GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 7, 1401, doi:10.1029/2002GL016813, 2003

The Sea Level at Port Arthur, Tasmania, from 1841 to the Present

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Received 20 December 2002; accepted 11 March 2003; published 10 April 2003.

[1] Observations of sea level at Port Arthur, Tasmania, southeastern Australia, based on a two-year record made in 1841–1842, a three-year record made in 1999–2002, and intermediate observations made in 1875–1905, 1888 and 1972, indicate an average rate of sea level rise, relative to the land, of 0.8 ± 0.2 mm/year over the period 1841 to 2002. When combined with estimates of land uplift, this yields an estimate of average sea level rise due to an increase in the volume of the oceans of 1.0 ± 0.3 mm/year, over the same period. These results are at the lower end of the recent estimate by the Intergovernmental Panel on Climate Change of global average rise for the 20th century. They provide an important contribution to our knowledge of past sea level rise in a region (the Southern Hemisphere) where there is a dearth of other such data. *INDEX TERMS:* 4556 Oceanography: Physical: Sea level variations; 1635 Global Change: Oceans (4203); 1724 History of Geophysics: Ocean sciences. **Citation:** Hunter, J., R. Coleman, and D. Pugh, The Sea Level at Port Arthur, Tasmania, from 1841 to the Present, *Geophys. Res. Lett.*, *30*(7), 1401, doi:10.1029/2002GL016813, 2003.

1. Introduction

[2] The global average sea level has risen at a rate of 1 – 2 mm/year over the 20th century [*Church et al.*, 2001]. This estimate was based on tide gauges distributed unevenly over the Earth; for example, a major contribution to this estimate was based on 24 sites, of which only 6 were in the Southern Hemisphere and none were in Australia [*Douglas*, 1997]. There are therefore large regions of the Southern Hemisphere for which there are no estimates of past sea level rise. On 1 July 1841, a sea level benchmark (Figure 1) was struck on a small cliff on the Isle of the Dead, near the penal settlement of Port Arthur, Tasmania (43° 9′ S, 147° 52′ E). The operation was instigated by T.J. Lempriere, an amateur scientist and storekeeper at Port Arthur, and Capt. James Clark Ross, who was visiting Tasmania during his explorations of 1839–43 [*Hamon*, 1985; *Ross*, 1847]. The benchmark has survived intact to this day. Lempriere had previously constructed a tide gauge at Port Arthur, where he made observations of the times and heights at approximately high and low water from mid-1837 [*Lempriere*, 1838] to at least the end of 1842. Here we compare Lempriere's measurements with modern observations made at Port Arthur, and with a number of intermediate estimates of sea level. Further historical details have been provided by *Pugh et al.* [2002].

2. The Historic Observations

[3] No detailed information about the construction of Lempriere's tide gauge appears to have survived. It was probably not self recording, (although the first self recording gauge was installed in the United Kingdom in 1831 [*Pugh*, 1987], the first such Australian gauge is believed to have been installed in Williamstown, Victoria, in 1858 [*Matthaus*, 1972]). However, it is likely that the tide gauge incorporated a form of stilling well, because such devices were described as early as 1666 [*Pugh*, 1987] and from the inference on the plaque which originally accompanied the benchmark and carried the words 'height of water in tide gauge 6 ft. 1 in.'. The benchmark on the Isle of the Dead indicated the level of the sea at a time near high water; this time and the simultaneous tide gauge reading were recorded on a plaque situated above the benchmark. Unfortunately, this plaque has been lost or destroyed, although the inscription was recorded by two observers [*Shortt*, 1889; *The Australasian*, 1892]. A single observation of sea level relative to the benchmark was also made in 1888 [*Shortt*, 1889].

[4] These observations were of little scientific value [*Hamon*, 1985] until recently, when Lempriere's original records were found. In late 1995 we discovered his data for 1841 and 1842 in the archives of the Royal Society in London, and in mid-1998 we found data for December 1839 and February 1840–January 1841 in the National Archives of Australia. Screening of the complete data set covering December 1839 to December 1842 indicated a datum shift in December 1840, coinciding with a relocation of Lempriere's observatory which was noted in his meteorological records. The data for 1841 and 1842 appear to be related to a common datum, which is referenced to the benchmark through the tide gauge reading at the time when the benchmark was struck. We estimated mean sea level by taking the *mean tide level* (the average of an equal number of high water and low water levels), for two reasons. Firstly, this approximation is a good one at Port Arthur where the shallow water constituents are very small and, secondly, tidal analysis of records consisting only of high

0094-8276/03/2002GL016813$05.00

Figure 1. The benchmark on the Isle of the Dead, Port Arthur. The horizontal line is about 0.4 m long.

and low water values can be problematic. Mean tide level for 1841 and 1842 differed by only 0.013 m, increasing our confidence that there was no datum shift during that period.

3. Modern Observations

[5] An Aquatrak acoustic tide gauge, mounted in a stilling well, was installed in the Port Arthur settlement in 1998. Subsequently, an almost continuous (99.97% data recovery) sea level record was obtained from August 1999 to August 2002, consisting of averages taken over 3 minutes, recorded every 6 minutes. Mean sea level was estimated using a conventional tidal analysis for 102 harmonic constituents. Our estimate of sea level rise is based on the difference between sea level derived from Lempriere's data for 1841–1842 and sea level derived from these modern measurements.

4. Intermediate Observations

[6] Intermediate indications of sea level are also available. On 24 February 1888, a single observation of sea level relative to the benchmark was made [*Shortt*, 1889]. We have adjusted this level using a tidal hindcast to obtain an estimate of mean sea level at that time. In 1905, the Tasmanian State Datum was defined, based on observations of mean sea level at Hobart, Tasmania, (which is 51 km northwest of Port Arthur) for the previous 30 years [*Government of Tasmanian*, 1941]. By transferring this level to the Isle of the Dead, we have estimated the mean sea level relative to the benchmark for 1875–1905. The Australian Height Datum (AHD) for Tasmania is based on mean sea level at Hobart and Burnie, Tasmania, for a single year, 1972 (*National Mapping Council of Australia*, 1986; Geocentric Datum of Australia Technical Manual Version 2.2, Intergovernmental Committee on Surveying and Mapping, chap. 8, February 2002, located at www.icsm.gov.au/icsm/gda/gdatm.htm). By transferring this level to the Isle of the Dead, we have estimated the mean sea level relative to the benchmark for 1972.

5. Uncertainties

[7] We have estimated the uncertainty in mean sea level from four sources: interannual variability, the nodal tide, survey leveling, and instrumental and observational error. The interannual variability for an N-year estimate of mean sea level was approximated by the standard deviation of sequential N-year averages of 16 years of modern tidal residual data from Spring Bay, 67 km to the north of Port Arthur (N = 2 and 3, for the 1841–1842 and 1999–2002 observations, respectively). For the single observation in 1888, the interannual variability was estimated from the standard deviation of 14 years of 6-hourly tidal residuals from Spring Bay. In addition, we used 130 years of the Southern Oscillation Index as a proxy for sea level at Port Arthur, in order to estimate the contribution of time scales longer than 16 years. We concluded that, at most, inclusion of these time scales would only increase the standard deviation of the interannual variability by about 9%, and are therefore reasonably confident in using only 16 years of data from Spring Bay. The nodal tide (the tidal harmonic caused by the regression of the moon's node), which has a period of 18.6 years, is imperfectly known [*Pugh*, 1987] and therefore an estimate of its magnitude was included as an error term (although it makes no significant difference to the total estimate of uncertainty). The leveling contribution for 1841–1842 was based on an estimate of the variation in the difference in sea level between the Isle of the Dead and the Port Arthur settlement (where it is believed that Lempriere's tide gauge was situated), which are separated by 1.2 km. This difference is predominantly caused by a seiche (a natural surface mode of oscillation) of 50-minute period, which we estimated to have a standard deviation of about 0.01 m, using a pair of tethered buoys equipped with Global Positioning System (GPS) receivers [*Watson*, 1999]. Leveling between the benchmark and our modern tide gauge (also situated in the Port Arthur settlement) was accomplished using GPS techniques and verified using optical surveying methods. The primary contribution to the leveling error was, in this case, uncertainty in the local geoid slope. For the Tasmanian State Datum and AHD, the total uncertainty was assumed to be dominated by a leveling error between Hobart and Port Arthur of ±0.1 m (the estimated difference in mean sea level between Hobart and Port Arthur, due to winds and varying water density, is almost certainly less than 0.02 m, which makes a negligible contribution to the total uncertainty). Instrumental and observational errors were dominated, for 1841–1842, by the physical size of the horizontal line on the benchmark. For 1999–2002, the instrumental error was estimated from a comparison of three

calibrations, made at the start of, during and at the end of the observation period.

6. The Historical Accounts

[8] There are some inconsistencies among the various historical accounts. Firstly, in his journal, Ross stated that the benchmark had been installed at mean sea level [*Ross*, 1847], whereas the level given in the two reports of the wording on the plaque [*Shortt*, 1889; *The Australasian*, 1892], combined with Lempriere's records for 1 July 1841, indicate that the benchmark was installed about one hour before high water. There is also a discrepancy between the recorded times at which the benchmark was struck, one [*Shortt*, 1889] being consistent with Lempriere's records, and the other [*The Australasian*, 1892] giving a time two hours earlier. From the position of the benchmark relative to mean sea level as estimated in 1875–1905, 1888 and 1972, and from our modern records (Figure 2), we believe that it is inconceivable that the benchmark could have been at mean sea level in 1841 (see Section 9). *Ross* [1847] also noted in his journal (in the same paragraph in which he stated that the benchmark was at mean sea level) that 'I may here observe, that it is not essential that the benchmark be made exactly at the mean level of the ocean, indeed it is more desirable that it should be rather above the reach of the highest tide'. We believe Ross was mistaken in stating that the benchmark was originally at mean sea level. From inspection of Lempriere's sea level records, and from a tidal hindcast for the day when the benchmark was struck, we believe the report of *Shortt* [1889] that recorded the time of striking of the benchmark as about one hour before high water.

7. Atmospheric Pressure and Vertical Motion of the Land

[9] Sea level measurements are often adjusted to some standard atmospheric pressure. We have not done this because of a number of uncertainties concerning barometric observations made in 1841–1842 at both Port Arthur and Hobart. These included the questions of whether temperature and height correction had been applied to the reported observations, and whether the barometers were adequately calibrated or checked for leakage.

[10] Tide gauges measure sea level relative to the land, which may itself be moving vertically. We have obtained estimates of the vertical motion of the land surface at Port Arthur from two sources. A model of glacial isostatic adjustment (GIA) indicates a present rise of the land of 0.17 mm/year (*Lambeck*, 2002; K. Lambeck, Australian National University, personal communication, 2002). Geological evidence from raised shell beds at Mary Anne Bay (42 km from Port Arthur) indicates an average rise of the land over the past 125,000 years (i.e. since the last interglacial) of 0.19 mm/year [*Banks and Leaman*, 1999]. We do not try to distinguish between GIA and tectonic components, but use the values as an indication of the magnitude of the local vertical motion of the land relative to the sea in the absence of an increase in the volume of the oceans. With the caveat that there could be substantial changes in average vertical land motion over the last 125,000 years, we therefore infer that the (upward) vertical motion of the land since 1841 is in the approximate range 0.2 ± 0.2 mm/year.

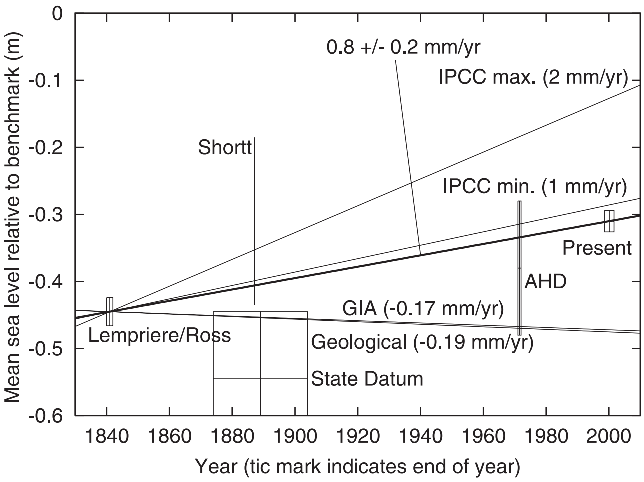

Figure 2. History of sea level estimates at Port Arthur. Each rectangular box represents an estimate of sea level relative to the benchmark; the length of a box shows the duration of the observations and the height provides an estimate of the uncertainty (± one standard deviation). References for these boxes: *Lempriere/Ross* [*Hamon*, 1985; *Ross*, 1847; *Shortt*, 1889; *The Australasian*, 1892], *Shortt* [*Shortt*, 1889], *State Datum* [*Government of Tasmania*, 1941], *AHD* [*National Mapping Council of Australia*, 1986]. *Present* indicates the results of our three years of observation at Port Arthur during 1999–2002. The two upper slanting lines indicate the range of estimates of the rate of global average sea level rise [*Church et al.*, 2001]. The two lower slanting lines show estimates of the rate of sea level change at Port Arthur relative to the land, in the absence of increase in volume of the ocean: *GIA* is from a model of glacial isostatic adjustment (*Lambeck*, 2002; K. Lambeck, Australian National University, personal communication, 2002); *Geological* is from geological evidence over the past 125,000 years [*Banks and Leaman*, 1999]. The central slanting (bold) line is our estimate of average sea level rise at Port Arthur, relative to the land; this passes through the best estimates of sea level for 1841–42 and for 1999–2002.

[11] We have also considered the difference between the GIA at Port Arthur (0.17 mm/year) and Hobart (0.04 mm/year; *Lambeck*, 2002), which could cause an error in the transfer of the Tasmanian State Datum and AHD from Hobart to Port Arthur (section 4), depending on the time when the transfer occurred. This would, however, make a negligible contribution to the total uncertainty (±0.1 m) attributed to these levels in section 5.

8. Results

[12] Figure 2 shows the history of sea level estimates for Port Arthur. A line passing through the best estimates from 1841–1842 and 1999–2002 lies within 1.5 standard deviations of the three other estimates, and yields an average sea level rise relative to the land since 1841–1842 of 0.8 ± 0.2 mm/year (indicating±one standard deviation). When combined with the estimates of land uplift given above, this

yields an estimate of average sea level rise at this location due to an increase in the volume of the oceans of 1.0 ± 0.3 mm/year. This is at the lower end of the range of global average sea level rise for the 20th century (1–2 mm/year) given by the Intergovernmental Panel on Climate Change [*Church et al.*, 2001]. If it is assumed that most of this sea level rise occurred since about 1890 (the indication from long tidal records from elsewhere; *Woodworth*, 1999), then the corresponding estimates of rise (1890 to the present) relative to the land, and due to an increase in the volume of the oceans, become 1.2 ± 0.2 mm/year and 1.4 ± 0.3 mm/year, respectively.

9. Discussion

[13] The above estimates of sea level rise due to an increase in the volume of the oceans may be compared with recent estimates for the two longest (continuous) Australian records. Fremantle (32° 3′ S, 115° 44′ E; 91 years to 1996) and Fort Denison (33° 51′ S, 151° 14′ E; 82 years to 1997) showed rates of rise of 1.6 and 1.2 mm/year, respectively, after adjustment for GIA [*Lambeck*, 2002].

[14] Statistical analysis of the data shown in Figure 2 reinforces our belief that the benchmark was not located at mean sea level in 1841. A least-squares fit of a linear trend to all the data shown, with due regard to the *a priori* uncertainty estimates, yields a slope that is not significantly different from the above trend (which was based only on the 1841–1842 and the 1999–2002 data), and a high (43%) 'goodness-of-fit' probability. However, if it is assumed that mean sea level in 1841 was at the benchmark, then the 'goodness-of-fit' probability becomes extremely low (0.003%), indicating that a constant trend would not fit such data; any curve that does fit the data would have to involve a steep fall (typically 10 mm/year) prior to 1890, followed by a rise of around 1 mm/year, which we believe to be physically unrealistic.

[15] Our results should be viewed in the context of present attempts to reconcile observations of sea level rise, the heat stored in the oceans, the rate of the earth's rotation rate, polar wander and the results of models of sea level rise [*Douglas and Peltier*, 2002; *Munk*, 2002; *Meier and Wahr*, 2002]. For example, models of the global ice and water budget indicate a global sea level rise of −0.8 to 2.2 mm/year, with a central value of 0.7 mm/year [*Church et al.*, 2001], favoring the lower end of the range of global sea level rise estimated from tide gauge records (i.e. 1 mm/year; *Church et al.*, 2001). On the other hand, some estimates derived from tide gauge records fall near the high end of the observational range (i.e. 2 mm/year; *Douglas and Peltier*, 2002), although *Cabanes et al.* [2001] have suggested that the sparse and uneven distribution of tide gauges may cause an overestimate of the rise. Further, observations from satellite altimeters indicate a global rise in mean sea level during the past decade that is generally greater than 2 mm/year [*Church et al.*, 2001], which may be a result of interdecadal variability, the beginning of a systematic acceleration in the rise, or an indication that the long-term rate of rise is higher than currently believed.

[16] In conclusion, historic and modern records from Port Arthur, Tasmania, cover the longest time span of any sea level observations in the Southern Hemisphere and are related to a single benchmark; they provide a significant contribution to our knowledge of past sea level rise in this data-sparse region.

[17] **Acknowledgments.** This work was partly supported by a grant from the Institutional Research Grant Scheme at the University of Tasmania. The tide gauge was installed with support from the University of Canberra and the Commonwealth Scientific and Industrial Research Organisation, Australia. We thank the Port Arthur Management Authority for permission to install and operate the gauge, and Chris Watson and Nick Bowden for surveying support. Sea levels and residuals for Spring Bay are supplied by the National Tidal Facility, The Flinders University of South Australia, Copyright reserved. Bruce Miller provided Figure 1.

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