Supplementary Information Report

Number 3

Key Factors for Sea Level Rise in the Singapore Region

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Contents

Executive summary

This report provides an overview of the key drivers of future changes in sea level extremes in the Singapore region as well as a discussion of the potential impacts. Broadly speaking, these drivers can be broken down into those that contribute to global and large-scale sea level rise (Section S3.2) and those regional processes that control the most extreme sea levels, which are often linked to local meteorology (Sections S3.3 and S3.4). The report also provides both a motivation and context for the coastal modelling simulations that are being carried out and described in Chapter 9.

Since the focus of the current report is on climatic drivers of sea level change, we will only discuss other factors that affect local vertical land movement in passing. However, of particular note for Singapore is tectonic activity associated with the Sumatra fault. Ongoing research at the Singapore Earth Observatory indicates that a major earthquake in this region could result in subsequent local subsidence and an associated sea level rise of several tens of centimetres over a number of decades (Emma Hill, personal communication).

Key Findings:

- The most severe scenario considered by the IPCC 5th Assessment Report gives a likely range for global average sea level rise of 0.45-0.82 m for the period 2081-2100 relative to 1986-2005.

- 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.

- Sea level change represents an integration of a complex range of Earth system processes that occur on a range of time and space scales. Many of these processes result in non-uniform patterns of sea level change and Singapore's equatorial location means that it may experience sea level rise that is up to 20% higher than the global average.

- Local sea level extremes in the Singapore region are influenced by both locally and remotely generate wind-waves, surges, tropical cyclones, the seasonal monsoon winds and ENSO variability.

- There is some indication from climate model projections of a possible increase in both surface winds and the associated wave heights in the Singapore region; e.g. in the South China Sea during the northeast monsoon.

- The current scientific evidence suggests that the global number of tropical cyclones will either decrease or remain essentially unchanged, but have higher maximum wind speeds and precipitation rates. The influence of climate change on tropical cyclones is likely to vary by region, but there is low confidence in region-specific details.

- A number of modelling studies show increased extreme rainfall associated with the monsoon under global warming with a subset of these also reporting an intensification of the monsoon circulation.

- Recent studies suggest that the amplitude of ENSO events may increase – at least until the middle of the 21st Century. Overall the frequency of El Niño events may decrease slightly over the next century.

S3.1. Introduction

Singapore is an island state located at the southern tip of the Malay Peninsula about 137 km north of the equator. With an area and coastline of 637.5 km^2 and 193 km respectively and considerable population, industries, commerce and transport located in coastal areas at elevations less than 2 m (Wong, 1992), Singapore is vulnerable to rising sea levels. Impacts from sea level rise will be felt most markedly during episodes of extreme sea level events. Extreme sea levels are caused by combinations of factors that occur on time scales that vary from short term severe weather events to seasonal and interannual variations in climate. The impacts of extreme sea levels include shoreline erosion, coastal flooding and inundation and salinisation of coastal wetlands, estuaries and aquifers. Increases in the regional time mean sea level and changes in weather patterns due to enhanced global warming therefore pose a significant risk to Singapore.

The latest projections of future climate change can be assessed from ensembles of Global Climate Model (GCM) simulations that are available from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al, 2012). At present, this comprises projections of the evolution of the global climate system over the 21st Century from over 40 climate models. Impact assessments often require information at higher spatial resolution than is provided by GCMs in order to represent the meteorological drivers of sea level extremes. This high spatial and temporal climate information is often generated over a region of interest using statistical or dynamical downscaling models (e.g. McSweeney et al, 2012). Changes in the time mean regional sea level can be assessed through a combination of GCM output and "offline" models of future changes land-based ice loss (e.g. Slangen et al, 2014).

Singapore 2nd National Climate Change Study – Phase 1 aims to provide a more complete understanding of the effects of sea level rise and climate change. The broader scope of this project is to model the future climate change over Singapore in "high resolution" (approximately 12 km) regional climate models under different future greenhouse gas emission scenarios. These downscaled climate simulations will also provide the boundary conditions to simulate future changes in sea level extremes in the vicinity of Singapore using coastal ocean models (see Chapter 9). However, the computational expense of running such models means that there is a need to select a subset of appropriate GCMs in which to downscale either regional climate and/or coastal ocean models (Chapter 3, McSweeney et al, 2013). Approaches for selecting climate models for downscaling have been discussed by, Wilby et al (2009), McSweeney et al (2012) and Whetton et al (2012). Criteria of particular importance in selecting climate models for impact studies are: (a) that the climate model, under historical climate conditions, accurately represents the processes or features that are of particular relevance to the impact study; (b) that future climate models are selected that sample the range of projected change in the features of interest; and (c) the fields required to provide forcing for downscaling models are available at suitable temporal resolution (Whetton et al, 2012).

The purpose of this report is to provide an overview of the key drivers of extreme sea levels for the Singapore region and to review how these drivers will change both globally and regionally under future scenarios of global warming. This includes a review of coastal impacts and their meteorological and climatological causes along the Singapore coast. The report is structured as follows. The key processes that contribute to global and regional sea level change are presented in Section S3.2. Contributors to extreme sea level and factors particularly important to the Singapore region are presented in Section S3.3. Section S3.4 discusses changes in the drivers of sea level extremes, including waves, tropical cyclones and monsoons. Potential impacts of extreme sea levels on the coastal areas, coastal reservoirs and drainage systems in Singapore are discussed in Section S3.5. Finally, we present a summary of the key findings in section S3.6.

S3.2. Global and regional sea level change

Sea level is defined as the height of the ocean surface measured with respect to either: (i) the solid Earth (relative sea level) or (ii); a geocentric reference, such as Earth's centre of mass (geocentric sea level, for example as measured by satellite altimeters). Relative sea level is the more relevant when considering coastal impacts and is also the expression of sea level that is recorded by tide gauge measurements. For the purposes of this report we will use the term sea level to mean relative sea level, unless explicitly stated otherwise.

In general, past variations and future projections of sea level change are spatially non-uniform (Figure S3.1). Some of the processes that contribute to regional departures from global mean sea level are summarized in the Sea Level Chapter of Working Group I of the IPCC 5th Assessment Report (AR5):

"*Shifting surface winds, the expansion of warming ocean water, and the addition of melting ice can alter ocean currents which, in turn, lead to changes in sea level that vary from place to place. Past and present variations in the distribution of land ice affect the shape and gravitational field of the Earth, which also cause regional fluctuations in sea level. Additional variations in sea level are caused by the influence of more localized processes such as sediment compaction and tectonics.*"

Although the focus of this report is on contemporary and future climate drivers of global and regional sea level change, it is important to note that other factors can dominate sea level records at some locations. The large sea level rise seen at Manilla is dominated by the influence of ground water extraction and local subsidence, while the sea level fall at Stockholm is the result of glacial isostatic adjustment, i.e., the slow viscous sub-lithosphere response to the last deglaciation (Figure S3.1; Church et al, 2013). Of particular note for Singapore is tectonic activity associated with the Sumatra fault. Ongoing research at the Singapore Earth Observatory indicates that a major earthquake in this region could result in subsequent local subsidence of several tens of centimetres over a number of decades (Emma Hill, personal communication).

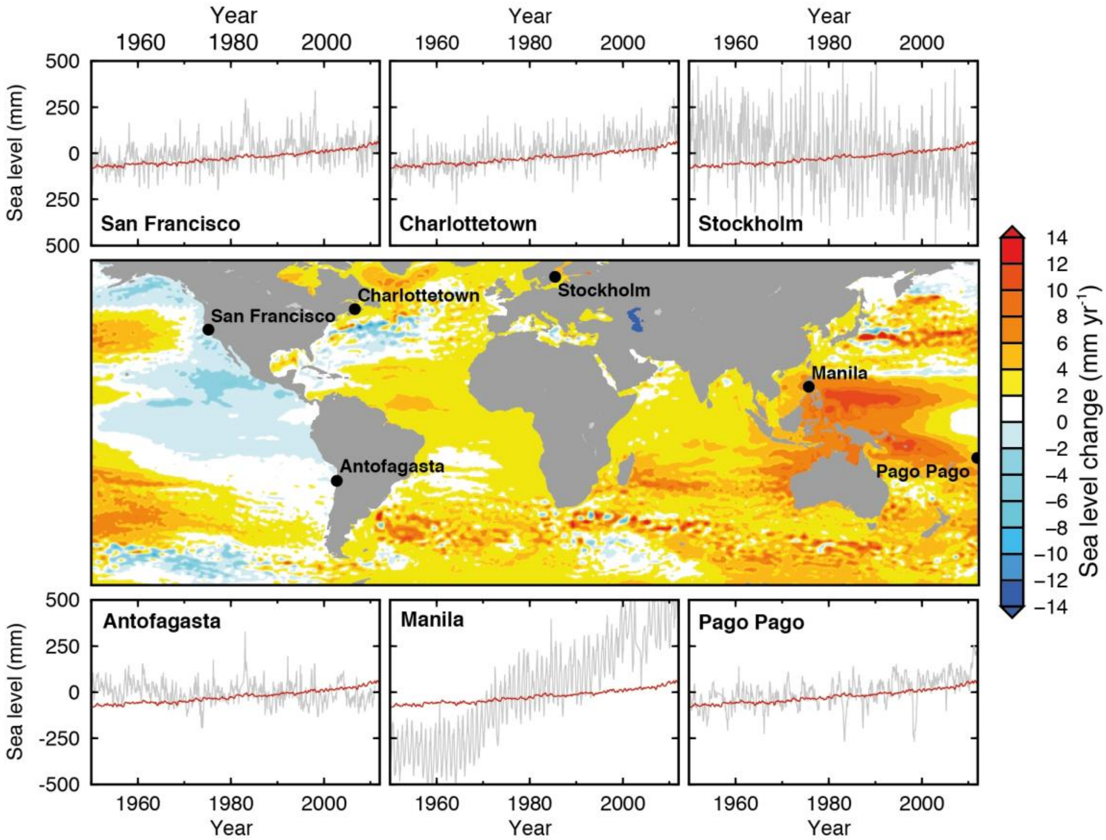

Figure S3.1: Map of rates of change in sea surface height (geocentric sea level) for the period 1993–2012 from satellite altimetry. Also shown are relative sea level changes (grey lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is also shown (red lines) with each tide gauge time series (source: FAQ13.1, Figure 1 of the IPCC AR5, Church et al, 2013).

S3.2.1 The sea level "jigsaw puzzle"

Figure S3.2 illustrates how the "jigsaw puzzle" of processes contributing to global and regional sea level change fit together. Under global warming, changes in global mean sea level arise primarily though thermal expansion of the oceans and mass addition to the ocean from melting glaciers and ice sheets. In addition, there can be small contributions from ground water extraction and building of reservoirs, which can become more important at regional scales (e.g. Slangen et al, 2014).

The large-scale patterns of sea level change bring about local departures from the global average change, due to factors such as ocean circulation, changes in atmospheric pressure (the "inverse barometer" effect) and both past and contemporary changes in land ice mass loss. These first two columns in Figure S3.2 describe the factors that bring about changes in the large-scale time average sea level. The third column shows processes that are superimposed on the time-average sea level to determine regional extremes, such as tides, surges, waves, seasonal cycles and the El Niño Southern Oscillation (ENSO), all of which could bring about changes in coastal flood risk. The drivers of global and regional time mean sea level change are expanded on in more detail in Section S3.2.2. Processes affecting sea level extremes in the Singapore region and how they may change in the future are discussed in Section S3.3.

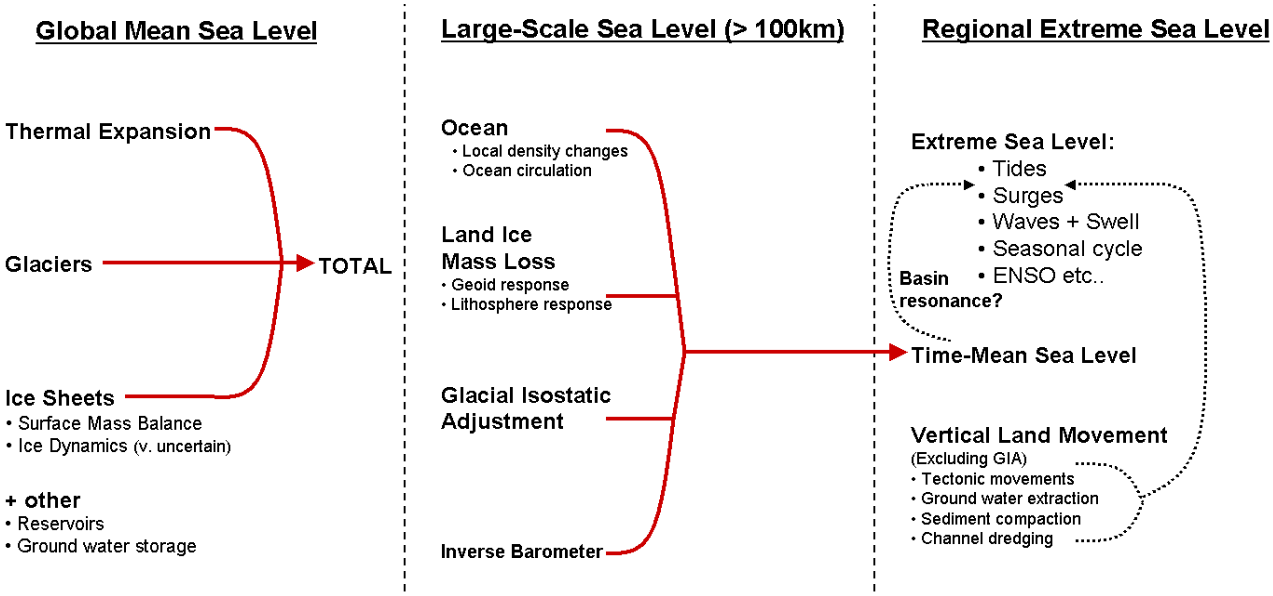

Figure S3. 2: Schematic of factors contributing to global and large-scale time-mean sea level change and changes in regional sea level extremes.

S3.2.2 Key drivers of global and regional sea level change

Figure S3.3 shows the contributions from thermal expansion and mass addition to global sea level for different scenarios of future global warming (Church et al, 2013). The mass addition terms for the Greenland and Antarctic ice sheets are further broken down into contributions from surface mass balance (the sum of snowfall and ice melt) and an ice dynamic term, which represents possible future changes in the ice flows in these regions. By 2100, thermal expansion accounts for approximately 30-40% of the global sea level rise, with larger values for the stronger warming scenarios. For comparison, observational estimates suggest that the contribution to global sea level rise from thermal expansion is about 40% over the period 1961-2008 (Church et al, 2011). The projections of global sea level rise over the 21st Century depend on the climate change scenario (Table S3.1) with a likely range of 0.52 to 0.98m at 2100 for the most severe scenario. However, for the first half of the 21st Century the rate of sea level rise is not very sensitive to choice of scenario (Figure S3.3). The IPCC AR5 state that global sea level rise is *likely* (medium confidence) to fall within these projected ranges for a given scenario. Only a collapse of the marine-based sectors of the Antarctic ice sheet could push global mean sea level rise above these likely ranges. It is estimated that such a collapse would not exceed a few tenths of a metre of additional sea level rise; current scientific understanding is not sufficient to provide higher precision than an order of magnitude (Church et al, 2013).

Scenario	**Likely range for sea level rise 2081-2100***
RCP2.6	0.26-0.55 m
RCP4.5	0.32-0.63 m
RCP6.0	0.33-0.63 m
RCP8.5	0.45-0.82 m

*computed as a change relative to 1986-2005.

Table S3.1: Process-based model estimates of global sea level rise from the IPCC AR5. Global mean sea level rise is *likely* (medium confidence) to fall within these ranges. 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).

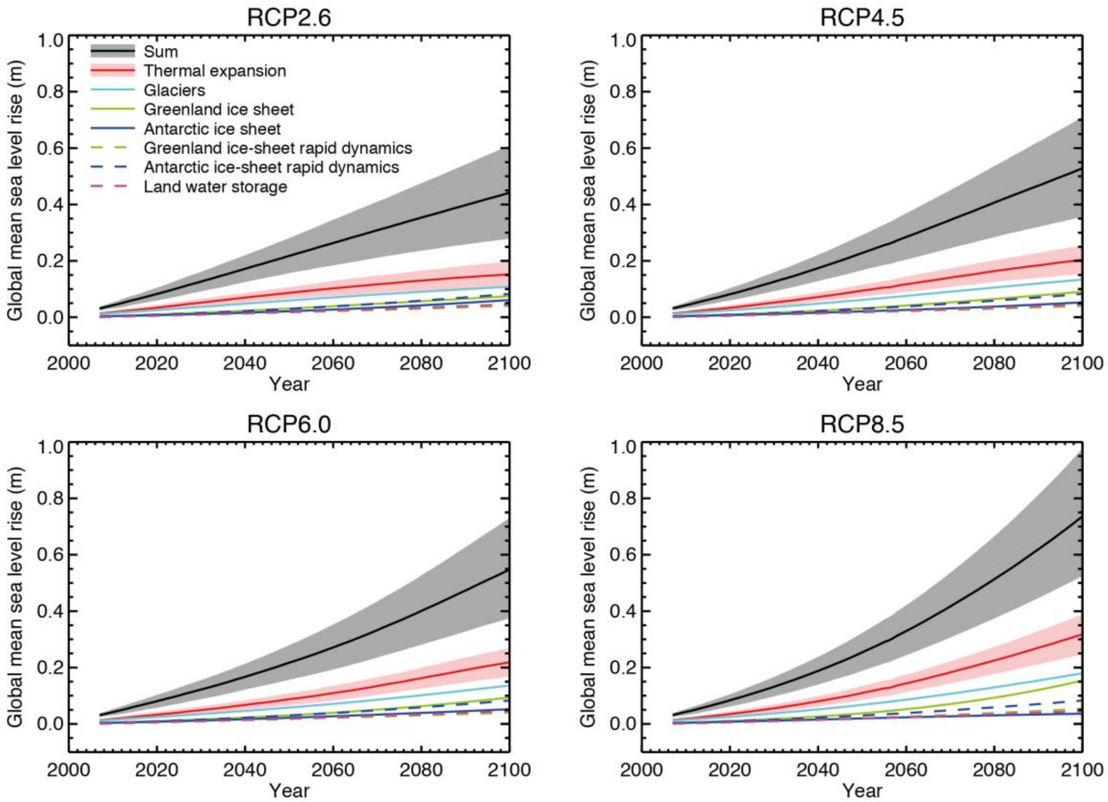

Figure S3.3: Projections from process-based models of (a) global mean sea level (GMSL) rise relative to 1986–2005 (see also Table 1). The lines show the median projections. For GMSL rise and the thermal expansion contribution, the likely range is shown as a shaded band. The ice sheet contributions include the ice-sheet rapid dynamical change, which are also shown separately. Source: Fig 13.11 of IPCC AR5 (Church et al, 2013).

The spatial pattern of sea level rise is non-uniform and horizontal variations from the global mean come from changes in: ocean circulation and density (Figure S3.4); changes in atmospheric pressure (not shown); glacial isostatic adjustment (GIA, Figure S3.5a) and the spatial patterns associated with glacier and ice sheet mass loss (Figure S3.5b,c). GIA is the slow viscous response of the asthenosphere to the last deglaciation and its rate is essentially time constant for the timescales of interest here. The glacier and ice sheet mass loss terms have a spatial pattern that is due to a combination of the fast lithosphere response, rotational effects and changes in Earth's gravitational field (Tamisiea and Mitrovica, 2011).

In general, the spatial patterns of glacier and ice sheet mass loss are characterized by a near-field drop in sea level and a far-field rise. These "fingerprints" of sea level change – illustrated in Figure S3.5b and c – are multiplied by estimates of glacier and ice sheet mass loss in order to estimate the contribution under different climate change scenarios (Church et al, 2013; Slangen et al, 2014).

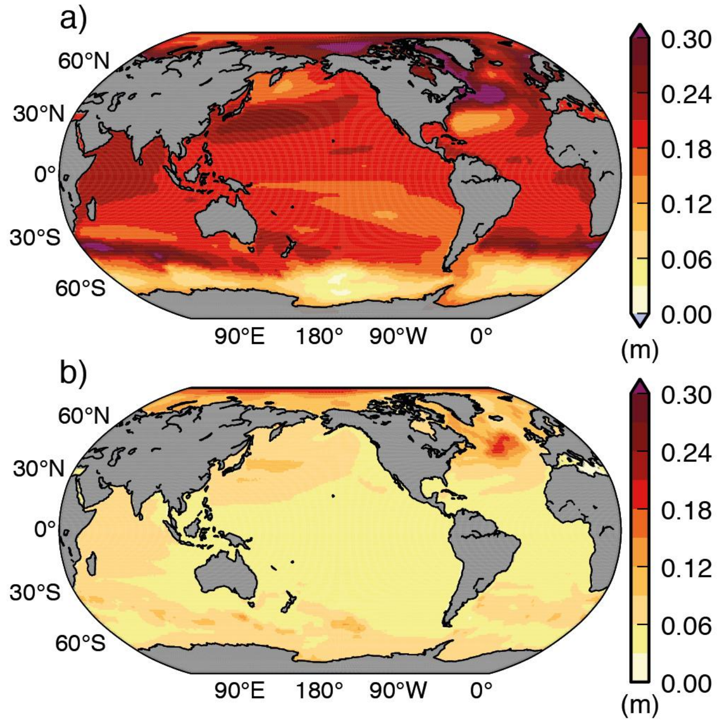

Figure S3.4: (a) Ensemble mean projection of the time-averaged dynamic and steric sea level changes for the period 2081–2100 relative to the reference period 1986-2005, computed from 21 CMIP5 climate models (in metres), using the RCP4.5 experiment. The figure includes the globally averaged steric sea level increase of 0.18 ± 0.05m. (b) Root-mean square (RMS) spread (deviation) of the individual model result around the ensemble mean (metres). Source: Fig 13.16 of IPCC AR5 (Church et al, 2013).

For a given climate change scenario, the various factors can be combined to provide spatial maps of regional time-mean sea level change (Figure S3.6). Local sea level rise can exceed the global mean by up to 20% in subtropical and equatorial regions and up to 30% in the mid-to-high latitudes (Figure S3.6, Slangen et al, 2014). Full details of the methods used to estimate the different sea level terms described in the IPCC AR5 (Figures S3.3-6) are available in Slangen et al (2014).

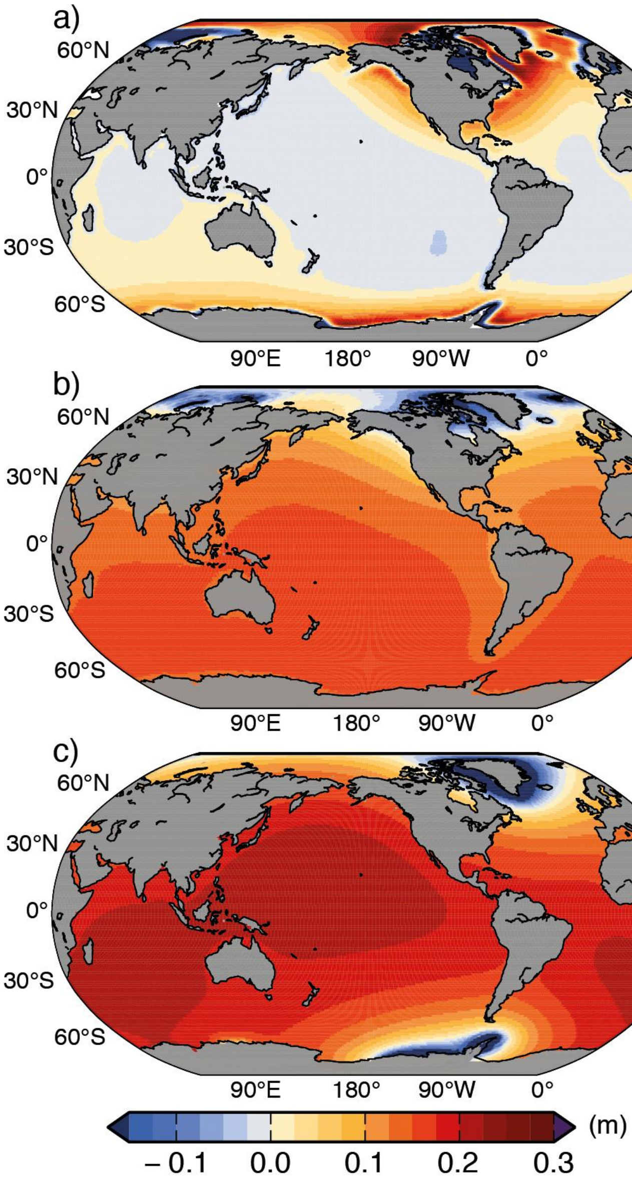

Figure S3.5: Ensemble mean regional contributions to sea level change (metres from (a) glacial isostatic adjustment (GIA), (b) glaciers and (c) ice-sheet surface mass balance (SMB). Panels (b) and (c) are based on information available from scenario RCP4.5. All panels represent changes between the periods 1986–2000 and 2081–2100. Source: Fig 13.18 of IPCC AR5 (Church et al, 2013).

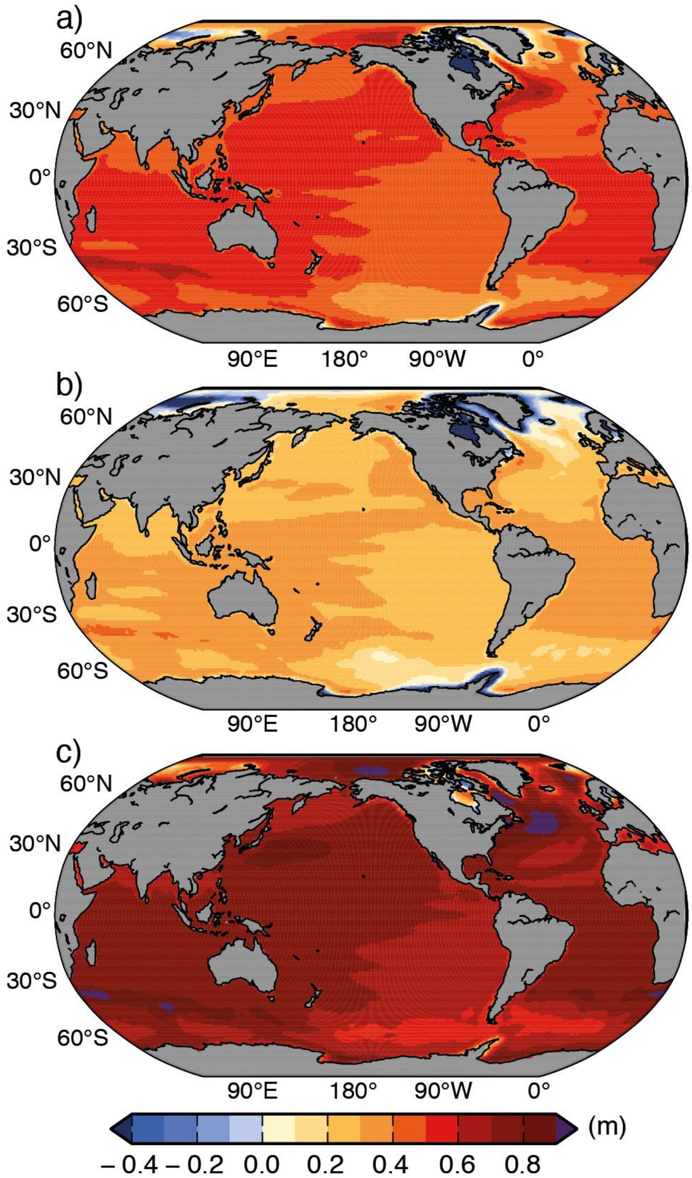

Figure S3.6: (a) Ensemble mean regional relative sea level change (m) evaluated from 21 models of the CMIP5 scenario RCP 4.5, including atmospheric loading, plus land-ice, GIA and terrestrial water sources, between 1986–2005 and 2081–2100. Global mean is 0.48 m, with a total range of -1.74 to +0.71 m. (b) The local, lower 90% uncertainty bound (p=0.05) for RCP4.5 scenario sea level rise (plus non-scenario components). (c) The local, upper 90% uncertainty bound (p=0.95) for RCP4.5 scenario sea level rise (plus non-scenario components). Source: Fig 13.19 of IPCC AR5 (Church et al, 2013).

In summary, relative sea level change represents an integration of a complex range of Earth system processes that occur on a range of time and space scales. Many of these processes result in non-uniform patterns of sea level change and Singapore's equatorial location means that it may experience sea level rise that is up to 20% higher than the global average. This additional rise comes primarily from local changes in ocean density and circulation and the non-uniform pattern of sea level rise associated with mass addition from the Antarctic and Greenland ice sheets.

S3.3. Sea level extremes

S3.3.1 Contributions to Extreme Sea Levels

Extreme water levels are caused by a combination of atmospheric and ocean processes that operate on a range of time and space scales (Figure S3.7). On the shortest time and space scales, severe weather events such as tropical cyclones cause storm surges and waves. The low atmospheric pressure associated with the storm, together with strong onshore winds, serve to increase the water levels against the coast. Wind generated waves breaking at the shore further elevate sea levels due to wave setup and wave runup (Figure S3.8). Wind generated waves also transport energy from remote areas of the ocean to the coast and play an important role in shaping coastlines. The timing of tides during such events will influence the severity of the impacts from storm surges and high waves. Tides vary on a range of time scales from daily high and low tides to fortnightly spring and neap cycles and also on seasonal and longer scales (e.g. Merrifield et al, 2013). Seasonal variations in sea levels arise from changes in ocean circulation and ocean steric properties which can occur due to changes in weather patterns with the seasons. Interannual climate variations such as the El Niño Southern Oscillation can also bring about changes in weather and climate features that can affect regional sea levels. Finally, long-term sea level rise due to the processes discussed in section 2 will also increase the impacts of extreme sea-level episodes.

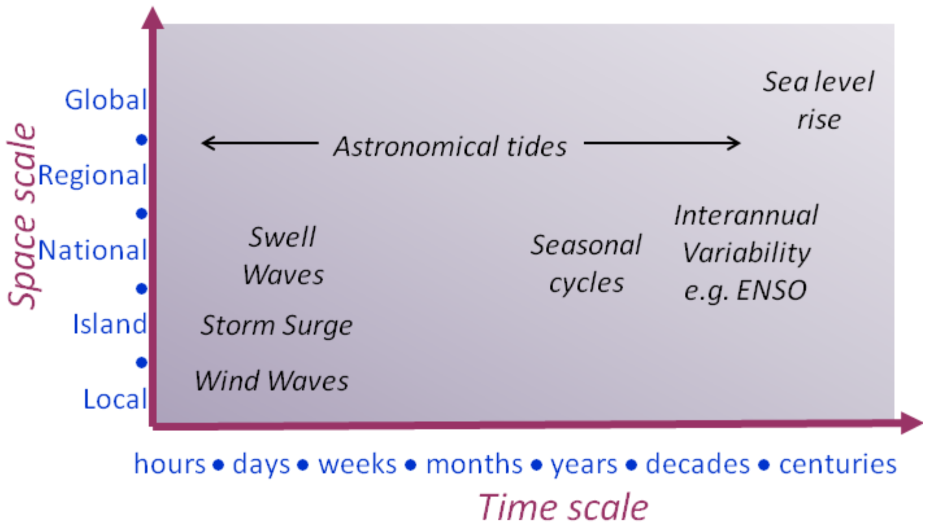

Figure S3.7: Different processes that can contribute to extreme sea levels and the typical time and space scales over which they occur.

S3.3.2 Sea Level Extremes in Singapore

Singapore is located on the southern tip of the Malay Peninsula (Figure S3.9) and is open to the South China Sea to the northeast and the Java Sea to the southeast. Sumatra, located to the southwest of Singapore, shields it from distant source swell waves from the Indian Ocean. Winds in Singapore are influenced by the northern and southern hemisphere monsoon systems. These give rise to prevailing winds in Singapore from the north or northeast during the northeast monsoon between December and early March and by winds from the south or southeast during the southwest monsoon season from June to September (Figure S3.9).

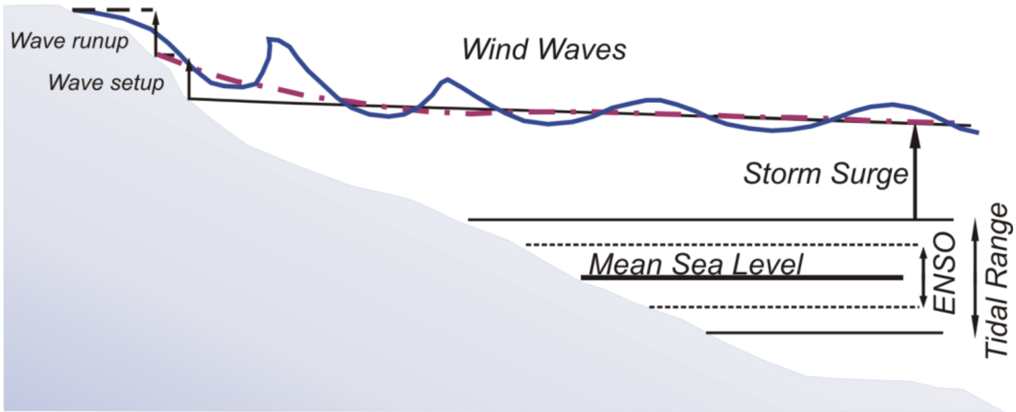

Figure S3.8: Different processes that can combine to produce coastal extreme sea levels. The dash-dotted line represents the average water levels on which surface waves are superimposed.

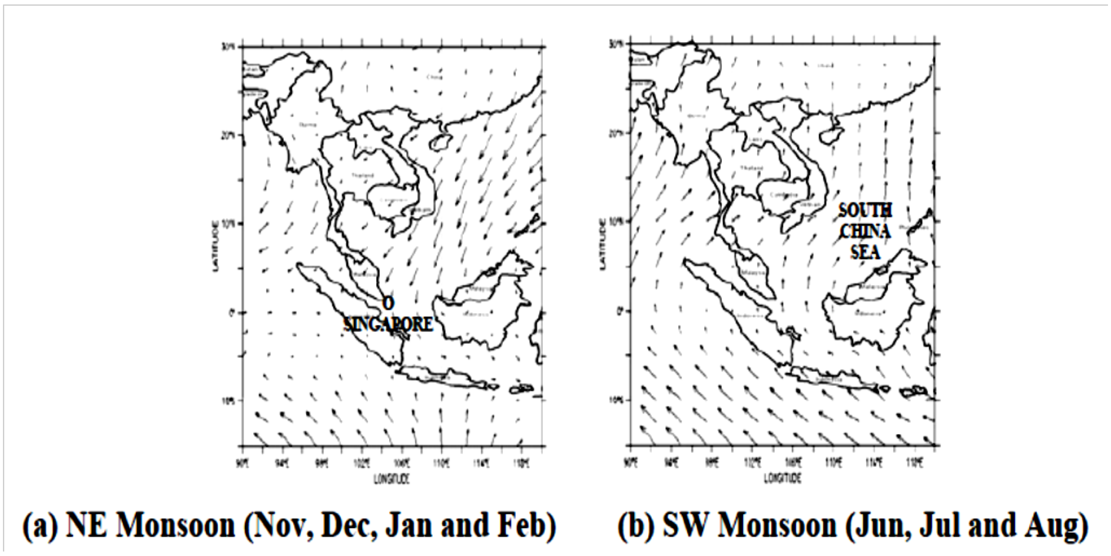

Figure S3.9: The NE monsoon prevails from November to February, whereas SW monsoon occurs from June to August (source: Tkalich et al, 2009).

An analysis of long term tide gauge data collected at Tanjong Pagar tide gauge reveals that wind is the primary causative factor for the sea level extremes at subannual timescales, especially during northeast (NE) and southwest (SW) monsoons (Tkalich et al, 2009). Even though currents in the Singapore Strait are predominantly tidal driven, they follow the regional trend of having NE monsoon drift when mean flow heads southwest, and SW monsoon drift pushing mean flow to the northeast. A sea level gradient is built up by the monsoon-driven wind forces along the longest axis of the South China Sea. This leads to a strong annual cycle with sea levels elevated by 30 cm or more during the NE monsoon over November to February and lower by around 20 cm during the SW monsoon from June to August as shown in Figure S3.11 (Tkalich et al, 2009; 2013a).

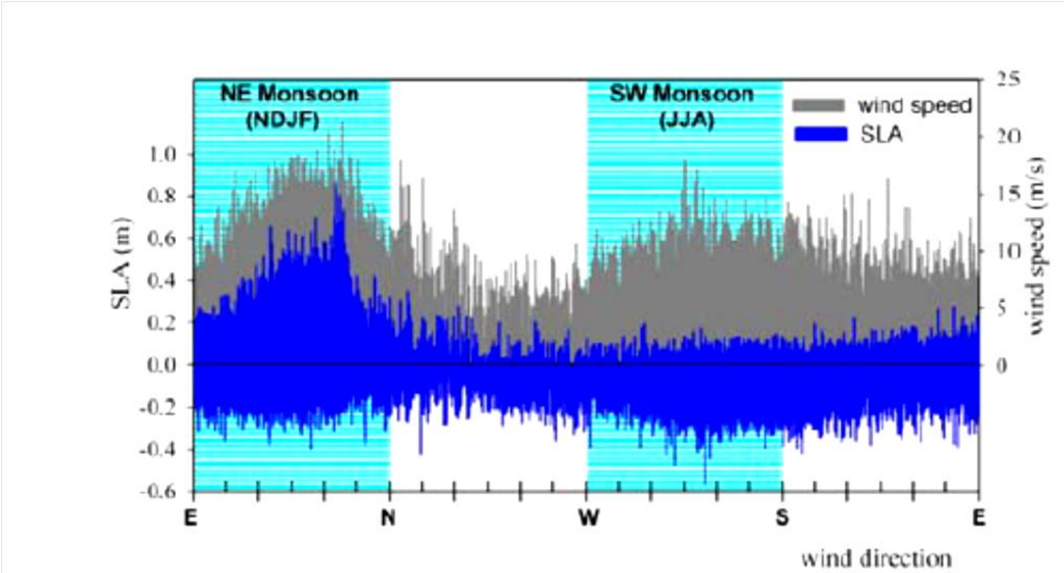

Figure S3.10: Sea Level Anomalies (SLA) at Singapore Strait versus winds off Vietnam for the period 1980-2006 (source: Tkalich et al, 2009)

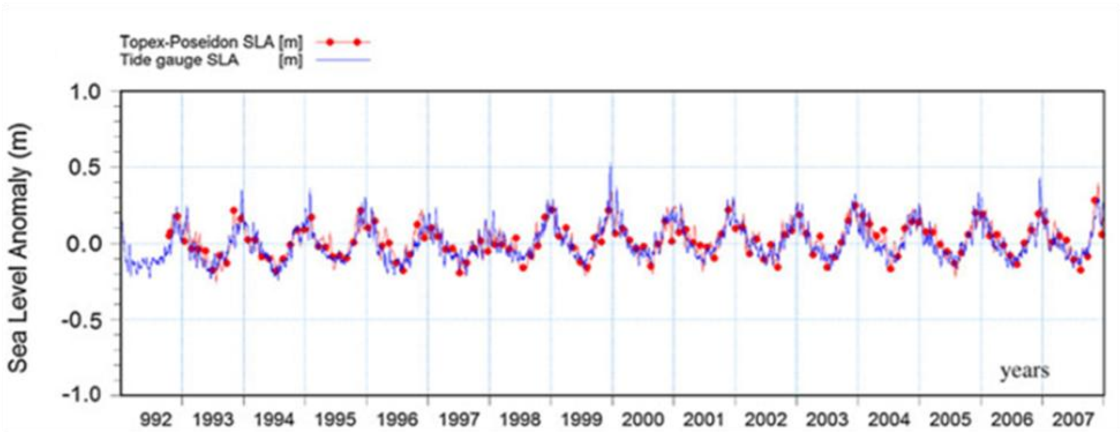

Figure S3.11: Sea Level Anomalies (SLA) derived from Tanjong Pagar tide gauge and satellite altimetry (source: Tkalich et al, 2013a).

On interannual time scales sea level anomalies in the Singapore Strait are also found to vary with ENSO cycles. During El Niño events sea levels are typically lower by around 5 cm while they are higher by a similar amount during La Niña events (Tkalich et al, 2013b).

Singapore's location just north of the Equator means that it lies outside the tropical cyclone genesis regions of the northern and southern hemisphere. However, on rare occasions severe tropical systems have occurred near Singapore. An example is typhoon Vamei on 27th December 2001, which was the first to develop within 1.5 degrees of the equator. It occurred as a result of the interaction between a persistent surge of cold air from the northeast during the northern hemisphere winter monsoon and a low-level cyclonic circulation that had drifted westward from the northwest coast of Borneo (Chang et al, 2003; Tkalich et al, 2009). Chang et al (2003) estimated that the development of such systems was likely only once in every 100-400 years. An investigation of the potential for such events to generate storm surges in Singapore was investigated by Xin (2010). It was found that an event with a return period of around 400 years could produce sea levels around the Singapore coast in the range of 2.0 to 2.8 m depending on location.

Wave fetch around Singapore is generally short and the directions of maximum fetch do not generally coincide with the direction of the strongest winds. However, during the Southwest Monsoon, wind squalls known locally as "Sumatra squalls", can produce winds of 20-25 m s^{-1} and waves of up to a metre in height along the southwest coast. However, the energy from these waves is mostly dissipated along offshore reefs before reaching the coast (Wong, 1992).

S3.4. Changes in Drivers of Sea level extremes

S3.4.1 Winds and Waves

An understanding of how coastlines may be affected in future requires an understanding of how surface wind and wave climates may change as a result of increasing greenhouse gases. Until recently, there have been few studies that have addressed future climate change in wind and wind-waves (Seneviratne et al, 2012). However, an examination of spatial patterns of surface wind climate change using CMIP3 models (phase 3 of the Coupled Model Intercomparison Project; Meehl et al, 2007) models was undertaken by McInnes et al (2011). Mean wind changes presented in that study indicated that the majority of models examined (at least 66% of a 19 member ensemble) projected a surface wind speed increase over the South China Sea during the NE monsoon season from December to February (Figure S3.12a) and an increase in winds to the southwest of Singapore during June to August (Figure S3.12b).

The Coordinated Ocean Wave Climate Project (COWCLIP; Hemer et al., 2013) has led to an increased focus on future ocean wave climate change. Several studies that employ global wave models to examine future wave climate change using wind forcing from a subset of the CMIP3 models have been completed (e.g. Mori et al., 2010; Hemer et al., 2013; Fan et al., 2013). Consistent with the wind speed changes reported in McInnes et al, (2011) these studies also indicated increases in Significant Wave Height (Hs) during December to January in the South China Sea (see for example Figure 4 of Fan et al, 2013 and Figure 2c of Hemer et al, 2013).

Wang et al (2014) used statistical downscaling techniques to investigate wave climate change in 20 CMIP5 model simulations. The ensemble average changes are shown in Figure S3.13 and indicate increases in significant wave height in the tropics and high latitudes. In particular, increases in Hs are seen in the South China Sea over the months of January to March during the period of the NE monsoon and to the southwest of Singapore during July to September. However, the direct modelling approach of Hemer et al. (2013) when applied to an ensemble of CMIP5 models produces less conclusive changes over the South China Sea with some models indicating an increase in Hs by the end of the Century and others a decrease (Hemer, personal communication). A summary of the models used in this dynamical downscaling is given in Table 2.

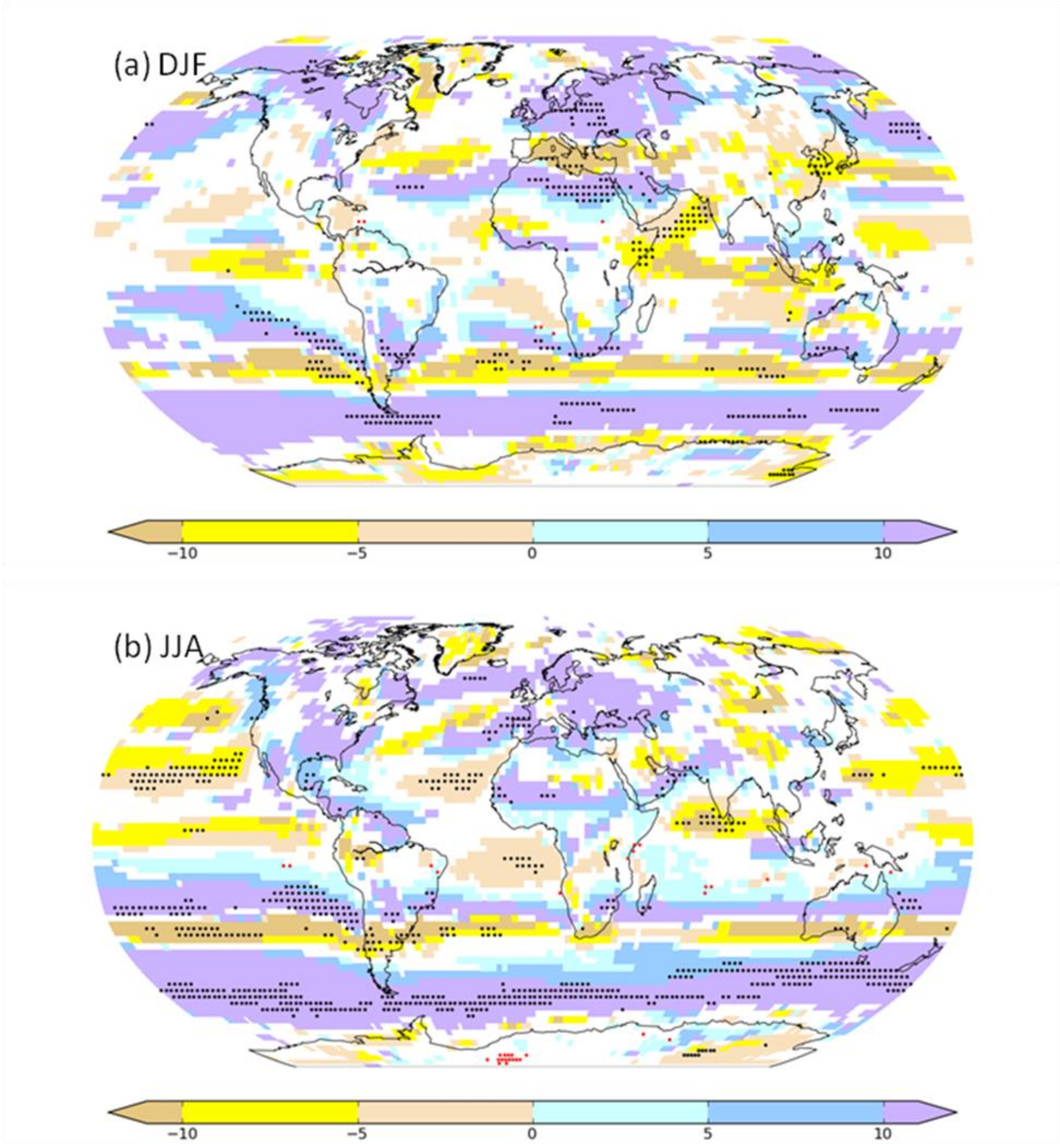

Figure S3.12: Ensemble average changes (in %) in the mean of the daily averaged 10-m wind speeds for the period 2081-2100 relative to 1981-2000 for (a) December to February and (b) June to August using 19 CMIP3 GCMs. Shaded areas indicate where more than 66% of the models agree on the sign of the change. Black stippling indicates areas where more than 90% of the models agree on the sign of the change. Red stippling indicates areas where more than 66% of models agree on a small change between ±2%. Adapted from McInnes et al. (2011)

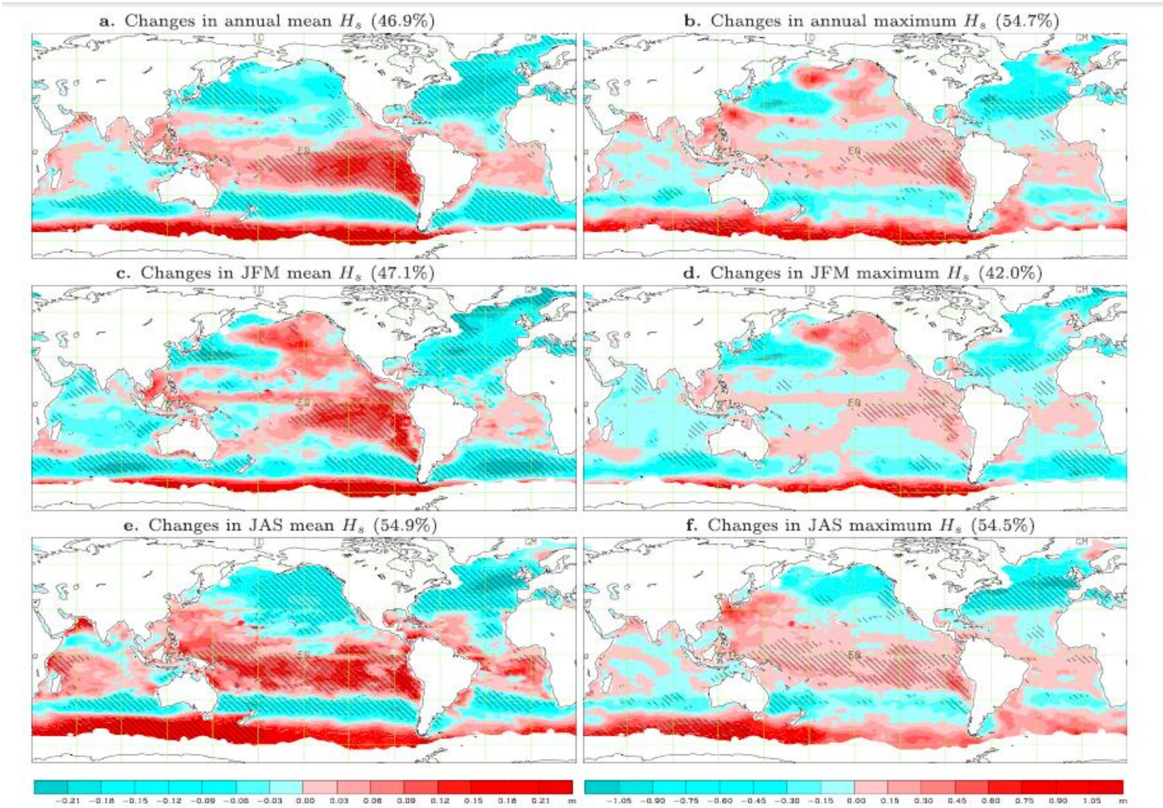

Figure S3.13: (a–f) The CMIP5 20-model ensemble mean of projected changes in annual/seasonal mean and maximum significant wave heights (Hs, m) for the period 2080–2099 relative to the period 1980–1999 for the RCP8.5 scenario. Hatched areas indicate where the multi-model ensemble mean exceeds the inter-model standard deviation. The percentage area with projected Hs increases are shown in parentheses on top of each panel. From Wang et al, (2014).

S3.4.2 Tropical Cyclones

Projected changes in tropical cyclone (TC) frequency and intensity could potentially impact storm surges and coastal impacts in Singapore. Tropical cyclones are small-scale phenomena and the relatively coarse horizontal resolution of global climate models limit their ability to realistically represent cyclone behaviour. Different methods are available for overcoming this problem (Knutson et al., 2010) that involve dynamic downscaling, or diagnosing cyclone favourable conditions through: (1) empirical methods, which utilise relationships between tropical cyclones and the large-scale environmental conditions that are known to affect their development; and (2) direct-detection schemes that, either identify synoptic features that have the characteristics of a tropical cyclone (i.e. a closed low pressure system accompanied by strong winds and a warm core through the depth of the atmosphere), or detect the environment that favours their formation directly from climate model output.

Assessments of global and regional tropical cyclone studies that have employed such methods have been undertaken in the IPCC AR5 (Christensen et al, 2013) which concluded:

"*Based on process understanding and agreement in 21st century projections, it is likely that the global frequency of occurrence of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean* *tropical cyclone maximum wind speed and precipitation rates. The future influence of climate change on tropical cyclones is likely to vary by region, but the specific characteristics of the changes are not yet well quantified and there is low confidence in region-specific projections of frequency and intensity*."

The results of a number of additional studies that have been recently completed are consistent with this assessment. For example, with regards to cyclone frequency, Yokoi et al (2013) found an increase in the frequency of TCs passing over the tropical central North Pacific and a decrease in TC frequency in regions to the west and northwest, including East Asian countries. Tory et al (2013) found a reduction in global TC numbers that was more evident in the Southern Hemisphere across the models than in the Northern hemisphere where the results tend to be mixed. A decrease in TC numbers was also found in the studies of Chattopadhyay and Abbs (2012) and Caron and Jones (2008). Murakami et al (2013) found no statistically significant change in TC frequency in the North Indian Ocean basin although the timing of cyclone occurrence throughout the year underwent changes and different convection schemes contributed to the uncertainty of results. With regards to future changes in TC intensity Knutson et al (2013) found that there was a marginal increase in TC intensity in the downscaled simulations using CMIP5 climate models.

S3.4.3 Monsoon

As discussed in Section S3.3.2, the monsoons that affect Singapore are responsible for strong seasonal changes in sea level with higher sea levels occurring during the NE monsoon and lower sea levels during the SW monsoon. Seo et al (2013) found a 10-15% increase in precipitation in the north and north-east Korean Peninsula, but a decrease over the East China Sea. Seo et al (2013) also report an increase in the strength of North Pacific Subtropical High (NPSH) during East Asian Summer Monsoon period which leads to an intensification of southerly to south-westerly wind. The stronger wind leads to an increase in moisture convergence and enhanced precipitation in the eastern part of Japan. Seth et al. (2013) have used 17 CMIP5 models to assess monsoon precipitation in the South-East Asian region. They show that the global monsoon is expected to increase in its area, total precipitation and intensity (Kitoh et al. 2013). Lee and Wang (2012) have also found an increase in monsoon rainfall intensity in the Asian Australian region compared to other parts of the world using CMIP5 model output. Hsu et al (2013) using CMIP5 model outputs also find a consistent increase across models assessed in monsoon precipitation intensity over the global monsoon area. They also report that the multi model mean of CMIP5 models shows a strengthening of wind speed in the global monsoon region but a decrease in wind speed over most of the tropical oceans. Kitoh et al (2013) indicates that the monsoon intensity and extreme precipitation indices will increase over Asia which shows that Asian monsoon is sensitive to global warming. This indicates that the strengthened global monsoon is a robust signal across the models and SST patterns. The increase of the global monsoon precipitation is attributed to the increases of moisture convergence and surface evaporation. The models used in this analysis are summarised in Table S3.2.

The "dynamical downscaling" (see Chapter 5) of the Singapore 2nd National Climate Change Study – Phase 1 will also evaluate the representation of Northeast monsoon cold surges (sub-seasonal bursts of wind in the South China Sea) in the regional atmospheric simulations, and how they may change in the 21st century. This may be an important process affecting extreme sea levels during the winter season in Singapore as discussed in Section S3.3.2. Research is currently being undertaken at the Centre for Climate Research Singapore to improve understanding of cold surges and their impacts.

S3.4.4 ENSO

Cai et al, (2013) used an ensemble of CMIP3 and CMIP5 GCMs to examine future changes to El Niño events. They found that although El Niño events decreased slightly in the future, extreme El Niño events such as those that occurred in 1982/83 and 1997/98 seasons increased from an average of 1 event every 20 years to 1 every 10 years. The increase in frequency was due to surface warming over the eastern equatorial Pacific that was projected to occur faster than in surrounding ocean waters, leading to more occurrences of atmospheric convection in the eastern equatorial region. 11 CMIP5 models were assessed as best performing with regards to representing the nonlinear ocean-atmospheric coupling process for this analysis and are summarised in Table S3.2.

Kim et al, (2014) examined ENSO sea surface temperature (SST) amplitude in CMIP5 models using the Bjerknes formula (Jin et al, 2006), which assesses ENSO magnitude in terms of mean state and air-sea coupled processes. Over the observational period they show that ENSO SST variability was enhanced over the last several decades with particularly intense ENSO over the period 1980 to 2000 during which time two of the most extreme El Niño events occurred in 1982 and 1997. They find that of 22 CMIP5 models assessed, nine perform more realistically in terms of representing the ENSO variability. The models are ACCESS1-0, CCSM4, FGOALS-g2, GFDL-CM3, GFDL-ESM2M, GISS-E2-R, MIROC5, NorESM1-M and NorESM1-ME. The poorer performance of the remaining 13 models is related to these models having a stronger cold-tongue bias in the eastern equatorial Pacific. Over the 21st Century they find an increasing trend in ENSO amplitude before 2040, followed by a decreasing trend thereafter.

S3.4.5 Summary

This section has reviewed literature on the key drivers of extreme sea levels in Singapore. A summary of the models that have been employed in those studies and generally assessed as being fit-for-purpose is provided in Table S3.2. It is clear that there is no single model or set of models that out performs all other models in representing the main variables and processes of interest in this region. Furthermore, it should be noted that there are differences in the criteria used to assess the models in these studies as well as in the companion report (McSweeney et al, 2013). It is for this reason that in climate impacts research, it is highly desirable to investigate future climate change in a range of different climate models. The set of climate models that have been selected by McSweeney et al (2013) for the regional downscaling over Singapore is shown in the final column of Table S3.2. It can be seen that this selection provides a reasonable sample of models for this purpose. For each of the processes listed, it is possible to find at least four of the UKMO-selected models that have been used in the reviewed literature for studying future changes to the listed processes.

Table S3.2: Models used in the studies reviewed in section 4. √ refers to those models used in the studies as indicated in the relevant sections and generally assessed by these studies to satisfactorily in modeling the listed processes.

Models	Wind and Waves (dynamical)	Tropical Cyclones	Monsoon	ENSO Intensity	ENSO variation with time	
ACCESS1.0	√	√			√	
ACCESS1.3		√				*
BCC_CSM1.1	√	√				*
BCC_CSM1.1 M						
CanESM2		√		√		*
CCSM4		√	√	√	√	
CMCC				√		
CNRM_CM5	√	√		√		**
CSIRO_MK3.6		√	√			**
FGOALS-G2		√			√	
FGOALS-S2						
GFDL-CM3	√	√		√	√	**
GFDL_ESM2M		√	√	√	√	
GFDL_ESM2G		√	√			**
GISS_E2R			√		√	
GISS_E2H						
HadGEM2-ES	√	√	√			**
HadCM3			√			
HADGEM-CC		√	√	√		
INMCM4	√	√				*
IPSL-CM5A-LR		√				
IPSL-CM5A-MR			√			*
IPSL-CM5B-LR				√		
MIROC-ESM		√				
MIROC-ESM-CHEM			√			
MIROC5	√	√	√	√	√	
NorESM-1M		√	√	√	√	
MPI-ESM-LR		√				
MPI-ESM-MR		√				
MRI-CGCM3	√	√	√	√		
BNU-ESM						

* model is in the UKMO primary selection of models
** model is in the UKMO secondary selection of models

S3.5. Extreme sea levels and potential impacts in Singapore

Coastal impacts such as inundation and erosion arise from a combination of physical processes such as waves and storm surges that elevate coastal sea levels above the normally occurring tidal levels. Elevated coastal water levels also slow the rate at which rivers and streams can drain to the ocean leading to backwater effects and enhanced upstream flooding.

S3.5.1 Coastal impacts in Singapore

Rising sea levels will likely impact the coast of Singapore in a number of ways. Higher sea levels will worsen the impact of wave attack during the occurrence of Sumatra squalls. Mangrove swamps on the west and north coasts could potentially become submerged, causing die-back and erosion of the seaward margins. Furthermore, there is limited scope for landward migration of the mangroves as there is a lack of suitable sediment supply from the drainage basins which have become increasingly urbanized (Wong 1992).

It should also be noted that projected increase in SSTs and ocean acidification will add further stress to fringing coral reefs, which are may increase the frequency of coral bleaching events and cause coral mortality. However, the relative importance of sea level rise, SST increase and pH decline on coral health is not well understood (Wong et al, 2014). Any decline in the health and distribution of coral reefs due to increases in SSTs and acidification may reduce the protective role these systems play in shielding coasts from the effects of wind-waves (Sheppard et al., 2005; Gravelle and Mimura, 2008). In Singapore, the fringing coral reefs on the offshore islands may also become submerged. The reefs are already in a degraded state and with a slow rate of growth they may not be able to keep pace with the rise in sea level (Wong, 1992) particularly with the additional stressors of SST increase and pH decline. Beaches on the reclaimed land on the southeast, the west and the north coasts as well as on reclaimed land and the offshore islands may undergo increased erosion due to sea level rise (Wong, 1992).

S3.5.2 Impact on coastal reservoirs

There are a number of coastal reservoirs in Singapore that have been formed by building dykes across the river mouths of former tidal estuaries (Wong, 1992). These are located mostly in the west (Kranji, Sarimbum, Murai, Poyan, and Tengeh reservoirs) and in the north (the Seletar Reservoir). In addition, the Pandan Reservoir in the southwest was reclaimed from the mangrove swamps and is almost completely surrounded by a dyke. Future increases in sea level may increase the incidence of salt water intrusion into these reservoirs with subsequent contamination of freshwater supplies (Wong,1992).

S3.5.3 Impact on drainage

The highly urbanised landscape of Singapore together with annual rainfall totals exceeding 2370mm, means that drainage channels are not always able to cope with heavy rainstorms especially during the Northeast Monsoon (November-February). This can lead to flooding and in some cases, damage to property. Programs have been implemented to improve drainage and reduce flooding and measures include canal widening, concrete lining of channels and the diversion of storm water to reservoirs. Tidal gates have been built at a number of canals to keep out the backflow of sea water during rising tides. With an increase in sea level this problem is expected to worsen. Tidal gates may need to be more extensively installed to prevent tidal inflow. Pumping systems may also be needed to cope with rainfall-induced runoff (Wong, 1992).

S3.6. Summary

This report has provided a review of the science around sea level rise and extreme sea level events for Singapore. Sea level change represents an integration of a broad range of Earth System processes that occur on a range of time and space scales. Many of the processes that contribute to sea level rise are not captured by climate models. As such the development of regional sea level scenarios must bring together a broader body of science that includes, in addition to climate modelling, process-based models of the response of ice sheets to sea level rise and the visco-elastic response of the earth to changes in mass loading. A review of the current understanding of these processes using the most recent models indicates that Singapore may experience sea level rise that is up to 20% higher than the global-averaged sea level rise, although more precise estimates than this have not been established.

The impacts of sea level rise will be felt most profoundly during episodes of extreme sea levels that arise during severe weather conditions. Extreme sea levels are caused by storm surges and ocean wind-waves and may be influenced by variations in weather and climate that occur on seasonal to interannual time scales. In Singapore, there is a strong seasonal cycle in extreme sea levels with sea levels higher by typically 30 cm during the northeast monsoon seasons of November through February and lower by around 20 cm during the southwest monsoon seasons of June through August. A further increase in sea levels of up to 5 cm occur in this region during La Niña events while a lowering by around the same amount occurs during El Niño . It is during the periods when sea levels are already elevated that further amplification of sea levels from other short term weather events pose a particular risk for Singapore. Such events may be associated with the northeast monsoon. The occurrence of a tropical cyclone event at this time of year close to Singapore provides another example of an extreme event that can generate severe coastal impacts.

Understanding how the drivers of extreme sea levels may change in the future is essential to understanding how extreme sea levels themselves may change. Winds and waves in the South China Sea are projected to increase in some models but decrease in others over the months of the northeast monsoon. Despite the uncertainty in these changes, it is important that scenarios of wind speed increase and associated hydrodynamic and wave climate response around Singapore is considered in coastal impact assessments. Furthermore, several studies report a future increase in the rainfall associated with the northeast monsoon which, in conjunction with elevated coastal sea levels, is likely to exacerbate coastal flooding. ENSO is likely to increase in its intensity although this change in intensity is not likely to be constant through time. Tropical cyclones, although rare for Singapore, are projected to become more intense although it is likely that they will become less frequent.

This review provides an independent assessment of the broader literature related to sea level rise and extreme sea levels in Singapore and will provide context for the analysis of high resolution hydrodynamic and wave model simulations for Singapore. A key finding of this review that warrants further investigation in the high resolution hydrodynamic and wave modelling is to better identify the synoptic weather events that lead to extreme sea levels and waves in the South China Sea and to assess how they will change in the future.

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