Long-term Terrestrial Carbon and Water Cycle Responses to Projected Climate Change Beyond 2100

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Introduction

Understanding the long-term responses of ecosystems to climate change is important for quantifying the strength of carbon–climate feedbacks and informing carbon management and energy policies. Using simulations from the Community Earth System Model version 1.0 (CESM1-BGC), we quantified the effects of increasing atmospheric CO_2 and the resulting increases in temperature and changes in precipitation from 1850 to 2300 on terrestrial ecosystems.

Description of Simulations

Simulations were performed using the **NSF-DOE Community Earth System Model version 1.0 (CESM1-BGC)** for four different radiative and biosphere coupling configurations. Standard Fifth Phase of the Coupled Modeling Intercomparison Project (CMIP5) protocol was followed for simulations of

- Historical for 1850–2005,
- Representative Concentration Pathway 8.5 (RCP8.5) for 2006–2100, and
- Extended Concentration Pathway 8.5 (ECP8.5) for 2101–2300.

Table 1: *Four simulation coupling model configurations.*

	Radiative Coupling		Biosphere Coupling		
	CO_2	Other GHG & aerosols	CO_2	Nitrogen deposition	Land use change
RAD	✓	✓			
BIO			✓	✓	✓
BIOGHG		✓	✓	✓	✓
FC	✓	✓	✓	✓	✓

Important hydrological and biogeochemical output variables, shown in Table 2, from all four simulations were analyzed over the entire 450 y period to diagnose the climate change impacts on terrestrial ecosystems and the hydrological cycle.

Table 2: *Model output variables.*

Name	Description	Units
ET	evapotranspiration rate	mm/d
GPP	gross primary production	$gC/m^2/y$
PME	precipitation − evapotranspiration	mm/d
PRECIP	total precipitation rate	mm/d
RH2M	relative humidity at 2 m height	%
RUNOFF	total runoff rate	mm/d
SMOIST	soil moisture to 1 m depth	mm
TLAI	total leaf area index	unitless
TSA	air temperature at 2 m height	K

Decadal means from the end of the simulation period were subtracted from decadal means at the beginning of the simulation period to map and quantify changes in these key output variables.

Change in Annual Mean Hydrological Cycle over Land (Historical, RCP 8.5, and ECP 8.5: 2291–2300 minus 1851–1860)

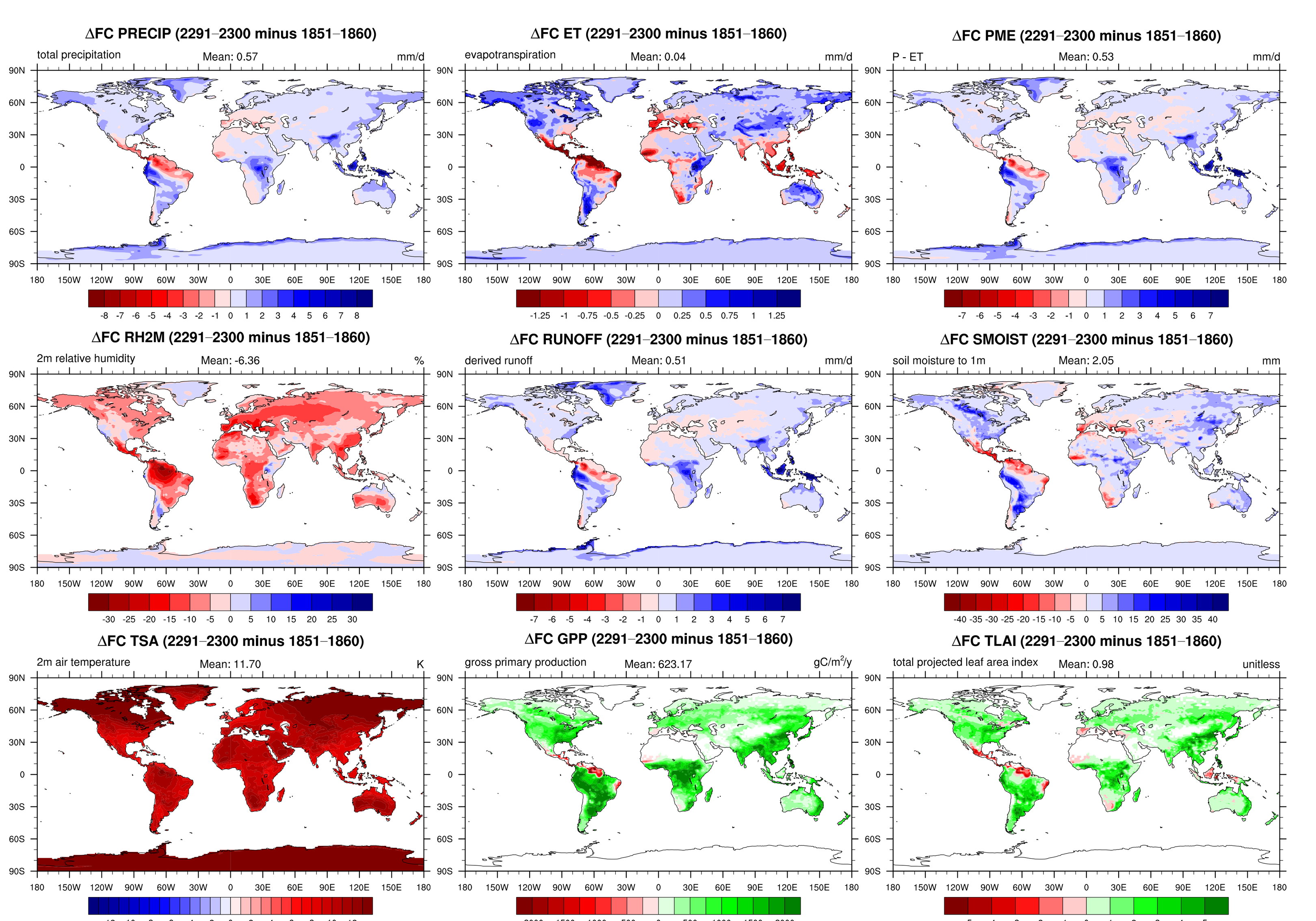

Figure 1: *Change in the annual mean hydrological cycle over land for the historical and future (RCP 8.5 & ECP 8.5) simulations (1850–2300).*

For land areas in the fully coupled simulation over the 450 years spanning 1850–2300,

- global mean 2 m air temperature increased by 11.7°C, with the largest warming occurring at high latitudes;
- global precipitation increased by 0.57 mm/d, with some regions experiencing increases and others decreases;
- global evapotranspiration rose by 0.04 mm/d, but regional patterns of increases and decreases are evident;
- global precipitation minus evaporation increased by 0.53 mm/d and is dominated by the increase in precipitation;
- global mean 2 m relative humidity decreased by 6.4%, but did not always correspond to the pattern of changes in precipitation, particularly in the extra-tropics;
- global runoff increased by 0.51 mm/d and broadly followed the pattern in changes in precipitation;
- global soil moisture increased by 2.1 mm, with regional increases and decreases, some of which deviated from changes in precipitation, likely due to permafrost melt and stomatal closure;
- global gross primary production increased by 623 $gC/m^2/y$, with the strongest increases in tropical South America and Central Africa; and
- global total leaf area index increased by almost one, with notable regional decreases.

As with most CMIP5 models, CESM1-BGC projected enhanced Walker Circulation in the Pacific that resulted in significant drying in Central America, Northeastern South America, and across the Atlantic Ocean to Eastern Sub-Saharan Africa (see Figure 2). Correspondingly, GPP declined in these regions. Changes in ET generally follow the pattern of changes in precipitation, except in the warm, moist tropics where the increased atmospheric CO_2 that drives stomatal closure may be causing reductions in ET. To decompose the influences of biosphere and radiative coupling of atmospheric CO_2 on GPP, we analyzed the changes of GPP in the FC, RAD, and BIO simulations.

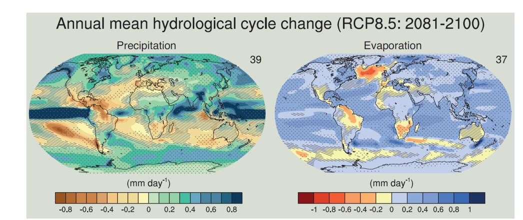

Figure 2: *Annual mean changes in precipitation and evaporation for 2081–2100 relative to 1986–2005 under the RCP 8.5 for a collection of CMIP5 models. Adapted from IPCC Fifth Assessment Report (AR5), Technical Summary (TFE.1, Figure 3).*

Attributing Changes in Gross Primary Production (GPP), Precipitation, and Temperature

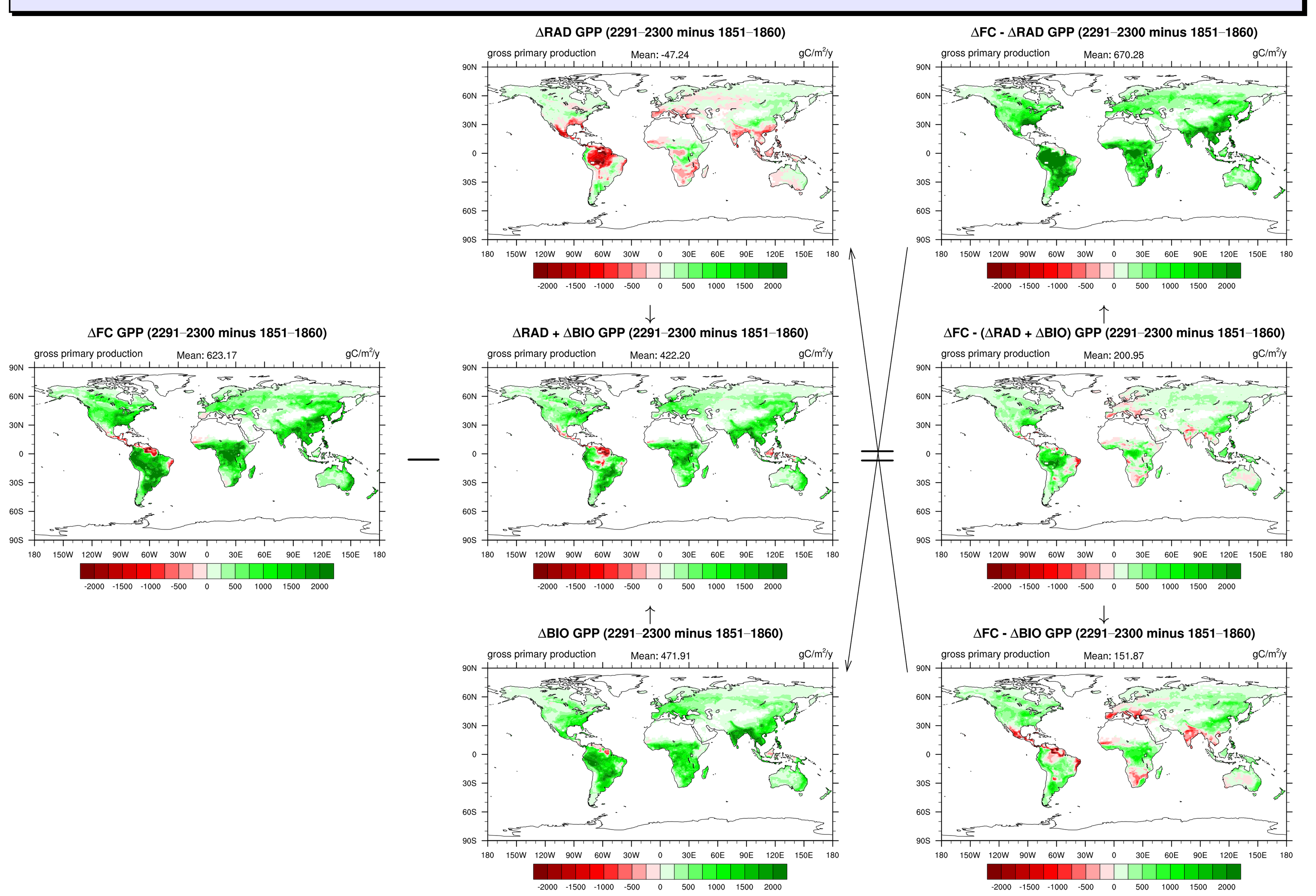

Figure 3: *Contributions of radiatively coupled and biosphere coupled changes in gross primary production (GPP) to the fully coupled GPP.*

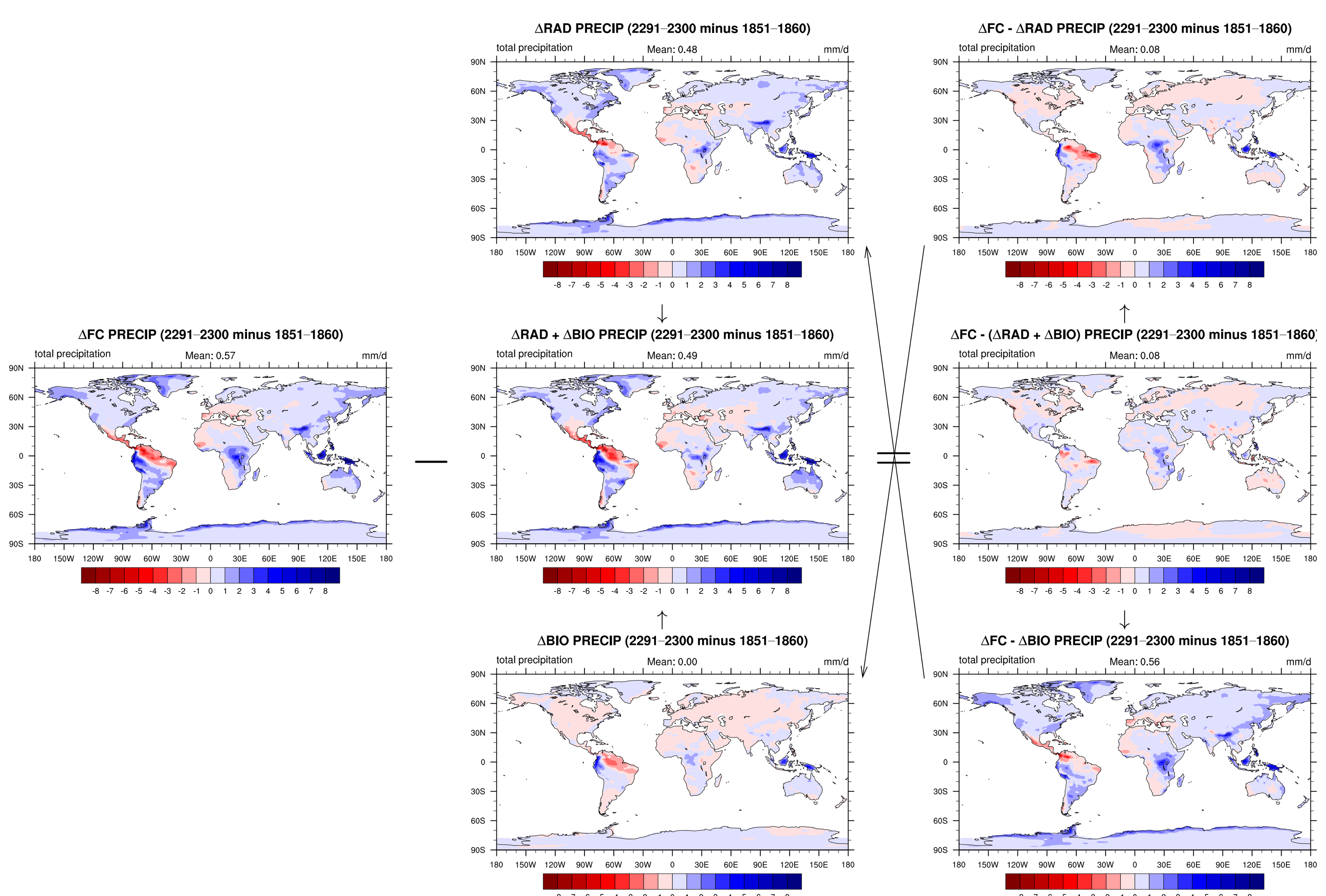

Figure 4: *Contributions of radiatively coupled and biosphere coupled changes in precipitation to the fully coupled precipitation.*

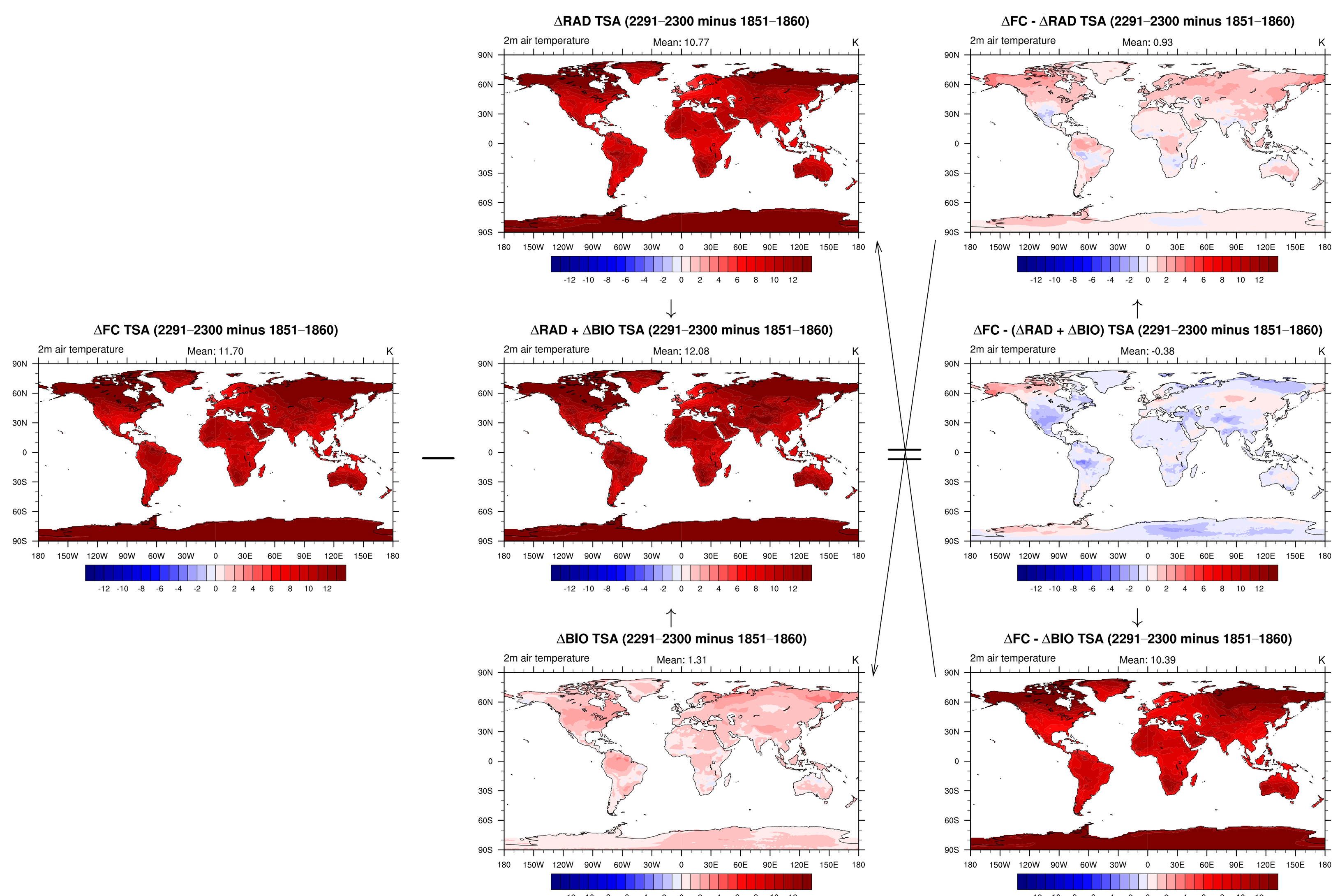

Figure 5: *Contributions of radiatively coupled and biosphere coupled changes in 2 m air temperature to the fully coupled temperature.*

Discussion and Conclusions

- Analysis of GPP from the RAD, BIO, and FC simulations showed a reduction in global mean GPP of 47 $gC/m^2/y$ in the radiatively coupled case and an increase of 471 $gC/m^2/y$ in the biosphere coupled case.
- The net mean change is 422 $gC/m^2/y$, which is significantly lower than the 623 $gC/m^2/y$ mean change in GPP from the fully coupled simulation.
- This strong non-linear effect is likely due to the combination of an extended growing season and the ameliorating effect of CO_2 on drought stress induced by the radiative coupling, which work in concert only in the fully couple simulation.
- The fully coupled simulation showed an overall increase in precipitation on land of 0.57 mm/d at 2300.
- Both the radiatively coupled and the biosphere coupled precipitation changes showed the effects of the strengthening Walker Circulation, resulting in drying in Northeastern South America and increased precipitation in Indonesia.
- Differences between the sum of the changes in the radiatively plus biosphere coupled simulations and the fully coupled simulation for precipitation showed wetter conditions in Central Africa and drier conditions in Central South America and India.
- The fully coupled simulation showed an increase in 2 m air temperature over land of almost 12°C.
- Non-linear effects observed, especially in GPP, but also in precipitation and 2 m air temperature, suggest that linear assumptions about calculating sensitivities to land carbon storage using separate radiatively coupled and biosphere coupled simulations do not hold over long time periods.
- Temperature change differences between the fully coupled and the radiatively plus biosphere coupled simulations show more mid-latitude cooling and a mixture of both high-latitude warming and cooling, with the fully coupled simulation getting slightly cooler than in the sum of the other two.

Acknowledgements

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