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Research Article

Recent and future higher sea levels in New Zealand: A review

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Abstract: Understanding past sea levels is essential to respond to the challenges of climate change. In the Pacific and Tasman, sea level has been up to 1.5 m higher during the mid-Holocene, similar to the predictions of some global warming models. Within New Zealand the knowledge of sea-level movements, especially during the recent past is poor, with the last major investigation being conducted 20 years ago. This paper reviews the state of local understanding of higher sea levels and suggests regions for further study and new methods of analysis to understand the nature of sea-level change in New Zealand.

Key words: Holocene, New Zealand, sea level.

Human-induced sea-level rise associated with global warming has become a critical issue for coastal researchers and planners. Flooding of lowland areas, dune erosion, beach recession and increased hazard from storm events are all expected to result from higher sea levels (IPCC 2007). This, combined with rapidly increasing human populations in the coastal zone (Hart & Bryan 2008), places more infrastructure at risk from these hazards. An understanding of how sea level responds to warming climates is therefore essential in assessing the future impacts of climate change. By understanding how sea level has behaved in the past, geomorphologists can determine how the oceans have responded to past warmer periods and their associated higher sea levels, such as occurred during the mid-Holocene warm period (*c.* 5 ka) and Last Interglacial periods (*c.* 80–125 ka), especially during oxygen isotope stage 5e (*c.* 125 ka) (Chappell 1987). Sedimentary systems can also yield records on the character of sea level rise, being either gradual or catastrophic.

In New Zealand, the understanding of sea-level variation is also critical in the calculation of rates of uplift and hence palaeoseismicity. Extensive marine terraces and other uplifted or drowned coastal landforms are found around the country, and it is the comparison of their age and elevation with current sea level that rates of vertical land movement are derived (Pillans 1983). For the Holocene, the eustatic curve of Gibb (1986) forms the benchmark for defining the position of sea level at any given time in the last 10 ka. This curve represents the most complete reconstruction of Holocene sea level for New Zealand based on field data. Subsequent to this work, research on the eustatic variation for the region has focused on modelling studies within the SW Pacific and Tasman Sea (e.g. Nakada & Lambeck 1989; Pirazzoli 1991), and the sea-level curve of the nearest coastal margin, Australia, is now well established (Thom & Roy 1985; Sloss *et al.* 2007); however, little attempt has been made in the last 20 years to integrate the growing body of local field evidence on Holocene sea-level change in New Zealand.

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This paper therefore sets out to review the state of knowledge of sea level in New Zealand. It does not aim to provide a new reconstruction of the Holocene sea-level curve, but to examine recently published field research and provide a framework for the further examination of sea-level change and the related effects that may occur on the New Zealand coast.

Climate change and future New Zealand sea levels

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) (Bindoff *et al.* 2007) succinctly summarizes the changes in global sea level that have occurred in the recent instrumented past and projections of future sea-level rise trends up to the year 2099. Historical observations for the period from 1961 to 2003 record an average global rise of 1.8 ± 0.5 mm/year and for the entire 20th century the average was 1.7 ± 0.5 mm/year. More recent satellite records of sea level change from 1993 to 2003 give a higher average rate of rise of 3.1 ± 0.7 mm/year (Bindoff *et al.* 2007). Significant decadal variability, however, occurs within this eustatic record which, for the southern hemisphere is strongly affected by El Nino Southern Oscillation (ENSO) fluctuations (Bindoff *et al.* 2007). For example, ENSO-driven variations in mean sea level occurred at the Port of Auckland during 1999–2000 when sea level rose 50–75 mm (MFE 2001).

Given this recent observed history, the global rate of sea-level rise is expected to increase towards the end of this century (IPCC 2007). One of the mid-range emission scenarios (A1B) predicts rates of 4 mm/year, with global sea level reaching 0.22–0.44 m above 1990 levels by 2090–2099 (Bindoff *et al.* 2007). Importantly, these predicted rates exclude future rapid changes in ice flow from continental glaciers and ice sheets (IPCC 2007). This is a very important distinction because the rate of glacio-eustatic sea-level rise as the climate warmed out of the last glacial maximum was on the order of 10–15 mm/year (Thom & Roy 1985; Gibb 1986), up to five times the measured rates for 1993–2003. These recent rises are attributed mostly to thermal expansion with contributions from ice sheets quite minor until now (IPCC 2007). In addition, evidence from drowned coral reefs in the Caribbean, dominated by the rapidly growing coral *Acropora palmata*, suggests that post-glacial marine transgression was also punctuated by periods of rapid rise in excess of 45 mm/year. Termed catastrophic rise events, they are thought to relate to ice sheet collapse in the northern hemisphere (Blanchon & Shaw 1995). This has important implications for coastal management as significant concern exists regarding the behaviour of the Western Antarctic ice sheet which currently extends into the Southern Ocean. It is estimated that if this was to break up and melt, sea level would rise by around 5 m (Mercer 1978). The recent collapse of the Larsen B ice shelf points to this being a rapid process (Domack *et al.* 2005) which on a larger scale could cause a catastrophic rise event.

State of knowledge of recent New Zealand sea level variation

According to Gibb (1986), from 10 to 6 ka the transgression of the New Zealand coast started at around –30 m with two stillstands at 9.2–8.4 ka and 7.5–7.3 ka, the last occurring at an elevation of -9.0 ± 2.8 m, which were followed by rapid rises of up to 15 mm/year (Fig. 1a). Although precise timing and length of these stillstands may be an artefact of plateaus within the radiocarbon record between 8 and 7.5 ka (Barbetti *et al.* 1995), hence they not being recognized on the eastern Australian coast, the rate of transgression is similar on both sides of the Tasman Sea (Thom & Roy 1985; Sloss *et al.* 2007). Sea level then stabilized at present levels around 6.5 ka from where it has varied by around 1.0 m, with the highest elevation being found in Pauatahanui Inlet, near Wellington, of 0.8 ± 0.8 m at 3.8 ka (Gibb 1986).

A period of higher sea level, known as the mid-Holocene highstand, is recognized within the Pacific (Pirazzoli 1991) and east Australia (Sloss *et al.* 2007), however, it appears to be highly variable within New Zealand. This is observed even in those sites of Gibb (1986) that were considered a true eustatic record, namely Blueskin Bay, in Otago and Weiti Estuary, in Northland (Fig. 1b). The data density for these areas is, however, low with

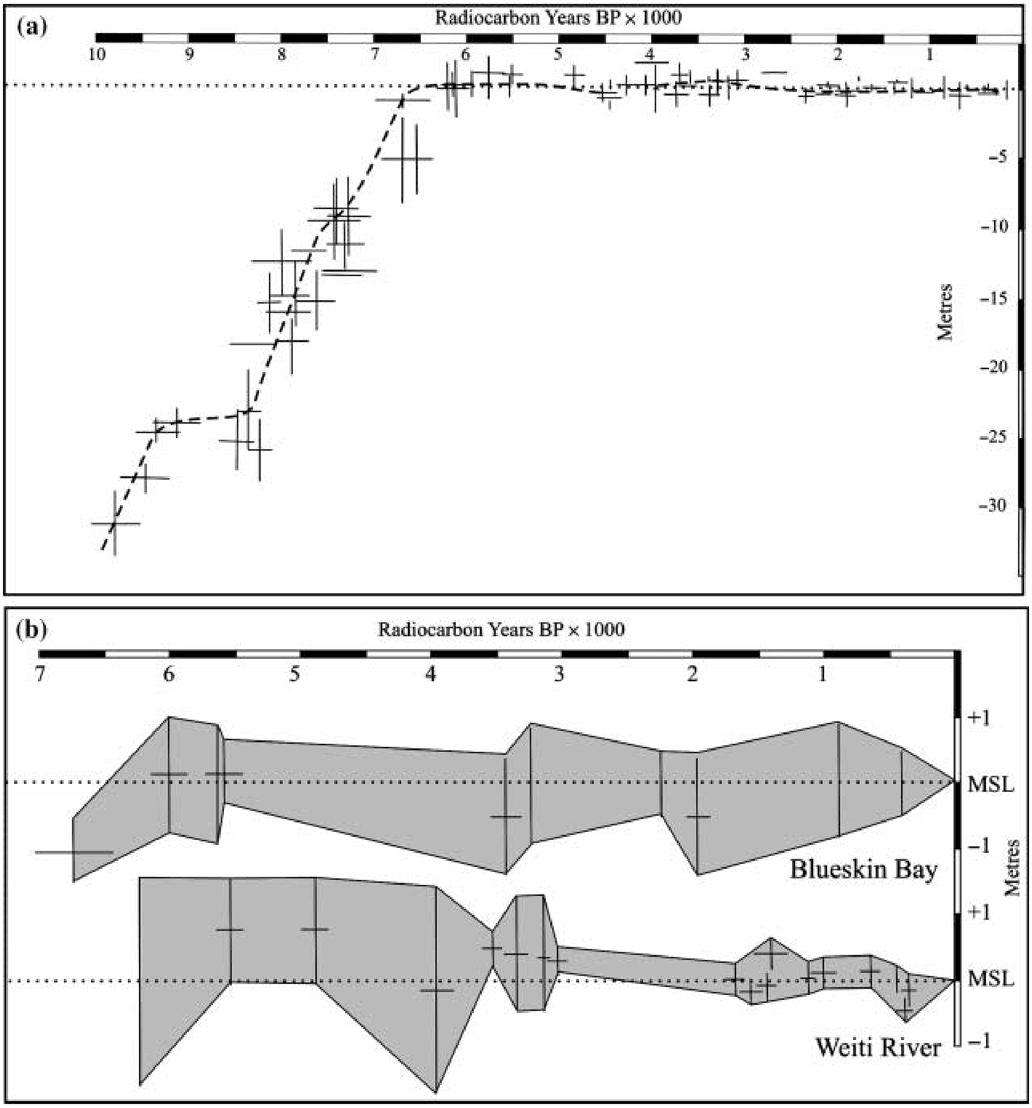

Figure 1 (a) The Holocene sea level curve of Gibb (1986). (b) Relative sea level curves for Blueskin Bay and Weiti River of Gibb (1986), which were assumed to be tectonically stable. Ages are reported in the original published format.

only 8 and 18 samples dated at each site, respectively. While these and other data, point towards a higher sea level during the mid Holocene the exact timing and height of it is still uncertain. This is an important scientific issue to address as recent IPCC best estimate predictions of sea-level rise for 2090–2099 are up to 0.6 m above present, associated with a global average surface warming of 2.4–6.4 °C (IPCC 2007), effectively returning the local coast to its mid Holocene state.

Discussion over the nature of the mid-Holocene optimum, the period of warmer and higher sea levels around 3–5 ka, is not new with much research being conducted on this issue in the Australasian region in the last 30 years (see reviews of Chappell 1987; Hopley 1987). The south-east Australian sea-level records are important for documenting higher sea level as they have been derived from a tectonically stable margin with a narrow continental shelf and therefore have limited hydro- and glacio-isostatic movement. They also occur within the same oceanic region as New Zealand (Clark & Lingle 1979; Pirazzoli 1991), so sea level can therefore be expected to be similar through the Tasman Sea, as is observed on Lord Howe Island (Woodroffe *et al.* 1995). In south–east Australia, this higher sea level (+1.0 to +1.5 m) likely occurred between 7.9 and 7.7 ka (Sloss *et al.* 2007) or 7 ka (Thom & Chappell 1975; Thom & Roy 1985), with the highstand lasting for 2 ka before slowly falling to present (Sloss *et al.* 2007). This contrasts to evidence derived from fixed biological indicators such as tube worms (e.g. *Galeolaria caespitosa*) and oysters on rocky shores in New South Wales, Australia, where an oscillating mid-Holocene sea level of up to +2.0 m has been proposed with a periodicity of around 1.4 ka (Baker & Haworth 2000; Baker *et al.* 2001). Even though most of these sites were located in sheltered locations, Sloss *et al.* (2007) suggested that the higher intertidal elevations of these organisms could relate to greater wave exposure of the open ocean sites where they were found thereby producing a greater vertical growth zone of each species. Such local variations in the elevation of coral microatolls, commonly used for sea level reconstructions in the tropics, have also been observed (Woodroffe & McLean 1990). These bio-indicator techniques still have potential for yielding sea-level curves; however, careful correlation between the tidal levels that organisms inhabit must be initially regionally (and locally) established, and this has yet to be done in New Zealand.

Sites and Environments for Study

New Zealand's position astride the Pacific and Indo-Australian Plates means that sites of tectonic stability are rare, with the majority of the country either rising or subsiding (Pillans 1983). Gibb (1986) selected two sites as type localities for his sea-level curve, as they had been stable throughout the Holocene and possibly the Late Pleistocene due to their location away from the major plate boundary fault lines and subduction related volcanic activity. Blueskin Bay in Otago (Fig. 2a) and Weiti Estuary, Northland, were selected and used as the benchmark from which other curves were corrected. This was conducted through copying the various curves onto plastic overlay and then physically tilting the relative record for that area having undergone vertical movement over the stable record to determine the rate of movement (Gibb 1986). While this is prone to error, the results of this analysis remain the scientific benchmark for sea level studies in New Zealand today.

Interestingly, despite the age of this work, little attention has subsequently been paid to these two sites to assess the geomorphic variability of the respective depositional systems. This is important to assess as the amount and rate of vertical sedimentation can affect the preservation of any sea-level signature. For example, in Whanganui Inlet, NW Nelson (Fig. 2b), the estuary infilled rapidly soon after 7 ka, meaning little sediment record is available from the late Holocene (Armour & Kennedy 2005; Kennedy *et al.* 2008), making detailed inferences of sea level position difficult for this period. Rapid infill also appears to have occurred in the Weiti Estuary, one of Gibb's key sites. Its lower part is occupied by a series of cheniers dating to around 3.5 ka (Gibb 1986) overlying transgressive muds and highstand sandy units (Heap & Nichol 1997). Infill of this estuary was influenced by a lack of accommodation space, which meant at the time of the maximum transgression (*c.* 6.5 ka) most of the estuary infill had taken place. This means that within 2 m of the current tidal flat surface, sediments of at least 7 ka age are found, capped by highstand open bay deposits dated at 5 880 ± 150 ^{14}C years BP (Heap & Nichol 1997). Blueskin Bay is also completely infilled (Fig. 2a), and although the detailed history of infill is still unknown, Thomas (1998) suggested that sea level oscillations in the estuary after 6.5 ka were a metre higher than suggested by Gibb (1986). The level of sea level detail that can be obtained from an estuarine sequence therefore will depend on when the infill occurred. For systems where all the accommodation space has been occupied soon after sea-level rise, the potential to record later oscillations is reduced, although may still occur such as along the margins of an estuary.

Landforms found above high tide limits can also be used as sea-level proxies. Cheniers form as coarse sand-gravel ridges atop finer, often muddy, sediment. Although they form through storm run-up, their heights have been

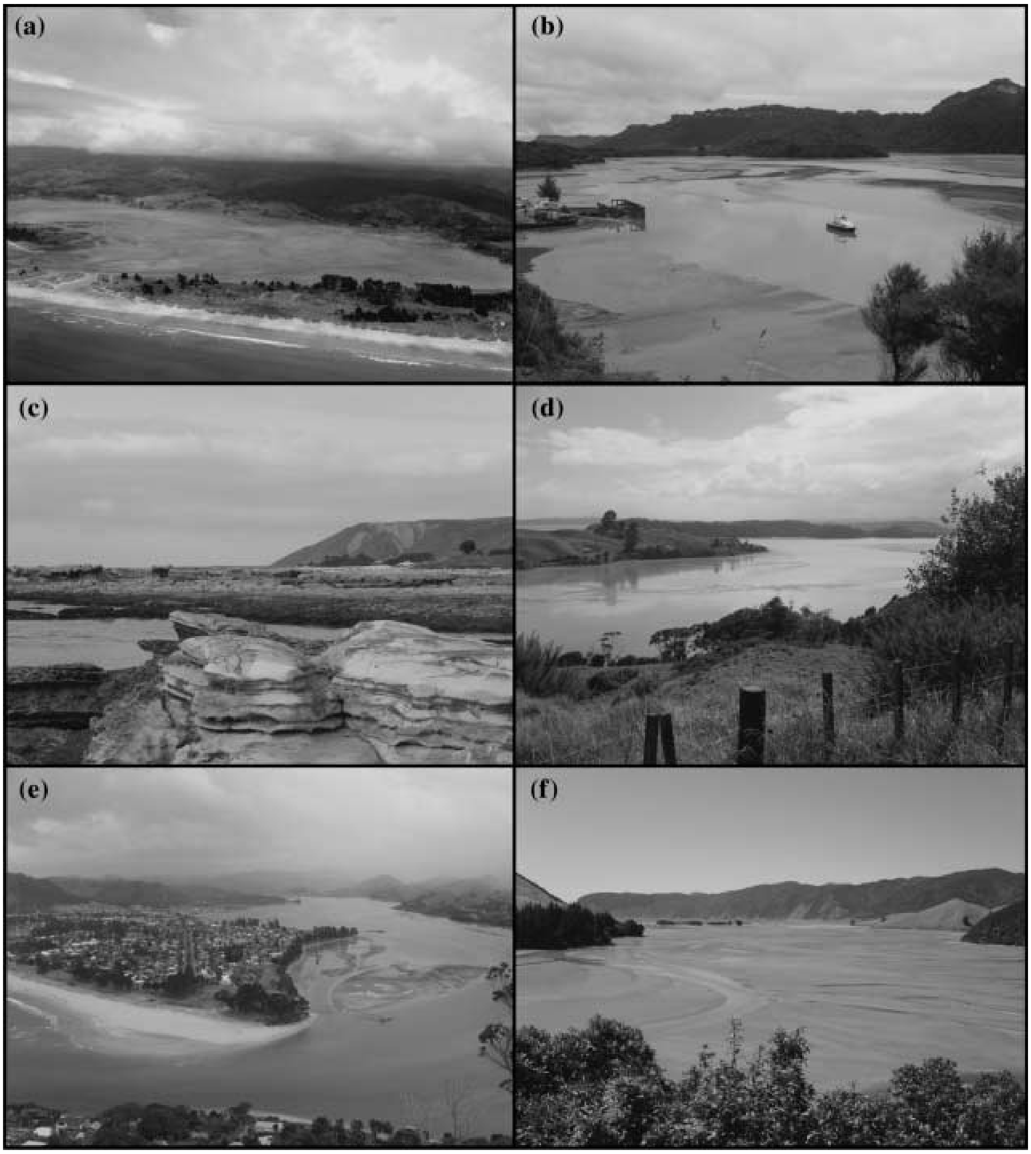

Figure 2 (a) Blueskin Bay, Otago, one of the two tectonically stable sites used as eustatic benchmarks for New Zealand sea-level studies (b) Whanganui Inlet, NW Nelson, infilled rapidly after sea level stabilization meaning records of sea-level change for the mid Holocene optimum are poor (c) Raised shore platforms of Holocene age on Mahia Peninsula. (d) Kawhia Estuary, central Waikato (e) Tairua Estuary, Coromandel and (f) Cable Bay, Nelson are infilled with Holocene sediment and have the potential to yield data on the nature of Holocene sea-level change.

used to reconstruct sea level, especially where they occur in more sheltered locations. Within New Zealand the cheniers of Miranda, Firth of Thames, were used to infer a sea level high-stand of 2.1 m at 4 000 ^{14}C years BP from where it fell to present levels around 2 000 ^{14}C years BP (Schofield 1960). Schofield (1973) later slightly revised the timing of this high-stand to 3 900 ^{14}Cyears BP, based on dune sequences of the South Kaipara Barrier, whereby it fell in an oscillating manner to present elevations. A reinterpretation of the Miranda cheniers by Woodroffe *et al.* (1983), noted significant variation in the height of the storm ridges from 1.7 to 3.1 m above mean sea level (MSL). A more reliable sea-level proxy was found in *in situ* shell beds in the tidal flats where a highstand of 0.7–0.9 m at 3 600 ^{14}C years BP was inferred which fell to present around 1 200 ^{14}C years BP.

Salt marshes on the other hand are an environment that has proven reasonably robust for the reconstruction of sea levels. Quantitative studies of foraminifera assemblages within marsh systems have shown them to have a strong affinity with tidal elevation especially in the vicinity of high tide level, with vertical accuracies of ±0.1 to 0.5 m being recorded in New Zealand (Hayward *et al.* 1999, 2004). Elsewhere, sea-level changes during the Holocene have been documented using these methods (e.g. Scott & Medioli 1986; Gehrels 1994; Cann *et al.* 2002), but only more recently directly applied locally, such as in the maar lakes of Auckland (e.g. Hayward *et al.* 2002). These assemblages have been used to measure vertical land movements from fault displacement, with the palaeo sea level compared with the curve of Gibb (1986). Studies of the Pakarae River, East Cape (Wilson *et al.* 2007a,b), Napier (Hayward *et al.* 2004), Akatore Estuary and Catlins Lake, South Otago (Hayward *et al.* 2007) are all examples of this. The upper part of the tidal limit generally has the best potential for recording a sea-level signature; however, this can also be affected by taphonomic alteration such as freshwater leaching of foraminifera tests (Hayward *et al.* 2004), such as was found in the salt marshes of southern Whanganui Inlet (Millar *et al.* 2002; Kennedy *et al.* 2008). In areas where foraminifera tests have been well preserved it is possible to extract quite high resolution records of recent sea-level change. In Otago at Pounawea, marsh sediments have been used to reconstruct a slow sea-level rise of 0.2 ± 0.3 mm/year from 1450 to 1900 AD followed by a higher rate of 3.1 ± 0.1 mm/year in the 20th century, the latter similar to the tide gauge record of sea level rise of 2.5 ± 0.3 mm/year at Lyttleton Harbour (Gehrels *et al.* 2007). They infer that the recent development of salt marshes in southern New Zealand and Tasmania, Australia, have been a direct result of recent rises in global sea level.

Erosional landforms, namely terraces and shore platforms, can also provide proxies for the position of the sea. Recently in the Corinth Gulf, Greece, sea-level fluctuations on the order of decimetres have been inferred for the mid to late Holocene based on a combination of fixed biological indicators and erosional notches (Palyvos *et al.* 2008). Such an approach is useful; however, it does require careful calibration between the height of the contemporary erosion surface and its equivalent level of tidal inundation. Shore platforms in the micro to mesotidal setting of New Zealand generally form as subhorizontal surfaces and lack the vertical range and sloping morphology of those developed in meso–macro tidal settings (Trenhaile 1987). It is, however, recognized that semihorizontal platforms may form at a range of elevations in the intertidal zone related to the offshore water depth (Sunamura 1991; Dickson 2004), rock hardness (Kirk 1977; Sunamura 1991; Dickson 2006) and rock structure (Trenhaile 2004). For example at Shag Point, Otago, platforms are found both at high and low tide levels at the same location, their elevation directly relating to the degree of jointing within the fine sandstone in which they are formed (Kennedy & Dickson 2006). In areas where contemporary shore platform development can be related to a specific tidal elevation, it is possible to infer different sea levels as is suggested to occur within northwest Nelson (Kennedy & Paulik 2007). Due to the difficulty in accurately ascribing platforms to a specific tidal level, such raised features are often assumed to have a vertical error of ±1 m in their original height of development and then used to investigate rates of uplift, such as around Mahia Peninsula (Berryman 1993a) (Fig. 2c). While scientifically sound for such uses, for studies of recent higher sea levels an error of 1 m is unacceptable.

It is generally because of this error that larger marine planation surfaces have been used for calculating uplift and sea level heights over the much larger Quaternary timescale (*c.* 2 ma). This can be best observed in the northern Wanganui Basin where a series of eight terraces dating back to 580 ka occur up to 300 m above sea level (Pillans 1983) which overlie probably the best preserved sequence of Plio-Pleistocene sediments formed through eustatic fluctuations in the world (Naish 2005; Naish *et al.* 2005a,b). Marine terraces relating to highstands are also found along the east coast of the country such as on northern East

Cape (Yoshikawa *et al.* 1980; Wilson *et al.* 2007c), Mahia Peninsula (Berryman 1993b), and Kaikoura–Malborough (Ota *et al.* 1996). While the Wanganui Basin sequence, and to a lesser extent other uplifted terraces, have been used for reconstruction of sea level through the entire Quaternary (Naish 1997), it is difficult to reconstruct eustatic movement to the accuracy required to identify fluctuations on the order of the mid-Holocene highstand.

Sites for further advancement of New Zealand sea level study

Probably the greatest limitation on the study of sea level in New Zealand is that a vertical movement of the coast ranges from average uplift of 4 m/ka to subsidence of 9 m/ka being recorded for Holocene coastal deposits (Pillans 1990; Berryman & Hull 2003). In many cases this uplift is instantaneous, occurring coseismically, such as during the Wairarapa Earthquake of 1855 which uplifted the Turakirae Head coast by 6.4 m (McSaveney *et al.* 2006) and southern Wellington by 1–1.5 m (Pillans & Huber 1995). The 1931 Napier earthquake simultaneously caused subsidence of 0.7 m in Haumoana while north of Napier rose 2.7 m, almost completely draining the Ahuriri Lagoon (Hull 1990). The resultant relative sea-level record for these areas is therefore complex (Fig. 3a,b) and it is difficult to use them for developing eustatic sea-level curves. Areas which have been tectonically stable for the Holocene are therefore seen as critical for investigation.

The Northland region is generally accepted to have remained stable for at least the past two sea-level cycles (Berryman & Hull 2003). This assumption is partly based on the coincidence between the height of global sea level and the height of terraces of Last Interglacial age in Northland (Osborne & Nichol 2006). Many barrier sequences in the region are characterized by multiple dune building phases related to different highstand periods. At One Tree Point, Whangarei these dates to 115 ka (Nichol 2002). The Holocene dune ridges at Henderson Bay (Millener 1981 in Osborne & Nichol 2006), One Tree Point (Nichol 2002), and Tokerau Beach, Karikari Peninsula (Hicks 1983) all show significant seaward progradation, and decrease in height, which may point towards a higher mid-Holocene sea level. A multiproxy study of a wetland bounded by dunes at Kowhai Beach using sedimentology, diatoms and pollen indicates a higher than present sea level of +1.2 m for the mid Holocene (Hicks & Nichol 2007). More investigation is needed however, as differing wave climates and sediment supply may have affected the evolution of these sequences and therefore modify the observed sea-level record.

Further south on the Coromandel Peninsula, uplift rates are also negligible and increase slightly to a maximum of 0.25 mm/year on the central Waikato coast (Kawhia, Aoeta and Raglan Harbours) (Berryman & Hull 2003). Extensive estuarine systems occur in these areas which are often infilled close to low tide levels (Fig. 2d). Coring results in Whangamata (Sheffield *et al.* 1995) and Tairua estuaries (Hume & Gibb 1987), Coromandel, suggests several phases of deposition occurred before and after human settlement in the region, with Holocene sediments occupying a significant proportion of the accommodation space (Fig. 2e). Much of this coast remains to be investigated, as does the Waikato coast where few subsurface investigations have taken place. Further to the west in Tauranga Harbour, the potential also exists for a detailed Holocene infill record (Davis & Healy 1993). Dating of the barrier system on Matakana Island, which forms the seaward edge of Tauranga Harbour, indicates several periods of formation back to the Last Interglacial period (Shepherd *et al.* 1997). All these areas have yet to be investigated in enough detail to produce a scientifically robust sea-level curve.

On the South Island of New Zealand two main areas of relative Holocene tectonic stability exist, coastal Otago and north-west Nelson (Pillans 1990; Berryman & Hull 2003). Like the aforementioned areas on the North Island, limited work has been conducted on these sites, especially when compared to the variety of erosional and depositional landforms found within these regions. Whanganui Inlet has recently received some scientific attention (Kennedy & Paulik 2007; Kennedy *et al.* 2008), however, many other environments with the potential to reconstruct sea level are yet to be studied. Golden Bay contains extensive estuarine sequences, protected by Farewell Spit which

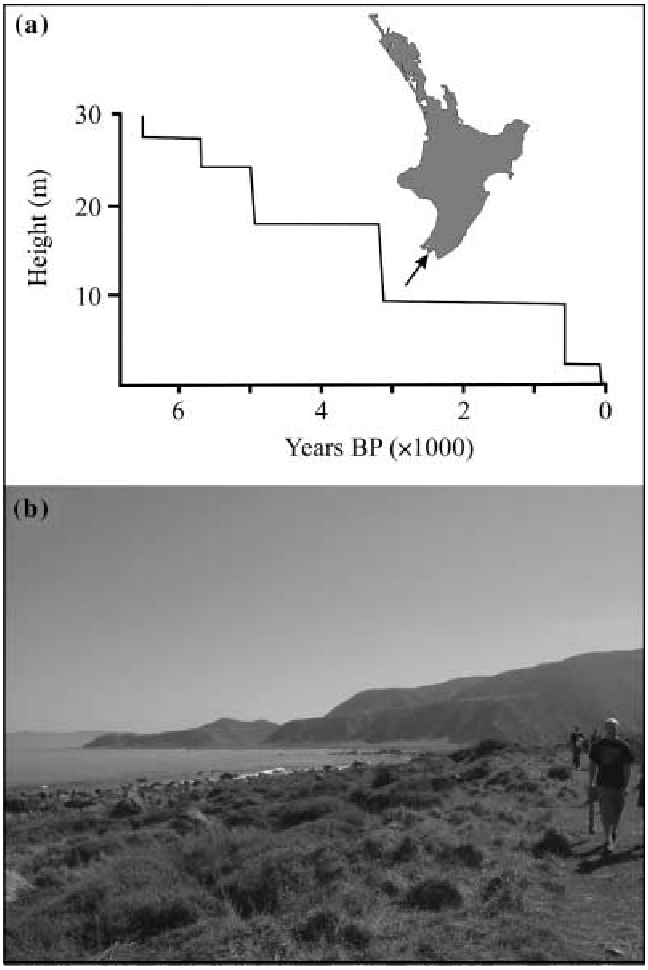

Figure 3 (a) Relative sea level on Turakerai Head has fallen during the Holocene as a result of coseismic uplift (modified from Pirazzoli 1991). (b) View along the seaward edge of 1855 beach ridge westwards towards Wellington (foreground). The terrace in the background represents the Last Interglacial marine surface (photo courtesy Mike Henry).

forms the northern boundary of the bay. Preliminary coring suggests that contemporary reworking of the Farewell Spit dune sequences have masked any potential sea level indicators older than a few hundred years (Tribe & Kennedy 2008). Studies on the evolution of the Nelson Boulder Bank (Dickinson & Woolfe 1997) and Cable Bay (Hartstein & Dickinson 2006) (Figure 2f) have focused on the subaerial sediments, yet on the low energy tidal flats that are enclosed by these barriers, there is likely the potential to reconstruct past levels of tidal inundation.

Further south in Otago, Holocene uplift is also virtually non-existent as evidenced by a lack of marine terraces younger than 200 ka (Bishop & Turnbull 1996; Forsyth 2001). Blueskin Bay was used by Gibb (1986) as one of his benchmark sites, and other estuarine systems also occur along this coast up to Oamaru where the gravel systems of large gravel bed rivers, such as the Waitaki River, form hapua estuaries. Hapua are very ephemeral landforms forming between large flood events (Kirk & Lauder 2000) and therefore are unlikely to preserve a record of sea level change in the predominantly coarse sediments. South of Blueskin Bay, the Otago Peninsula also contains many low energy settings; however, further south of Dunedin uplift during the past few thousand years starts to complicate sedimentary records (e.g. Litchfield & Norris 2000; Hayward *et al.* 2007). Finally, a further opportunity for the study of recent sea level change also occurs on the Chatham Islands which have remained stable during the recent past and contains dune and lagoonal sediments dating through the entire Holocene (McFadgen 1994).

Conclusions

Climate change is predicted to raise sea level around New Zealand by close to a metre in the next 100 years. The last time that the ocean was at this level was during the mid Holocene optimum, where it remained elevated for a few thousand years. An understanding of the nature of sea-level change during this period can therefore provide a proxy for predicting how the coast may respond to human-induced global warming. At present the measured rate of sea-level rise is much less than that during the last deglaciation; however, catastrophic rise events during this period indicate that much more rapid rates of rise than presently observed are possible.

Our understanding of sea-level change during the mid Holocene optimum is based on the benchmark study of Gibb (1986), whose curve forms the basis of coastal evolution science in New Zealand today. In the past few decades understanding of sea-level change has significantly advanced on the south-east Australian coast, which is in the same oceanic region as New Zealand. These studies point to a higher and earlier mid-Holocene optimum than described locally so far. This pattern is likely to occur within New Zealand; however, the active tectonics of the country has hindered new studies of sea-level change. Differing rates of uplift and subsidence mean that inferences based on relative sea-level variations at a given site to another are difficult. The future of sea-level studies therefore lies in the study of new sites and reinterpretation of existing areas that occur in areas of relative tectonic stability. On the North Island, Northland and Coromandel regions hold the greatest prospect for increasing the understanding of sea-level change, as do the north-west Nelson and Otago regions on the South Island. Such new investigations will also benefit from the application of new methodologies such as foraminiferal proxies. In redefining and refining the understanding of recent sea-level change planners and managers will be in a better position to predict how the coast will respond to future sea-level rise.

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