Modulation of the Southern Hemisphere climate by solar radiation management

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1. Introduction

Geoengineering is increasingly being discussed as a means to lessen the climatic impacts of greenhouse gas (GHG) emissions. Solar radiation management (SRM) via stratospheric injection of sulphate aerosols has, in particular, been proposed as a fast-acting and cost-effective solution. However, geoengineering is not without significant risks of its own, including a potential weakening of the hydrological cycle.

The aim of this study is therefore to use simulations conducted by the Geoengineering Model Intercomparison Project (GeoMIP) to explore how the Southern Hemisphere (SH) atmospheric circulation and hydrological cycle may be modulated by global-scale SRM.

2. Data and methods

We analyse two of the GeoMIP experiments: G3 and G3solar. These simulate the application of SRM to counteract rising GHG concentrations under the RCP4.5 emissions scenario:

- G3 simulates the gradual introduction of stratospheric sulphate aerosols during the period 2020 to 2069, with the aim of keeping the net radiative forcing constant at the 2020 level.
- G3solar has the same aim as G3, but uses a reduction in the solar constant to balance the radiative forcing due to increasing GHGs.

In each experiment, geoengineering ceases abruptly in 2070, such that the radiative forcing returns to what it would have been under RCP4.5. The simulations then continue for a further 20 years.

We examine the output of six climate models that undertook G3 and/or G3solar: BNU-ESM, CCSM4, CSIRO-Mk3L-1-2, HadGEM2-ES, IPSL-CM5A-LR and MPI-ESM-LR. Within this multi-model ensemble, three distinct approaches are taken towards the treatment of stratospheric ozone: semi-offline chemistry (BNU-ESM, CCSM4, IPSL-CM5A-LR), prescribed changes (HadGEM2-ES, MPI-ESM-LR), and fixed ozone concentrations (CSIRO-Mk3L-1-2).

3. Global and hemispheric response

During the geoengineering phase, SRM reduces the simulated warming (Figure 1a–b). In contrast to an increase in global-mean temperature of more than 1°C between 2020 and 2070 under RCP4.5, there is an increase of only ~0.3°C in G3 and G3solar. However, as soon as geoengineering ceases, the global temperature rapidly converges towards the levels simulated under RCP4.5.

The changes in global-mean precipitation mirror the temperature response (Figure 1c–d). SRM causes a reduction in precipitation relative to RCP4.5, with global-mean precipitation remaining close to 2020 levels during the geoengineering phase in most of the models. An abrupt cessation effect is again apparent, with the effects of geoengineering largely dissipating within 10 years.

The historical shift towards a more positive phase of the Southern Annular Mode (SAM) is projected to continue into the future under RCP4.5 (Figure 1e–f). SRM counteracts this trend by shifting the SAM towards a more neutral state, with the SAM Index being stabilised at around 2020 levels during the geoengineering phase. A termination effect is also apparent after 2070, with the mean values of the SAM Index rapidly converging towards the levels simulated under RCP4.5.

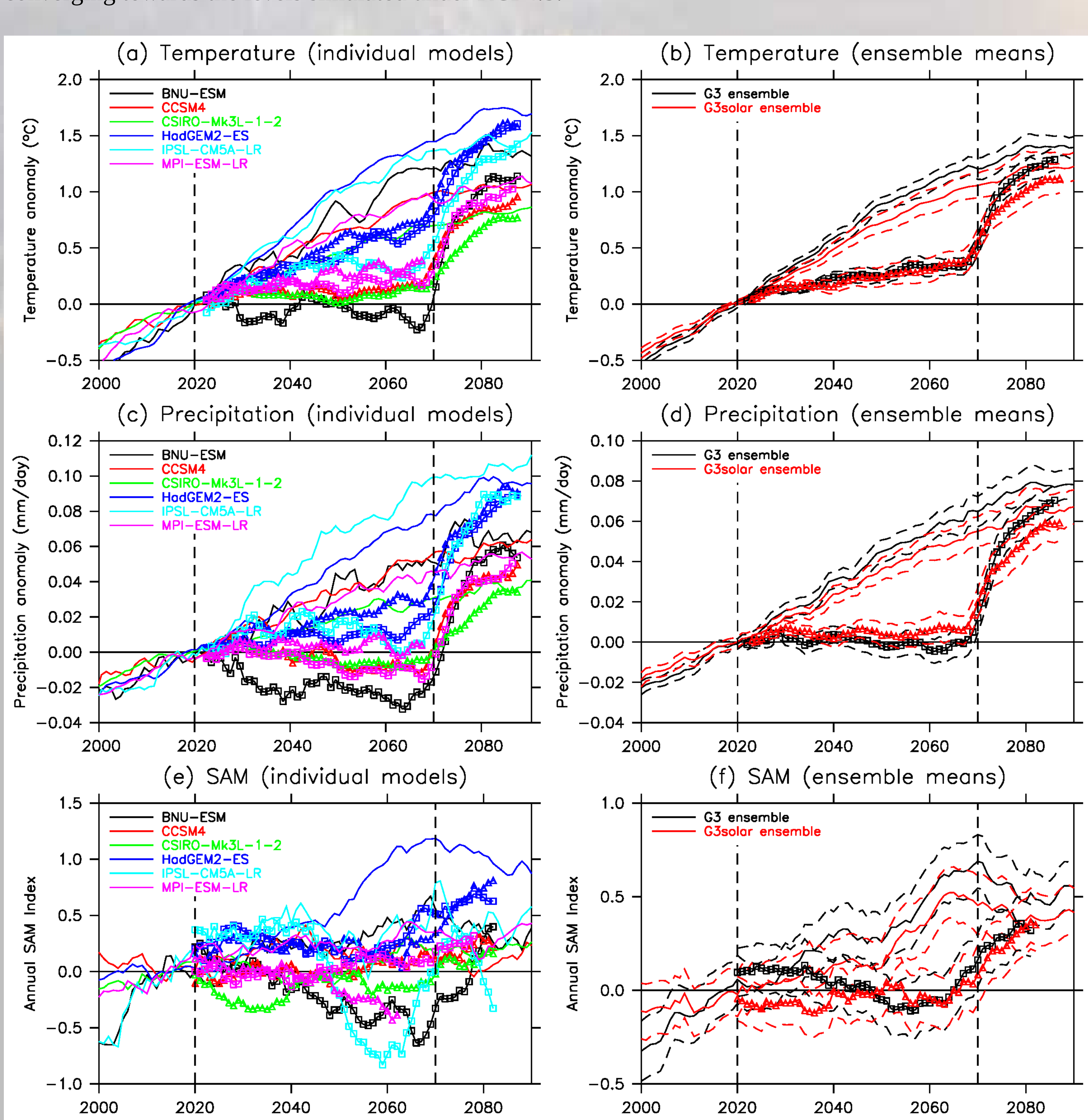

Figure 1. The evolution of the global climate within experiments RCP4.5 (no symbols), G3 (squares) and G3solar (triangles): (a)–(b) global-mean surface air temperature, (c)–(d) global-mean precipitation, and (e)–(f) the annual SAM Index. All values shown are anomalies relative to the mean state of the RCP4.5 experiment during the period 2010–2029. In panels (b), (d) and (f), dashed lines indicate the 95% confidence interval. Vertical dashed lines indicate the start and end of geoengineering.

4. Atmospheric circulation

The response to anthropogenic forcing is dominated by two features: a strengthening and a poleward shift of the SH mid-latitude westerlies, which is consistent with the shift towards a more positive phase of the SAM; and a decrease in zonal wind speed in the SH subtropics, which is consistent with a strengthening and expansion of the Hadley Cell (Figure 2a). There is an increase in the zonal wind speed centred at ~60°S, accompanied by a smaller decrease centred at ~30°S (Figure 2d).

SRM causes the SH westerly winds to experience a weakening and an equatorward shift, relative to the changes which occur under RCP4.5 (Figure 2b). There is a concomitant increase in zonal wind speed in the subtropics, consistent with a weakening and contraction of the Hadley Cell. The zonal-mean response is the opposite of that to anthropogenic forcing (Figure 2d).

Overall, SRM is effective at mitigating the 21st century circulation changes under RCP4.5. In most regions, there is no statistically-significant difference between the mean circulation during the final 20 years of G3/G3solar and the mean circulation during the 2010–2029 reference period (Figure 2c).

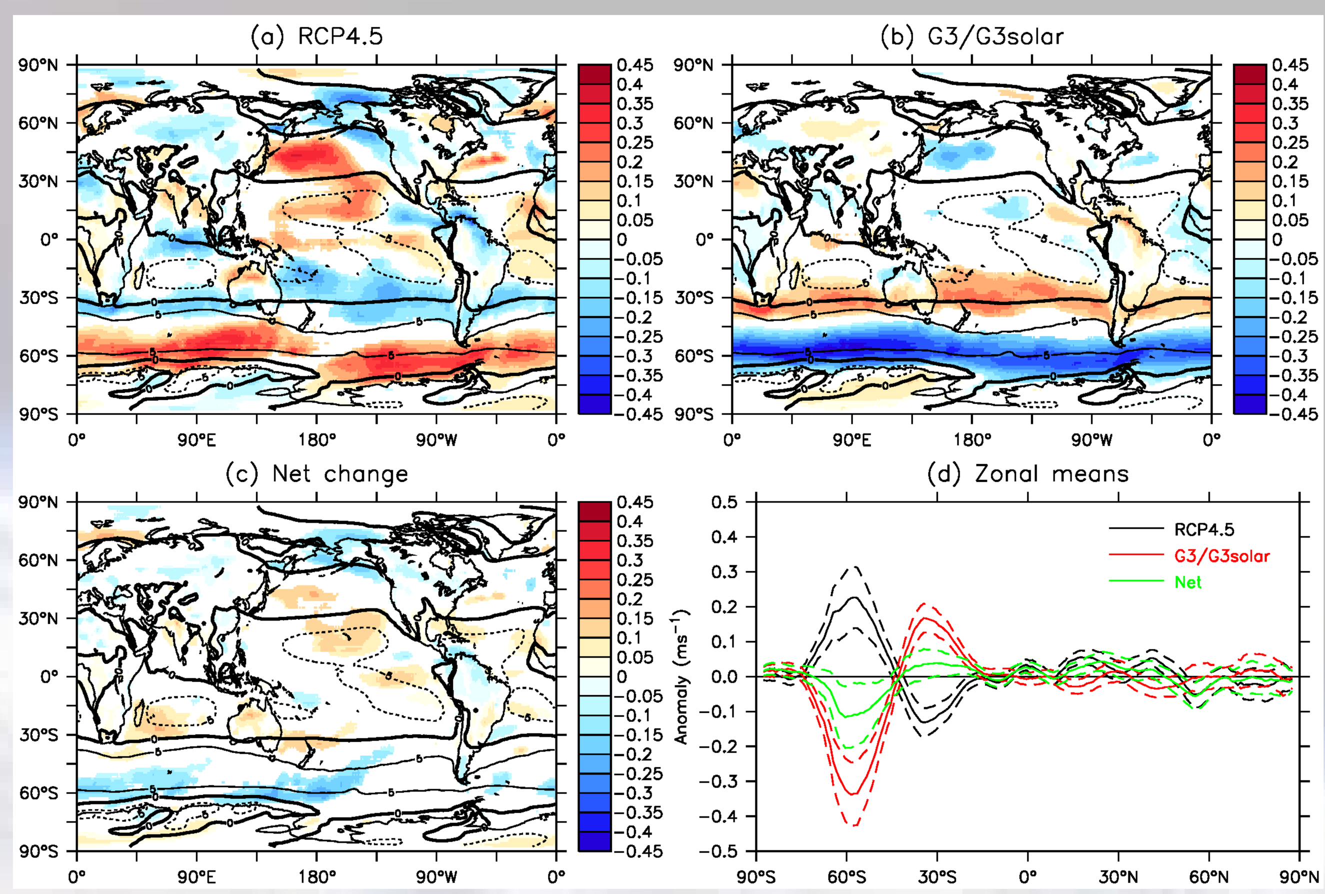

Figure 2. The relative impacts of anthropogenic forcing and SRM on the zonal surface wind speed (m s^{-1}): (a) RCP4.5 (2050–2069 minus 2010–2029), (b) G3/G3solar (2050–2069) minus RCP4.5 (2050–2069), (c) G3/G3solar (2050–2069) minus RCP4.5 (2010–2029), and (d) the zonal means. In panels (a)–(c), contours show the climatology for the period 2010–2029 in RCP4.5; shading shows anomalies that are significant at the 5% probability level. In panel (d), dashed lines indicate the 95% confidence interval.

5. Hydrological cycle

Under RCP4.5, there is an increase in precipitation and P-E in the tropics and at high latitudes (Figure 3a–b). This is accompanied by a decrease over large parts of the subtropics, particularly in the SH.

SRM largely offsets the response to anthropogenic forcing (Figure 3c–d). There is a relative reduction in precipitation and P-E at most latitudes, and particularly in the equatorial regions. Importantly, however, there is a band of increased precipitation and P-E within the SH subtropics.

Overall, SRM is effective at mitigating the changes in the hydrological cycle under RCP4.5 (Figure 3e–f).

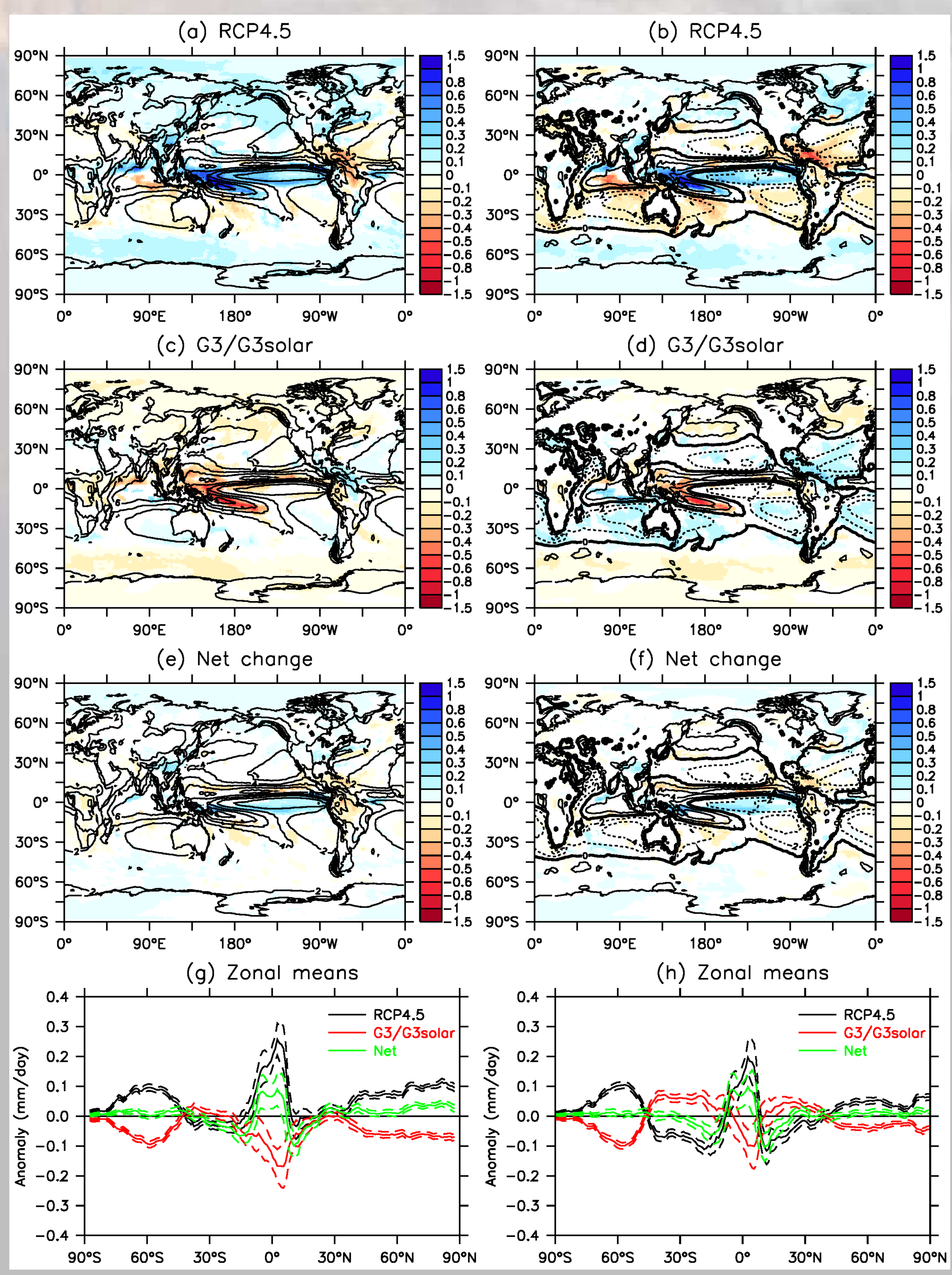

Figure 3. As Figure 2, but for precipitation (mm/day; left column) and P-E (mm/day; right column).