Regional 21st Century Sea Level Projections for the NSW Coast

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Abstract

Sea levels have been rising globally, around Australia and along the NSW coast during the 20th century. Sea levels are projected to continue to rise during the 21st century and beyond, with significant regional differences. Based on Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models, sea level projections for the Australian region in the 21st century relative to 1986-2005 have been produced for four Representative Concentration Pathways (RCPs), which includes all components contributing to sea level changes, such as regional dynamic changes and ocean thermal expansion, glaciers, Greenland and Antarctic ice sheets, land water storage and Glacial Isostatic Adjustment (GIA). However, these regional projections have coarse-resolution (~100 km and above), while sea level adaptation and mitigation planners demand information on local sea level changes. To address this issue, we use a near-global 1/10^{o} ocean model to downscale both historical period and projections of the ensemble average of the CMIP5 models under a high emission scenario (RCP8.5). We then produce a high-resolution (1/10^{o}) total sea level projection, by combining dynamic sea level derived from the downscaling with all other contributing processes. This combination is based on the understanding that fingerprints associated with the GIA, melting of glaciers and ice sheets are large-scale (particularly true for the "far field" regions like Australia) and thus can be safely regridded to finer resolution. Regional sea level distribution around Australia associated with each contributing process is examined to demonstrate how they combine to generate the total sea level projection. The relationship of the high sea level projection off the NSW coast with changes of ocean gyre circulation, boundary currents and mesoscale eddies are much better represented in the high-resolution sea level projection. Our total sea level projection should be a valuable product for detailed coastal planning to address upcoming sea level changes.

1. Introduction

Sea level rise is one of central subjects related to anthropogenic climate change. Global mean sea level (GMSL) has been rising according to tide gauge and satellite altimetry measurements, and is projected to continue to rise in the future. Several physical processes can affect GMSL, including ocean thermal expansion, loss of mass of glaciers and ice caps (GIC), the surface mass balance and dynamic response to melting of the Antarctica ice sheet (AIS) and the Greenland ice sheet (GIS), and changes in land water storage. According to the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5) (Church et al. 2013), the GMSL rose 19 [17 to 21] cm between 1901 and 2010, while the projected GMSL changes between the periods 1986-2005 and 2081-2100, for the 5% to 95% confidence limits, are 26-55 cm under the low emission scenario - Representative Concentration Pathways (RCP) 2.6, and 45-82 cm under the high emission scenario - RCP8.5, with the possibility of a larger rise if there were a significant ice sheet instability.

Sea level changes are not expected to be spatially uniform, since several physical processes can cause regional sea level distributions such as ocean density and circulation change, melting of land ice (GIC, AIS and GIS), and Glacial Isostatic Adjustment (GIA) (e.g., Slangen et al. 2012; Church et al. 2013). It is the local sea level that the local communities directly experience and thus care about.

The regional sea level distribution associated with contemporary land ice melting (aka sea level fingerprint) has been estimated by solving the so-called "sea level equation", in which effects of gravitation, solid-earth deformation and rotation are all considered. The melting of land ice generally induces a non-uniform sea level distribution, with a sea level fall in the near field and a greater than global average sea level rise in the far field (e.g., Mitrovica et al. 2011). Similarly, ocean density and circulation changes can also cause significant regional sea level distributional features. Dynamic sea level (DSL), i.e., regional sea level relative to the global mean, which is determined by the dynamical balance associated with ocean density distribution and circulation. DSL is the only regional sea level process directly simulated by climate models so far, while the other contributing processes for regional sea level changes are generally computed off line. DSL in some regions can be quite large based on climate model simulation (e.g., Church et al. 2013).

Australia is a large island nation, with about half of its population living within 7 km of the coast (Chen and McAneney, 2006). White et al. (2014) completed a comprehensive review analysis of regional sea level around Australia from the 1880s to the present, and found that Australian sea levels can be generally explained by the global mean rise plus regional departures associated with climate variability and vertical land motion induced by the GIA and other local factors. In the 21st century, sea levels around Australia are projected to rise (McInnes et al. 2015). According to a recent report by the Climate Council of Australia, a 1.1 metre sea level rise (a high-end scenario in 2100) would put at risk $200 billion worth of infrastructure (including residential, recreational and commercial buildings, road and rail) (Steffen et al. 2014). The mean sea level rise will likely be felt through extreme sea level events, which lead to coastal flooding, inundation and erosion. Hence careful consideration, based on reliable projection of sea level rise, is critical for building up resilience to sea level rise or mitigating against its negative impacts.

In this study we produce mean sea level projections in the 21st century around Australia, in particular off the NSW coast, mainly based on the IPCC AR5 and

CMIP5 climate models, and further examine how different sea level processes combine to generate the total sea level projection with some interesting regional features. These coarse-resolution projections, similar to those reported in the IPCC AR5, are primarily designed for large-scale (~100 km and above) sea level changes, while sea level adaptation and mitigation planners demand information on local sea level changes. To address this issue, we use a near-global eddy-resolving (1/10^o) ocean model to downscale the DSL for both historical period and projections of the ensemble average of 17 CMIP5 models under the high emission scenario - RCP8.5. High-resolution (1/10^o) total sea level projections are also produced, by combining the DSL derived from downscaling with all other sea level contributing processes. Distinctive differences between the coarse- and high-resolution projections, and underlying dynamic processes are going to be examined.

2. Data Processing and Methodology

2.1 CMIP5 DSL Processing

Sea surface height relative to the Geoid, i.e., “ZOS” variable from CMIP5 models, are used in this study. The DSL, defined as regional sea level deviation from the global mean, is derived from “ZOS” with time-dependent global mean removed (e.g., Yin et al. 2012). Projections of future climate change in the 21st century are defined with reference to the “current-day” mean state over 1986-2005. The artificial drift in RCP experiments is estimated and removed (Sen Gupta et al. 2013). CMIP5 models have different horizontal grids, thus regridding and ensemble averaging may lead to missing values in the coastal regions. To better preserve information from individual model and provide ensemble averages close to coastline as much as possible, each model is regridded to a common global 0.5°×0.5° grid first, then any missing values close to the coastline are filled in with nearby grids with valid values, finally multi-model ensemble averages are derived. This mathematical in-filling technique provides a reasonable DSL distribution around Australia, though it’s fundamentally different from the physics-based in-filling technique, i.e., dynamical downscaling discussed later. The multi-model ensemble mean of DSL for each emission scenario is used to represent the regional sea level changes associated with ocean density and circulation changes.

2.2 Regional Sea Level Projections

Only in recent years have total sea level projections at the regional scale been attempted (e.g., Slangen et al. 2012, 2014; Church et al. 2011, 2013), with the basic idea that various sea level contributing processes can be linearly summed. Our projections of regional sea level generally follows Church et al. (2011), by combining published GMSL contributions by the IPCC and regional sea level contributions (including DSL and various sea level fingerprints) processed by CSIRO sea level group. Overall our regional sea level projections under all RCPs are very similar (but not identical) to those reported in the IPCC AR5 (Church et al.

2013), and provide data closer to coastline mainly because of our tailored DSL processing.

2.3 High-resolution Regional Sea Level Projections

CMIP-type global climate models, with coarse spatial resolution (e.g., typical 1^{o} resolution in the ocean component), are primarily designed to study large-scale climate change and variability globally over decades to centuries. Nonetheless, for the purpose of local applications including climate adaption and mitigation planning, end users want much finer resolutions than the typical resolutions of global climate models, at least tens rather than one hundred kilometres (IPCC 2014). Therefore, there are significant gaps in spatial resolution and reliability of climate information between what the state-of-the-art global climate models currently provide and what the end users wish to obtain, although gaps have been gradually shrinking because of ongoing model development efforts and advances in computational capacity.

The CSIRO Ocean Downscaling Strategic Project (CODSP), as a pioneering attempt to address these scale gaps mentioned above, uses a global high-resolution (1/10^{o}) ocean general circulation model (OGCM) to dynamically downscale climate changes in the 21st century derived from CMIP5 climate models. Global high-resolution (sometimes referred to as “eddy-resolving”) ocean models are highly desired for climate studies, but are challenging to run, because they require careful configuration and substantial computational resources. In the CODSP project, several strategies were developed so that a near-global high-resolution OGCM can be integrated for climate studies. The OGCM is basically the Ocean Forecasting Australia Model version 3 (OFAM3)(Oke et al. 2013; Zhang et al. 2016), based on the 4p1d version of the GFDL Modular Ocean Model (Griffies, 2009), which is configured to have 0.1^{o} grid spacing for all longitudes between 75^{o}S and 75^{o}N, and 51 vertical layers. The near-global OGCM is integrated over the historical period (1979-2014) driven by 3-hourly Japanese 55-year Reanalysis (JRA-55; source: http://jra.kishou.go.jp/JRA-55/index_en.html) fields of atmospheric forcing through bulk formula. The model is further integrated from the present to 2100, driven by merged atmospheric forcings which include high-frequency (daily to interannual) components from current-day JRA-55 reanalysis and long-term climate change signals from the ensemble of 17 CMIP5 models under RCP8.5. The “downscaled” changes in the ocean are derived by comparing ocean states from the future experiment with reference to those in the historical experiment, which, by design, are not affected by mean state biases in the 17 CMIP5 models. The consistently designed model runs (historical + future) from experiment over 1979 to 2100 provide high-resolution (1/10^{o}) climate change projections for all popular ocean state variables such as sea level.

The high-resolution DSL derived from dynamical downscaling is then merged with all other sea level contributing processes to produce a high-resolution (1/10^{0}) total sea level projection. This combination is based on the understanding that sea level fingerprints associated with the GIA, loss of mass of land ice (GIC, AIS and GIS) are large-scale, which is particularly true for the “far field” regions like Australia, therefore can be safely regridded to finer resolution (Mitrovica et al. 2011). The key difference between the high- and low-resolution total sea level projections is the DSL component, with the former coming from dynamical downscaling and the latter directly from CMIP5 models.

3. Results

DSL projections from CMIP5 models around Australia over 2080-2099 relative to 1986-2005 under 4 RCPs are shown in Fig. 1. DSL changes are strongest under the business-as-usual scenario – RCP8.5, the weakest under the strong-mitigation scenario – RCP2.6. The higher sea levels off the southeast coast are obvious under all RCPs except RCP2.6.

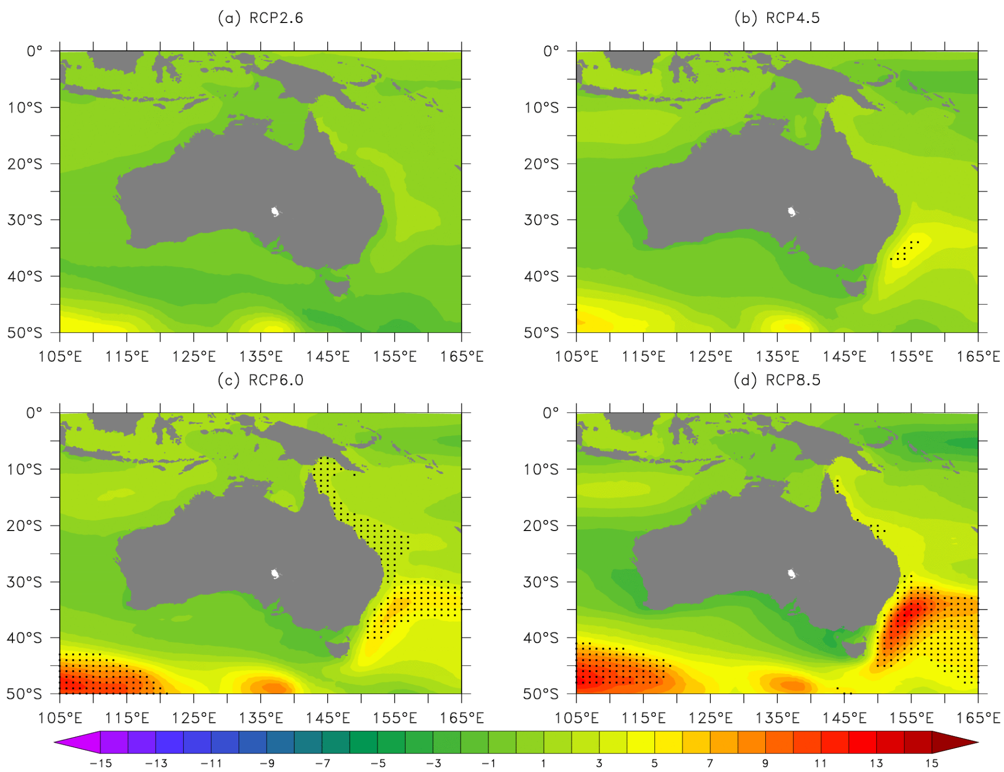

Figure 1. Dynamic sea level projections (cm) due to ocean density and circulation change for the Australian region over 2080-2099 relative to 1986-2005 under four emission scenarios. Stippling denotes regions where climate models tend to agree, defined as the regions where the magnitude of multi-model mean exceeds the inter-model standard deviation.

Using RCP8.5 as an example (Fig. 1d), there are high DSLs of 6~12 cm off the southeast coast of Australia, extending from ~30^{o}S to 45^{o}S. To the north, there is 3+ cm high DSLs along the east coast up to the Torres Strait. So there is a strong north-south contrast of DSL changes off the east coast, with smaller (higher) rise in the north (south). Along and off the Australian south coast, there are 2~4 cm negative DSL changes (lower sea level rise than the global average), with the maximum located just west of the Bass Strait. More negative DSL changes also extend to the southwest coast, implying possible common underlying process (ocean gyre circulation as discussed later). Along the Australian northwest and north coasts, the DSL changes are close to zero, although there is a zonal band of high DSL of 2 cm off the northwest coast, along 14^{o}S from 105^{o}E to 115^{o}E. Note that DSL is the only regional sea level process that is directly simulated by CMIP-type climate models so far, whose changes are closely related to changes in ocean density and circulation (e.g., Church et al. 2013; Zhang et al. 2014).

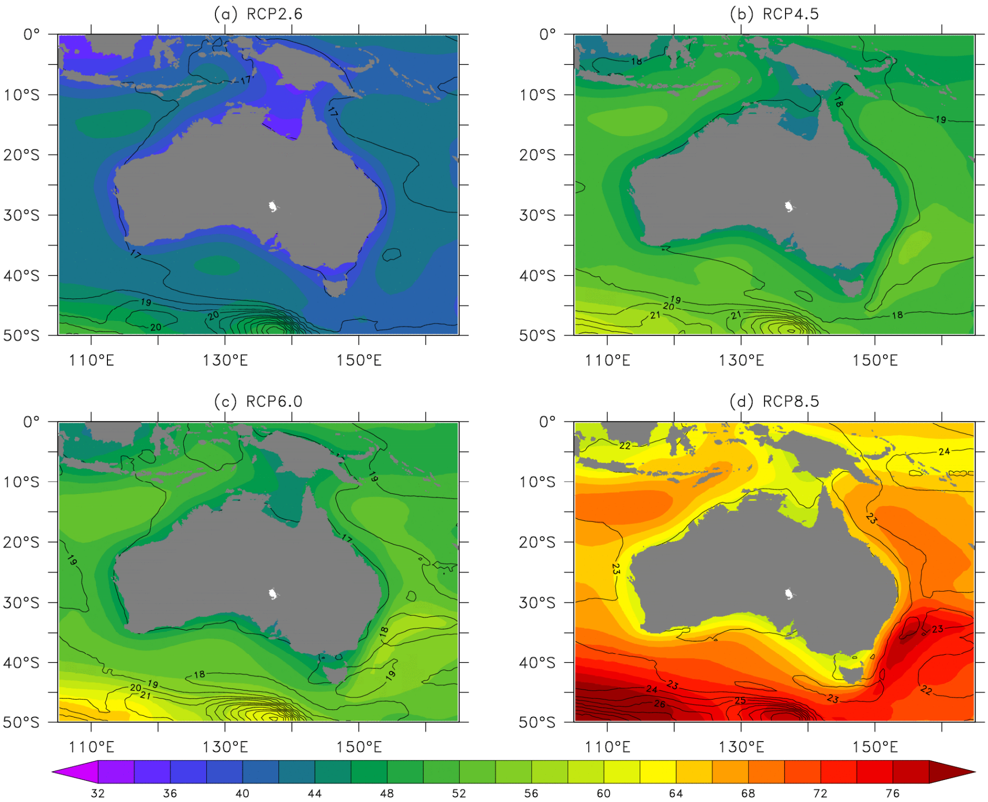

Figure 2. Total sea projections (cm) for the Australian region over 2080-2099 relative to 1986-2005 under four emission scenarios, with uncertainty indicated by contours.

Fig. 2 shows the total sea level projections around Australia over 2080-2099 relative to 1986-2005 under 4 RCPs. Higher projections can be found under the higher emission scenarios. Using RCP8.5 distribution in Fig. 2d as the reference, the spatial regression slope is 0.40 for RCP2.6 (Fig. 2a), 0.58 for RCP4.5 (Fig. 2b), and 0.74 for RCP6.0 (Fig. 2c). Obviously some regional features in the total sea level originate from regional DSL distribution (compare Fig. 1 and 2), implying that DSL is the dominant process determining regional distribution of total sea level projection. This is because that Australia is in the far fields of various fingerprints associated with loss of mass from the GIC, GIS and AIS, the combined sea level fingerprint has quite smooth regional distribution features around Australia. Along Australian coasts, the melting fingerprints causes 3~4 cm sea level rises (relative to global means), which are mainly compensated by the negative sea levels induced by GIA. So the total sea level projection around Australia is a result of a complex combination of various regional and global sea level processes.

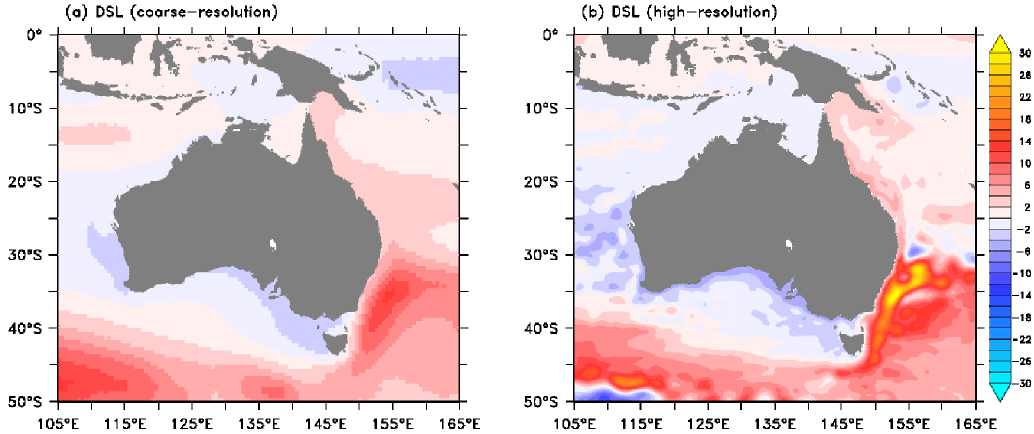

Figure 3. Dynamical sea level (DSL) change (cm) under RCP8.5 over 2081-2100 relative to 1986-2005, for the Australian region (a) from coarse-resolution CMIP5 ensemble and (b) the high-resolution downscaled product.

Although DSL is the dominant process determining regional distribution of sea level projection around Australia, CMIP climate models usually can't represent DSL sufficiently, mainly due to their coarse-resolution. Moreover, tailored data processing procedures, such as mathematical in-filling to ameliorate missing data near coast because of ensemble averaging, have to be carefully designed to get information up to the coast. In contrast, dynamic downscaling provides an alternative in-filling method, based on high-resolution model physics rather than mathematical technique.

The large-scale DSL distribution has similar patterns between coarse- and high-resolution products (Fig. 3a, b), but the high-resolution downscaled DSL has many detailed regional features which are absent in the coarse-resolution DSL. Especially, there is a narrow meridional band of high sea levels of 20~30 cm immediately off the southeast Coast, extending from ~30^{o}S to 45^{o}S (Fig. 3b). This regional distribution barely shows up in the coarse-resolution product, although smooth high sea levels with maximum slightly above 10 cm can be found further offshore (Fig. 3a).

Without the DSL contribution, the total sea level projections have a quite smooth spatial distribution, with quite uniform value along the coastline, as well as only a weak cross-shelf gradient (Fig. 4a). Including DSL contribution, for both low- and high-resolutions, dramatically increases regional diversity (Fig. 4). The contrast between low- and high-resolution DSL is preserved well in the contrast between two total sea level projections (see Fig. 3a, b and 4b, c). The mixing of low-resolution fingerprints with high-resolution DSL should be treated as an interim step towards high-resolution total sea level projection, but we show here it's an efficient solution especially for those "far-field" regions (far away from the sources of land ice melting).

The regional distribution of DSL with relatively high (low) sea levels off the southeast coast (south and southwest coast) is closely related to ocean circulation changes. Especially, subtropical ocean gyres in the southern hemisphere are projected to strengthen and shift poleward, the so-called “super-gyre spinup”, in response to the westerly wind changes (Ridgway and Dunn 2007; Cai et al. 2010; Zhang et al. 2014). So the DSL changes around Australia, especially high sea levels off the southeast coast, associated changes of ocean gyre circulation and boundary currents, are not just regional distributional features, but rather part of basin-scale oceanic changes in response to atmospheric forcing changes.

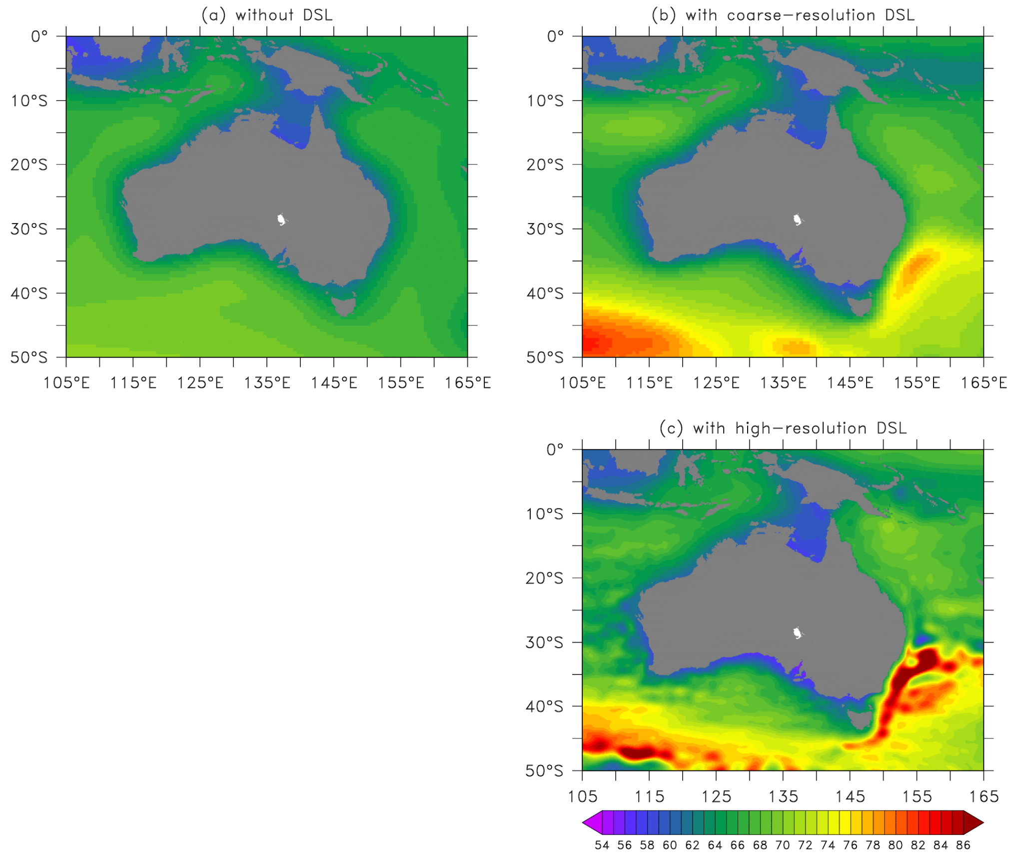

Figure 4. Projected sea level change (cm) for the Australian region over 2080-2099 relative to 1986-2005 under RCP8.5: (a) without DSL contribution, with (b) low-resolution (0.5°×0.5°) DSL and (c) high-resolution (0.1°×0.1°) DSL contribution. The figure is intentionally plotted to show its natural grids without interpolation.

4. Summary and Discussion

In this study, we presented total sea level projections around Australia by the end of 21st century, and examined different contribution processes. We found that among several regional processes, the dynamic sea level is the dominant term, leading to high sea level deviation on the order of 20~30 cm in the high-resolution projection (or ~10 cm in low-resolution projection) off the southeast coast of Australia.

We developed two data infilling methods - one is based on mathematical technique – fill missing value with nearby valid values, and the other is based on high-resolution model physics, i.e., dynamical downscaling. The latter method is shown to be a powerful tool to provide high-resolution sea level information, which is based on model physics thus can be interpreted with ocean dynamics well.

As a large island nation but with much of the population living near the coast, Australia will be significantly impacted by projected sea level rise. Hence careful consideration, based on a reliable forecast of sea level rise, is critical for building resilience to sea level rise and to be able to mitigate its negative impacts. Our sea level projections, in particular the high-resolution version, will be valuable products for cities and councils to develop their plans for adaptation and mitigation.

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