Originally published as:

Fleming, K., Tregoning, P., Kuhn, M., Purcell, A., McQueen, H. (2012): The effect of melting land-based ice masses on sea-level around the Australian coastline. - Australian Journal of Earth Sciences, 59, 4

DOI: 10.1080/08120099.2012.664828

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

K. Fleming^{*,1,3}, P. Tregoning², M. Kuhn¹, A. Purcell² and H. McQueen²

¹ Department of Spatial Sciences and The Institute for Geoscience Research,
Curtin University,
GPO Box U1987, Perth, Western Australia, 6845, Australia.

² Research School of Earth Sciences,
The Australian National University,
Canberra, ACT, 0200, Australia.

³ Earthquake Risk and Early Warning,
Helmholtz Centre Potsdam German Research Centre for Geosciences,
D-14467, Potsdam, Germany.

* Corresponding author

Phone: +49 (0) 331 288 28662

E-mail: kevin@gfz-potsdam.de

Keywords: *Australia, sea-level change, glacial isostatic adjustment, ice-mass changes,
ocean loading, tide gauges.*

22 Abstract

23 Changes in relative sea-level (RSL) are generally caused by variations in sea surface
 24 heights from steric effects (thermal expansion and salinity changes) and the mechani-
 25 cal response of the Earth to past and current redistributions of ice and water between land
 26 and oceans. This paper focuses on the latter, where we present scenario calculations of
 27 the spatial variability in present-day RSL change around the Australian coastline result-
 28 ing from melting land-based ice masses. Three scenarios are investigated: (1) the ongoing
 29 effect of glacial isostatic adjustment (GIA) arising from ice- and water-load redistribution
 30 during the last glacial-interglacial transition, (2) the effect of present-day changes in the
 31 Greenland and West and East Antarctic ice sheets (GIS, WAIS and EAIS, respectively)
 32 and two regions of major mountain glaciation, Alaska and Patagonia, and (3) a hypothet-
 33 ical complete melting of the GIS, WAIS and EAIS occurring over 5000 years. The first
 34 scenario shows falling RSL around Australia of the order of 0.4 to 1.2 times the average
 35 value around the coast (equivalent to a RSL fall of between 0.2 to 0.6 mm a⁻¹). For the
 36 second scenario, the spatial variability is strongly dependent upon the location of each
 37 ice mass relative to Australia. For Greenland and Patagonia, the resulting changes to the
 38 Earth's rotation strongly affect the spatial variability, while the direct gravitational effect
 39 is more important when considering the Antarctic ice sheets. The variability associated
 40 with the first two scenarios becomes clearer when examining RSL change estimates for
 41 the locations of tide-gauge stations around the Australian coast, especially for the ongoing
 42 GIA (a south to north increase in the simulated rate of RSL change), the WAIS (east to
 43 west increase) and the EAIS (south to north increase), with the melting of the EAIS po-
 44 tentially having the greatest influence on the variability of the melting land-based ice con-
 45 tribution to RSL change around Australia. The spatial variability associated with the third

46 scenario is strongly influenced over century-length time scales by the resulting changes
47 in the Earth's rotation and the direct gravitational attraction of the ice masses, while after
48 several thousand years the uplift of the continent by mantle material displaced towards it
49 by increased ocean loading becomes more prominent. It must, however, be kept in mind
50 that the spatial variability associated with these scenarios is generally a small proportion
51 of the total RSL change, and that the steric (especially thermosteric) contribution is not
52 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 $3.4 \pm 0.4 \text{ mm a}^{-1}$ based on satellite altimetry (Cazenave & Llovel, 2010) and $3.3 \pm 0.5 \text{ mm a}^{-1}$ 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

147 over a period of 5000 years. The results are presented for the Australian region as a
148 whole and for the locations of a series of tide-gauge stations along the Australian coast-
149 line. These tide gauges are currently operating, with each providing >25 years of data
150 (National Tidal Centre, 2009). The reason for choosing these sites is that observations
151 from such instrumentation are a fundamental means of identifying RSL change in coastal
152 areas. We concentrate on the spatial pattern of ice-mass-induced RSL change around
153 Australia, as opposed to the actual quantities involved, because there is considerable un-
154 certainty in the extent of the changes in these ice masses.

155 [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 η_{UM} and η_{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, $\Delta\zeta_{\text{eus}}^{\text{ice}}$. 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

178 degree of trade off between our assumptions about the volumes and distribution of ice and
 179 the Earth's viscoelastic structure. By this, we mean that the same vertical displacement
 180 history of the Earth's surface may arise from ice models with different mass distributions
 181 and growth and decay histories when coupled with an appropriate earth model. Therefore,
 182 to gain some measure of the uncertainty in our simulated values of RSL change, a range
 183 of ice and earth models is necessary. For the uncertainty associated with our assumed ice
 184 history, we employ versions of the nominal ice model scaled by $\pm 10\%$. The total volumes
 185 of the major ice sheets are chosen to be compatible with the ESL estimates derived from
 186 far-field RSL observations. The error bars on these observations allow us to be confident
 187 that the total inferred ice volume is accurate to well within $\pm 10\%$, however, we employ
 188 $\pm 10\%$ for the sake of caution (Lambeck et al., 2002). For these calculations, a nominal
 189 viscosity profile is used, where $H = 80$ km, $\eta_{UM} = 2 \times 10^{20}$ Pa s and $\eta_{LM} = 10 \times 10^{21}$ Pa
 190 s (e.g., Lambeck, 2002; Yokoyama et al., 2006). To quantify the uncertainty related to the
 191 Earth's imperfectly known viscosity structure, we use the nominal ice model and assess
 192 the scatter of RSL change estimates from an ensemble of forward model calculations
 193 where we vary each of the earth-model parameters one at a time, using H values of 70
 194 and 90 km, η_{UM} of 1.5 and 3×10^{20} Pa s, and η_{LM} of 5 and 30×10^{21} Pa s (Lambeck,
 195 2002; Yokoyama et al., 2006). The uncertainty associated with each parameter at a given
 196 location is then given by half of the range between each pair of calculations, leading to
 197 the total uncertainty given by:

$$\delta\zeta_{\text{tot}} = \sqrt{\delta\zeta_{\text{ice}}^2 + \delta\zeta_H^2 + \delta\zeta_{UM}^2 + \delta\zeta_{LM}^2} \quad (1)$$

198 where $\delta\zeta_{\text{tot}}$ is the total uncertainty at a location, $\delta\zeta_{\text{ice}}$ is the uncertainty associated with the

ice model, and $\delta\zeta_{\text{H}}$, $\delta\zeta_{\text{UM}}$, and $\delta\zeta_{\text{LM}}$ 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, $\Delta\zeta_{\text{ave}}^{\text{GIA}}$, 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 $\Delta\zeta_{\text{ave}}^{\text{GIA}}$ 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 $\Delta\zeta_{\text{rsl}}^{\text{GIA}}/\Delta\zeta_{\text{ave}}^{\text{GIA}}$ 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 (Bindshadler, 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 $+0.25 \text{ mm a}^{-1}$, respectively, giving a total rate of eu-
static sea-level change of $+1.53 \text{ mm a}^{-1}$. 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.

270 The loading of the oceans by the melt water from these ice masses is again seen to displace
 271 mantle material towards the interior of the land areas, reducing slightly the rise in RSL
 272 change with respect to the eustatic value, most noticeable for the non-rotating cases of
 273 Greenland (Fig. 3e) and Alaska-Patagonia (Fig. 3f). For the Antarctic ice sheets, and
 274 the EAIS in particular (Figure 3c,d,g,h), the direct gravitational effect is more prominent,
 275 given the greater size and proximity of these ice sheets compared to the other ice masses
 276 considered. While the EAIS in this scenario has a negative eustatic contribution (i.e., the
 277 ice sheet has a positive mass balance), the actual spatial variability would remain the same
 278 if this were positive (i.e., the ice sheet has a negative mass balance), assuming the spatial
 279 distribution of ice-mass change stays proportionally the same.

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

291 [FIGURE 3]

292 Figure 4 presents the total normalised RSL change arising from the melting of the present-

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

304 [FIGURE 4]

305 We now present these results in terms of the variability in RSL change at the locations of
 306 tide-gauge stations along the Australian coast (Table 1, Figure 5). Table 1 lists our esti-
 307 mates for the normalised RSL change at each site associated with the employed scenarios
 308 of ongoing GIA, the present-day contributions of the ice masses considered, and the total.
 309 From Figure 5a, one sees that there is a general decreasing trend from the south-west to
 310 north-east in the RSL change associated with land-based ice-mass changes plus the ongoing
 311 GIA contribution. This leads to differences from the combined average ongoing GIA
 312 and total eustatic contribution ranging from +32% for Hobart, to -4% for Port Pirie. In
 313 terms of actual amounts of RSL rise modelled using the nominal ice and earth models (not
 314 listed in Table 1), over a 100-year period and assuming the rates are constant, town plan-
 315 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.

[TABLE 1]

[FIGURE 5]

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, $\Delta\zeta_{\text{rsl}}^{\text{hyp}}$, is normalised by the total eustatic contribution $\Delta\zeta_{\text{eust}}^{\text{hyp}}$. 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

401 actual RSL change values are, of course, dependent upon the estimates of present day ice-
402 mass loss employed, in which there is still some degree of uncertainty (e.g., Cazenave &
403 Llovel, 2010). This includes the spatial pattern of the mass change in the glaciated regions
404 considered in this study, although this would have a relatively minor effect given the large
405 distances between Australia and these regions. Finally, for a more complete picture of the
406 spatial variability in RSL change around Australia, the other land-based ice masses will
407 need to be considered, as well as the steric contributions.

408 **5 Acknowledgments**

409 We thank the suggestions made by the reviewers, whose comments have greatly improved
410 this manuscript. This research was supported under the Australian Research Council's
411 Discovery Projects funding scheme (project DP087738, *Environmental geodesy: varia-*
412 *tions of sea level and water storage in the Australian region*). M. Kuhn acknowledges the
413 support of a Curtin Research Fellowship. This work is Tiger publication number 398.

References

- Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., & Valentine, V. B., 2002. Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level, *Science*, **297**, 382–386, DOI: 10.1126/science.1072497.
- Bamber, J., Riva, R., Vermeersen, B., & LeBrocq, A., 2009. Reassessment of the potential sea-level rise from a collapse of the West Antarctica Ice Sheet, *Science*, **324**, 901–903, DOI: 10.1126/science.1169335.
- Barker, P., Barrett, P., Cooper, A., & Huybrechts, P., 1999. Antarctic glacial history from numerical models and continental margin sediments, *Paleogeography, Palaeoclimatology, Palaeoecology*, **150**(3-4), 247–267, DOI: 10.1016/S0031-0182(98)00224-7.
- Barrows, T., Stone, J., Fifield, L., & Cresswell, R., 2002. The timing of the Last Glacial Maximum in Australia, *Quaternary Science Reviews*, **21**, 159–173, DOI: 10.1016/S0277-3791(01)00109-3.
- Belperio, A., 1993. Land subsidence and sea level rise in the Port Adelaide estuary: Implications for monitoring the greenhouse effect, *Australian Journal of Earth Sciences*, **40**(4), 359–368, DOI: 10.1080/08120099308728087.
- Bettadpur, S., 2007. UTCSR Level-2 Processing Standards Document for Level-2 Product Release 0004, Gravity Recovery and Climate Experiment (GRACE) Rev 3.1, GRACE 327-742 (CSR-GR-03-03), Center for Space Research, The University of Texas at Austin.
- Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., C., L. Q., Levitus, S., Nojiri, Y., Shum, C., Talley, L., & Unnikrishnan, A., 2007.

- 436 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I*
 437 *to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*,
 438 chap. Observations: Oceanic Climate Change and Sea Level, Cambridge University
 439 Press.
- 440 Bindshadler, R., 2006. The environment and evolution of the West Antarctic ice sheet:
 441 setting the stage, *Philosophical Transactions of the Royal Society*, **364**, 1583–1605,
 442 DOI: 10.1098/rsta.2006.1790.
- 443 Cazenave, A. & Llovel, W., 2010. Contemporary sea level rise, *Annual Review of Marine*
 444 *Science*, **2**, 145–173, DOI: 10.1146/annurev-marine-120308-081105.
- 445 Chao, B., Wu, Y., & Li, Y., 2008. Impact of artificial reservoir water impoundment on
 446 global sea level, *Science*, **320**, 212–214, DOI: 10.1126/science.1154580.
- 447 Church, J., Hunter, J., McInnes, K., & White, N., 2006. Sea-level rise around the Aus-
 448 tralian coastline and the changing frequency of extreme sea-level events, *Australian*
 449 *Meteorological Magazine*, **55**, 253–260.
- 450 Church, J., White, N., & Hunter, H., 2006. Sea-level rise at tropical Pacific
 451 and Indian Ocean islands, *Global and Planetary Change*, **53**, 155–168, DOI:
 452 10.1016/j.gloplacha.2006.04.001.
- 453 Church, J., Gregory, J., White, N., Platten, S., & Mitrovica, J., 2011. Under-
 454 standing and projecting sea level change, *Oceanography*, **24**(2), 130–143, DOI:
 455 10.5670/oceanog.2011.33.
- 456 Clark, J. & Lingle, C., 1977. Future sea-level changes due to West Antarctic ice sheet
 457 fluctuations, *Nature*, **269**, 206–209, DOI: 10.1038/269206a0.

- Clark, P., Dyke, A., Shakun, J., Carlson, A., Clark, J., Wohlfarth, B., Mitrovica, J.,
Hostetler, S., & McCabe, A., 2009. The Last Glacial Maximum, *Science*, **325**, 710–
714, DOI: 10.1126/science.1172873.
- Domingues, C., Church, J., White, N., Gleckler, P., Wijffels, S., Barker, P., & Dunn, J.,
2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise,
Nature, **453**, 1090–1094, DOI: 10.1038/nature07080.
- Ekholm, S., 1996. A full coverage, high resolution, topographic model of Greenland
computed from a variety of digital elevation data, *Journal of Geophysical Research*,
101(B10), 21961–21972, DOI: 10.1029/96JB01912.
- Farrell, W. & Clark, J., 1976. On postglacial sea level, *Geophysical Journal of the Royal
Astronomical Society*, **46**, 647–667, DOI: 10.1111/j.1365–246X.1976.tb01252.x.
- Gomez, N., Mitrovica, J., Tamisiea, M., & Clark, P., 2010. A new projection of sea level
change in response to collapse of marine sectors of the Antarctic Ice Sheet, *Geophysical
Journal International*, **180**, 623–634, DOI: 10.1111/j.1365–246X.2009.04419.x.
- Harvey, N., Belperio, A., Bourman, R., & Mitchell, W., 2002. Geologic, isostatic and an-
thropogenic signals affecting sea level records at tide gauge sites in southern Australia,
Global and Planetary Changes, **32**, 1–11, DOI: 10.1016/S0921–8181(01)00145–X.
- Huntington, T., 2008. Can we dismiss the effect of changes in land-based water storage
on sea-level rise, *Hydrological processes*, **22**, 717–723, DOI: 10.1126/hyp.7001.
- Huybrechts, P. & De Wolde, J., 1999. The dynamic response of the Greenland and Antarc-
tic ice sheets to multiple-century climatic warming, *Journal of Climate*, **12**(8), 2169–
2188, DOI: 10.1175/1520–0442(1999)012<2169:TDROTG>2.0.CO;2.

- Johnston, P., 1993. The effect of spatially non-uniform water loads on prediction of sea-level change, *Geophysical Journal International*, **114**, 615–634, DOI: 10.1111/j.1365–246X.1993.tb06992.x.
- Johnston, P. & Lambeck, K., 1999. Postglacial rebound and sea level contributions to changes in the geoid and the Earth’s rotation axis, *Geophysical Journal International*, **136**, 537–558, DOI: 10.1046/j.1365–246x.1999.00738.x.
- Johnston, P., Lambeck, K., & Wolf, D., 1997. Material versus isobaric internal boundaries in the Earth and their influence in postglacial rebound, *Geophysical Journal International*, **129**, 252–268, DOI: 10.1111/j.1365–246X.1997.tb01579.x.
- Kuhn, M., Featherstone, W., Makarynskyy, O., & Keller, W., 2010. Deglaciation-induced spatially variable sea level change: A simple-model case study for the Greenland and Antarctic ice sheets, *International Journal of Ocean and Climate Systems*, **1**(2), 67–83, DOI: 10.1260/1759–3131.1.2.67.
- Lambeck, K., 1990. Glacial rebound, sea-level change and mantle viscosity, *Quarterly Journal of the Royal Astronomical Society*, **31**, 1–30.
- Lambeck, K., 1993. Glacial rebound and sea-level change: an example of a relationship between mantle and surface processes, *Tectonophysics*, **223**, 15–37, DOI: 10.1016/0040–1951(93)90155–D.
- Lambeck, K., 2002. Sea level change from the mid Holocene to recent time: An Australian example with global implications, in *Ice Sheets, Sea Level and the Dynamic Earth*, edited by J. Mitrovica & B. Vermeersen, Geodynamics Series 29, pp. 33–50, DOI: 10.1029/029GD03, American Geophysical Union.

- 502 Lambeck, K. & Nakada, M., 1990. Late Pleistocene and Holocene sea-level change along
503 the Australian coast, *Palaeogeography, Palaeoclimatology, Palaeocology*, **89**(1-2), 143–
504 176, DOI: 10.1016/0031-0182(90)90056-D.
- 505 Lambeck, K., Johnston, P., Smither, C., & Nakada, M., 1996. Glacial rebound of the
506 British Isles - III. Constraints on mantle viscosity, *Geophysical Journal International*,
507 **125**, 340–354, DOI: 10.1111/j.1365-246X.1996.tb00003.x.
- 508 Lambeck, K., Yokoyama, Y., & Purcell, T., 2002. Into and out of the Last Glacial Max-
509 imum: sea-level change during Oxygen Isotope Stages 3 and 2, *Quaternary Science*
510 *Review*, **21**, 343–360, DOI:10.1016/S0277-3791(01)00071-3.
- 511 Lemoine, F., Kenyon, S., Factorm, J., Trimmer, R., Pavlis, N., Chinn, D., Cox, C., Klosko,
512 S., Luthcke, S., Torrence, M., Wang, Y., Williamson, R., Pavlis, E., Rapp, R., & Ol-
513 son, T., 1998. The Development of the Joint NASA GSFC and the National Imagery
514 and Mapping Agency (NIMA) Geopotential Model EGM96, NASA Technical Paper
515 NASA/TP-1998-206861, Goddard Space Flight Center.
- 516 Meier, M., Dyurgerov, M., Rick, U., O’Neel, S., Pfeffer, W., Anderson, R., Anderson, S.,
517 & Glazovsky, A., 2007. Glaciers dominate eustatic sea-level rise in the 21st century,
518 *Science*, **317**, 1064–1067, DOI: 10.1126/science.1143906.
- 519 Milne, G., Gegrels, W., Hughes, C., & Tamisiea, M., 2009. Identifying the causes of
520 sea-level change, *Nature Geoscience*, **2**, DOI: 10.1038/NGE0544.
- 521 Milne, G. A. & Mitrovica, J. X., 1998. Postglacial sea-level change on a rotat-
522 ing Earth, *Geophysical Journal International*, **133**, 1–19, DOI: 10.1046/j.1365-
523 246X.1998.1331455.x.

- 524 Mitrovica, J. & Peltier, W., 1991. On postglacial geoid subsidence over the equa-
 525 torial oceans, *Journal of Geophysical Research*, **96**(B12), 20053–2007, DOI:
 526 10.1029/91JB01284.
- 527 Mitrovica, J., Wahr, J., Matsuyama, I., & Paulson, A., 2005. The rotational stability of an
 528 ice-age earth, *Geophysical Journal International*, **161**, 491–506, DOI: 10.1111/j.1365–
 529 246X.2005.02609.x.
- 530 Mitrovica, J., Gomez, N., & Clark, P., 2009. The sea-level fingerprint of the West Antarc-
 531 tic collapse, *Science*, **323**, 753, DOI: 10.1126/science.1166510.
- 532 Mitrovica, J., Tamisiea, M., Ivins, E., Vermeersen, L., Milne, G., & Lambeck, K., 2010.
 533 Surface Mass Loading on a Dynamic Earth: Complexity and Contamination in the
 534 Geodetic Analysis of Global Sea-level Trends, in *Understanding Sea-level Rise and*
 535 *Variability*, edited by J. Church, P. Woodworth, T. Aarup, & W. Wilson, pp. 285–325,
 536 Blackwell Publishing Ltd.
- 537 Mitrovica, J., Gomez, N., Morrow, E., Hay, C., Latychev, K., & Tamisiea, M., 2011. On
 538 the robustness of predictions of sea level fingerprints, *Geophysical Journal Interna-*
 539 *tional*, **187**, 729–742, DOI: 10.1111/j.1365–246X.1011.05090.x.
- 540 Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A., 2001. Recent mass balance
 541 of polar ice sheets inferred from patterns of global sea-level change, *Nature*, **409**, 1026–
 542 1029, DOI: 10.1038/35059054.
- 543 Munk, W., 2003. Ocean Freshening, Sea Level Rising, *Science*, **300**, 2041–2043,
 544 10.1126/science.1085534.
- 545 Murray-Wallace, C. & Belperio, A., 1991. The last interglacial shoreline in Aus-

- 546 tralia - a review, *Quaternary Science Reviews*, **10**, 441–461, DOI: 10.1016/0277–
547 3791(91)90006–G.
- 548 Nakada, M. & Lambeck, K., 1987. Glacial rebound and relative sea-level variation: a new
549 appraisal, *Geophysical Journal of the Royal Astronomical Society*, **90**, 171–224, DOI:
550 10.1111/j.1365–246X.1987.tb00680.x.
- 551 Nakada, M. & Lambeck, K., 1989. Late Pleistocene and Holocene sea-level change in
552 the Australian region and mantle rheology, *Geophysical Journal*, **96**, 497–517, DOI:
553 10.1111/j.1365–246X.1989.tb06010.x.
- 554 National Tidal Centre, 2009. Australian mean sea level survey 2009, Tech. rep., National
555 Tidal Centre, Australian Bureau of Meteorology.
- 556 Nicholls, R., 2011. Planning for the impacts of sea level rise, *Oceanography*, **24**(2), 144–
557 157, DOI: 10.5670/oceanog.2011.34.
- 558 Nicholls, R. & Cazenave, A., 2010. Sea-level rise and its impact on coastal zones, *Science*,
559 **328**, 1517–1520, DOI: 10.1126/science.1185782.
- 560 Nicholls, R. & Mimura, N., 1998. Regional issues raised by sea-level rise and their policy
561 implications, *Climate Research*, **11**, 5–18, DOI: 10.3354/cr011005.
- 562 Oppenheimer, M., 1998. Global warming and the stability of the West Antarctic Ice Sheet,
563 *Nature*, **393**, 325–332.
- 564 Peltier, W., 1999. Global sea level rise and glacial isostatic adjustment, *Global and Plan-*
565 *etary Change*, **20**, 93–123, DOI: 10.1016/S0921–8181(98)00066–6.

- 566 Peltier, W. R., 2004. Global glacial isotasy and the surface of the ice-age earth: The ICE-
567 5G (VM2) model and GRACE., *Annual Reviews of Earth and Planetary Science*, **32**,
568 111–149, DOI: 10.1146/annurev.earth.32.082503.144359.
- 569 Prandi, P., Cazenave, A., & Becker, M., 2009. Is coastal mean sea level rising faster than
570 the global mean? A comparison between tide gauges and satellite altimetry over 1993-
571 2007, *Geophysical Research Letters*, **36**(L05602), DOI: 10.1029/2008GL036564.
- 572 Rignot, E. & Thomas, R., 2002. Mass Balance of Polar Ice Sheets, *Science*, **297**, 1502–
573 1506, DOI: 10.1126/science.1073888.
- 574 Rignot, E., Rivera, A., & Casassa, G., 2003. Contribution of the Patagonia Icefields
575 of South America to Sea Level Rise, *Science*, **302**, 434–437, DOI: 10.1126/sci-
576 ence.1087393.
- 577 Riva, R., Bamber, J., Lavallée, D., & Wouters, B., 2010. Sea-level fingerprintng of
578 continental water and ice mass change from GRACE, *Geophysical Research Letters*,
579 **37**(L19605), DOI: 10.1029/2010GL044770.
- 580 Shepherd, A. & Wingham, D., 2007. Recent sea-level contributions of the Antarctic and
581 Greenland ice sheets, *Science*, **315**, 1529–1532, DOI: 10.1126/science.1136776.
- 582 Slangen, A., Katsman, C., van de Wal, R., Vermeersen, L., & Riva, R., 2011. Towards
583 regional projections of twenty-first century sea-level change based on IPCC SRES sce-
584 narios, *Climate Dynamics*, pp. DOI: 10.1007/S00382–011–1057–6.
- 585 Tapley, B., Bettadpur, S., Ries, J., Thompson, P., & Watkins, M., 2004. GRACE
586 measurements of mass variability in the Earth system, *Science*, **305**, 503–505,
587 DOI:10.1126/science.1099192.

- 588 Velicogna, I., 2009. Increasing rates of ice mass loss from the Greenland and Antarc-
589 tic ice sheets revealed by GRACE, *Geophysical Research Letters*, **36**(L19503),
590 DOI:10.1029/2009GL040222.
- 591 Walsh, K., Betts, H., Church, J., Pittock, A., McInnes, K., Jackett, D., &
592 McDougall, T., 2004. Using sea level rise projections for urban planning in
593 Australia, *Journal of Coastal Research*, **20**(2), 586–598, DOI: 10.2112/1551–
594 5036(2004)020[0586:USLRPF]2.0.CO;2.
- 595 Wunsch, C., Ponte, R., & Heimbach, R., 2007. Decadal Trends in Sea Level Patterns:
596 1993–2004, *Journal of Climate*, **20**(24), 5889–5911, DOI: 10.1175/2007JCLI1840.1.
- 597 Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P., & Fifield, L., 2000. Timing
598 of the Last Glacial Maximum from observed sea-level minima, *Nature*, **406**, 713–716,
599 DOI: 10.1038/35021035.
- 600 Yokoyama, Y., Purcell, A., Marshall, J., & Lambeck, K., 2006. Sea-level during the early
601 deglaciation in the Great Barrier Reef, Australia, *Global and Planetary Change*, **53**,
602 147–153, DOI: 10.1016/j.gloplacha.2006.01.014.

603 **Table and Figure Captions**

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

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

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

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

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

621 **Figure 5:** (a) Location of the tide-gauge stations listed in Table 1 (National Tidal Centre,
 622 2009) and the associated total normalised RSL change. The large black circle denotes
 623 Spencer Gulf. (b) Normalised RSL change for tide gauges around Australia (Table 1)
 624 resulting from ongoing GIA and the present-day melting of the GIS, WAIS and EAIS.

625 The light grey band identifies the tide gauges in Spencer Gulf.

626 **Figure 6:** Normalised RSL change around the Australian coastline resulting from the
627 complete melting of the GIS, WAIS and EAIS. (a) 100 years after melting begins, (b)
628 when melting has been completed after 5000 years.

Table 1:

	Location	Longitude [°]	Latitude [°]	GIA	GIS	Patagonia	Alaska	WAIS	EAIS	Total
1	Darwin	130.8500	-12.4667	1.17 ± 0.02	1.00	1.21	1.11	1.17	1.03	1.06 ± 0.01
2	Melville Bay	136.7000	-12.2167	1.31 ± 0.12	1.01	1.22	1.15	1.17	1.04	1.02 ± 0.05
3	Weipa	141.8830	-12.6667	1.25 ± 0.05	1.00	1.21	1.15	1.16	1.03	1.03 ± 0.03
4	Booby Island	141.9170	-10.6000	1.27 ± 0.09	1.03	1.20	1.16	1.16	1.06	1.04 ± 0.04
5	Cairns	145.7830	-16.9167	1.17 ± 0.08	0.98	1.25	1.17	1.16	1.00	1.06 ± 0.03
6	Townsville	146.8330	-19.2500	1.23 ± 0.02	0.96	1.26	1.18	1.16	0.98	1.03 ± 0.01
7	Mackay	149.2330	-21.1167	1.14 ± 0.02	0.95	1.28	1.19	1.16	0.97	1.06 ± 0.01
8	Gladstone	151.2500	-23.8330	1.04 ± 0.03	0.94	1.29	1.20	1.15	0.94	1.09 ± 0.01
9	Bundaberg	152.3830	-24.7667	0.95 ± 0.04	0.94	1.30	1.23	1.15	0.94	1.13 ± 0.02
10	Brisbane	153.1670	-27.3667	0.89 ± 0.04	0.93	1.31	1.21	1.14	0.91	1.14 ± 0.03
11	Lord Howe	159.0670	-31.5170	0.39 ± 0.17	0.94	1.35	1.27	1.13	0.88	1.34 ± 0.10
12	Newcastle	151.8000	-32.9167	0.88 ± 0.04	0.90	1.34	1.21	1.11	0.82	1.12 ± 0.02
13	Fort Denison	151.2330	-33.8500	0.88 ± 0.03	0.89	1.35	1.22	1.12	0.80	1.13 ± 0.02
14	Port Kembla	150.9170	-34.4833	0.86 ± 0.04	0.89	1.35	1.20	1.11	0.79	1.13 ± 0.02
15	Stony	145.2170	-38.3670	0.82 ± 0.11	0.87	1.37	1.16	1.11	0.70	1.13 ± 0.04
16	Geelong	144.4330	-38.1667	0.83 ± 0.11	0.87	1.37	1.16	1.11	0.71	1.13 ± 0.04
17	Portland	141.6000	-38.3330	0.74 ± 0.02	0.87	1.38	1.15	1.12	0.70	1.17 ± 0.03
18	Burnie	145.9170	-41.0500	0.57 ± 0.09	0.88	1.40	1.20	1.11	0.65	1.25 ± 0.04
19	Hobart	147.3330	-42.8833	0.35 ± 0.10	0.88	1.41	1.20	1.08	0.61	1.32 ± 0.04
20	Victor Harbour	138.6330	-35.5667	1.05 ± 0.02	0.87	1.37	1.14	1.15	0.76	1.06 ± 0.01
21	Port Adelaide	138.5000	-34.8500	1.12 ± 0.04	0.86	1.36	1.12	1.13	0.76	1.02 ± 0.02
22	Port Pirie	138.0170	-33.1667	1.23 ± 0.05	0.86	1.33	1.11	1.13	0.78	0.96 ± 0.03
23	Wallaroo	137.6000	-33.9000	1.19 ± 0.03	0.86	1.35	1.12	1.14	0.78	0.99 ± 0.02
24	Port Lincoln	135.8670	-34.7167	1.07 ± 0.10	0.88	1.38	1.13	1.17	0.78	1.06 ± 0.04
25	Thevenard	133.6500	-32.1500	1.22 ± 0.08	0.87	1.35	1.10	1.16	0.81	0.99 ± 0.03
26	Esperance	121.9000	-33.8667	0.84 ± 0.04	0.89	1.41	1.07	1.22	0.81	1.18 ± 0.03
27	Albany	117.8830	-35.0333	0.64 ± 0.04	0.90	1.44	1.05	1.25	0.82	1.28 ± 0.04
28	Bunbury	115.6330	-33.3167	0.73 ± 0.09	0.90	1.42	1.04	1.24	0.85	1.24 ± 0.04
29	Fremantle	115.7330	-32.0500	0.82 ± 0.11	0.90	1.40	1.04	1.24	0.86	1.20 ± 0.05
30	Geraldton	114.5830	-28.7833	0.86 ± 0.09	0.92	1.38	1.04	1.24	0.90	1.19 ± 0.04
31	Carnarvon	113.6170	-24.8833	0.83 ± 0.12	0.94	1.35	1.06	1.23	0.95	1.20 ± 0.05
32	King Bay	116.7500	-20.6330	0.89 ± 0.07	0.96	1.31	1.07	1.22	0.98	1.18 ± 0.03
33	Port Hedland	118.5830	-20.3000	0.98 ± 0.05	0.95	1.30	1.07	1.21	0.98	1.13 ± 0.02
34	Broome	122.2170	-18.0000	1.08 ± 0.03	0.95	1.26	1.09	1.18	0.98	1.08 ± 0.01
35	Wyndham	128.1000	-15.4500	1.18 ± 0.04	0.96	1.22	1.09	1.15	0.99	1.03 ± 0.02

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6: