Chapter 10

Long Term Projections of Sea Level, Temperature and Rainfall Change

Authors: Matthew Palmer[1], Jason Lowe[1], Dan Bernie[1], Daley Calvert[1], Laila Gohar[1] and Jonathan Gregory[1]

Met Office internal reviewers: Anne Pardaens[1], Carol McSweeney[1]

1 - Met Office, Exeter, UK

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10.1. Introduction

The purpose of this work is to explore plausible projections of temperature, rainfall and time-mean sea level for the Singapore region out to 2300, using state-of-the-art model simulations and methods. The intention is that the information provided will aid risk assessment and impacts studies in the Singapore region. This information should be used alongside the accompanying work done as part of the wider Singapore 2nd National Climate Change Study – Phase 1 and described in previous Chapters. Of particular relevance is the work described in Chapters 8 and 9, which focuses on changes in both time-mean sea level and drivers of sea level extremes over the period 21st Century.

The scientific background and regional context is been presented in Supplementary Information Report 1 and in Chapter 8 (Palmer et al. 2014a; Palmer et al., 2014b). We do not repeat that information again here, but note that there have been very few climate projection studies of time-mean sea level rise for Singapore, and this is the first such study to consider changes out to 2300 that we are aware of.

We highlight that uncertainties in climate projections beyond 2100 are very large, due to both uncertainty in emissions scenario and uncertainty in physical response to the scenario. Our consideration of this period is intended as an horizon-scanning exercise, to make people aware of the need to think beyond 2100 for some decisions and to give an approximate set of plausible climate change values against which vulnerabilities might be compared. Given the large uncertainty there may be advantages of "vulnerability first" type approaches rather than the more regularly used "science first" approach.

10.2. Methodology

In this section we present our methods for providing projections of sea level rise and temperature and rainfall changes for the Singapore region over the period out to 2300. For further details on the AR5 methods for estimating global sea level rise, we refer the reader to the Chapter 8: Changes in Time-Mean Sea Level (Palmer et al., 2014b).

10.2.1 Model considerations

There were fundamentally two options open to us for estimating regional climate change for RCP4.5 and RCP8.5 out to 2300. The first option was to use a subset of CMIP5 climate models that have data available for the required variables over the full period. The second option was to use a version of the MAGICC4.1 (Wigley 2008, section 3.1) simple climate model, set up to sample uncertainty, and relationships established from CMIP5 models (e.g. "pattern scaling", Collins et al, 2013, Appendix 10.1) to relate global climate quantities back to the regional climate of Singapore.

MAGICC4.1 is an upwelling diffusion energy balance model that has demonstrated skill in emulating global average surface temperature response when set up and tuned to represent the large-scale emergent behaviour of a wide range of more complex models, (Raper et al., 1996; Raper et al., 2001), and variants of this modelling approach have been used extensively during several IPCC assessments. The version of MAGICC4.1 used in this study includes climate uncertainty by perturbing the values for the transient climate response (the global annual mean temperature at the time of doubling atmospheric CO2 concentrations) and a measure of the climate-carbon cycle feedback strength (regulating how much carbon is emitted and absorbed naturally in response to climate change) (Bernie et al 2013).

In the following sections we present our choices of methodology and the rationale behind the different approaches.

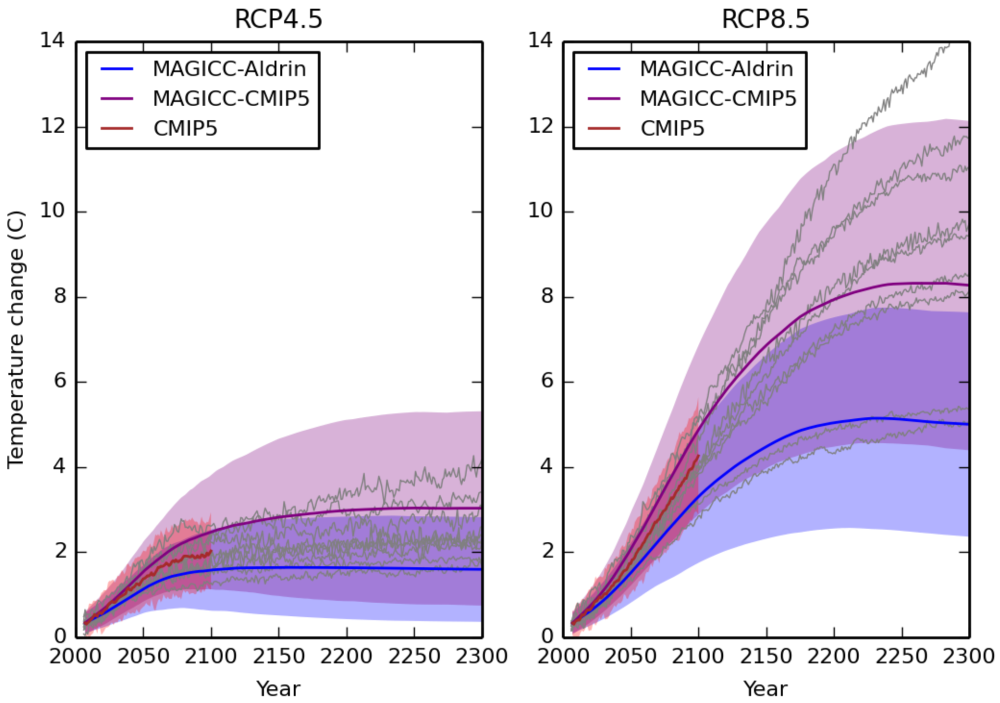

Figure 10.1: Projections of global surface temperature, relative to the 1986-2005 mean, for MAGICC simulations and the 21 CMIP5 models used for 21st Century sea level projections reported in the IPCC AR5 (Church et al., 2013). Two versions of MAGICC simulations are shown, each described by the sampled climate sensitivity distribution and noted in the legend. The shaded regions indicate the 5th to 95th percentiles for MAGICC and the CMIP5 model ensembles. Also shown are individual CMIP5 models used in projections of Singapore regional temperature and rainfall change out to 2300 (grey lines).

Figure 10.1 shows a comparison of global surface temperature rise over the period 2006 to 2300 for: (i) the CMIP5 model ensemble used for 21st Century global sea level projections in AR5 (Church et al., 2013); (ii) two versions of the MAGICC simple climate model used in this study (see section 10.3 for more details); and (iii) the 9 individual CMIP5 model simulations that have both temperature and rainfall data available for the full period.

We can see that the individual CMIP5 simulations capture the spread of the full CMIP5 ensemble used in the AR5. We can also see that the two MAGICC ensembles generally capture the spread of the 9 individual CMIP5 simulations. There is a divergence in the temperature change response between MAGICC and the CMIP5 simulations for RCP8.5 after about 2200. This difference arises from the CMIP5 simulations being concentrations-driven and MAGICC simulations being emissions-driven, and the latter showing substantial carbon uptake during this period (and therefore lowers atmospheric

CO_2 concentrations). Such large sustained emissions and such a long lead time both push all climate models toward their limits and some discrepancy between different credible models is not unexpected in this situation

There is a strong scenario dependency on the magnitude of global surface temperature rise post 2100 and, as expected, the largest uncertainties are for the stronger radiative forcing of RCP8.5. The stabilisation of surface temperature change exhibited for both climate change scenarios is directly related to atmospheric CO_2 concentrations, with stabilisation occurring at about 2080 and 2250 for RCP4.5 and RCP8.5 respectively. We note that for the large temperature changes realised under RCP8.5, other feedbacks – such as permafrost and methane hydrates – would likely come into play (Collins et al., 2013), which are not accounted for in any of the models presented here. In addition, it is debatable from a policy perspective whether such large temperature changes would ever be realised.

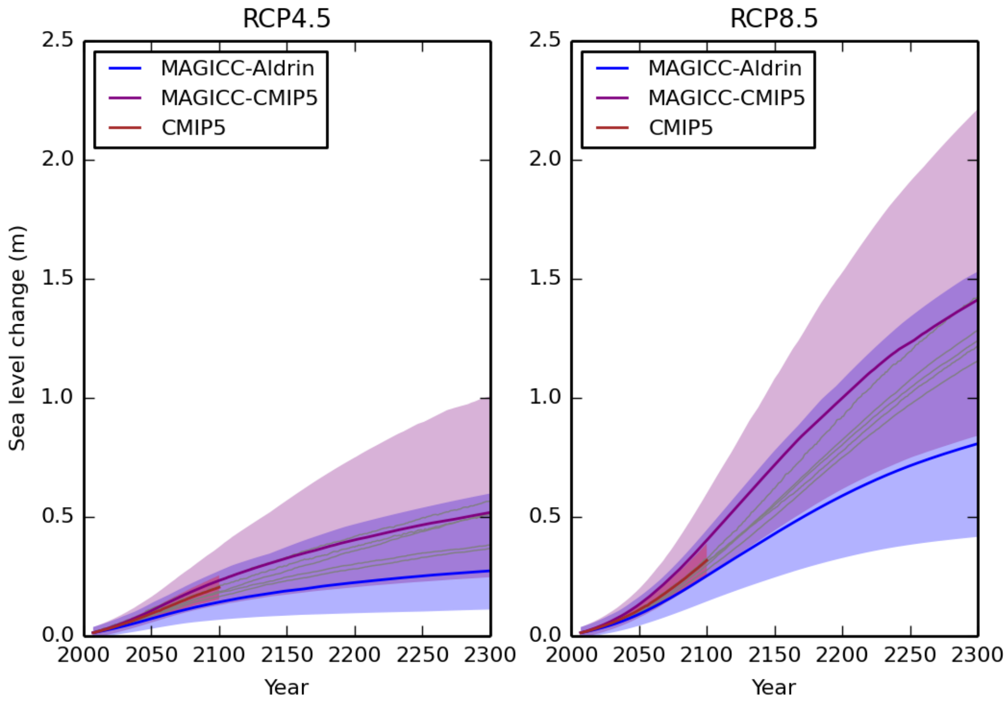

Figure 10.2: Projections of global thermal expansion, relative to the 1986-2005 mean, for two versions of MAGICC simulations and the 21 CMIP5 models used for 21st Century sea level projections reported in the IPCC AR5 (Church et al., 2013). The shaded regions indicate the 5th to 95th percentiles for MAGICC and the CMIP5 model ensembles. Also shown are individual CMIP5 models with data available for both RCP4.5 and RCP8.5 out to 2300 (grey lines).

Figure 10.2 shows a comparison of global sea level rise associated with thermal expansion over the period 2006 to 2300 for: (i) the CMIP5 model ensemble used for global sea level projections in AR5 (Church et al., 2013); (ii) two versions of the MAGICC simple climate model used in this study (see section 10.3 for more details); and (iii) the 5 individual CMIP5 model simulations that have global thermal expansion data available over the full period for both RCP4.5 and RCP8.5.

The 5 individual CMIP5 simulations do not account for the range represented by the larger CMIP5 ensemble used in AR5 projections of 21st Century sea level rise (Church et al., 2013). In addition, the MAGICC ensemble simulations represent a larger range of uncertainty that is seen for the CMIP5 ensemble, which is expected due to the runs being emission driven (rather than using prescribed concentrations – see section 10.3.1). All model simulations show a more sustained rate of rise for thermal expansion than we see for global surface temperature (Boucher et al., 2012). This is because radiative equilibrium of the Earth system does not stabilise until long after surface temperature – hence the ocean continues to gain heat for both scenarios up to 2300 (and beyond). This has profound implications for the ability of mitigation options to reduce future sea level rise, which has much greater "inertia" than global surface temperature.

Thus, we conclude that the global average estimates from the simple model are not suitably conservative for the case of global average temperature in this study, but the thermal expansion estimates are. The next section will consider the needs of obtaining a spatial pattern of change.

10.2.2 Projections of temperature and rainfall change out to 2300

We were unable to establish any robust relationships between global rainfall and rainfall in the Singapore region (Appendix A10) across the subset of 9 CMIP5 models shown in Figure 10.1. When combined with the issues raised above of the global mean response, this precludes use of the MAGICC simulations in our analyses. Therefore, we use the 9 individual CMIP5 simulations available to explore changes in temperature and rainfall for the Singapore region out to 2300 as the best available pragmatic approach. Our analyses focus on the RCP8.5 scenario and we note that the 9 individual CMIP5 simulations place an upper bound on global temperature change at 2300 (Figure 10.1).

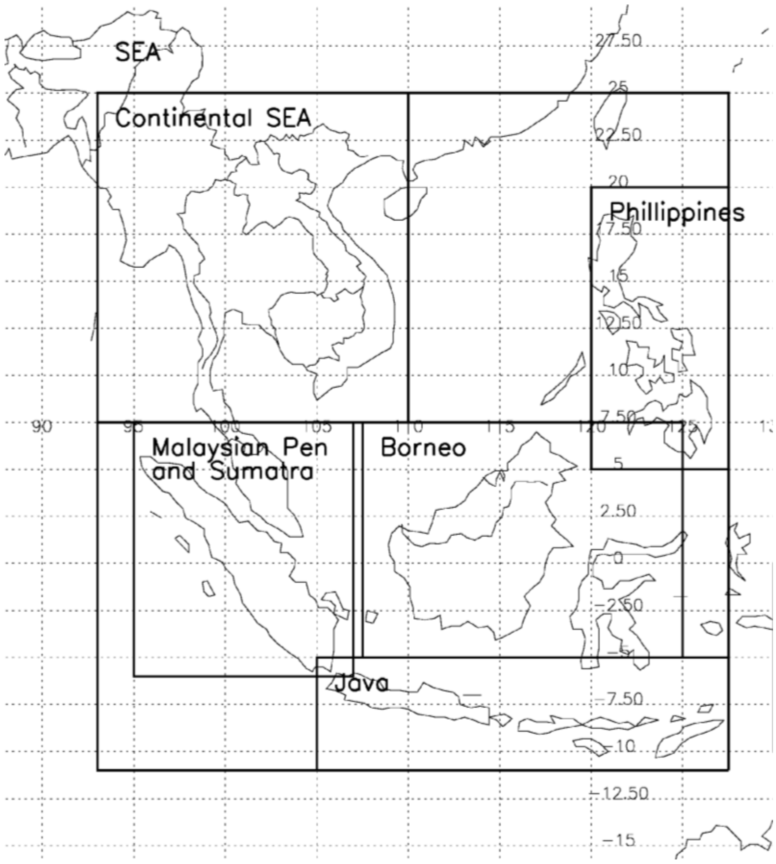

Figure 10.3: Regions in Southeast Asia used in the Singapore 2nd National Climate Change Study. This report makes use of the whole Southeast Asia region (SEA, 83-127.5E, 11S-25N) and the Malaysian Peninsular (95-107E, 6S-7.5N).

Given the deficiencies in representation of small-scale rainfall in CMIP5 models we characterise the broad-scale changes in rainfall and temperature out to 2300 by taking a spatial average over the Malaysian Peninsular and Sumatra region (hereafter "Malaysian Peninsular"), illustrated in Figure 10.3. We produce time series of annual-average temperature and season-average rainfall for the December-January-February (DJF) and June-July-August (JJA) seasons, which approximately coincide with the phase of the North East and South West Monsoon, respectively. These seasons are a subset of those considered by Chapter 3 (McSweeney et al., 2014) and that earlier work provides a useful context for the changes reported here (see section 10.3.2).

10.2.3 Projections of sea level rise out to 2300

In order to sample the greatest range of uncertainty in projections of global thermal expansion, which accounts for approximately 50% of the future global sea level rise signal, we make use of the MAGICC simulations (Figure 10.2) of both global thermal expansion and global surface temperature rise. While there is a slightly large upper bound for the individual CMIP5 models at 2300 under RCP8.5 (Figure 10.1), we note that the Glacier and Greenland surface mass balance terms for global sea level rise are not dependent on global surface temperature rise during the 23rd Century for RCP8.5 (glacier mass is zero from about 2150 and the rate of Greenland surface mass balance is held constant at 2100 values – see section 10.4.2). Since we are able to find robust relationships between regional sea level change and global thermal expansion from

CMIP5 models the approach of using MAGICC and a pattern scaling approach is the best option available (see Appendix A10).

We take the 5th and 95th percentiles of global surface temperature and global thermal expansion estimated by MAGICC as upper and lower bounds (following the approach outlined in AR5). Sea level rise from surface mass balance (SMB) for the ice sheets and glaciers were estimated from MAGICC global surface temperature change using the regression coefficients from AR5 (Church et al., 2013). The maximum sea level rise from Glaciers was capped at 0.32 m, to reflect current estimates of total glacier mass. For the Greenland ice sheet, the rate of loss associated with SMB was held constant from 2100 to 2300. This was to account for attrition of the ice sheet not represented in the regression model (e.g. for RCP8.5 loss rates would otherwise continue to accelerate past 2100). Global sea level rise from ice sheet dynamics and terrestrial water storage are the same of those reported in AR5 (Church et al., 2013) up to 2100 with rates held constant between 2100 and 2300.

Table 10.1: Ratios of sea level change at Singapore to the global mean

Component	Scaling Factor	Basis
1. Thermal expansion/ocean density + circulation	1.11 (+11%)	CMIP5 models (appendix 1)
2. Greenland –surface mass balance	1.14 (+14%)	Slangen et al (2014) fingerprint
3. Antarctica – surface mass balance	1.13 (+13%)	Slangen et al (2014) fingerprint
4. Greenland – ice sheet dynamics	1.16 (+16%)	Slangen et al (2014) fingerprint
5. Antarctica – ice sheet dynamics	1.19 (+19%)	Slangen et al (2014) fingerprint
6. Glaciers	1.11 (+11%)	Slangen et al (2014) fingerprint
7. Land water	0.81 (-19%)	Slangen et al (2014) fingerprint

As with the methods presented in Chapter 8, there is a need to take account (at least to first-order) for spatial variations in the different global sea level rise terms. For all of the ocean mass addition terms (table 10.1, 2.-7.), this was done by simply applying a scaling factor for Singapore, based on the gravitational fingerprints estimated by Slangen et al. (2014, see Chapter 8 (Palmer et al., 2014b). The main assumption here is that the ratios of mass loss among the glaciers and, for the ice sheet fingerprints, amongst the sub-regions of the ice sheets, are constant, which is reasonable to first-order.

In order to take account of spatial variations in local ocean density and circulation changes, we used the available CMIP5 models to establish linear relationships between local sea level at Singapore (using grid boxes illustrated in Chapter 8, Palmer et al., 2014b) and global thermal expansion, for each model. We found that these relationships were largely independent of both time and scenario. Therefore all 21 models could be used to estimate this linear relationship and the median value was taken as a scaling factor for the MAGICC output (see Appendix A10).

In addition to the components outlined above (Table 10.1), regional sea level change is subject to the effects of glacial isostatic adjustment (GIA, e.g. Tamisiea and Mitrovica, 2011) and changes in atmospheric loading (the ‘inverse barometer’ effect). The rate of sea level change due to GIA was estimated using the ICE5G model (Peltier, 2004) as -

0.036 m century^{-1} owing to the slow uplift at Singapore in response to the last deglaciation. The rate of change of sea level due to the inverse barometer effect over the 21st Century is an order of magnitude smaller than GIA, and is neglected from our regional projections. We refer the reader to Chapter 8 (Palmer et al., 2014b) for further discussion of these terms.

Following the AR5 methods, the uncertainties associated with regional time series of the different sea level components are combined according to the equation below:

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

Here (σ_{tot}) is the total uncertainty, expressed as a variance. It is assumed that contributions that correlate with global air temperature have correlated uncertainties and are therefore added linearly, i.e. local steric/dynamic sea level and the ice sheet surface mass balance terms. This combined uncertainty is then added to the other component uncertainties in quadrature. The uncertainties in the projected ice sheet surface mass balance changes were assumed to be dominated by the magnitude of climate change, rather than their methodological uncertainty, 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, Palmer et al., 2014a) in our method.

10.2.3 Plausible high-end (H++) sea level rise scenarios for Singapore

Recent IPCC assessments (Bindoff et al., 2007; Church et al., 2013) of physical climate change have tended to focus their projection information on the likely range of future global and regional changes, although within the text of the reports there is information on potentially larger changes – the so called "tail risks". For the coastal planning community there is a growing appetite to include not only the likely range of future sea level rise in decision-making but also to examine plausible high-end climate change scenarios. These are typically used to look for no-regret adaptation options, or as a guide to which adaptation options might be needed in the future if sea level rise increases faster than the likely projection range. The UK's Thames Estuary 2100 project (UKCP09 chapter 7, Lowe et al., 2009a) and the Dutch Delta study (Katsman et al., 2011) were two key examples of incorporating information on the tail risks. Here we describe potential high-end but plausible scenarios, for the Singapore region (hereafter referred to as H++).

In the IPCC AR5 (Church et al., 2013) the likely range of global mean 21st century sea level rise extends to approximately 1m by 2100 in the highest emission scenario case (e.g. Table 10.2 "AR5 method"). Additionally, the report states that 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. There is medium confidence that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century. Within the IPCC report there are also semi-empirical model studies (which use statistical relationships based on past changes to infer future changes) that typically extend to twice the projection range from process based models, although these are judged in the report to have lower confidence than physical model estimates.

It is not possible to produce a robust probability density function of the upper tail of the sea level rise distribution. The approach we use here is to present possible H++ values against the sources of evidence that support such a rise being plausible. This evidence and our recommended use of these H++ scenarios are presented in section 10.4.3.

Table 10.2: Illustrative ranges for sea level rise at Singapore based on the different methods used in chapter 8 and chapter 10. The "H++" scenario gives a plausible high-end range for sensitivity testing of adaptation options. All ranges expressed as a change relative to a baseline period of 1986-2005.

	2100	2200	2300
RCP4.5 IPCC AR5 Method (chapter 8)	0.29 - 0.73 m	-	-
RCP8.5 IPCC AR5 Method (chapter 8)	0.46 - 1.02 m	-	-
RCP4.5 "low sensitivity" (chapter 10)	0.19 - 0.65 m	0.30 - 1.42 m	0.36 - 2.10 m
RCP8.5 "high sensitivity" (chapter 10)	0.47 - 1.29 m	0.88 - 3.57 m	0.94 - 5.48 m
Hi-end "H++" scenario	1.0 - 2.0 m	2.0 - 4.0 m	3.0 - 6.0 m

10.3. Data

10.3.1 The MAGICC simple climate model

The global and regional sea level rise projections presented here use global surface temperature change and global thermosteric sea level rise data from the MAGICC 4.1 simple climate model (Wigley, 1993; Wigley and Raper, 2001; Wigley 2008). MAGICC has demonstrated skill in emulating global average surface temperature response when set up and tuned to represent the large-scale emergent behaviour of a wide range of more complex climate models (Raper and Cubasch 1996). Variants of this modelling approach have been used extensively during several IPCC assessments.

The key advantage of MAGICC is that it allows us to run many more simulations than are available from CMIP5 allowing us to explore a wider range of future climates, based on uncertainties in our understanding of the climate system. Following the approach of Lowe et al (2009b) we make use of perturbed physics ensembles of MAGICC simulations accounting for uncertainties in ocean diffusivity, equilibrium climate sensitivity (ECS) and the strength of carbon cycle feedbacks.

While the CMIP5 models encapsulate the current state-of-the-art in terms of climate modelling, they do not capture the full range of climate sensitivities estimates from different lines of evidence such as the instrumental and paeleoclimate data (IPCC AR5: Bindoff et al., 2013; Collins et al., 2013). Two better sample this uncertainty we draw on two sets of perturbed physics ensembles of MAGICC simulations following Bernie et al 2013; (i) a low sensitivity set, based on the equilibrium climate sensitivity (ECS, see below) distribution from Adlrin et al (2012, "MAGICC-Aldrin"); and, (ii) a high sensitivity set, which uses ECS values from CMIP5 models (Forster et al., 2013, "MAGICC-CMIP5"). While the latter of these uses a distribution of ECS from CMIP5, we use

MAGICC to systematically sample uncertainties in ocean diffusivity and carbon cycle feedbacks so it is expected to lead to a wider spread of results than the CMIP5 ensemble. Additionally, MAGICC is used with prescribed emissions to allow a full expression of carbon cycle feedbacks, while the CMIP5 projections presented here use prescribed concentrations and therefore limit the impact of carbon cycle feedbacks on temperature changes (Booth et al., 2013). The projections made using the "Aldrin" and "CMIP5" ECS distributions in MAGICC provide a useful bounding set of simulated climate change out to 2300.

Table 10.3: CMIP5 models used in analysis of temperature and rainfall projections out to 2300.

Climate model	Modeling Center (or Group)
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
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
CCSM4	National Center for Atmospheric Research
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
HadGEM2-ES	Met Office Hadley Centre
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
MPI-ESM-LR	Max-Planck-Institut für Meteorologie

Both the low sensitivity MAGICC-Aldrin and high sensitivity MAGICC-CMIP5 perturbed physics ensembles were populated using a permutation of three probability distributions following Lowe et al (2009b): (i) equilibrium climate sensitivity (ECS - defined as the equilibrium global mean temperature increase for a doubling of atmospheric carbon $CO_{2;}$ "Aldrin" or "CMIP5"); (ii) ocean diffusivity (which determines how quickly the warming at the surface is mixed throughout the ocean); (iii) climate-carbon cycle feedback strength (regulating how much carbon is emitted and absorbed naturally in response to climate change. Both configurations sample the same distributions of ocean diffusivity (based on CMIP3) and carbon cycle feedback (based on C4MP: Freidlingstein et al 2006), differing only in the ECS distribution used to name each set of simulations. A total of 1620 simulations were run for RCP4.5 and RCP8.5 using the MAGICC-Aldrin set of model configurations and 1863 simulations for the same two scenarios were carried out for the higher climate sensitivity MAGICC-CMIP5 set.

10.3.2 CMIP5 model data

The models used to explore temperature and rainfall changes in the Singapore region are a nine-member subset (table 10.3) of those presented in Chapter 3 (McSweeney et al., 2014).

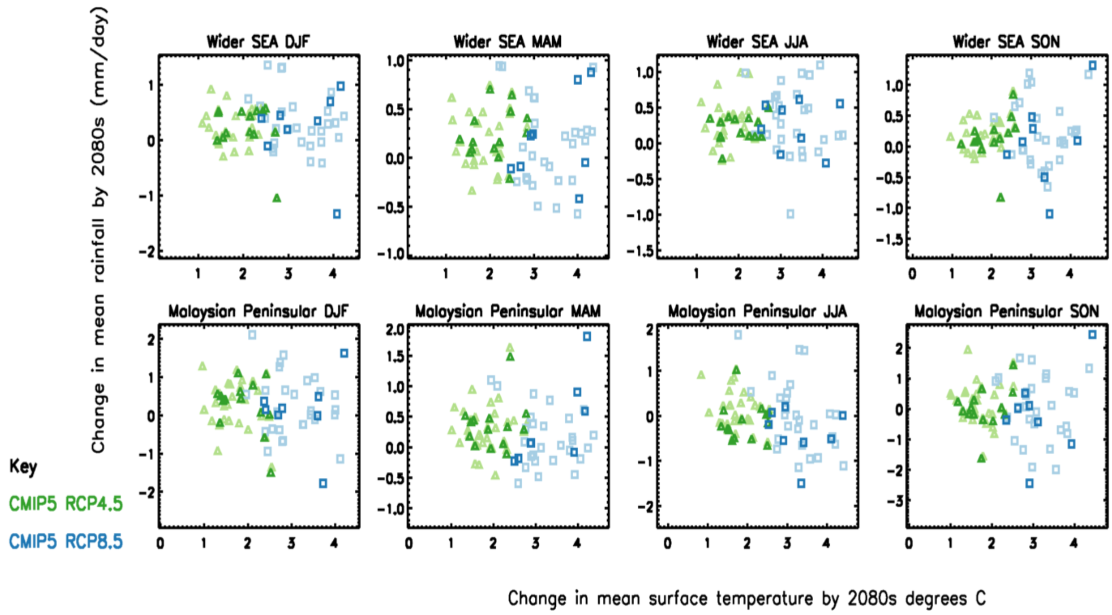

Figure 10.4: Scatter plots of the area-average change in temperature and rainfall over the 21st Century (computed as the difference between mean values over 1961-1990 and 2070-2100) for two regions: the wider Southeast Asia region (83-127.5E, 11S-25N) and the Malaysian Peninsula (95-107E, 6S-7.5N) from CMIP5 models under RCP4.5 and RCP8.5 (Chapter 3). The darker coloured symbols indicate the subset of 9 CMIP5 models used in our assessment of changes out to 2300.

In order to place our regional temperature and rainfall projections in the wider model context, we examine the range of model changes over the 21st Century (Figure 10.4). Our focus is on the DJF and JJA seasons, since these roughly correspond to the North East and South West Monsoon seasons in Southeast Asia and are also the focus of our rainfall projections.

The subset of CMIP5 models used to explore projections out to 2300 account for between 80-95% of the range of temperature responses for all models over the 21st Century (table 10.4) for the larger Southeast Asia domain (Figure 10.1). This percentage falls to 70-75% for the smaller Malaysian Peninsular region. For rainfall response the range over the 21st Century accounted for by the model subset depends on both the scenario and the season. During DJF the model subset accounts for ≥ 85% of the model range for both scenarios – this is also true for JJA under RCP4.5. However, under RCP8.5 the model subset accounts for only 60% and 40% of the total range for the Southeast Asia and Malaysian Peninsular domains, respectively.

Table 10.4: The percentage of the full model ensemble ranges represented by the 9-member subset used for projections of temperature and rainfall out to 2300 (based on Figure 10.1).

Scenario/variable	**Southeast Asia (SEA)**		**Malaysian Peninsular**	
	DJF	**JJA**	**DJF**	**JJA**
RCP4.5 – temperature	95%	85%	70%	70%
RCP8.5 – temperature	95%	80%	75%	70%
RCP4.5 – rainfall	85%	85%	>95%	85%
RCP8.5 – rainfall	95%	60%	90%	40%

For regional sea level projections at Singapore the same 21 CMIP5 models used by Slangen et al. (2014) and in Chapter 8 (Palmer et al., 2014b) are retained here. The variables used were global thermal expansion ('zostoga') and dynamic sea level (the departure of local sea level from the global average, 'zos'). For models that carried out several simulations for each scenario, we use only the first ensemble member and the pre-processing steps were applied as described in Palmer et al. (2014b). The analyses presented here are based on annual time series extracted at the nearest grid box to Singapore for each model, as described in Palmer et al. (2014b).

10.3.3 Other data sources

We use the gravitational fingerprints (Slangen et al., 2014) and glacial isostatic adjustment estimate (Peltier, 2004) provided by Aimée Slangen. The full details of these data are available in Chapter 8 (Palmer et al., 2014b).

10.4. Results

10.4.1 Projections of temperature and rainfall changes out to 2300 for the Singapore region

Regional temperature projections for the Malaysian Peninsular under RCP8.5 are presented for our 9-member CMIP5 model subset (Figure 10.5). All models show a very clear warming signal, with very little interannual variability over the spatial averages presented here. While the profiles of temperature change are similar, the magnitude shows large differences among the models. Circa 2300, the temperature change ranges from about 5C (GISS-E2-R and GISS-E2-H) to 12C (CSIRO-Mk3-6-0), relative to a 1961-1990 baseline.

In contrast to the consistent emergence of regional warming among the models, the seasonal changes in rainfall appear to show no consistency among the models (Figure 10.6). The amplitude and sign of the season-average rainfall varies among models for both seasons, with some models showing no obvious trend. While some models show similarities in the change characteristics between the DJF and JJA seasons, others do not. A couple of models such as CSIRO-Mk3-6-0 show a levelling of in the drying trend by the end of the 23rd century. CSIRO-Mk3-6-0 displays this behaviour for both the DJF and JJA seasons where after a drying in precipitation trend the rainfall appears to show signs of stabilising. The stabilisation occurs around the same time as when the CO2 concentrations stabilise and the temperature (as simulated by CSIRO-Mk3-6-0 see figure 10.5)) show signs of stabilising for the RCP85 scenario.

The stabilisation of precipitation, following a rapid ramp up of atmospheric CO2 and subsequent stabilisation has previously been studied for global average quantities (for instance Wu et al., 2010). The behaviour can be understood by considering the energetic balance of the atmosphere, including that associated with the phase changes of evaporation and formation of precipitation. Additionally, since surface temperature and CO2 increase have been shown to impact on tropical precipitation changes through influences on the atmospheric circulation (Andrews et al 2010, Bony et al 2013), a transition to a stable CO2 level and temperature may also plausibly cause a levelling off the precipitation.

Thus, while we can speculate on the causes for the shape of the precipitation response curve, a more detailed study and differing experimental design would be needed to robustly understand which mechanisms are causing the changes in our region of interest, and in particular to separate the thermodynamic and dynamically driven components (Chadwick et al., 2013).

It is interesting note the large multi-decadal rainfall variability seen in many models. Based on the results presented here it could take many centuries for the climate change signal to emerge from the background variability, even under this severe global warming scenario. We conclude that there is no model consensus in projections of rainfall for the Singapore region. This result seems to be consistent with the findings of the IPCC AR5 (Collins et al., 2013, Box 21.1, Figure 1) for rainfall changes over the 21st Century, who identify the Malaysian Peninsular as a region with “small signal or low agreement of models”.

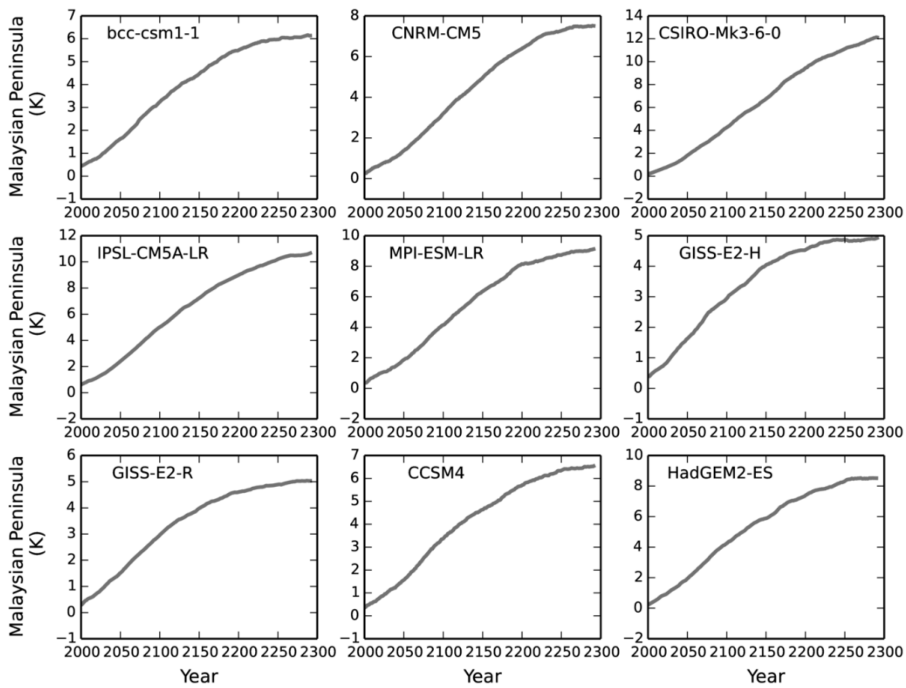

Figure 10.5: Regional area average time series of annual temperature change for the Malaysian Peninsular (95-107E, 6S-7.5N) under the RCP8.5 climate change scenario, relative to a 1961-1990 baseline.

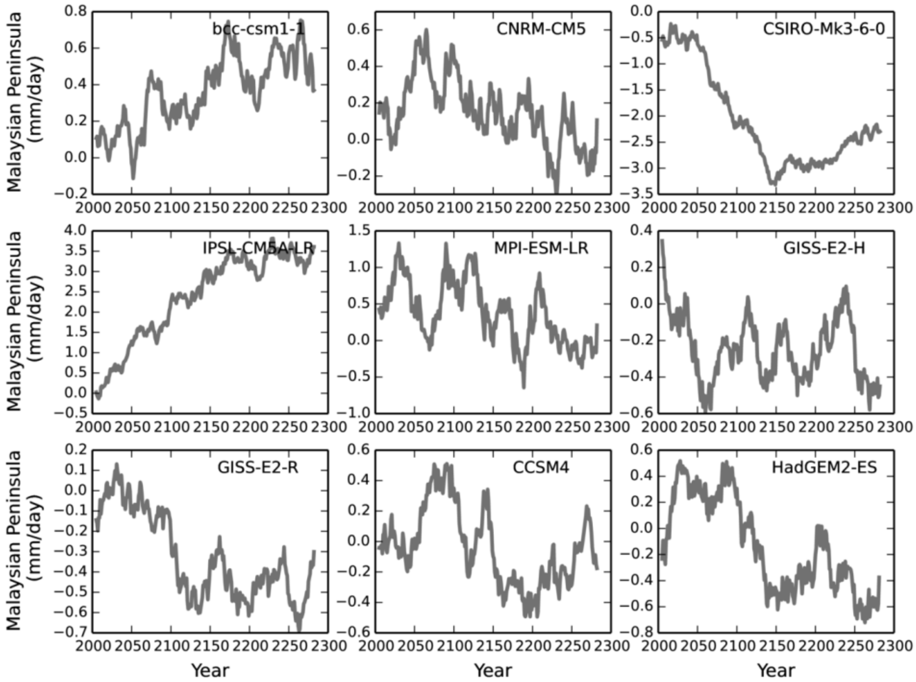

Figure 10.6: Regional area average time series of DJF rainfall change for the Malaysian Peninsular (95-107E, 6S-7.5N) under the RCP8.5 climate change scenario, relative to a 1961-1990 baseline. Points are rolling 20-year running averages and therefore the time series extends to 2280.

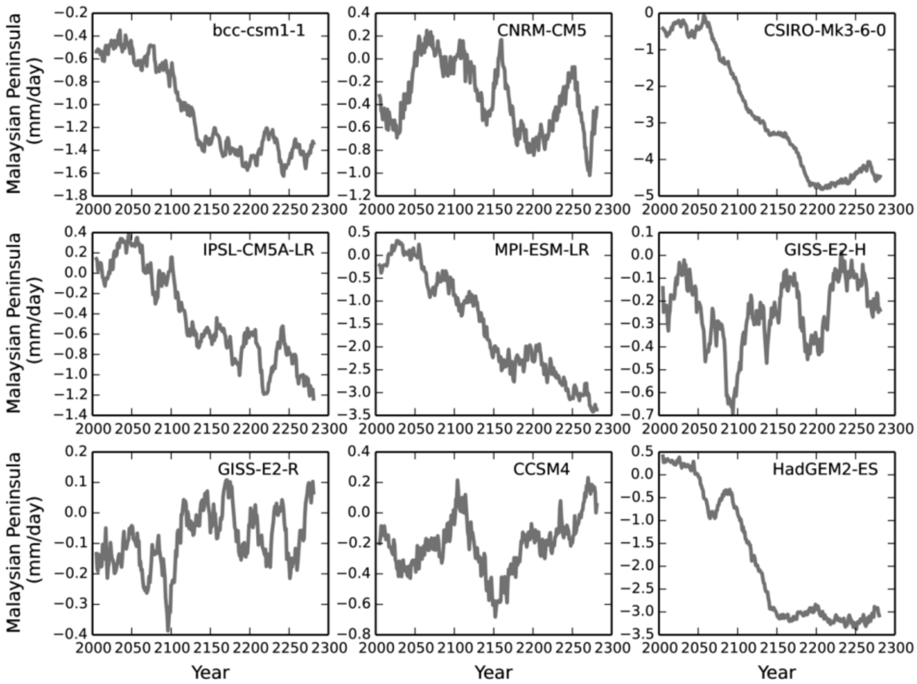

Figure 10.7: Regional area average time series of JJA rainfall change for the Malaysian Peninsular (95-107E, 6S-7.5N) under the RCP8.5 climate change scenario, relative to a 1961-1990 baseline. Points are rolling 20-year running averages and therefore the time series extends to 2280.

10.4.2 Projections of sea level rise out to 2300 for the Singapore region

The approach taken in reporting sea level projections for the Singapore region is to span the range of outcomes associated with uncertainty in both climate response and future emissions. Thus, we present the lower sensitivity MAGICC-Aldrin projections for RCP4.5 and the higher sensitivity MAGICC-CMIP5 projections for RCP8.5. The former can be thought of as illustrating a potential minimum level of sea level rise under moderate mitigation of greenhouse gas emissions. The latter can be thought of as illustrating potential sea level rise that is towards the upper end of that which may be realised under a plausible fossil-fuel intensive greenhouse gas emissions scenario with no climate policies.

RCP4.5 MAGICC-Aldrin gives a steady rate of rise in sea level over 2006-2300, despite the strong mitigation of greenhouse gas emissions for that scenario (Figure 10.8). The totals for Singapore are similar to the global values – with the small negative contribution from GIA offsetting the amplification of the glacier and ice sheet terms associated with the Slangen et al. (2014) fingerprints (Table 10.2).

The range of total sea level rise for Singapore at 2300 is 0.36-2.10m, with the thermal expansion, glaciers and the ice sheets making similar contributions. Even under this modest scenario and low sensitivity version of MAGICC, there is substantial sea level rise at Singapore. The central estimate and range of sea level rise for Singapore at 2300 are larger than the global values by 3% and 23%, respectively.

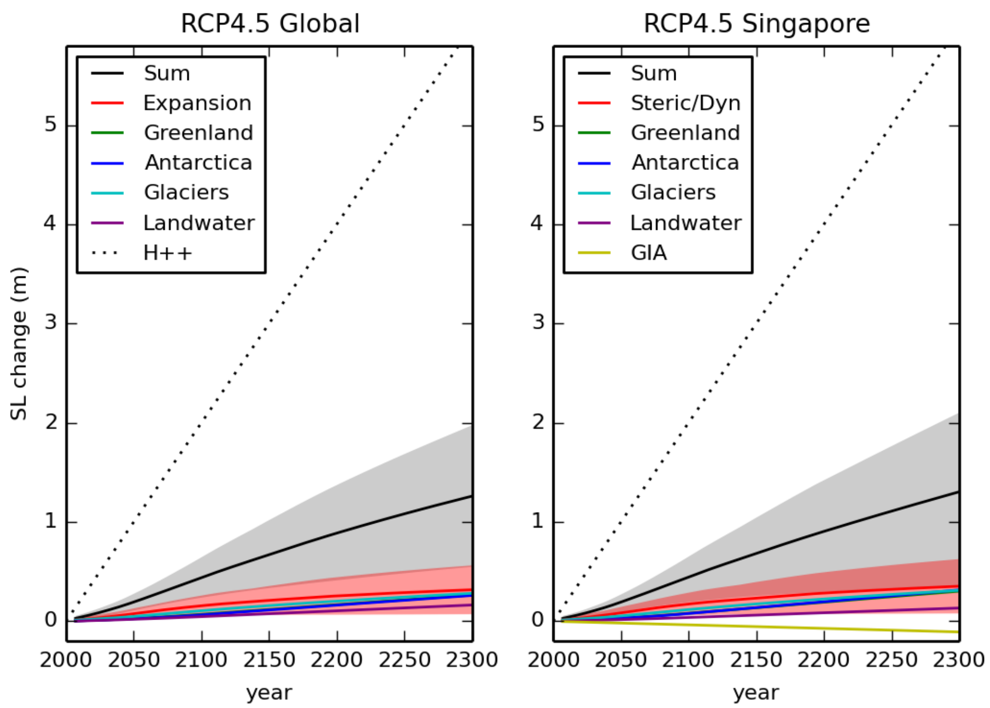

Figure 10.8: Projections of sea level rise relative to 1986-2005 and its contributions as a function of time for the RCP4.5 scenario for global mean sea level (left) and the Singapore region (right), based on MAGICC-Aldrin. The lines show the median projections. The likely ranges for the sum and thermal 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 maximum sea level rise associated with the H++ scenario (see section 10.4.3).

RCP8.5 MAGICC-CMIP5 projections of sea level rise show a strong acceleration over the 21st Century (Figure 10.9). After 2150 there is a marked reduction in the rate of sea level rise due to the total glacier mass having been exhausted. Thereafter a reduction in rate continues due to lesser thermal expansion and increasingly negative contribution of the Antarctic surface mass balance (associated with increased atmospheric moisture transport in a warmer climate).

The range of total sea level rise for Singapore at 2300 is 0.94-5.48m with largest contribution from thermal expansion, which accounts for > 50% of the total. The central estimate and range of sea level rise for Singapore at 2300 are larger than the global values by 7% and 50%, respectively.

10.4.3 H++ scenarios for global sea level rise

The approach here is to present H++ values of sea level rise against the sources of evidence that support such a rise being plausible (table 10.5). It is typically a choice for the adaptation planner or coastal practitioner to choose how to apply the scenario information (Nicholls et al., 2014). However, for consistency with the Thames Estuary project and its level of risk appetite we suggest a plausible high end scenario range of 1m to 2m over the 21st Century, as a recommendation for sensitivity testing of adaptation options. This choice is based on the significantly reduced lines of evidence for higher rates of 21st century change in the table above.

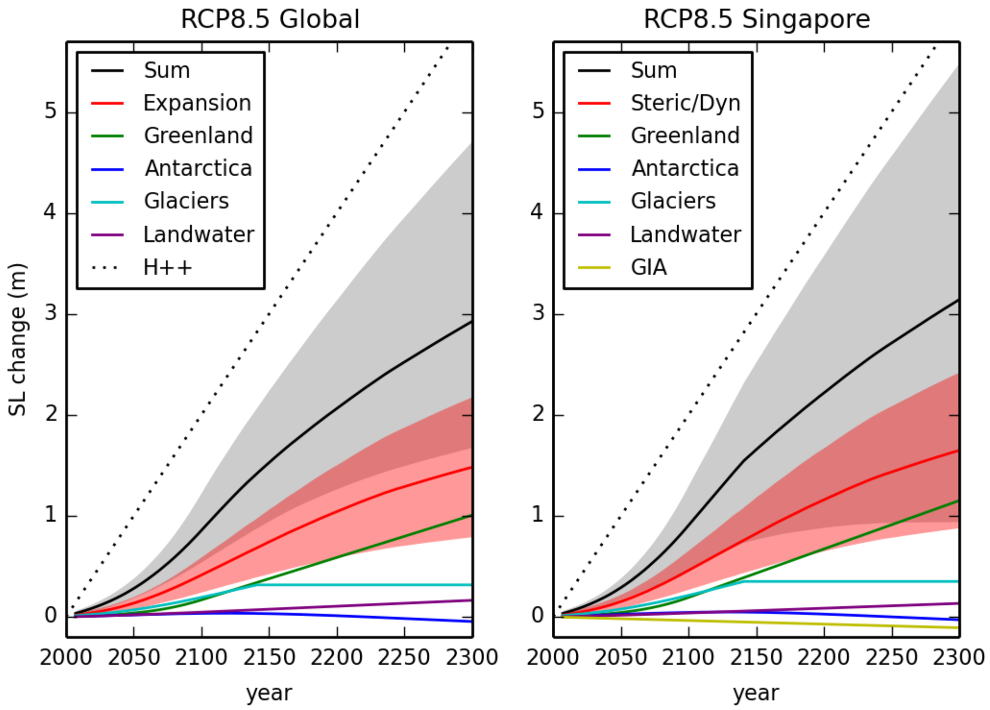

Figure 10.9: As Figure 10.8, but for the RCP8.5 climate change scenario.

The uncertainty in a 21st century H++ scenario is large. Beyond 2100 this uncertainty is expected to be larger still. For pragmatic purposes we suggest an H++ century rate of sea level rise for the 22nd and 23rd centuries as being identical to that of the 21st century. This gives a range of plausible sea level rise of 2m to 4m at 2200 and 3m to 6m at 2300, relative to the end of the 20th Century. We based this on the nature of the evidence from the palaeoclimate studies and the Pfeffer et al (2008) study. This is also consistent with the estimate of Katsman et al (2011) for a global rise of up to 3.5m by 2200. However, we reiterate that uncertainty in this time period is considered very large.

There is considerable debate about whether high end scenarios should be used as a global average number of regionalised to the location of interest. The regionalisation adds additional uncertainty to an already uncertain number, especially where the H++ scenario has not been split into different sea level components. For the Singapore region we can be guided by the ratio of global mean changes to regional changes in the process-based results for the RCP8.5 scenario (see Chapter 8). Omitting the small historic GIA term the ratio for this region varies between 0.94 and 1.09, which means omitting the regional calculation will likely introduce an error that is small compared with other uncertainties. Furthermore, as the H++ scenario is used out to 2300 there are questions regarding the suitability of some of the ice melt fingerprints. For this reason the global H++ is applied to the Singapore region in this study.

It is important to recognise that the types of plausible but unlikely high end scenarios we have discussed here are not projections of likely future sea level rise. Nor are they, typically, theoretical maximum increases. Whilst there is information that these increases could occur, these increases are currently judged to be unlikely although the precise probability cannot be robustly stated. The scenarios need to be used with caution and have typically been used as part of sensitivity studies or risk management approaches (Ranger et al., 2013).

Table 10.5: Evidence sources for high-end sea level rise

21st century sea level rise	Evidence types	Comment
Up to 1m	Process based models, palaeo studies of last interglacial, semi-empirical methods, kinematic constraints, expert narratives, amount of land ice available	
Up to 1.5m	A limited number of process based models, palaeo studies of last interglacial, semi-empirical methods, kinematic constraints, expert narratives, amount of land ice available	Katsman et al. (2008) expert narratives in this range.
Up to 2m	Some process based models estimates from perturbed parameter type experiments, palaeo studies of the last interglacial, a minority of the semi-empirical methods, kinematic constraints, expert narratives.	Pfeffer et al. (2008); Bamber and Aspinal (2013); and Jevrejeva et al (2014) reach this range.
Up to 2.5m	Upper estimate of last interglacial palaeo estimates, a small minority of very extreme semi-empirical methods.	
Above 3m	Simple calculation of amount of land ice. Evidence from palaeo but for periods that are a poor analogue to present day	

10.5. Summary

We have presented an exploratory analysis of plausible projections of temperature, rainfall and sea level rise for the Singapore region over the next three centuries. The analysis of temperature and rainfall focuses on the more severe RCP8.5 climate change scenario and uses a subset of 9 CMIP5 climate models (all the data currently available). The regional sea level projections presented combine data from the MAGICC simple climate model with regional sea level information from CMIP5 models, gravitational fingerprint data from Slangen et al (2014) and local vertical land movement rates from glacial isostatic adjustment from Peltier (2004), for both RCP4.5 and RCP8.5

Our summary findings are as follows:

- Projections of annual mean temperature rise for the Singapore region (Malaysian Peninsular) under RCP8.5 show changes in temperature between about 5C and 12C circa 2300, relative to a 1961-1990 baseline period. The profile of temperature varies somewhat among models, with a general decrease in the rate of warming over the 22nd and 23rd Centuries, approaching stable values at 2300.

- Individual CMIP5 model simulations show that the magnitude of warming at Singapore under RCP8.5 is less than the global mean, by up to about 30%, depending on model.

- We find no robust signals in rainfall under RCP8.5 for the DJF and JJA seasonal averages in our projections out to 2300. This result seems consistent with the IPCC AR5 findings (Collins et al., 2013), based on changes over the 21st Century.

- Compared to global surface temperature change, there is a much greater degree of global and regional sea level rise “in the pipeline” for both RCP4.5 and RCP8.5. This result comes about due to the long-term uptake of heat by the ocean (which continues long after temperature stabilises) and the dependency of the ice mass addition terms on global temperature, rather than rate of temperature change.

- Projections of sea level rise for the Singapore region are slightly larger (~ 5%) than the global average values. This arises from: (i) the amplification of the global ice mass addition terms by the associated gravitational fingerprints; (ii) a additional contribution from local ocean processes.

- Our lower bounding range for sea level rise for Singapore at 2300 is 0.36 - 2.10m. This is based on the lower climate sensitivity version of MAGICC under the less severe emissions scenario of RCP4.5. This range could be considered a useful guideline for minimum future adaption requirements.

- Our upper bounding range for sea level rise for Singapore at 2300 is 0.94 - 5.48m. This is based on the higher climate sensitivity version of MAGICC under the more severe emissions scenario of RCP8.5. However, it is debateable whether future international government policy would allow such a large associated global surface temperature rise to ever be realised.

- For sensitivity testing of adaptation options, we recommend a plausible upper limit range of sea level rise at Singapore of 1-2m for the 21st, 22nd and 23rd Centuries. This equates to a range of 3-6m for 2300.

10.6. Recommendations and Limitations

- The work presented here is very exploratory in nature and should be considered illustrative of potential changes in future sea level in the Singapore region.

- The results for steric/dynamic sea level are based on CMIP5 models that do not fully represent the shelf and marginal seas. 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.

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