Internal- and intra-model variability in CMIP5 interactive carbon cycle projections of fossil fuel CO_2 invasion into the ocean

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Introduction

A new set of CMIP5 simulations with **interactive carbon cycle** (**ICC**) includes prognostic carbon fluxes between the atmosphere and ocean and land reservoirs which affect the atmospheric CO_2 concentration and hence climate. It allows us to investigate climate-carbon cycle feedback mechanisms within the Earth System. In ICC simulations minor deficits of processes within the submodels may become more prominent due to the coupling and, therefore, add further uncertainties to climate projections. We investigate internal- and intra-model variability by comparing simulations with ICC versus simulations with **prescribed atmospheric CO_2 concentrations** (**PAC**) provided by seven Earth System models within the CMIP5 framework.

Models and simulations

We use simulations from the following seven Earth System models within the CMIP5 framework, i.e., **CanESM2, GFDL-ESM2G, GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM, HadGEM2-ES, and MPI-ESM-LR. MME** is short for multi-model ensemble.

Table 1. Summary of CMIP5 simulations. Experiments name with "**esm**" mark ICC runs forced by emissions, others are PAC runs forced by CO_2 concentration.

Experiment	Time period	CO_2 forcing
Cntl	1850+500yrs	Preindustrial CO_2 concentration
esmCntl	1850+500yrs	No CO_2 emissions
Hist.	1850-2005	Historical CO_2 concentration
esmHist.	1850-2005	Historical CO_2 emissions
RCP8.5	2006-2100	High CO_2 scenario
esmRCP8.5	2006-2100	High CO_2 scenario

Conclusions

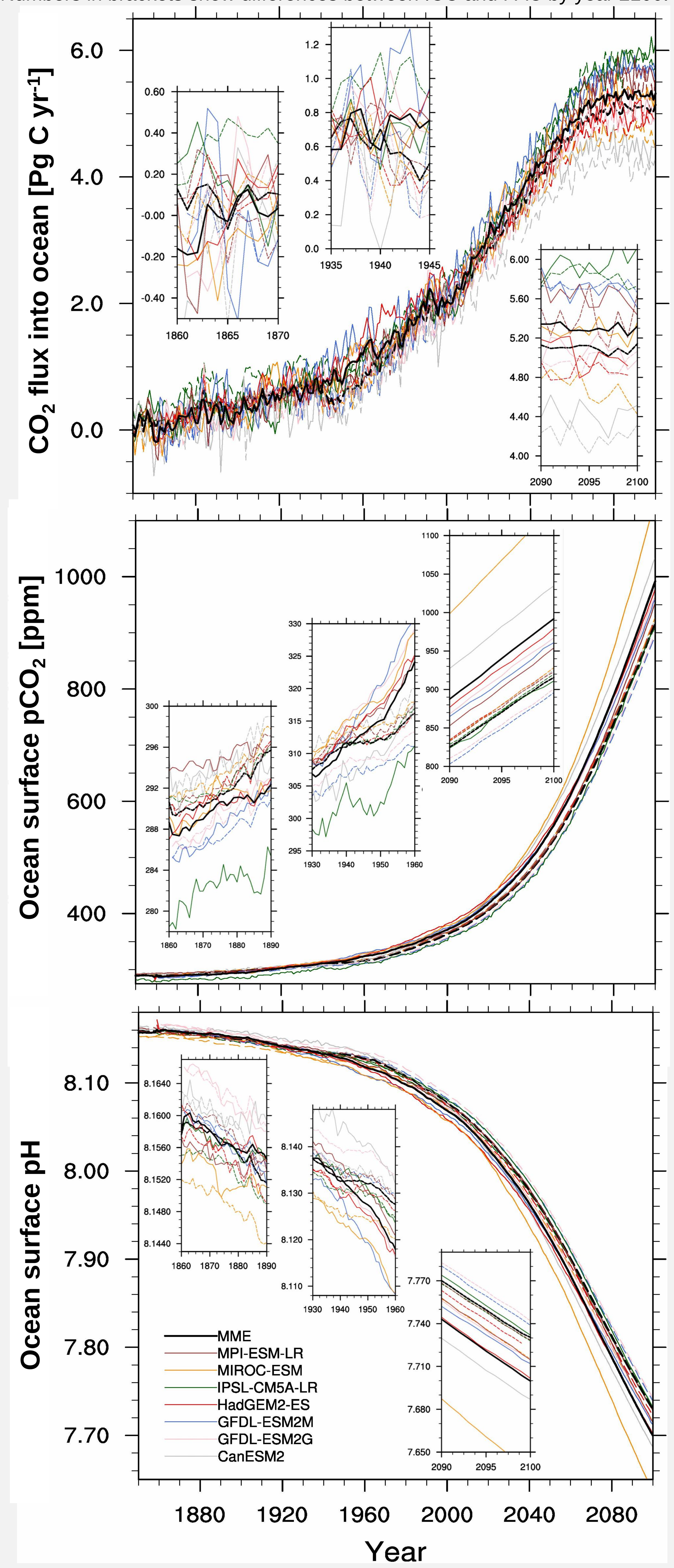
- The ICC simulations show higher CO_2 concentrations in lower atmosphere especially over the northern hemisphere. This is a combined effect of the forcing by emissions and climate-carbon cycle feedbacks. It triggers a different land-sea thermal contrast, resulting in different atmospheric and oceanic circulation and a warmer climate.
- The ocean in ICC run takes up more CO_2 from the atmosphere, shows higher pCO_2 and lower pH at ocean surface as the atmospheric pCO_2 is increasing, which becomes apparent from the 1940s.
- Larger differences of pH between ICC and PAC simulations are located in North Pacific and North Atlantic, where model spread is also larger than in other regions.
- The ICC simulations show larger interannual variability of global CO_2 flux due to the less constrained carbon cycle. Also most models show larger or comparable interannual variability of CO_2 flux in the preindustrial and historical simulations than in the RCP8.5 simulations.

Temporal evolution: Hist.+RCP8.5

The simulations with ICC produce a slightly different oceanic carbon cycle:

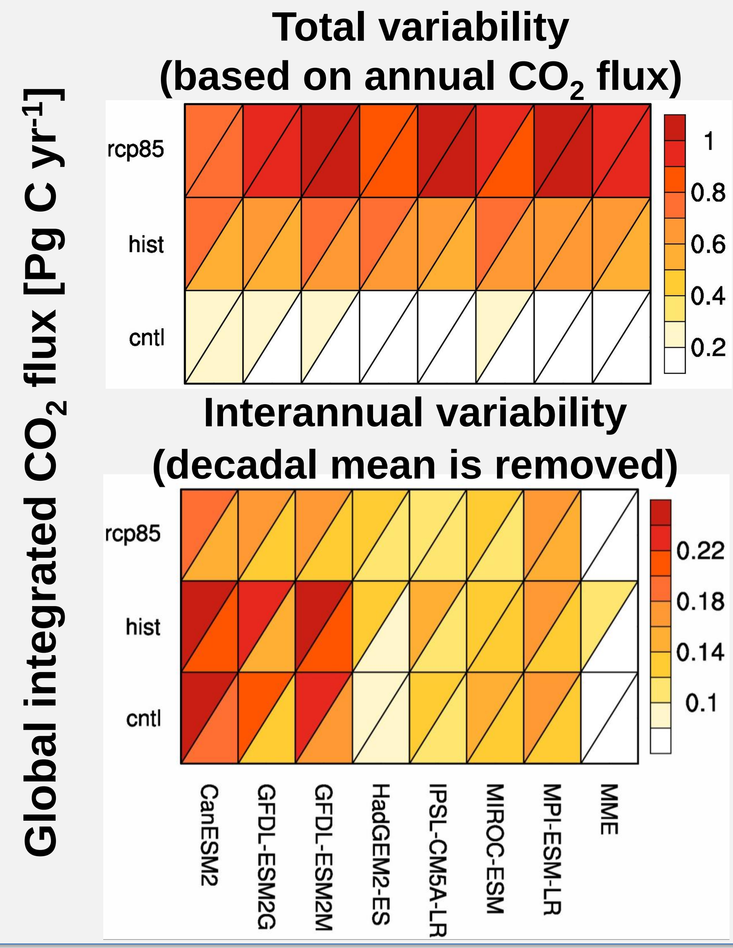
- Ocean takes up more CO_2 from atmosphere (0.25 Pg C yr^{-1});
- Ocean surface pCO_2 is higher (80 ppm);
- Ocean surface pH values are lower (0.03 unit).

Numbers in brackets show differences between ICC and PAC by year 2100.



Temporal evolution of global integrated CO_2 flux (upper panel), global mean ocean surface pCO_2 (middle panel), and global mean ocean surface pH (lower panel). Simulations with ICC (PAC) are shown with solid (dashed) curves. The inner boxes show enlarged time slices, note different scales are used.

Temporal variability: global accumulation and regional mean (MPI-ESM-LR)



The temporal variability is expressed by standard deviation.
Upper triangle: ICC
Lower triangle: PAC

- The majority of models shows that the ICC simulations produce larger total and interannual variability in global integrated CO_2 flux.
- Larger interannual variability is found in Cntl and Hist. simulations.

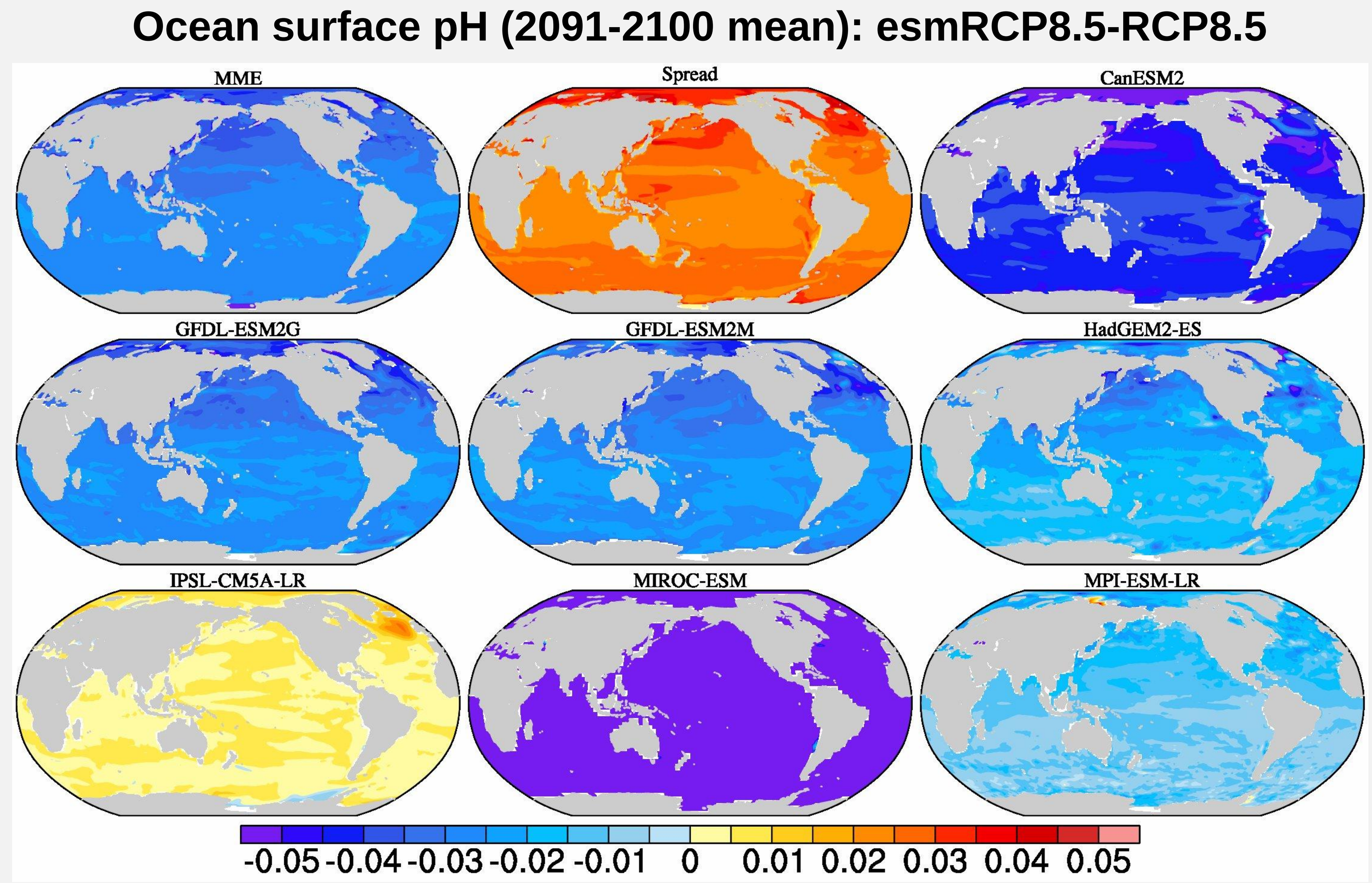
Table2. Standard deviation of oceanic pCO_2, DIC, and pH in observations and **MPI-ESM-LR** simulation.

Var.	Data	BATS	HOT	ESTOC
pCO_2 [ppm]	Obs	30.38	17.20	23.28
	Hist.	32.79	16.34	22.16
	esmHist.	32.21	14.37	20.16
DIC [umol/kg]	Obs	28.06	16.4	7.96
	Hist.	13.67	18.28	10.39
	esmHist.	13.71	15.13	9.43
pH	Obs	0.031	0.018	0.023
	Hist.	0.037	0.017	0.023
	esmHist.	0.034	0.014	0.021

MPI-ESM-LR fairly well reproduces the temporal variability of in-situ ocean carbon parameters.

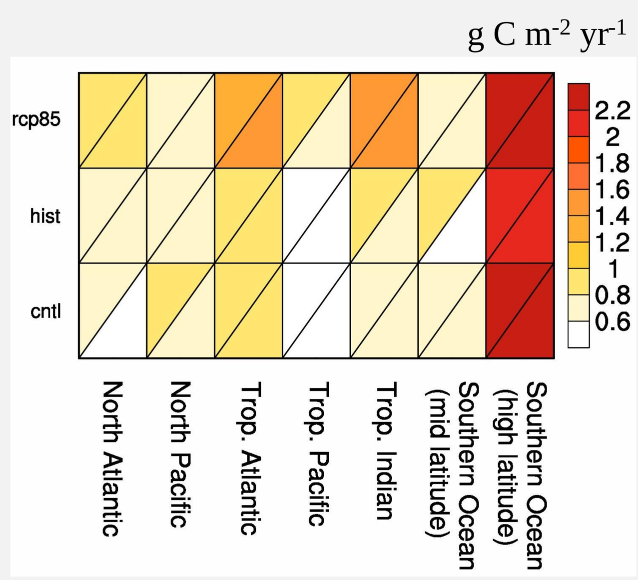
Spatial variability: comparison of spatial distribution and regional variability

Ocean surface pH (2091-2100 mean): esmRCP8.5-RCP8.5



Lower pH values are found in ICC simulations from all the models except for IPSL-CM5A-LR. The largest differences between ICC and PAC simulations are located in the North Pacific and North Atlantic, where model spread is also larger than in other regions.

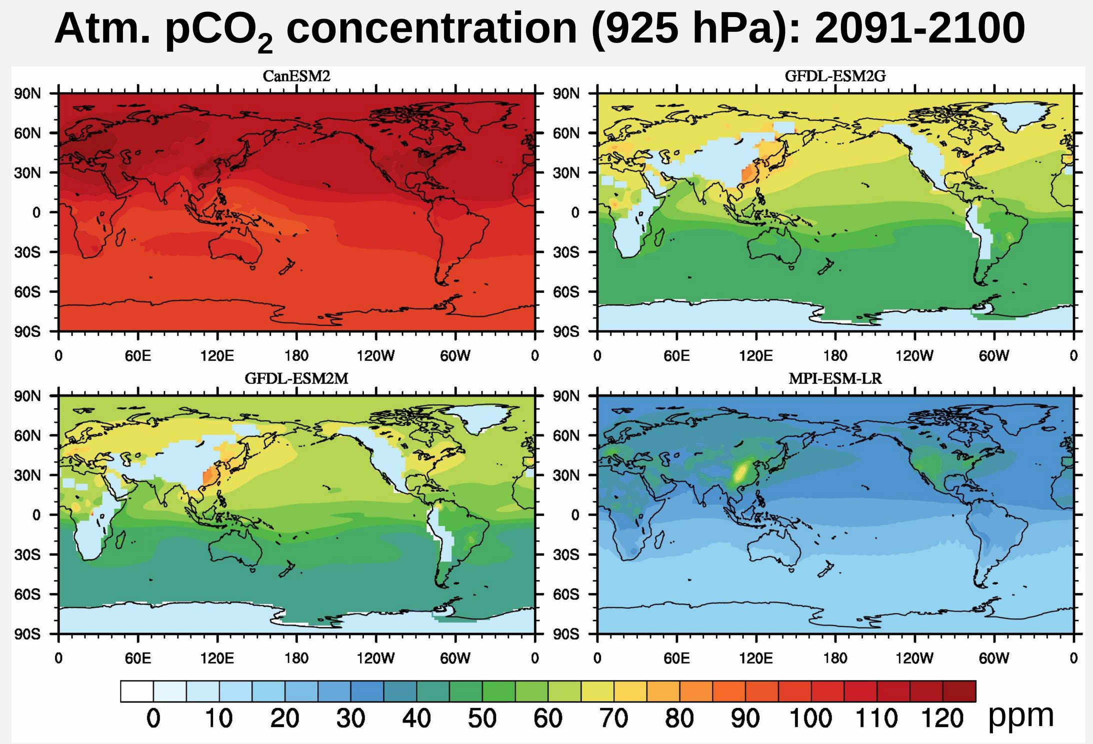
Variability of regional mean CO_2 flux from MPI-ESM-LR simulation (decadal mean is removed)



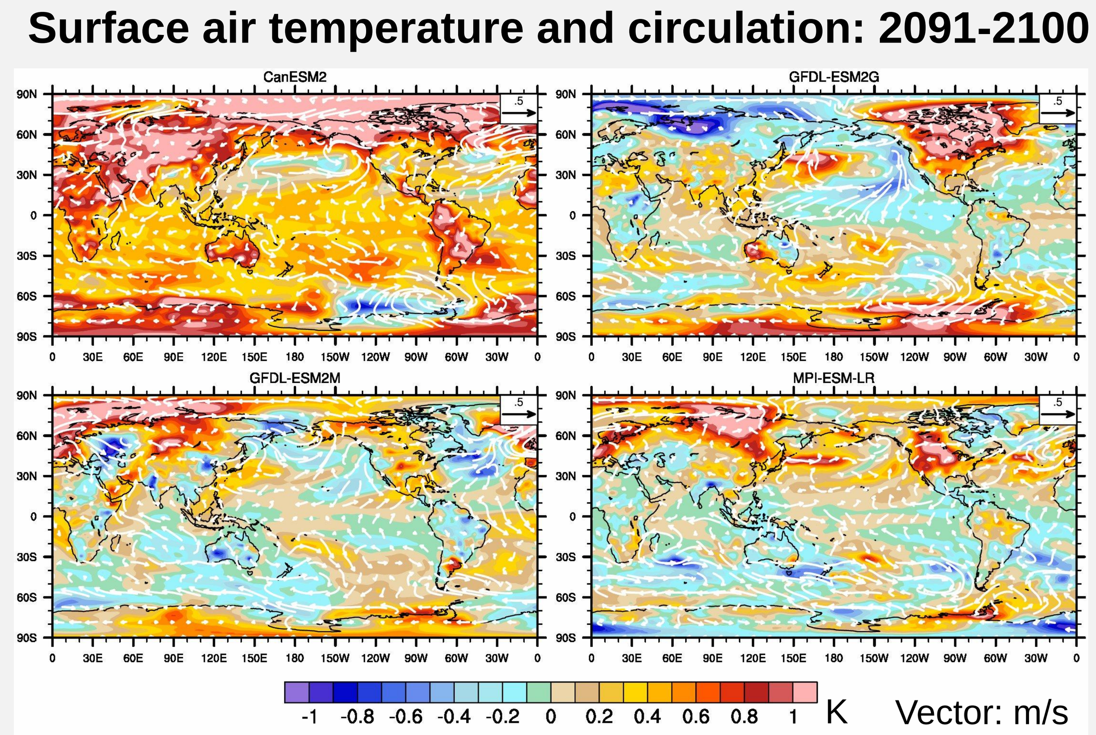
Larger variability is found in high latitude Southern Ocean, tropical Atlantic, Tropical Indian, and North Atlantic regions in the **MPI-ESM-LR** simulations.

Projected differences in pCO_2, climate and circulation: esmRCP8.5 –RCP8.5

Atm. pCO_2 concentration (925 hPa): 2091-2100



Surface air temperature and circulation: 2091-2100



The CO_2 concentration in the lower atmosphere is higher in ICC simulations, which triggers a different land-sea thermal contrast, produces a warmer climate and a slightly different large scale circulation.

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