The effect of melting land-based ice masses on sea level around the Australian coastline

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Abstract

Changes in relative sea-level (RSL) are generally caused by variations in sea surface heights from steric effects (thermal expansion and salinity changes) and the mechanical response of the Earth to past and current redistributions of ice and water between land and oceans. This paper focuses on the latter, where we present scenario calculations of the spatial variability in present-day RSL change around the Australian coastline resulting from melting land-based ice masses. Three scenarios are investigated: (1) the ongoing effect of glacial isostatic adjustment (GIA) arising from ice- and water-load redistribution during the last glacial-interglacial transition, (2) the effect of present-day changes in the Greenland and West and East Antarctic ice sheets (GIS, WAIS and EAIS, respectively) and two regions of major mountain glaciation, Alaska and Patagonia, and (3) a hypothetical complete melting of the GIS, WAIS and EAIS occurring over 5000 years. The first scenario shows falling RSL around Australia of the order of 0.4 to 1.2 times the average value around the coast (equivalent to a RSL fall of between 0.2 to 0.6 mm a$^{-1}$). For the second scenario, the spatial variability is strongly dependent upon the location of each ice mass relative to Australia. For Greenland and Patagonia, the resulting changes to the Earth’s rotation strongly affect the spatial variability, while the direct gravitational effect is more important when considering the Antarctic ice sheets. The variability associated with the first two scenarios becomes clearer when examining RSL change estimates for the locations of tide-gauge stations around the Australian coast, especially for the ongoing GIA (a south to north increase in the simulated rate of RSL change), the WAIS (east to west increase) and the EAIS (south to north increase), with the melting of the EAIS potentially having the greatest influence on the variability of the melting land-based ice contribution to RSL change around Australia. The spatial variability associated with the third
scenario is strongly influenced over century-length time scales by the resulting changes in the Earth’s rotation and the direct gravitational attraction of the ice masses, while after several thousand years the uplift of the continent by mantle material displaced towards it by increased ocean loading becomes more prominent. It must, however, be kept in mind that the spatial variability associated with these scenarios is generally a small proportion of the total RSL change, and that the steric (especially thermosteric) contribution is not included in these results.
1 Introduction

Rising sea level is the aspect of climate change that has possibly attracted the most attention, both scientifically (e.g., Church et al., 2011; Slangen et al., 2011) and in terms of the general public’s concern, especially considering the potentially dire consequences to coastal urban areas and low-lying island nations (e.g., Nicholls & Mimura, 1998; Walsh et al., 2004; Church et al., 2006b,a; Nicholls & Cazenave, 2010; Nicholls, 2011). The Intergovernmental Panel on Climate Change 4th Assessment Report states that global sea level is rising at a rate of 3.1 mm a\(^{-1}\) (Bindoff et al., 2007), in close agreement with more recent estimates, for example 3.4 \(\pm\) 0.4 mm a\(^{-1}\) based on satellite altimetry (Cazenave & Llovel, 2010) and 3.3 \(\pm\) 0.5 mm a\(^{-1}\) from tide gauges (Prandi et al., 2009).

Relative sea-level (RSL) change is the vertical movement of the ocean surface relative to land at a given location, arising from changes in the volume of water that makes up the global ocean and/or movement of the land surface at the point in question. The volume of the ocean is most strongly affected by mass-balance changes in land-based ice masses (e.g., Shepherd & Wingham, 2007; Meier et al., 2007) and steric effects (ocean-volume changes without mass changes), especially the thermosteric (temperature) effect (e.g., Domingues et al., 2008). Halosteric (salinity) sea-level changes arising from freshwater input and the melting of sea ice, while relatively unimportant on a global scale, can have a significant effect regionally, sometimes almost counteracting the thermosteric component (e.g., Munk, 2003; Wunsch et al., 2007; Bindoff et al., 2007). Other processes affecting RSL include the Earth’s ongoing response to the melting of the late-Pleistocene ice sheets and the subsequent loading of the ocean basins following the Last Glacial Maximum (LGM, 26.5 to 19 ka BP, Clark et al., 2009), termed glacial isostatic adjustment.
(GIA, Lambeck, 1990, 1993; Peltier, 1999, 2004; Mitrovica et al., 2010), which also accompanies current ice-mass changes (see below). In addition, there is the exchange of water between terrestrial reservoirs and the oceans by natural and anthropogenic processes (e.g., Chao et al., 2008; Huntington, 2008), while over smaller spatial scales, tectonic displacement, sediment loading and anthropogenic activities such as groundwater and hydrocarbon extraction lead to RSL changes that are completely unrelated to climatic processes. These smaller-scale effects therefore need to be corrected for when employing datasets such as tide-gauge observations to enable the identification of climate-induced RSL changes (e.g., Belperio, 1993; Harvey et al., 2002).

RSL changes associated with land-based ice-volume fluctuations consist of the equivalent or eustatic component, which is the amount of water resulting from changes in ice volume divided by the area of the global ocean (e.g., Yokoyama et al., 2000), and the above mentioned GIA, leading to non-uniform RSL changes across the Earth (e.g., Clark & Lingle, 1977; Lambeck, 1993; Mitrovica et al., 2001, 2009; Milne et al., 2009; Kuhn et al., 2010; Mitrovica et al., 2010, 2011). The GIA contributions include the decreased gravitational attraction between the diminished ice mass and nearby ocean water, leading to sea level in the vicinity of the ice mass (known as the near-field) to rise at rates less than the global average, and in some cases fall, while far from the ice sheets (in the far-field) sea level will rise at rates greater than the global average (Lambeck, 1993). Accompanying this is the uplift of the Earth’s surface in the vicinity of the melting ice mass due to the reduced loading. For continental-scale ice sheets, the material forced from beneath the continent by the ice sheet’s earlier growth now flows back towards the area of ice loss, causing the collapse of the peripheral bulge or forebulge which surrounds the glaciated area (Lambeck, 1993; Peltier, 1999, 2004). If the forebulge is located above
mean sea level, then the collapse will contribute to a rise in RSL, while if it lies beneath the ocean, an increase in ocean basin volume results, contributing to a decrease in global sea level (Mitrovica & Peltier, 1991). The additional water mass from the melting ice sheets also loads the ocean basins, changing the ocean bathymetry (and volume) with mantle material being forced under land masses, contributing to the RSL change in coastal areas (e.g., Nakada & Lambeck, 1989; Lambeck & Nakada, 1990). The redistribution of mass between the land and oceans also modifies the Earth’s rotation, further affecting the spatial distribution of water across the globe (e.g., Milne & Mitrovica, 1998). In addition, a portion of the ocean water that floods areas following the collapse of marine-based ice sheets (e.g., West Antarctica) would be expelled as the ocean floor rebounds in response to the reduced loading (Mitrovica et al., 2009; Gomez et al., 2010), further complicating near-field RSL signals.

It is therefore clear that the spatial variability in RSL changes arising from land-based ice fluctuations must be considered. Different regions of ice-mass loss will induce a characteristic sea-level change signature or fingerprint across the Earth (Clark & Lingle, 1977; Mitrovica et al., 2001, 2009, 2010; Gomez et al., 2010; Riva et al., 2010; Mitrovica et al., 2011). What is relevant to today’s (and future) societies is therefore not only the globally averaged change in sea level, although this is the primary concern, but the change that can be expected in a particular region or locality. Such a question is especially of importance to populated coastal areas, where urban planning authorities need to consider future sea levels (e.g., Walsh et al., 2004; Nicholls, 2011).

Australia is generally considered to be tectonically stable, however, there are areas of minor tectonic activity as evident by irregularities in the height of the Last Interglacial...
(LIG, *ca.* 125 ka BP) shoreline. For example, in Stumpy Bay, northeast Tasmania, LIG sediments have been found at a height of 32 m, implying a tectonic uplift rate of *ca.* 0.2 mm a\(^{-1}\) (Murray-Wallace & Belperio, 1991; Lambeck, 2002). Nonetheless, there are extensive areas where the LIG shoreline reveals tectonic stability, e.g., the west coast of the Eyre Peninsula, South Australia, where the LIG shoreline is located at +2 m along 500 km of coastline. In addition, despite Australia experiencing limited glaciation during the LGM (Barrows et al., 2002), there is still ongoing GIA arising from the above mentioned process where the oceans loaded by melt water force mantle material towards the continent, leading to uplift, as well as the continuing adjustment of the ocean’s volume due to collapsing forebulges and ocean floor loading. Combined, this has caused RSL to fall by up to 3 m over the past 6000 to 7000 years around the Australian coastline (Lambeck & Nakada, 1990; Lambeck, 2002).

While the steric contribution (especially the thermosteric) also displays a great deal of spatial variability (e.g., Slangen et al., 2011), the aim of this study is to examine the spatial variability of sea-level change associated with melting land-based ice masses. Although a number of works have dealt with this issue on a global scale, this is the first work to our knowledge where these contributions to RSL change have been assessed specifically for the case of Australia. We do this by presenting simulated RSL changes corresponding to three scenarios: (1) the contribution arising from the ongoing GIA response of the Earth to the last glacial-interglacial transition, (2) the effect of the present-day melting of the Greenland and West and East Antarctic ice sheets (GIS, WAIS and EAIS, respectively) and two regions of mountain glaciation that are significant contributors to contemporary global sea-level change, Alaska and Patagonia (Figure 1), and (3) the RSL change that would occur if there was a hypothetical complete melting of the GIS, WAIS and EAIS
over a period of 5000 years. The results are presented for the Australian region as a whole and for the locations of a series of tide-gauge stations along the Australian coastline. These tide gauges are currently operating, with each providing >25 years of data (National Tidal Centre, 2009). The reason for choosing these sites is that observations from such instrumentation are a fundamental means of identifying RSL change in coastal areas. We concentrate on the spatial pattern of ice-mass-induced RSL change around Australia, as opposed to the actual quantities involved, because there is considerable uncertainty in the extent of the changes in these ice masses.

[FIGURE 1]
2 Methodology

In order to examine the contribution of the melting of land-based ice masses to the variability of RSL change along the Australian coastline, we employ the GIA modeling tool CALSEA (Nakada & Lambeck, 1987; Johnston, 1993; Lambeck et al., 1996; Johnston et al., 1997; Johnston & Lambeck, 1999). This tool is based on a formulation of the governing integral equation for sea-level change (e.g., Farrell & Clark, 1976) and incorporates the isostatic and gravitational responses of land and oceans to the transfer of ice and water mass, the associated variations in the Earth’s rotation and changing coastlines.

We assume a three-layer compressible earth model made up of an elastic lithosphere of thickness $H$, and upper and lower Maxwell viscoelastic mantles of viscosities $\eta_{UM}$ and $\eta_{LM}$, respectively (see below for the assumed values).

In the following, we present our results in terms of RSL change normalised to some quantity, henceforth referred to as the normalised RSL change. For the case of the ongoing GIA, we normalise our estimates with respect to the average change in RSL of a series of equidistant sites around the Australian coast, leading to $\Delta \zeta_{\text{RSL}}^{\text{GIA}} / \Delta \zeta_{\text{ave}}^{\text{GIA}}$, where $\Delta \zeta_{\text{RSL}}^{\text{GIA}}$ is the rate of RSL change associated with ongoing GIA at a given location, and $\Delta \zeta_{\text{ave}}^{\text{GIA}}$ is the average rate of the considered points. For estimates of RSL change associated with the present-day ice mass changes and the hypothetical complete melting of the GIS, WAIS and EAIS, $\Delta \zeta_{\text{RSL}}^{\text{ice}}$, we replace $\Delta \zeta_{\text{ave}}^{\text{GIA}}$ with the ice masses’ eustatic contributions, $\Delta \zeta_{\text{eust}}^{\text{ice}}$. This allows us to investigate the spatial variability in sea-level change independently of the actual magnitudes involved.

Since these calculations are a function of the ice and earth models used, there is some
degree of trade off between our assumptions about the volumes and distribution of ice and the Earth’s viscoelastic structure. By this, we mean that the same vertical displacement history of the Earth’s surface may arise from ice models with different mass distributions and growth and decay histories when coupled with an appropriate earth model. Therefore, to gain some measure of the uncertainty in our simulated values of RSL change, a range of ice and earth models is necessary. For the uncertainty associated with our assumed ice history, we employ versions of the nominal ice model scaled by ±10%. The total volumes of the major ice sheets are chosen to be compatible with the ESL estimates derived from far-field RSL observations. The error bars on these observations allow us to be confident that the total inferred ice volume is accurate to well within ±10%, however, we employ ± 10% for the sake of caution (Lambeck et al., 2002). For these calculations, a nominal viscosity profile is used, where \( H = 80 \text{ km} \), \( \eta_{UM} = 2 \times 10^{20} \text{ Pa s} \) and \( \eta_{LM} = 10 \times 10^{21} \text{ Pa s} \) (e.g., Lambeck, 2002; Yokoyama et al., 2006). To quantify the uncertainty related to the Earth’s imperfectly known viscosity structure, we use the nominal ice model and assess the scatter of RSL change estimates from an ensemble of forward model calculations where we vary each of the earth-model parameters one at a time, using \( H \) values of 70 and 90 km, \( \eta_{UM} \) of 1.5 and \( 3 \times 10^{20} \text{ Pa s} \), and \( \eta_{LM} \) of 5 and \( 30 \times 10^{21} \text{ Pa s} \) (Lambeck, 2002; Yokoyama et al., 2006). The uncertainty associated with each parameter at a given location is then given by half of the range between each pair of calculations, leading to the total uncertainty given by:

\[
\delta \zeta_{tot} = \sqrt{\delta \zeta_{\text{ice}}^2 + \delta \zeta_{H}^2 + \delta \zeta_{UM}^2 + \delta \zeta_{LM}^2}
\]  

(1)

where \( \delta \zeta_{tot} \) is the total uncertainty at a location, \( \delta \zeta_{\text{ice}} \) is the uncertainty associated with the
ice model, and $\delta Z_H$, $\delta Z_{UM}$, and $\delta Z_{LM}$ are the uncertainties associated with the lithosphere, upper-mantle and lower-mantle parameters, respectively. As we are mainly interested in the spatial variability of RSL change, we also express the uncertainties in terms of normalised RSL change.
3 Melting ice mass contributions to sea-level change

3.1 Ongoing contribution of the last glacial-interglacial transition

To estimate the spatial variability in the contribution to RSL change made by ongoing
GIA arising from the last glacial-interglacial transition, we employ as the nominal ice
model a recent compilation that incorporates changes in the major former and reduced ice
sheets (Laurentide, Fennoscandian, British Isles, Greenland, and Antarctica) as well as
areas of significant mountain glaciation (Patagonia, Alaska, and Tibet). In this scenario,
it must be emphasised that no water mass is being added or removed from the ocean
today. That is, the estimated present-day RSL changes for this scenario are only due to the
Earth’s ongoing mechanical response (surface displacement, gravity field and rotational
changes) to surface-load changes during the last glacial-interglacial transition (ca. 26 to 7
ka BP), with no steric effects included. Figure 2a presents our estimates of the normalised
RSL change around Australia arising from this process, where the average RSL change,
\( \Delta \zeta_{\text{GIA}}^{\text{ave}} \), for a series of equidistant points around the coast as found using the nominal
earth and ice models is -0.42 mm a\(^{-1}\), while Figure 2b shows the associated uncertainty
in the normalised RSL change (Eqn. 1). Note that to normalise the uncertainty, we find
the average of \( \Delta \zeta_{\text{GIA}}^{\text{ave}} \) considering each earth/ice model combination, the values of which
range from -0.37 to -0.47 mm a\(^{-1}\).

[FIGURE 2]

From Figure 2a, a north to south decrease in the rate of RSL change relative to the average
is observed, ranging from ca. 1.4 in the north to ca. 0.3 in the south. This corresponds to
actual values of ca. -0.6 to -0.2 mm a\(^{-1}\) around most of the coastline. The dominance of
the water-load contribution is apparent by how the contours tend to follow the coastline, reflecting the displacement of mantle material towards the interior of the continent and the uplift of the coastline (Lambeck & Nakada, 1990; Lambeck, 2002). The values of $\Delta \zeta_{GIA}^{rsl} / \Delta \zeta_{GIA}^{ave}$ are statistically significant, with uncertainties of ca. 0.1 mm a$^{-1}$ (Figure 2b). The bulk of the uncertainty comes from the upper-mantle viscosity (not shown here), followed by the ice-load model, the lower-mantle viscosity, and the lithosphere thickness. The choice of the latter three parameters appears to have a relatively minor effect on the results, corresponding to uncertainties equivalent to RSL changes of less than 0.05 mm a$^{-1}$.

### 3.2 Present-day melting of ice masses

We next examine our calculations of RSL change around Australia due to the GIA changes arising from the melting of contemporary ice masses, namely the GIS, WAIS, EAIS, and the Patagonian and Alaskan glaciers. The estimated change in the GIS is based on inferring the spatial distribution of mass loss from the RL04 release of the Gravity Recovery and Climate Experiment (GRACE), Center for Space Research, University of Texas at Austin (Tapley et al., 2004; Bettadpur, 2007) scaled to the value proposed by Velicogna (2009) (286 Gt a$^{-1}$). The mass loss from Alaska is based on estimates derived from airborne laser altimetry (Arendt et al., 2002) and for Patagonia from a time series of aerial photographs (Rignot et al., 2003). The WAIS and EAIS are treated as structurally distinct entities, separated by the Transantarctic Mountains (Bindschadler, 2006). The WAIS is a marine-based ice sheet that is thought to be experiencing considerable melting and its possible collapse and the accompanying sea-level rise is of great concern (e.g., Oppen-
heimer, 1998; Bamber et al., 2009). On the other hand, changes in the EAIS are still uncertain, with the possibility that it may be gaining mass, although not enough to offset the loss from the WAIS (e.g., Shepherd & Wingham, 2007). The spatial distribution of mass-change for these ice masses is from Rignot & Thomas (2002), which is, in turn, scaled to the estimate of Velicogna (2009) (246 Gt a\(^{-1}\)). Incidentally, the mass balance estimate from Rignot & Thomas (2002) indicates a positive change in the EAIS, hence its present-day eustatic contribution would be negative. The resulting rates of eustatic sea-level change for the GIS, WAIS, EAIS and the combined Alaska/Patagonia glaciers are thus +0.77, +0.66, -0.15 and +0.25 mm a\(^{-1}\), respectively, giving a total rate of eustatic sea-level change of +1.53 mm a\(^{-1}\). We use these values when we normalise the effects of each ice sheet (and their sum) around Australia. It needs to be stated that this is not an exhaustive list of ice masses, as considering only the Alaskan and Patagonian ice masses accounts for around 25% of the contribution of glaciers and ice caps (Meier et al., 2007). However, they are major contributors, and their different locations leads to some differences in their effects.

Figure 3 shows the resulting normalised RSL change for each of these ice masses (note, Alaska and Patagonia are treated together). As mentioned in the introduction, the melting of ice masses also affects sea level by modifying the Earth’s rotation. This effect is more difficult to visualize because it is strongly dependent upon the position of the ice mass relative to the site in question, the general global form being dominated by the degree-two/order-one spherical harmonic (e.g., Figure 12 in Mitrovica et al., 2005). This effect is illustrated in Figure 3, where the normalised RSL change for each ice mass is presented with (Fig. 3a-d) and without (Fig. 3e-h) the rotational contribution.
The loading of the oceans by the melt water from these ice masses is again seen to displace mantle material towards the interior of the land areas, reducing slightly the rise in RSL change with respect to the eustatic value, most noticeable for the non-rotating cases of Greenland (Fig. 3e) and Alaska-Patagonia (Fig. 3f). For the Antarctic ice sheets, and the EAIS in particular (Figure 3c,d,g,h), the direct gravitational effect is more prominent, given the greater size and proximity of these ice sheets compared to the other ice masses considered. While the EAIS in this scenario has a negative eustatic contribution (i.e., the ice sheet has a positive mass balance), the actual spatial variability would remain the same if this were positive (i.e., the ice sheet has a negative mass balance), assuming the spatial distribution of ice-mass change stays proportionally the same.

With regards to the effect of the changes to the Earth’s rotation, it is most obvious in the example of Greenland (Figure 3a,e) where incorporating the rotational component produces a markedly smaller change in RSL than in the case where it is neglected. For the combined Alaska-Patagonia results (Figure 3b,f), the rotational contribution of the Patagonian glaciers is the greater, since the relative locations of Alaska and Australia are such that Australia lies within a nodal line of the Alaskan rotational effect. Since Patagonia is approximately aligned longitudinally with Greenland, but in the opposite hemisphere, it induces the opposite effect (i.e., an increase in the normalised RSL change). Because of their relatively high latitudes (i.e., closer to the rotation pole), the Antarctic ice sheets’ rotational contributions are not as apparent as for the other ice masses studied here that are further from the poles (e.g., Gomez et al., 2010).

[FIGURE 3]

Figure 4 presents the total normalised RSL change arising from the melting of the present-
day ice masses (Figure 4a), the total normalised RSL change (Figure 4b) considering on-
going GIA (Figure 2) and present-day melting (Figure 3), along with the total uncertainty
(Figure 4c) (in this figure we mask out the land areas to emphasise the change along the
coast). We determine the total normalised RSL change by adding the change associated
with the ongoing GIA to that from all ice masses considered and dividing this sum by the
sum of the average of the ongoing GIA and the total eustatic contribution. The ongoing
GIA contribution is still apparent by the contours following the coastline, which leads to
considerably lower rates of local sea-level rise around Australia when compared to the
present-day melting. In terms of actual values, the contribution to RSL change from these
processes is of the order of ca. +1.1 to +1.5 mm a\(^{-1}\), with an uncertainty of ca. 0.15 mm
a\(^{-1}\).

We now present these results in terms of the variability in RSL change at the locations of
tide-gauge stations along the Australian coast (Table 1, Figure 5). Table 1 lists our esti-
mates for the normalised RSL change at each site associated with the employed scenarios
of ongoing GIA, the present-day contributions of the ice masses considered, and the total.
From Figure 5a, one sees that there is a general decreasing trend from the south-west to
north-east in the RSL change associated with land-based ice-mass changes plus the ongo-
ing GIA contribution. This leads to differences from the combined average ongoing GIA
and total eustatic contribution ranging from +32% for Hobart, to -4% for Port Pirie. In
terms of actual amounts of RSL rise modelled using the nominal ice and earth models (not
listed in Table 1), over a 100-year period and assuming the rates are constant, town plan-
ners in Darwin (site 1, Table 1) would need to consider the processes outlined in this work
as leading to a sea-level rise of 11.8 cm, while their counterparts in Hobart (site 19) will be confronted with a rise of around 14.8 cm, while for Port Pirie (site 22), this would be of the order of 10.7 cm. This variability in the land-based ice-mass RSL change between tide-gauge stations is shown in Figure 5b, where a general south-to-north increase in the amount associated with the ongoing GIA is apparent, with strong variability being discerned amongst the Spencer Gulf tide gauges (numbers 20 to 24). Examining the GIS and WAIS results, the values show less variability, with only a slight north-south decreasing trend from the GIS and an east-west increasing trend resulting from the WAIS. However, the EAIS shows a stronger south-north increasing trend, leading to the situation where, if the EAIS were to begin to contribute significant amounts of melt water to the oceans, then the north-south difference in the expected sea-level rise would be of the order of 40% of its eustatic contribution.

3.3 Hypothetical total melting of present-day ice sheets

As a final exercise, we examine the RSL change around Australia that would arise from the hypothetical complete melting of the GIS, WAIS and EAIS, making use of the ice thickness estimates of Ekholm (1996) (GIS) and Lemoine et al. (1998) (WAIS and EAIS). Similarly to Kuhn et al. (2010), we assume this melting would take place linearly over a period of 5000 years. While the choice of 5000 years is somewhat arbitrary, for example, some workers have proposed that the GIS could lose ca. 75% of its mass within 1000
years (Huybrechts & De Wolde, 1999), the purpose of this exercise is to show how the
spatial variability associated with the melting of these ice masses will vary over time as
a result of the Earth’s mechanical response. Based on the above mentioned descriptions
of these ice sheets and as determined by the CALSEA program, the complete melting of
these ice sheets provides an eustatic sea-level rise of 7.0, 8.6 and 55.9 metres for the GIS,
WAIS and EAIS, respectively.

As the spatial variability associated with each ice sheet displays a similar pattern to that
discussed in the previous section, we only present in Figure 6 the combined effect of the
melting of these ice sheets, where the total response, $\Delta \zeta_{hyp}^{rsl}$, is normalised by the total
eustatic contribution $\Delta \zeta_{eust}$. Comparing the results after 100 years of melting with those
after it has been completed, we note that the GIA effects are more apparent after 5000
years owing to the loading of the oceans and the subsequent forcing of mantle material
to beneath the Australian continent with the accompanying uplift, although still only of
the order generally of 5 to 15% of the total RSL change. As the EAIS is the largest mass
considered, the spatial variability associated with its melting dominates the combined
signal. The uncertainties associated with the choice of earth model (not shown) in the
normalised RSL change also vary over time, although it is rather small, increasing from
less than 1% at 100 years after melting starts to around 2% after 5000 years.

[FIGURE 6]
4 Conclusions

We have examined the variability in RSL change around the Australian coastline resulting from the ongoing effect of the Earth’s adjustment to the last glacial-interglacial transition, the melting of present-day ice masses and a possible future melting scenario. We summarize our results as follows:

• The ongoing readjustment of the Earth to changes in surface loading (land-based ice and ocean water) following the LGM causes a fall in sea level around Australia of the order of 1.4 to 0.3 times the mean value found from a series of equidistant points around the coastline (corresponding to actual values of between -0.6 to -0.2 mm a\(^{-1}\)), with an uncertainty in the normalised RSL change of ca. 0.1 (Figure 2). This is a result of the adjustment of the global ocean’s bathymetry to the increased water load, and accompanying uplift of the coastline caused by the forcing of mantle material to beneath the Australian continent.

• The form of the spatial variability in RSL change associated with the melting of present-day ice masses is strongly dependent upon the location of each ice mass relative to Australia (Figure 3). For Greenland and Patagonia, the rotation effect has a significant effect on the variability pattern, while for Alaska this is less important owing to Australia being located around a nodal line. For the Antarctic ice sheets, the direct gravitational effect dominates, especially in the case of the EAIS. When examined for the locations of representative tide-gauge stations (Figure 5 and Table 1), the variability arising from each contribution becomes more apparent, especially for the ongoing GIA (a south to north increase), the WAIS (east to west increase)
and the EAIS (south to north increase). Of the present-day ice sheets, the EAIS has
the potential to influence most the variability of RSL change across the continent
owing to its proximity compared to the other ice masses considered. However,
the actual variability is usually only a relatively small proportion of the eustatic
contribution.

- The spatial variability of the sea-level rise associated with a hypothetical complete
melting of the major ice sheets is dominated at first (over century-length time scales)
by the changes in the Earth’s rotation and direct gravitational attraction of the ice
masses. After several thousand years, however, the effect of the ocean loading
and earth deformation becomes more prominent, modifying the ocean volume and
inducing uplift of the continent and slightly reducing the total change. Again, the
EAIS is seen to potentially dominate the variability around Australia (Figure 6).

In summary, assuming the melting regime as applied in this work, the contribution to
RSL change from melting land-based ice will be less for areas along the Great Australian
Bight and northern Australia, with a greater contribution along much of Western Australia
and Tasmania, although this is naturally dependent upon the actual behaviour of the ice
masses. For example, this scenario assumes the EAIS melts proportionally at the same
rate as the WAIS, although it is considered to be more stable than the WAIS (e.g., Barker
et al., 1999). Hence, we caution readers that the spatial variability seen in Fig. 5 cannot be
simply extrapolated to higher melt rates without going back to Table 1 and recomputing
the last column with different (higher) weightings on the melt sources. Nonetheless, it
needs to be emphasised that the differences in RSL change around the Australian coastline
are generally relatively small when compared to the eustatic contribution. Likewise, the
actual RSL change values are, of course, dependent upon the estimates of present day ice-mass loss employed, in which there is still some degree of uncertainty (e.g., Cazenave & Llovel, 2010). This includes the spatial pattern of the mass change in the glaciated regions considered in this study, although this would have a relatively minor effect given the large distances between Australia and these regions. Finally, for a more complete picture of the spatial variability in RSL change around Australia, the other land-based ice masses will need to be considered, as well as the steric contributions.
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Murray-Wallace, C. & Belperio, A., 1991. The last interglacial shoreline in Aus-


Table and Figure Captions

Table 1: Normalised RSL change for tide-gauge stations around the Australian coastline (Figure 5a, National Tidal Centre, 2009) when considering ongoing GIA, the ice sheets considered in this work and the total.

Figure 1: The location of the ice sheets and glaciers considered in this work. (a) The northern hemisphere ice masses (light grey - Greenland, dark grey - Alaskan mountain glaciers), (b) the southern hemisphere ice masses (light grey - West and medium grey - East Antarctica, dark grey - Patagonia).

Figure 2: (a) The normalised RSL change around Australia arising from ongoing GIA. (b) The uncertainty in these values (see Eqn. 1).

Figure 3: The normalised RSL change around Australia arising from present-day melting in (a,e) Greenland, (b,f) Alaska and Patagonia, (c,g) West Antarctica, (d,h) East Antarctica. Left-hand column (a-d) includes the effect of Earth-rotation changes, while for the right-hand column they are excluded.

Figure 4: (a) Total normalised RSL change around Australia resulting from the present-day ice mass changes. (b) The total normalised RSL change combining ongoing GIA (Figure 2) and present-day ice-mass loss (Figure 3). (c) The uncertainty associated with the values in (b), based on the range of model parameters.

Figure 5: (a) Location of the tide-gauge stations listed in Table 1 (National Tidal Centre, 2009) and the associated total normalised RSL change. The large black circle denotes Spencer Gulf. (b) Normalised RSL change for tide gauges around Australia (Table 1) resulting from ongoing GIA and the present-day melting of the GIS, WAIS and EAIS.
The light grey band identifies the tide gauges in Spencer Gulf.

**Figure 6:** Normalised RSL change around the Australian coastline resulting from the complete melting of the GIS, WAIS and EAIS. (a) 100 years after melting begins, (b) when melting has been completed after 5000 years.
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<th>Latitude [°]</th>
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<th>GIS</th>
<th>Patagonia</th>
<th>Alaska</th>
<th>WAIS</th>
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Figure 2:
Figure 3:
Figure 4:
Figure 5:
Figure 6: