 | 9.80±0.07 |
| Longwave         | 4.63±0.08 | 5.28±0.11 | -0.61±0.12| -0.42±0.13|
| Surface (W m⁻², positive downward) |        |           |           |          |
| Shortwave        | 1.65±0.10 | 0.18±0.09 | 1.22±0.10 | 7.04±0.08 |
| Longwave         | 0.91±0.09 | 2.40±0.08 | -1.47±0.09| -0.32±0.08|
| Sensible heat    | -1.82±0.04| 0.39±0.06 | -2.24±0.07| -0.71±0.07|
| Latent heat      | 4.30±0.19 | 1.33±0.26 | 2.09±0.20 | -0.80±0.26|