Balancing a quadrupling of CO_2 by a reduction of solar irradiance: Climate responses simulated by four Earth system models

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Introduction

In this study we compare the response of four state-of-the-art Earth system models to climate engineering under scenario G1 of two model intercomparison projects: GeoMIP (Geoengineering Model Intercomparison Project) and IMPLICC (EU project "Implications and risks of engineering solar radiation to limit climate change"). In G1, the radiative forcing from an instantaneous quadrupling of the CO_2 concentration, starting from the preindustrial level, is balanced by a reduction of the solar constant. Model responses to the two counteracting forcings in G1 are compared to the preindustrial climate in terms of global means and regional patterns and their robustness. While the global mean surface air temperature in G1 remains almost unchanged compared to the control simulation, the meridional temperature gradient is reduced in all models. Another robust response is the global reduction of precipitation with strong effects in particular over North and South America and northern Eurasia. In comparison to the climate response to a quadrupling of CO_2 alone, the temperature responses are small in experiment G1. Precipitation responses are, however, in many regions of comparable magnitude but globally of opposite sign.

Tab. 1: Main characteristics of the participating ESMs

Name of the ESM	IPSL-CM5A	MPI-ESM	NorESM	HadGEM2-ES
reference	Dufresne et al. (2011)	Giorgetta et al. (2012)	Alterskjær et al. (2012)	Collins et al. (2011)
Atmosphere model	LMDz	ECHAM6	CAM-Oslo (based on CAM4)	HADGEM2-A
(resolution; lid)	(2.5°x3.75°/L39; 65 km)	(T63/L47; 0.01 hPa)	(1.9°x2.5°/L26; 2 hPa)	(1.25°x1.875°/L38; 40 km)
reference	Hourdin et al. (2011)	Stevens et al. (2012)	Seland et al. (2008)	Martin et al. (2011)
Ocean model	NEMO	MPIOM	(based on) MICOM	HadGEM2-O
(resolution)	(96x95 gridpoints, L39)	(∼1.5°, L40)	(∼1°, L70)	(1/3 to 1°, L40)
reference	Madec (2008)	Marsland et al. (2003)	Assmann et al. (2010)	Martin et al. (2011)
Land/Vegetation model	ORCHIDEE	JSBACH	CLM4	MOSES-II
reference	Krinner et al. (2005)	Raddatz et al. (2007)	Oleson et al. (2010)	Essery et al. (2003)

"LXX": XX indicates the number of vertical layers; "TYY": triangular truncation at wavenumber YY.

Experimental Setup

Four different Earth system models (ESM, see Table 1) have been used in this study to perform the GeoMIP experiment **G1** in which an instantaneous quadrupling of the CO_2 concentration is balanced by a decrease of solar irradiance represented by the solar constant. The reduction of the solar constant had to be chosen such that the flux imbalance at the TOA is below 0.1 Wm^2 for the first 10 years of G1. One reference experiment for G1 is the CMIP5 experiment 6.3 (called **abrupt4xCO2**) which is started from the preindustrial control run (CMIP5 experiment 3.1; CO_2 vmr: 285 ppmv), and runs for 150 years after the quadrupling of CO_2 to 1139 ppmv. The second reference experiment is precisely this preindustrial control run (**called piControl**). Aompared are the first 50 years of G1 and piControl, and years 101 to 150 of abrupt4xCO2. It should be noted that the letter simulation is still not in equilibrium at this period.

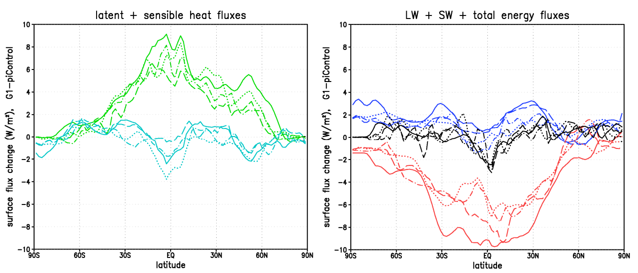

Fig. 1: Differences in zonally-averaged surface net downward energy fluxes between the simulations G1 and piControl in Wm^{-2} from the four ESMs. Solid: IPSL-CM5A, dashed: MPI-ESM, dotted: NorESM, dot-dashed: HadGEM2-ES. Left panel: latent (green) and sensible (cyan) heat fluxes; right panel: longwave radiation (blue), shortwave radiation (red) and sum of all four components (black). All fluxes are defined as positive in the downward direction.

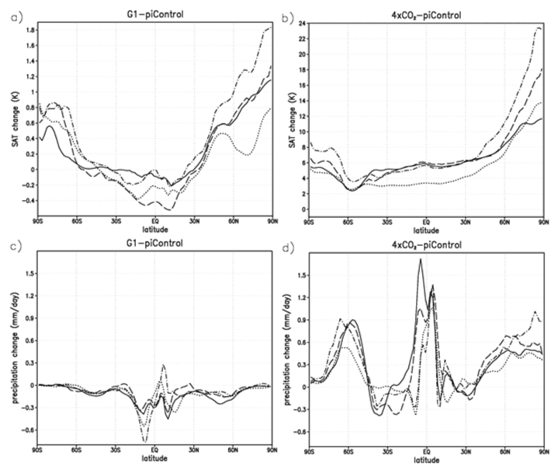

Fig. 2: Differences in zonally-averaged quantities between the simulations G1 and piControl (left), and abrupt4xco2 and piControl (right) from the four ESMs. Top panels: Near surface air temperature (K), bottom panels: precipitation (mm day^{-1}). Solid: IPSL-CM5A, dashed: MPI-ESM, dotted: NorESM, dot-dashed: HadGEM2-ES. Note the different scaling of the temperature axes in the top panels.

Tab. 2: Comparison of TOA forcings from quadrupling CO_2, total solar irradiance (TSI) reduction, and clouds.

	IPSL-CM5A	MPI-ESM	NorESM	HadGEM2-ES
Forcing from 4xCO_2 (Wm^{-2})	6.4	9.6	7.5	6.8
TSI reduction in G1 (Wm^{-2})	48	64	55	53
(percentage)	(3.5%)	(4.7%)	(4.0%)	(3.9%)
Forcing from TSI reduction (Wm^{-2})	-8.4	-11.3	-9.6	-9.4
Efficacy of TSI reduction	0.76	0.85	0.78	0.72
SW cloud forcing (piControl) (Wm^{-2})	-53.3	-49.4	-54.3	-43.6
(G1-piControl, estimated) (Wm^{-2})	1.9	2.3	2.2	1.7
(G1-piControl, simulated) (Wm^{-2})	3.9	4.8	4.2	2.5

Tab. 3: Comparison of multi-model mean responses to the forcings in G1 and abrupt4xCO2 simulations, respectively, with respect to piControl. Responses are calculated for the individual models both in terms of spatially averaged differences and in terms of root mean square differences, and then averaged over the four ESMs. RMS differences are calculated after interpolation of the results from the individual models to a 192x96 grid. Besides global mean values also averages over land surface only are provided.

	SAT (K)		Precipitation (mm day^{-1})	
	G1	4xCO2	G1	4xCO2
global average	0.1	5.5	-0.14	0.25
(percentage)			(-4.7%)	(8.8%)
land average	0.4	7.5	-0.12	0.16
(percentage)			(-6.3%)	(8.3%)
rms (global)	0.5	6.1	0.35	0.91
(percentage)			(12.2%)	(31.6%)
rms (land)	0.7	7.7	0.31	0.68
(percentage)			(16.4%)	(36.4%)

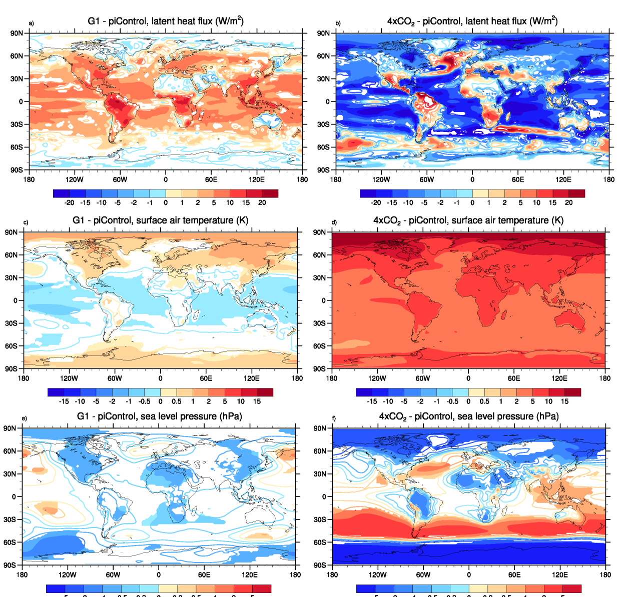

Fig. 3: Differences between the simulations G1 and piControl (left), and abrupt4xCO2 and piControl (right), averaged over the four ESMs. Top: Surface latent heat flux (Wm^{-2}; defined as positive downward), middle: near surface air temperature (K), and bottom: sea level pressure (hPa). In regions with filled color shading all models agree in the sign of the response. The value represented by the contours is given by the upper edge of the respective range in the color bar, i.e., the zero line is colored light blue.

Robust model responses

- Solar forcing is less effective than the forcing caused by the increase of CO2. This is related to the change in cloud cover. Consequently, between 18 and 38% ``more'' CE than expected had to be implemented (**Tab. 2**).
- The globally-averaged temperature is kept almost constant but the meridional temperature gradient is reduced. Polar regions are still warmer than the pre-industrial control simulation by about 1~K, while the tropics are slightly cooler. On average, land masses show a more positive temperature response than adjacent oceans. (**Figs. 2a, 3c**)
- In the surface energy budget, the decrease of incoming solar radiation is largely balanced by a decrease in the latent heat flux. This decrease is particularly strong over vegetation-covered land masses (**Figs. 1, 3a**).
- As a consequence of the reduced water vapor flux, globally-averaged precipitation decreases on average by 4.7%. In particular, a strong decrease is simulated for large areas of North America, northern Eurasia and central South America (**Figs. 2c, 4a**).
- Globally averaged precipitation changes simulated for the quadrupled CO2 scenario are about a factor of two larger in magnitude, but of opposite sign than the precipitation change for the G1 scenario (**Tab. 3**).

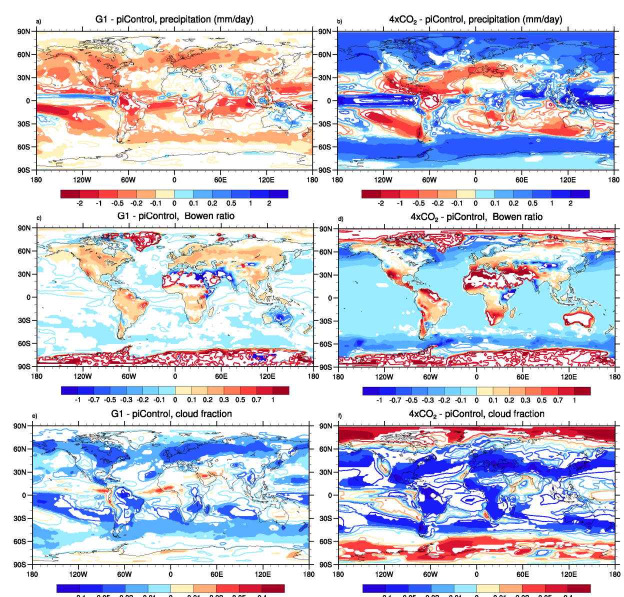

Fig. 4: Differences between the simulations G1 and piControl (left), and abrupt4xco2 and piControl (right), averaged over the four ESMs. Top: precipitation (mm day^{-1}), middle: Bowen ratio (ratio of sensible and latent heat fluxes), and bottom: total cloud fraction. In regions with filled color shading all models agree in the sign of the response. The value represented by the contours is given by the upper edge of the respective color bar, i.e., the zero line is colored light blue (light yellow in the case of precipitation).

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Reference: Schmidt, H., Alterskjær, K., Bou Karam, D., Boucher, O., Jones, A., Kristjansson, J. E., Niemeier, U., Schulz, M., Aaheim, A., Benduhn, F., Lawrence, M., and Timmreck, C.: Solar irradiance reduction to counteract radiative forcing from a quadrupling of CO2: climate responses simulated by four earth system models, Earth Syst. Dynam., 3, 63-78,

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