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A 20th century acceleration of sea-level rise in New Zealand

W. Roland Gehrels,[1] Bruce W. Hayward,[2] Rewi M. Newnham,[1] and Katherine E. Southall[3]

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[1] Sea levels in New Zealand have remained relatively stable throughout the past 7000 years, but salt-marsh cores from southern New Zealand show evidence of a recent rapid rise. To date and quantify this rise we present a proxy sea-level record spanning the past 500 years for Pounawea, southeastern New Zealand, based on foraminiferal analyses. Ages for ten sea-level index points are established from AMS^{14}C, Pb concentrations, stable Pb isotopes, pollen markers, charcoal concentrations and ^{137}Cs. Sea level was rising slowly (0.3 ± 0.3 mm yr^{-1}) from AD 1500 to AD 1900, but during the 20th century the rate increased to 2.8 ± 0.5 mm yr^{-1}, in agreement with instrumental measurements commencing in 1924. This is the first sea-level record from the southern hemisphere showing a significantly higher rate of sea-level rise during the 20th century as compared with preceding centuries. **Citation:** Gehrels, W. R., B. W. Hayward, R. M. Newnham, and K. E. Southall (2008), A 20th century acceleration of sea-level rise in New Zealand, *Geophys. Res. Lett.*, *35*, L02717, doi:10.1029/2007GL032632.

1. Introduction

[2] The mean global rate of sea-level rise during the last century is estimated at ~1.7–1.8 mm yr^{-1} [*Church and White*, 2006; *Holgate*, 2007]. Analyses of instrumental sea-level observations cannot fully resolve when this rate of sea-level rise commenced and whether any long-term accelerations of sea-level rise occurred in the 19th and 20th centuries. Some studies have identified sea-level accelerations around the end of the 19th century [*Woodworth*, 1999; *Wöppelmann et al.*, 2005; *Jevrejeva et al.*, 2006] and around 1930 [*Church and White*, 2006]. Others have proposed decelerations within the 20th century [*Woodworth*, 1990; *Holgate*, 2007]. This debate is of critical importance in determining whether global warming is, wholly or partly, responsible for modern rapid rates of sea-level rise. Unfortunately, instrumental records of sea-level change are generally too short and provide insufficient spatial coverage to give definitive answers.

[3] Recent investigations in the North Atlantic have shown that analyses of microfossils preserved in salt-marsh sediments can produce valuable sea-level records that are in good agreement with 20th century tide-gauge observations [*Gehrels et al.*, 2002, 2005, 2006]. North Atlantic proxy records show an increase in the rate of sea-level rise between the middle of the 19th and the beginning of the 20th century [*Donnelly et al.*, 2004; *Gehrels et al.*, 2005, 2006]. In this paper we report on a salt-marsh proxy sea-level record obtained from Pounawea in southeastern New Zealand. This is the first southern hemisphere sea-level record that directly compares rates of 20th century sea-level rise with sea-level changes during preceding centuries.

2. Methods

[4] We cored salt marshes in four locations in southern New Zealand during several field visits between April 2003 and December 2006 (Figure S1[1]). We analysed the sediments for foraminiferal content to detect transgressive and regressive tendencies and evidence of sea-level changes. Details of foraminiferal sampling and preparation techniques are described by *Gehrels* [2002].

[5] Ages of sea-level index points (Table S1) were determined by Accelerator Mass Spectrometry (AMS)^{14}C, ^{137}Cs, total Pb concentrations, Pb isotopic ratios, charcoal and pollen analyses. AMS^{14}C analyses were conducted by Beta Analytic and Waikato University and ^{137}Cs was measured at the University of Liverpool. We also measured ^{210}Pb, but found levels to be too low for reliable determination, presumably due to low ^{210}Pb deposition rates in southern New Zealand [*Preiss et al.*, 1996]. Total Pb and Sc concentrations and stable lead ratios were determined at the University of Plymouth using an ICP-MS PlasmaQuad PQ2+ Turbo and an Axiom Multicollector ICP-MS PlasmaQuad PQ2+ Turbo, respectively. Charcoal analyses followed methods described by *Mooney and Black* [2003]. Pollen was identified using standard pollen texts [e.g., *Moar*, 1993] and with reference to reference pollen slides for both New Zealand and northwest Europe held at the University of Plymouth.

3. Salt Marshes

[6] Salt-marsh surfaces are located in the upper part of the intertidal zone (roughly between mean high and extreme high water) where sediments accumulate during flooding by the highest tides. Thick salt-marsh sediment accumulations form when accommodation space is created by rising sea level. Salt-marsh deposits in southern New Zealand, however, are rarely thicker than 0.5 m, which is a reflection of the length of time that sea level has remained close to its present level through the middle and late Holocene [*Gibb*, 1986]. Nonetheless, a proportion of their thickness can be attributed to recent sea-level rise, which has been measured by New Zealand tide gauges. The Lyttelton tide gauge shows an increase of 2.1 ± 0.1 mm yr^{-1} for the period 1899–2001. The New Zealand average, calculated from the records of Auckland, Wellington, Lyttelton and Dunedin, is $\sim 1.6 \pm 0.2$ mm yr^{-1} over the 20th century [*Hannah*, 2004].

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[1] School of Geography, University of Plymouth, Plymouth, UK.
[2] Geomarine Research, St. Johns, Auckland, New Zealand.
[3] Department of Geography, Trinity College, University of Dublin, Dublin, Ireland.

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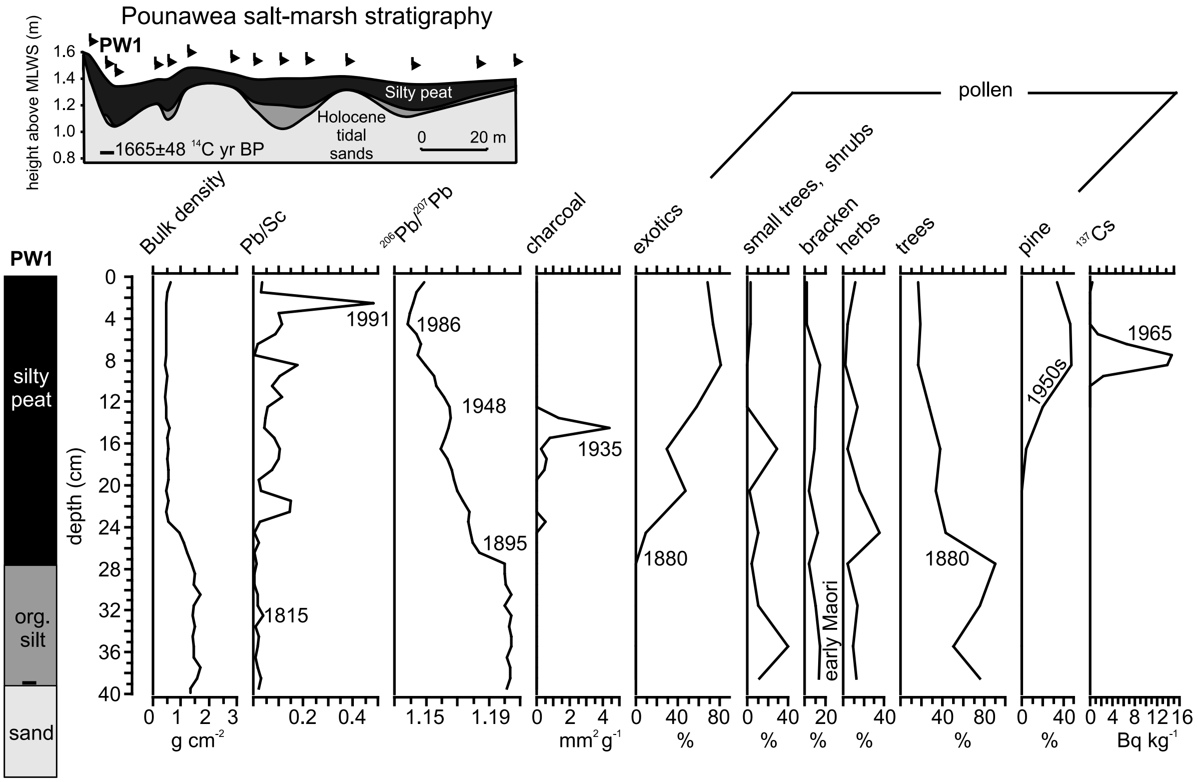

Figure 1. Litho- and chronostratigraphy of Pounawea salt marsh. Derivation of ages is discussed in the text. MLWS = mean low water of spring tides.

[7] In upper-marsh cores collected from Mokomoko Inlet, Waikawa Harbour, Pounawea and Akatore (Figure S1) we found a consistent pattern of changes in assemblages of salt-marsh foraminifera. At the base of all cores, at depths of 0.3 to 0.5 m, *Trochamminita salsa* and *Haplophragmoides wilberti* are present. These species are found near the level of extreme high water in modern salt marshes [*Hayward et al.*, 1999, 2007; *Southall et al.*, 2006] and indicate, therefore, a rise of the high water mark by 0.3–0.5 m.

[8] We conducted detailed stratigraphic analyses at Pounawea. This area is highly suitable for quantitative sea-level investigations: the height of the Last Interglacial shoreline is found at ~4 m above sea level [*Litchfield and Lian*, 2004] and detailed stratigraphic analyses show that vertical land movements have not occurred since ~1000 cal. yr BP [*Hayward et al.*, 2007]. In Pounawea salt marsh, cores bottomed out in a medium- to fine-grained, medium- to well-sorted sand unit (Figure 1). The substrate topography is slightly undulating and in hollows we encountered an organic-rich salt-marsh silt which is overlain by a 0.3 m thick silty salt-marsh peat unit.

4. Sea-Level Index Points

[9] We established twelve sea-level index points for the Pounawea marsh, ten of which allowed a precise reconstruction of sea-level rise during the past ~500 years. Two index points are older than 500 years. From foraminiferal analyses (Table S2) we determined for each sea-level index point its 'indicative meaning' (i.e. the elevation relative to sea level at which the sample was deposited) based on the transfer function of *Southall et al.* [2006]. This approach assumes that the foraminifera exhibited in the past the same elevation gradient as observed in the modern environment. Quantitative analyses on modern foraminifera show that the indicative meaning can be calculated with a precision of ±0.035 to ±0.05 m [*Southall et al.*, 2006]. Surveying errors are insignificant, as surface and core samples were collected from the same transect. We apply a conservative error of ±0.05 m to our sea-level index points.

[10] The sand below the salt-marsh sediments contains the intertidal foraminifera *Ammonia* spp., *Elphidium* spp., *Trochammina inflata* and *Cibicides marlboroughensis*. These species are indicative of a high intertidal sand-flat environment [*Hayward et al.*, 2007]. In core PW-1 we dated a *Paphies australis* shell from the sand unit which yielded an age of 1665 ± 48 ^{14}C yr BP. An *Austrovenus stutchburyi* shell from the same lithostratigraphical unit was dated by *Hayward et al.* [2007] to 3756 ± 36 ^{14}C yr BP. The heights of these samples and their associated foraminifera indicate that late Holocene sea level in this area was at −0.2 ± 0.2 m.

[11] The silty sediments overlying the sands contain abundant salt-marsh foraminifera (Table S2) and sustained levels of *Pteridium* (bracken) spores (Figure 1), suggesting deposition after the first forest clearances undertaken by Polynesian settlers in New Zealand, estimated as early 14th century [*Newnham et al.*, 1998]. This evidence is consistent with three ^{14}C ages we obtained from a detrital plant fragment at the base of the salt-marsh sediments at 0.39 m depth in the core (410 ± 40, 420 ± 40, 410 ± 40 ^{14}C yr BP; average 410 ± 23 ^{14}C yr BP; AD 1451–1623). The upper marsh foraminifera associated with this sample (predomi-

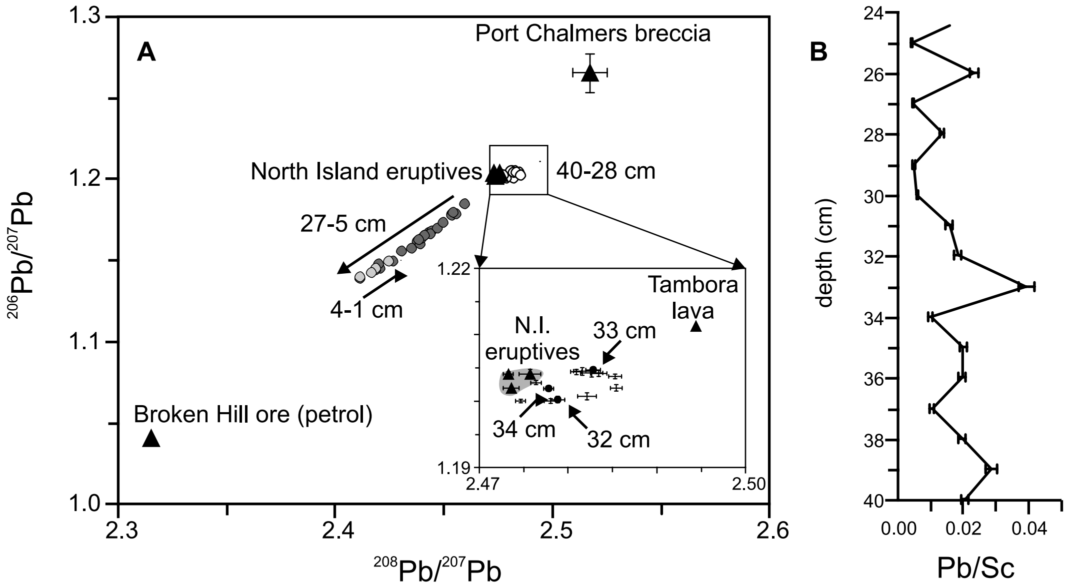

Figure 2. A. Pb 3-isotope plot for core PW1. Also included are values for andesites and basalts from the Egmont and Taupo volcanic zones on the North Island [*Graham et al.*, 1992; *Price et al.*, 1992], Tambora lava [*Turner and Foden*, 2001], regional basement rocks [*Price et al.*, 2003], and Broken Hill Pb ore, the primary constituent of petrol Pb [*Vallelonga et al.*, 2002]. Enlargement shows pre-industrial samples (28–40 cm). The Pb maximum at 33 cm shows an isotopic shift towards Tambora lava values. B. Expanded Pb/Sc curve (from Figure 1) for lower section of core PW1. The maximum at 33 cm is proposed to result from fallout of the 1815 Tambora eruption.

nantly *Haplophragmoides wilberti*) place sea level at −0.39 ± 0.05 m at this time. The foraminiferal stratigraphy indicates that sea level must have fallen before re-flooding the late Holocene sands.

[12] At 0.33 m depth we correlate a maximum in Pb concentrations with fallout from the 1815 Tambora eruption. The Pb/Sc ratios at this level are the highest in the pre-industrial period and more than twice the pre-industrial mean (0.039 vs. 0.016, Figure 2B). Ratios of ^{206}Pb/^{207}Pb and ^{208}Pb/^{207}Pb of pre-industrial Pb samples are very similar to those of North Island eruptives from the Taupo and Egmont volcanic zones [*Graham et al.*, 1992; *Price et al.*, 1992], and dissimilar to South Island basement rocks [*Price et al.*, 2003], indicating that the Pb supply to the marsh surface resulted from atmospheric transport of North Island volcanic aerosols. However, the Pb maximum at 0.33 m contains a distinct isotopic excursion towards values of Tambora lava [*Turner and Foden*, 2001, Figure 2]. The shape of the Pb peak, comprising a sudden jump and a tail, and its stratigraphic position, make it likely that it can be related to the AD 1815 Tambora eruption, globally the largest volcanic eruption in recorded history [*Pyle*, 2000] with aerosols reaching as far as Law Dome in Antarctica [*Vallelonga et al.*, 2003]. Based on the presence of the foraminifer *Haplophragmoides wilberti*, we reconstruct a sea-level position of −0.31 ± 0.05 m in 1815.

[13] The organic section between 0.285 m and the top of the core contains the sea-level record for the late 19th and 20th centuries. At 0.285 m in the core we find evidence for European land clearance, signalled by the appearance of exotic tree pollen (primarily *Cytisus* and *Salix*), and the first radiogenic excursion in the Pb isotopic ratios. Radiogenic Pb in the southern hemisphere appears in the Antarctic ice-core record around 1895 [*Vallelonga et al.*, 2002; *Van de Velde et al.*, 2005], while we estimate that exotic pollen would be detectable around 1880, ~20 years after European settlement of the area [*Wilson*, 1993]. Pollen analyses were conducted at lower resolution (4 cm) than Pb analyses (1 cm), so these ages are compatible. The presence of the foraminifera *Trochamminita salsa* and *Haplophragmoides wilberti* indicate a sea-level position of −0.285 ± 0.05 m in 1900 (Table S1).

[14] At 0.165 m a distinct charcoal peak is correlated to the 1935 Catlins Forest 'Big Fire' [*Wilson*, 1993]. The temporary ^{206}Pb/^{207}Pb maximum at 0.145 m can be related to the depressed global Pb production of the late 1940s recorded in Pb concentrations and Pb isotopes in Antarctica [*Wolff and Suttie*, 1994; *Van de Velde et al.*, 2005]. The *Pinus* pollen curve (Figure 1) shows an expansion from 0.16 m, reaching a peak at 0.10 m, consistent with a major expansion phase of pine forest plantations in southern New Zealand in the 1950s [*Wilson*, 1993]. The 1965 ^{137}Cs maximum is clearly detected at 0.08 m. The introduction of unleaded petrol in the late 1980s produced an isotopic signal towards less radiogenic values in the upper 4 cm (Figure 2), where also a pronounced Pb maximum is found, probably related to a large catchment flood in 1991 [*Tyrrell*, 2006]. The reconstructed sea-level positions for all stratigraphic levels are listed in Table S1.

5. Discussion and Conclusions

[15] At Blueskin Bay, about 100 km to the northeast, *Gibb* [1986] reported ten middle to late Holocene sea-level index points on shells collected from beach and tidal flat sediments. Vertical errors on *Gibb*'s [1986] sea-level index points range from ±0.5 to ±0.9 m, so that it is not possible to distinguish a clear sea-level trend during the middle and late

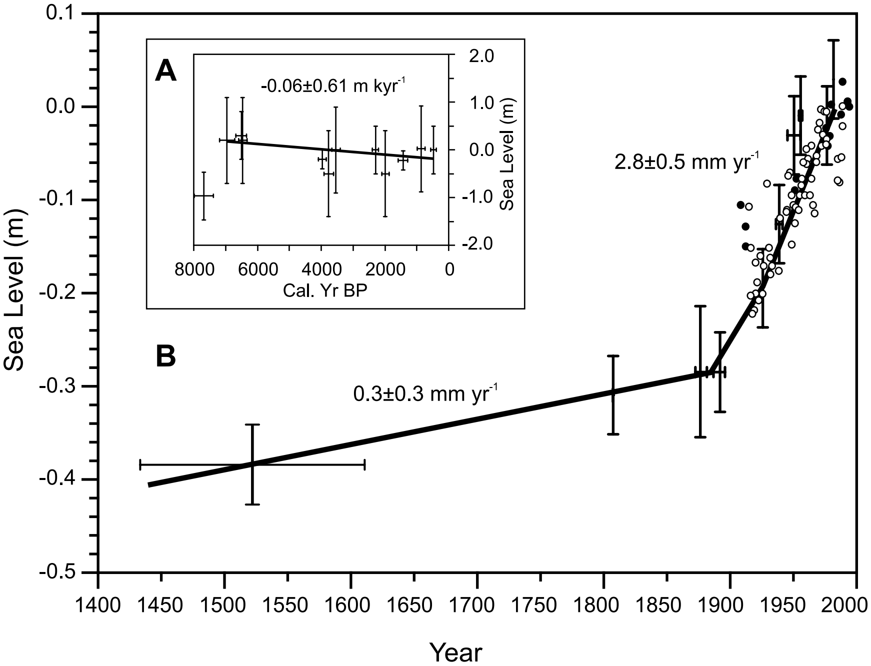

Figure 3. A. Middle and late Holocene sea-level data for southern New Zealand (*Gibb* [1986], *Hayward et al.* [2007], and this study). B. Reconstructed sea-level changes at Pounawea, southern New Zealand, since AD 1500. Also shown are annual tide-gauge observations at Lyttelton (open dots) and Bluff (black dots) from the Permanent Service for Mean Sea Level at http://www.pol.ac.uk/psmsl. The nearby Dunedin tide-gauge data are not shown due to supposed wharf subsidence [*Hannah*, 2004].

Holocene. However, it is evident that sea level has been mostly stable, or slightly falling, during the past seven millennia (Figure 3A). Our sea-level reconstruction for Pounawea is shown in Figure 3B. On the basis of four new sea-level index points we reconstruct a slow sea-level rise between AD 1500 and AD 1900 of 0.3 ± 0.3 mm yr^{-1} which is broadly in line with the millennial-scale middle and late Holocene trend.

[16] We estimate a rate of sea-level rise of 2.8 ± 0.5 mm yr^{-1} during the 20th century, considerably higher than the rate reconstructed for preceding centuries, but compatible with the nearest reliable tide-gauge record at Lyttelton which has recorded a rise of 2.1 ± 0.1 mm yr^{-1} between 1924 and 2001 [*Hannah*, 2004]. Our reconstruction also agrees with scattered 20th century sea-level data from the tide station at Bluff (Figure 3; available from the Permanent Service for Mean Sea Level at http://www.pol.ac.uk/psmsl).

[17] The Holocene sands at Pounawea provide a firm substrate so that long-term compaction can be ruled out. Bulk density is constant throughout the silt (~1.5 g cm^{-3}) and organic units (~0.5 g cm^{-3}) (Figure 1), indicating that stratigraphic levels have not been displaced by compaction. Agreement with tide-gauge observations also signifies the absence of compaction in the upper part of the sequence.

[18] We conclude that the 20th century rate of sea-level rise in southern New Zealand was significantly faster than the rates reconstructed for the preceding four centuries and for the entire middle and late Holocene. A 20th century sea-level acceleration is also observed in proxy records from the North Atlantic Ocean [*Gehrels et al.*, 2002, 2005, 2006; *Donnelly et al.*, 2004] and in the longest European instrumental records [*Woodworth*, 1999; *Wöppelmann et al.*, 2005]. The twentieth century rate in southern New Zealand is higher than the global average (~1.7–1.8 mm yr^{-1} [*Church and White*, 2006; *Holgate*, 2007]), a difference that can be attributed to regional thermal expansion (estimated at 0.4–0.8 mm yr^{-1} for the period 1955–2003 [*Ishii et al.*, 2006]). The 20th century acceleration of sea-level rise appears to be of a global nature and is therefore likely related to the concurrent rise in global temperatures.

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W. R. Gehrels and R. M. Newnham, School of Geography, University of Plymouth, Plymouth PL4 8AA, UK. (wrgehrels@plymouth.ac.uk)

B. W. Hayward, Geomarine Research, Swainston Road, St. Johns, Aukland, New Zealand.

K. E. Southall, Department of Geography, Trinity College, University of Dublin, Dublin 2, Ireland.