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Is There Evidence Yet of Acceleration in Mean Sea Level Rise around Mainland Australia?

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ABSTRACT

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As an island nation with some 85% of the population residing within 50 km of the coast, Australia faces significant threats into the future from sea level rise. Further, with over 710,000 addresses within 3 km of the coast and below 6-m elevation, the implication of a projected global rise in mean sea level of up to 100 cm over the 21st century will have profound economic, social, environmental, and planning consequences. In this context, it is becoming increasingly important to monitor trends emerging from local (regional) records to augment global average measurements and future projections. The Australasian region has four very long, continuous tide gauge records, at Fremantle (1897), Auckland (1903), Fort Denison (1914), and Newcastle (1925), which are invaluable for considering whether there is evidence that the rise in mean sea level is accelerating over the longer term at these locations in line with various global average sea level time-series reconstructions. These long records have been converted to relative 20-year moving average water level time series and fitted to second-order polynomial functions to consider trends of acceleration in mean sea level over time. The analysis reveals a consistent trend of weak *deceleration* at each of these gauge sites throughout Australasia over the period from 1940 to 2000. Short period trends of acceleration in mean sea level after 1990 are evident at each site, although these are not abnormal or higher than other short-term rates measured throughout the historical record.

ADDITIONAL INDEX WORDS: *Relative sea level rise, acceleration, Australasia.*

INTRODUCTION

The coastal zone, with such a rich diversity of beaches, estuaries, headlands, and foreshore landscapes, is one of the key environmental assets in Australia. In addition to its environmental value, the coastal zone is also home to a large proportion of the country's resident population and is one of the key national recreational amenities, tourism drivers, and peak economic margins.

Human settlement has greatly modified the coastal environment over the past 100 years. Australia has become a coastal society: around 85% of the population live within 50 km of the coast. Buildings, utilities, public amenities, and transport networks have been constructed in areas that already experience periodic flooding, wind damage, and shoreline erosion. The Australian coastal zone has been developed with the expectations that the shoreline will remain stable, that extreme events will occur within a range defined by historical experience, and that mean sea level will not change (Australian Government, 2009a).

It is estimated that there are over 710,000 addresses sited within 3 km and below 6 m elevation of Australia's coast, with more than 60% of those addresses located in New South Wales and Queensland (Australian Government, 2009b). Clearly there is a need to carefully manage the many interrelated environmental, social, economic, and planning issues within the coastal zone into the future, particularly in response to one of the major physical threats: sea level rise.

There is unequivocal measured evidence of a global average rise in mean sea level during the 20th century on the order of 17 ± 5 cm (IPCC, 2007). Current scientific projections lean toward an upper bound global rise in mean sea level on the order of 80–100 cm over the course of the 21st century (IPCC, 2007; ISC, 2009). Satellite altimeters that have been measuring changes in the world's ocean water surface since late 1992 with improved global accuracy and reliability have focussed attention on measured global trends that appear to be increasing at rates exceeding 3 mm/y, generally in line with the upper bound projections of global average sea level rise (IPCC, 2007).

It is, however, important to understand that there will be specific localised or regional variations compared with the global average sea level rise projections. In addition to international scientific endeavours, it is imperative to analyse and understand the trends emerging from the longest Australasian tide gauge records to improve the picture of "regional" sea level rise to augment forecasting capabilities. Very long, continuous records from Fremantle (1897), Auckland (1903), Fort Denison (1914), and Newcastle (1925) have been analysed to investigate whether there is evidence of

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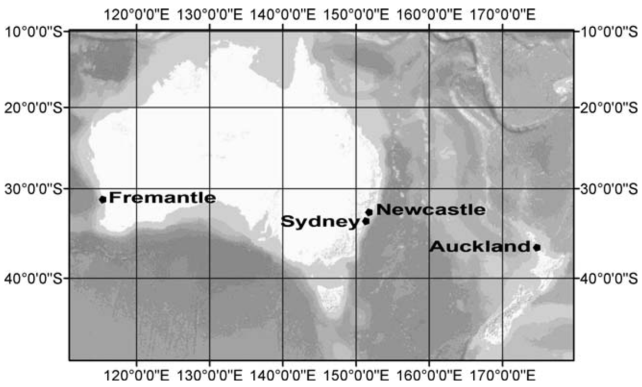

Figure 1. Locality diagram for Australasian tide gauge records used in this study.

acceleration in the rise of mean sea level over the longer term at these particular locations (see Figure 1 for locality diagram).

INFLUENCES ON OCEAN WATER LEVELS

The ocean water surface is a dynamic entity, continually moving in response to the varied forcing functions applied to it that include large-scale wind fields, changing air pressures, air–sea heat, freshwater fluxes, tidal processes, oceanographic processes (waves, currents, *etc.*), and changes in the physical properties of the water mass including density, salinity, temperature, *etc.*

The full range of lunar influences on tides at a given location occurs over a nodal cycle of approximately 18.6 years, during which time the Moon's declination varies between approximately 18.3° and 28.6°. Throughout this cycle the moon is known to induce a small amplitude harmonic influence on the position of mean sea level at a fixed location. The nodal cycle influence is a maximum around the poles with zero influence on the equilibrium nodal tide occurring at latitudes of around 35°N and 35°S (Pugh, 1987). The amplitude of the nodal tide for the Australasian tidal records is considered negligible, given the gauge locations considered in this study are situated around the nodal line between 32°S and 37°S.

Localised, seasonal, or regional meteorological influences (including atmospheric pressure, winds, and weather systems) can significantly influence ocean water levels over varying spatial and time scales. Of these influences, the short- and long-term atmospheric phenomena known as El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation, respectively, are significant factors influencing ocean water levels around the Australian mainland.

The El Niño Southern Oscillation is measured by a simple index, known as the Southern Oscillation Index (SOI), which can be related to specific changes in the temperature of the underlying ocean, commonly referred to as El Niño and La Niña events. The sea level anomalies around Australia generally follow the SOI, whereby higher average sea levels coincide with high values of the SOI and lower average sea levels coincide with low values of the SOI (NTC, 2007). On average, El Niño events occur every 3 to 8 years (Australian Government, 2010a).

Recent analysis of 20 New South Wales (NSW) ocean water level recorders clearly highlights the influence of ENSO on recorded data around the period from early 1998 to the middle of 1999, which corresponds with moving from the end of a very strong El Niño episode to relatively strong La Niña conditions. As expected, the majority of mainland station records depicted very low monthly average water levels during January 1998 (SOI = −23.5) and extremely high monthly averages during April 1999 (SOI = +18.5). This analysis indicated that although there are other localised meteorological and oceanographic processes embedded within this dataset, the predominant ENSO factor could influence monthly average water level data along the NSW coastline by as much as ≈300 mm in swinging from El Niño to La Niña (in this case) or *vice versa*.

More recently, scientists have determined the existence of a so-called Pacific Decadal Oscillation (PDO) based on fluctuations of sea surface temperatures around the Pacific with similar characteristics to ENSO, but operating on timescales of 20–30 years (JISAO, 2010; Minobe, 1997; Zhang, Wallace and Battisti, 1997). The PDO is similarly measured by a simple index based on monthly sea surface temperature of the Pacific Ocean north of 20°N (JISAO, 2010). During positive phases of the PDO, the east coast of Australia could be expected to experience lower than normal sea surface temperatures and hence lower than normal water levels, whilst the converse exists for negative phases of the PDO.

The above-mentioned range of dynamic processes are all superposed upon a comparatively low measured rate of underlying rise in mean sea level resulting from climate change processes, evident in the records of a global network of long-term tide gauge records and other environmental and physical markers.

SEA LEVEL MONITORING PROJECTS IN AUSTRALASIA

There are various sea level monitoring projects in Australasia that have been operational since the early 1990s. The Australian Baseline Sea Level Monitoring Project (ABSLMP) was established in 1991 and involves 14 standard sea level fine resolution acoustic measuring equipment (SEAFRAME) stations around mainland Australia managed by the National Tidal Centre with assistance from the Australian Climate Change Science Program. The key objective of the program is to identify long-period sea level changes, with particular emphasis on the enhanced greenhouse effect on sea level. The ABSLMP is accompanied by a geodetic levelling program supported by the state surveying organisations and Geoscience Australia. Periodic surveys are conducted at each SEAFRAME station to relate the gauge to a nearby array of deep benchmarks to monitor any vertical movements of the instrumentation (Australian Government, 2010b).

The South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) was similarly established in 1991 involving 11 SEAFRAME stations in the South Pacific that are jointly managed by the Australian Government and Pacific Island member countries. Since 2001, these stations have been equipped with a continuous global positioning system (CGPS) to similarly monitor vertical movements in the gauge over time (Australian Government, 2010c).

These projects are a very important investment in gathering regional data on ocean water level measurements that will become increasingly important for sea level rise measurements as the record length increases. At present the record lengths (currently ≈ 20 y) are generally insufficient to isolate the underlying trend of sea level rise from the more dynamic decadal (and longer) influences such as ENSO and PDO.

ISOLATING CLIMATE CHANGE INDUCED SEA LEVEL RISE FOR ANALYSIS

As discussed previously, there are numerous meteorological and oceanographic processes that affect ocean water levels over differing timescales and spatial scales. Several influences are on timescales less than a year, such as seasonal factors, weather systems, and variability of ocean water properties (temperature, salinity, *etc.*). Other longer term influences such as ENSO (up to 10 y) and PDO (20–30 y) will influence ocean water levels over much longer time frames.

The difficulty arises in attempting to isolate the comparatively smaller, omnipresent signal of climate change induced sea level rise from these dynamic influences, which are operating over considerably different timescales and spatial scales. One technique is to consider ocean water level records that are sufficiently long that the more dynamic and cyclical influences can be averaged out. The abovementioned timescales of relevant processes provide some guidance on the length of record required to mitigate their influence on measured ocean water levels.

The National Tidal Centre (Australia) advises that large interannual and interdecadal sea level fluctuations associated with climate variability (such as El Niño) can obscure underlying trends of climate change induced sea level rise where the station record is less than 25 years (NTC, 2008). Douglas, Kearney, and Leatherman (2001) advise that record lengths of at least 60 years are recommended to distinguish between trends and long-period relative sea level fluctuations in individual records. Similarly, analysis of the long Fort Denison tide gauge record by You, Lord, and Watson (2009) suggests that the record length may have to exceed 50–60 years in order to isolate with reasonable confidence the low-amplitude sea level rise signal from the large dynamic influences on ocean water level records.

Using tidal data records of sufficient length, there are numerous analytical filtering and averaging procedures that can then be applied to sufficiently smooth the dynamic ocean water level influences to reveal water level time-series reflective of the low-amplitude sea level rise signal.

INTERNATIONAL LITERATURE ON SEA LEVEL RISE ACCELERATION

There have been numerous studies undertaken to investigate the existence of acceleration in sea level rise over the period for which there is generally sound, reliable data (after 1870) upon which to measure such attributes. IPCC (2007) provides a relatively extensive literature review.

From the longer term perspective, Woodworth, Menédez, and Gehrels (pers. comm.) analysed the small number of international sea level records spanning two or three centuries, with all records providing evidence for long-term acceleration in sea level rise. A major conclusion of this work was that the global (or at least the northern hemisphere) ocean experienced an acceleration in the rate of sea level change between the 19th and 20th centuries, within which there had been particular periods of increasing or decreasing acceleration.

Douglas (1992, 2008) presented several global examples demonstrating significant upward inflexions in the mean sea level tide records from around 1920–1930 (positive accelerations) and a distinct flattening (or negative inflexion) in the same tidal record after 1960. Douglas remarked on the post-1960 negative acceleration in the longer Australian records and their similar behaviour to that of Auckland, New Zealand, and on the well-known post-1960 decelerations in Europe (Woodworth *et al.,* 2009).

Jones *et al.* (2001) note the 1920–1930s was one of the main periods of sustained rise in global air and sea surface temperatures in the 20th century. Woodworth *et al.* (2009) noted the 1920–1930s inflexion was followed in the 1940s by a high rate of global sea level rise coinciding with a period of enhanced glacier melt. The low-frequency signal of deceleration in mean sea level records after 1960 has been attributed in part, by Church, White, and Arblaster (2005), to atmospheric cooling associated with volcanic forcings, most notably from Mount Agung (Indonesia, 1963), El Chichon (Mexico, 1982), and Mount Pinatubo (Philippines, 1991). Woodworth *et al.* (2009) note that a major shift in atmospheric and oceanic circulations occurred during the 1960s, with the northern hemisphere cooling relative to the southern hemisphere.

The two abovementioned acceleration features occur in many individual records, even if they do not have the same amplitudes at each location and are not universal (Woodworth *et al.,* 2009). Further, Woodworth *et al.* (2009) concluded that global average sea level time-series reconstructions by Church and White (2006) and Jevrejeva *et al.* (2006) possessed common features that reflected correctly the main characteristics of accelerations to be found in the sparse data set of individual records and demonstrated considerable similarity on a global basis. Woodworth, Menédez, and Gehrels (pers. comm.) note that the negative inflexion found in many European and North American sea level records around 1960 is a main contributor in deceleration trends, which one tends to find using 20th century data alone (as discussed by Douglas, 1992; Holgate, 2007; Woodworth, 1990).

A detailed analysis of 25 U.S. tide gauge records exceeding 80 years in length by Dean and Houston (pers. comm.) advised there was "no evidence to support positive acceleration over the 20th century as suggested by the IPCC, global climate change models and some researchers." Rather, Dean and Houston (pers. comm.) conclude that this extensive analysis points toward a consistent trend of extremely weak deceleration in the rise of mean sea level over this time frame, noting these results may not be representative of broader global characteristics.

Much attention in recent times has been dedicated toward understanding how the high global average sea level rise rates after 1990 compare in the historical context. In particular, many researchers question whether there is evidence that increasing anthropogenic-induced climate change forcings are being directly reflected in the recent record of long-term ocean water level measurements or whether these high rates are merely a reflection of decadal (and longer) variability.

Woodworth *et al.* (2009), in considering several global sea level time-series reconstructions (Church and White, 2006; Gornitz and Lebedeff, 1987; Holgate, 2007; Jevrejeva *et al.,* 2006; Trupin and Wahr, 1992), observed that much of the continuing sea level rise, had the post-1960s flattening off not occurred, was restored and exceeded by the higher rates of the 1990s and possibly before. Woodworth *et al.* (2009) noted that the 1990s rates were unquestionably high, as verified by independent tide gauge and altimeter information (Bindoff *et al.,* 2007).

In a review of a large number of global tide gauge records (177) for the period between 1955 and 1998, Holgate and Woodworth (2004) concluded that the globally averaged rate of coastal sea level rise for the decade centred on 1995 was the largest over the period of analysis. Using nine long and nearly continuous records from around the world, Holgate (2007) extended the work of Holgate and Woodworth (2004) to cover the whole century (1904–2003), concluding that the high decadal rates of change in global mean sea level observed during the last 20 years of the record were not particularly unusual in the longer term context. Similarly, Hannah (2004), in updating previous analysis of long-term sea level change in New Zealand (Hannah, 1990), concluded there had been neither a significant change in the rate of sea level rise nor any detectible acceleration during the intervening period (that is, considering additional data spanning the period 1989 to 2001).

AUSTRALASIAN SEA LEVEL DATA

The analysis to detect underlying trends in acceleration of mean sea level over time has been undertaken using only continuous monthly average ocean water level data records exceeding 80 years in length with a data capture rate after 1920 exceeding 95%. These criteria were necessary to ensure use of the longest essentially continuous data sets available. Relative average monthly water level data has been analysed from the four longest, continuous Australasian records available:

- Fremantle, Western Australia (from January 1897 to present)
- Auckland Harbour, New Zealand (from November 1903 to present)
- Fort Denison, Sydney Harbour, New South Wales (from June 1914 to present)
- Pilot Station, Newcastle, New South Wales (from April 1925 to present)

Although long tide records exist at Dunedin, New Zealand, from as early as January 1900, there are large gaps throughout the data record; thus these data were not considered further. Data for analysis have been sourced from the publicly available archives of the permanent service for mean sea level (PSMSL, 2010). Monthly average data have been supplied by the National Tidal Centre to extend the record at each Australian station up to and including December 2009. Similarly, data were supplied by the Ports of Auckland Limited to extend the Auckland record from May 2000 to December 2009.

Although water level recording commenced at Fort Denison with the first entry in the Tide Register dated May 11, 1866, data prior to June 1914 contain various errors that render the earlier records less reliable (Hamon, 1987).

The PSMSL database contains three separate archived records for the Pilot Station location at Newcastle (1925–1988, 1928–1961, and 1972–1986). None of the archived records cover the complete period from the commencement of the record in April 1925. As part of this investigation, Newcastle Port Corporation provided all original Tide Registers available for the Pilot Station gauge to consider the possibility of piecing together a seamless continuous record. Notations inside the cover of the Tide Register commencing in April 1925 make mention of a record high water level on July 14, 1912, indicating formal records were collected that predate available records. Despite exhaustive searches, we could not locate these valuable earlier tide records.

Nonetheless, from inspection of the available records, it is apparent that the separate Pilot Station records in the PSMSL database represent various compilations of data corresponding to different gauges. Evidence confirms that as various gauges were upgraded with improved technology, gauges were run in parallel for a period of up to 2 years to ensure appropriate calibration of the new gauge with the long-term record. Several of the older gauges are still operating side by side at the Pilot Station with the current sonar gauge. The Tide Registers enabled a continuous record to be pieced together from April 1925 to present, representing an invaluable record that ranks as the third longest Australian ocean water level record.

ANALYTICAL TECHNIQUES

The examination of trends of acceleration in ocean water level records essentially involves two steps.

Step 1

The initial step requires transforming “relative average monthly tide gauge data” to a water level time series with the larger dynamic oceanographic and meteorological influences filtered. This has been achieved though the application of a 20-year “rolling” or “moving” average (10 y either side of the data point in question) to the monthly average data set. The fixed averaging window of 20 years is sufficiently wide to dampen the dynamic influences to reveal a transformed time series from which signals of comparatively low-amplitude sea level rise (or fall) can be more readily isolated.

The width of the averaging window means that the moving average time series will start and end 10 years inside the extremity of the data record considered. Whilst relatively simple and straightforward, the multiyear moving average technique offers the benefits of using the actual data record and producing a measurable time series that accurately reflects nonlinear trended data records (such as sea level rise). Each moving average time series has then been normalised to January 1940 for direct comparison. This arbitrary reference was selected for two reasons, first the latest common date using the 20-year rolling average (10 y either side) was 1935 (Newcastle), and second records at Fort Denison prior to 1940 were transcribed using different techniques from the rest of the record and may contain different errors (Hamon, 1987).

It should be recognised that the analysis to detect rates of change in ocean water levels involves the use of "relative" monthly average tide gauge data. These records have not been corrected for any movement in the ground surface housing the gauge due to influences including tectonics, glacial isostatic adjustment, or land subsidence. It has been assumed that these influences (if present at the sites under investigation) would be occurring at a constant rate throughout the data record and therefore not influencing any trend of acceleration evident in the long-term movement of the mean water surface.

Step 2

The second step involves examining the relative 20-year moving average water level time series to detect rates of change (or accelerations) with the rise in mean sea level over time. Where changes in the time series are nonlinear, standard second-order polynomials (or quadratic functions) can be fitted to the data (see Equation (1)). For water level time series fitted to a quadratic function, the leading coefficient (A) provides a direct indication of any trend of acceleration. For example, if the leading coefficient (A) is positive, the fitted curve will be concave upward in shape, and the time series to the right of the apex of the curve will reflect an acceleration trend, moving forward in time. Conversely, if the leading coefficient is negative, the fitted curve will be concave downward in shape, and the time series approaching the apex of the curve will reflect a deceleration trend, moving forward in time. In either case, the acceleration or deceleration in the nonlinear function is equivalent to $2A$ (mm/y^2).

$$Y_{ma} = Ax^2 + Bx + C \tag{1}$$

where Y_{ma} is the mean sea level based on the moving average, x represents time, and A, B, and C are constants. When fitting trendlines to data, the square of the correlation coefficient (R^2) provides an indication of how a trendline accounts for the variation in a data field. For example, a fitted trendline to a 20-year moving average water level time series with an R^2 of 0.995 would indicate that 99.5% of the variation in the data is accounted for by the fitted second-order polynomial function, inferring an almost perfect mathematical representation of the measured data. Hence, R^2 has been determined for each fitted polynomial to estimate the degree of "representativeness" a fitted acceleration or deceleration trend has over the 20-year moving average data field.

DISCUSSION OF RESULTS

The 20-year moving average time series for each of the relative monthly average water level data sets are depicted in Figure 2. Irrespective of localised differences in the record at each gauge location, the moving average technique substantially removes much of the variability to reveal a comparatively smaller trend of underlying increase in mean sea level over time. Despite the smoothing afforded by the 20-year averaging technique, embedded influences of decadal (and longer) processes within the ocean water level data sets remain clearly evident in the resulting time series at each site.

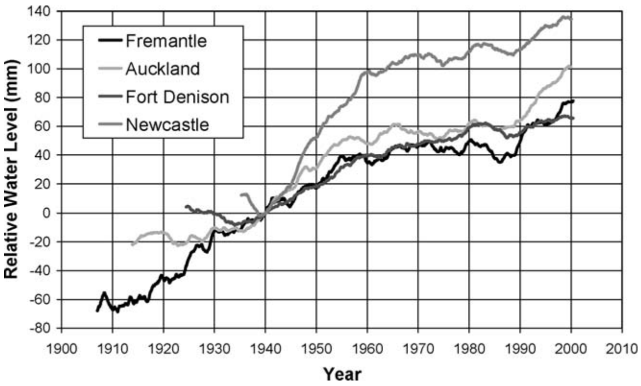

Figure 2. Relative 20-y moving average water level time series (all stations). Based on monthly average water level data provided by Permanent Service for Mean Sea Level (U.K.), National Tidal Centre (Australia), and Ports of Auckland Limited (New Zealand). Water levels have been normalised at January 1940 for direct comparison.

Improved smoothing of the data set to further isolate the underlying trend of sea level rise could possibly be achieved through widening the averaging time aperture (beyond 20 y) and correcting for ENSO influences (if this can be rationally achieved). Notwithstanding, the 20-year moving average water level time series through to 2000 (see Figure 2) clearly depict relative water level changes that are increasing over time, though at a reducing rate. In particular, the longer records at Fremantle and Auckland, at the western and eastern periphery of the Oceania region, respectively, exhibit remarkably similar overall trends in mean sea level for the period between 1920 and 2000 (data period 1910–2010) as depicted in Figures 3a and 3b and summarised in Table 1. Over this timeframe, the relative 20-year moving average water level time series indicate sea level rise on the order of 120 mm. Perhaps more significantly, both time series are well represented by fitted second-order polynomial trendlines ($R^2 \geq 0.93$) that strongly reflect a weak deceleration over time on the order of 0.022–0.034 mm/y^2.

The relative 20-year moving average water level time series provide direct comparison of all sites between 1940 and 2000 (data period 1930–2010). Over this timeframe the Fremantle, Auckland, and Fort Denison time series exhibit broadly similar characteristics of sea level rise; however, the Newcastle time series shows a relative increase in water levels at a significantly higher rate (see Figure 2). Prior to 1940, though, the normalised records appear increasingly divergent, perhaps reflective of less comparable and reliable measurement technologies and transcribed records moving back in time.

One of the probable reasons for the clear disparity in the relative water level record from the Pilot Station gauge at Newcastle is that it is sited on a large area known to be affected

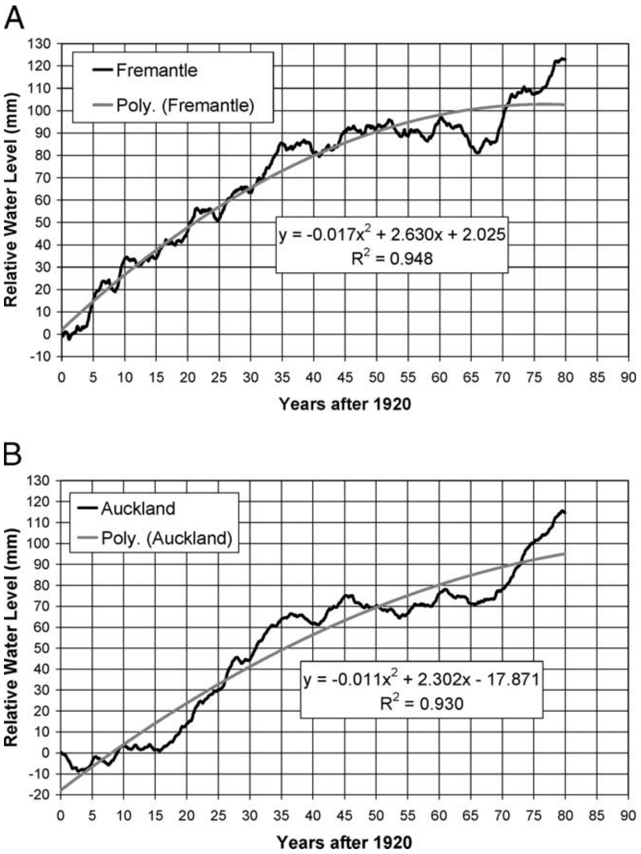

Figure 3. Relative 20-y moving average water level time series (after 1920) for Fremantle (A) and Auckland (B). The fitted trendline is a second-order polynomial function that is denoted on the chart along with the square of the correlation coefficient (R^2).

by mine subsidence. Known coal mine workings exist for three separate seams (Borehole Seam, Yard Seam, and Dirty Seam) below the surface in the vicinity of the tide gauge. These workings possibly predate the 20th century and are at depths ranging from as shallow as 20 m to exceeding 70 m at this location. Underground convict coal mine workings are also evident in this area, but their extent is largely unknown (Gary Hartley, Mine Subsidence Board, NSW, pers. comm.). Without rigorous survey data to confirm the extent of possible mine subsidence or other influences on the relative water level data record for Newcastle, this record is not recommended for use in sea level rise trend analyses.

Table 1. *Summary of results (1920–2000).*

Location	Relative Rise in Mean Sea Level (mm)*	Average Rate of Acceleration in Mean Sea Level (mm/y²)†	Square of Correlation Coefficient (R^2)‡
Fremantle	123	−0.034	0.948
Auckland	115	−0.022	0.930

* Rise in mean sea level based on 20-year moving average.

† Acceleration determined through fitting second-order polynomial function.

‡ Square of the correlation coefficient (R^2) is based on the fitted polynomial function.

After 1940, the relative 20-year moving average water level time series for each gauge are similarly well represented by second-order polynomial trendlines that reflect a tendency toward a general slowing in the rise of mean sea level (or deceleration) over time as depicted in Figures 4a–d and summarised in Table 2. Interestingly, the rates of deceleration at Fremantle, Auckland, and Fort Denison after 1940 are similar and also in the range of 0.01–0.04 mm/y². Whilst the correlation of the fitted second-order polynomial for the Fort Denison water level time series is very high ($R^2 = 0.974$), the correlation is reduced for Fremantle and Auckland compared with the post-1920 time-series analysis.

From examination of that portion of the relative 20-year moving average water level time series for the period after 1990, each record exhibits a similar short-term trend of increase (see Figure 2). Figure 5 provides a comparison of average decadal rates of change (mm/y) for each gauge over the historical record based on the relative 20-year moving average water level time series. Examination of Figure 5 indicates a high rate of relative sea level rise averaged over the decade centred around 1994, in the context of the 20th century historical record for each site. This feature is well recognised in the international literature (*e.g.*, Bindoff *et al.,* 2007; Holgate, 2007; Holgate and Woodworth, 2004).

The peak decadal rate of rise centred around 1994 at Auckland is of the same magnitude as that which was measured in the decade centred around 1943. Similarly, the peak decadal average rate measured in the 1990s at Fremantle is equivalent to average decadal rates of rise centred on 1950 and during the 1920s. However, the peak average decadal rate measured during the 1990s at Fort Denison is lower than average decadal rates measured between the early 1940s and the late 1950s. Although average decadal rates of rise in relative ocean water levels are clearly high during the 1990s, they are not remarkable or unusual in the context of the historical record available for each site over the course of the 20th century. Similar conclusions have been drawn by Holgate (2007) in examining global data and by Hannah (2004) examining long-term sea level records for New Zealand.

The Fremantle water level time series indicates two substantial periods of short-term increases in the relative water level time series after the late 1980s (see Figure 2). Importantly, there is evidence that this portion of the Fremantle record (located within the Perth region of Western Australia) may be influenced by nonlinear subsidence, which has been experienced more widely over the Perth region as a result of sediment compaction due to increased groundwater extraction. From analysing detailed ground movement data and tidal records in the Perth region, Dawson (2008) observed direct correlation between the global positioning system (GPS) and sea level records (at Hillarys and Fremantle) to groundwater observations, suggesting the observed subsidence in Perth was explained by water extraction from the Yarragadee and the Leederville aquifers.

Dawson (2008) concludes that the GPS observations indicate the maximum rate of subsidence was ≈ 5 mm/y between 2000 and 2005, consistent with interferometric synthetic aperture

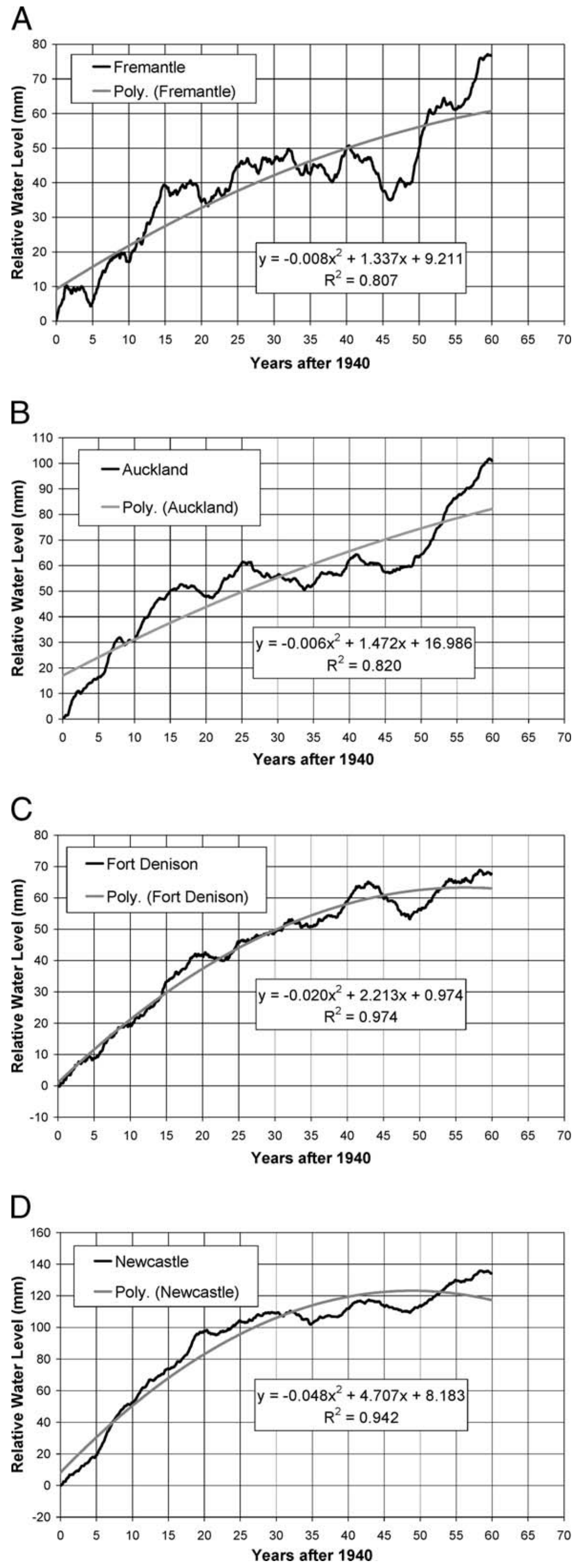

Figure 4. Relative 20-y moving average water level time series (after 1940) for Fremantle (A), Auckland (B), Fort Denison (C) and Newcastle (D). The fitted trendline is a second-order polynomial function that is denoted on the chart along with the square of the correlation coefficient (R^2).

Table 2. *Summary of results (1940–2000).*

Location	Relative Rise in Mean Sea Level (mm)*	Average Rate of Acceleration in Mean Sea Level (mm/y^2)†	Square of Correlation Coefficient (R^2)‡
Fremantle	77	−0.016	0.807
Auckland	101	−0.012	0.820
Fort Denison	68	−0.040	0.974
Newcastle	134	−0.096	0.942

* Average rise in mean sea level determined based on 20-year moving average.
† Acceleration determined through fitting second-order polynomial function.
‡ Square of the correlation coefficient (R^2) is based on the fitted polynomial function.

radar results, which suggested relative subsidence has only occurred in this region sometime after 1997. Dawson (2008) cautions that the correlation between groundwater observations and vertical subsidence across Perth suggests that care must be taken in interpreting the relative sea level rates determined from tide gauges in the region.

IMPORTANCE OF GROUND MOVEMENT MEASUREMENTS

Long continuous tide gauge records are invaluable for sea level rise research because dynamic oceanographic and meteorological impacts can be increasingly averaged out (or isolated) over time to reveal the comparatively low underlying rise in mean sea level. The relative tide gauge measurements are, however, a combination of the actual rise in mean sea level and the vertical movement of the land upon which the tide gauge installation is located.

The land surface can move because of a complex range of factors, including tectonic movements, glacial isostatic adjustment, compaction of reclaimed land, and subsidence. Knowledge of these contributions through direct survey measurements is becoming increasingly important to detect the absolute rate of sea level rise from tide gauge records.

Owing to their length and continuity, the Fremantle, Auckland, Fort Denison, and Newcastle tide gauge records are the most important continuous sea level records available for the southern hemisphere. Perhaps surprisingly, none of these critical gauges are part of the Australian Baseline Sea Level Monitoring Project (ABSLMP) or South Pacific Sea Level and Climate Monitoring Project (SPSLCMP), but they are instead managed by individual port authorities. The gauges are satisfactorily managed to facilitate the day-to-day operational requirements of commercial ports but do not utilise consistent technologies or operating procedures or contain sufficient survey records to consider vertical land movements at each individual gauge over the record length.

Since 2000, GNS Science and Otago University have operated continuous global positioning system (CGPS) instruments at New Zealand's four longest running tide gauge sites (Auckland, Wellington, Lyttelton, and Dunedin) with a view to measuring tectonic land level changes (Denys *et al.,* pers. comm.). Analysis of International Terrestrial Reference Frame (ITRF) 2008 data for the surface monitoring station adjacent to the Auckland Harbour tide gauge indicates a vertical velocity of

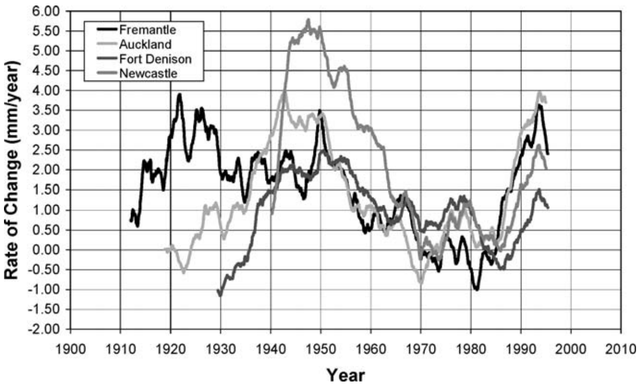

Figure 5. Comparison of decadal rates of change over historical record. Analysis based on relative 20-y moving average water level time series.

−0.8 ± 0.1 mm/y, measured over the timeframe from December 1996 to July 2009 (see Table 3).

However, none of the long record Australian gauges (Fremantle, Fort Denison, and Newcastle) are currently fitted with CGPS or integrated with regular geodetic levelling to an array of deep benchmarks to accurately measure vertical landform movements. Analysis of ITRF2008 data for two surface monitoring stations within ≈30 km of the Fremantle tide gauge indicates measured vertical velocities of at least −2.6 mm/y over the past decade in the Perth region (see Table 3), similar to results attained previously by Dawson (2008). Although these measurements are some distance from the Fremantle tide gauge, they confirm concerns that subsidence in the Perth region, due principally to increased groundwater extraction, might be reflected (at least in part) in the latter portion of the tide gauge record. Given the likelihood of subsidence contaminating the historical record at Newcastle and possibly the later (or after the mid-1990s) portion of the Fremantle record, it would be essential to upgrade the Fremantle, Fort Denison, and Newcastle tide gauges with collocated CGPS to enable direct measurements of land movements at each site in order to improve our regional understanding of eustatic sea level rise.

CONCLUSIONS

The 20-year moving average water level time series provide a satisfactory methodology for smoothing the large-scale dynamic water level influences to isolate the low-amplitude signal of mean sea level rise over time. It is evident, however, that multidecadal and other influences still persist in the "smoothed" water level time series.

Although a continuous water level time series was able to be constructed from the various Newcastle records from 1925 to present, it is readily apparent that the relative water level record is contaminated by mine subsidence or other indeterminate factors. With insufficient survey records available to isolate the extent of possible subsidence, the difference between the relative 20-year moving average water level time series of the nearest gauge record (Fort Denison) implies the Pilot Station gauge may have subsided by approximately 60–70 mm over the period from 1940 to 2000 alone. For this reason, the Newcastle record should be considered with extreme caution for sea level rise measurements.

The tide gauge records of Fremantle, Auckland, Fort Denison, and Newcastle are the most valuable for sea level rise monitoring in the Southern Hemisphere because of their length and continuity. Given the critical importance of accurately understanding sea level rise, it is imperative that these gauge facilities are managed accordingly, given that they are of key international interest. There is evidence of significant mine subsidence embedded in the historical tide gauge record for Newcastle and a likelihood of inferred subsidence within the later (after the mid 1990s) portion of the Fremantle record. In this respect, it is timely and necessary to augment these relative tide gauge measurements with CGPS to gain accurate data on the vertical movement (if any) at each gauge site to measure eustatic sea level rise. At present only the Auckland gauge is fitted with such precision levelling technology.

The longest continuous Australasian records, Fremantle and Auckland, situated on the western and eastern periphery of the Oceania region, respectively, exhibit remarkably similar trends in the relative 20-year moving average water level time series after 1920. Both time series show a rise in mean sea level of approximately 120 mm between 1920 and 2000 with strong correlation ($R^2 \geq 0.93$) to fitted second-order polynomial trendlines that reflect a tendency toward a general slowing in the rise of mean sea level (or deceleration) over time on the order of 0.02–0.04 mm/y^2. The Fort Denison water level time series after 1940 similarly reflects a decelerating trend in sea level rise at a rate of 0.04 mm/y^2 based on a strongly correlated fit ($R^2 = 0.974$) to the second-order polynomial function.

This decelerating trend was also evident in the detailed analysis of 25 U.S. tide gauge records longer than 80 years in

Table 3. *Estimated vertical velocities near tide gauges from ITRF2008.*

Land Movement Measuring Station	Vertical Velocity[*] (mm/y)	Period of Measurements	Proximity to Tide Gauge (km)
Perth, WA (PERT 50133M001)[†]	−2.6 ± 0.1	Dec 1996–July 2009	32
Hillarys, WA (HIL1 50141S001)[†]	−5.7 ± 0.3	Dec 1998–July 2009	27
Sydney, NSW (SYDN 50124M003)[‡]	−0.3 ± 0.1	Nov 2004–July 2009	11
Auckland, NZ (AUCK 50209M001)[§]	−0.8 ± 0.1	Dec 1996–July 2009	adjacent

[*] Vertical velocities based on analysis of International Terrestrial Reference Frame (ITRF) 2008 data provided by Geoscience Australia (John Dawson, pers. comm.).

[†] Perth and Hillarys measuring stations are located in proximity of the Fremantle tide gauge. WA = Western Australia.

[‡] Sydney measuring station is located in proximity of the Fort Denison tide gauge. NSW = New South Wales.

[§] Auckland measuring station is collocated with the Auckland Harbour tide gauge. NZ = New Zealand.

length (Dean and Houston, pers. comm.) and a general 20th century deceleration, driven predominantly by the negative inflexions around 1960 evident in many global records, are well noted in the literature (Douglas, 1992; Holgate, 2007; Woodworth, 1990; Woodworth, Menédez, and Gehrels, pers. comm.).

In considering shorter term recent accelerations, it is evident that there is a high rate of relative sea level rise averaged over the decade centred around 1994. Although average decadal rates of rise in relative ocean water levels are clearly high during the 1990s, they are not remarkable or unusual in the context of the historical record available for each site over the course of the 20th century. Similar conclusions have been drawn by Holgate (2007) in examining global data and by Hannah (2004) examining long-term sea level records for New Zealand. These recent post-1990s short-term accelerations fit within the overall longer term trend of deceleration evident in these long Australasian ocean water level records.

Using a 20-year moving average (10 y either side) water level time series limits the current analysis to the year 2000 (although the year 2000 uses data up to 2010). It is probable that if there is any longer term increase of significance in the rate of sea level rise embedded within the latter portion of the record, as distinct from a cyclical short-term attribute, this may take a further 10 to 20 years to influence the longer term time series.

Further research is required to rationalise the difference between the acceleration trend evident in the global sea level time-series reconstructions and the relatively consistent deceleration trend evident in the long-term Australasian tide gauge records. These differences are likely to have a significant bearing on the global average and "regional" projections for sea level rise into the future.

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