Physical climate response to a reduction of anthropogenic climate forcing

Arindam Samanta[1*], Bruce T. Anderson[1], Sangram Ganguly[2], Yuri Knyazikhin[1], Ramakrishna R. Nemani[3] and Ranga B. Myneni[1]
[1]Geography and Environment, Boston University, Boston, MA *arindam.sam@gmail.com | [2]BAERI/NASA Ames Research Center, CA |
[3]NASA AMES Research Center, CA.

Abstract. Recent research indicates that the warming of the climate system resulting from increased greenhouse gas (GHG) emissions over the next century will persist for many centuries after the cessation of these emissions, due principally to the persistence of elevated atmospheric carbon dioxide (CO_2) concentrations and their attendant radiative forcing. However, it is unknown whether the responses of other components of the climate system—including those related to Greenland and Antarctic ice cover, the Atlantic thermohaline circulation, the West African monsoon, and ecosystem and human welfare—would be reversed even if atmospheric CO_2 concentrations were to recover to 1990 levels. Here, using a simple set of experiments employing a current-generation numerical climate model we examine the response of the physical climate system to decreasing carbon dioxide (CO_2) concentrations following an initial increase. Results indicate that many characteristics of the climate system, including global temperatures, precipitation, soil moisture and sea ice, recover as CO_2 concentrations decrease. However, other components of the Earth system may still exhibit non-linear hysteresis. In our experiments for instance, increases in stratospheric water vapor, which initially result from increased CO_2 concentrations, remain present even as CO_2 concentrations recover. These results suggest that identification of additional threshold behaviors in response to human-induced global climate change should focus on sub-components of the full Earth system, including cryosphere, biosphere, and chemistry.

INTRODUCTION

International efforts are presently underway to reduce future GHG emissions as a means of limiting human-induced global-scale temperature increases to 2° C, relative to the pre-industrial era (Council of the European Union 2005). However, the efficacy of these proposed efforts is unknown as there is scant evidence, save for a few studies (e.g., Tsutsui et al. 2007; Wigley et al. 2007; Matthews and Caldeira 2008; Lowe et al. 2009; Solomon et al. 2009), that any subsequent reduction of atmospheric GHG concentrations would reverse or mitigate the intervening climate changes (IPCC 2007a) or their impacts (IPCC2007b).

- ☐ To explicitly examine the response of the climate system to decreasing GHG concentrations, we performed a simple set of experiments with a coupled atmosphere-ocean general circulation model (GCM), in which the carbon dioxide (CO_2) concentrations were increased from 350 to 700 ppmv (parts per million by volume) and then decreased back to 350 ppmv (Fig. 1a).
- ☐ The 350 ppmv CO_2 concentration is the desired stabilization level (Hansen et al. 2008) and roughly corresponds to the base year 1990 CO_2 concentration (355 ppmv) adopted by the Kyoto Protocol and IPCC-SRES scenarios (IPCC 2007a).
- ☐ The intervening 350 ppmv CO_2 increase corresponds to a radiative forcing of 3.6 W/m^2, which is well within the realm of what can be expected in the 21st century from anthropogenic contributions of radiatively-active chemical constituents to the atmosphere, absent major emission cuts (IPCC 2007a).
- ☐ We recognize that this rate of decline in CO_2 is unrealistic, barring significant advancements in carbon sequestration technologies (IPCC 2005).
- ☐ This experiment helps us determine the non-linear response of the climate system, separate from the non-linear radiative forcing associated with the long-lived decay of atmospheric CO_2 concentration, as investigated by others (Matthews and Caldeira 2008; Lowe et al. 2009; Solomon et al. 2009).

MODEL AND EXPERIMENTS

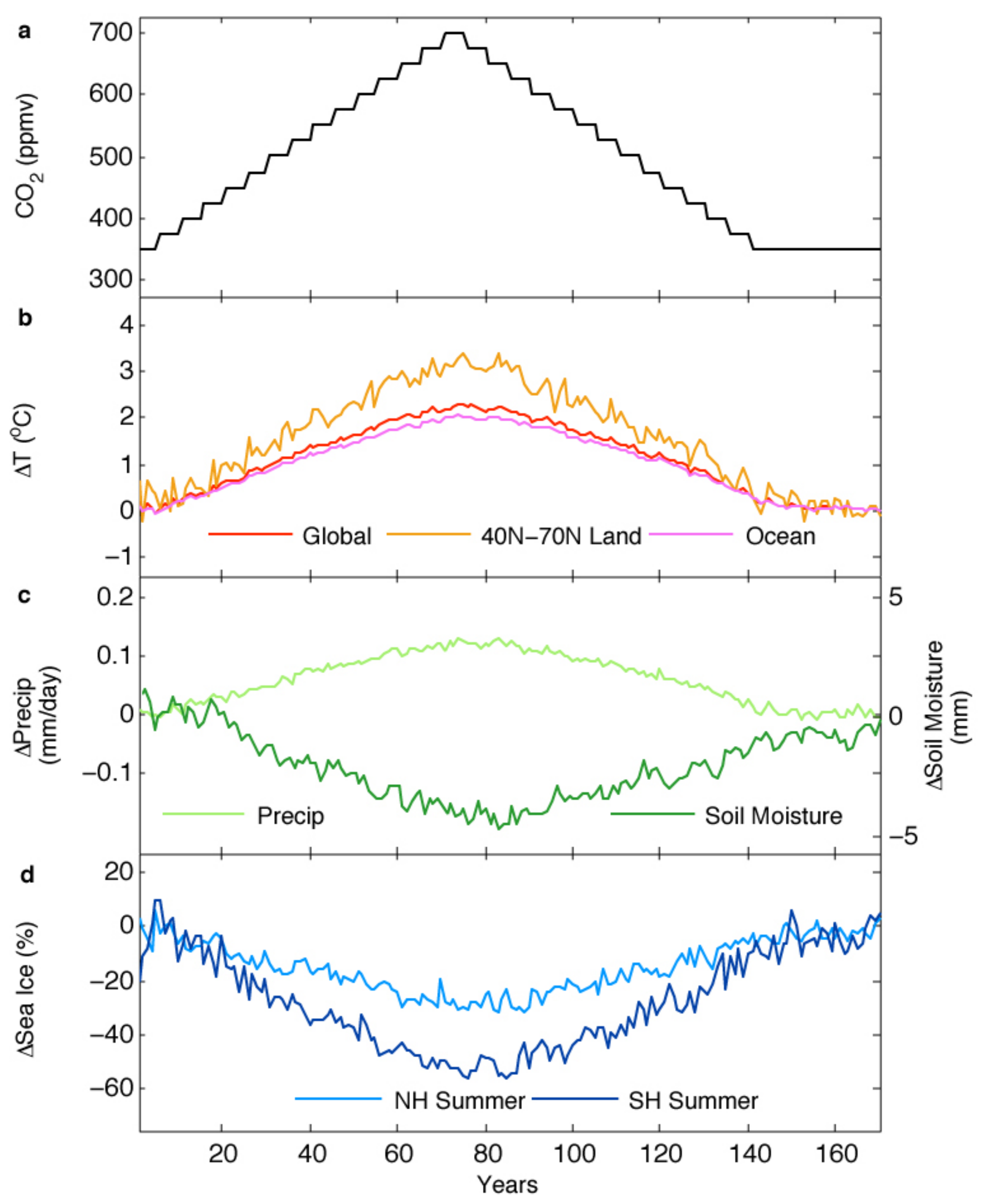
Model

- ☐ Version 3 of the National Center for Atmospheric Research Community Atmosphere Model (NCAR-CAM 3.0).
- ☐ This GCM consists of a fully dynamic atmosphere model (CAM 3.0) coupled to an interactive land model (CLM 3.0), a thermodynamic sea-ice model and a slab ocean model (Collins et al. 2006).
- ☐ The atmosphere (CAM 3.0) and land (CLM 3.0) models are part of the Community Climate System Model version 3 (CCSM3; Keihl et al. 2006).
- ☐ This GCM configuration allows short equilibration times while still attaining representative climate states in response to a given forcing (Kiehl et al. 2006). As such, slab ocean versions of coupled atmosphere-ocean GCMs similar to this one are used in a variety of climate sensitivity studies (e.g., Kiehl et al. 2006; Gregory and Webb 2008; Bala et al. 2008).

Experiments

- ☐ 150-year control run with CO_2 concentrations fixed at 350 ppmv.
- ☐ 3 transient ensemble runs, each initialized off the control run, in which the $CO\text{-}_2$ concentrations are increased from 350 to 700 ppmv (ascending phase) and then decreased back to 350 ppmv (descending phase) in steps of 25 ppmv every 5 years (Fig. 1a). At that point, the CO_2 concentration is held fixed at 350 ppmv for the next 30 years (Fig. 1a).
- ☐ All model simulations are performed at T42 (~2.8°x2.8° horizontal resolution) spectral truncation with 26 layers in the vertical extending from the surface to approximately 3 hPA.
- ☐ Changes in the climate response to imposed CO_2 concentrations are calculated as the difference between the ensemble-mean value taken from the transient simulations and the 150-year mean value derived from the control run.

RESULTS



- ☐ Global annual mean surface temperature is 2.3°C warmer (3.4°C in the high latitude land areas) at 700 ppmv CO_2 compared to the control (Fig. 1b).
- ☐ Global mean precipitation increases by approximately 0.14 mm/day (Fig. 1c).
- ☐ The loss in summer sea ice extent is about 30% in the Arctic and 55% in the Antarctic (Fig. 1d).
- ☐ Both temperature and precipitation return to their initial levels as CO_2 concentration is decreased from 700 to 350 ppmv and held constant for 30 years.
- ☐ The amplification of warming in the high latitudes also disappears.
- ☐ Soil moisture and summer sea ice extent in the Northern and Southern Hemispheres recover within this 30-year period as well (Fig. 1c, d).

Fig. 1 (**a**) Atmospheric CO_2 concentration used in the experimental runs. (**b**), (**c**) and (**d**) show changes in ensemble-mean climate variables relative to 100-year mean values derived from the same model but forced with atmospheric CO_2 concentrations fixed at 350 ppmv (control run). (**b**) Annual mean surface temperature (°C) averaged over the globe (red), oceans (magenta), and extra-tropical land surfaces (orange). (**c**) Annual mean globally-averaged precipitation (mm/day – light green) and soil moisture (mm - dark green). (**d**) Fractional coverage of summertime mean sea ice extent over the Arctic ocean from 60°N-90°N during July-September (% - light blue) and the Southern ocean (Antarctic Ocean) from 60°S-90°S during January-March (% - deep blue).

RESULTS

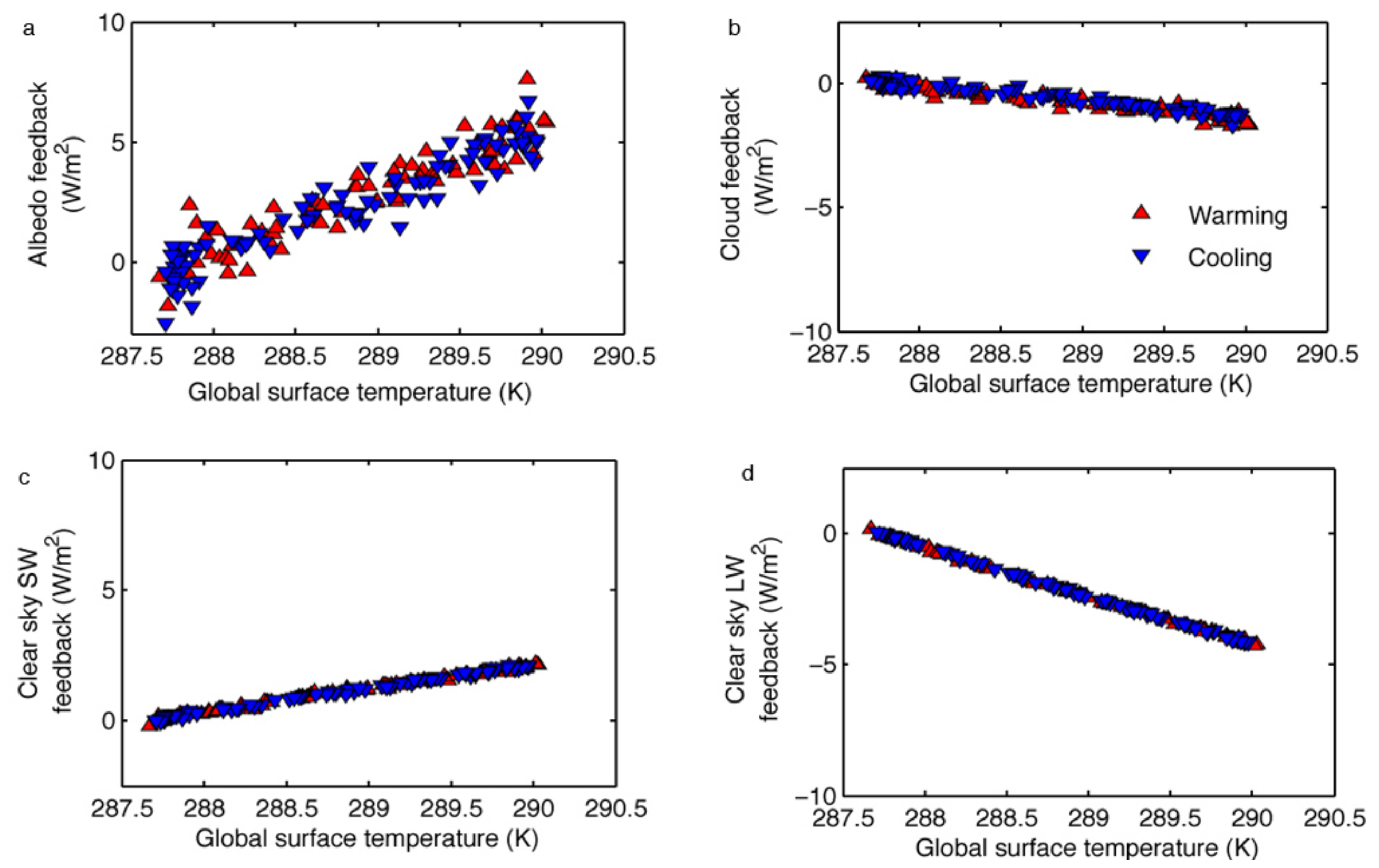


Fig. 2 (**a**) Change in Northern Hemisphere (NH) extra-tropical spring season (March-May) absorbed shortwave radiation (W/m^2) at the surface plotted as a function global annual mean surface temperature (K) during ascending phase (red) and descending phase (blue) of CO_2 concentrations seen in Figure 1a. Absorbed shortwave radiation is calculated using the mean surface albedo multiplied by the fractional dependence of planetary albedo on surface albedo (W/m^2) (*Qu and Hall*, 2006). (**b-c**) Same as (**a**) but for global annual mean cloud radiative forcing (W/m^2), global annual mean clear sky short-wave (SW) feedback (W/m^2), and global annual mean clear sky long-wave (LW) feedback (W/m^2). All lines shifted such that initial values start at 0.

- ☐ Snow-albedo feedback changes quasi-linearly with surface temperature both during the warming and cooling phases (Fig 2a) .
- ☐ Cloud radiative forcing adjusts quasi-linearly with surface temperature (Fig. 2b) .
- ☐ Both the clear sky SW and LW feedbacks change linearly with surface temperature (Fig. 2c, d).

DISCUSSION

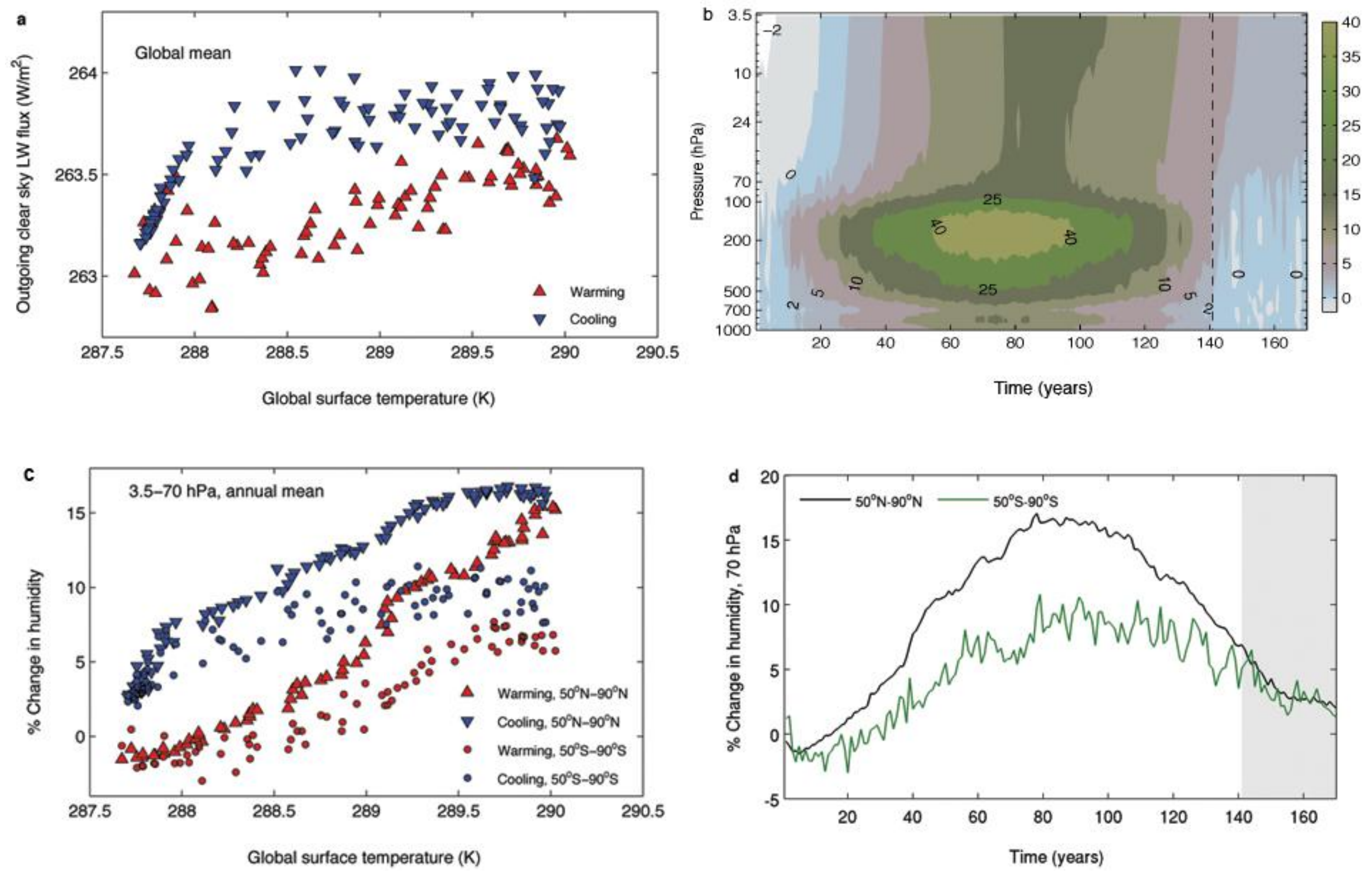


Fig. 3 (**a**) Global annual mean outgoing top of atmosphere clear sky long-wave (LW) flux (W/m^2) plotted as a function global annual mean surface temperature (K) during ascending phase (red) and descending phase (blue) of CO_2 concentrations seen in Figure 1a. (**b**) Height (pressure) – time contour of percentage change (%) in global annual mean specific humidity. Dashed line marks the year when CO_2 is stabilized at 350 ppmv (**c**) percentage change (%) in annual mean stratospheric (3.5-70 hPa) specific humidity averaged over 50°N-90°N (triangles) and 50°S-90°S (circles), plotted as a function global annual mean surface temperature (K) during ascending phase (red) and descending phase (blue) of CO_2 concentrations seen in Figure 1a. (**d**) Percentage change (%) in annual mean lower stratospheric (70 hPa) specific humidity averaged over 50°N-90°N (black) and 50 °S-90°S (dark green). Shading shows the time period during which CO_2 is stabilized at 350 ppmv.

- ☐ The outgoing Top of Atmosphere (TOA) clear sky longwave flux increases linearly with increasing temperatures but remains elevated even as global temperatures decrease, producing an asymmetric time trajectory (Fig. 3a).
- ☐ Water vapor in the stratosphere, particularly in the high latitudes, evolves non-linearly (Fig. 3b) leading to the asymmetric evolution of the TOA outgoing clear sky LW flux.
- ☐ The high-latitude water vapor trajectory has a significant positive offset, particularly over the southern hemisphere where it does not begin to decrease until temperatures approach their initial levels (Fig. 3c, d).
- ☐ We hypothesize that during the cooling phase, the removal of the excess water vapor is controlled by the imbalance between the upwelling and downwelling of the Brewer-Dobson circulation (Holton et al.1995).

CONCLUSIONS

- ☐ Overall, the physical climate system simulated by the numerical model shows a slightly lagged response to changing CO_2 concentrations.
- ☐ This quasi-linear evolution arises from the linear (albeit unrealistic—Solomon et al. 2009) nature of the imposed forcing, as well as the quasi-linear response of prominent feedback mechanisms associated with snow-ice albedo, clouds, water-vapor/lapse-rate, and radiative cooling.
- ☐ Similar results are not found in all components of the Earth system however. In our study, stratospheric water vapor remains elevated despite decreasing tropospheric and stratospheric temperatures.
- ☐ It is still unknown whether potential changes to other physical subsystems—including Greenland and Antarctic ice cover, the Atlantic thermohaline circulation and the West African monsoon (IPCC 2007a; IPCC 2007b; Lenton et al. 2008)—and biological systems—including impacts to ecosystems and human welfare—accrued during the warming phase (IPCC 2007b) will show similar non-linear recoveries.
- ☐ Results presented here need to be tested for reliability using other modeling systems. They should also be investigated using climate models that incorporate additional components of the full Earth system.

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