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The earliest days of Oceanography in British Columbia —Resolution Cove, April 1778

Nick Doe

> *Research into the nature of the sea is very difficult, and this is perhaps the reason why so many learned men–because they could not see an end to such an undertaking–were of the opinion that it was useless to make a beginning.*
>
> **From a five-part monograph on the seas**
> **by Count Luigi Ferdinando Marsigli.**
> **Amsterdam 1725.**

Introduction

The European Age of Enlightenment, born in the 17th century and reaching maturity in the 18th, saw scientists of every discipline journeying to the New World to study its geography, geology, natural history, and to inquire into the customs and religions of its peoples. Even Canada's Pacific coast could not escape its share of attention, remote as it then was from Europe, and never-before visited by Europeans until the voyage of Juan Pérez in 1774. Explore-the-world scientific expeditions from Great Britain (Captain James Cook), France (Compte de la Pérouse), and Spain (Don Alejandro Malaspina) stopped for a while on the northwest coast, and with enthusiasm and curiosity, expedition members took out their notebooks and sketchpads and began recording their observations, "unfettered from the notion that ancient authority alone was sufficient to describe or explain the natural world".

One need look no further than the inventory of scientific instruments brought to the coast by Cook in 1778 to show that included in the interests of those who came was the then-infant branch of science devoted to the study of the oceans that we now know as Oceanography.[1] Among the sextants and the telescopes, the azimuth compasses and the inclinometers, the pendulum-driven clocks and the watches, the thermometers and the barometers, we find listed "a wooden bucket to fetch up Sea Water from great depths to try its saltiness & coldness with two Barometers belonging to it" [2] together with a "hydrostatical balance with three bottles for weighing sea Water".[3]

The events of Cook's sojourn in Nootka Sound from March 31 to April 26, 1778 are well-known, for his was the first and the most widely publicised of the visits to the Pacific

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[1] Beaglehole, J.C., ed., *The Journals of Captain James Cook - The Voyage of the Resolution and Discovery 1776-1780*, p.1499, Hakluyt Society, Cambridge University Press, 1967.

[2] The so-called "bucket" is more precisely described as an 18-inch wooden pipe that was lashed to the lead line normally used for sounding. The pipe was square in cross-section with 3-inch (external) sides, and fitted top and bottom with valves which opened as the pipe was lowered and closed as the pipe was hoisted. A thermometer was suspended inside the pipe about half way down. Wales, William and Bayly, W., *The Original Observations made in the course of a Voyage towards the South Pole and round the World.* London, 1777. Note contained in the introduction.

[3] Bayly, William, *The Original Astronomical Observations made in the course of a Voyage to the North Pacific Ocean,* p.v., Commissioners of Longitude, London, 1782. Bayly's list is similar to Cook's but is less quotable. His list shows only a thermometer belonging to the bucket, which obviously makes more sense than two barometers. Also his listed balance had two, not three, bottles.

coast.[4] The French Revolution and the subsequent Napoleonic wars of the early-19th century detracted attention from the work of the continental Europeans, and even today, the part played by the Spanish scientists is not widely known.[5] Thanks to the work of John Webber and William Ellis, Cook's visit is as well illustrated as it is well documented.[6]

The portion of the records of the expedition that we would today characterize as being in the domain of the oceanographer is small, and these have inevitably had less attention paid them than those that relate to only the second contact between Europeans and the Nuu-chah-nulth people who live in Nootka Sound, but they are nevertheless there, and they mark unequivocally the beginning of modern Oceanography in British Columbia.

Anchorage at Resolution Cove

If the original intent of Cook's landing at Resolution Cove was to recuperate from his Pacific crossing from Hawaii, and the subsequent battle against westerly gales, vicious squalls, and the rain and fog of the Oregon and Washington coasts, he could scarcely have made a better choice than Nootka Sound. He was greeted cordially by the Native people who traded freely with the crew, and there was an ample supply of fresh water and building materials for the repair of two of the *Resolution*'s three masts, both of which were badly rotted and in no condition to be used for the planned voyage to Alaska in search of the northwest passage. Although the cove, which he knew simply as the Ship Cove,[7] offered an indifferent anchorage and is rarely used even today, he was somewhat protected from both the deep-ocean swells and the sometimes over-zealous attentions of the inhabitants of the settlement at Yuquot on the north side of the sound, now more widely known among non-native people as Friendly Cove.

The observers

By the time that Cook reached the coast of British Columbia on the third of his three famous voyages around the world he was an accomplished and experienced observer. This was by no means his first visit to what are now Canadian waters, for he had been introduced to hydrography by the army Lieutenant Samuel Holland in Nova Scotia in 1758, and after assisting in upgrading the French charts of the St. Lawrence in 1758 and 1759, he had gone on to make the finest surveys of his career along the coasts of Newfoundland and southern Labrador in the five summers of 1763–1767.[8]

Most of the detailed oceanographic observations of the particular expedition that visited British Columbia were made not by

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[4] All dates in this paper are according to Cook's reckoning. Cook considered time on the west coast of Canada to be 16 hours ahead of Greenwich time, not 8 hours behind as we do today. In the 18th-century, the navigational day started at noon, 12 hours ahead of civil time, while the astronomical day started 12 hours behind civil time. This was probably every bit as confusing as it sounds; discrepancies of one day among dates in various 18th-century records are common. The times reported by the astronomers on Cook's voyages often differ by 12 hours from times in Cook's journal.

[5] Engstrand, Iris H.W., *Spanish Scientists in the New World - The Eighteenth Century Expeditions.* Seattle and London, University of Washington Press, 1981.

[6] Nick Doe, Kayaking to Resolution Cove.

[7] Resolution Cove is just around the eastern side of the southern tip of Bligh Island at latitude 49°36.4'N, longitude 126°31.7'W. Nootka Sound itself is off the west (outer) coast of Vancouver Island, about half-way between Cape Flattery at the entrance to the Juan de Fuca Strait and Cape Scott at the northern end of Vancouver Island.

[8] Fillmore, Stanley & Sandilands, R.W., *The Chartmakers—A History of Nautical Surveying in Canada*, pp.17–25, Toronto, NC Press Limited, 1983.

Cook himself, who was busily occupied with the repair and reprovisioning of the ships and with negotiations of various sorts with the Native peoples, but by William Bayly. Bayly was a self-taught mathematician who by this time was also a veteran observer having started his career as an assistant at the Royal Observatory at Greenwich and sailed in the company of Cook and Cook's fellow Yorkshireman, the renowned navigator and mathematician William Wales, on Cook's second voyage to the southern Pacific.

Bayly's task of observing the tides was probably a thankless one—one can imagine the kind of ribbing he might have got from the crew on the days he sat out in the rain on sea-weed-covered rocks, probably alone, watching the water creeping up and down his pole.

Mention should also be made of Charles Clerke, second in command of the expedition and evidently an astute observer of oceanographic phenomenon, a valuable attribute of a captain accustomed to venturing into uncharted waters.[9]

Thomas Edgar, sailing master of the *Discovery*, spent some of his time drawing a small chart of the cove complete with soundings.

Other members of the expedition, such as the surgeon's mate William Ellis, have inserted a remark or two of an oceanographic nature in their journals, but for the most part these have clearly been copied, albeit seldom accurately, from the notes of the primary observers.[10]

Tide gauges

There are no descriptions in the expedition's published records of the tidal gauges that were used, and even the inventory of scientific instruments mentioned in the introduction to this paper fails to mention them. Presumably, they were not regarded as valuable, which is just as well as the Native people of the Pacific were avid collectors of such memorabilia!

Bayly's one-time boss, the Rev. Neville Maskelyne, who was Astronomer Royal from 1767 to 1812, describes a simple tidal staff about ten foot long and painted black with white paint marks every three inches.[11] Maskelyne's solution to the problem of swell was characteristic. He advocated recording forty or more observations of the high and low points of the waves and then computing an average height arithmetically—this was after all the man who brought navigators the lunar-distance method of determining longitude, the arithmetic of which it took one manual seventeen pages to explain.

Thanks to an unplanned separation of Wales and Bayly in the fog and ice of Antarctica on the second of Cook's voyages, we have a good description of Wales's solution to the problem of swell. When the *Resolution* anchored in Pickersgill Harbour, South Island, New Zealand in April 1773 in similar circumstances to the British Columbian visit exactly five years later, Wales was left without gauges. These were in Bayly's possession aboard the *Adventure* which made its way directly to the rendez-vous point in Queen Charlotte's Sound. William Wales, one can guess, being the robust Yorkshireman he was, did not make a habit of sitting around in foul

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[9] Clerke, Charles in Beaglehole (*ibid)*, pp.1332–1333.

[10] Ellis, William, *An authentic narrative of a Voyage performed by Captain Cook & Captain Clerke in His Majesty's Ships Resolution & Discovery during the years 1776, 1777 ... and 1780,* p.211, London, 1782.

[11] Maskelyne, Nevil, *Observations on the Tides in the Island of St. Helena.* Letter to Thomas Birch published in the Philosophical Transactions of the Royal Society 52 (2), pp.586–606, 1762.

weather, and so he had fashioned a wooden gauge comprising "a long square tube whose internal side is about 3 inches, (in which) a square float is fitted ... and fixed to the end of a long slender rod which is divided into feet and inches from the float upwards." Water was allowed into the tube only be means of a small aperture at the bottom, thereby causing the "rise and fall of the water occasioned by the surf (to be) inconsiderable or at least much lessened".[12]

Bayly, in his notes on the second of Cook's voyages, mentions his use of a glass tube, 7/10th of an inch (18 mm) in internal diameter, which was lashed to a scale that was in turn lashed to a post. It was he notes, good for use in swells of up to two feet.[13] He also notes without much elaboration the use of two graduated staves, one for high and one for low tides, made vertical and relatively positioned by use of one of the expedition's quadrants.[14]

Timing of spring tides

On the outer coast of British Columbia, the average range of the spring tides is about four metres (12 ft.) and no one spending time near the shoreline can fail to notice the periodic rise and fall of the level of the sea throughout the synodic cycle. Establishing the time of the high tide on the day of a full or new moon (syzygy)[15] was a routine task for hydrographers in the days before printed tidetables came into use. Knowing the time of day that spring tides occurred, seafarers could reckon the time of the tide on any other day by adding or subtracting 50 minutes per day,[16] depending on whether the day of the prediction was after or before the day of the syzygy.[17]

Bayly's determination of the timing of high tide at syzygy in Resolution Cove was good. His value of 20 minutes after local noon is close to the average value calculated from modern tables of 15 minutes.

Cook in his journal implies that the Bayly's value was determined by observation of the spring tides at syzygy, but although this would

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[12] Beaglehole, J.C. ed., *The Journals of Captain James Cook - The Voyage of the Resolution and Adventure 1772-1775*, pp.778–779, Hakluyt Society, Cambridge University Press, 1969. I am indebted to Larry Robbins of Auckland, New Zealand for drawing my attention to this reference.

[13] Wales & Bayly (*ibid*), p.46.

[14] Exactly as described and illustrated in Forrester, Warren, *Canadian Tidal Manual*, pp.83–86., Dept. Fisheries and Oceans, Ottawa, 1983.

[15] Known as "the full and change" in the 18th-century.

[16] A popular little device between the late-16th and early-18th centuries was a tidal calculator. Typically this consisted of two concentric discs, usually made of brass or ivory, the smaller one being inset into the larger one. The larger disc was engraved with a 24 h scale, and the inner disc with a 29½ day scale. The inner disc was rotated relative to the outer disc with an attached arm that acted as the cursor. The position of the arm on the inner disc could be adjusted, and this was done so that with the zeroes on the two scales aligned, the arm indicted the number of hours past noon or midnight that the high tide occurred on the day of a full or new moon. To calculate the time of high tide on any other day, the pointer was twisted until the zero on the hour scale was adjacent to the number of days that had elapsed since full or new moon. The pointer then indicated the predicted number of hours after noon or midnight that the high tide would occur on that day. Randier, Jean, *Marine Navigation Instruments*, pp.168–172, John Murray, London, p.152, 1980.

[17] The 50 min. (plus 24 hours) is the long-term average elapsed time between the high or low tide on any one day and the corresponding tide on the next. Actual elapsed times at Tofino BC show a standard deviation of roughly ±17 min. and range over a year from 15 to 90 min. Because these times vary only slowly from day-to-day, the error in the predicted times of high and low tides can be cumulative over a period of several days. A tidetable constructed by the author for the year 1984 (a random choice) for Tofino BC based on the constant elapsed-time principal showed a standard deviation in the predicted timing of the high tides from the modern predictions of ±45 min. with a maximum error for the year of about two hours.

have been the simplest way to do it, it was not the best. In Nootka Sound, this timing has a standard deviation of about ±28 minutes, so a single observation is seldom sufficient to establish an accurate value.[18] Bayly's figure was derived more carefully from multiple observations.

Cook also notes the observation that the highest tides occur a few days after new or full moon:[19]

> "…It is high-Water on the days of the New and Full Moon at $12^h20'$; the perpendicular rise and fall 8 feet 9 Inches [2.7 m], which is to be understood of the day Tides and those which happen two or three days after Full and New Moon." [20]

Diurnal tides

From his previous experience in the Pacific, it is unlikely that Cook was surprised to find that the two high tides of the day were unequal in height, unlike in the Atlantic where the two daily high tides tend to have similar heights.[21]

Since the moon causes the tides, and the moon "comes out" at night, the tides at night must be stronger than those in the day...right? This was, and maybe still is (my father believed it to be true) a common piece of folklore among seamen in Cook's time.

Cook himself doubted that this was true. In the process of determining longitude, he frequently observed the moon during daylight, but, nevertheless, there may have been some nudge-nudge, wink-winking among his crew when it was found that the high night-time tide in mid-April in Resolution Cove was higher than the high tide during the day.[22]

Cook remarks:

> "The night Tides at this time rise near two feet higher [than the Day Tides]; this was very conspicuous during the Spring tide of the full Moon which happened soon after our Arrival, and it was obvious it would be the same in those of the New Moon, tho' we did not wait to see the whole of its effect."

And:

> "... the night time tides floated away the wood ... for three or four days in the height of the spring tides.."

Cook had made detailed observations of the Pacific tides whilst stuck on the Great Barrier Reef in 1770. In his letter to the Royal Society on this experience he wrote:

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[18] Bayly's note refers to "constant observations" made to determine the value of twenty minutes, so he had derived his figure by comparing actual times of high tides with those predicted by the simple 50 minutes a day formula. The ships had in fact arrived at the cove two days after the new moon on March 29 (Cook's date), and left one day before the new moon on April 27, so Bayly never had an opportunity to observe a spring tide on the day of a new moon, and he saw only one on the day of a full moon on April 12, 1778.

[19] Due to the inertial delay of the Pacific's response to gravitational forces.

[20] Beaglehole (*ibid*), p.333. William Ellis quotes 26 minutes, not 20, almost certainly a mis-quote. A modern tidetable gives 8 ft 7 in.

[21] The Pacific basin is larger and deeper than that of the Atlantic, and so the Pacific basin supports the lower-frequency diurnal resonances more than does the Atlantic basin where the higher-frequency semidiurnal resonances predominate.

[22] Diurnal tides mostly arise because the orbital planes of the moon and sun are tilted relative to the earth's equatorial plane. Although the combined lunar and solar tidal forces result in two, almost-equally-strengthed, peaks in the tidal force on opposite sides of the earth, because of the tilt, the two peaks are at different latitudes; one north of the equator, and the other south of it.

Whenever the declination (celestial latitude) of the moon or sun is northerly (lunar or solar summer), its contribution to the tidal force at places with northerly latitudes is greater at (lunar or solar) noon than it is at mid-night. However, the ocean has inertia, its basins resonate, and the earth's surface is not just one big ocean, and so sea level at any particular time is far from being just the result of the tidal forces in effect at that particular time.

> "…At this time [11 in the evening] I judged it was about high water, and that the tides were taking off, or decreasing, as it was three days passed the full Moon; two circumstances by no means in our favour. As our efforts to heave her [*Endeavour*] off, before the tide fell, proved ineffectual, we began to lighten her, by throwing over-board our guns, ballast, &c, in hopes of floating her the next high water; but, to our great surprize, the tide did not rise high enough to accomplish this by near two feet.
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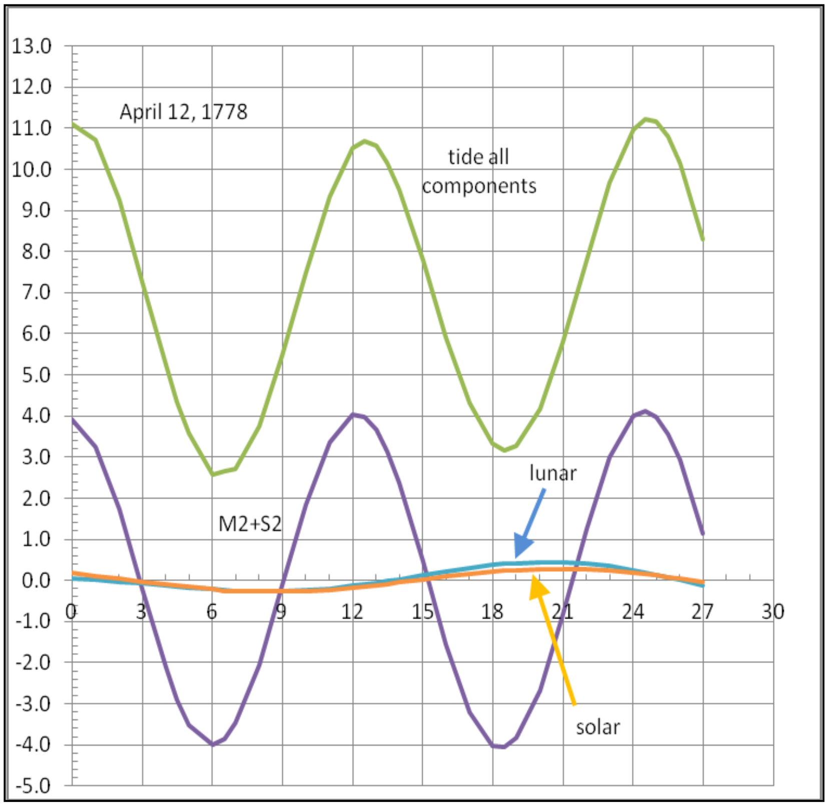
> "We had no hopes but from the tide at midnight; and there only founded on a notion, very general indeed among seamen, but not confirmed by any thing which had yet fallen under my observation, that the night-tide rises higher than the day-tide. We prepared, however, for the event, which exceeded our most sanguine expectations; for about 20 minutes after 10 o'clock in the evening, which was a full hour before high-water, the ship floated."[23]



Tides at Nootka, April 12, 1778 (Cook's date) full moon. Green shows all components as in a modern analysis (feet). Purple shows only the two semidiurnal components M2 and S2. Blue shows the two diurnal lunar components (K1m+O1), and orange shows the two diurnal solar components (K1s+P1). Time is PST.

In April 1778, the diurnal solar component of the tidal force was favouring higher tides during the day, though as it was only a short time after the vernal equinox, the effect was not great. The diurnal lunar component of the tidal force was also favouring higher tides during the day, although again, the effect was weak. The combined effect of the tidal forces should therefore have produced diurnal components (O1 + K1m) for the moon, and (P1 + K1s) for the sun that resulted in higher tides during the day than at night.[24] That this was not so, was due to the fortuitous almost-

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[23] Capt. James Cook to Sir John Pringle, Philosophical Transactions, Royal Society London, **66**, pp.447–449, 1776.

[24] The three diurnal harmonic components of tides are O1 (lunar diurnal), P1 (solar diurnal), and K1 (luni-solar diurnal). Questioners who wonder why there are three components, not just two (lunar and solar), are not encouraged by the answer that there are actually four components, two each for the moon and sun. Little reference is made these days to the fact that these four reduce to three because one lunar component and one solar component have exactly the same frequency (K1) and hence are not distinguishable by observation in the almost-universally-used frequency-domain analysis of tides. O1 + the lunar component of K1 (here designated K1m) are the double-sideband suppressed carrier components centred on the lunar day (M1) modulated at the rate of the tropical month; and P1 + K1 (here designated K1s) are the double-sideband suppressed carrier components centred on the solar day (S1) modulated at the rate of the tropical year. K1 is the

complete reversal in phase of these components due to the delay in the response of the ocean. The higher tides at night that Cook observed were actually a delayed reaction to the earlier higher lunar and solar diurnal forces at noon.

Although night-time tides are often, but not always, higher than daytime tides on the west coast of Vancouver Island in summer, this is not true year round. From October through to February, daytime tides are usually higher than night-time tides. This apparent dependence of the nature of the diurnal tide on the seasons of the sun, is to a certain extent an illusion. It arises because the moon's orbit is inclined only slightly to that of the sun, so whenever the sun is positioned to be favourable to day- or night-time tides, the moon, which produces stronger tidal forces, tends to be also, especially at the syzygies.[25]

Cook remarked in his letter to the Royal Society in 1776 that:

> "…the wind for the most part, blew a brisk gale, and rather stronger during the day than at night. How far this last circumstance might affect the evening-tide, I shall not pretend to determine; nor can I assign any other cause for this difference in the rise and fall of the tide, and therefore must leave it to those who are better versed in this subject than I."[26]

He was wise to do so; it wasn't really until the 20th-century that mathematicians and astronomers were able to produce accurate

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vector addition of K1m and K1s, though these terms are never evaluated separately.

[25] The plane of the moon's orbit is inclined only 5º to that of the sun, so when tossing around in one's head the problem as to why night-time tides on the Pacific coast are higher than the daytime tides in summer, and the reverse in winter, it is best to just assume, for the sake of argument, that the planes of the lunar and solar orbits are roughly the same and inclined 23º to the equatorial plane.

Because of the ocean's tardy response to tidal forces, we have to remember that in looking for a reason for the night-time tide to be higher than the daytime tide, we are looking for a reason why the diurnal tidal forces are stronger in the day than they are at night (not as one might at first think, the reverse). Night-time tides are a delayed response to day-time forces.

At northerly latitudes, the diurnal tidal force is strongest when the moon or sun have a northerly declination and are overhead (lunar or solar noon); and conversely, when the moon or sun have a southerly declination and are on the opposite side of the earth (lunar or solar mid-night).

Then, thinking about <u>summer</u>, because the sun at that time of year has a northerly equatorial latitude or declination, the moon must too have a northerly declination if it is scarcely visible in daylight, and a southerly declination if it is on the opposite side of the earth to the sun and is illuminated at night. Both situations lead to a strengthening of the diurnal tidal forces during day-light hours.

In the first case, lunar noon is closer to solar noon than in the other half of the month, and with both bodies having a northerly declination, the diurnal tidal forces work together during day-light hours.

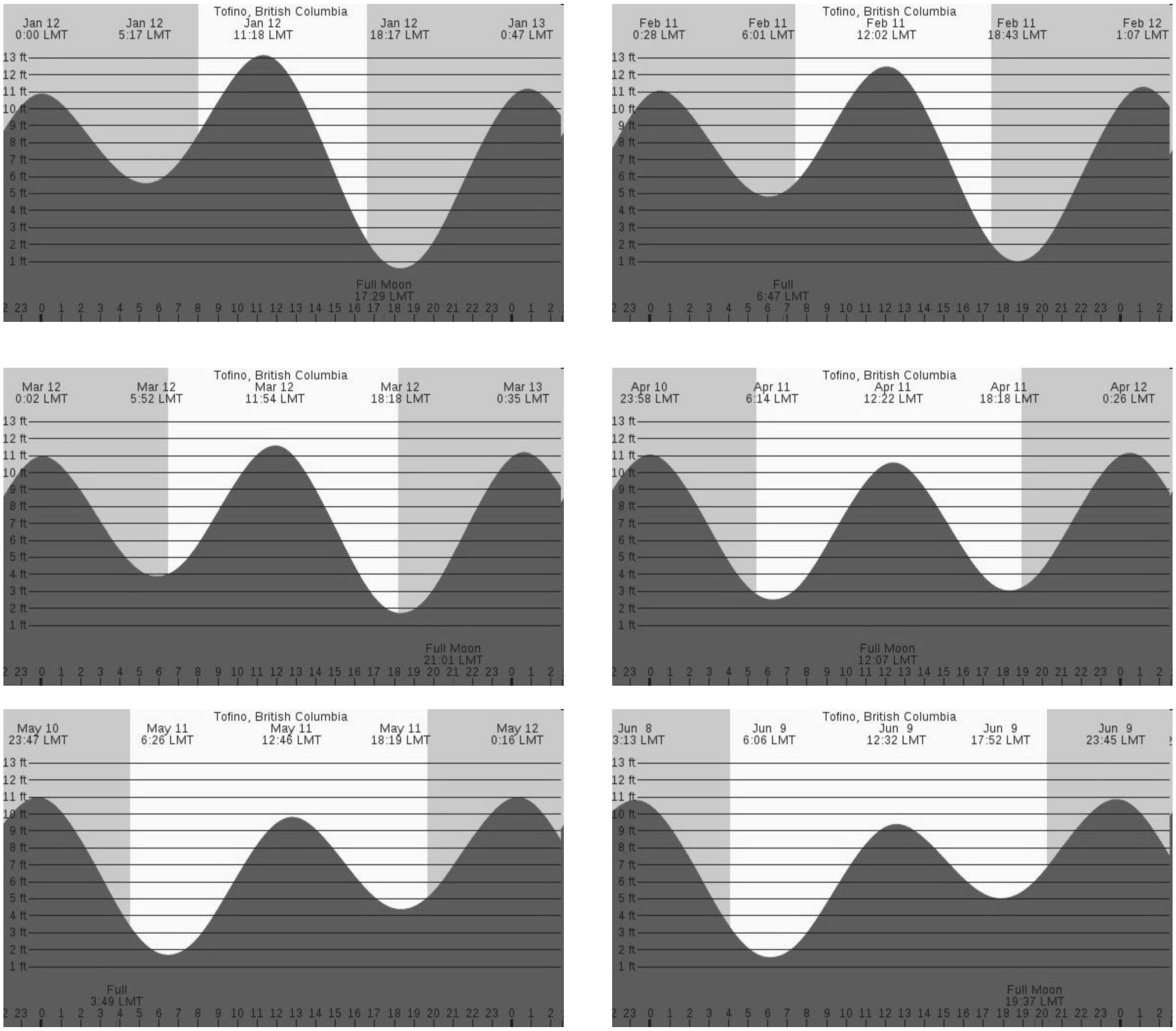
And in the second case, it is lunar mid-night that is closer to solar noon than in the other half of the month and with the moon having a southerly declination and the sun a northerly declination, the diurnal tidal forces again work together during day-light hours.

In <u>winter</u>, everything is reversed. Because the sun at that time of year has a southerly declination, the moon must too have a southerly declination if it is scarcely visible in daylight, and a northerly declination if it is on the opposite side of the earth to the sun and is illuminated at night. Both situations lead to a strengthening of the diurnal tidal forces during the night.

In the first case, lunar mid-night is closer to solar mid-night than in the other half of the month, and with both bodies having a southerly declination, the diurnal tidal forces work together during the night.

And in the second case, lunar noon is closer to solar mid-night than in the other half of the month, and with the moon having a northerly declination and the sun a southerly declination, the diurnal tidal forces again work together during the night.

[26] Cook to Pringle (*ibid*).



Tides on the Pacific coast (Tofino) during the first six months of 1778, all on the day of the full moon. Top left is January, top right February, through to bottom right June. Day-tides are higher in winter (January, February, March), and night-tides are higher in summer (April, May, June). Dates are modern dates and time is local mean time (PST - 23.7 min.).

tables based on years of observation at numerous locations.[27]

Estuarine circulation

Charles Clerke remarks in his Journal that:

"...Notwithstanding (the) uniform operation of the Tides, there was an Outset down the Sound; which, tho' irregular in itself, was always far the major part of the 24 hours. This

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[27] Arthur Doodson (1921) and Gabriel Godin (1972) are two workers that come to mind. For a thorough analysis, tides have to be observed over the full 18.6-year cycle of the moon's orbit. During this rotation of the plane of the 5° inclined lunar orbit, differences between night- and day-tides are enhanced when the moon's ascending node is near the vernal equinox on the ecliptic, and diminished somewhat when the moon's ascending node is near the autumnal equinox. When the moon's ascending node is near the summer solstice, as it was in 1778, or near the winter solstice, there is a slight change in the timing of the two annual seasonal transitions. All-in-all though, the effects on the tides are very minor although they are accounted for in modern computer-generated tables.

> more than usual Ebb of the Water I suppose must be a consequence of the melting of the Snow, & the Cataracts occasion'd by the Rain falling from the various surrounding Hills into the Sound, which must swell this Body of Water; and it of course empties itself by more than a customary Ebb into the Sea."

Clerke was thereby making a good introduction to the topic of estuarine circulation, a topic of particular interest on the coast of British Columbia where at certain seasons of the year there is a large freshwater discharge from creeks, rivers, and snow-melt at the heads of inlets. These flows, as Clerke observed, create currents in the inlets that may greatly modify the tidal currents.[28]

Although Clerke had correctly surmised that the freshwater, being lighter than saltwater, tends to skim over the surface on its way to the sea, he had not appreciated that this outward flow at the surface was actually much greater than the inflow of freshwater, not just equal to it. Unfortunately, Clerke had neither the time nor the opportunity to take the "bucket" out into the sound to sample the saltiness of the water. Had he done so he would undoubtedly have discovered that the near-constant outward flow of water was indeed, as he surmised, brackish water, but that it was skimming over the surface of heavier saltier water which was moving slowly in the opposite direction into the sound along the sea floor. This happens because the lower layer of the outflowing freshwater dilutes the sea water and carries some of the sea water along with it. This in turn creates a salt imbalance that is righted by an inward flow of sea water at depth. The current experienced by a kayaker or other small-craft in the inlet at the relevant time of year is thus quite different in strength and direction to that that would be experienced by a submarine.

The main effect on the tides of this estuarine circulation is for the deep-water inflow of sea water to aid the flood tide, and work against the ebb tide, with the result that the duration of high-water slack in the inlet is prolonged, and that of low-water slack is shortened.[29] In general though, freshwater flow has little effect on the heights of tides in inlets because the volumetric flow in and out due to the tide greatly exceeds the volumetric flow due to estuarine circulation

Estuarine circulation is a subject of continuing interest to marine biologists as it is a mechanism for trapping creek-borne organic and inorganic nutrients.[30]

Salinity

The salinity of the sea at various depths, latitudes, and temperatures is a vital part in understanding currents in the ocean, heat exchange with the atmosphere, and ultimately the earth's climate.

A letter to the Royal Society from Capt. Henry Ellis aboard the ship *Earl of Hallifax* in 1751 describes perhaps one of the earliest attempt at measuring the temperature and salinity of the ocean at depths:

> "Upon the passage [Bristol to Cape Monte, Liberia] I made several trials, with the bucket sea-gage…. I charged it, and let it down to different depths, from 360 ft. [110 m] to 5346 ft. [1629 m], when I discovered, by a small thermometer of Fahrenheit's made by Mr.

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[28] William Ellis (*ibid*) p.53 also notes this observation. "Besides this flow of the tides, we observed an irregular kind of outset down the cove which must have been occasioned either by the melting snow, or the rain which fell very plentifully at times and consequently cause a more than usual overflow."

[29] This is somewhat similar to the modification of tides by shallow water which causes flood tides to rise faster than ebb tides fall.

[30] Thompson Richard E. (1981). *Oceanography of the British Columbia Coast.* Department of Fisheries and Oceans, Ottawa, pp.16–19.

> Bird, which went down with it, that the cold increased regularly, in proportion to the depths, till it descended to 3900 ft. [1189 m]: from whence the mercury in the thermometer came up at 53 degrees [11.7ºC]; and tho' I afterwards sunk it to a depth of 5346 ft. [1629 m], that is a mile and 66 ft., it came out no lower. The warmth of the water upon the surface, and that of the air, was at that time by the thermometer 84 degrees [28.9ºC]." [31]
>
> "…when the air had render'd it equally warm with the water on the surface, I tried their weight, by weighing equal quantities very exactly, as also by the hydrometer, and found from great depths the heaviest, and consequently the saltest water."

Captain Ellis concludes his letter by noting that "…this experiment, which seem'd at first but mere food for curiosity, became in the interim very useful for us. By its means we supplied our cold bath, and cooled our wines or water at pleasure; which is vastly agreeable to us in the burning climate."[32]

Meteorological observations

Bayly's meteorological observations included temperature, precipitation, cloud cover, wind speed and direction, and, thanks to an instrument invented by Edward Nairne in the early 1770s, barometric pressure.

Rather than just reproducing Bayly's tables here, I'll present his findings in graphical form, using where necessary modern units.[33]

The prevailing movement of weather systems throughout the year on the west coast of Vancouver Island is west to east, but the fine, mild, high-pressure, only light wind conditions in the first five days (0-5) suggest a fairly stationary ridge of high pressure to the east. This is characteristic of El Niño winters when storm tracks are well to the south of British Columbia. The year 1778 may have been a moderate-to-strong El-Niño year.[34]

Regionally, the weather on the west coast is strongly influenced by the mountain chains of Vancouver Island, which run southeast–northwest. Strong winds from the ocean are deflected and strengthened at the surface to become southeast—the winter norm, but common throughout the year, while weaker winds from the ocean become at the surface, northwest—frequent only in summer. Most winds from other than the southeast and northwest directions are either transitory, or are secondary deflections off the flanks of nearby hills.[35]

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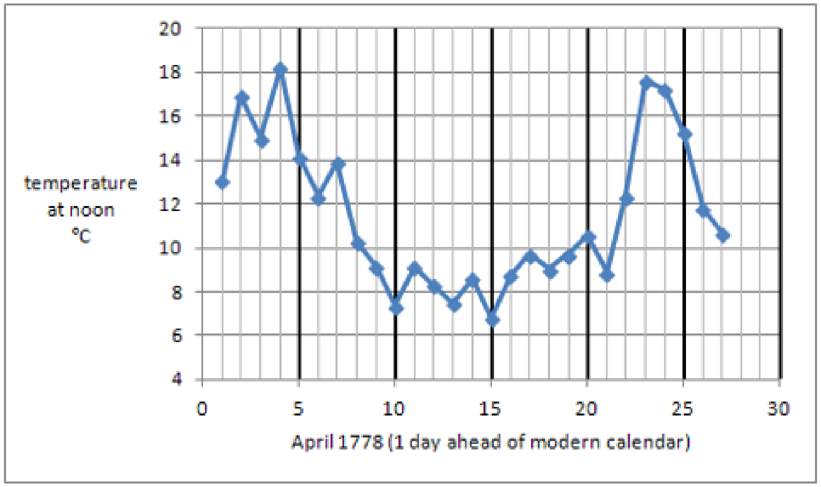
[31] Royal Society Philosophical Transactions, Letter …from Captain Ellis… dated Jan. 7, 1750-51", **47**, doi: 10.1098/rstl.1751.0033, 1 Jan. 1751.

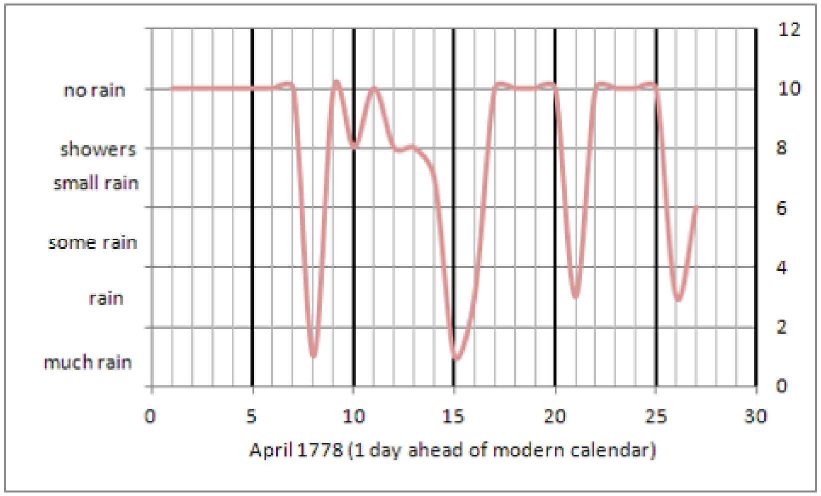
[32] The "bucket sea-gage" used by Henry Ellis was an adapted common household pail with valves described in detail by Stephen Hales in a letter to the Royal Society dated June 8, 1751. Cook's "bucket" was a more compact device attached to the sounding line—more practical, but with fewer secondary uses.

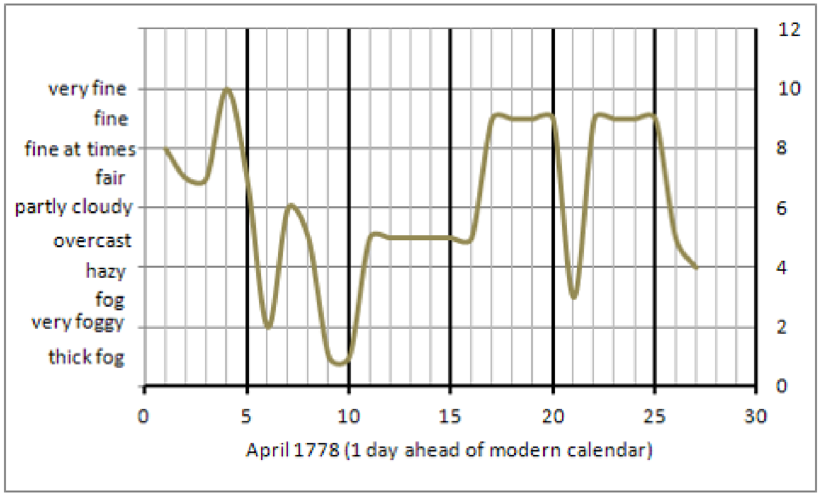
[33] It needs an expert to interpret these weather conditions, which I am most definitely not, but since this article is not going to be peer-reviewed, there's nothing stopping me from having some fun trying.

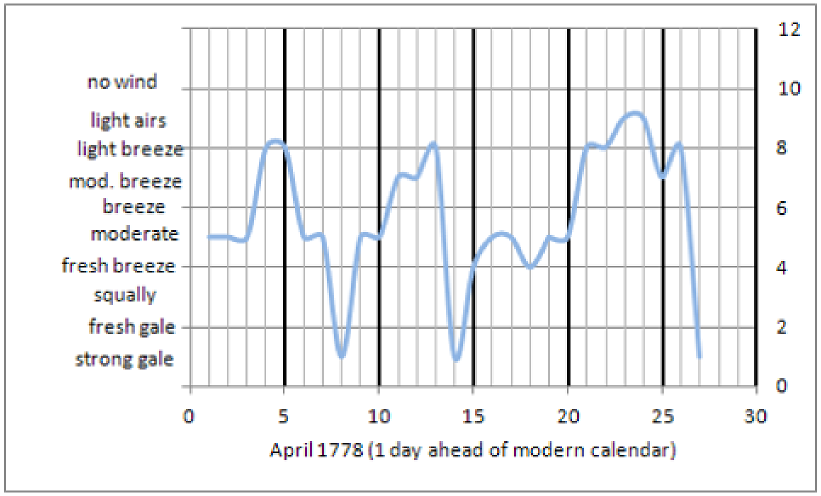
[34] Jinbao Li et al., International Pacific Research Center, Press Release, May 6, 2011.

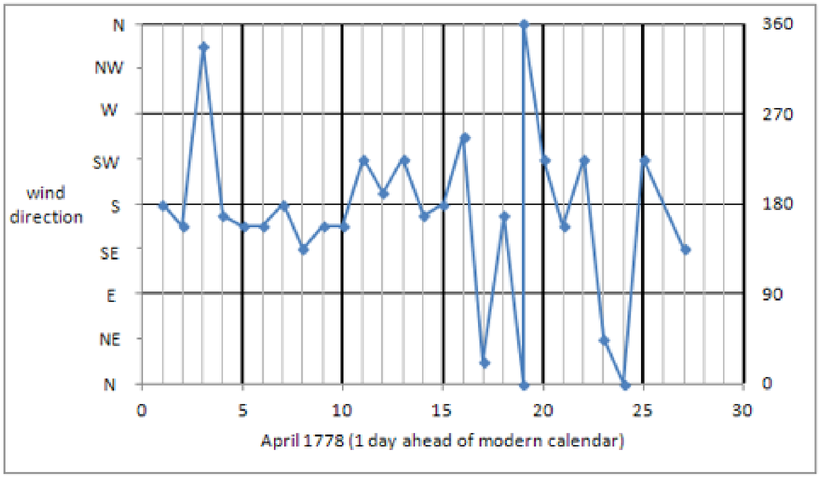
[35] Secondary deflections can be very large; a wind rose at one location may be very different from a wind rose a few miles away or in the next inlet along the coast. At the lighthouse at Yuquot in Nootka Sound, for example, light summer winds are mostly SW rather than NW because the cove is sheltered by Nootka Island. Light winter winds there are often N winds, a direction only experienced elsewhere in summer as a result of thermally-driven outflow. At Spring Island at the entrance to Kyuquot Sound, the winter SE winds are not uncommonly from the NE, a wind direction almost never seen, for example, at Estevan Point, a hundred kilometres to the south. And so on.

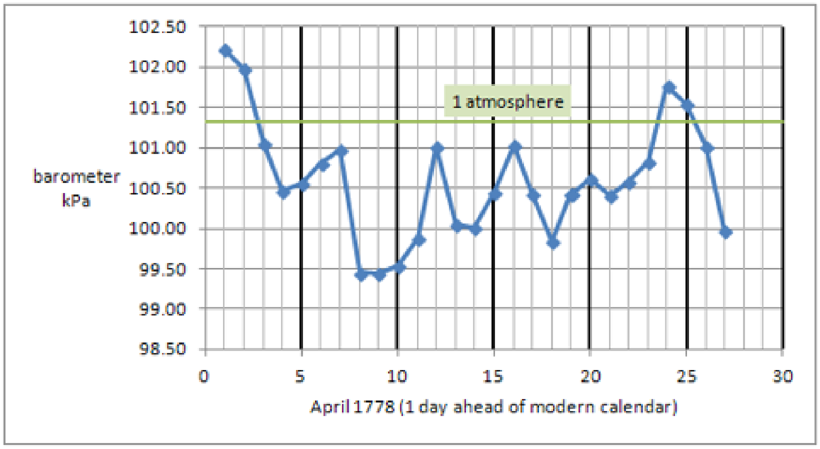

temperature at noon °C
20
18
16
14
12
10
8
6
4
0
5
10
15
20
25
30
April 1778 (1 day ahead of modern calendar)


no rain
showers
small rain
some rain
rain
much rain
12
10
8
6
4
2
0
0
5
10
15
20
25
30
April 1778 (1 day ahead of modern calendar)


very fine
fine
fine at times
fair
partly cloudy
overcast
hazy
fog
very foggy
thick fog
12
10
8
6
4
2
0
0
5
10
15
20
25
30
April 1778 (1 day ahead of modern calendar)


no wind
light airs
light breeze
mod. breeze
breeze
moderate
fresh breeze
squally
fresh gale
strong gale
12
10
8
6
4
2
0
0
5
10
15
20
25
30
April 1778 (1 day ahead of modern calendar)





The pleasant conditions in early April ceased as the high-pressure ridge weakened and moved east. The temperature dropped in the next five days (6-10) and there were periods of heavy rain and gale-force winds.

The cooling temperature could indicate passage of a cold front, or more likely in my estimation, the passage of a cold-core or polar low.[36] Cold fronts associated with depressions (Aleutian lows) are preceded by warm fronts, but there's little sign of a warm front in the 1778 records. A warm front usually results in a several-day-long period of overcast skies and rain as the front approaches.

Cold-core or polar lows are counter-clockwise rotating areas of cool air that have spun off like eddies from the maritime arctic air mass. They are smaller than depressions and, in the late spring on the west coast of Vancouver Island, one cold-core low is frequently followed by another. They bring cold and miserable spring weather with cloud and rain, often with only short breaks between systems. Most of the action in a cold-core low is above the earth's surface, and winds are moderate by west-coast standards, but these lows may sometimes produce brief spells of very violent weather ("bombs") and deepening low pressure that develops surprisingly quickly. Cold-core lows can cause upwellings of cold water off-shore, and with warmer air at the surface, these upwellings result in dense fog, which was observed and noted by Bayly.

Meteorological effects on tides

The wind was commonly used in Cook's time as a factor contributing to the difference between observed tides and tides calculated from astronomical data. It wasn't until the 19th century that the importance of barometric pressure was realized.[37] Even very modest variations of atmospheric pressure in the range ±2 kPa can raise or lower tides by ±7–8 inches. These pressure changes are often enhanced by the wind on the coast of British Columbia where the effects of the two are correlated—sea-level-raising cyclonic-lows generate winds that blow in coastal sea-level-raising directions.

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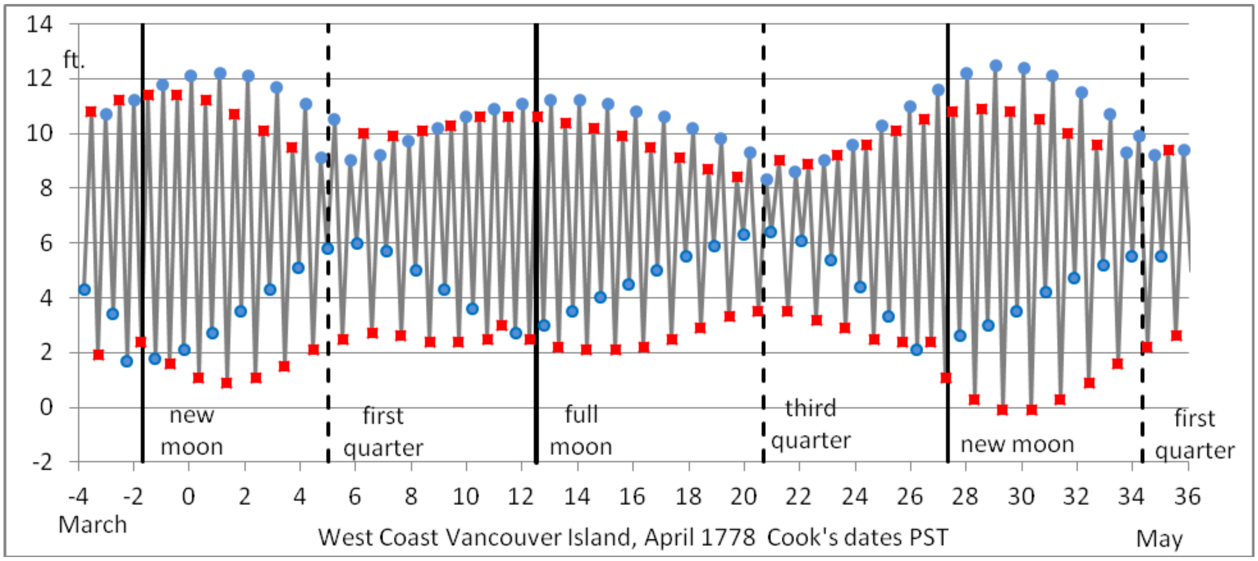
[36] The term "cold-core low" is not to be confused with a regular cyclone containing cold air at high altitudes. Some meteorologists call cold-core lows, polar lows, coastal lows, cold-air depressions, Arctic lows, etc.

[37] Daussy, M., *Mémoire sur les Marées des Côtes de France*, Connaissance des Temps, 1834.



Tides throughout April 1778 at Nootka Sound with high and low tides indicated.
Red squares = day (6 am- 6 pm); blue circles = night (6 pm - 6 am).

Just possibly William Bayly provides some evidence for this effect, although he was unaware of it. He wrote:[38]

> "The water ebbed out much lower at the time of the quadratures than at full and change, which is contrary to what is generally the case."

What's curious about this remark is that modern tidetables constructed for those dates show no such effect. The lowest low-water (LLW) at the first quarter (April 5 by Cook's reckoning) was during the day and was at about the same level, both as it had been at the earlier new moon, and as it was to be at the following full moon. The LLW on the day of the third quarter (April 21) was substantially higher than at the full moon and at the following new moon. The night-time high low-waters (HLW) at the quarters were both also higher than at the full and new moons.[39]

One obvious, and perhaps the most likely, explanation for Bayly's comment is that it is just a mistake—a comment about some other occasion. But another explanation is that Bayly was actually right, and that the weather had made the LLW at the quarters exceptionally lower than a tidetable would have predicted. The weakness of this theory however is that the weather was very different at the first and third quarters while Bayly maintains the tides on those days were similar.[40] In addition, if the cold-core low explanation of the weather that the expedition experienced is right, then it too would rule out the possibility that weather conditions influenced the tide sufficiently to explain the differences between Bayly's observation and

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[38] Bayly, William (*ibid*) p.53.

[39] The diurnal solar component of the tidal force is especially small when the sun is near one of the equinoxes, but the moon at the quarters at these times is at one of the solstices, and so the diurnal lunar component is as large as it gets. After allowing for the delays in response by the ocean, this configuration gives rise to strongly diurnal, essentially lunar-diurnal, low tides. This is despite the fact that the tides at the quarters are neap tides, and the sun and moon's contributions are in opposition.

[40] To which one could add that sea level fluctuations caused by the weather operate over periods of several days rather than hours and thus tend to affect high and low tides equally.

those predicted by modern methods. To influence the tide, the atmospheric high pressure has to be effective over a wide geographical area and persist for several days. While these conditions might have applied at the first quarter, there was no such high pressure at the third quarter; it was raining on that day.[41] The wind also was not exceptional on either occasion.[42]

The direction of the flood tide

Cook adds one more observation to ponder in his journal writing:

> "I cannot say weather the Flood Tide fall into the Sound from the NW, SW, or SE, from the latter I think it does not, but this is only conjecture, founded upon the following Observations. The SE gales which we had in the Sound were so far from increasing the rise of the tide that it rather dimenished it; which would hardly have happened had the flood and the wind been in the same direction. " [43]

The long axis of Vancouver Island runs from the southeast up to the northwest; consequently, most of the open-ocean side of the island generally faces southwest. Cook's choice of possible directions from which the flood tide reached the coast, NW, SW, or SE, correspond therefore to down the coastline from the north, directly off the sea, or up the coastline from the south.

Determining the direction of the tidal current is far from simple because currents differ in the deep ocean beyond the continental shelf, over the continental shelf, and close inshore.

Flood tides actually progress northward up the west coast of North America as part of the counter-clockwise rotation around the Gulf of Alaska, and the direction over the continental shelf is mainly from the west mid-way though a rising tide. As the shore is approached, the flood flows to the northwest parallel to the coast.[44] This flow tends to bank the tide toward the shore (a Coriolis effect).

Cook's argument that the flood could not be from the southeast on account of the lack of augmentation by the southeast winds appears therefore to be wrong, though Cook could hardly be faulted for his logic. Further offshore, the winter southeast gales are associated with more westerly and southwesterly cyclonic winds, and these do have an appreciable effect on the sea level in Nootka Sound because they are in the general direction of the offshore flood of the tide.

Attempting to estimate the effect of the wind on the tide is a tricky problem of course without tidetables. The sea level is constantly changing, with or without the wind, as a result of the purely gravitational forces exerted by the moon and sun. Exactly how Cook

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[41] At Tofino (8615) on Vancouver Island's outer coast, the standard deviation of the difference between observed and predicted heights, low and high, and observed and predicted times of the extrema is about ±6 inches and ±6 minutes respectively. In the summer, the standard deviation of the height difference drops to about half the annual value, but the timing error remains much the same. The probability of a prediction error exceeding three times the standard deviation is between 4 and 5 tides a year. Figures were obtained by analysis of data presented in Dohler G.C., *The Accuracy of Tide Predictions within Canadian Waters*, Proceedings of the Symposium on Tides, International Hydrographic Bureau, Monaco, April 28-29 1967.

[42] An analysis of the influence of weather on tides is: Crawford W.R., *Sea Level Changes in British Columbia at Periods of Two Days to a Year*. Pacific Marine Sciences Report 80-8, Institute of Ocean Sciences, Sidney B.C. 1980. Also interesting is Armstrong, John B., *The effect of meteorological conditions on sea level*, Vancouver Meteorological Office, CIR-3747 TEC-429, Nov. 1, 1962.

[43] Beaglehole (*ibid*), p.333.

[44] There is also a nearshore northwesterly flow throughout the year likely of relatively low density water emanating from the Juan de Fuca Strait.

separated the two in his mind is a puzzle, and it is not at all surprising that on this occasion he got the correlation wrong. Even in the late-20th century, there remained uncertainties about the tidal and nontidal currents along the west coast of Vancouver Island principally because of the lack of data from offshore locations where currents differ significantly from those observed near the land.[45]

Conclusion

In conclusion, we can note that the observations made at Nootka in April 1778 cover most of the topics to be found in any modern treatise on the Oceanography of the British Columbia coast. It was a commendable start.

Given more time and resources, and given their interest in such matters, they would have inevitably added a few remarks on waves, salinity, and sea temperature, and in calmer summer weather, investigated seafloor topography, leaving perhaps only tsunamis for another occasion. ◊

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[45] Thompson Richard E, *Oceanography of the British Columbia Coast*, chap.13, Department of Fisheries and Oceans, Ottawa, 1981.