Supplemental material submitted for the paper:

Long–term surface pCO_2 trends from observations and models

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1 Introduction

In this supplemental document, we briefly describe the five Earth system model used and analyzed in our paper. Additionally, we also present plots of the long-term change surface salinity from each model, which are not included but support the analysis presented in the paper.

2 Description of the models

2.1 NorESM1-ME

The Norwegian Earth System Model (NorESM1-ME) was developed in Norway in collaboration with researchers from the National Center for Atmospheric Research at the United States. Some of the NorESM1-ME components are therefore based on the version 4 of the Community Climate System Model (CCSM4), namely the atmospheric general circulation (Community Atmospheric Model, CAM4), land (Community Land Model, CLM4), and sea-ice (Community, CICE4) components (Gent et al., 2011). The atmospheric chemistry in CAM4 was modified following Seland et al. (2008). The ocean general circulation is based on the Miami Isopycnic Coordinate Ocean Model (MICOM), coupled together with the Hamburg Oceanic Carbon Cycle (HAMOCC5) model (Assmann et al., 2010). HAMOCC5 consists of an NPZD-type ecosystem model, where the phytoplankton growth is co-limited by nitrate, phosphate, and dissolved iron. For the simulations analyzed here, there is no riverine influx of biogeochemical tracers. For the air-sea gas exchange, the steady winds gas transfer rate from Wanninkhof (1992) is used. The inorganic carbon chemistry follows the Ocean Carbon Model Intercomparison Project (OCMIP) protocols. In addition to the above modules, NorESM-ME also adopts the CCSM4 coupler (CPL7), which handles the communication exchanges between the different components. More detailed description of the model is available in Tjiputra et al. (2013).

2.2 HadGEM2-ES

The Hadley Centre Earth system model (HadGEM2-ES) is based on the HadGEM1 (Johns et al., 2006) with further improvement including ocean and terrestrial biogeochemistry, interactive atmospheric chemistry, and aerosol components (Collins et al., 2011). The ocean carbon cycle component of HadGEM2-ES, the Diat-HadOCC, is an improved version of the original HadOCC model (Palmer and Totterdell, 2001), which simulates multi-functional groups of phytoplankton, nitrogen cycle, marine dimethylsulphide (DMS) emission, and multi-nutrient limitations of silica and iron. As with the NorESM1-ME, the HadGEM2-ES does not include biogeochemical tracers in the riverin fluxes. The land carbon cycle is represented by the MOSES2 land surface scheme, which implements exchange of water, energy, and carbon with the land-atmosphere interface. It also includes the TRIFFID dynamic global vegetation model, simulating five plant functional types (Cox, 2001).

2.3 IPSL-CM5A-LR

The latest version of the IPSL ESM includes improvements in tropospheric chemistry, aerosols, and online interactions with land vegetation. The atmospheric and oceanic general circulation models are LMDZ (Hourdin et al., 2006) and NEMOv3.2 (Madec, 2008), respectively. The land surface model is represented by ORCHIDEE (Krinner et al., 2005) and the ocean carbon cycle is PISCES (Aumont and Bopp, 2006). PISCES simulates multi-functional groups of phytoplankton and zooplankton, with phytoplankton growth rates being limited by several nutrients and availability of light. PISCES also differentiates between small and large sinking particles, by simulating different vertical sinking speeds. The air-sea gas exchange parameterization also follows the quadratic wind speed formulation by Wanninkhof (1992). The IPSL-CM5A-LR uses climatological riverine fluxes of DIC, DOC and POC. It assumes that all POC is lost in the estuaries, and that DOC is labile and thus remineralized.

2.4 MPI-ESM-LR

The Max Planck Institute for Meteorology's Earth System Model (MPI-ESM) was developed in Hamburg, Germany. It consists of the atmospheric general circulation models ECHAM6 and the oceanic z-layer model MPIOM (Roeckner et al., 2003; Jungclaus et al., 2006). The land surface model, JSBACH, simulates energy, water, momentum, and CO_2 fluxes between the land and atmosphere (Raddatz et al., 2007). In addition, dynamical vegetation with 12 plant functional types is also included in the model. MPI-ESM-LR uses HAMOCC5 (Maier-Reimer et al., 2005) as its ocean carbon cycle component. Riverine input of DIC/ALK are set similar to the losses to the sediment ($CaCO_3$) and to DOC to balance the loss of organic carbon. The riverine input rates are determined by diagnosing the loss to the sediment over a few hundred years in the control/spinup run. A more detailed description of HAMOCC as used in CMIP5 can be found in Ilyina et al. (2013).

2.5 CESM1

The Community Earth System Model (CESM1) is a fully-coupled, global climate model consisting of land, atmosphere, ocean, and sea-ice components (Gent et al., 2011). The marine ecosystem module utilizes multiple phytoplankton functional groups and a single zooplankton class. Phytoplankton growth is controlled by temperature, light, and available nutrients (N, P, Si, Fe). The behavior of the marine carbon cycle is documented by Long et al. (2013). The land surface model, CLM4 (Lawrence et al., 2012) includes a biogeochemical module with coupled carbon-nitrogen dynamics (Thornton et al., 2009).

3 Regional pCO_2 trends using varying starting date

Figure S1 shows the models simulated surface pCO_2 trend in each of the 14 regions. It highlights how the computed pCO_2 trends change when different starting period is used. The figure was motivated by the fact that most of the observations are biased toward recent periods with generally poor coverage prior to the 1990s. The figure shows that in nearly all regions and all models, the pCO_2 trends increase when the starting year is closer to the present day (e.g., trends for the 1990-2011 is stronger than 1970-2011 periods). This result is consistent with the fact that atmospheric CO_2 concentration also grows at a faster rate in the later part of 1970-2011 period.

4 Spatial changes in sea surface salinity

Figure S2 shows the long-term change in the sea surface salinity (SSS) for the contemporary period and the last 40-yrs of this century under RCP8.5 scenario as simulated by the five ESMs used in this study.

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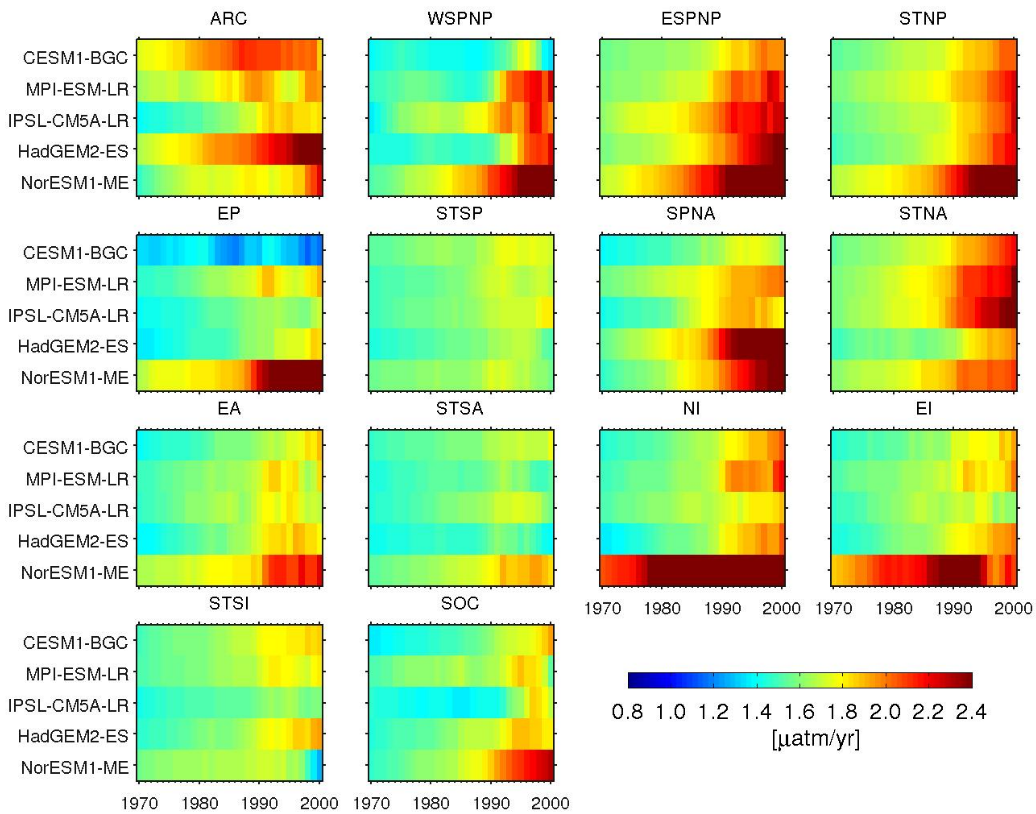

Figure S1. Mean regional trends of surface pCO_2 simulated by five ESMs for the periods starting from years given in x-axis and ending at year 2011. Units are in [μatm yr^{-1}].

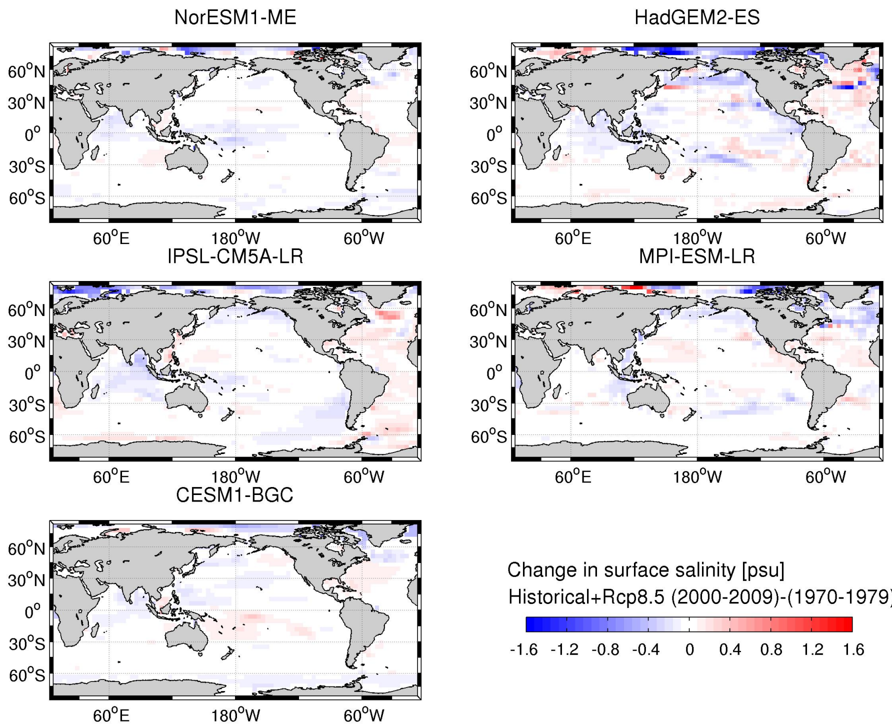

Figure S2. Simulated mean change in sea surface salinity by the NorESM1-ME, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR, and CESM1-BGC models for the contemporary period: mean(2000–2009) minus mean(1970–1979). Units are in [psu].

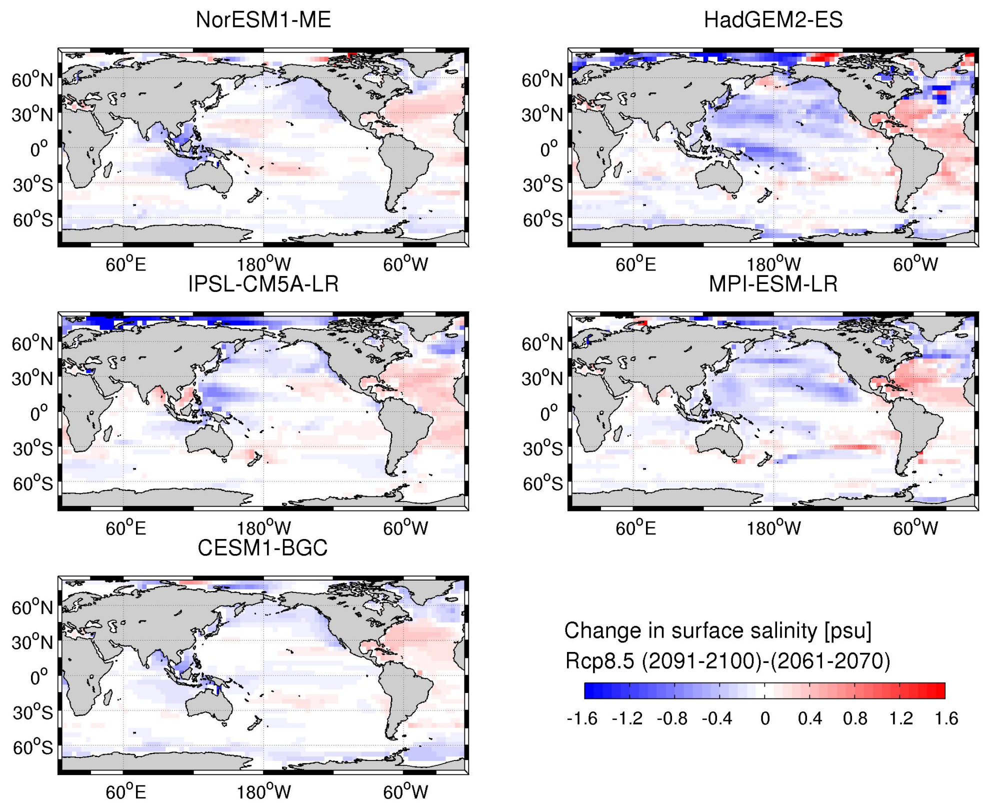

Figure S3. Simulated mean change in sea surface salinity by the NorESM1-ME, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR, and CESM1-BGC models for the last 40-yrs period of this century uncer RCP8.5 scenario: mean(2091–2100) minus mean(2061–2070). Units are in [psu].