

Appendix to Chapter 8

Changes in Time Mean Sea Level

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Contents

Appendix A8.1: Supplementary figures.....	2
Appendix A8.2: Exploring observational constraints.....	6

Appendix A8.1: Supplementary figures in support of the main report text

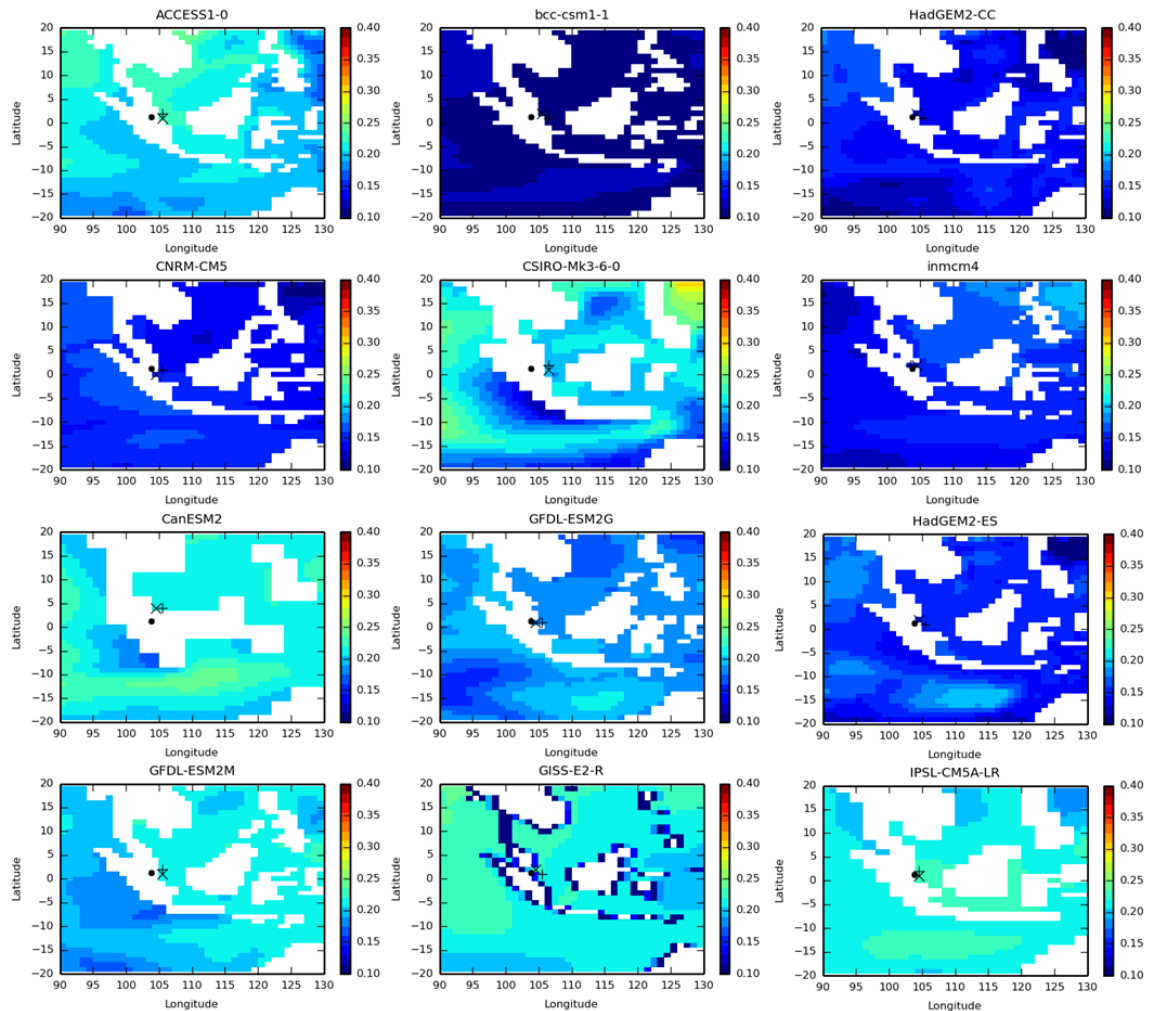


Figure A8.1a: Projections of steric/dynamic sea level rise (metres) for RCP4.5 computed as the difference between 1986-2005 and 2081-2100. The location of Singapore is shown by the black circle. The primary and secondary grid boxes used to extract time mean sea level for Singapore are shown by an x and +, respectively. Note the grid box selections for GISS-E2-R are away from potential problem areas for the land mask.

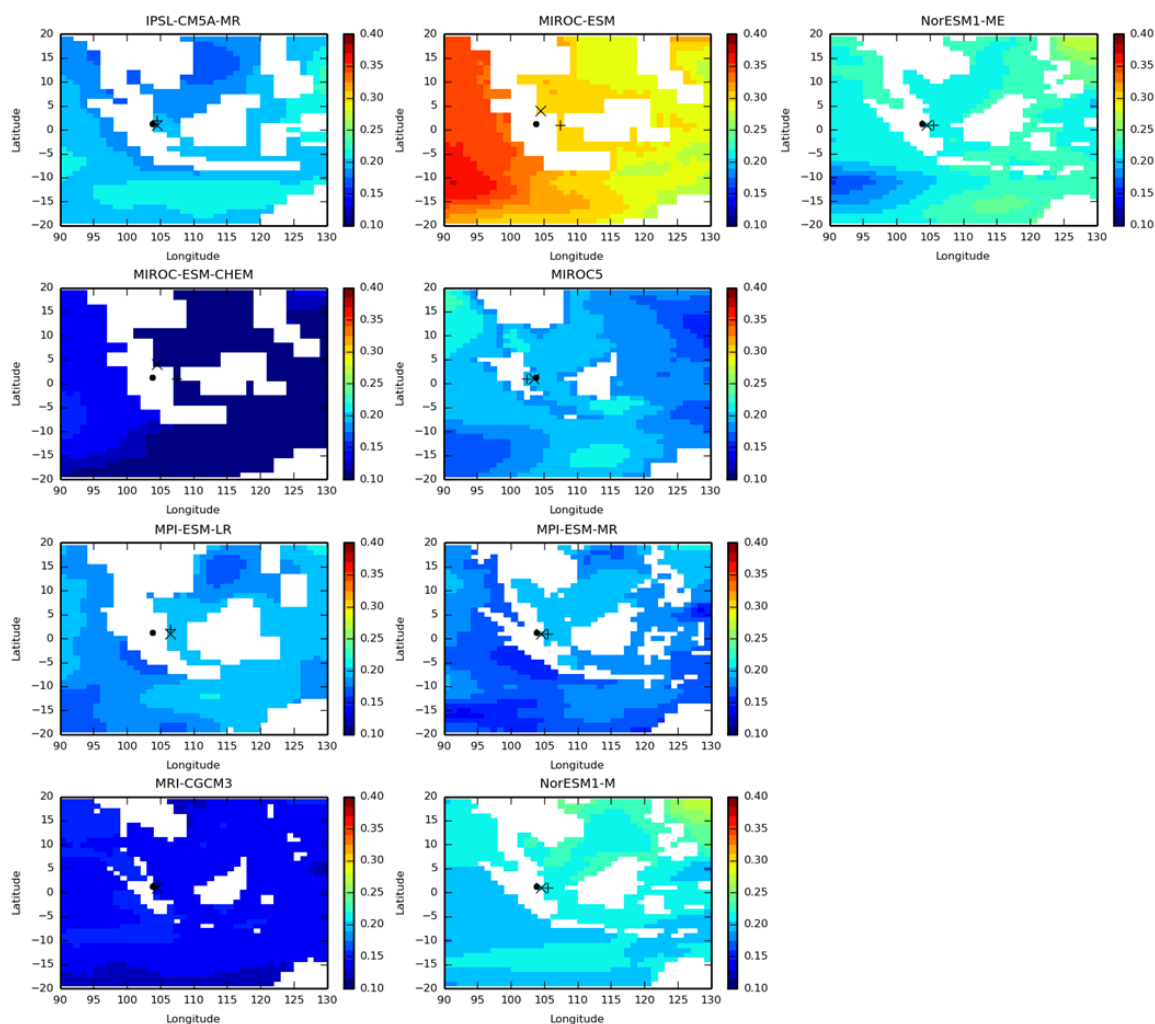


Figure A8.1b: Projections of steric/dynamic sea level rise (metres) for RCP4.5 computed as the difference between 1986-2005 and 2081-2100. The location of Singapore is shown by the black circle. The primary and secondary grid boxes used to extract time mean sea level for Singapore are shown by an x and +, respectively.

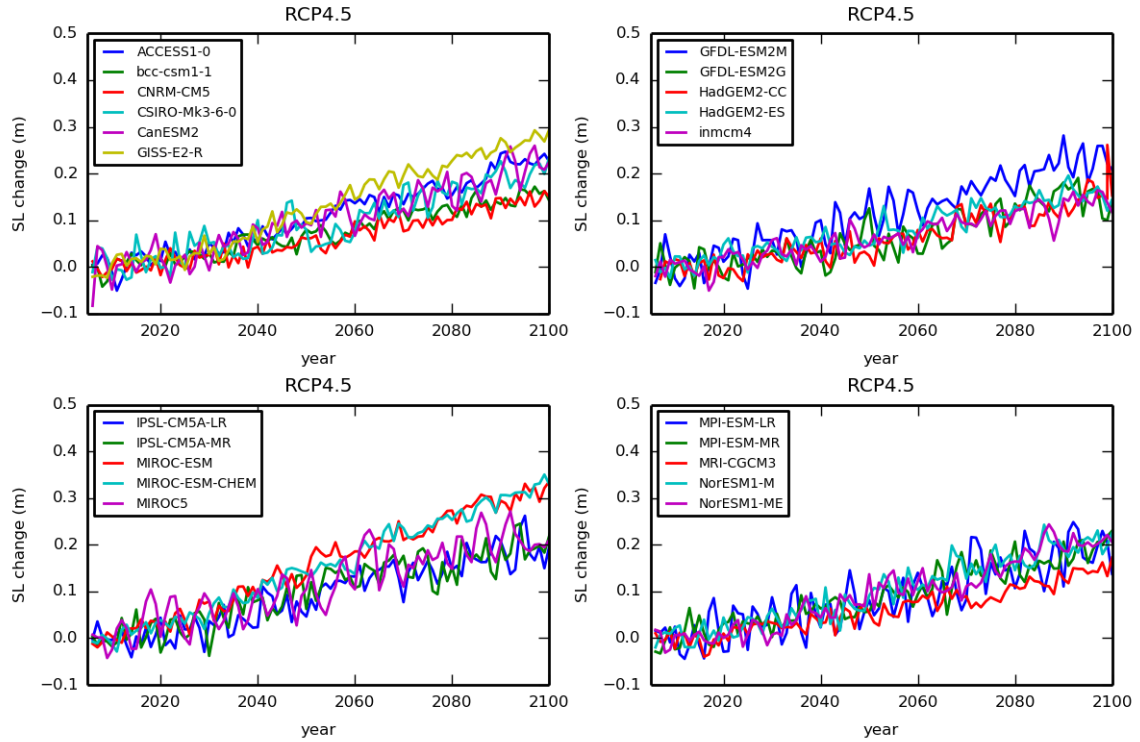


Figure A8.2: Time series of steric/dynamic sea level change for RCP4.5 over the period 2006-2100. Values are computed relative to the mean over the 2006-2015 period and are intended to illustrate the time evolution of change across the different models.

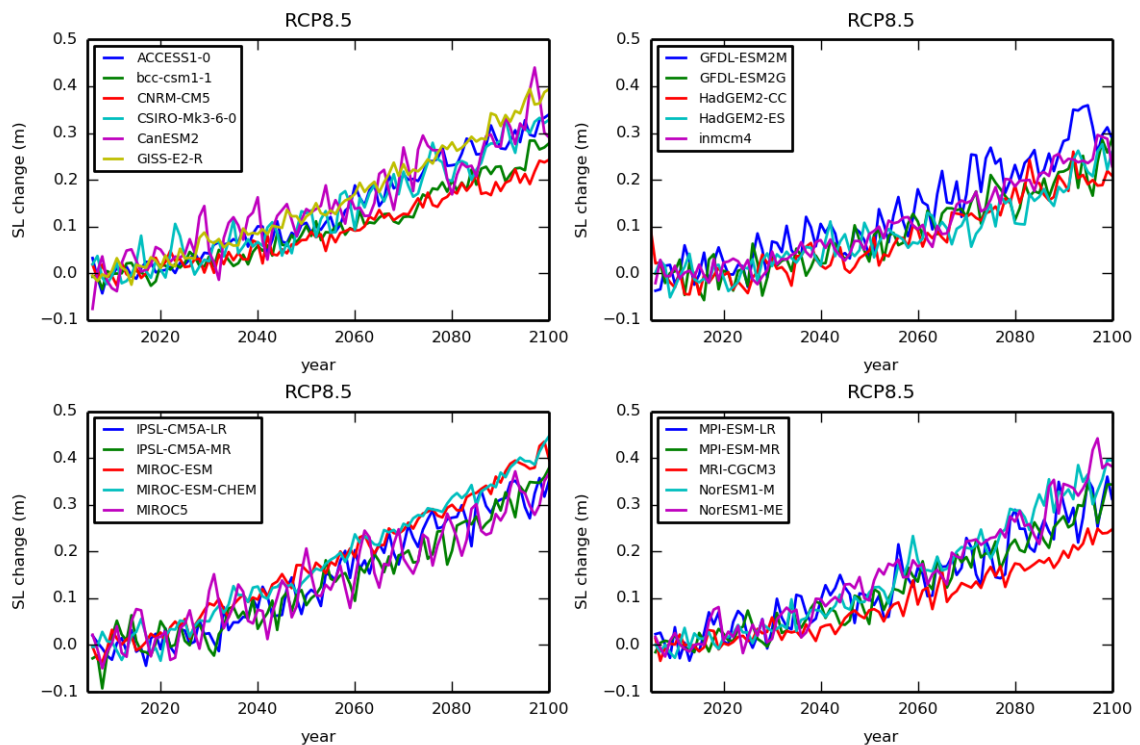


Figure A8.3: As figure A8.2, but for RCP8.5.

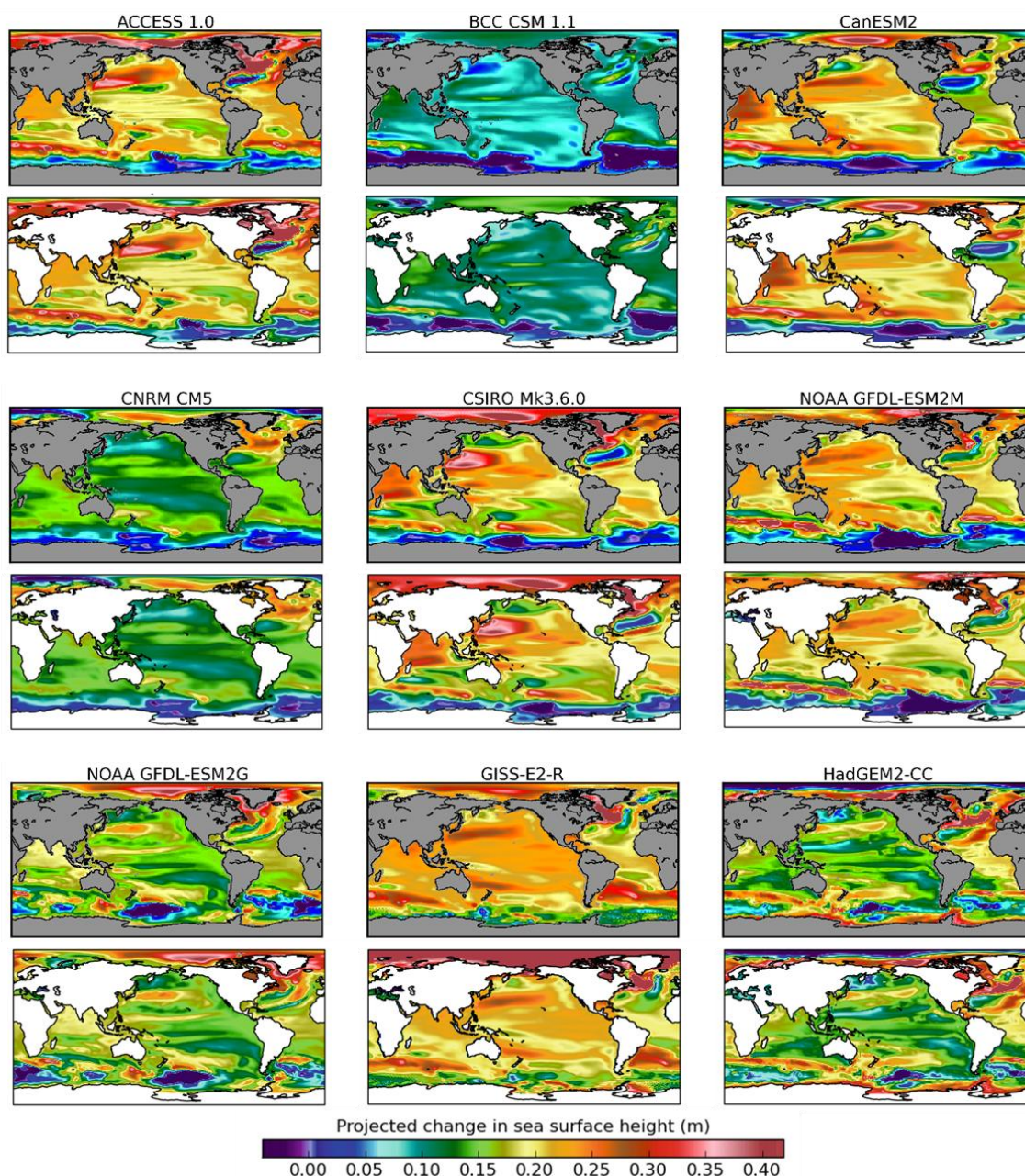


Figure A8.4: Examples of steric/dynamic sea level change over the 21st Century for RCP4.5 from Slangen et al. (2014) figure S1 (upper rows and grey land mask) and Met Office V2 study (lower rows and white land mask) over the 21st Century for RCP4.5. Note that the colour contours used are not quite identical.

Appendix A8.2: Exploring potential for observational constraints on projections of regional sea level rise

Executive summary

We present an initial exploration of relationships between: (i) model representation of internal (unforced) climate variability; and (ii) simulated trends over the historical period 2006-2100, with the long-term response to climate change under the RCP4.5 scenario. Any emergent relationships could potentially be used to provide observational-constraints on the model ensemble as a basis for providing a weighted average of their climate response, and reduce the uncertainty in regional sea level projections. For dynamic sea level, we find no robust connections between either the representation of internal variability or simulated trends of historical climate change, and changes over the 21st Century. Therefore, we see no reason to diverge from the AR5 approach (Church et al., 2013) of giving models equal weight in our central estimates of time mean regional sea level change – as reported in the main text.

1. Introduction

A large part of the uncertainty in regional projections of sea level rise comes from the ocean response – both in terms of the global ocean heat uptake (and associated thermal expansion) and the regional changes in ocean density and circulation (Church et al., 2013). Similarly, there is large uncertainty in the way in which the surface mass balance of ice sheets and glaciers will respond under future global warming, which is dependent regional changes temperature and precipitation. There is potential to reduce both of these uncertainties if suitable “observational constraints” can be found, with which to weight the model ensembles used to provide climate change projections (Hegerl et al., 2007; Stott and Forest, 2007).

Observational constraints are often based on models’ ability to accurately simulate some aspect of the mean current climate. For example, Wang and Overland (2009) used a simple observational constraint – selecting a subset of models that simulated the mean minimum and seasonality of Arctic sea ice extent with less than 20% error of the observations – to give projections of summer sea ice loss. While observed past climate change would seem to be more clearly related to future climate change, in practice uncertainties in both the climate forcing and estimated response have hampered their application as observational constraints (Hegerl et al., 2007). In addition, we note that details of regional climate change are often dependent on the response of atmospheric (and oceanic) circulation, which is more poorly understood than the basic thermodynamic response of the system that controls more fundamental aspects of change, such as global average temperature (Shepherd, 2014).

The aim of the present scoping study is to establish whether there is any emergent relationship between the representation of climate variability from pre-industrial control simulations and response to greenhouse gas forcing, for spatial patterns of surface temperature and dynamic sea level (i.e. the shape of the ocean surface arising from variations in density and ocean circulation). We also explore relationships between the spatial patterns of change over the historical period since 1950 and the future response

to global warming. Establishing some emergent relationship across models between an observable quantity and future climate change is a pre-requisite for application of an observational constraint. We do not consider the seasonal cycle as a potential observational constraint in the current work, since there is not the same obvious connection between the governing physics in the climate response for regional sea level as has been previously exploited for aspects of the cryosphere (Wang and Overland, 2009; Hall and Qu, 2006). In addition, a wide variety of CMIP5 model behaviour has been noted in ocean heat content variability (Palmer and McNeall, 2014) and this may relate to changes in long-term ocean heat uptake with associated implications for global sea level and surface temperature rise (Kuhlbrodt and Gregory, 2013).

2. Methodology

Two-dimensional monthly fields of dynamic sea level ('zos') and near surface temperature ('tas') were downloaded from the CMIP5 archive for the following experiments: (i) pre-industrial control run ('piControl'); (ii) the historical 20th Century simulations ('historical'); (iii) the RCP4.5 climate change scenario ('rcp45'). These fields were converted to annual means and mapped onto a regular 1 x 1 latitude-longitude grid with bilinear interpolation, using the Climate Data Operator tools developed at the Max Planck Institute for Meteorology.

Maps of interannual variability from the piControl simulation were produced for each model and variable by computing the standard deviation for each grid box following the removal of a linear trend. Spatial trends for the historical (1950-2006) and RCP4.5 simulations (2006-2100) were created by performing a least-squares linear regression fit to each grid box. For both surface temperature and dynamic sea level, the area-weighted field average was set equal to zero before the trends were computed (this was necessary to ensure that fields represented only the departure from the global mean at each time-step).

To evaluate the level of similarity in the spatial structure of trends and variability across scenario, we calculate area-weighted pattern correlations for each model. For our comparison of trends in historical and RCP4.5 scenarios, this is a straightforward correlation between the two patterns. For our comparison of variability in control simulations and the trends in RCP4.5, correlations are calculated between standard deviations of annual mean data in a control simulation and the absolute magnitude of trends in RCP4.5. The relevant correlations are specified within the subtitles of each figure in this section.

3. Data

Table A8.1: CMIP5 models used in the analysis of patterns of sea level and surface temperature change.

Climate model	Modeling Center (or Group)
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
BCC-CSM1.1-M	Beijing Climate Center, China Meteorological Administration
CanESM2	Canadian Centre for Climate Modelling and Analysis
CCSM4	National Center for Atmospheric Research
CESM1-FASTCHEM	Community Earth System Model Contributors
CNRM-CM5	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
HadGEM2-CC	Met Office Hadley Centre
HadGEM2-ES	Met Office Hadley Centre
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
IPSL-CM5A-MR	Institut Pierre-Simon Laplace
IPSL-CM5B-LR	Institut Pierre-Simon Laplace
MPI-ESM-LR	Max-Planck-Institut für Meteorologie
MPI-ESM-MR	Max-Planck-Institut für Meteorologie
MPI-ESM-P	Max-Planck-Institut für Meteorologie
NorESM1-M	Norwegian Climate Centre
NorESM1-ME	Norwegian Climate Centre

4. Results

4.1 Spatial patterns of surface temperature

The spatial maps and associated pattern correlations in figures A8.5-A8.7 reveal that, across CMIP5 models, there is a positive association between the spatial structure of surface temperature change in the historical period and the changes in the 21st Century in RCP4.5 ($r = 0.45 \pm 0.25$, mean and standard deviation across ensemble). This positive correlation is expected because the surface temperature response to external climate forcings—characterized by Arctic intensified warming and a land-sea contrast in response to increasing greenhouse gases—has already been detected in the historical record (Bindoff et al. 2013). In addition, there is some evidence for an association between regions of larger magnitude interannual variability in control simulations and regions that deviate most from the global mean response in RCP4.5 ($r = 0.35 \pm 0.09$). This association is due to the correspondence between high-latitude regions of large magnitude variability and the high-latitude intensification of the surface temperature response to external climate forcings in both historical and RCP4.5 simulations. The results presented here suggest that there may be merit in further investigation into

observational constraints into spatial patterns of surface temperature rise. However, glacier and ice sheet surface mass balance are also dependent on regional changes in snowfall, which is a variable strongly connected to changes in atmospheric circulation. Therefore, any such efforts to find regional temperature constraints may be confounded by uncertainties in this more challenging aspect of regional climate change.

4.2 Spatial patterns of dynamic sea level

In contrast to the results for surface temperature, the spatial maps and associated pattern correlations for dynamic sea level (Figures A4.8-A4.10) reveal that there is no robust association between the spatial structure of trends in the historical period (1950-2005), or interannual variability in control simulation, and the long-term response of dynamic sea level in RCP4.5 (2005-2100). The weak link between patterns of interannual variability and the magnitude of signals in RCP4.5 ($r = 0.17 \pm 0.08$) is likely a result of leading modes of climate variability (e.g. ENSO) that play an important role in driving variability on regional scales but exhibit no consistent response to external forcings. Perhaps more surprising is the fact that spatial trends in dynamic sea level during the historical period are generally an unreliable indicator of trends in the 21st Century ($r = 0.16 \pm 0.26$). For example, in some models (e.g. GFDL-CM3, bcc-csm1-1-m) the pattern of dynamic sea level change is anti-correlated in the historical and RCP4.5 scenarios and linked to changes in the sense of trends in the Southern Ocean relative to the global mean. However, in other models (e.g. CCSM4), the spatial pattern of changes in the historical period are very similar to those in RCP4.5. It is possible that these differences are a consequence of the differences in the nature and global extent of external forcings (e.g. volcanic eruptions) prescribed in during historical and RCP scenarios. Alternatively, model-dependent manifestations of multi-decadal internal variability may be obscuring the climate change response in the historical simulations. Further work is required to understand the origins of these differences.

Standard deviation of tas in CMIP5 piControl experiments
 Ensemble mean pattern correlation with magnitude of trends in rcp45: 0.35 +/- 0.09

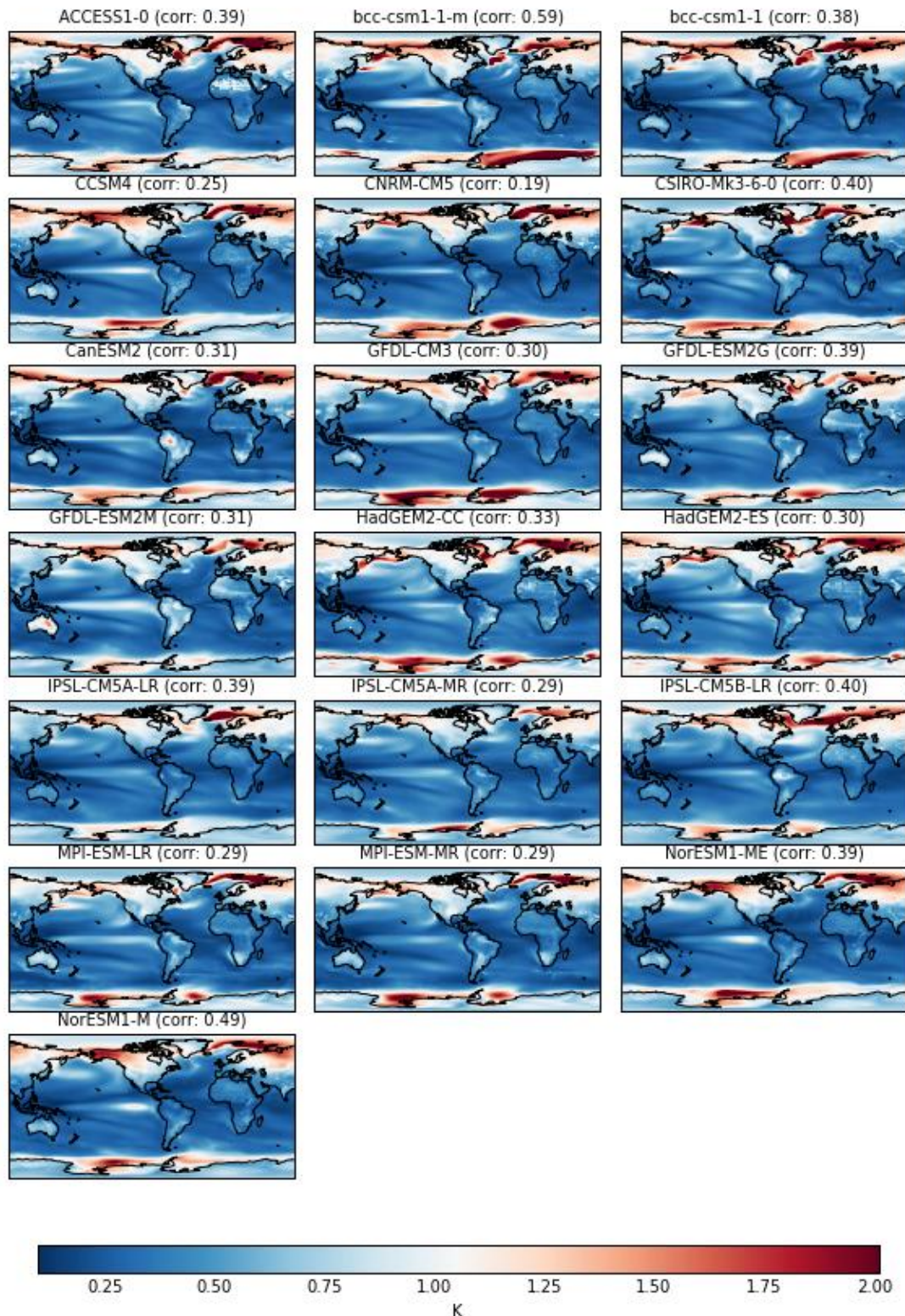


Figure A8.5: Standard deviation (K) of near-surface temperature in preindustrial control simulations. Included in each subtitle is the area-weighted pattern correlation between the standard deviations shown and the absolute magnitude of surface temperature trends in RCP4.5 (fig A8.7).

Trend in tas in CMIP5 historical experiments
Ensemble mean pattern correlation with rcp45: 0.45 +/- 0.25

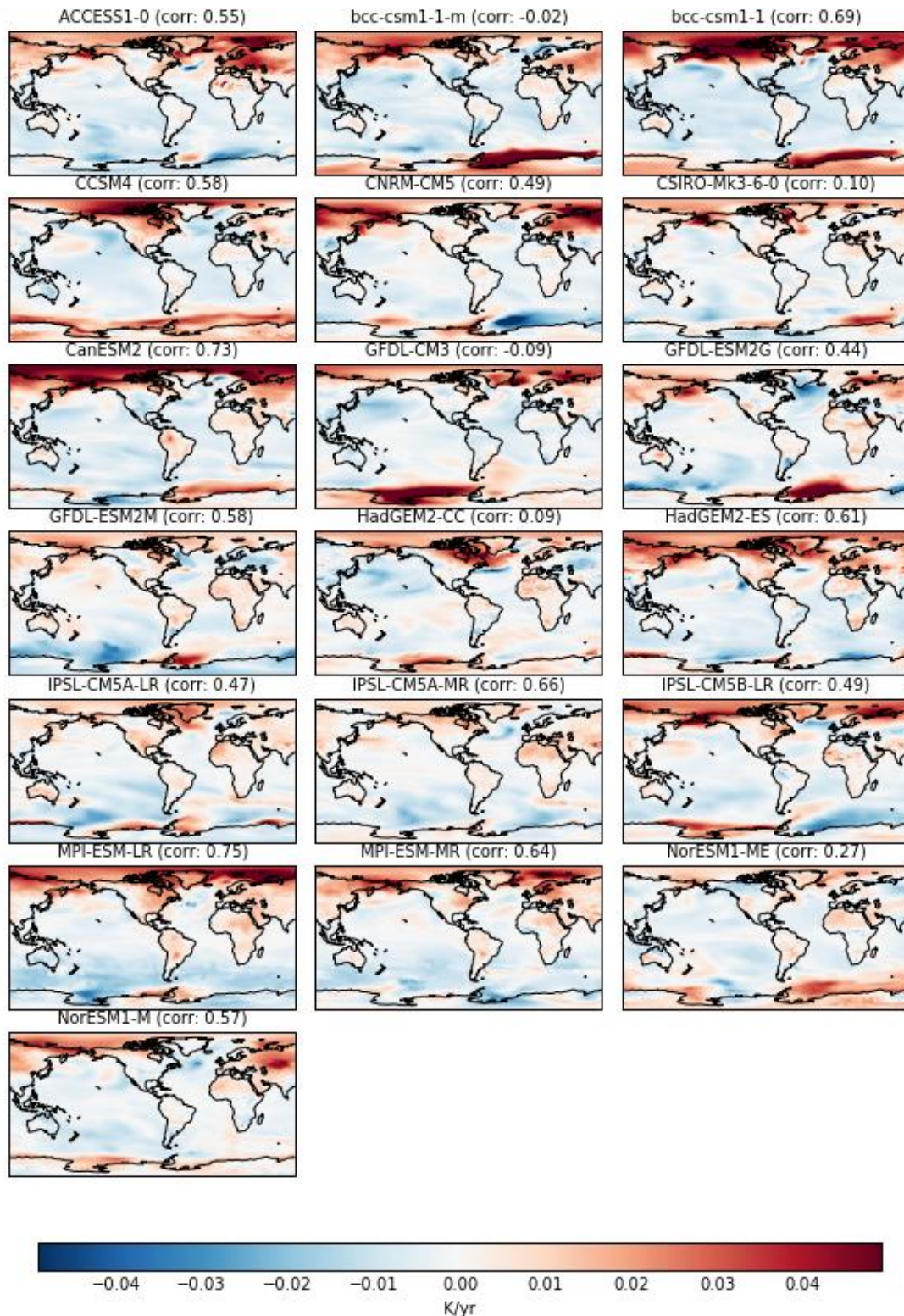


Figure A8.6: Linear trends in near-surface temperature (global mean removed) in historical simulations for the period 1950-2006. The area-weighted pattern correlation with surface temperature trends in RCP4.5 (fig A8.7) are specified within the subtitles

Trend in tas in CMIP5 rcp45 experiments
Ensemble mean pattern correlation with rcp45: 1.00 +/- 0.00

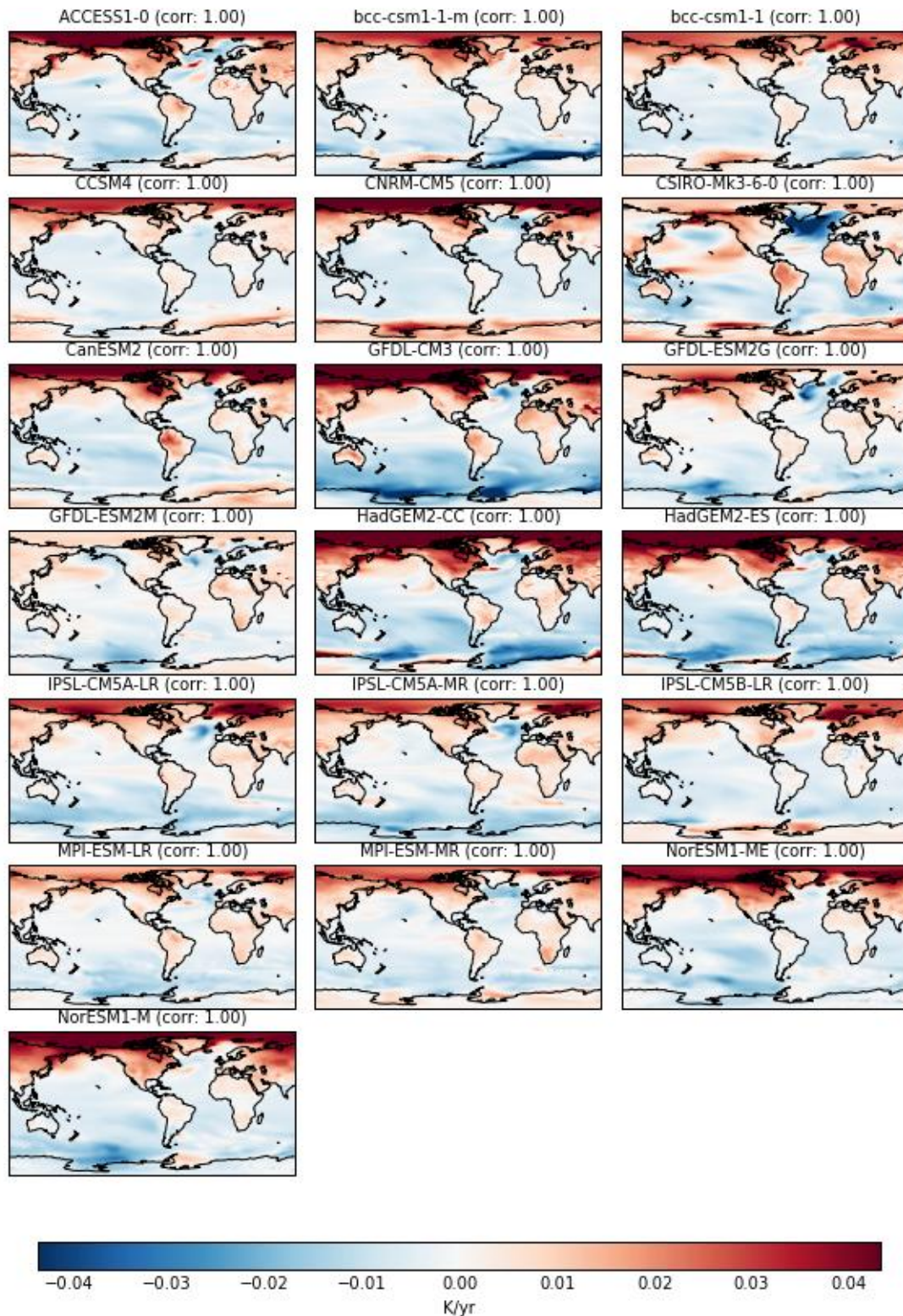


Figure A8.7: Linear trends in near-surface temperature for the period 2006-2100 (global mean removed) in RCP4.5 simulations.

Standard deviation of zos in CMIP5 piControl experiments
 Ensemble mean pattern correlation with magnitude of trends in rcp45: 0.17 +/- 0.08

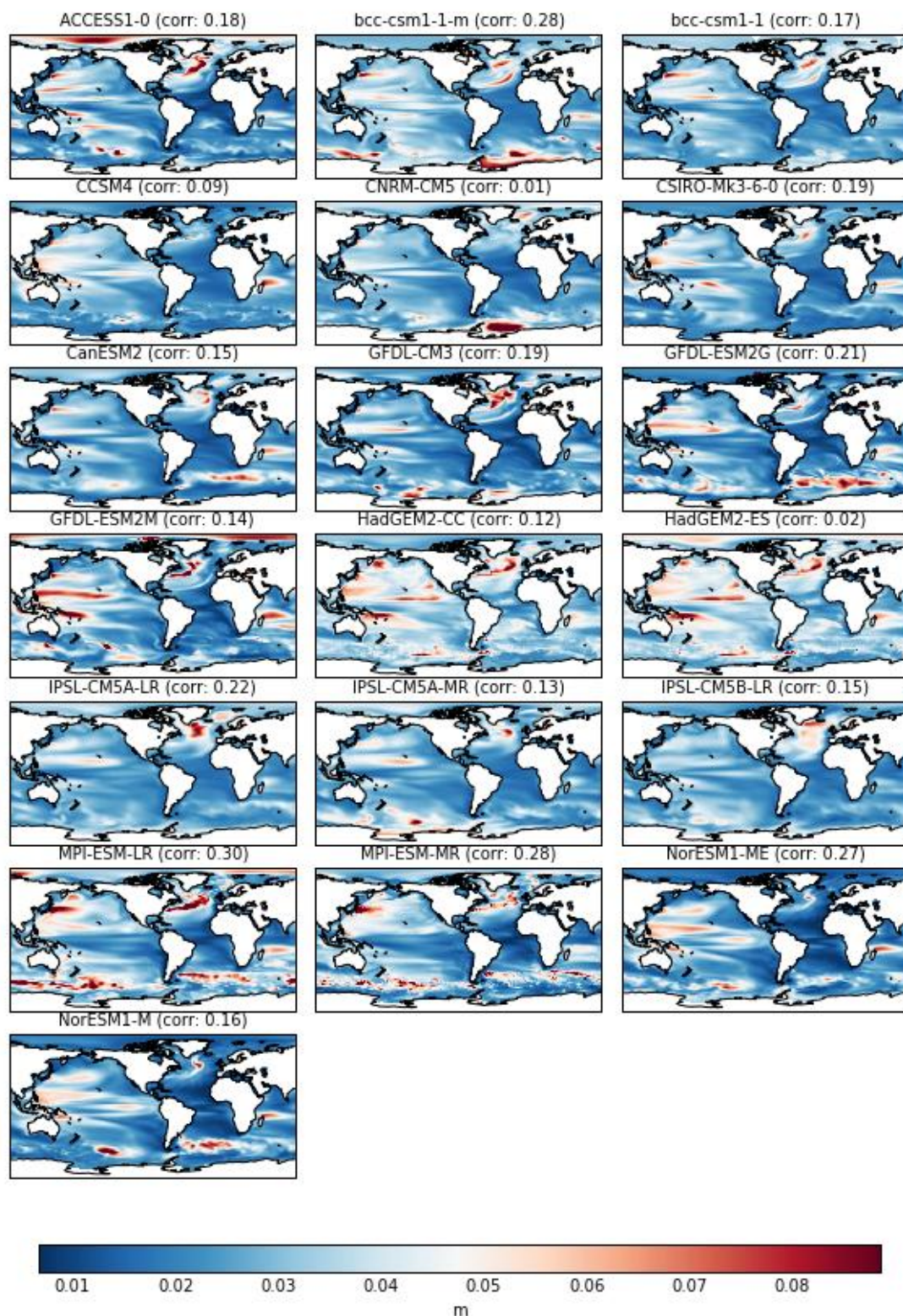


Figure A8.8: Standard deviation (m) of near-surface temperature in preindustrial control simulations. Included in each subtitle is the area-weighted pattern correlation between the standard deviations shown and the absolute magnitude of dynamic sea level trends in RCP4.5 (fig A8.7).

Trend in zos in CMIP5 historical experiments
Ensemble mean pattern correlation with rcp45: 0.16 +/- 0.26

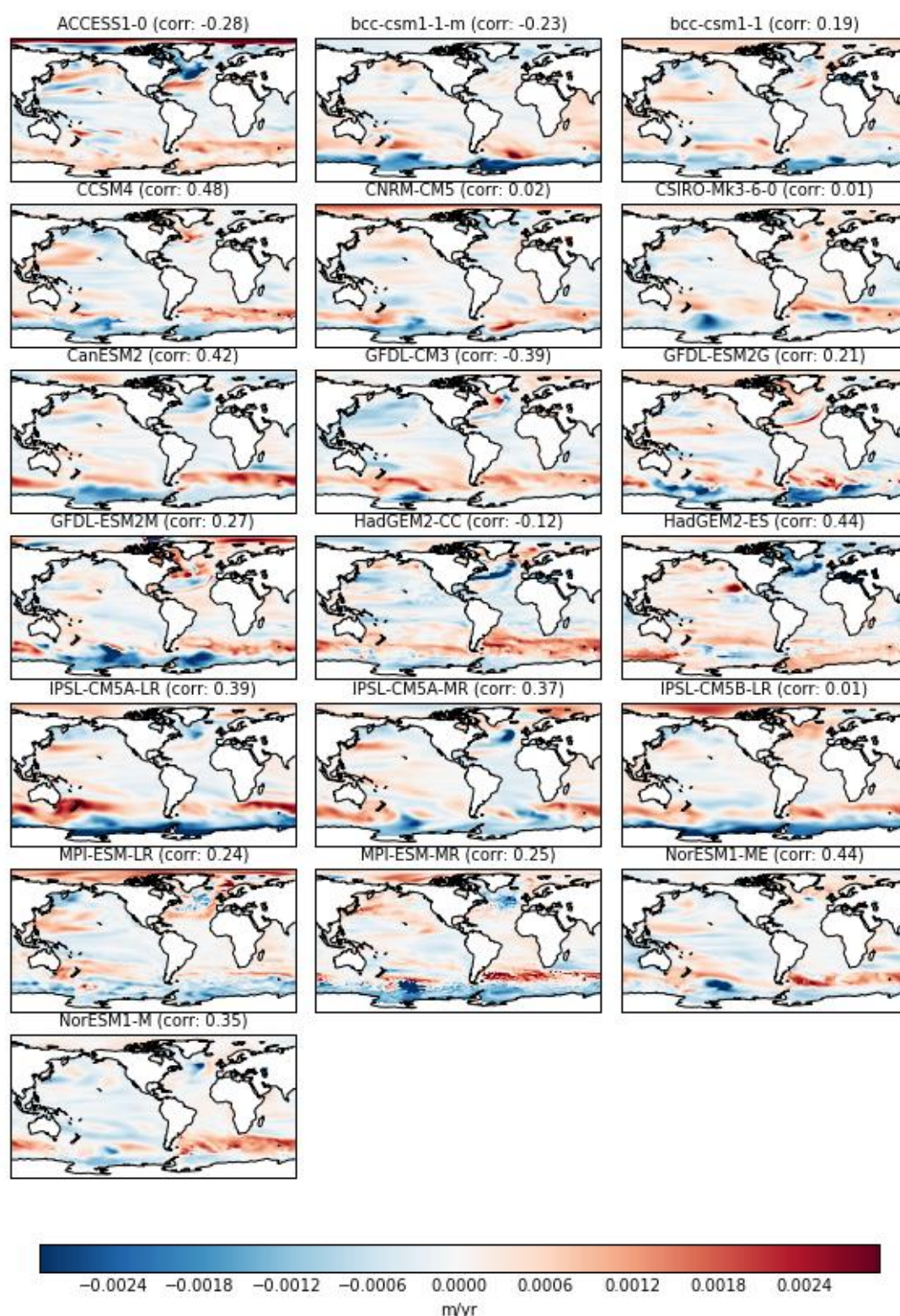


Figure A8.9: Linear trends in dynamic sea level (global mean removed) in historical simulations for the period 1950-2006. The area-weighted pattern correlations with surface temperature trends in RCP4.5 (fig A8.7) are specified within the subtitles. Note: the positive correlation for HadGEM2-ES is a consequence of large negative changes in the Mediterranean in both RCP4.5 and historical experiments, despite the otherwise anti-correlated patterns.

Trend in zos in CMIP5 rcp45 experiments
Ensemble mean pattern correlation with rcp45: 1.00 +/- 0.00

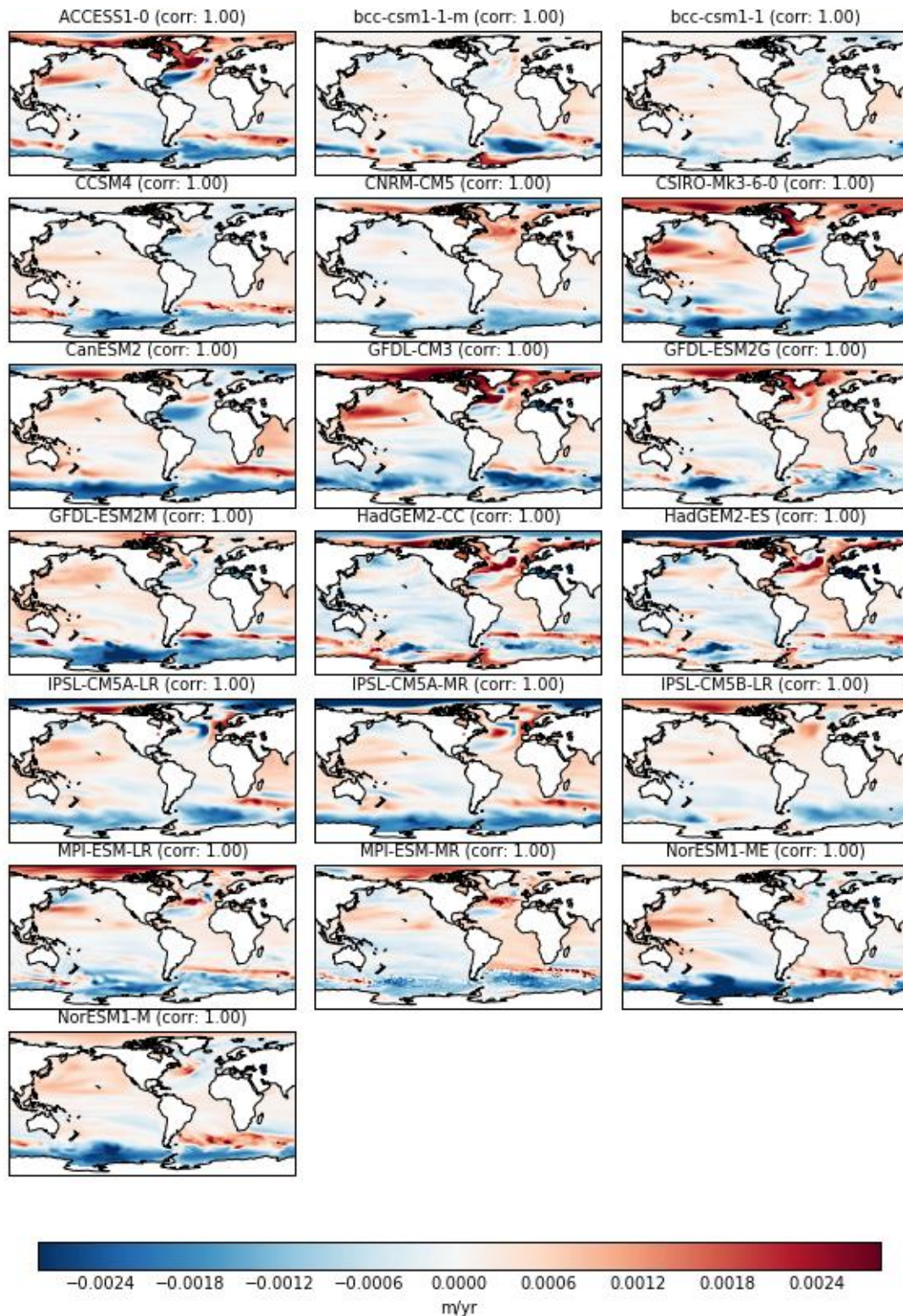


Figure A8.10: Linear trends in dynamic sea level (global mean removed) in RCP4.5 simulations for the period 2006-2100.

5. Summary

We have presented an initial exploration into spatial relationships between: (i) internal climate variability, (ii) simulated historical trends, and the emergent patterns of climate change for regional temperature and dynamic sea level. While we are able to find some relationships for regional temperature change, we have found no robust connections for dynamic sea level. For this reason, we find no reason to diverge from the AR5 approach (Church et al., 2013) of giving models equal weight in our central estimates of time mean regional sea level change – as reported in the main text.

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