A COMPARISON OF HISTORICAL AND RECENT SEA LEVEL MEASUREMENTS AT PORT ARTHUR, TASMANIA

By

D Pugh[1], J Hunter[2], R Coleman[2] and C Watson[2].

[1]Southampton Oceanography Centre, United Kingdom
[2]University of Tasmania

ABSTRACT

Estimates of anticipated sea level rise as a consequence of ‘greenhouse’ warming depend both on the increased global temperatures, and on the way in which this heat and the water formed from melting ice are absorbed in the global ocean (Church et al, 2001). Various numerical models of ocean responses have shown that the increase in sea level will not be uniform worldwide; the validity of these models can be confirmed if these regional differences are consistent with direct observations. For this, measurements of actual mean sea level changes over long periods are needed. Unfortunately, very few early sea level measurements have survived, especially in the Southern Hemisphere.

A unique series of sea level measurements, made at Port Arthur, Tasmania, between 1837 and 1842, and linked to a benchmark which still exists, has been used to estimate sea level changes in the region over the past 160 years. The estimated rise (0.13 +/- 0.03 metres) gives an average rate of increase of 0.8 +/- 0.2 mm/year. Correction for local vertical land movement, based on best available models and observations, increases this value by about 0.0 to 0.2 mm/year. This rate of increase is significantly less than the observed globally averaged mean sea level rise over the same period (Church et al, 2001). However, it is broadly consistent with the reduced rate of rise at high southern latitudes shown by numerical models (Gregory et al, 2001). A major uncertainty arises in the estimate of recent vertical land movement, which will be resolved only when our geocentric measurements of the benchmark coordinates are repeated after a sufficiently long interval.

INTRODUCTION

Scientific and popular interest in possible rises of global sea level, with attendant increased risks of coastal flooding, have emphasised the need for long time series of sea level measurements. Unfortunately, few records exist from the nineteenth century and earlier. Even fewer have well documented benchmark information against which changes can be monitored. This paper reports analyses of measurements made at the penal settlement of Port Arthur, Tasmania (Figure 1) between 1837-1842. The sea level measurements were initiated by Sir John Franklin during his time as Lieutenant Governor General of Tasmania (then known as Van Diemen's Land) and sustained by the diligence of Thomas Lempriere, the Deputy Assistant Commissary General at the Port Arthur penal settlement. Port Arthur is 52 km to the southeast of Hobart, then as now the principal administrative centre of Tasmania. The benchmark was made at the suggestion of James Clark Ross who was over-wintering in Hobart during his Antarctic expeditions; Ross had been encouraged to begin sea level measurements relative to permanent benchmarks by the German geophysicist Baron Von Humboldt. From the original correspondence it appears that the Port Arthur benchmark is probably the first ever installed for measuring relative land-sea vertical movements at an ocean site.

When Sir John Franklin, the famous Arctic explorer was appointed as Lieutenant Governor of Tasmania, he took with him as a member of his entourage, Lt Thomas Burnett, a maritime surveyor appointed by the Admiralty. They arrived in Tasmania on the *Fairlie* on 6 January 1837 (Heard, 1981). Burnett was drowned shortly afterwards while surveying the marine approaches to Hobart. On 30 September 1837 Sir John Franklin wrote to Sir John Herschel a member of the Royal Society of London. Herschel spent the period January 1834 to May 1838 making astronomical (and some tidal) observations at the Cape of Good Hope; and Franklin would probably have discussed observations with him on passage to Tasmania.

I also now forward the Meteorological and Tidal Registers which have been kept at Port Arthur on Tasmans Peninsula our most Southern Settlement…

I dare say you have heard by way of Sydney of the truly great loss I and this Colony have sustained by the death of my indefatigable friend, Lt. Burnett. He was drowned by the upsetting of a boat – on the D'Entrecasteaux Channel where he was surveying…We were preparing a portable observatory for him at the time and making other arrangements for his making a series of observations at this place where he took up his quarters… All these have been of necessity stopped by his death for there happens not to be any person in the Colony…qualified for his duties – and I am certainly prevented by the constancy and intricacy of my other duties to give any time either to magnetic or astronomical observations - …our instruments are good and it is painful to me to see them lying idle… (Royal Society Archives, Location HS7-358).

On 2 November 1838 Franklin wrote to Herschel:

.. I send you a series of tidal heights and intervals, observations made at Port Arthur for one year complete – together with the observations at the Equinox. The Registers have been very carefully kept since poor Burnett's death by Mr Lempriere an officer of the Commissariat Department. They will be continued and forwarded at the close of each year unless requested oftener – by Beaufort or? (illegible). I forward these through the Colonial Office and address them to the Royal Society where you will perhaps make enquiry for them. (Royal Society Archives, Location HS7-359).

Thomas Lempriere (1796-1852) was a man with a wide range of interests and accomplishments. In addition to his military duties – he was in charge of stores – he was a talented artist, part-time scientist, and diarist. His activities are summarised in the Australian Dictionary of Biography, and more fully in Whitley (1966). His interest in maintaining meteorological, tidal and other environmental observations sustained the work at Port Arthur for several years. The sea level observations were given permanent value by the fixing of a benchmark, at James Ross's instigation (Ross, 1847), on 1 July 1841.

The significance of the 1841 benchmark was discussed by Shortt (1889) and more recently by Hamon (1985). Neither author succeeded in finding the original sea level records. More general accounts are found in The Australian (1892), Glover (1979) and Lord (1985). After a careful analysis Hamon concluded that the single reading of sea level at the time when the benchmark was struck would be inadequate for mean sea level studies because of uncertainties due to the effects of ocean water density, currents and winds. However, Hamon concluded that "the position would of course be different if Lempriere's original observations ever came to light". We have now located many of the original observations in the archives of the Royal Society in London, and locally in the official Australian archives in Hobart. For the first time we can determine the full significance of the 1841 benchmark at Port Arthur.

HISTORICAL NARRATIVE

a) Sea Level Measurements

Summaries of Lempriere's meteorological and tidal data were published at that time (Lempriere, 1842; 1846). Lempriere kept a detailed diary over the period 1 January 1837-12 September 1838 now held in the Tasmania section of the State Library, Hobart.

1 May 1837 – I commenced the meteorological journal.

25 May 1837 – as a system of instruction for Edward and Tom (Lempriere's sons) we go every evening to the museum at six. Mercer assists me and we give them lessons in French, History, Geography, Geometry etc. At eight we take the observations and come home. By the Bye talking of the Museum, I think I have not noticed that since the 1st of this Month I have been keeping meteorologist Journals.

Indicate with an attached thermometer, a barometer, the winds, weather etc.

Dr Schotsky's old quarters is the site of the observatory and of a museum we are forming.

1 June 1837 – Set the pluviometer, the Tide Gauge not yet complete.

From Franklin's letter of September 1837 we know that the tide gauge became operational shortly after this, but the first year of records, described in the letter of 2 November 1838 has not been found. The Royal Society archives contain:

(<u>Location AP23.25</u>) Tidal register at Port Arthur, bound in a volume of other correspondence; this is the tidal register for August 1838-July 1839, archived 9 July 1840. Received from Sir John Herschel 26 March 1840, communicated by Captain Sir John Franklin.

(<u>Location MA59</u>) six folders of meteorological and tidal data at Port Arthur including:

A Register of tides, January-August 1841.

B Register of tides, September 1841-April 1842.

C Register of tides, May-December 1842.

Other folders contain meteorological observations February 1840-June 1841 and meteorological data for 1840 in a complicated radial tabulation “adapted from that arranged for Greenwich”. The sixth folder contains duplicate tidal records for 1842.

It appears that several copies were made by hand of the original observations. The Australian archives in Hobart contain (reference P2472/box 1) tidal data for December 1839 (folder 8) and for February 1840-January 1841 (folder 9) as well as extensive meteorological observations.

Our investigations have located tide gauge data from August 1838 to December 1842, with gaps for August-December 1839, and January 1840. In our analyses we concentrated on the years 1841 and 1842, for reasons which will become apparent.

Nevertheless, neither the exact location nor the type of the tide gauge used for these measurements is clearly specified in the records.

Lempriere (1839) provides a possible clue to the location of the tide gauge, in the following description of buildings located near the water at Port Arthur:

The same building comprises the Commissariat Office and a museum in which specimens of the animal, vegetable and mineral production of the Peninsula are preserved; the meteorological registers are also kept here, they contain the height of the barometer, attached and external thermometers, direction and force of the wind, weather, also a tide gauge and pluviometer, the whole observations except the last two being taken at 8 am, 2 pm, and 3 pm.

This is ambiguous, because “registers” could refer to the records rather than the instruments. Further, it is not clear whether “tide gauge and pluviometer” refers to the location of the actual instruments or to the resultant data. Throughout the monthly records the coordinates are given as:

Longitude 147^{o} 51' 33" East; Latitude 43^{o} 9' 6" South.

The coordinates given for both the meteorological instruments and the tide gauge are the same.

These coordinates remain unchanged after 20 December 1840 when the meteorological records are annotated “instruments removed to new observatory 65' 5" above level of the sea. Subsequent meteorological records give a height of instruments 52' 3" above the level of the sea. It is likely that the meteorological instruments were within the Port Arthur settlement, near to the tide gauge.

From Lempriere’s accounts it is clear that the tide gauge and meteorological instruments were closely co-located. Suggestions that both could have been on the Isle of the Dead are not tenable because the island is not high enough for the 65 feet barometer elevations. Also, apart from a gravedigger, the Isle of the Dead was not inhabited, and because the instruments were not automatic, it would have been impossibly difficult to sustain an observatory there, day and night for five years.

The gauge may have been a simple marked pole mounted at the sea surface. However, such poles are generally difficult to read when waves are present and are sometimes replaced by a float that is allowed to move vertically in a “stilling well” (a vertical tube with a small connection to the sea near the bottom) which removes most of the wave motion. The position of the float can then be read against a marked rule. Simple gauges of this type, for reading by eye at regular intervals, were used by Ross on his expedition, and have been described in contemporary accounts, by Whewell (1833) and in standard publications (Admiralty, 1849). The inscription on the benchmark plaque (see below) contained the phrase "height of water in tide gauge" which suggests that some form of stilling well was used.

It is highly unlikely that the gauge was self-recording. The first self-recording tide gauge was believed to have been installed in the River Thames at Sheerness in 1831 (Matthaus, 1972; Pugh, 1987). A self-recording tide gauge was installed at Williamstown, Victoria, in 1858 (Matthaus, 1972). Franklin would have been familiar with the Sheerness gauge as reported to the Royal Society (Palmer, 1831). However, the detailed analysis of the tide records (see below) suggest very strongly that readings were taken at particular times when high and low waters were expected, and that the mixed diurnal/semi-diurnal character of the tides at certain times of the year which would have been evident on an automatic gauge were not recognised. From known contemporary practice, the tide gauge was probably a stilling well containing a pole which moved up and down with the changing sea level and which could be read against a vertical scale.

b) The Port Arthur Benchmark

The main scientific purpose of the Voyage (Ross, 1982) under the command of Sir James Clark Ross to the southern and Antarctic regions (1839-1843) was to measure the earth's magnetic field, and to locate the South Magnetic Pole. However, the Royal Society and the Admiralty had issued him with detailed instructions for other measurements that should be taken (Pugh, 2003). In his detailed account Ross (1847) describes how when over-wintering in Hobart he visited Port Arthur to compare his standard barometer with the one used by Lempriere:

…and also to establish a permanent mark at the zero point, or general mean level of the sea as determined by the tidal observations which Mr Lempriere had conducted with perseverance and exactness for some time: by which means any secular variation in the relative level of the land and sea, which is known to occur on some coasts, might at any future period be detected, and its amount determined. The point chosen for this purpose was the perpendicular cliff of the small islet off Point Puer, which, being near to the tide register, render the operation more simple and exact; the Governor, whom I had accompanied on an official visit to the settlement, gave directions to afford Mr Lempriere every assistance of labourers he required, to have the mark cut deeply in the rock in the exact spot which his tidal observations indicated as the mean level of the ocean. The tides in the Derwent were too irregular being influenced greatly by the prevalence of winds outside and the freshes from the interior, so that we could not ascertain with the required degree of exactness the point of mean level.

Ross continues: *I may here observe, that it is not essential that the mark 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: it is, however, important that it be made on some part of a solid cliff, not liable to rapid disintegration, and the exact distance above the mean level (which may also be marked more slightly) recorded on a plate of copper, well protected from the weather, by placing a flat stone with cement between, upon the plain surface or platform which should constitute the mark from which the level of mean tide should be measured (see Cosmos, p288 and note p95).*

The reference to Cosmos, a treatise by Baron Von Humboldt (1845), is discussed below. Ross continues:

The fixing of solid and well secured marks for the purpose of showing the mean level of the ocean at a given epoch, was suggested by Baron Von Humboldt, in a letter to Lord Minto, subsequent to the sailing of the expedition, and of which I did not receive any account until our return from the Antarctic seas, which is the reason for my not having established a similar mark on the rocks of Kerguelen Island, or some part of the shores of Victoria Land.

The first part of Cosmos was published in 1845. The page numbers given by Ross are not consistent with our German edition (Stuttgart and Tubingen, 1845). The quotation he refers to in his book is found on page 474 in footnote 24, on evidence for large-scale vertical crustal movements. The footnote reads:

Sur la mobilité de fond de la Mer Caspienne. In My Asiecentr. T. II. p283-294. At my request the Royal Academy of Sciences at St Petersburg in 1830 arranged for fixed marks (indicators giving mean water level at a set epoch) to be engraved at various places by the learned physicist Lenz. Also in a supplement to the Instructions given to Captain Ross for the Antarctic expedition in 1839, I requested that wherever opportunity presented itself in the Southern Hemisphere, marks might be engraved on rocks, as in Sweden and in the Caspian Sea. Had this happened in the earlier voyages of Bougainville and Cook, we would now know: whether the secular relative change in height of land and sea is a universal or local natural phenomenon; whether a pattern could be recognised in the direction of the points, which simultaneously rises or falls.

Von Humboldt's correspondence with the British Admiralty was published by the Royal Society in the reports of the Committee of Physics, including Meteorology, in 1840. *It will be important to place marks on the coasts of continents and islands, at a carefully determined height above the highest tides. I would prefer (Des Barres de Cuivre) prepared in advance in England having an inscription of the date and the name of Captain Ross.*

Von Humboldt goes on to say that Lenz had placed iron marks two feet long on the rocky coast of the Caspian Sea near to Bazou (probably Baku in modern Azerbaijan). It was a happy coincidence that Humboldt's instructions reached Ross at a time when he was in contact with Lempriere and the sea level measurements at Port Arthur. (See also Von Humboldt, 1839.)

The Port Arthur benchmark was cut in the form of a broad arrow on 1 July 1841 (Figure 2). It is carved into a vertical rock face on the north side of the Isle of the Dead, which was used as a cemetery for the Port Arthur complex. It is perhaps surprising that the mark was not made near to the tide gauge itself, but Lempriere and Ross probably considered the isolated island as a more secure location for the benchmark than on the mainland near Port Arthur, which was being rapidly developed at that time. Information on the fixing of the benchmark is given in Shortt (1889).

He reports that at that time:

For on a tablet still existing a little above the tide mark in question is the following record. "On the rock fronting this stone a line denoting the height of the tide now struck on 1st July 1841, mean time 4H 44M pm; moon's age 12 days; height of water in tide gauge 6 ft. 1 in.".

It would have been easy to take a simultaneous reading of the tide gauge on the mainland while fixing the benchmark on the island, by signalling across the 1200 m of intervening water. Local mean time sunset of 1 July 1841 was at 1643.

There is no evidence that Ross himself was present in Port Arthur at the time and it seems unlikely, as the logs of *Erebus* and *Terror*, now in the UK Public Record Office, London, show that the expedition was fully occupied preparing for the next season's voyage into the Antarctic for which it left Hobart on 7 July (Ross, 1983).

The Australasian (1892) provides a slightly different version of the wording on the tablet:

It bears the following inscription: 'On the rock fronting this stone a line, denoting the height of the tide, was struck on the 1st July, 1841. Mean time, 2.44 p.m. Moon's age, 12 days. Height of water in tide gauge, 6ft. 1in.'

This is substantially the same as Shortt's version, except for the quoted time of striking of the mark (2:44 instead of 4:44). We believe, from inspection of Lempriere's sea level records, and from a tidal hindcast for the day when the benchmark was struck, that the time given by Shortt was correct.

ANALYSIS OF NINETEENTH CENTURY SEA LEVEL DATA

We have recovered from archives and digitised all but the missing months August-November 1839 and January 1840 for the overall observing period between August 1838 and December 1842. The records for each month are tabulated separately. Records give the high water and low water times and height for the morning and afternoon of each day. They also show the range of the tide and the approximate wind force and direction. Although Lempriere signed each monthly record, not all of the records are in his handwriting; it seems that a number of fair copies of the original readings were prepared at the end of each month. Heights are given in feet and inches, and times to the nearest minute. Figure 3 shows the record for March 1840.

For our comparisons we digitised the 48 months of records; however, our more detailed analyses were of the 1841 and 1842 data. After converting the heights to centimetres, some initial editing was made to remove obvious errors in the transcription (for example levels wrong by a foot) and occasional duplicated readings. Further editing and comparison was made by matching the nineteenth century data with tidal predictions based on our 1999-2001 measurements (described below).

Any systematic differences may be due to real tidal changes but more probably to systematic errors in the nineteenth century readings. The International Hydrographic Bureau has published tidal analyses for Hobart which show relatively stable tidal constants; and the close hydraulic connection between Port Arthur and the open ocean where tides are very stable, precludes any local significant changes in the tidal constituents. Comparison between the predictions and the recorded nineteenth century tides shows the following differences:

1 Several high water/low water events were observed in the nineteenth century which are not shown in the predictions.

2 The observations are generally at earlier times than the predicted turning points (see Table 1). This is increasingly so towards the end of 1842.

Year	Months	Mean (mins)	Std. Dev (mins)	Total values
1839	Dec	-4	71	111
1840	Feb-Dec	-70	71	1266
1841	Jan-Dec	-39	69	1393
1842	Jan-Jun; Nov-Dec	-44	73	944

Table 1 : Table of time differences (observed minus predicted) high and low waters.

3 The times between turning points are much more variable in the predictions than in the observations (see Figure 4).

4 The observed ranges of the tides are higher than the predicted ranges.

We consider the implications of these in turn:

1 Analysis of recent measurements at Port Arthur and earlier analysis in the region have shown that although the lunar semi-diurnal tides are the biggest factor, the diurnal tides are comparable (there is a solar semi-diurnal amphidrome just south of Port Arthur). In the predictions, at times of large diurnal tides (which had their maximum in the 18.6-year nodal cycle in1839-1840), some of the semi-diurnal turning points are not present, but they are recorded in the observations.

2 The systematic difference in the observed and predicted times of high water and low water shows that the observers did not consider the absolute time as critical; the predictions were prepared for time zone (GMT – 1000), whereas the observations were probably nominally to a local time, based on the longitude of Hobart (147^{o} 20' E), which would make the predicted times about 11 minutes later. The differences in Table 1 between observed and predicted times, with observed times on average about 50 minutes ahead of predictions, cannot be explained by this alone.

3 The much greater scatter in the interval between predicted tides than those observed is very revealing. It shows that readings were taken at the times of <u>expected</u> high and low waters, based on the assumption of a semi-diurnal tidal regime. Although the times of the readings are recorded to the nearest minute, it appears that there was no attempt to make a series of readings around each turning point time which would be necessary to fix it exactly: instead the observers were probably instructed to take readings at specified times. On average these would be close to high water or low water, but not the true times for the tidal regime at Port Arthur. This pattern seems to prove that the observations were made by eye rather than with an automatic recording tide gauge, as such differences would have become apparent very quickly for automatic recording gauges. The relative lack of concern about the exact time of turning points is understandable, given that Lempriere's main concern was to compute the ranges of the tide.

4 Table 2 summarises the difference between the predicted and the observed high and low water levels for 1841 and 1842. It shows that the observed high water levels were consistently higher than the predicted high water levels, by 0.088 m in 1841, and by 0.115 m in 1842. Conversely, the observed low water levels were consistently lower than the predicted low water levels, by 0.086 m in 1841 and by 0.136 m in 1842. These systematic differences contribute to the fact that the standard deviation between the 1841 and 1842 data and predictions is 0.34 m, which is nearly three times as large as the standard deviation of the difference between our modern observations and predictions (0.13 m).

	Mean (m)	Std. Dev (m)	Total Values
1841			
High waters	0.088	0.189	698
Low waters	-0.086	0.235	698
1842			
High waters	0.115	0.253	705
Low waters	-0.136	0.262	705

Table 2 : Table of level differences (observed minus predicted) high and low waters (There are fewer predicted turning points in 1841 because of the phase of the nodal cycle - see text).

> The fact that the observed ranges are slightly greater than the predicted ranges may be explained by the tendency of an observer to read the highest (or lowest) reading on a staff over a five minute period near the specified time. A notable feature of our modern records is a persistent seiche of period close to 50 minutes, with average and maximum amplitudes of 0.036 m and 0.30 m, respectively. The seiches could have had an effect in encouraging the observers to note levels which were increased (or decreased) by the seiche amplitude.

Note that meteorological effects on the turning points would tend to increase the scatter in the intervals between observed tidal turning points but, importantly, would not have any systematic effect on either the time difference between observed turning points and predicted tides, nor the range of the observed tides.

The differences in the computed mean tide levels for the various twelve-month periods from 1840 to 1842 (1840, 1.651 m; 1841, 1.415 m; 1842, 1.403 m) relative to the zero of Lempriere's gauge are also understandable. The original records show that the Observatory, including the meteorological instruments, was moved in December 1840. For our purposes, the very close agreement between the two mean sea levels for 1841 and 1842 is important. It shows that the mean tidal level obtained using the procedures deduced above is consistent. Furthermore, because the shallow water terms are virtually non-existent (from our modern observations, the amplitudes of M_4 and MS_4 are only 2mm) mean tide level and mean sea level will be the same. Meteorological effects will not have a systematic effect on the high and low water levels recorded; and the tendencies to read high at high water and low at low water will cancel each other.

For our comparison with recent sea level measurements, we use the mean sea levels for 1841 and 1842, which are related to the benchmark on the Isle of the Dead through the wording on the tablet.

A direct check for internal consistency is possible by comparing observed and predicted sea levels. Figure 5 shows the predicted tides for 1 July 1841. At the time of fixing the benchmark (1644 local time) the water level was approaching high water. The stated level of water in the gauge (6 ft 1 in) is equivalent to 1.854 metres. The predicted level relative to gauge zero is 1.910 metres. However, this also has to be adjusted for the weather at the time, for which the record shows a weak wind from the west to northwest, between force 2 and force 1. The Erebus barometer in Hobart, corrected for temperature, read 1024 hPa at the time (Public Records Office, Kew), while the average atmospheric pressure for Hobart for 1912-1999 was 1013 hPa (Bureau of Meteorology, Australia). The difference in these pressures (11 hPa) would lead to a change in sea level of 0.11 m. The estimated level for comparison with 1.854 m is therefore (1.91 - 0.11) = 1.80 m (see Figure 5).

We believe that Lempriere and his colleagues in making the water level measurements, at the time of the fixing of the benchmark, would have taken special care and our later estimates of errors assume this. Ross may have been present, although preparations for the departure of his expedition from Hobart on 7 July (Ross, 1982) would have also demanded his attention. Examination of the copy of the official letter-book (now in the Scott Polar Research Institute, Cambridge; called "Ross Family Papers" in Ross, 1982) shows that no official letters were signed by Ross around 1 July. Examination of the readings of the other high and low waters in Figure 5 shows that they were not so carefully made, as there is substantial scatter from the predicted tides in both times and heights. Tables 1 and 2 summarise the average discrepancies between the observations and the predictions over the whole 1841-1842 period, which are on average less than those plotted in Figure 5. Because these tides are so close to the Summer Solstice on 21 June and the nodal phase was so favourable, the diurnal tides are very strong, as discussed earlier.

Shortt (1889) reported a single observation of the benchmark on 24 February 1888, at which time the sea level was 2.5 feet below the mark. As noted by Hamon (1985), a single value of sea level, even after adjustment using the predicted tide, may deviate from the long-term mean sea level by at least 0.1 m. We do, however, include this observation, with an appropriate error estimate, in our final results.

Mean tidal level for the period 1841-1842 was found to be 0.445 m below the benchmark.

TWENTIETH CENTURY MEASUREMENTS AND ANALYSIS

An Aquatrak acoustic tide gauge, installed on the ferry jetty at Port Arthur, became fully operational in August 1999. The gauge is mounted above a 168 mm diameter stilling well, equipped with an orifice assembly of a similar design to that used by the US National Oceanic and Atmospheric Administration and provided by the Australian National Tidal Facility (NTF). The sea level and ancillary data are recorded on a Vitel WLS2 data logger. The instrumentation is housed in a small hut (Figure 6), which is about 1.2 km from the Isle of the Dead and within 300 m of the probable location of Lempriere's tide gauge.

At present, two years of data have been analysed (August 1999 to August 2001). Missing data constituted only 0.032% of the record. Preliminary data processing involved adjustment for clock drift, correction for temperature variation in the stilling well, and relating the water level to the benchmark (see next section).

A typical period of data (two days in February 2000) is shown in Figure 7. Not unexpectedly, as in Lempriere's measurements, the tides are mixed (ie with comparable diurnal and semi-diurnal components) and of typical amplitude 0.3 m. The 1841 benchmark is approximately at today's tidal High Water as expected from discussion above.

For practical reasons we believe that Lempriere sited his tide gauge in the settlement at Port Arthur, about 1.2 km from the benchmark on the Isle of the Dead. By some means (unknown to us) he obtained a reading of his tide gauge at the exact time when the water was at the level of the benchmark on 1 July 1841. He therefore used the sea as a "spirit level" to relate the benchmark to his tide gauge. Any sea level slope associated with the seiche could have corrupted this "levelling" exercise. Simultaneous seabed pressure measurements at four sites in March 2000 showed that the oscillation is in phase over the whole of Port Arthur bay, with increasing amplitudes towards the head. We also deployed a GPS buoy near the benchmark and another near the supposed site of Lempriere's tide gauge, in order to investigate more exactly any difference of level at these two sites caused by the seiche motion.

A conventional least-squares tidal analysis (eg Pugh, 1987, p 112) has been used to abstract the mean level and 102 tidal constituents from the record. The record was sufficiently long to render the method of "related constituents" unnecessary, but 18.6 year nodal corrections are included. The amplitudes and phases of the four major tidal constituents are shown in Table 2. A notable feature is the almost complete absence of the S_2 tide in this region which, as previously noted, is close to an S_2 amphidrome. The comparable magnitudes of the remaining three constituents emphasises the mixed nature of the tides.

	h	g
O1	0.138	52.8
K1	0.205	87.11
M2	0.240	243.7
S2	0.015	249.0

Table 3 : Amplitude, h (m) and phase, g (degrees, relative to local time (UTC + 10 hours)) of major constituents from modern observations at Port Arthur.

The mean sea level from the recent 2-year analysis was found to be 0.315 m below the benchmark.

TWENTIETH CENTURY LEVELLING

It was necessary to place a number of survey marks in the area, both at the Port Arthur settlement and on the Isle of the Dead, in order to relate the new tide gauge measurements to the historic tidal benchmark. A number of different survey techniques were used to make this height connection – for a detailed description of the survey see Watson (1999).

Tide Gauge Benchmarks

The tide gauge hut at Port Arthur (see Figure 6) has two specific reference points for height. The first point is used for fundamental GPS positioning of the tide gauge in an 'absolute' geodetic reference frame and consists of a steel pole passing through the tide gauge hut, independently bolted to the concrete wharf. The second point of reference is the calibrated external reference mark on the acoustic tide gauge itself, and comprises a rounded stainless steel dome. This mark serves as the external reference point for all modern-day tidal observations.

A number of additional tide gauge benchmarks (TGBMs) have been placed throughout the Port Arthur settlement to monitor the local stability of the tide gauge reference points. Four epochs of precise levelling have been carried out (August and October 1998, October 1999 and August 2001), with sub-mm accuracy for all levelling runs. No significant relative displacements have been observed between these stations and the acoustic tide gauge. Conservative error estimates of ± 0.5 mm are used for height differences between these reference marks.

Isle of the Dead

Several TGBMs were placed on the Isle of the Dead during May 1998. The benchmarks were placed so that a transfer of orthometric height could be made from the historic tidal benchmark on the Isle of the Dead to the acoustic gauge at the Port Arthur settlement. The first component of the height transfer was a direct levelling measurement from the centre of the horizontal benchmark cut to a nearby placed TGBM. From this TGBM, a level run was made via a series of TGBMs to the other side of the Isle of the Dead where a GPS reference point was placed. Two epochs of precise levelling were made from the historic tidal benchmark and the GPS reference point, with a precision of the height difference of ± 0.4 mm.

Connection between Port Arthur and the Isle of the Dead

The height transfer across the 1.2 km stretch of water between the GPS reference point and the tide gauge site at Port Arthur was made using three different survey techniques – GPS observations, terrestrial survey measurements of reciprocal vertical angles and slope distances, and a technique of optical levelling using four levels and two calibrated staves.

The GPS observations were made using two static campaigns (13 hours on 5 September 1998 and 21 hours during 17-18 February 1999). Both campaigns were processed independently in two suites of software yielding agreement at the 5 mm level. In order to compute the orthometric height difference from the GPS-derived ellipsoidal height difference, the geoid slope must be accounted for. Information on the geoid slope was obtained from the geoid model AUSGeoid98 (Johnston and Featherstone, 1998) and verified using data from two GPS buoys deployed between Port Arthur and the Isle of the Dead (Watson, 1999).

The terrestrial observations yielded two estimates of orthometric height difference and they agreed within 5 mm of each other and differed at most by 7 mm from the GPS result. Overall the precision of this connection was of the order of 5-10 mm.

The above results allow the relative connection to be made between the historic benchmark and the modern acoustic tide gauge. Hence the relative change in sea level can be determined using the mean sea level values from 1841-1842 and the current observations from 1999-2001.

ESTIMATIONS OF ERRORS AND UNCERTAINTIES

Our estimates of historical and recent mean sea level relative to the benchmark involves a number of errors and uncertainties which may be estimated.

1 An error due to the natural variability of sea level over time scales not captured by the span of the observational data sets (two years),

2 An error due to the levelling between the benchmark and the tide gauge (separated by 1.2 km, and

3 Instrumental, reading and other experimental errors.

We estimated error (1) using a sea level record from Spring Bay, which is on the east coast of Tasmania 67 km north of Port Arthur. The tide gauge is an Aquatrak, similar to the one installed at Port Arthur, operated by the NTF. Tidal residual data for Spring Bay for the period 1985-2001 was obtained using a tidal filter. The variability of sea level derived from a two-year average was estimated from the standard deviation of the Spring Bay data filtered with a box-car of length two years. We acknowledge that this provides an underestimate of the total variability, as it fails to include time scales longer than 16 years. We tested the importance of these longer time scales by using the Southern Oscillation Index (SOI) as a proxy for sea level. One hundred and thirty years of monthly SOI data for 1866-1995 inclusive (Allan et al, 1991) were filtered with a two-year box-car filter. The resultant data set therefore represented samples from populations of two-year estimates of mean sea level. This 130-year data set was then subdivided into ten 13-year data sets (ie approximately the length of the record from Spring Bay). It was found that the variance of the whole 130-year set exceeded the mean of the variances of each 13-year set by 11%. We therefore expect that our estimate of the standard deviation of the variability of 2-year mean sea level, based on 16 years of data from Spring Bay, underestimates the true variability by only about 5%. We are therefore confident in using 16 years of sea level data from Spring Bay for estimating error (1). For 2-year averages, the error is 0.012 m.

Different techniques were used for levelling Lempriere's and our own gauges to the benchmark. We presume that Lempriere simply used the sea as a "spirit level", assuming it to be horizontal at the time when the benchmark was struck on 1 July 1841: he obtained a reading from his tide gauge at the time when sea level coincided with the benchmark. The major error in this case would be due to any sea level slope between the Isle of the Dead and the settlement (where we presume the gauge was located). We have estimated the standard deviation of this error (2) to be 0.014 m, using observations of the difference in height recorded by two GPS buoys during a period of large seiche activity. (The seiches at that time had a standard deviation of 0.050 m, which has an equivalent amplitude of 0.071 m, or roughly twice the average seiche amplitude 0.036 m.)

For our present observations, we employed GPS levelling for which the dominant uncertainty is the angle between the geoid and the ellipsoid (the "geoid slope"). In this case, we estimate error (2) to be 0.011 m.
Since virtually no description of Lempriere's techniques survive, only an approximate estimate can be made of the remaining historical error (3). The horizontal line on the benchmark is about 0.02 m thick. Lempriere recorded his tidal heights to the nearest inch (0.0254 m), and it is also known that sea level at Port Arthur is subject to a persistent seiche of average amplitude 0.036 m. Either of these errors makes only a small (<0.001 m) error contribution to a 2-year estimate of mean sea level composed of about 2800 independent observations. We have therefore, somewhat arbitrarily, attributed an error (3) to Lempriere's observations of 0.01 m (half the thickness of the line on the benchmark), believing that this is the order of any systematic error resulting from the original striking of the benchmark in 1841. The 1 July 1841 was a calm day, according to Lempriere's tide gauge records, and a careful observer would be able to take an average sea level reading, averaging waves by eye, to this accuracy.

The observational error of our present measurements of sea level is probably dominated by the effect of temperature variations in the stilling well. Such variations affect the speed of sound in the acoustic waveguide, and cause thermal expansion of the section of waveguide between the acoustic sensor and the calibration hole (see Porter and Shih, 1996 for a description). We have applied approximate corrections for these effects, which change our estimate of mean sea level by about 0.001 m. We also conducted two calibrations of the gauge, one prior to installation and one (in situ) after two years of data collection; they agreed to within 0.0016 m, the figure which we assume for our observational error.

Errors (1) to (3) have been combined as if they are independent. They are summarised in Table 4.

Observations (m)	Error (1) (m)	Error (2) (m)	Error (3) (m)	Combined Error
1841-1842 (2 years)	0.012	0.014	0.010	0.021
1999-2001 (2 years)	0.012	0.011	0.0025	0.016

Table 4 : Errors of estimated mean sea level

For completeness we refer to a radically different interpretation of the data. Ross (1847) is quite explicit that Lempriere should have labourers “to have the mark cut deeply in the rock in the exact spot which his tidal observations indicated as the mean level of the ocean.” If the mark is indeed at the mean level from Lempriere’s 1841 observations, then mean sea level at Port Arthur has fallen by the 0.317 m shown in Table 5. While acknowledging the strength of Ross’s text, the actual observations are not compatible. If the mark on 1 July 1841 had been made at mean sea level (Figure 5) the time of the mark should have been many hours earlier on the rising tide, and Lempriere’s tide gauge should have been reading 4ft 7ins. These are very different from the values reported by Shortt (1889). In his account, Ross also emphasises that it would be more desirable to have the benchmark above the reach of the highest tide, and this is a practice he adopted subsequently on his voyage, for sea level measurements made at Port Louis, Falkland Islands (Pugh 2003). Von Humboldt’s correspondence with the Admiralty showed that he favoured marks placed at carefully determined heights above the highest tides. A possible way to explain this anomaly would be for a relative rise of the land due to glacial isostatic adjustment or local tectonic movement. However no such movement is predicted from glacial isostatic models (Lambeck and Nakada, 1990; Lambeck 2001). Similarly, it would require a sea level fall at Port Arthur that was very dissimilar to sea level changes at other Australian sites (Mitchell et al, 2000).

DISCUSSION

We have obtained estimates of mean sea level from Thomas Lempriere’s observations made in 1841-1842, and from our own observations made in 1999-2001. These are summarised in Table 4, and indicate a rate of relative mean sea level rise during the period 1841-2001 of 0.8 ± 0.2 mm/year.

Observations	Height of mean sea level relative to benchmark (m)	Estimated error in height relative to benchmark (m)
1841-1842 (2 years)	-0.445	0.021
1999-2001 (2 years)	-0.315	0.016

Table 5 : Summary of mean sea level relative to the benchmark.

These long-term trends could be influenced by effects of atmospheric pressure and vertical land movement.

Lempriere collected meteorological data at Port Arthur for a number of years. We had hoped to also provide an estimate of sea level rise adjusted for atmospheric pressure (ie with the inverse barometer effect removed), but this presents a number of problems. Firstly, meteorological data for Port Arthur for July to December 1841 was apparently never published and has not been found in any archives. It would therefore be necessary to use data from Hobart for the missing period. Secondly, it is uncertain whether the Hobart or Port Arthur data were corrected for temperature or for height above sea level (these uncertainties typically amount to ± 2 hPa). Thirdly, during 1841 to 1842 there were systematic differences in 6-monthly and annual means of atmospheric pressure between Hobart and Port Arthur of at least 1 hPa. Fourthly, the annual mean atmospheric pressures for Hobart and Port Arthur for 1841 and 1842 are typically 3 hPa lower than the long-term (1912-1999) mean for Hobart. This low bias of atmospheric pressure observations is symptomatic of barometers which contain only a partial vacuum and when Ross and Crozier checked Lempriere's barometer on 25 October 1840 it was reading 0.642 inches of mercury (22 hPa) low. However, the 1912-1999 observations for Hobart suggest a systematic increase in atmospheric pressure of 0.017 hPa/year, which, if extrapolated back to 1841, would be consistent with the observations from that time. In summary, there are a number of uncertainties in atmospheric pressure observations for 1841 to 1842, which are of order 1-3 hPa, equivalent to changes of mean sea level of 0.01-0.03 m. We therefore do not provide an estimate of sea level rise adjusted for atmospheric pressure.

We have also estimated the vertical motion of the land surface at Port Arthur. Direct observations of vertical movement, by regular updates of our GPS measurements are needed, but are not yet of sufficient duration to yield estimates of sufficient accuracy. We therefore present two indirect estimates. One is from the observations of a shell bed at Mary Anne Bay (about 42 km from Port Arthur), dated to the Last Interglacial Stage (125,000 years ago) at 24 m above present mean sea level (Murray-Wallace and Goede, 1991; Banks and Leaman, 1999). This leads to an estimation of the average uplift rate since that time of 0.19 mm/year. It should be noted that this very long-term averaged rate might not necessarily apply to the period since 1840.

An alternative estimation of uplift/subsidence rate may be obtained from models of GIA. These models simulate the apparent change of sea level relative to land due to varying ice load histories and prescribed regional mantle parameters. The estimated rate of land uplift at Port Arthur from Lambeck's model (Lambeck 2001) is 0.04 mm/yr, which implies that our estimate of relative sea level rise should be increased to yield an estimate of absolute sea level rise.

Two points should be noted about these estimates of uplift. Firstly, they are not estimates of the same effects, and secondly, they may not simply be added together to produce an estimate of total uplift. Instead, they are presented here as an indication of the magnitude of the local vertical motion of the land relative to the sea.

In summary, our observations indicate a rate of sea level rise over the period 1841 to the present of 0.8 ± 0.2 mm/year relative to the local land surface. In order to obtain an estimate of sea level rise adjusted for vertical land movement, this figure should be increased by an amount that is of order 0 to 0.2 mm/year.

These observations may be compared with present estimates of global sea level rise and with long-term measurements from other Australian sites. The estimate of global sea level rise for the last century lies in the range 1 to 2 mm/year (IPCC, 2001). Sea level records for Fremantle (91 years) and Fort Denison (Sydney; 82 years) show rises of 1.38 and 0.86 mm/year respectively (Mitchell et al, 2000). Our observations are hence broadly consistent with the lower end of the IPCC estimates and with records from Fremantle and Fort Denison.

Finally, we can compare this observed rise with the predictions of numerical models. Gregory et al (2001) have discussed the results of various atmosphere-ocean general circulation models, projecting global and regional sea level changes. They note that several models show a lower than average sea level rise in the Southern Ocean south of 60^o. One reason for this may be the low thermal expansion coefficient at the colder high latitude water temperatures.

Figure 8 summarises the historic and present observations. It should be noted that the IPCC figures only relate to the last century and that sea level rise is not identified in historic tide gauge records (primarily from the northern hemisphere) until after 1860. Our figure for sea level rise since 1841 is probably, therefore, an underestimate of the rate of rise during the past century. Also shown is the single observation reported by Shortt (1889) where the error has been estimated using the same techniques that were employed for the other sea level data. 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 error (± one standard deviation). The two upper slanting lines indicate the range of estimates of the rate of global average sea level rise (IPCC, 2001). The two lower slanting lines show estimates of the rate of sea level change relative to the land at Port Arthur, in the absence of any increase in volume of the oceans ("GIA": from model of glacial isostatic adjustment, Lambeck, 2001; "Geological": from geological evidence over the past 125,000 years, Banks and Leaman, 1999, Murray-Wallace and Goede, 1991). The central slanting line is our estimate of average sea level rise at Port Arthur, relative to the land.

EPILOGUE

Lempriere had been allowed three shillings and sixpence *per diem* for his observations from Port Arthur on the authority of the Lt Governor Sir John Franklin, but this was subsequently refused by the military authorities.

During searches at the UK Hydrographic Office in Taunton we discovered a detailed chart of the bay at Port Arthur, prepared by Lempriere (Lempriere, 1839). It is obviously a very carefully prepared and illustrated work but there is no evidence that it was ever used by the Admiralty who continued to publish a less detailed chart based on an 1828 survey by Mr I Welsh, until a new survey in 1883 by HMS Nelson.

Similarly, there is no evidence that Lempriere's sea level measurements sent to the Royal Society were used then for tidal analyses. The archives at the Hydrographic Office in Taunton contain a letter from Lempriere to Captain Beaufort who was then Hydrographer of the Navy, dated 4 October 1841. Lempriere hopes that the records sent to the Royal Society have arrived. And:

You will perceive that it is all done by hand and completed with as much exactness as my official duties would afford me the necessary time to give to that pursuit…

I sent home similar registers for 1838 and 1839 – they were first to go to Sir John Herschel and then I expected to the Royal Society.

Might I intrude on your politeness so far as to request you will favour me with a line, informing me whether my work is acceptable to the Royal Society. I am anxious to know because it would be in vain to continue so laborious an undertaking if it is not attended with satisfactory results.

I have the honour to be

Sir

Your most obedient humble servant

T J Lempriere DACG

The Admiralty received this letter on 17 February 1842. However, it appears that the measurements stopped at the end of 1842, although Lempriere remained stationed at Port Arthur until 1848.

The minutes of the meeting of the Tasmanian Society of 17 May 1843 contain a reference to the Port Arthur observations:

Extracts were then read from a letter from Sir John Herschel, (2nd Nov 1842) expressing his satisfaction "more especially for the very valuable series of Meteorological and Tidal Observations set on foot by Sir John Franklin at Port Arthur, and conducted by Mr Lempriere in a manner which does him the greatest credit".

Sir John Franklin was replaced as Lt Governor of Van Diemens Land in August 1843. He died in northern Canada in June 1847, leading the expedition to traverse the Northwest Passage. Lempriere died on passage to England in 1851, and is buried in Aden.

ACKNOWLEDGEMENTS

Specialists in many institutions in both Australia and England have assisted us in our archive searches. At Port Arthur we have been helped in many ways by the Port Arthur Historic Site authorities, and especially by Peter Roche, who operates the harbour ferry services. Sea levels and residuals for Spring Bay are supplied by the National Tidal Facility, The Flinders University of South Australia, Copyright reserved. The University of Canberra (Peter Morgan) provided the tide gauge, which was installed with help from the CSIRO. This work was partly supported by the Institutional Research Grant Scheme, held at the University of Tasmania. David Blackman at the Proudman Oceanographic Laboratory prepared historical tidal predictions. We are also grateful for help and encouragement from Nick Bowden, John Church and Philip Woodworth.

REFERENCES

Admiralty, 1849. A manual of scientific enquiry, ed. Sir John F.W. Herschel, London.

Allan, R.J., Nicholls, N., Jones, P.D. and Butterworth, I.J., 1991. A further extension of the Tahiti-Darwin SOI, early SOI results and Darwin pressure, *J. Climate*, **4**, 743-749.

The Australasian, 1892. Notes of a yachting trip, *The Australasian*, Feb. 6, 1892, 281.

Banks, M.R. and Leaman, D., 1999. Charles Darwin's field notes on the geology of Hobart Town – a modern appraisal, *Papers and Proceedings of the Royal Society of Tasmania*, **133(1)**, 29-50.

Church, J.A., J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin and P.L. Woodworth, 2001. Changes in Sea Level. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Deng, D.J. Griggs, M. Noguer, P.J. van Linden, X. Dai, K. Maskell and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Cornford, S.G., 1997. Colonial Observatories – Today's Heritage. Chapter 15 in *Colonial Observatories and Observations: meteorology and geophysics*, Eds Kenworthy, J.M. and Walker, J.M., Royal Meteorological Society publications.

Glover, M., 1979. Some Port Arthur experiments, *Tasmanian Historical Research Association*, **26**, 4, 132-143.

Gregory, J.M., J.A. Church, G.J. Boer, K.W. Dixon, G.M. Flato, D.R. Jackett, J.A. Lowe, S.P. O'Farrell, E. Roeckner, G.L. Russell, R.J. Stouffer and M. Winton, 2001. Comparison of results from several AOGCMs for global and regional sea-level change 1900-2100. Climate Dynamics, **18**, 225-240.

Hamon, B., 1985. Early mean sea levels and tides in Tasmania, *Search*, **16**, 9-12, 274-277.

Heard, D., 1981. The Journals of Charles O'Hara Booth, *Tasmanian Historical Research Association*, Hobart.

IPCC, 2001. *Climate Change 2001; The Scientific Basis*, Eds, Houghton, J.T., Deng, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A., Intergovernmental Panel on Climate Change, Cambridge University Press, 881 pp.

Johnstone, G. and Featherstone, W., 1998. *AUSGeoid98: A New Gravimetric Geoid for Australia*, AUSLIG report, 12pp.

Lambeck, K., 2001. Sea level change from mid-Holocene to recent time: An Australian example with global implication. (In) glacial Isostatic Adjustment and the Earth System, J.D. Mitrovica and B. Vermeersen, (eds), *American Geophysical Union,* (in press).

Lambeck, K. and M. Nakada, 1990. Late Pleistocene and Holocene sea level change along the Australian coast, *Paleogeography Paleoclimatology Paleoecology*, Vol. 89, pp. 143-176.

Lempriere, T.J., 1839. *The Penal Settlement of van Diemen's Land*, reprinted by Royal Society of Tasmania, Northern Branch, 1954.

Lempriere, T.J., 1842. **From** *The Tasmanian Journal of Natural Science*, **1**, 225.

Lempriere, T.J., 1846. Meteorological observations made at Port Arthur, during the year 1842, *The Tasmanian Journal of Natural Science*, **2**, 70.

Lord, R., 1985. The Isle of the Dead, Port Arthur, Richard Lord and Partners, Tasmania.

Matthäus, W., 1972. On the history of recording tide gauges. *Proc. R. Soc. Edinburgh*, Section B, **73**, 3, 25-34.

Mitchell, W., Chittleborough, J., Ronai, B. and Lennon, G.W., 2000. *Sea level rise in Australia and the Pacific*, The South Pacific Sea Level and Climate Change Newsletter, Quarterly Newsletter, **5**, 10-19.

Murray-Wallace, C.V. and Goede, A., 1991. *Aminostratigraphy and electron spin resonance studies of late Quaternary sea level change and sea level change and coastal neotectonics in Tasmania, Australia*, Zeitschrift fur Geomorphologie, N.F., **35(2)**, 129-149.

Palmer, H.R., 1831. Description of graphical register of tides and winds, *Phil. Trans. Roy. Soc*., **121**, 209-213.

Peltier, W.R.,1999. *Global sea level rise and glacial isostatic adjustment*, Global and Planetary Change, **20(2-3)**, 93-123.

Porter, D.L. and H.H. Shih, 1996. Investigations of temperature effects on NOAA's Next Generation Water Level Measurement System, **J. Atmos. Ocean. Tech.**, Vol. 13, pp. 714-725.

Pugh, D.T., 2003. James Clark Ross: a sea level pioneer (in preparation).

Pugh, D.T., 1987. Tides, Surges and Mean Sea Level, John Wiley and Sons.

Ross, J.C., 1847. A Voyage of Discovery and Research in the Southern Antarctic Regions, John Murray, London.

Ross, M., 1982. Ross in the Antarctic, Caedmon of Whitby, 276 pp.

Royal Society, 1840. *Proceedings*, **IV**, 232.

Shortt, Capt., 1889. Notes on the possible oscillation of levels of land and sea in Tasmania during recent years, *Papers and Proc. Roy. Soc. Tasmania*, 18-20.

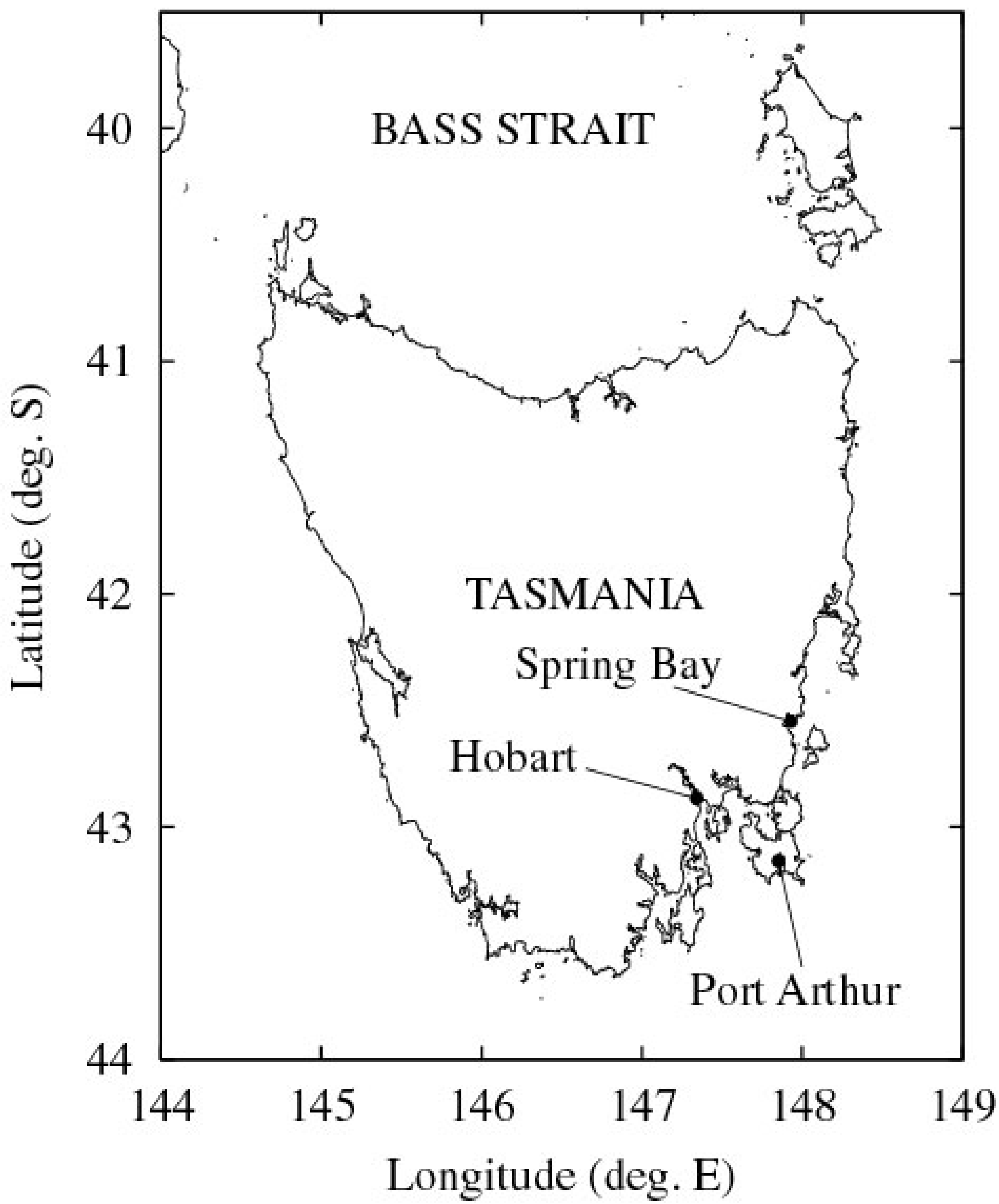
von Humboldt, A., 1839. Letter to Royal Society, **in** *Report of the Committee of Physics including Meteorology*, 1840, 91.

von Humboldt, A., 1845. Cosmos (first book).

Watson, C.S., 1999. *A Contribution to Absolute Sea Level in Tasmania*, B.Surv(Hons) thesis, University of Tasmania, Hobart, Tasmania, Australia, December 1999, 200 pp.

Whewell, W., 1833. Memoranda and directions for tide observations, *Naut. Magazine*, **Vol.2**, 662-665; continued in **Vol.3**, 1834.

Whitley, G.P., 1966. T.J. Lempriere, An early Tasmanian naturalist, *Aust. Zoologist*, **XIII**, 350-355.



BASS STRAIT
TASMANIA
Spring Bay
Hobart
Port Arthur
Latitude (deg. S)
Longitude (deg. E)
40
41
42
43
44
144
145
146
147
148
149

Figure 1

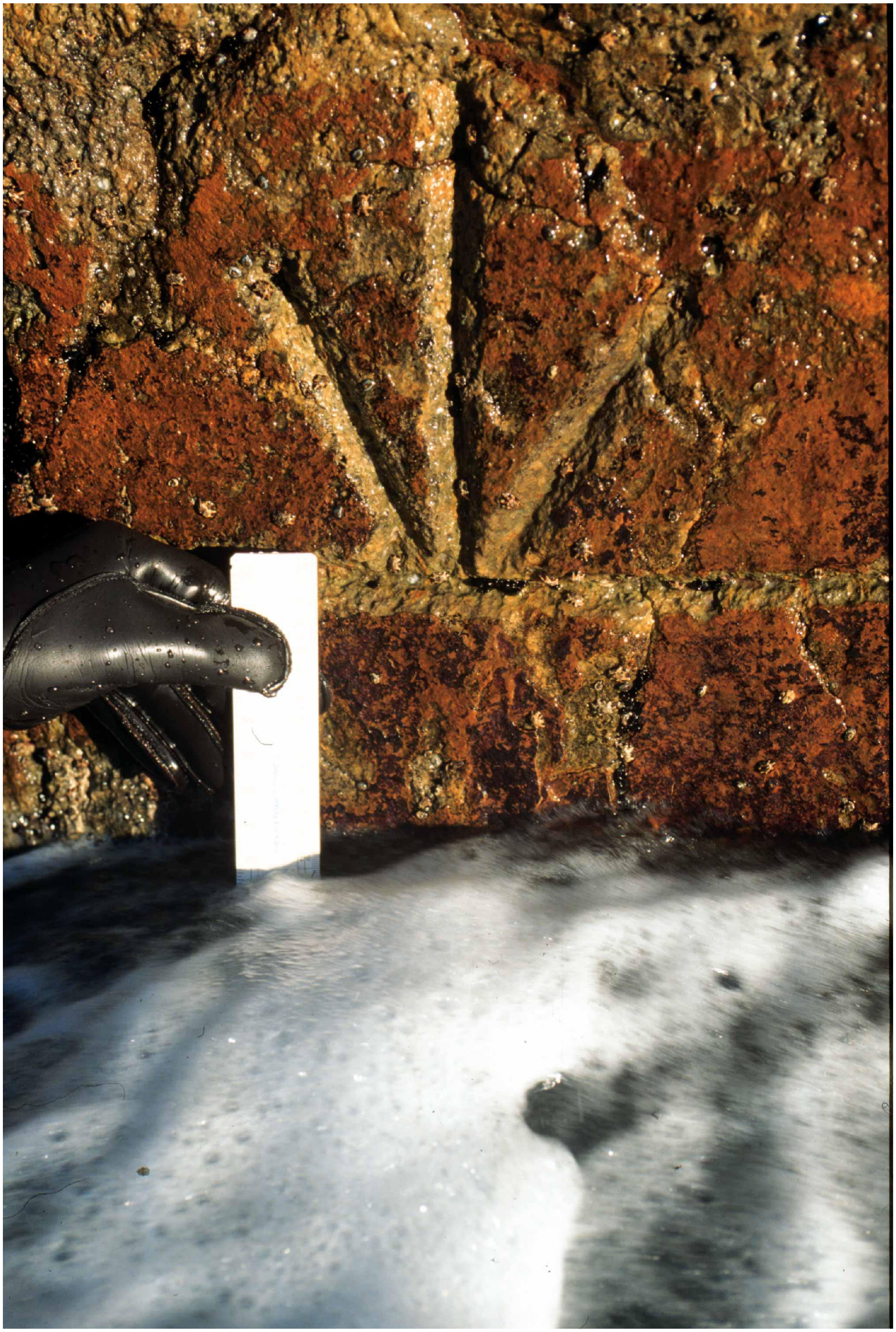
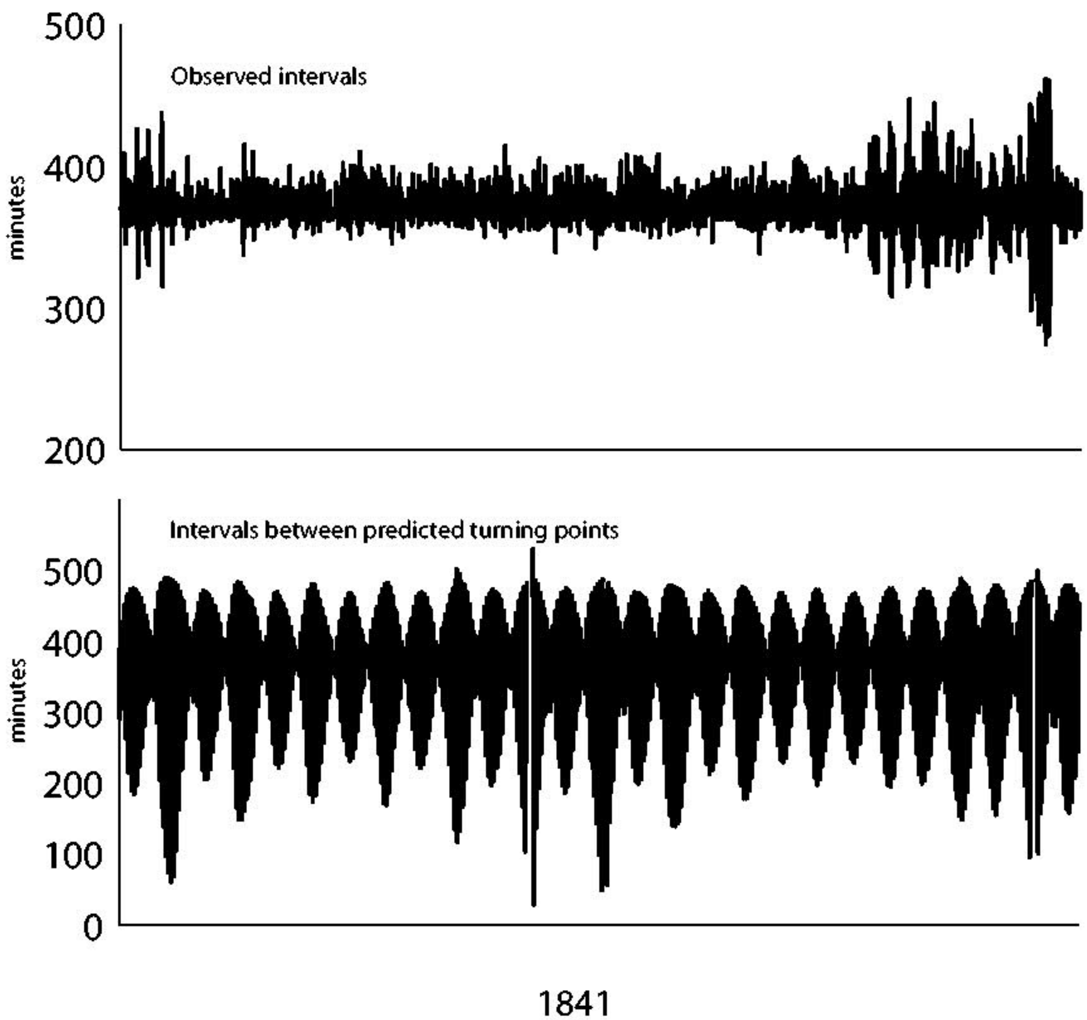


Figure 2

Register of Tides taken at Port Arthur Van Diemen's Land by Depy. Asst. Commy. General Lempriere during the Month of March 1840.
Lat 43. 9' S. Longe. 147. 51. 33 Et.

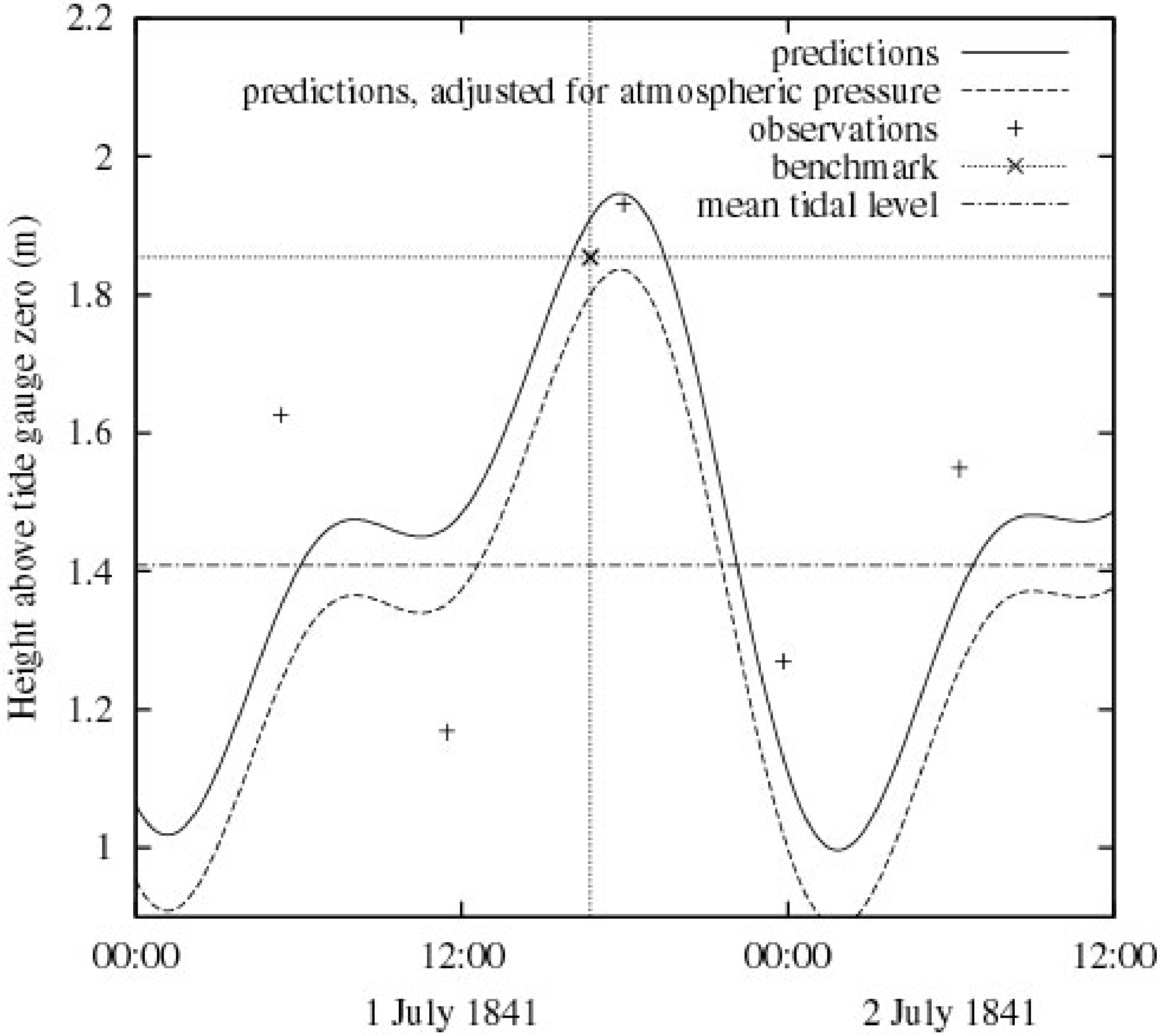
March		High Water		Low Water			Wind		
1840		Time	Height	Time	Height	Range of Tide	Direct	Force	Remarks
		h. m	ft. in	h. m	ft in	ft in			
1	Am	5.16	6.10	11.15	3.3	3.7	E	2	
	Pm	5.40	5.3	11.40	4.6	— 9	E	1	
2	Am	6.4	6.8	12.5	3.3	3.5	NE	2	
	Pm	6.25	5.3	12.26	4.4	— 11	NE	3	
3	Am	6.52	6.8	12.51	3.5	3.3	NE	3	
	Pm	7.18	5.7	—	—	—	E	3	
4	Am	7.40	6.10	1.17	4.6	2.4	W	1	
	Pm	8.0	5.10	1.44	3.7	2.3	Calm	—	
5	Am	8.22	6.7	2.6	4.4	2.3	Do	—	
	Pm	8.46	6.2	2.29	3.7	2.7	Calm	—	
6	Am	9.10	6.3	2.50	4.1	2.2	S	1	
	Pm	9.33	6.6	3.16	3.10	2.8	E	2	
7	Am	9.56	6.4	3.44	3.10	2.6	SWt	1	
	Pm	10.18	6.10	4.18	4.2	2.8	S	3	
8	Am	10.46	6.1	4.37	3.8	2.5	NE	3	
	Pm	11.10	7.5	5.0	4.9	2.8	NE	4	
9	Am	11.36	6.2	5.30	3.7	2.7	N	4	
	Pm	12.5	8.0	5.59	5.0	3.0	N	4	
10	Am	12.34	6.3	6.30	3.10	2.5	W	2	
	Pm	—	—	7.0	4.10	—	SWt	1	
11	Am	1.2	7.6	7.24	3.3	4.3	N	2	
	Pm	1.30	6.0	7.50	5.2	— 10	NE	1	
12	Am	2.0	7.4	8.16	3.7	3.9	S	1	
	Pm	2.27	6.6	8.42	5.6	1.0	S	1	
13	Am	3.0	8.4	9.8	4.3	4.1	N	4	
	Pm	3.31	7.3	9.33	5.8	1.7	NWt	3	
14	Am	4.0	8.0	10.0	3.7	4.5	NWt	3	
	Pm	4.30	6.6	10.29	5.1	1.5	NWt	1	
15	Am	5 "	7.7	11.0	3.8	3.11	Calm	—	
	Pm	5.29	6.4	11.28	4.7	1.9	N	2	
16	Am	6.80	7.9	12.0	3.7	4.2	Calm	—	
	Pm	6.27	6.8	12.29	5.0	1.8	NWt	1	
17	Am	6.59	8.0	12.58	4.8	3.4	WSWt	4	
	Pm	7.23	7.0	—	—	—	SWt	8	
18	Am	7.48	6.8	1.21	4.7	2.1	Calm	—	
	Pm	8.5	6.6	1.47	3.10	2.8	Do	.	
19	Am	8.21	6.5	2.0	4.4	2.1	SWt	2	
	Pm	8.47	6.5	2.24	4.5	2.0	SSWt	1	

Figure 3



500
400
300
200
minutes
Observed intervals
Intervals between predicted turning points
500
400
300
200
100
0
minutes
1841

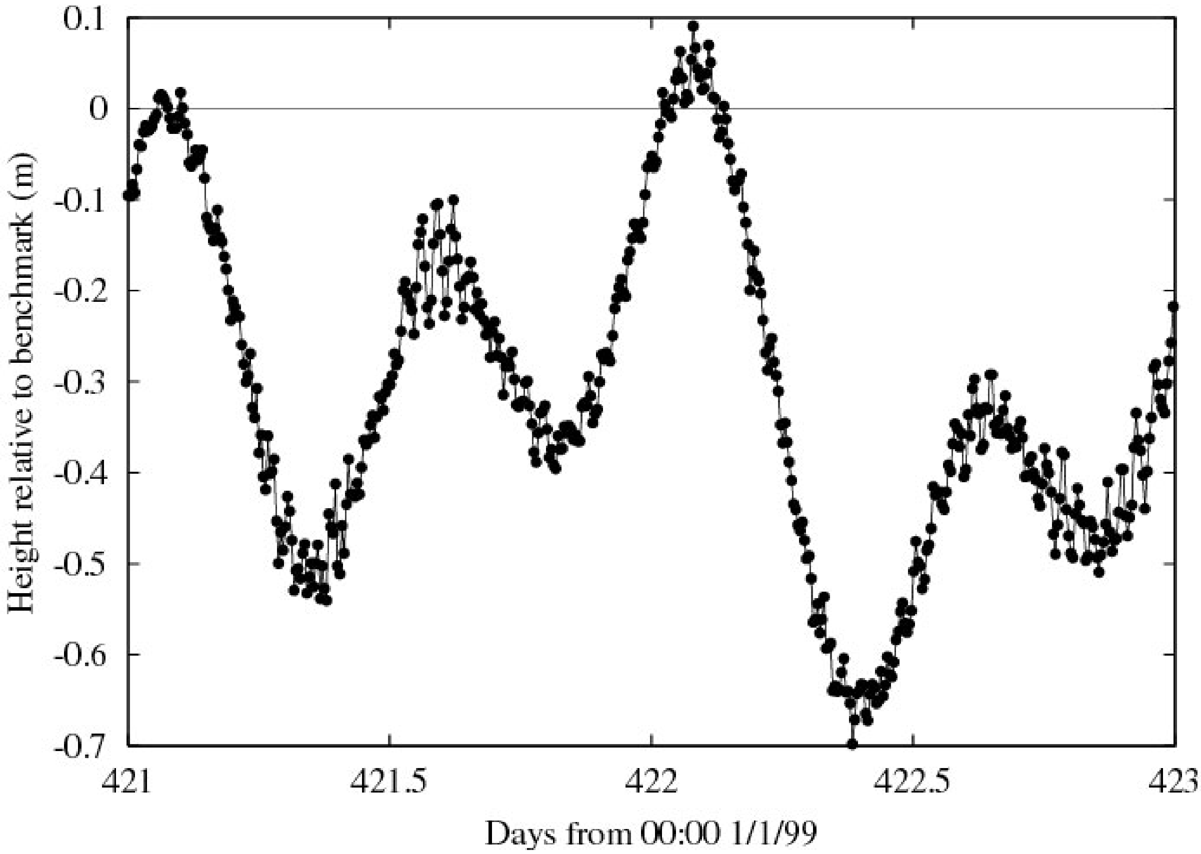
Figure 4



predictions
predictions, adjusted for atmospheric pressure
observations
benchmark
mean tidal level
Height above tide gauge zero (m)
2.2
2
1.8
1.6
1.4
1.2
1
00:00
12:00
00:00
12:00
1 July 1841
2 July 1841

Figure 5

Figure 6



0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
Height relative to benchmark (m)
421
421.5
422
422.5
423
Days from 00:00 1/1/99

Figure 7

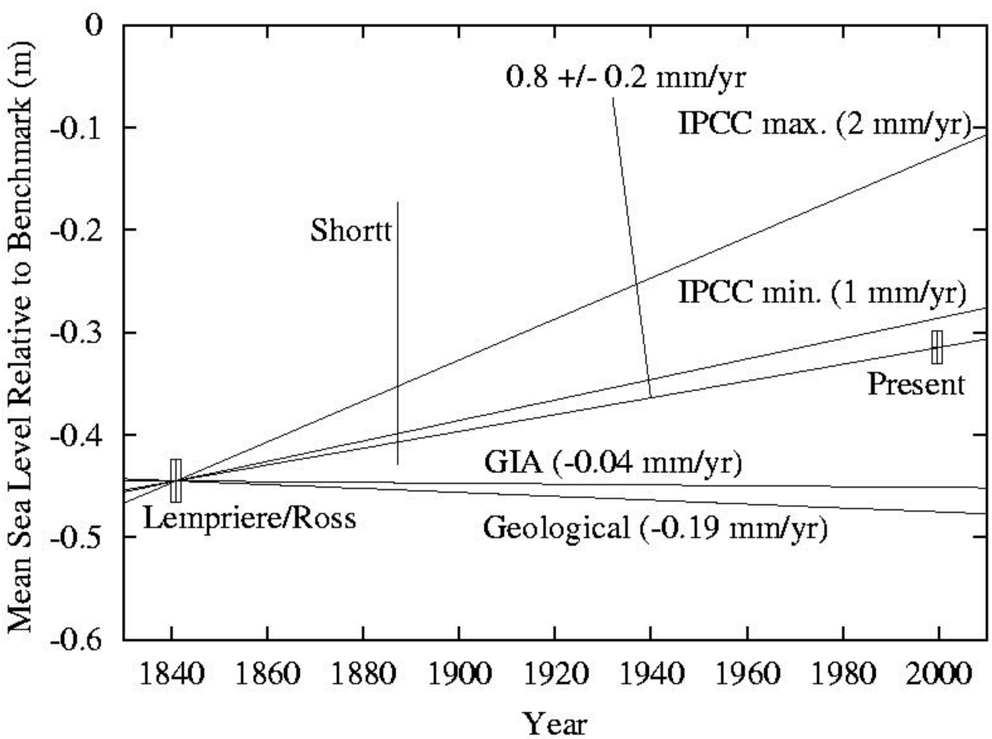

0.8 +/- 0.2 mm/yr
IPCC max. (2 mm/yr)
Shortt
IPCC min. (1 mm/yr)
Present
GIA (-0.04 mm/yr)
Lempriere/Ross
Geological (-0.19 mm/yr)
Mean Sea Level Relative to Benchmark (m)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year

Figure 8