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# New Zealand's first tide gauge-based sea level measurements

Glen H. Rowe

Toitū Te Whenua Land Information New Zealand, Wellington, New Zealand

*Correspondence to*: Glen H. Rowe (growe@linz.govt.nz)

**Abstract.** James Cook's second voyage to the South Seas, undertaken to settle the question regarding the existence or otherwise of the Great Southern Continent (*Terra Australis Incognita*), involved two vessels, the *Resolution* and *Adventure*. The Board of Longitude appointed two astronomers from the Royal Observatory, Greenwich, to the voyage, William Bayly and William Wales, one to each vessel. They were instructed, in addition to their astronomical duties, to observe the height and time of the tides. To this end, Bayly and Wales fabricated tide gauges and conducted timed measurements of sea level during their stopovers at Dusky Sound and Queen Charlotte Sound in 1773. This paper reviews those tidal observations, the first of their kind in New Zealand, using modern understanding of the tide, assuming that no significant change to the tidal regime at each location has taken place during the intervening period. When compared to the predicted (hindcast) astronomical tide, the majority (80 %) of the observed ranges and times agreed within 20 cm and 30 min respectively. Whilst their observations have little scientific value today (other than indicating the quality attainable in the late-18$^{th}$ century), Bayly and Wales can not only rightfully lay claim to making New Zealand's first tide gauge measurements but also, as far as it possible to ascertain, be justifiably proud of the quality of their endeavours

## 1 Introduction

When James Cook (1728 – 1779) embarked on his first voyage to the South Seas (1768 – 1771) aboard HMS Bark *Endeavour*, he carried two sets of secret orders. The second of these, to be opened on completion of observing the transit of Venus on 3 June 1769 from Tahiti (the subject of the first order), directed Cook to sail south to a "Continent or Land of great extent … or the Latitude of 40°" (Beaglehole, 1955, p. cclxxxii) whichever he arrived at first.

Although Cook's voyage was judged a success by many measures, the question of the Great Southern Continent remained unanswered. In the postscript to his *Endeavour* journal Cook suggested that New Zealand would serve as an ideal staging location for further discoveries in the South Seas, particularly in support of exploring the highest of latitudes (Beaglehole, 1955, p. 479).

Plans for another expedition began to unfold little more than two months after Cook's return to England. The Admiralty instructed the Navy Board to purchase "two proper vessels of about 400 tons for service in remote parts" (Beaglehole, 1961, p. 899) – two ex-merchant colliers were duly acquired, refitted and renamed HMS *Resolution* and HMS *Adventure*.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




Cook (now promoted to the rank of Commander) was assigned to the *Resolution*, and Lieutenant Tobias Furneaux (1735 – 1781) was appointed captain of *Adventure*, the smaller of the two vessels. The Board of Longitude appointed two astronomers to the voyage; William Bayly (1737 – 1810) and William Wales (1734 – 1798), both from the Royal Observatory, Greenwich. Bayly joined the company aboard the *Adventure* while Wales accompanied Cook on the *Resolution*.

In addition to their astronomical duties, Bayly and Wales were to "Observe the height of the Tides and the time of high & low water, particularly at the full & change of the Moon and Whether there be any difference & What, between Night & Day tides" (Beaglehole, 1961, p. 727). These instructions were more specific than those given to Cook for his *Endeavour* voyage, which simply required the "direction and Course of the Tides and Currents" to be obtained. Woodworth and Rowe (2018) provides a review and assessment of the quality of the tidal observations made by Cook during his *Endeavour* voyage, based on modern tide information.

During stopovers made in 1773 by the *Resolution* and *Adventure* at Dusky Bay[1] and Queen Charlotte's Sound[2], Wales and Bayly conducted the first tide gauge-based sea level measurements made in New Zealand. These observations, along with the astronomers' extensive celestial observations, determinations of time, and comparisons of the time keepers carried on the ships, were published in Wales and Bayly (1777).

**Table 1. Locations and dates of tide observations carried out in New Zealand during 1773 by Bayly and Wales, and the vessels they sailed on.**

| **Location** | **William Bayly**<br>**HMS *Adventure*** | **William Wales**<br>**HMS *Resolution*** |
|---|---|---|
| Dusky Bay | | April |
| Queen Charlotte's Sound | May and December | November |

Whilst the intent of Cook's second voyage (1772 – 1775) was, prima facie, to discover and explore any lands that might lie in the unexplored part of the Southern Hemisphere, the voyage, being commissioned by the British government, also had the strategic objective of taking, in the name of the King of Great Britain, any land encountered, subject to the consent of any natives should it be inhabited (Beaglehole, 1961, p. clxviii). Cook was to observe the characteristics of his discoveries (and the nature of any peoples), including gathering information that would be useful to either navigation or commerce, such as the tide observations made by Bayly and Wales during their stopovers in New Zealand (ibid.). This paper details those

[1] When Cook sighted this inlet during his first voyage of discovery he named it Duskey Bay, however Dusky became the usual spelling during the second voyage stopover; today it is known as Tamatea / Dusky Sound. The second voyage nomenclature is used when referring to the work carried out by Bayly and Wales, and the current name when using modern sources.

[2] Cook visited this sound during his first voyage and named it after the wife of King George III; it is now known as Queen Charlotte Sound / Tōtaranui.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023

Open Access History of Geo- and Space Sciences Discussions

observations and examines their results in terms of tide predictions based on modern data recorded at tide stations near the sites that Bayly and Wales occupied during 1773.

## 2 The astronomer tide observers

### 2.1 William Bayly (1737–1810)

A farmers son, William developed an early interest in mathematics which was fostered by those who recognised the boy's abilities. Such was his aptitude that Bayly came to the attention of Dr Maskelyne (1732 – 1811), the Astronomer Royal, and was duly appointed as an Assistant at the Royal Observatory, Greenwich. Bayly would serve as astronomer on Cook's second and third (1776 – 1779) voyages, otherwise fulfilling his duties at the observatory until 1785. During this period, Bayly was involved in writing the scientific account of Cook's third voyage. On leaving the observatory, Bayly took up the post of Headmaster at the Royal Naval Academy at Portsmouth, a position he held for 22 years before retiring aged 70. No known portrait of Bayly is known to exist (Orchiston, 2016: 152–153).

### 2.2 William Wales (1734–1798)

Like Bayly, William Wales showed an ability in mathematics from an early age and, in 1766, was commissioned by the Astronomer Royal to carry out the computations for the first *Nautical Almanac*. After returning from the voyage that is the subject of this paper, Wales accepted the position of Master of the Royal Mathematical School and also undertook, with Bayly, the task of publishing the scientific observations made during the voyage. Later still, Wales completed the scientific account of Cook's first voyage which he published 17 years after that voyage had ended. Wales married Mary, the sister of the astronomer on Cook's first voyage, in 1765 and his accomplishments were recognised when ~~Wales~~ was elected Fellow of the Royal Society in 1776. At the time of his death, Wales was Secretary of the Board of Longitude (Orchiston, 2016: 154-155).

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


Open Access History of Geo- and Space Sciences Discussions

**Figure 1. Pastel portrait of William Wales painted by J. Russell in 1894, now at Christ's Hospital, Horsham (photograph courtesy: Wayne Orchiston).**

## 3 Tide observations – 1773, an overview

### 3.1 Tide gauges

In their extensive introduction to Wales and Bayly (1777), the authors describe the use of the various items of equipment with which they had been provided, but tide gauges are conspicuously absent from the inventory. It would seem that Bayly and Wales were each responsible for supplying or constructing their own tide gauge device.

Bayly used a narrow glass tube which functioned as a stilling well during his first visit (May 1773) to Queen Charlotte's Sound, the zero being set near low water, but there were times when he recorded negative tide heights. Upon his return in December 1773, Bayly deployed a pair of wooden posts which served as tide boards from which visual readings could be made. The zero of each post was offset such that the difference between the zeroes had to be added to the high water readings to obtain values consistent with the low water readings. Bayly read the water level on his gauges to a precision of ¼ inch (~6 mm).

Wales employed a square wooden tube at Dusky Bay, and a simple wooden post arrangement half a year later at Queen Charlotte's Sound as his tube had, in the meantime, been taken away by natives at Tahiti (Wales and Bayly, 1777, p. 56). Wales set zero for both his gauges high so that all his water levels were measured downwards from the reference mark. Wales normally recorded his heights to the inch, only on rare occasions to half that interval.

More detailed descriptions of these tide gauges are included in the discussion of each set of tide observations (see Sect. 6.1 – 6.4).

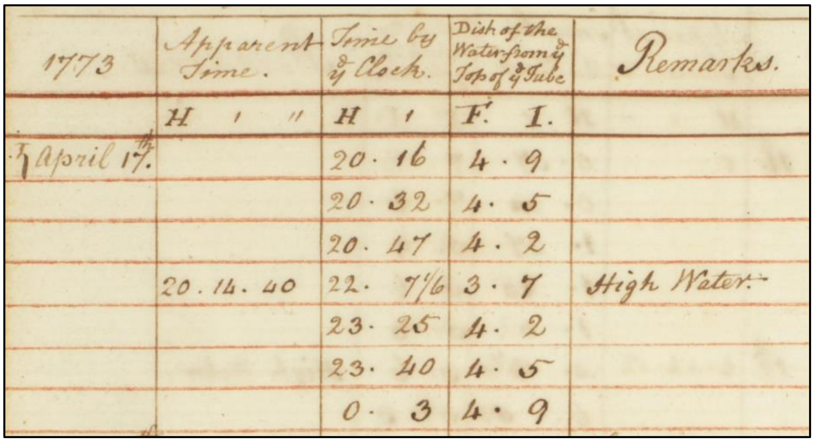
### 3.2 High water observations

As those discussions will show, the astronomers' measurements at high water were more comprehensive than those of low water, the latter being rarely more than a single observation. In addition to timing and measuring the highest water level, equal numbers of tide gauge readings were made before and after the maximum level. The clock time was recorded at every observation, as well as apparent time at high water.

Bayly's observations were often made at 10-minute intervals and twice as numerous as those made by Wales. Figure 2 shows a typical sequence of sea level measurements made by Wales at Dusky Bay, in this case high tide on 17 April 1773. Here we see his gauge readings when the water level was 7, 10 and 14 in. below, before and after, high water – unlike Bayly, Wales did not make his observations at regular time intervals. Note that the distances to the water level are made in a top-down direction. Clock time is given for each measurement, and apparent time is included for the time of high water.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



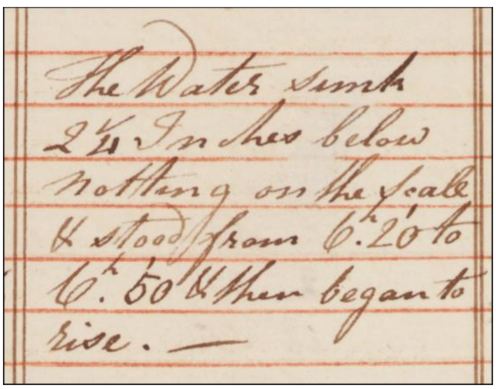



| 1773 | Apparent Time. | Time by ye Clock. | Dist of the Water from ye Top of ye Tube | Remarks. |
|---|---|---|---|---|
| | H ' '' | H ' | F. I. | |
| ♄ April 17th | | 20 · 16 | 4 · 9 | |
| | | 20 · 32 | 4 · 5 | |
| | | 20 · 47 | 4 · 2 | |
| | 20 . 14 . 40 | 22 · 7 1/6 | 3 · 7 | High Water. |
| | | 23 · 25 | 4 · 2 | |
| | | 23 · 40 | 4 · 5 | |
| | | 0 · 3 | 4 · 9 | |

**Figure 2. Wales's sequence of observations before, at, and following a high tide on 17 April 1773 at Dusky Bay (Wales, 1775b, p. 8).**

### 3.3 Low water observations

As mentioned previously, Bayly and Wales paid far less attention to low water than they did for high water. Indeed, low water observations normally consisted of a single reading of the gauge, and many by Wales consisted of a height only, without an associated clock time. Bayly appears to have been more conscientious by recording the period that the water level stood still for his low water observations, an example of such a comment is shown in Fig. 3: "The Water sunk 2¼ Inches below nothing on the scale & stood from $6^h$.20' to $6^h$.50'& then began to rise".



The Water sunk
2¼ Inches below
nothing on the scale
& stood from 6h.20' to
6h.50' & then began to
rise.

**Figure 3. Bayly's observation of a low water on 7 May 1773 at Queen Charlotte's Sound (Bayly, 1774b, p. 36)**

### 3.4 Comments

Whilst there appears to be no reason to doubt the veracity of the observations that Bayly and Wales recorded in their hand-written records (Bayly, 1774b; Wales, 1775b), and subsequently published in Wales and Bayly (1777), these surely cannot be the only gauge readings they made to determine the time and height of these tide events. Hand-written records (as illustrated in Fig. 2) are too immaculate to have been penned at the gauge, and so it seems likely that a subset of the

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




observations was transferred from a field book to their respective observation log books (Bayly, 1774b; Wales, 1775b). Without access to those original records, it is not possible to know how extensive their tide measurements really were, nor the criteria used to select the subset of observations that were published (and used in this paper).

## 4 Tide predictions from modern sea level data

Tide predictions have been generated for 1773 based on our modern knowledge of the tide and with an implicit assumption that the main characteristics of the tide have not changed in the last 250 years. The modern information comes from measurements of the sea level at stations located near to where Bayly and Wales carried out their observations.

### 4.1 Modern tide stations

Modern tide stations at Motuara Island and Many Islands, at Queen Charlotte Sound and Dusky Sound respectively, are indicated by the blue squares in Fig. 4a and 4b, whilst the locations of the 1773 observations are shown by the red dots.

### 4.2 Tide predictions

Analysis and prediction software, based on that of Foreman (1977, updated 2004) was used to calculate the times and heights of high and low waters, and heights at 10-minute intervals (for plotting purposes), throughout 1773 at Motuara Island and Many Islands.

Normally, the times of such tide predictions would be in terms of a standard time meridian – for New Zealand today this is 180°E, ~~being~~ NZ Standard Time. Obviously, Bayly and Wales were not operating in a standard time zone regime, however their recorded clock and apparent times can be converted to local mean time (see Sect. 5.1). To generate tide predictions in terms of local mean time, the phase lags of the modern harmonic constituents for Motuara Island and Many Islands were transformed from the standard meridian (180°) to the meridians of Meretoto / Ship Cove (174° 14'E) and Pickersgill Harbour (166° 34'E)[3]. The predicted times then had 12 hr deducted to align with the astronomical day (which begins at noon), to conform to the time system used by Bayly and Wales. The amplitudes of the harmonic constituents for the modern tide stations have been assumed to be also applicable to the historic sites.

[3] The harmonic constituents are provided in Appendix B.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



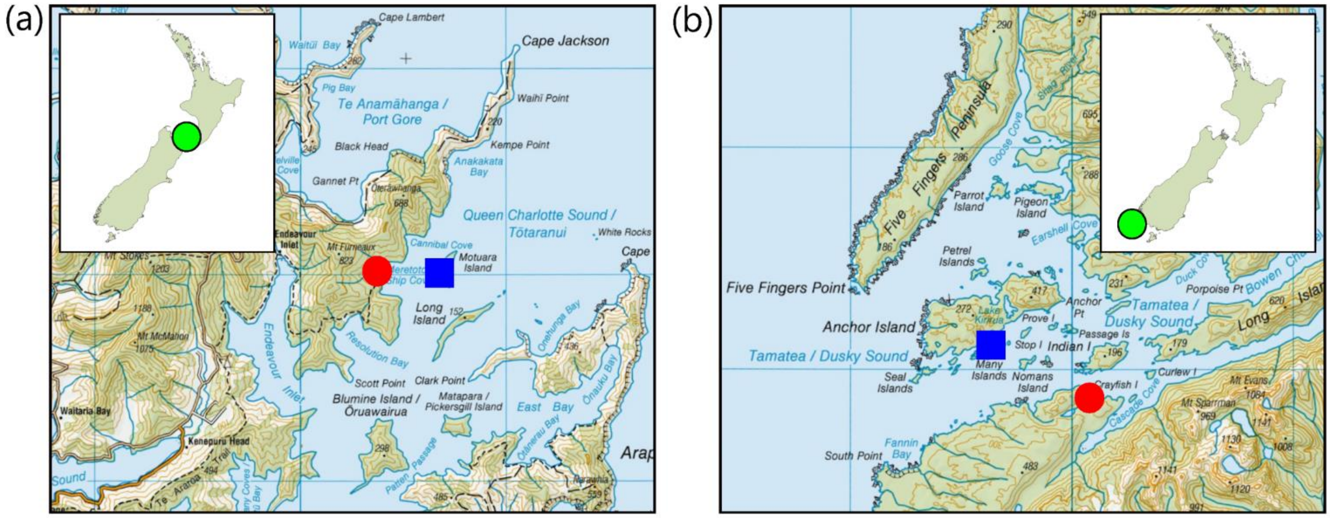




**Figure 4. (a) Map of Queen Charlotte Sound / Tōtaranui showing Ship Cove, the location of Bayly's and Wales's tide gauges (now known as Meretoto / Ship Cove) at the red dot, and a blue square at Motuara Island. (b) Map of Tamatea / Dusky Sound showing the location of Wales's gauge at Pickersgill Harbour (red dot), and a blue square at Many Islands. Insets show location in New Zealand. The grid lines are at a spacing of 10 km. (Maps: 4(a) extract from LINZ Topo250 Map 13, 4(b) extract from LINZ Topo250 Map 24, coastline polygon for insets from LINZ Data Service https://data.linz.govt.nz/).**

## 5 Comparing observations to predicted data

In order to compare the observations made by Bayly and Wales to the predicted data, both datasets must be expressed in terms of the same time system.

However, as there is no vertical reference common to the historic and predicted sea level heights, it is not possible to relate the heights of the observed and predicted tides, therefore water level comparisons must be limited to tidal range to avoid the unknown zero offset.

### 5.1 A common time system – local mean time

As mentioned above (Sect. 3.2 and 3.3), a clock time was recorded for almost every tide gauge observation, with apparent time included whenever the time of high or low water was recorded with a clock time. Whilst the reliability and accuracy of clocks were improving during the 18$^{th}$ century, they were not yet perfect. For this reason, the astronomers were required to attend to the watches, compare them to apparent time derived from morning and afternoon observations of the sun, and against one another. The time kept by the clocks entrusted to Bayly and Wales (they had two time-keepers each) could differ from true time by an hour or two, so the astronomical determinations of time (apparent time) were needed to find the offsets and rates of the clocks.

The rate of apparent time is not uniform due to the varying speed of the earth in its elliptical orbit around the sun, so this irregularity, known as the equation of time, needs to be corrected for. Accordingly, the apparent times of the high and low

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




waters published in Wales and Bayly (1777) were transformed to local mean time by applying the equation of time from an on-line calculator (PlanetCalc, 2022). By differencing each so-derived local mean time and its associated clock time, the clock error at that local mean time could be found. Now the local mean time of each tide gauge observation could be calculated by applying the clock error, and any correction for clock drift, to the observation's clock time.

Now the 1773 observations could be compared to the predicted tides as the latter were also expressed in local mean time as described in Sect. 4.2.

### 5.2 Sea level heights

When introducing the gauges erected by Bayly and Wales (Sect. 3.1) it was noted that the zero point of their measurements was seldom near the lowest level to which the water fell.

For one of his gauge installations, Bayly set two zero points, one for low water, the other for high water readings. Applying the measured offset between these zeroes allows all the heights of his sea level measurements to be determined relative to the zero of the low water gauge.

All Wales's measurements were made downwards – these data have been inverted and expressed relative to an arbitrary zero below low water to avoid negative values.

After the historic measurements had been converted to upward values, arbitrary offsets were applied for the purpose of creating Fig. 5, 7, 8, 11 and 12 to present the observed and predicted datasets together.

## 6 Tide observations during 1773 - details and discussion

The following is a detailed description of each of set of observations made by Bayly and Wales, and compare their measurements to the predictions based on modern data. The first series of observations made by Bayly at Queen Charlotte's Sound, and Wales at Dusky Bay, spanned more than a single spring-neap cycle, whilst their second tide gauge deployments, both at Queen Charlotte's Sound late in 1773, were somewhat shorter in duration.

Figures 5, 7, 8, 11 and 12 present either Bayly's or Wales's observations plotted along with a predicted tidal curve. To avoid repetition in the captions of those figures, the following description applies unless stated otherwise. Red crosses show all sea level observations[4] made by either Bayly or Wales with recorded time and height. Wales frequently recorded a single height at low or high water without noting the time – these observations are represented by green circles in Fig. 5 and 8, plotted according to the predicted time of the relevant low or high water. The predicted tide curve, based on modern data, is shown in blue. Orange and black dots indicate the time of full and new moon respectively[5], and green lines (Fig. 11 and 12) denote

[4] More correctly, only those published in Wales and Bayly (1777) – refer comments in Sect. 3.4.

[5] Dates and times of these lunar phases are given in Table C1 in Appendix C.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




periods when the moon was above the horizon[6]. The times of all lunar phenomena have been calculated using Gray (2020). Dates and times are in terms of local mean time, with each day commencing with 00:00hrs at noon.

Tables A1 – A4 in Appendix A give the times and heights of the high and low waters observed by Bayly and Wales, the predicted values, and the differences between them.

### 6.1 Dusky Bay, April 1773 - Wales

Following the *Resolution's* arrival in Dusky Bay on 26 March 1773, Wales set about first establishing his observatory, before turning his attention to the tides.

In his journal, Wales describes the construction of his tide gauge, and the modifications required before measurements could commence (Wales, 1774, p. 127):

> 3 April
>
> Fixed up a Thermometer & Barometer, and made a machine for trying the Tydes: It consists of a long square Tube whose internal side is about 3 inches: A square float is fitted to this Tube & fixed to the end of a long slender Rod which is divided into feet and Inches from the float upwards. I propose to put down this rod into the Tube until the float just touches the water & then mark the feet & Inches on the Rod which are even with the top of the Tube: As the water is addmitted into the Tube only by a small aperture at the bottom the rise and fall of the water occassioned by the surf will be inconsiderable or at least much lessened.
>
> 4 April
>
> Fixed up my Tyde-Instrument & began to observe; but to my inexpressible surprize found it too short by many feet: It was about 6 feet long & Several People, amongst whom I was one had all along concluded that the Tydes did not rise & fall more than 4 feet or four feet & an half at most; We judged by the Shore; & I mention this circumstance to shew how erroneous estimations of the rise and fall of the Tydes may sometimes be when made in this manner, as I believe they often are.
>
> 5 April
>
> Set about a new Tyde-measurer, which I now made 11 feet long.
>
> 6 April
>
> Finished and fixed up my Tyde Instrument. I placed the bottom of the Tube in the Hollow of a Rock a little below low-water-mark and tyed its top to a Tree which grew out of the bank & hung over the water.

[6] Moonrise and set times are given in Table C2 in Appendix C.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




Wales observed at least one tide every day for the following three weeks, measuring either water level height and time before, at and after high or low water, or the height alone at high or low water. In total he recorded 27 high and 24 low waters as shown in Fig. 5.

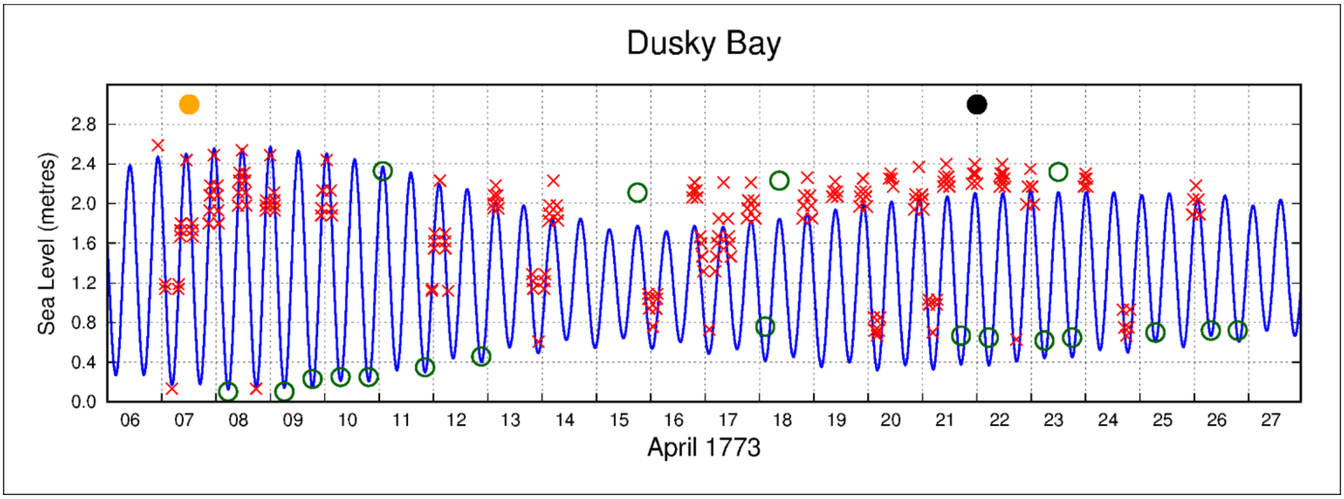



**Figure 5. Sea level observations made by William Wales at Dusky Bay during April 1773 plotted with a predicted tidal curve based on modern data.**

225 Table A1 lists the observed and predicted times and heights for each high and low water observed by Wales at Dusky Bay, and calculated tidal ranges. The table also gives the differences between the observed and predicted times and tidal ranges. Of the 32 time differences only two exceed 30 min (both being 39 min), whilst four range differences are greater than 20 cm (the largest being 29 cm). These results are testament to the quality of Wales's observations.

In his *Resolution* log book, Wales notes that "The time of High water on the Full and Change Days was at 10$^{H}$ 57'; and they both agreed; but the water rose 8 feet at the former, and only 5 feet 8 inches at the Latter: I cannot account for this difference; but am certain it is not owing to any error in the Observations" (Wales, 1775a, p. 38).

In his journal, Cook commented that the difference "is a little extraordinary and probably was occasioned at this time by some accidental cause such as Winds &c$^{a}$" (Beaglehole, 1961, p. 138).

Wales was right to trust his observations, as the difference in the ranges of successive spring tides is indeed a real feature of the tide in Dusky Sound as illustrated in Fig. 6.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



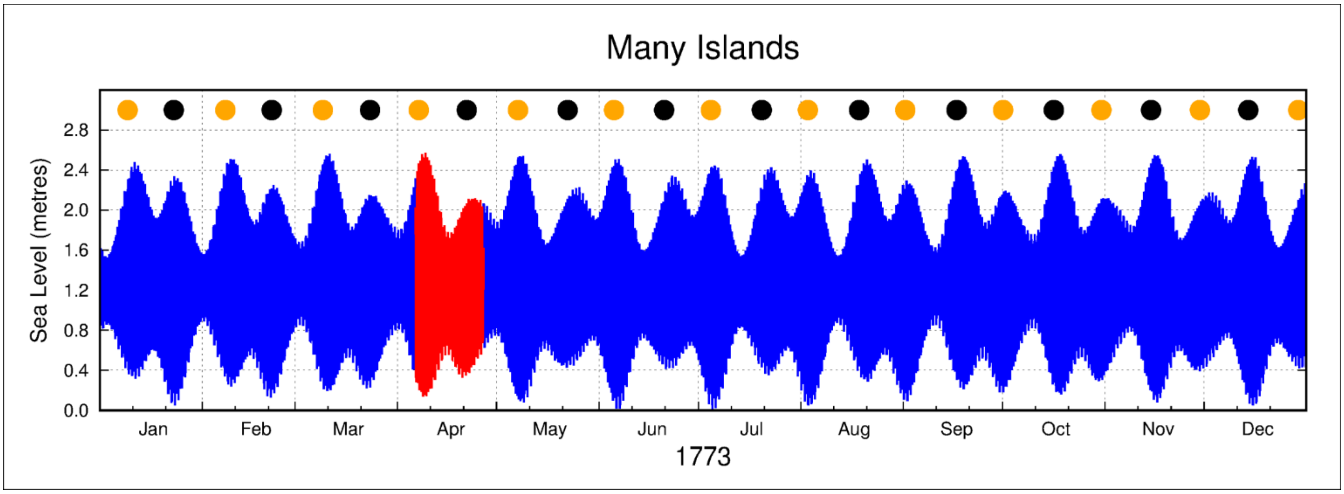




**Figure 6. The predicted tide curve throughout 1773 at Many Islands; the portion in red corresponds to the period when Wales was making his observations.**

Whilst the difference between periods of spring and neap tides varies for each month, it was greatest in 1773 during the period that Wales carried out his tide gauge measurements. Furthermore, whilst Wales observed the greater range at full moon, this is not always the case as can be seen from August onwards when spring tides occur close to new moon.

This inequality between spring tides in Dusky Sound is driven by the tidal constituent N2 (the larger lunar elliptic semidiurnal) which, having an amplitude of 20cm, is almost as significant as the 22cm amplitude of the principal solar semidiurnal constituent, S2.

Of course, it would be unreasonable to expect that Wales and Cook should have understood the tidal regime at Dusky Sound in greater detail than the spring-neap cycle. Knowledge of the tides was still evolving in the late-18$^{th}$ century and the reasons for their variability were yet to be properly understood (Cartwright, 1999).

### 6.2 Queen Charlotte's Sound, May 1773 - Bayly

In early February 1773 the *Adventure*, having become separated from the *Resolution*, made for Queen Charlotte's Sound in accordance with the instructions that Cook had handed to Furneaux (Beaglehole, 1961, p. 683), arriving there on 7 April for what turned out to be a stay of two months.

One month later, Bayly commenced his tide measurements, observing 20 high waters and 14 low waters over the following two weeks as shown in Fig. 7.

In the *Adventure*'s log book, Bayly describes his tide gauge and the precision to which he was able to measure the water level.

I made use of the following method (Viz), took a glass tube of 4 feet long, the diam of its Apperture 0,7 of an inch, to one end of which I fixed a bamboo cane of a convenient length both of which I made water tight, leaving one end of the glass tube open, then I made a very small hole thro' one side of the cane at the end not joined to the glass (as lowered) so that

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




when put down in the water perpendicular it would fill up to the Middle of the glass tube in the Space of 5 or 6 Minutes; these were lashed close and fast to a 10 foot Fir Rod, which was divided into feet Inches and quarters of Inches, & served as a scale, & this rod or scale was made fast to a post set firm in the water, in such manner that the surface of high water came up near half way the glass tube. by this means I could ascertain the hight of the water to a quarter on an Inch or less, at any time, for notwithstanding the water would rise a foot above & then sink as much below the column of water in the Tube, I never observed that the surface of the water in the glass tube altered its height so much as 1/10 of an Inch. & I imagine this method is capable of great Exactness with a glass tube of a proper Aperture. I was obliged to lengthen my tube with a cane because it was not of a sufficient length of itself which likewise obliged me to fix another tube at bottom to show the fall and time of Low Water (Bayly, 1774b, p. 36).

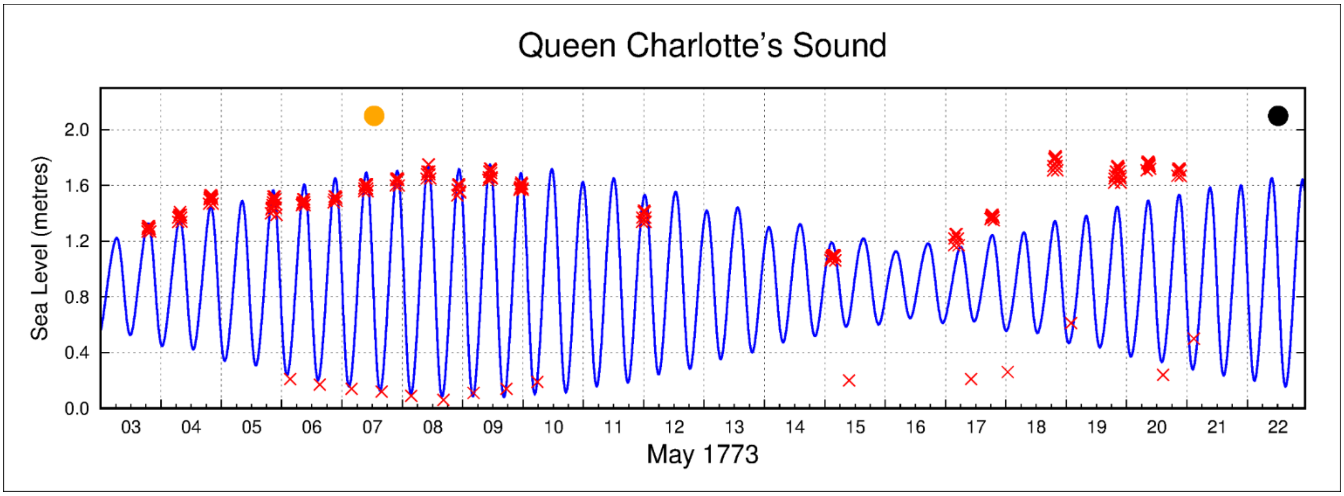



**Figure 7. Sea level observations made by William Bayly at Ship Cove, Queen Charlotte's Sound, during May 1773 plotted with a predicted tidal curve based on modern data.**

Table A2 lists the observed and predicted times and heights for each high and low water observed by Bayly at Queen Charlotte's Sound during May 1773, and calculated tidal ranges. The table also gives the differences between the observed and predicted times and tidal ranges. Whilst a significant number (41 %) of Bayly's time differences are greater than 30 min, this is not necessarily indicative of careless work. With a relatively small tidal range at this location (spring tide: ~1.6 m, neap tide: ~ 0.5 m), the rate of change of water level within half an hour of high or low water at spring and neap astronomical tides is less than 30 and 10 mm respectively. Estimating the true time of high or low tide under such circumstances would not be easy. Although most (18) of Bayly's tidal range differences are less than 15 cm, differences of 30 – 60 cm between 17 – 20 May are clearly evident in Fig. 7. These results can not be explained as Bayly noted that the weather during this period was either "quiet and serene", "calm and serene", "good", "calm" or "fine", with sea conditions described as being "still", "undisturbed" or "smooth".

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



Having meanwhile sailed from Dusky Bay, the *Resolution* regained the company of the *Adventure* in Queen Charlotte's Sound. Prior to both vessels departing on 7 June for the South Pacific, Cook wrote at length in his journal regarding this stopover at Ship Cove, including:

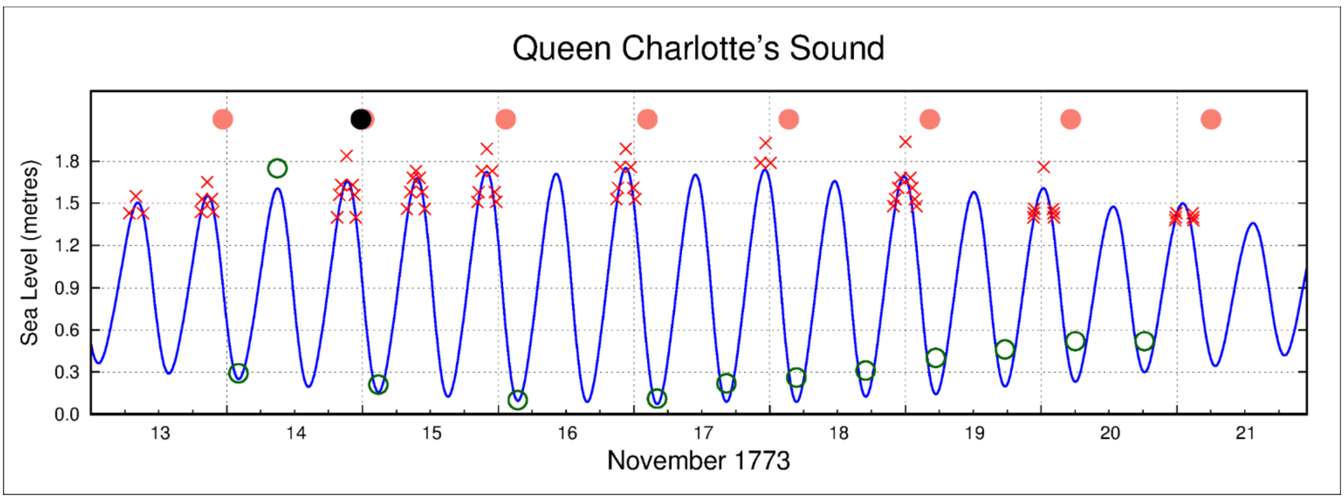
> M^r Bayley commun[i]cated to me … High-Water at the full and change of the Moon at 9 o'Clock & the greatest rise 6½ perpendicular; … Tides are confirmable enough to the like observations I made when I was here in Jan^ry 1770, … (Beaglehole, 1961, p. 173)

This claim that the greatest tidal range is 6½ ft is curious. According to Bayly's observations log, the greatest range, on 8 May 1773, was 5 ft 6.6 in. (from 5½ in. below zero to 5 ft 1.1 in. above) (Bayly, 1774b, p. 36). The predicted tide range on this date is 1.63 m (5 ft 4 in.), which is in close agreement with his measurements that day. It would seem that Cook did not mis-quote Bayly, as in his *Adventure* log book Bayly wrote "6^Ft..5^In perpendicular" (Bayly, 1774a, p. 63). Modern sea level data shows the largest astronomical range at Motuara Island to be 1.76 m (5 ft 9 in.); Bayly's observations fall within this range, but not the conclusion in his log.

Cook had spent three weeks at Ship Cove during his first voyage to the Pacific on the *Endeavour* and found that the tides "flow 9 or 10 oClock at the full and change of the Moon and rises and falls upon a perpendicular 7 or 8 feet". (Beaglehole, 1955, pp. 246-247). As noted in Woodworth and Rowe (2018), there is no information on how Cook made his tidal observations on the *Endeavour* voyage but, by whatever method he employed, Cook's range is clearly overstated. Nevertheless, he welcomed Bayly's (overstated) result as bestowing some degree of confirmation of his own.

### 6.3 Queen Charlotte's Sound, November 1773 – Wales

After voyaging in the South Pacific and spending time at Tahiti, the *Resolution* returned to Queen Charlotte's Sound on 3 November 1773 and stayed at Ship Cove for three weeks. Wales commenced water level measurements on 13 November and over the next eight days made detailed observations of 10 high waters and untimed water level readings of one high and 11 low waters as shown in Fig. 8.



https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




**Figure 8. Sea level observations made by William Wales at Ship Cove, Queen Charlotte's Sound, during November 1773 plotted with a predicted tidal curve based on modern data. Salmon-coloured dots indicate the time of lunar transit[7], as calculated using Gray (2020), and the black dot is new moon.**

Table A3 lists the observed and predicted times and heights for each high and low water observed by Wales at Queen Charlotte's Sound during November 1773, and calculated tidal ranges. The table also gives the differences between the observed and predicted times and tidal ranges. The greatest time difference is 19 min and the largest range difference is 17 cm – these results are commendable.

As mentioned earlier (Sect. 3.1), Wales's rectangular wooden tube was stolen from him in Tahiti, so at Ship Cove his "observations were made by means of two posts, divided into feet and inches, from their tops downwards; and their tops were placed truly level by the astronomical quadrant" (Wales and Bayly, 1777, p. 64).

Wales, 1775a, p. 69:

> I further found that the time of High-water preceeded the moon's transit over the meridian by 3 Hours, and the greatest rise of the Water whilest I was here was 5 feet & 10 Inches; but there were evident tokens on the Beach of the Water's having risen full 2 feet more than that, since we were here before.

Wales's determination of the rise agrees with Bayly's assessment six months earlier and the predictions, as discussed in the previous section. However, the higher line of tokens (driftwood?) on the beach would most likely have been driven there by wave action, not the astronomical tide. Perhaps it was evidence similar to this (i.e., driftwood) that led Cook, in 1770, to believe the rise was 7 or 8 ft.

To explore Wales's statement about the interval that high water preceded lunar transit, Table 2 lists the times of the high waters prior to lunar transit, lunar transit time, and the time difference between these two events. Lunar transit times have been calculated using Gray (2020). The average difference of 3 hr 53 min is one hour longer than Bayly found it to be.

**Table 2. Local mean times of high water and lunar transit, and the interval between tide and transit.**

| High Water | Lunar Transit | Difference hh:mm |
|---|---|---|
| 13 November 20:34 | 13 November 23:20 | 02:46 |
| 14 November 21:12 | 15 November 00:20 | 03:08 |
| 15 November 21:59 | 16 November 01:22 | 03:23 |
| 16 November 22:34 | 17 November 02:24 | 03:50 |
| 17 November 23:18 | 18 November 03:24 | 04:06 |
| 18 November 23:59 | 19 November 04:21 | 04:22 |
| 20 November 00:29 | 20 November 05:14 | 04:45 |
| 21 November 01:20 | 21 November 06:04 | 04:44 |

[7] Dates and times of lunar transit are given in Table C3 in Appendix C.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023

History of Geo- and Space Sciences Discussions
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Wales also remarked:

> In these 8 Days the time of High-water has advanced only $4^{H}$,,44’: it ought, I conceive, to have advanced $6^{H}$,,40’: whatever may have been the Cause of this, I am certain it arises not from an error in the Observations, although circumstances did not admit of my making them with so much Accuracy as might be wished. (Wales, 1775b, p. 305).

Figure 9 shows Meretoto / Ship Cove (red dot) situated near the northern entrance to Queen Charlotte Sound / Tōtaranui, beyond which lies Cook Strait which separates New Zealand’s North Island from the South Island. The sound is a drowned river valley that extends more than 30km south-westward and connects to Tory Channel / Kura Te Au, another drowned valley, which heads eastwards and also connects to Cook Strait.


**Figure 9. Map showing the location of Meretoto / Ship Cove (red dot), the connected waterways Queen Charlotte Sound / Tōtaranui and Tory Channel / Kura Te Au, and Cook Strait separating New Zealand’s North and South Islands. (Map based on coastline polygon from LINZ Data Service https://data.linz.govt.nz).**

The flood and ebb of the tide through this region are affected by the complex nature of these waterways (Heath, 1977). One of the consequences of this regime is the variability of the interval between tides. Wales’s expectation that the advance of high water over eight days should have amounted to 6 hr 40 min is based on what is now known as the equilibrium tidal model which indicates a progression of 50 min per day (i.e, an interval of 24 hr 50 min).

Figure 10 shows that throughout 1773 the daily progression of high waters oscillated from 29 to 119 min, so that the interval can be as short as 24 hr 29 min, or as long as 25 hr 59 min. The mean and median advance times are 51 and 40 min respectively. Wales’s eight days of measurements fell within a period when the daily progression was near the low end of its range (as indicated by the part of the curve coloured red) with the average over those days being less than that of the equilibrium model, hence his concern about the accuracy of his observations. We, however, know that the effect is real and

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


that it was the quality of his work that detected the phenomenon which led Wales to question his abilities. Had Wales commenced observations at least two days earlier, he would surely have been surprised that the daily advance was twice that expected.

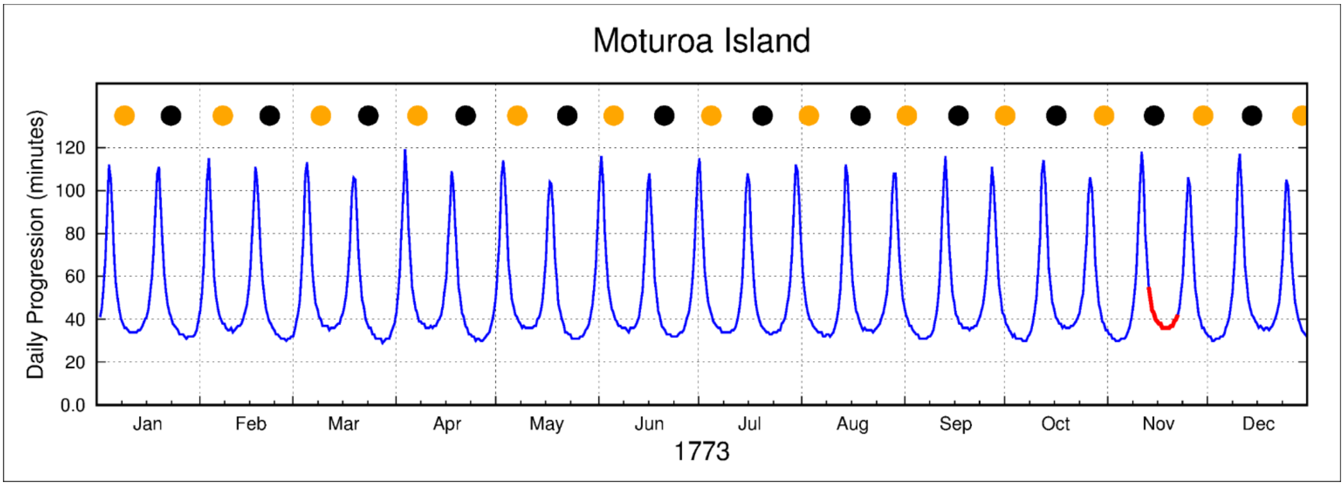


**Figure 10. The predicted daily progression of high waters throughout 1773 at Moturoa Island; the portion in red corresponds to the period that Wales was making his observations.**

On 25 November the *Resolution* set off to explore higher latitudes during the summer before retreating to the tropics for much of 1774. After calling at the Marquesas Islands, Tahiti, New Hebrides and New Caledonia, Cook brought the *Resolution* back to Ship Cove in October 1774 for a 3-week stopover before departing for England via Cape Horn. Although Wales carried out a considerable number of astronomical observations during this sojourn, no further tide measurements were made.

### 6.4 Queen Charlotte's Sound, December 1773 – Bayly

Towards the end of October 1773, the *Resolution* and *Adventure* became separated off the east coast of the North Island of New Zealand. Furneaux had great difficulty in getting to Ship Cove, the agreed rendezvous location should the ships part company (Beaglehole, 1961, p. 689), eventually arriving several days after Cook had departed. The ship's company set about refitting the *Adventure*, restocking water and wood and preparing to depart for England on 23 December.

Bayly's tide observations during this stay, carried out over a period of just a few days, comprised only three high waters and their following low waters, as shown in Fig. 11. Bayly set up two posts, their zero marks being offset, they were, in effect, one gauge in two parts – one for high water, the other low water.

> Here follow a few observations on the Tides at the bottom of Ship Cove where I was obliged to set up two posts one for to observe high water at, & the other to observe low water at, where nothing (on the Scale of my Tide Instrument) was always fixed to a notch or stroke across each post, this notch on the post at high water was just 4:0¾ above the level of the notch on the post at Low water; therefore

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



> nothing on the Scale at high water was so much above nothing on the Scale at Low water (Bayly, 1774b, p. 58).

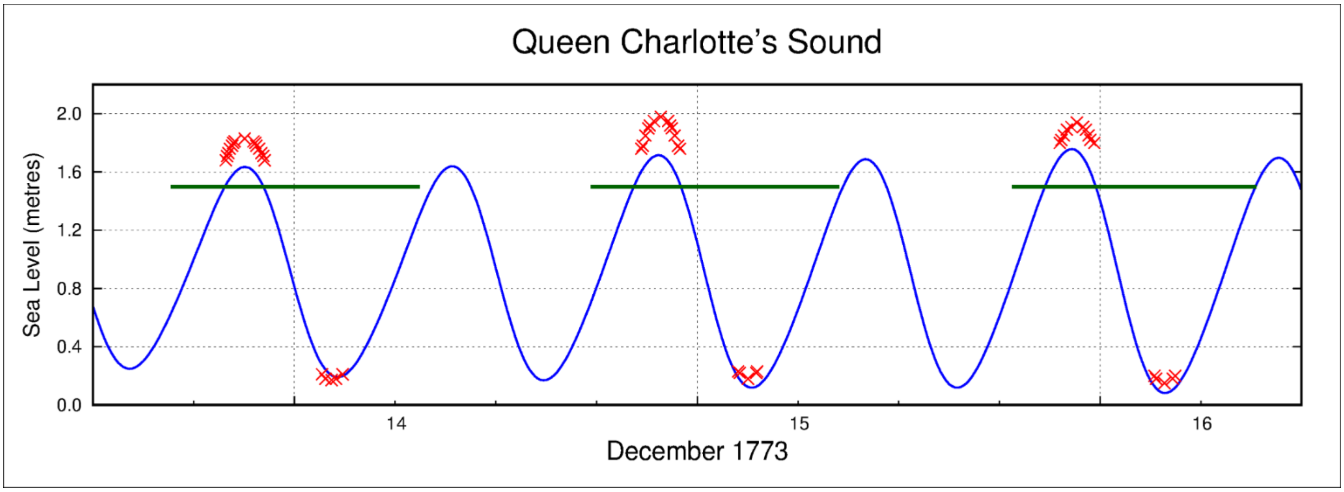


**Figure 11. Sea level observations made by William Bayly at Ship Cove, Queen Charlotte's Sound, during December 1773 plotted with a predicted tidal curve based on modern data, and lines indicating when the moon was above the horizon.**

Table A4 lists the observed and predicted times and heights for each high and low water observed by Bayly at Queen Charlotte's Sound during December 1773, and calculated tidal ranges. The table also gives the differences between the observed and predicted times and tidal ranges. The greatest of the six time differences is 22 min and the three range differences are 22, 21, and 12 cm. It would not be appropriate to draw any conclusions from this small sample.

Bayly also noted:

> The water seemed to rise about 6 Inches higher when the Moon was above the horizon than when she was below it. Being obliged to fix my posts at some distance from the Tents, rendered it unsafe to observe the night Tides (ibid.).

When he had visited Ship Cove earlier in the year Bayly recorded, alongside his water level measurements, when the moon was above the horizon, but did not repeat this practice with his second set of observations. Bayly's proposition that higher tides are somehow correlated with the presence of the moon in the sky could not have arisen from this visit as the moon was above the horizon for all high waters he observed as shown in Fig. 11. Was this idea based on the observations Bayly made during his earlier time at Ship Cove? Figure 12 shows periods when he observed consecutive high waters during that visit.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


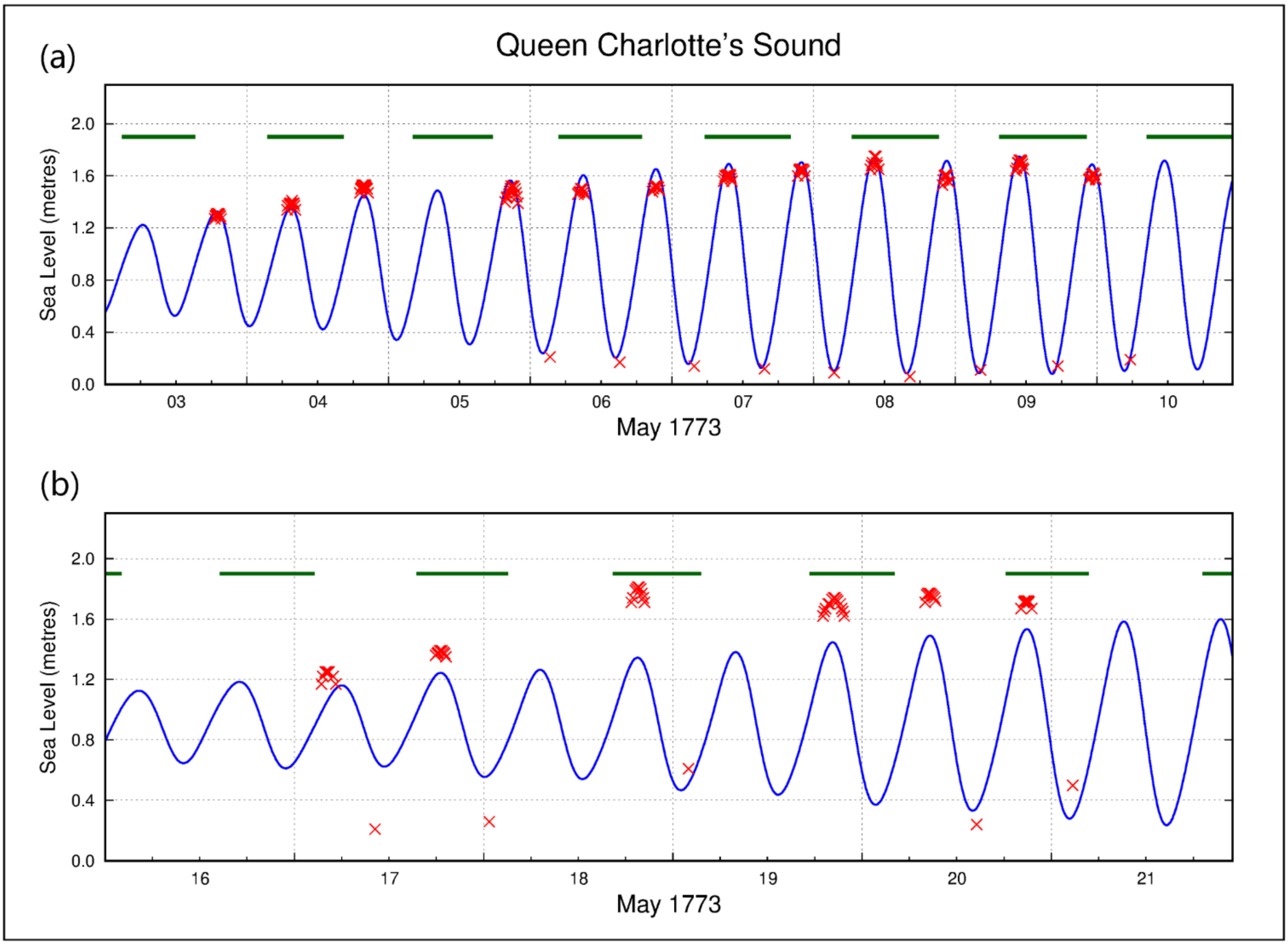


**Figure 12. Sea level observations made by William Bayly at Ship Cove, Queen Charlotte's Sound, during May 1773 plotted with a predicted tidal curve based on modern data, and lines indicating when the moon was above the horizon.**

Between 3 and 7 May, the tidal range was increasing from neap towards spring – it follows that each high water would be higher than the preceding one, so Bayly's hypothesis could not have been based on those observations. Spring tides occurred on 8 and 9 May and, indeed, the diurnal inequality has the higher tide both days when the moon is visible. The height differences, by Bayly's measurements, were 5.6 and 4.5 in.

During the latter part of his time-series, Bayly's observations not only became sparser, as shown in Fig. 12b, but once again they occurred as the tide was progressing from neap towards spring. Although it appears that his premise holds true on 17 and 20 May, this is more likely due to the neap-to-spring transition than the presence of the moon in the sky.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023

Open Access History of Geo- and Space Sciences Discussions

## 7 Conclusions

This paper has investigated the quality of the sea level measurements made in New Zealand during Cook's second voyage to the Pacific by comparing those observations with hindcast predictions based on modern data. These comparisons assume, firstly, that the tides have not changed materially during the intervening period and, secondly, that the observed tides were not affected by any meteorological conditions prevailing at the time.

Comparisons of individual high and low waters have been made possible as Bayly and Wales employed tide gauges for their sea level measurements – the first time this type of instrument had been deployed in New Zealand. This is in contrast to the lack of information about how Cook made his tidal observations to estimate spring range and high water full and change during his first voyage to this part of the world (Woodworth and Rowe, 2018).

Of the 83 observed tides, the difference between observed and predicted tide times exceeded 30 min on 16 occasions, six of which being greater than one hour with a maximum of 1 hr 51 min. Whilst Table A2 shows that almost all (14) of the time differences greater than 30 min were found in Bayly's observations at Queen Charlotte's Sound during May 1773, this does not necessarily suggest that his work was in any way inferior. With a relatively small tidal range at this location (spring tide: ~1.6 m, neap tide: ~ 0.5 m), the rate of change of water level within half an hour of high or low water at spring and neap astronomical tides is less than 30 and 10 mm respectively, making it a challenge to ascertain the true time of high or low tide.

Regarding tidal ranges, the comparisons show that the majority (82 %) of the differences between the observed and predicted ranges of consecutive tides were less than 20 cm. The largest of the differences (30 – 60 cm), clearly evident in Fig. 7, can not be explained as Bayly's notes show that good weather and sea conditions prevailed during this period of greater differences (17 – 20 May).

There is a growing awareness that tide observations accumulated over many decades, or shorter periods a similar period apart, provide an opportunity to investigate possible long-term tidal changes (for example Haigh et al., 2019). With almost 250 years separating Bayly's and Wales's measurements and our modern sea level datasets, the possibility that insights into any nonastronomical changes might be gained from analysing these data has some appeal. However, on close inspection, it is evident that the historical data is unable to be applied to such a study. This is not a criticism of the astronomers' work; their focus was to gather information for navigation, primarily to determine when high water could be expected and the range of the tide. They had no need to relate their sea level heights to a fixed terrestrial mark that future measurements might also reference (should the mark survive in the meantime). Furthermore, to go beyond the simple comparative analysis of tide ranges presented in this paper would require many months of data from 1773, ideally at regular intervals (e.g. hourly) which, given the nature of Cook's voyage, was never a possibility.

Whilst the sea level observations made by Bayly and Wales are of little scientific value today (but would have provided valuable information for mariners, in the absence of further observations meanwhile, until the mid-20$^{th}$ century), now they are historically significant as the first measurements by tide gauge in New Zealand. This study has shown that the quality of

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023




their work was of at least a high standard. This is perhaps not surprising, for although it is not known how much training and experience they had in making sea level measurements prior to the voyage, as astronomers they would most certainly have been skilled in the art of observing and the use of instruments to make measurements.

It is timely to cast a light on this non-astronomical aspect of the work undertaken by Bayly and Wales during Cook's second voyage to mark the 250th anniversary of the earliest tide gauge measurements of sea level made in New Zealand.

## Appendix A

The tables in Appendix A list the times and heights of the high and low waters observed by Bayly and Wales in New Zealand during 1773. The times of the observations are given in terms of local mean time, as derived according to the method described in Sect 5.1. The observed heights have been processed as described in Sect. 5.2 and converted to metres. The predicted times are also in terms of local mean time (see Sect. 4.2), whilst chart datum (lowest astronomical tide) is the reference for the predicted heights. Tidal ranges have been calculated from observed heights, and associated predicted values, where a high and its immediately following low water, or a low water and its following high water, were observed.

**Table A1.** High and low waters observed by Wales at Dusky Bay during April 1773. Refer Fig. 5.

| | High Water / Low Water | | | | Time Difference | Range | | Range Difference |
|---|---|---|---|---|---|---|---|---|
| | Observed | | Predicted | | | | | |
| April 1773 | Time | Height (m) | Time | Height (m) | Observed minus Predicted (hh:mm) | Observed (m) | Predicted (m) | Observed minus Predicted (m) |
| 6 | 22:17 | 2.59 | 22:21 | 2.47 | -00:17 | | | |
| 7 | 04:30 | 0.13 | 04:35 | 0.17 | -00:05 | 2.46 | 2.30 | +0.16 |
| 7 | 10:58 | 2.44 | 10:48 | 2.50 | +00:10 | 2.31 | 2.33 | -0.02 |
| 7 | 23:03 | 2.49 | 23:10 | 2.55 | -00:07 | | | |
| 8 | | 0.10 | | 0.13 | | 2.39 | 2.43 | -0.03 |
| 8 | 11:28 | 2.54 | 11:35 | 2.55 | -00:07 | 2.44 | 2.42 | +0.02 |
| 8 | 17:39 | 0.13 | 17:47 | 0.14 | -00:08 | 2.41 | 2.41 | 0.00 |
| 8 | 23:54 | 2.49 | 23:59 | 2.57 | -00:05 | 2.36 | 2.43 | -0.13 |
| 9 | | 0.10 | | 0.14 | | 2.39 | 2.43 | -0.04 |
| 9 | | 0.23 | | 0.15 | | | | |
| 10 | 00:47 | 2.44 | 00:48 | 2.50 | -00:01 | 2.21 | 2.35 | -0.14 |
| 10 | | 0.25 | | 0.21 | | 2.19 | 2.29 | -0.10 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | | 0.23 | | 0.21 | | | | |
| 11 | | 2.33 | | 2.37 | | 2.10 | 2.16 | -0.06 |
| 11 | | 0.35 | | 0.30 | | | | |
| 12 | 02:43 | 2.23 | 02:32 | 2.19 | +00:11 | 1.88 | 1.89 | -0.01 |
| 12 | | 0.46 | | 0.41 | | | | |
| 13 | 03:32 | 2.18 | 03:29 | 2.00 | +00:13 | 1.72 | 1.59 | +0.13 |
| 13 | 22:22 | 0.61 | 22:15 | 0.50 | +00:07 | 1.57 | 1.50 | +0.05 |
| 14 | 04:45 | 2.23 | 04:32 | 1.84 | +00:13 | 1.62 | 1.34 | +0.29 |
| 15 | | 2.11 | | 1.77 | | | | |
| 16 | 00:43 | 0.76 | 00:33 | 0.54 | +00:10 | 1.35 | 1.23 | +0.12 |
| 16 | 19:20 | 2.21 | 19:15 | 1.77 | +00:05 | 1.45 | 1.23 | +0.22 |
| 17 | 01:46 | 0.73 | 01:37 | 0.49 | +00:09 | 1.48 | 1.28 | +0.20 |
| 17 | 08:03 | 2.21 | 07:54 | 1.76 | +00:09 | 1.48 | 1.27 | +0.21 |
| 17 | 20:13 | 2.21 | 20:15 | 1.82 | +00:02 | | | |
| 18 | | 0.76 | | 0.42 | | 1.45 | 1.40 | +0.05 |
| 18 | | 2.23 | | 1.84 | | 1.47 | 1.42 | +0.05 |
| 18 | 21:00 | 2.26 | 21:06 | 1.90 | -00:06 | | | |
| 19 | 09:15 | | 09:34 | | -00:19 | | | |
| 19 | 21:40 | 2.25 | 21:50 | 1.98 | -00:10 | | | |
| 20 | 03:47 | 0.67 | 04:02 | 0.32 | -00:15 | 1.58 | 1.66 | -0.08 |
| 20 | 09:54 | 2.30 | 10:15 | 2.01 | -00:21 | 1.63 | 1.69 | -0.06 |
| 20 | 22:21 | 2.37 | 22:31 | 2.05 | -00:10 | | | |
| 21 | 04:28 | 0.70 | 04:41 | 0.33 | -00:13 | 1.67 | 1.72 | -0.05 |
| 21 | 10:27 | 2.40 | 10:52 | 2.06 | -00:25 | 1.70 | 1.73 | -0.03 |
| 21 | | 0.67 | | 0.38 | | | | |
| 21 | 22:59 | 2.40 | 23:08 | 2.10 | -00:09 | 1.73 | 1.72 | +0.01 |
| 22 | | 0.85 | | 0.37 | | | | |
| 22 | 11:07 | 2.40 | 11:26 | 2.09 | -00:19 | 1.55 | 1.72 | -0.15 |
| 22 | 17:24 | 0.63 | 17:33 | 0.41 | -00:09 | 1.77 | 1.68 | +0.09 |
| 22 | 23:34 | 2.35 | 23:42 | 2.12 | -00:08 | 1.72 | 1.71 | +0.01 |
| 23 | | 0.62 | | 0.45 | | 1.73 | 1.67 | +0.06 |
| 23 | | 2.32 | | 2.11 | | 1.70 | 1.66 | +0.04 |
| 23 | | 0.65 | | 0.45 | | 1.67 | 1.66 | +0.01 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 00:00 | 2.30 | 00:15 | 2.11 | -00:15 | 1.65 | 1.66 | -0.01 |
| 24 | 17:57 | | 18:36 | | -00:39 | | | |
| 26 | 00:39 | 2.18 | 01:18 | 2.03 | -00:39 | | | |
| 26 | | 0.72 | | 0.67 | | 1.46 | 1.36 | +0.10 |

**Table A2.** Details of high and low waters observed by Bayly at Queen Charlotte's Sound during May 1773. Refer Fig. 7.

| | **High Water / Low Water** | | | | **Time Difference** | **Range** | | **Range Difference** |
|---|---|---|---|---|---|---|---|---|
| | **Observed** | | **Predicted** | | | | | |
| **May 1773** | **Time** | **Height (m)** | **Time** | **Height (m)** | **Observed minus Predicted (hh:mm)** | **Observed (m)** | **Predicted (m)** | **Observed minus Predicted (m)** |
| 3 | 19:05 | | 18:54 | | +00:11 | | | |
| 4 | 07:39 | | 07:29 | | +00:10 | | | |
| 4 | 19:48 | | 19:52 | | -00:04 | | | |
| 5 | 21:00 | 1.52 | 20:38 | 1.56 | +00:42 | | | |
| 6 | 03:22 | 0.21 | 02:08 | 0.24 | +01:14 | 1.31 | 1.32 | +0.01 |
| 6 | 08:46 | 1.50 | 09:00 | 1.60 | -00:14 | 1.29 | 1.36 | -0.07 |
| 6 | 15:10 | 0.17 | 14:28 | 0.21 | +00:42 | 1.33 | 1.39 | -0.06 |
| 6 | 21:18 | 1.52 | 21:19 | 1.65 | -00:01 | 1.35 | 1.44 | -0.09 |
| 7 | 03:47 | 0.14 | 02:49 | 0.16 | +00:58 | 1.38 | 1.49 | -0.11 |
| 7 | 09:38 | 1.61 | 09:39 | 1.69 | -00:01 | 1.47 | 1.53 | -0.06 |
| 7 | 15:42 | 0.12 | 15:09 | 0.13 | +00:33 | 1.49 | 1.56 | -0.07 |
| 7 | 21:53 | 1.65 | 21:57 | 1.70 | -00:04 | 1.53 | 1.57 | -0.04 |
| 8 | 03:29 | 0.09 | 03:27 | 0.11 | +00:02 | 1.56 | 1.59 | -0.03 |
| 8 | 10:23 | 1.75 | 10:15 | 1.74 | +00:08 | 1.66 | 1.63 | +0.03 |
| 8 | 16:19 | 0.06 | 15:47 | 0.09 | +00:32 | 1.69 | 1.68 | +0.04 |
| 8 | 22:25 | 1.61 | 22:34 | 1.71 | -00:09 | 1.55 | 1.62 | -0.07 |
| 9 | 04:18 | 0.11 | 04:03 | 0.09 | +00:15 | 1.50 | 1.62 | -0.12 |
| 9 | 11:00 | 1.72 | 10:51 | 1.74 | +00:09 | 1.61 | 1.65 | -0.04 |
| 9 | 17:25 | 0.14 | 16:25 | 0.09 | +01:00 | 1.58 | 1.65 | -0.07 |
| 9 | 23:22 | 1.62 | 23:10 | 1.68 | +00:12 | 1.48 | 1.59 | -0.11 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | 05:40 | 0.19 | 04:40 | 0.11 | +01:00 | 1.43 | 1.57 | -0.14 |
| 12 | 00:08 | | 00:23 | | -00:15 | | | |
| 15 | 03:31 | 1.10 | 02:46 | 1.19 | | | | |
| 15 | 09:36 | 0.20 | 08:28 | 0.58 | +01:08 | 0.90 | 0.61 | +0.29 |
| 17 | 04:10 | 1.25 | 06:01 | 1.16 | -01:51 | | | |
| 17 | 10:13 | 0.21 | 11:25 | 0.63 | -01:12 | 1.04 | 0.53 | +0.51 |
| 17 | 18:34 | 1.39 | 18:33 | 1.24 | +00:01 | 1.18 | 0.61 | +0.57 |
| 18 | 00:44 | 0.26 | 00:08 | 0.55 | +00:36 | 1.13 | 0.69 | +0.44 |
| 18 | 19:39 | 1.81 | 19:32 | 1.34 | +00:07 | | | |
| 19 | 01:59 | 0.61 | 01:01 | 0.44 | +00:58 | 1.20 | 0.90 | +0.30 |
| 19 | 20:27 | | 20:19 | | +00:08 | | | |
| 20 | 08:29 | 1.77 | 08:37 | 1.49 | -00:08 | | | |
| 20 | 14:32 | 0.24 | 14:01 | 0.34 | +00:31 | 1.53 | 1.15 | +0.38 |
| 20 | 20:52 | 1.72 | 20:54 | 1.53 | -00:02 | 1.48 | 1.19 | +0.29 |
| 21 | 02:43 | 0.50 | 02:19 | 0.28 | +00:24 | 1.22 | 1.25 | -0.03 |

**Table A3.** Details of high and low waters observed by Wales at Queen Charlotte's Sound during November 1773. Refer Fig. 8.

| November 1773 | High Water / Low Water | | | | Time Difference | Range | | Range Difference |
|---|---|---|---|---|---|---|---|---|
| | Observed | | Predicted | | | | | |
| | Time | Height (m) | Time | Height (m) | Observed minus Predicted (hh:mm) | Observed (m) | Predicted (m) | Observed minus Predicted (m) |
| 13 | 07:58 | | 08:17 | | -00:19 | | | |
| 13 | 20:34 | 1.65 | 20:40 | 1.55 | -00:06 | | | |
| 13 | | 0.29 | | 0.25 | | 1.36 | 1.30 | +0.06 |
| 13 | | 1.75 | | 1.60 | | 1.46 | 1.35 | +0.11 |
| 14 | 21:12 | 1.84 | 21:20 | 1.65 | -00:08 | | | |
| 15 | | 0.21 | | 0.16 | | 1.63 | 1.49 | +0.14 |
| 15 | 09:27 | 1.73 | 09:39 | 1.67 | -00:12 | 1.52 | 1.51 | +0.01 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 15 | 21:59 | 1.89 | 21:58 | 1.72 | +00:01 | | | |
| 16 | | 0.10 | | 0.10 | | 1.79 | 1.62 | +0.17 |
| 16 | 22:31 | 1.89 | 22:34 | 1.75 | -00:03 | | | |
| 17 | | 0.11 | | 0.07 | | 1.78 | 1.68 | +0.10 |
| 17 | | 0.22 | | 0.09 | | | | |
| 17 | 23:18 | 1.93 | 23:10 | 1.74 | +00:08 | 1.71 | 1.65 | +0.06 |
| 18 | | 0.26 | | 0.09 | | 1.67 | 1.65 | +0.02 |
| 18 | | 0.31 | | 0.13 | | | | |
| 18 | 23:59 | 1.94 | 23:46 | 1.69 | +00:13 | 1.63 | 1.56 | +0.07 |
| 19 | | 0.40 | | 0.14 | | 1.54 | 1.55 | -0.01 |
| 19 | | 0.46 | | 0.20 | | | | |
| 20 | 00:29 | 1.76 | 00:23 | 1.60 | +00:06 | 1.30 | 1.40 | -0.10 |
| 20 | | 0.52 | | 0.23 | | 1.24 | 1.37 | -0.13 |

**Table A4.** Details of high and low waters observed by Bayly at Queen Charlotte's Sound during December 1773. Refer Fig. 11.

| December 1773 | High Water / Low Water | | | | Time Difference | Range | | Range Difference |
|---|---|---|---|---|---|---|---|---|
| | Observed | | Predicted | | | | | |
| | Time | Height (m) | Time | Height (m) | Observed minus Predicted (hh:mm) | Observed (m) | Predicted (m) | Observed minus Predicted (m) |
| 13 | 21:02 | 1.83 | 21:03 | 1.63 | -00:01 | | | |
| 14 | 02:13 | 0.17 | 02:35 | 0.19 | -00:22 | 1.66 | 1.44 | +0.22 |
| 14 | 21:50 | 1.98 | 21:42 | 1.71 | +00:08 | | | |
| 15 | 03:01 | 0.18 | 03:15 | 0.12 | -00:14 | 1.80 | 1.59 | +0.21 |
| 15 | 22:37 | 1.94 | 22:18 | 1.75 | +00:19 | | | |
| 16 | 03:50 | 0.15 | 03:52 | 0.08 | -00:02 | 1.79 | 1.67 | +0.12 |

**Appendix B**

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023

Open Access History of Geo- and Space Sciences Discussions

As described in Sect. 4.2, the original phase lags for the modern locations have been modified to align with the historic tide gauge sites to enable valid time comparisons. Harmonic constituents from modern measurements have been provided by Toitū Te Whenua Land Information New Zealand.

**Table B1.** Harmonic constituents used as inputs to Foreman (1977) to generate tide predictions based on modern data from Many Islands for comparison with Wales's observations.

| Harmonic constituent | Amplitude (cm) | Phase (degrees) |
|---|---|---|
| Z0 | 127.0 | |
| MM | 7.8 | 306.9 |
| MSF | 4.9 | 93.1 |
| 2Q1 | 1.2 | 312.8 |
| O1 | 3.7 | 43.6 |
| K1 | 3.0 | 138.9 |
| EPS2 | 1.3 | 220.1 |
| MU2 | 5.2 | 278.3 |
| N2 | 19.9 | 278.4 |
| M2 | 73.7 | 304.6 |
| L2 | 2.0 | 313.5 |
| S2 | 21.9 | 350.7 |

**Table B2.** Harmonic constituents used as inputs to Foreman (1977) to generate tide predictions based on modern data from Motuara Island for comparison with Bayly's and Wales's observations.

| Harmonic constituent | Amplitude (cm) | Phase (degrees) |
|---|---|---|
| Z0 | 90.0 | |
| O1 | 2.4 | 33.2 |
| K1 | 2.6 | 153.2 |
| N2 | 5.0 | 226.3 |
| M2 | 51.8 | 233.0 |
| L2 | 2.2 | 251.7 |
| S2 | 25.7 | 312.8 |
| M4 | 4.2 | 206.0 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


Open Access History of Geo- and Space Sciences Discussions

| | | |
|---|---|---|
| MS4 | 2.5 | 261.2 |

## Appendix C

The tables in Appendix C list the lunar phenomena used in this paper, being calculated in terms of local mean time by Gray (2020), then converted to align to the astronomical day.

**Table C1.** Local mean times and dates of new moon and full moon throughout 1773.

| **New moon** | | **Full moon** | |
|---|---|---|---|
| January 23 | 09:30 | January 9 | 09:35 |
| February 22 | 00:47 | February 7 | 23:26 |
| March 23 | 17:27 | March 9 | 11:06 |
| April 22 | 00:05 | April 7 | 12:12 |
| May 22 | 12:18 | May 7 | 12:48 |
| June 20 | 17:10 | June 5 | 12:15 |
| July 20 | 05:55 | July 4 | 19:40 |
| August 18 | 17:16 | August 3 | 04:26 |
| September 17 | 03:45 | September 1 | 15:41 |
| October 16 | 13:47 | October 1 | 06:00 |
| November 14 | 23:44 | October 30 | 23:08 |
| December 14 | 09:58 | November 29 | 18:00 |
| | | December 29 | 13:06 |

**Table C2.** Local mean times and dates of lunar rise and set at Queen Charlotte's Sound, 1773.

| **May** | | | **December** | | |
|---|---|---|---|---|---|
| | **Date** | **Time** | | **Date** | **Time** |
| Rise | 3 | 02:52 | Rise | 13 | 16:38 |
| Set | 3 | 15:15 | Set | 14 | 07:27 |
| Rise | 4 | 03:28 | Rise | 14 | 17:40 |
| Set | 4 | 16:27 | Set | 15 | 08:27 |
| Rise | 5 | 04:07 | Rise | 15 | 18:45 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023



| | | | | | |
|---|---|---|---|---|---|
| Set | 5 | 17:41 | Set | 16 | 09:19 |
| Rise | 6 | 04:49 | | | |
| Set | 6 | 18:55 | | | |
| Rise | 7 | 05:36 | | | |
| Set | 7 | 20:06 | | | |
| Rise | 8 | 06:29 | | | |
| Set | 8 | 21:13 | | | |
| Rise | 9 | 07:26 | | | |
| Set | 9 | 22:14 | | | |
| Rise | 10 | 08:27 | | | |
| Set | 10 | 23:06 | | | |
| Rise | 15 | 13:34 | | | |
| Set | 16 | 02:06 | | | |
| Rise | 16 | 14:31 | | | |
| Set | 17 | 02:35 | | | |
| Rise | 17 | 15:28 | | | |
| Set | 18 | 03:05 | | | |
| Rise | 18 | 16:24 | | | |
| Set | 19 | 03:36 | | | |
| Rise | 19 | 17:20 | | | |
| Set | 20 | 04:08 | | | |
| Rise | 20 | 18:15 | | | |
| Set | 21 | 04:44 | | | |
| Rise | 21 | 19:10 | | | |
| Set | 22 | 05:24 | | | |

**Table C3.** Local mean times and dates of lunar transit at Queen Charlotte's Sound, November 1773.

| Date | Time |
|---|---|
| 10 | 20:34 |
| 11 | 21:27 |

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023

Open Access History of Geo- and Space Sciences Discussions

| | |
|---|---|
| 12 | 22:22 |
| 13 | 23:20 |
| 15 | 00:20 |
| 16 | 01:22 |
| 17 | 02:24 |
| 18 | 03:24 |
| 19 | 04:21 |
| 20 | 05:14 |
| 21 | 06:04 |
| 22 | 06:51 |
| 23 | 07:36 |

**Data availability.** All data discussed in this paper and the harmonic constituents used to generate tide predictions are included in the Appendices**.**

**Competing interests.** The author declares that there is no conflict of interest.

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**References**

Bayly, W.: Log book of HMS Adventure, Board of Longitude, Vol. XLIV, Royal Greenwich Observatory 14/56, https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00056/1, 1774a.

Bayly, W.: Observations on HMS Adventure, Board of Longitude, Vol. XLV, Royal Greenwich Observatory 14/57, https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00057/1, 1774b.

Beaglehole, J. C.: The Journals of Captain James Cook on his Voyages of Discovery: I. The Voyage of the Endeavour 1768-71, The Hakluyt Society, 684 pp., 1955.

Beaglehole, J. C.: The Journals of Captain James Cook on his Voyages of Discovery: II. The Voyage of the Resolution and Adventure 1772-1775, The Hakluyt Society, 965 pp., 1961.

Cartwright, D. E.: Tides: A Scientific History. Cambridge University Press, Cambridge, 292 pp., 1999.

Gray, B.: Guide v. 9.1, Project Pluto www.projectpluto.com, 2020.

https://doi.org/10.5194/hgss-2022-16
Preprint. Discussion started: 9 February 2023


Foreman, M. G. G.: Manual for tidal heights analysis and prediction, Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Patricia Bay, Sidney, B.C., 58 pp., https://www.dfo-mpo.gc.ca/science/data-donnees/tidal-marees/index-eng.html, 1977 (updated 2004).

Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., Hill, D. F., Horsburgh, K., Howard, T., Idier, D., Jay, D. A., Jänicke, L., Lee, S. B., Müller, M., Schindelegger, M., Talke, S. A., Wilmes, S., Woodworth, P.L.: The tides they are a-changin': A comprehensive review of past and future nonastronomical changes in tides, their driving mechanisms and future implications. Rev. Geophys., 57, https:///doi.org/10.1029/2018RG000636, 2019.

Heath, R. A.: Phase distribution of tidal constituents around New Zealand, New Zeal. J. Mar. Fresh, 11:2, 383-392, https://doi.org/10.1080/00288330.1977.9515684, 1977.

Orchiston, W.: Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits. Springer, Cham (Switzerland), 688 pp., https://link.springer.com/book/10.1007/978-3-319-22566-1, 2016.

PlanetCalc: https://planetcalc.com/9198/, PlanetCalc Version: 3.0.4165.0, last access: 10 August 2022.

Wales, W.: Journal on the Resolution 21 June 1772-17 Oct. 1774, https://archival.sl.nsw.gov.au/Details/archive/110328362, 1774.

Wales, W.: Log book of HMS Resolution, Board of Longitude, Vol. XLVI, Royal Greenwich Observatory 14/58, https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00058/1, 1775a.

Wales, W.: Observations on HMS Resolution, Board of Longitude, Vol. XLVII, Royal Greenwich Observatory 14/59, https://cudl.lib.cam.ac.uk/view/MS-RGO-00014-00059/1, 1775b.

Wales, W. and Bayly, W.: The original astronomical observations made in the course of a voyage towards the south pole and around the world in his Majesty's … , Board of Longitude, London, https://cudl.lib.cam.ac.uk/view/PR-PBC-04091/1, 1777.

Woodworth, P. L. and Rowe, G.H.: The tidal measurements of James Cook during the voyage of the Endeavour, Hist. Geo Space. Sci., 9, 85–103, https://doi.org/10.5194/hgss-9-85-2018, 2018.