# Chapter 8

## Changes in Time Mean Sea Level

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## Contents

# 8.1 Introduction

The work presented here forms part of the larger Singapore 2nd National Climate Change Study – Phase 1 project to assess Singapore's vulnerability to future climate change and provide information to inform climate impacts studies in the region over the 21st Century. Given its considerable population, industries, commerce and transport located in coastal areas at elevations less than 2 m (Wong, 1992), Singapore is particularly vulnerable to changes in extreme sea levels.

Changes in extreme sea levels can arise through some combination of: (i) changes in time mean regional sea level, including vertical movement of the land; (ii) changes driven by regional processes that control the most extreme sea levels, such as waves and surge activity, which are often linked to local meteorology. The purpose of this chapter is to evaluate regional changes in time mean sea level over the 21st Century using the process-based climate model data and methods presented in the IPCC AR5 (Church et al. 2013). Potential changes in wave and surge activity are assessed in the companion Chapter 9: Extreme Sea Level Projections. The scientific background to changes in sea level extremes for the Singapore region is presented in Supplementary Information report 3 (Palmer et al., 2014).

A survey of the literature suggests that there have been very few studies of contemporary and future sea level change for Singapore. Ng and Mendelsohn (2005) considered three global sea level rise scenarios over the period 2000-2100, based on the IPCC Third Assessment Report (Church et al., 2001). Under the assumption of a linear increase in global (and regional) sea level, they assessed coastal adaptation options for several sites around Singapore. More recently, Tkalich et al. (2013) have analysed local tide gauge records and satellite data to investigate the trends and variability of sea level in the Singapore Strait. The authors discuss the important role of the Monsoon circulation in the seasonal cycle of sea level and the interannual variations associated with the El Nino Southern Oscillation (ENSO). Tkalich et al. (2013) also present linear trends in sea level for the Singapore Strait, which provide useful context for the results presented in this report (Figures 8.6 and 8.7).

The various contributions to globally averaged sea level rise have been assessed by the IPCC AR5 (Church et al., 2013) for a range of climate change scenarios. The AR5 presents a *likely range*,of global mean sea level rise for each scenario, representing the expert judgement of the AR5 authors that for global mean sea level the 5th-95th percentiles of the CMIP5 multi-model distribution have a 66-100% chance of including the value that will actually be realised. The extra uncertainty implied by this arises from the authors' expert judgement of methodological or structural uncertainty that is not captured by the CMIP5 ensemble, and the *likely* range represents the best scientific assessment of global sea level change available at present.

The processes contributing to global sea level rise are generally associated with non-uniform spatial patterns of change, which must be taken into account when investigating regional sea level rise. The methods presented in this chapter combine the *likely range* of global sea level rise from the IPCC AR5 with the spatial "fingerprints" associated with these changes from Slangen et al. (2014). This information is combined with analysis of CMIP5 model simulations of ocean circulation and density/expansion change in the vicinity of Singapore. Following the AR5 approach, we express the estimates of total sea level rise at Singapore as a *likely range* about a central estimate (50th percentile), meaning that for a given scenario our judgement is that there is a 66-100% chance that the future sea level rise will fall within the ranges presented.

There are a number of potential sources of sea level change that are not directly related to anthropogenic climate change. These include land movement due to geological processes such as glacial isostatic adjustment (GIA), as well as direct natural or anthropogenic changes to geomorphology. Our sea level estimates include an estimate of the effects of GIA, which is a small, negative contribution for Singapore. Future changes in geomorphology in response to seismic activity, or through anthropogenic modification (e.g. land reclamation or effects of resource extraction), are not included in this study.

# 8.2 Methodology

## *8.2.1 AR5 estimates of global mean sea level rise*

Here we briefly outline the methodologies used in the IPCC AR5 to estimate the different components of global mean sea level (GMSL) rise: (i) global thermal expansion; (ii) glacier mass addition; (iii) ice sheet mass addition (from surface mass balance and rapid ice dynamics); (iv) changes in land water storage. The full details are available in IPCC AR5 Chapter 13 main text and supplementary materials (Church et al., 2013).

Global thermal expansion, which is associated with ocean heat uptake under anthropogenic climate change, were estimated directly using a set of 21 climate models: ACCESS1-0; ACCESS1-3; CCSM4; CNRM-CM5; CSIRO-Mk3-6-0; CanESM2; GFDL-CM3; GFDL- ES-M2G; GFDL-ESM2M; HadGEM2-ES; IPSL-CM5A-LR; IPSL-CM5A-MR; MIROC-ESM; MIROC-ESM-CHEM; MIROC5; MPI-ESM-LR; MPI-ESM-MR; MRI-CGCM3; NorESM1-M; NorESM1-ME; and inmcm4. These models were chosen on data availability for both for the future scenarios and a parallel pre-industrial control run (from which a quadratic drift correction was applied). Following the AR5 assumptions and approach the multi-model median and 5$^{th}$ and 95$^{th}$ percentiles, assuming a normal distribution were used to provide a central estimate and upper and lower bounds of this component over the 21$^{st}$ Century for each scenario.

A number of global glacier models have used observed glacier mass balance timeseries to construct empirical relations between local surface air temperature and precipitation change and glacier mass balance change, and then extrapolate this to the ensemble of the world's glaciers, the vast majority of which have not been monitored. They used these relations to predict future change in glacier mass balance from CMIP5 projections of local surface air temperature and precipitation change, and they take into account the reduction of glacier area as ice volume is lost. The scheme used in the AR5 is a parametrisation of their results in terms of global mean surface air temperature change. The factor f represents the sensitivity of the global glacier mass balance to global mean temperature change, and the power law represents the effect of glacier mass loss on the sensitivity. Because the exponent is less than unity, the sensitivity diminishes.

The contributions of the Greenland and Antarctic sheets to global sea level rise were split into a part relating to surface mass balance and “rapid ice sheet dynamics”. This latter contribution refers to changes in ice velocity that occur on a decadal timescale, predominantly because of changes in ice-shelves and at the grounding line – allowing ice discharge into the ocean to increase.

Projections of global sea level rise from rapid ice sheet dynamics were formulated by considering 2005-2010 rates of mass loss and *likely* ranges for mass loss at 2100, based on the current literature. Maximum and minimum values at 2100 were estimated separately for each ice sheet and a quadratic function of time was fitted to give a continuous projection – under the simple assumption that the rate changes linearly with time. Intermediate time series for the rapid dynamic contribution were constructed as combinations of the bounding time series assuming a uniform probability density between the extremes.

Estimates of Greenland surface mass balance used the cubic polynomial formula of Fettweis et al. (2013), which relates anomalies of SMB to global surface temperature. The polynomial fit was obtained using results from a regional climate model and input from several CMIP5 models for RCP4.5 and RCP8.5. The 5$^{th}$ to 95$^{th}$ percentiles of the multi-model mean were use to determine the *likely* range for this component of global sea level rise. Changes in Antarctic surface mass balance were assumed to be due solely to an increase in accumulation, based on the results of Gregory and Huybrechts (2006). This increased accumulation arises from a warmer atmosphere being able to hold and transport more moisture and constitutes a negative contribution to future GMSL rise. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the estimated *likely* ranges during the 21st century. This potential additional contribution cannot be precisely quantified but there is medium confidence that it would not exceed several tenths of a metre of sea level rise during the 21st century (Church et al, 2013).

Long-term changes in land water storage are associated with anthropogenic reservoir impoundment and groundwater depletion and can make a substantial contribution to global sea level change. Potential changes in the rates of groundwater depletion and reservoir impoundment over the 21$^{st}$ Century were estimated based on the literature, following the same approach as for ice sheet dynamics. These contributions are treated as independent of climate change scenario, since the current state of knowledge does not permit a quantitative assessment of the dependence.

### *8.2.2 Regional sea level projections for Singapore*

All of the global sea level rise terms that involve mass re-distribution in the Earth System (glaciers, ice sheets and land water storage) are associated with non-uniform spatial patterns of sea level change (e.g. Tamisiea and Mitrovica, 2011, Slangen et al, 2014). Spatial variations can arise from:

- changes in the geoid (from gravitational and rotational effects) and the elastic solid Earth response to changes in local mass loading from changing glaciers,ice sheets and water storage
- Longer term regional land response to glacial isostatic adjustment
- Changes in ocean dynamics and heat/fresh water storage
- Changes in atmospheric pressure (the “inverse barometer effect”).

These processes each have a spatial “fingerprint” which must be taken into account for projections of regional sea level rise. The methods used in this study are described in the following paragraphs and summarised in Table 8.1.

The fingerprint patterns of Slangen et al (2014) represent the ratio of a local sea level change to a unit rise in GMSL for a number of different components. For example, Singapore will experience amplified sea level rise from ice sheets and glaciers by 10-20%, depending on the component (Figures 8.1 and 8.2, Table 8.1). This is essentially because the gravitational attraction from ice mass at high latitudes will reduce under climate change, leading to a redistribution of ocean mass towards the low latitudes; elastic adjustment of the lithosphere to the changing mass loading also plays a role and is taken into account in the fingerprint. In contrast to the land ice terms, Singapore will only experience about 80% of the global changes associated with changes in anthropogenic land water storage. Time series of the glacier, ice sheet and land water storage contributions to global sea level rise from the AR5 supplementary data files (available at http://www.climatechange2013.org/report/full-report/) are converted into local values for Singapore by simply multiplying by a local scaling factor (Table 8.1) from the Slangen et al (2014) fingerprints, using a “nearest neighbour” approach.

Glacial isostatic adjustment represents the slow viscous response of the Earth’s mantle to the last deglaciation (e.g. Tamisiea and Mitrovica, 2011, Slangen et al, 2014). Though small in the global mean, the resulting vertical land movement can be important for local relative sea level change, particularly in high latitude regions. We use the ICE5G (Peltier, 2004) estimates provided by Slangen et al (2014) and extract a rate for the Singapore region (using a “nearest neighbour” approach). Given the long timescales associated with this process, the rates of change are assumed to be constant and are independent of climate change scenario. For Singapore they are negative but small relative to other terms (Figure 8.2), reflecting the fact that Singapore is far from the centre of action of ice sheet changes. The negative isostatic adjustment for Singapore is the result of additional ocean mass from the last deglaciation depressing the sea floor and causing mantle material to flow underneath the continents, causing uplift.

Local changes in ocean density (steric change) and circulation can be important for projections of regional sea level (e.g. Pardaens et al., 2011). We follow the approach taken in IPCC AR5 (Church et al., 2013; Slangen et al., 2014) and combine changes in local dynamic sea level (‘zos’, which represents local departures from global mean sea level) with changes in global thermal expansion (‘zostoga’) to estimate the combined effects of local density and ocean circulation (the “steric/dynamic” term). The sea level change for Singapore is computed as the difference between the 1986-2005 and 2081-2100 periods for each individual model, using an appropriate local grid box (Figure 8.5). The median of the model ensemble change is taken as the central estimate and we compute the $5^{th}$ and $95^{th}$ percentiles based on the multi-model standard deviation, assuming a normal distribution. In order to provide an estimate of the projected steric/dynamic sea level rise that is continuous with time, we assume that the change signal (and model spread) emerges proportionally to the global thermal expansion time series of the IPCC AR5. This approach is justified since, to a good approximation, all models show a linear relationship between the local steric/dynamic sea level change near Singapore, and global thermal expansion (see Chapter 10: Long Term Projections) report). This permits us to estimate the sea level change for the Singapore region throughout the $21^{st}$ century for each scenario.

IPCC AR5 estimates of the effect of changes in atmospheric loading for the RCP4.5 and RCP8.5 scenarios are available as part of the Chapter 13 supplementary data files

(Church et al., 2013). However, the projections for the Singapore region are very small compared to the other terms – representing only about 1% of the total estimated sea level change (Figure 8.3) and with relatively little spread among different model projections. Given the substantial combined uncertainties of the leading terms in total sea level change, we do not include the inverse barometer effect in our final projections as we consider them to make a negligible contribution.

**Table 8.1: Summary table of methodologies employed to estimate the different components of sea level rise at Singapore.**

| **Component** | **Methodology** |
|---|---|
| 1. Steric/dynamic sea level | CMIP5 climate model estimates of global thermal expansion ('zostoga') and dynamic sea level ('zos') are combined for each model. Differences between the two periods 2086-2005 and 2081-2100 are computed for each climate change scenario. A multi-model mean and spread in this component is extracted for Singapore using a nearest-neighbour approach. Time series are constructed based on the assumption that the change signal emerges proportionally to AR5 estimates of global thermal expansion (this approach is justified in Chapter 10: Long Term Projections). |
| 2. Glaciers | Time series of global sea level rise from AR5 data files are scaled by a factor of 1.11, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.2). |
| 3. Greenland surface mass balance | Time series of global sea level rise from AR5 data files are scaled by a factor of 1.14, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.1). |
| 4. Antarctica surface mass balance | Time series of global sea level rise from AR5 data files are scaled by a factor of 1.13, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.1). |
| 5. Greenland dynamics | Time series of global sea level rise from AR5 data files are scaled by a factor of 1.16, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.1). |
| 6. Antarctica dynamics | Time series of global sea level rise from AR5 data files are scaled by a factor of 1.19, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.1). |
| 7. Land water storage | Time series of global sea level rise from AR5 data files are scaled by a factor of 0.81, according to the spatial fingerprint information provided by Slangen et al. (2014, Figure 8.2). |
| 8. Glacial isostatic adjustment (GIA) | Estimate based on ICE5G (Peltier, 2004) model as provided by Slangen et al. (2014, Figure 8.2). |
| 9. Inverse barometer | Assessed from AR5 supplementary data files. Not included in projections, given the negligible contribution (Figure 8.3) |

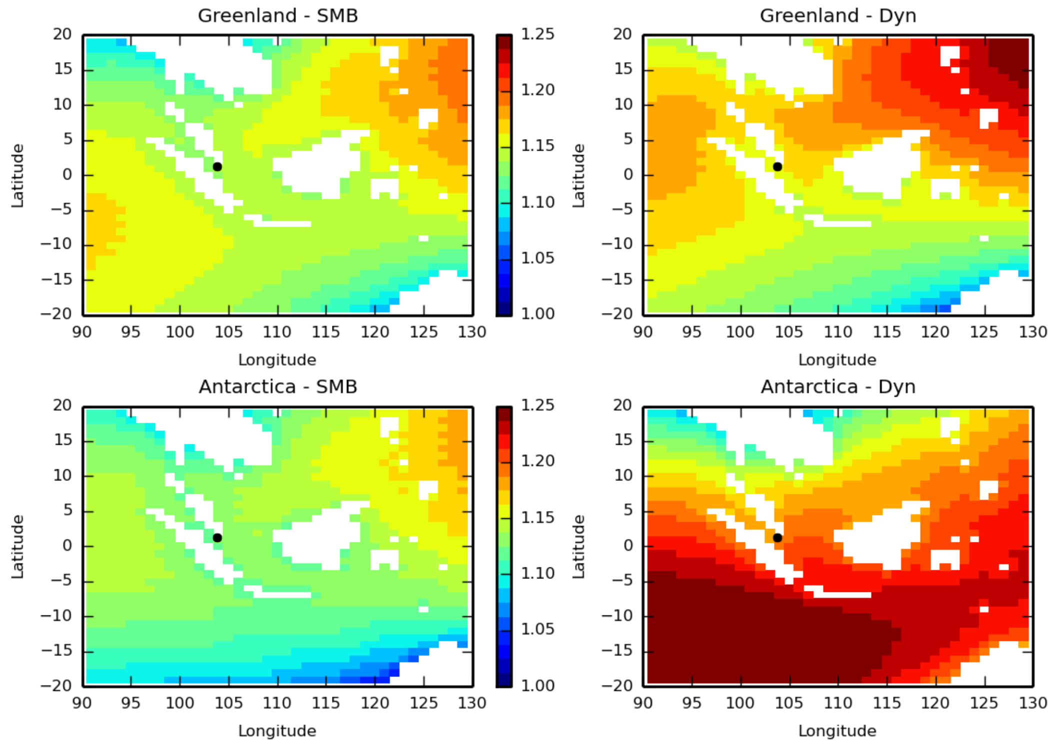


**Figure 8.1: Spatial fingerprints for changes in: Greenland surface mass balance (upper left); Greenland dynamical change (upper right); Antarctica surface mass balance (lower left); and Antarctica dynamical change (lower right). All panels represent the ratio of local relative sea level change per unit of GMSL rise associated with mass input to the oceans. The location of Singapore is shown by the black circle. Source: Slangen et al (2014).**

## *8.2.3 Combining uncertainties*

In the previous section, we have outlined methods for arriving at time series for the different components of sea level rise at Singapore. Each of these time series has a central estimate (often based on the median) and both an upper and lower bound, which are indicative of the 5th and 95th percentiles of the distribution and/or the *likely range* assessed in the IPCC AR5. The central estimates of the different components are simply added together to arrive at values for total sea level change at Singapore. Combining the associated uncertainties is more complicated, and we follow the approach outlined by Church et al (2013):

$$\sigma_{tot}^2 = (\sigma_{steric/dyn} + \sigma_{smb\_a} + \sigma_{smb\_g})^2 + \sigma_{glac}^2 + \sigma_{LW}^2 + \sigma_{dyn\_a}^2 + \sigma_{dyn\_g}^2$$

The total uncertainty ($\sigma_{tot}$), expressed as a variance, is estimated according to the above equation. It is assumed that contributions that have a strong correlation with global air temperature have correlated uncertainties and are therefore added linearly. This combined uncertainty is then added to the other components' uncertainties in quadrature. The uncertainties in the projected ice sheet SMB changes were assumed to be dominated by the magnitude of climate change, rather than their methodological uncertainty (see AR5 Chapter 13 supplementary materials for details), while the uncertainty in the projected glacier change was assumed to be dominated by its methodological uncertainty. Note that we do not include an uncertainty contribution for

GIA or the inverse barometer effect (negligible contribution – see Section 8.3.2) in our method. Note that the departures from the central estimates for the upper and lower bounds are computed separately using the equation above – there is no assumption that the combined uncertainties should be symmetric about the central estimate.

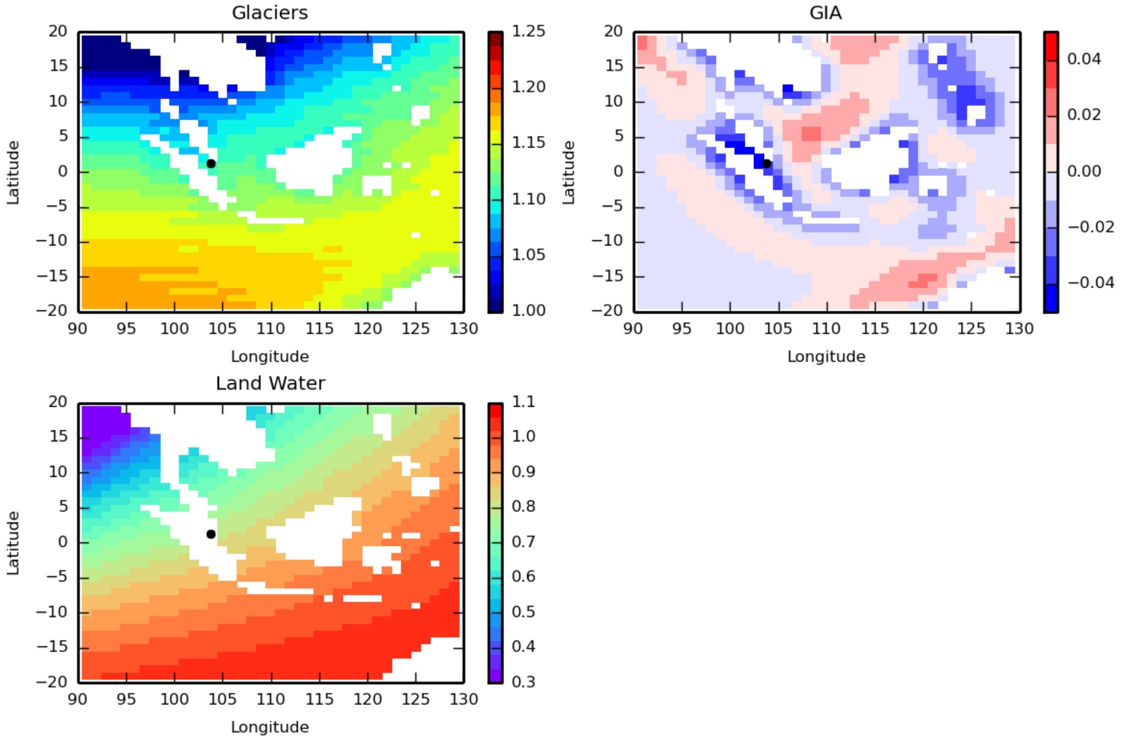


**Figure 8.2: Spatial fingerprints for changes in: Glaciers (upper left); and land water storage (lower left). These panels represent the ratio of local relative sea level change per unit of GMSL rise associated with mass input to the oceans. Changes in local sea level from GIA (upper right) are presented as the total change over the periods 1986-2005 and 2081-2100. The location of Singapore is shown by the black circle. Source: Slangen et al (2014).**

# 8.3 Data and pre-processing

## *8.3.1 Spatial fingerprints and GIA data from Slangen et al. (2014)*

NetCDF files of GIA and sea level change fingerprint data used by Slangen et al (2014) were provided by Aimée Slangen. The estimates of GIA come from the ICE5G model (Peltier, 2004) and represent the relative sea level change between the periods 1986-2005 and 2081-2100 (Figure 8.2). These sea level change fingerprints for terrestrial ice and water storage changes represent the local sea level change per unit rise of GMSL (Figures 8.1 and 8.2).

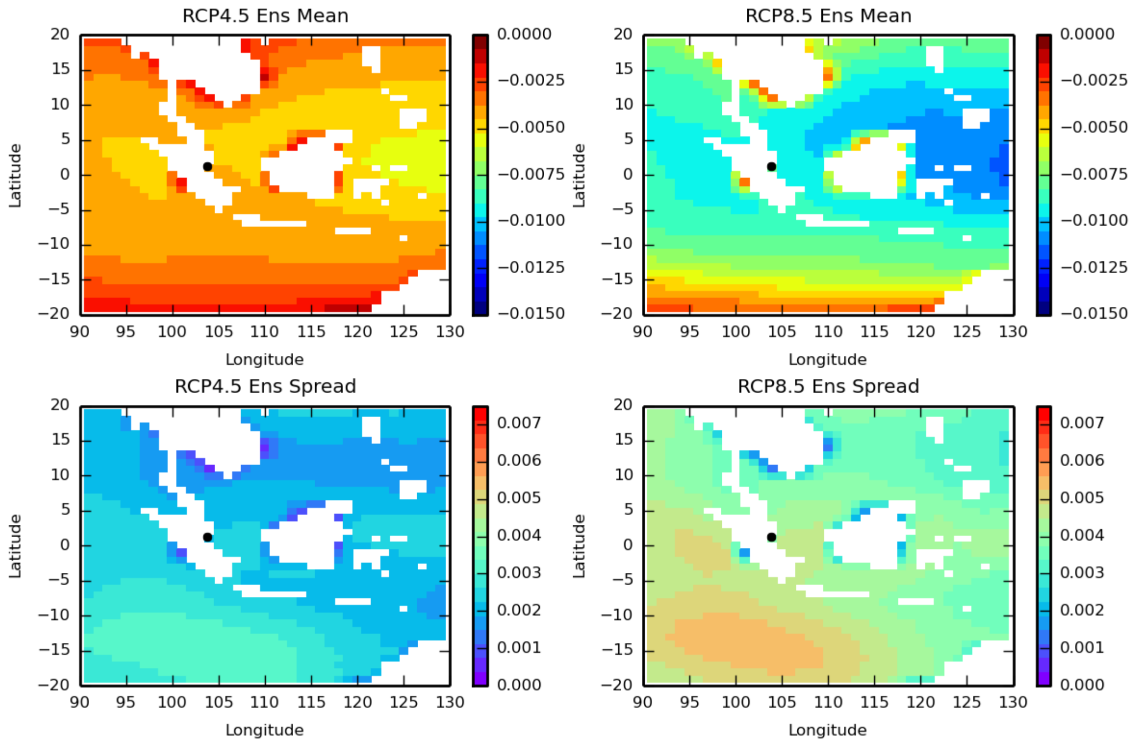


**Figure 8.3: Projected ensemble mean sea level change (metres) due to changes in atmospheric pressure loading over the period from 1986–2005 to 2081–2100 for RCP4.5 and RCP8.5 (upper panels). Also shown is the standard deviation of the model ensemble for RCP4.5 and RCP8.5 (lower panels). The location of Singapore is shown by the black circle. Source: AR5 WG1 supplementary data files available at [http://www.climatechange2013.org/report/full-report/](http://www.climatechange2013.org/report/full-report/).**

## *8.3.2 Supplementary data files from IPCC AR5*

Time series of the various components of GMSL rise and spatial maps of projected change in the inverse barometer effect (‘fig13.17.nc’) for RCP4.5 and RCP8.5 were downloaded from the IPCC AR5 Chapter 13 supplementary data files. These data are available from [http://www.climatechange2013.org/report/full-report/](http://www.climatechange2013.org/report/full-report/).

## *8.3.3. CMIP5 climate model data*

The work presented here draws substantially on model data provided by the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). In order to estimate ocean heat uptake and circulation contributions to regional sea level in Singapore, we required data for the following variables and experiments.

**Table 8.2: CMIP5 models used in analysis of thermal expansion and dynamic sea level 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 |
| CanESM2 | Canadian Centre for Climate Modelling and Analysis |
| 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-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory |
| GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory |
| GISS-E2-R | NASA Goddard Institute for Space Studies |
| HadGEM2-CC | Met Office Hadley Centre |
| HadGEM2-ES | Met Office Hadley Centre |
| INM-CM4 | Institute for Numerical Mathematics |
| IPSL-CM5A-LR | Institut Pierre-Simon Laplace |
| IPSL-CM5A-MR | Institut Pierre-Simon Laplace |
| MIROC5 | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology |
| MIROC-ESM | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies |
| MIROC-ESM-CHEM | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies |
| MPI-ESM-LR | Max-Planck-Institut für Meteorologie |
| MPI-ESM-MR | Max-Planck-Institut für Meteorologie |
| MRI-CGCM3 | Meteorological Research Institute |
| NorESM1-M | Norwegian Climate Centre |
| NorESM1-ME | Norwegian Climate Centre |

Variables: (i) dynamic sea level (‘zos’ $f$(x,y,t) ), which represents the local departures from global mean sea level arising from density and circulation; (ii) global thermal expansion (‘zostoga’ $f$(t) ), which represents the change in global mean sea level associated with ocean heat uptake. Both of these were downloaded at monthly resolution and on the native model grids.

Experiments: (i) simulations using all available climate forcings over the period 1850-2005 (‘historical’); (ii) projections of climate change over the period 2006-2100 for RCP4.5 (‘rcp45’); (iii) projections of climate change over the period 2006-2100 for RCP8.5 (‘rcp85’); (iv) simulations with time-constant atmospheric constituents representative of the pre-industrial period (‘piControl’). We use only the first ensemble member for each simulation, following the approach documented in the AR5 (Church et al., 2013).

The requirement for the above variables and experiments provided a strong constraint on the CMIP5 models that we were able to use for this study. Even though the GFDL models do not include the ‘zostoga’ variable on the CMIP5 archive, we were able to obtain these data from Jonathan Gregory at the University of Reading. The 21 CMIP5 models used and their corresponding modelling Centers are listed in Table 8.2. These are identical to those used by Slangen et al. (2014) in support of the sea level projections presented in AR5.

The CMIP5 data pre-processing steps are outlined below:

1. The monthly fields of ‘zos’ and ‘zostoga’ were converted into annual mean values and ‘zos’ was re-mapped to a common 1°×1° latitude-longitude grid using bilinear interpolation (Figure 8.4). This step was carried out using the Climate Data Operator tools developed at the Max Planck Institute for Meteorology.
2. ‘zos’ and ‘zostoga’ are corrected for model drift using a linear fit to the pre-industrial control run – this is applied to each grid box for ‘zos’.
3. Each two-dimensional ‘zos’ field is checked to make sure the global average value is equal to zero, and a uniform correction applied if needed.
4. ‘zos’ and ‘zostoga’ are added together to provide a consistent model field of combined global thermal expansion and ocean circulation for each year of simulation (the “steric/dynamic” sea level).

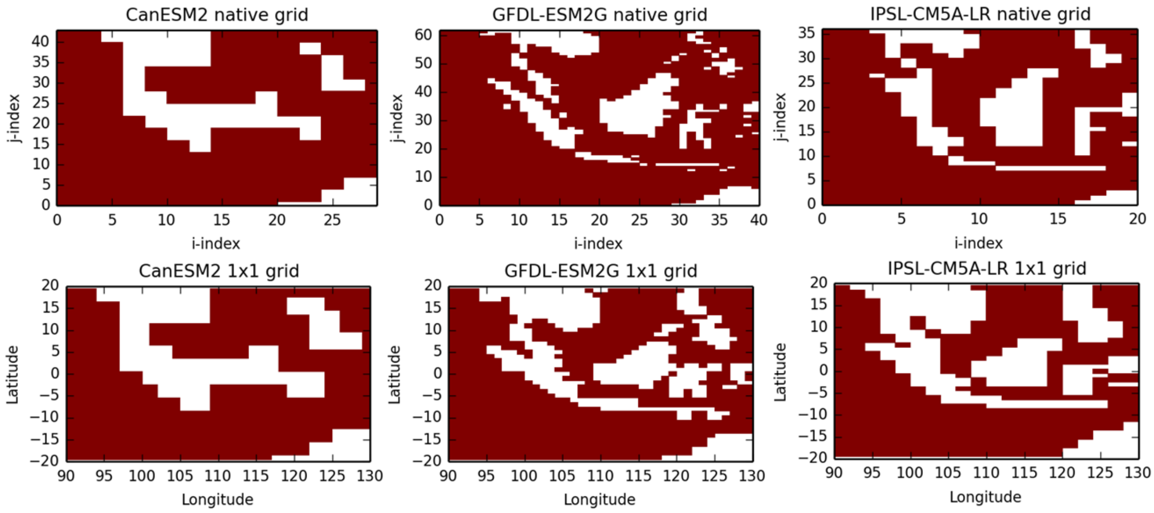


**Figure 8.4: Examples of the land mask representation of South East Asia for CMIP5 models on the native model grid and re-mapped 1°×1° latitude-longitude grid.**

While the processing steps differ slightly from those applied by Slangen et al. (2014), whose work underpins the sea level projections presented in IPCC AR5, we are able to reproduce their estimates of steric/dynamic sea level rise (see Appendix A8, Figure A8.4). This gives us confidence that the details of drift correction and re-mapping procedures do not materially affect the results and that the analyses presented here are consistent with those presented in the AR5.

Figure 8.4 shows examples of the land mask representation following the re-mapping onto a regular 1°×1° latitude-longitude grid. The representation of the S.E.Asia region varies considerably according to model resolution. While the UKCP09 study (Lowe et al., 2009) estimated regional sea level changes around the UK using grid boxes that were common to all climate models, that approach is not feasible here. Instead, we ‘hand select’ grid boxes for each model to represent regional sea level change at Singapore.

## 8.4. Results

### *8.4.1 Spatial maps of steric/dynamic sea level change*

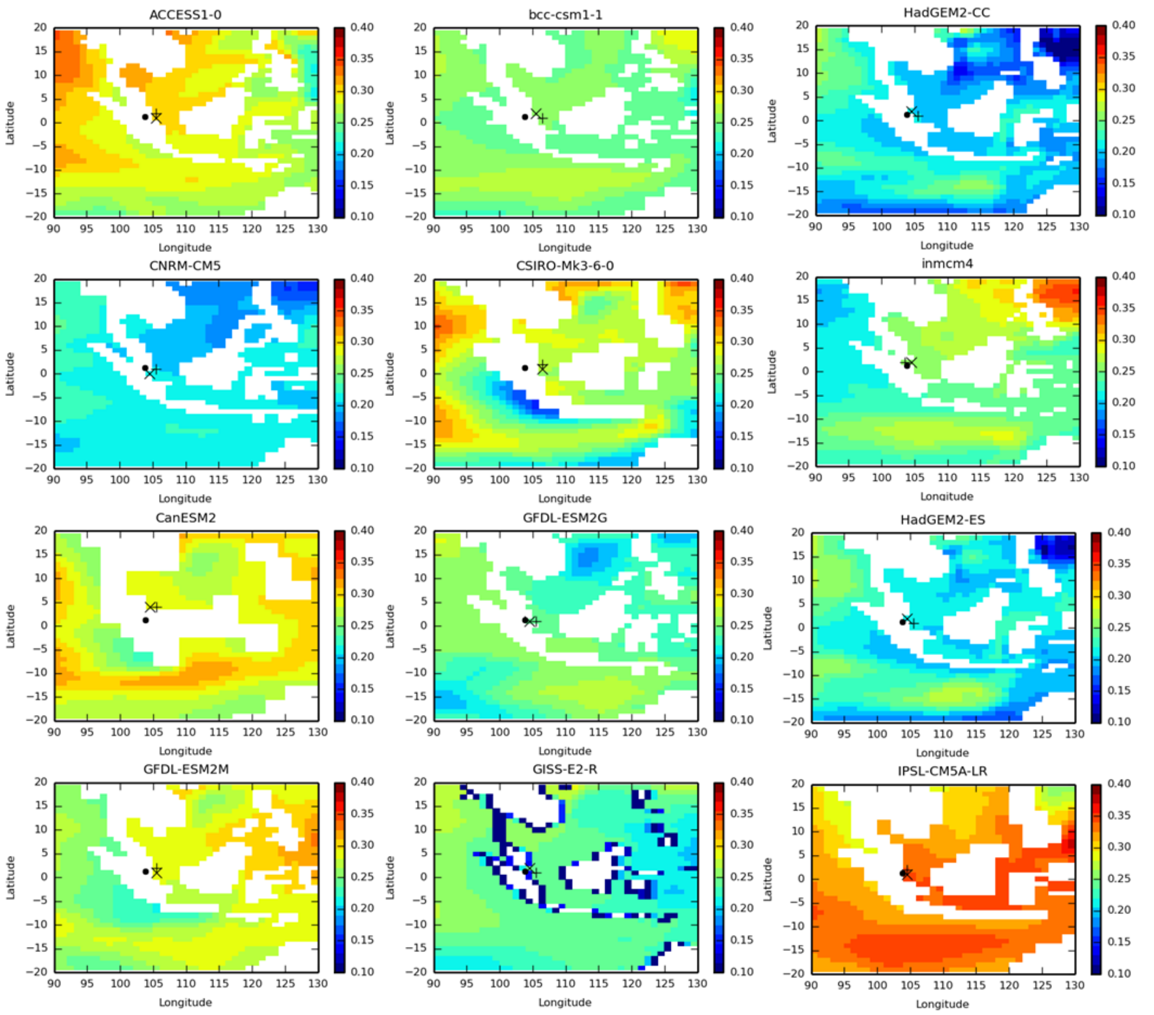


**Figure 8.5a: Projections of steric/dynamic sea level rise (metres) for RCP8.5 computed as the difference between 1986-2005 and 2081-2100. The location of Singapore is shown by the black circle. The primary and secondary grid boxes used to extract time mean sea level for Singapore are shown by an × and +, respectively. Note the grid box selections for GISS-E2-R are away from potential problem areas for the land mask.**

As has been shown by previous studies (Pardaens et al., 2011, Slangen et al., 2014), we find a large model spread in projections of regional steric/dynamic sea level rise (Figures 8.5 for RCP8.5, A8.1 for RCP4.5). However, all models show relatively weak gradients in the pattern of change in the vicinity of Singapore, a result that appears to be largely independent of the underlying model resolution. We test the sensitivity of our results to choice of grid box by selecting a primary and secondary grid box to represent Singapore. The difference in multi-model median estimates between boxes is about +/-1mm and 2mm for RCP4.5 and RCP8.5 respectively. This represents less than 1% of the change signal and therefore is considered a negligible uncertainty.

Time series of steric/dynamic sea level rise for individual models from the primary grid boxes show a variety of magnitudes of interannual variability, but the underlying trends are very clear over the 21$^{st}$ Century for all models in both scenarios (Figures A8.2, A8.3).

Following AR5 (Church et al., 2013; Slangen et al 2014), we compute the multi-model median change and standard deviations as the mean of the primary and secondary grid box time series based on the periods 1986-2005 and 2081-2100 (note the first period is based on 'historical' simulations, not shown). We find a median change value for RCP4.5 of 0.12m and 0.18m for RCP8.5. This represent 103% and 99% of the AR5 median values for global thermal expansion based on the same periods – i.e. the changes at Singapore for the steric/dynamic component are very close to the global average.

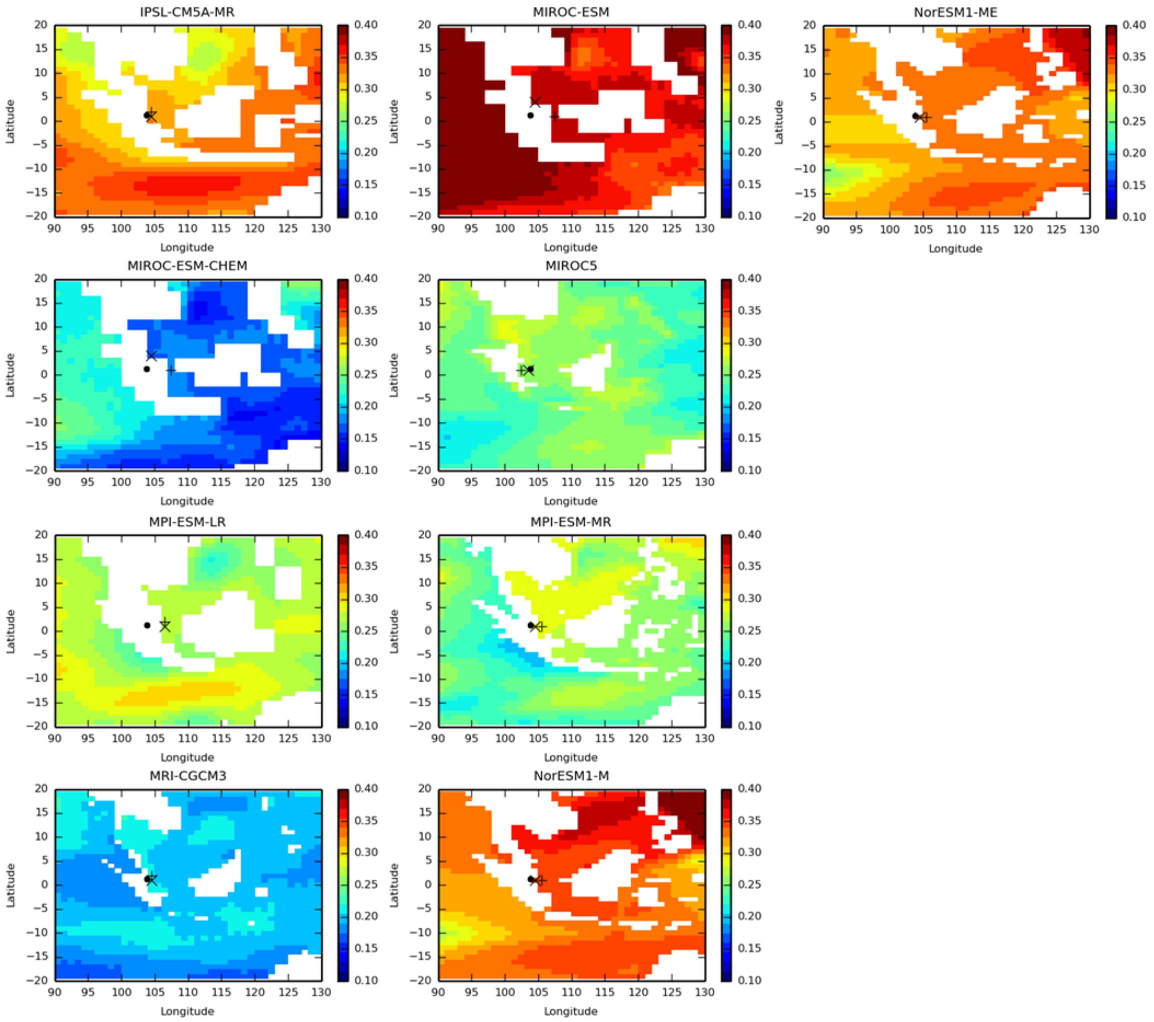


**Figure 8.5b: Projections of steric/dynamic sea level rise (metres) for RCP8.5 computed as the difference between 1986-2005 and 2081-2100. The location of Singapore is shown by the black circle. The primary and secondary grid boxes used to extract time mean sea level for Singapore are shown by an × and +, respectively.**

## *8.4.2 Time series of sea level change at Singapore*

Time series of projected total sea level rise at Singapore and its components are presented for RCP4.5 and RCP8.5 (Figures 8.6 and 8.7). The central estimates of total sea level rise for Singapore are similar to the global mean, but with substantially larger range of uncertainty. This increase in the ranges arises from uncertainty in the climate model representation of the local steric/dynamic sea level change and the scaling up of the ice sheet and glacier terms using the Slangen et al (2014) fingerprints (table 8.1).

**Table 8.3: Median values and *likely* ranges (square brackets) for projections of time mean sea level rise and its contribution in metres for 2081-2100 relative to 1986-2005 for Singapore and the global average (as reported in Table 13.5 of AR5, Church et al., 2013).**

| Sea level component | RCP4.5 change (m) | | RCP8.5 change (m) | |
|---|---|---|---|---|
| | Singapore | Global | Singapore | Global |
| Expansion / Steric/Dynamic | 0.20 [0.12,0.27] | 0.19 [0.14,0.23] | 0.27 [0.18,0.36] | 0.27 [0.21,0.33] |
| Glaciers | 0.14 [0.07,0.22] | 0.12 [0.06,0.19] | 0.18 [0.10,0.26] | 0.16 [0.09,0.23] |
| Greenland SMB | 0.05 [0.01,0.18 | 0.04 [0.01,0.09] | 0.08 [0.03,0.18] | 0.07 [0.03,0.16] |
| Antarctica SMB | -0.02 [-0.06,-0.01] | -0.02 [-0.05,-0.01] | -0.05 [-0.08,-0.01] | -0.04 [-0.07,-0.01] |
| Greenland Dyn | 0.05 [0.01,0.07] | 0.04 [0.01,0.06] | 0.06 [0.02,0.08] | 0.05 [0.02,0.07] |
| Antartica Dyn | 0.08 [-0.01,0.19] | 0.07 [-0.01,0.16] | 0.08 [-0.01,0.19] | 0.07 [-0.01,0.16] |
| Land Water | 0.03 [-0.01,0.07] | 0.04 [-0.01,0.09] | 0.03 [-0.01,0.07] | 0.04 [-0.01,0.09] |
| GIA | -0.03 | N/A | -0.03 | N/A |

However, the additional sea level rise from ice sheets and glaciers at Singapore is offset by the negative contribution from glacial isostatic adjustment.

Both RCP4.5 and RCP8.5 show a substantial acceleration in the rate of global sea level rise over the 21st Century. This acceleration is amplified at Singapore due to the scaling up of the non-linear ice sheet and glacier terms, which are offset by a linear trend in GIA. Hence, a simple extrapolation of long-term trends from tide gauges in the region (Tkalich et al., 2013) is likely to grossly underestimate future sea level rise.

Over the first half of the 21st Century, we see a similar amount of sea level rise for both RCP4.5 and RCP8.5. Hence on this timescale the sea level rise is largely independent of emissions pathway and methodological/model uncertainties dominate. Towards the end of the century both scenario uncertainty and methodological/model uncertainty play a substantial role for the projections of sea level rise. The breakdown of the different components and their uncertainties, based on the change between 1986-2005 and 2081-2100, are presented in table 8.3. The ranges of total sea level rise out to 2050 and 2100 are presented in table 8.4.

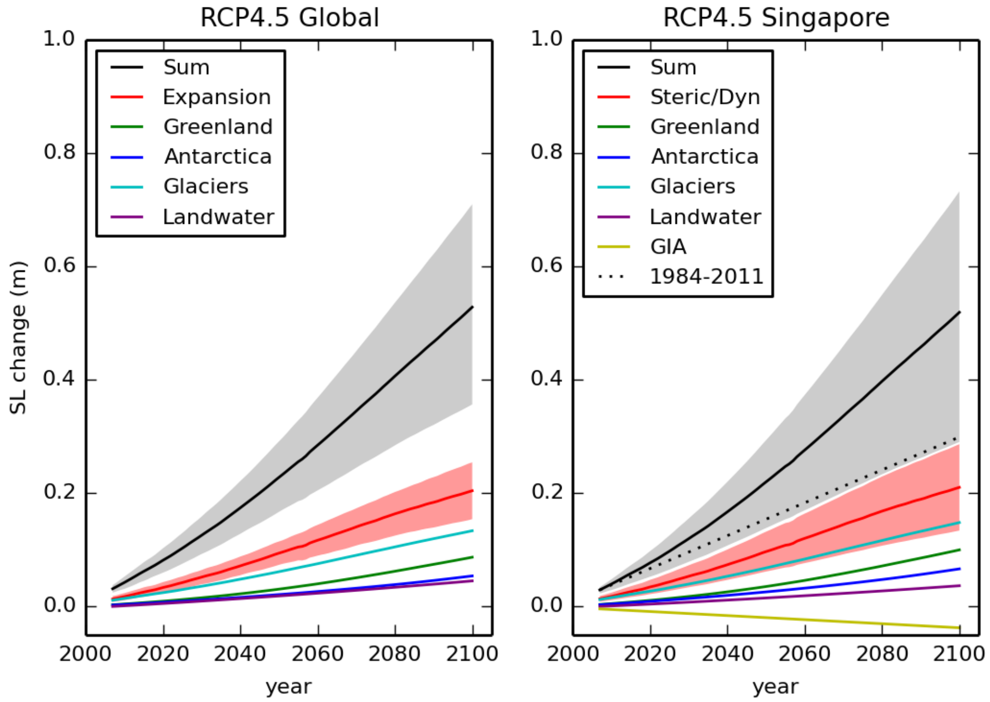


**Figure 8.6: Projections of sea level rise relative to 1986-2005 and its contributions as a function of time for the RCP4.5 scenario for global mean sea level (left) and the Singapore region (right). The lines show the median projections. The *likely* ranges for the sum and thermal expansion or steric/dynamic sea level changes are shown by the shaded regions. The contributions from ice sheets include the contributions from ice sheet rapid dynamical change. The dotted line shows the 1984-2011 rate of sea level change for the Singapore Strait reported by Tkalich et al. (2013).**

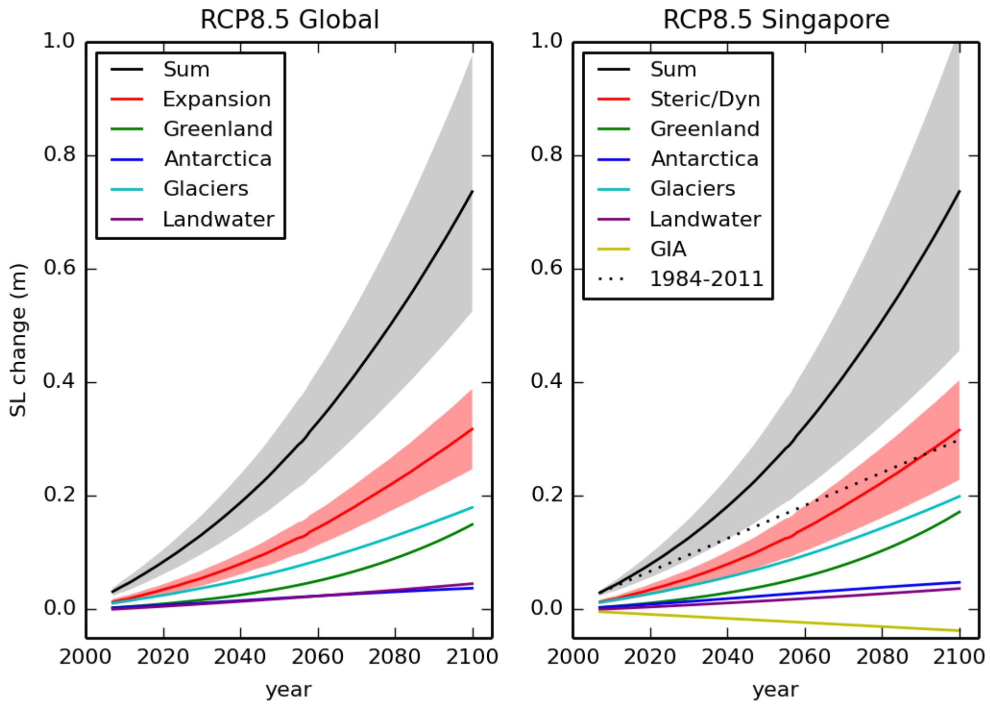


**Figure 8.7: As Figure 8.6, but for the RCP8.5 climate change scenario.**

**Table 8.4: Estimates of global sea level rise from the IPCC AR5 (Church et al., 2013) alongside our regional estimates for Singapore. Following the definitions in AR5, there is a 66-100% chance that future sea level rise will fall within the ranges quoted . Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is medium confidence that it would not exceed several tenths of a meter of sea level rise during the 21st century (Church et al, 2013).**

| Scenario | | 2050 | | | 2100 | | |
|---|---|---|---|---|---|---|---|
| | | Central | Lower | Upper | Central | Lower | Upper |
| RCP4.5 | Global | 0.23 | 0.17 | 0.29 | 0.53 | 0.36 | 0.71 |
| | Singapore | 0.22 | 0.14 | 0.30 | 0.53 | 0.30 | 0.74 |
| RCP8.5 | Global | 0.25 | 0.19 | 0.32 | 0.74 | 0.52 | 0.98 |
| | Singapore | 0.25 | 0.17 | 0.32 | 0.73 | 0.45 | 1.02 |

# 8.5. Summary

We have presented sea level projections over the 21$^{st}$ Century for the Singapore region, under the RCP4.5 and RCP8.5 climate change scenarios. The data and methods follow the process-based projections of global mean sea level rise from the IPCC AR5 (Church et al., 2013). These global sea level projections are tailored for Singapore by taking into account the associated spatial patterns of ocean mass changes from land ice and land water storage, using the numerical model estimates of Slangen et al. (2014). The local sea level change from ocean density and circulation changes, have been estimated directly from the available CMIP5 climate models. In addition, we have estimated a local vertical land movement rate based on the solid Earth response to the last de-glaciation using data from the ICE5G model (Peltier, 2004). In Chapter 9 these results are combined with coastal downscaling simulations of waves and surge activity in the region to explore potential changes in sea level extremes; our conclusion is that the changes in mean sea level presented in this chapter dominate the changes in extremes...

Our summary findings are as follows:

- The projections of sea level rise for Singapore at the end of the 21$^{st}$ Century are very close to the global estimates presented in the IPCC AR5.

- Singapore will experience a 10-20% increase in sea level rise (compared to the global mean) associated with mass loss from ice sheets and glaciers, but this is offset by a time-constant negative contribution from glacial isostatic adjustment.

- The acceleration of sea level rise at Singapore will be greater over the 21$^{st}$ Century than for the global mean.

- The *likely* ranges of projected sea level rise at Singapore are substantially larger that for the global mean, owing to both the amplified ice mass loss changes and uncertainty associated with representation of the regional ocean changes from CMIP5 models. This increased uncertainty is larger for RCP8.5 than for RCP4.5.

- Extrapolation of long-term records at tide-gauge locations do not provide a reliable estimate of future sea level change over the 21st Century, and systematically underestimate the magnitude of future sea level rise for both scenarios.

- Up to about 2050, we see a similar amount of sea level rise for both RCP4.5 and RCP8.5. Hence on this timescale the sea level rise is largely independent of emissions pathway and methodological/model uncertainties dominate

- By 2100, both scenario uncertainty and methodological/model uncertainty play a substantial role for the projections of sea level rise.

## 8.6. Interpretation and Limitations

Our projections are presented as *likely* (66-100% probability) ranges for the RCP4.5 and RCP8.5 scenarios of future greenhouse gas concentrations. As shown in Chapter 9, these projected changes in time-mean sea level are the dominant factor in projected changes in extreme sea level for the Singapore region.

The analysis presented here is based on the data and methods outlined in the IPCC AR5 report (Church et al., 2013). While this is the state-of-the-art for sea level projections, the full range of uncertainties may not be captured. In particular we draw attention to the following caveats, which should be borne in mind in interpreting the results:

- The projections presented here do not consider the unlikely event of a collapse of the marine-based sectors of the Antarctic ice sheet. Based on current understanding, AR5 assessed that only such a collapse, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but AR5 assessed with medium confidence that it would not exceed several tenths of a metre of sea level rise during the 21st century (Church et al, 2013).

- Our projections for Singapore are based on CMIP5 models that do not fully represent shelf and marginal seas processes (for example tidal mixing and the dynamics of cross-shelf-break exchange). Following previous studies (e.g. Lowe et al., 2009; Perrette et al., 2013), we have assumed that the large-scale ocean signals propagate freely to the coastal region. However this remains a source of structural uncertainty in the method. Propagation of open ocean signals onto the shelf, and their potential impact on mean sea level, is currently a research topic which we expect will advance significantly over the next few years. Meanwhile, we note that preliminary evidence from climate change projections of the Northwest European Shelf (under peer review at the time of writing) suggests a strong link between open ocean changes and those observed on the shelf.

- The patterns of change associated with land ice, land water and GIA are taken from the single estimates used by Slangen et al. (2014). While these are considered very credible estimates based on current understanding, we do not include here any estimate of uncertainties in sea level change that could arise from using alternative estimates of these patterns. This is again a research topic which we expect will advance in the next few years.

- We note that there are many non-climatic drivers of local vertical movement and this may well dominate the regional sea level change on multi-annual to decadal timescales. These include the potential effects of future seismic activity in the region, and effects of anthropogenic disturbance such as resource extraction and land reclamation. Observations of local vertical land movement and attribution to the underlying processes should be taken into account for future impact and adaptation studies, but assessment of these is beyond the scope of the present study.


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