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On the Meteorological Instruments and Observations Made during the 19th Century Exploration of the Canadian Northwest Passage

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Abstract

Meteorological records from about 30 British Navy ships that overwintered in the Canadian Arctic islands between 1818 and 1859 are the earliest detailed baseline of direct historical data in this region against which modern and future climate trends can be assessed. We describe the types of meteorological instruments and the observational methods employed aboard these ships. For measuring air temperatures, both mercurial and spirit thermometers were used. Observations of atmospheric pressure were made using marine and aneroid barometers. Wind direction and speed were also logged. The Royal Navy's ordered and disciplined daily regime was well-suited to regular scientific observations. Individual instruments on most Navy ships were calibrated against established Royal Observatory standards before and after expeditions. Many recording officers commented on the relative unreliability of spirit thermometers below the freezing point of mercury. Little contemporary written evidence exists regarding absolute accuracy or precision of meteorological instruments taken to the Arctic, but some calibration data are available to assess typical instrument errors between 32° and −38°F (0° and −39°C). Our comparison of minimum daily temperatures from four overwintering ships in 1853 and 1854 shows very high correlation coefficients. The mutual consistency of these records implies good instrumental precision. Although the absolute accuracy of temperatures recorded below the freezing point of mercury is in doubt, those above this point are relatively accurate. Guidance on the preferred methods of observing and recording were codified in, for example, the Admiralty's *Manual of Scientific Enquiry* (Herschel, 1851). Meteorological registers were regarded as official documents that were, as far as possible, required to be complete and no attempt was to be made to fill in missing data. The need to screen or cover instruments from both solar and terrestrial radiation was also recognized from the earliest expeditions. It was not until the 1850s that standardizing the exposure of thermometers was resolved through the introduction of louvered screens. This unique set of ships' meteorological registers presents opportunities to investigate a variety of meteorological parameters for the Canadian High Arctic in the 19th century, allowing quantitative assessment of change relative to contemporary climate.

Introduction

It was recognized by both the Royal Society and the British Admiralty that 19th century voyages to the Canadian Arctic in search of the Northwest Passage, and later for Sir John Franklin and his missing ships HMS *Erebus* and *Terror*, could be used to advance the physical sciences. The Royal Navy's ordered and disciplined daily regime lent itself well to ensuring regular scientific observations. The examination of archival ships' meteorological registers highlights the diligence and personal interest of the recording officers making these regular meteorological observations. The Admiralty's *Manual of Scientific Enquiry* (Herschel, 1851, p. 280) records, "There is no branch of physical science which can be advanced more materially by observations made during sea voyages than meteorology".

Today, there is increasing recognition that global climate warming is a reality, and that such change is likely to be amplified in the Arctic (IPCC, 2001; ACIA, 2004). The meteorological data recorded in the registers of the 30 or so British Navy ships that each spent up to three years in the Canadian Arctic islands is of particular significance in this context, because these data represent the only detailed baseline of historical climate measurements against which modern and future climate trends in this part of the Arctic can be assessed. The geographical distribution of overwintering ships during the search for the Northwest Passage is shown in Figure 1.

When using archival records, such as the meteorological registers of British Navy ships, to reconstruct past meteorological conditions, it is important to understand the instruments that were used for data acquisition and their limitations. The focus of this paper is, therefore, to describe the types of meteorological instruments and the observational methods used by the officers aboard ships voyaging to the Canadian Arctic during the period of British 19th century exploration between 1818 and 1859. Many of these ships were beset in sea ice for several years, providing ideal platforms for the continuous observation of temperature, pressure, and wind at sea level over extended periods.

Historical Context

During the 19th century, a range of meteorological instruments was available to the officers of Royal Navy ships voyaging to the Arctic. The majority of these instruments were loaned to ships from the Royal Observatories at Greenwich or Kew. Each instrument was accompanied by instructions and guidance on maintenance and

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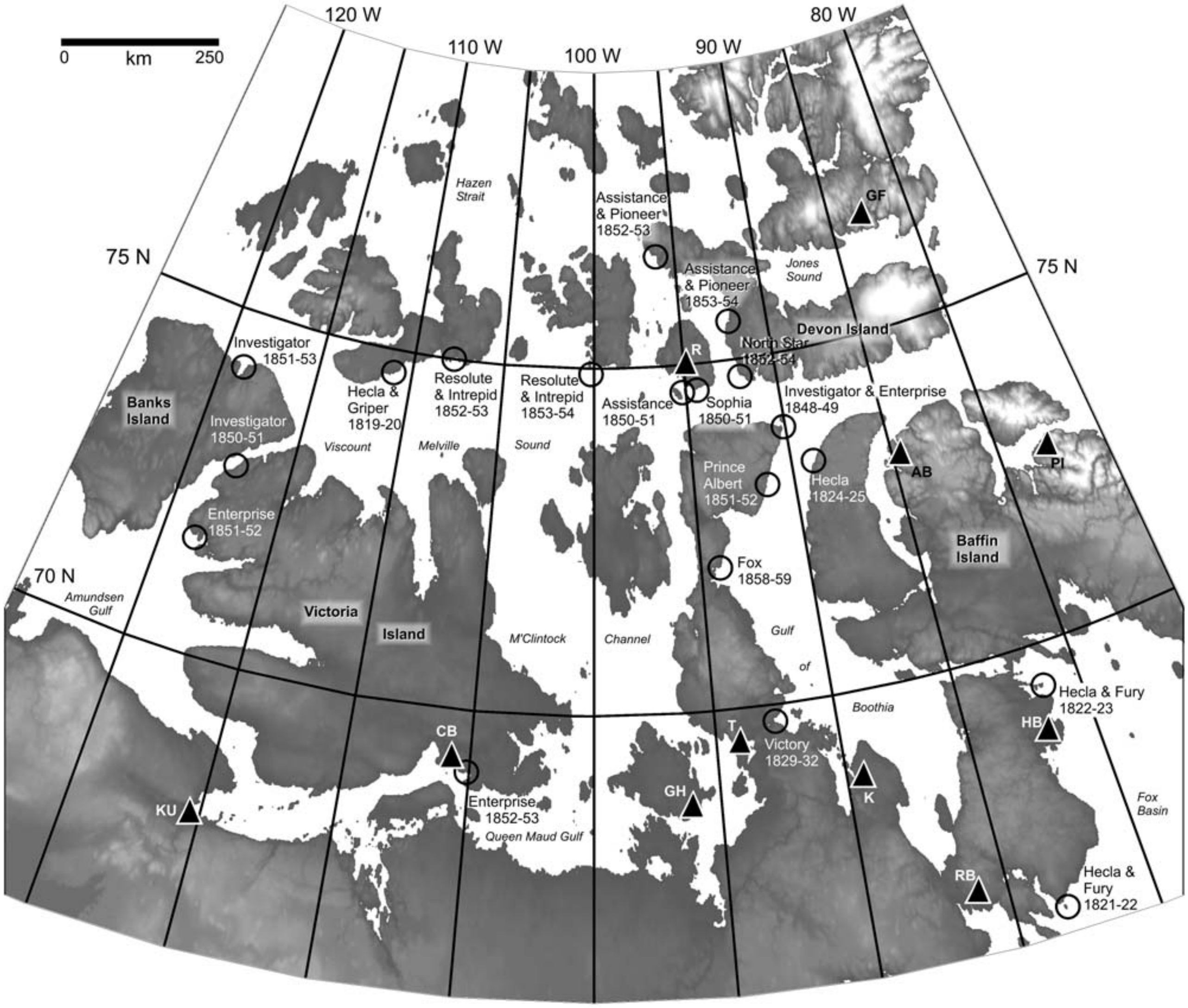

FIGURE 1. The geographical distribution of British Navy and other ships of exploration in the Canadian Arctic in the early to mid-19th century, during the search for the Northwest Passage (each ship is located with an open circle). Modern settlements and meteorological stations are also shown as black triangles, labeled as follows: AB: Arctic Bay, CB: Cambridge Bay, GH: Gjoa Haven, K: Kugaaruk, KU: Kugluktuk, GF: Grise Fiord, HB: Hall Beach, PI: Pond Inlet, RB: Repulse Bay, R: Resolute, and T: Taloyoak. The scale bar is accurate at 72.5°N.

calibration. In 1818, at the Royal Society in London, a committee was formed to "examine the state of the meteorological instruments of the Society". This Meteorological Instruments Committee included, among others, John Pond (Astronomer Royal from 1811 to 1835), Captain Henry Kater (associated with the standardization of weights and measures and the reversible pendulum), and Edward Troughton (a leading maker of precision astronomical instruments). The minutes of their first meeting on the 9 January 1818 read, "The president of the council proposed to take into consideration the proper instruments to be employed in the expedition to the North West Passage. The following instruments were accordingly suggested: 4 marine barometers, 4 portable barometers, and a number of spirit and mercurial thermometers". This list of suggestions was then sent to John (later Sir John) Barrow, Second Secretary of the Admiralty, recommending the instruments for use on the first two such Arctic expeditions.

The Royal Society continued to play an important role in directing scientific instrumentation and methodology throughout the period of 19th century British exploration of the Canadian Arctic islands (Levere, 1993). Instructions concerning the most suitable instruments and observational methods became more formalized in 1839, when the Royal Society produced guidelines on the instruments and methods used to record the weather in a report written for James Clark Ross's expedition to the Antarctic (Royal Society, 1839, 1840). A decade later the Admiralty produced the *Manual of Scientific Enquiry*, which was effectively a reworking of the 1839 report with an additional section written by Sir John Herschel, Chairman of the Royal Society Physics and Meteorology Committee. Advances in instrument accuracy and precision continued throughout the 19th century and, since the majority of instruments was obtained from Kew, Greenwich, or reputable London manufacturers, each voyage is likely to have been furnished with the most accurate instruments of the time.

Thermometers and Barometers

THERMOMETERS

For measuring air temperatures, British Navy ships of the 19th century were furnished with a number of thermometers, both mercurial and spirit. Air and sea temperatures were recorded using a variety of thermometer types (maximum, minimum, differential, black bulb, and wet bulb).

FIGURE 2. Newman (London) ivory spirit thermometer used on Franklin's second expedition (1825–1827). The lower half of the thermometer is shown with graduations in both Fahrenheit and Centigrade. The tube has been damaged. On the back of the thermometer is an inscription: "this thermometer was used in the observatory in the two sets? of winter observations. It was then removed? on the 1st May 1827 to register the temperature of the open air". (On display in Scott Polar Research Institute Museum, Cambridge, U.K.)

Various mercury-in-glass thermometers were issued to each expedition. These thermometers indicated the temperature by means of the expansion of mercury within a tube (Middleton, 1966). During the first Canadian Arctic expeditions, it rapidly became clear that the exclusive use of mercurial thermometers was compromised because mercury freezes at –37.90°F (–38.83°C). It was normally noted in the meteorological register when this occurred.

Below the freezing point of mercury, these thermometers would not function properly and spirit thermometers would usually have been employed (Fig. 2). The spirit thermometers contained ethyl alcohol that freezes at –115°F (–82°C). Spirit thermometers, however, were not regarded as particularly reliable at very low temperatures, although some were better than others. Since alcohol is organic, its composition changes over time and it can adhere to the glass, particularly when there is a sudden change in temperature. The liquid column also tends to break up more easily than mercury and is not as quick to respond to changes in temperature due to its lower thermal conductivity (Strangeways, 1999). Although spirit thermometers were used once temperatures had fallen below the freezing point of mercury, they were sometimes used at higher temperatures, too.

BAROMETERS

All meteorological registers from the ships visiting the Canadian Arctic in the 19th century recorded observations of atmospheric pressure made using both marine and aneroid barometers. The marine barometer (Fig. 3) was designed with a special tube and cistern for maritime deployment that prevented the mercury smashing the tube with the movement of the ship (Insley, 2000). Guidance manuals were issued to officers with the tables of corrections to allow for accurate calculation of air pressure.

The aneroid barometer used the expansion or contraction of a sealed metal bellows to measure pressure. This was unlike the marine barometer, which relied on a column of mercury to balance atmospheric pressure (Strangeways, 2000). The aneroid barometer was viewed as the successor to the mercury barometer. It was smaller, and therefore more portable, and was consequently well designed to be taken on board ships and was advertised as such.

> But to no class of person will the nautical use of the aneroid offer advantages so great and so pre-eminently important to the mariner. When we consider the life and property entrusted to his care and the influence of the atmosphere on his safety. He knows too well, by experience, only with the tardy indicator he is forced to be content with, from the sluggish action of the barometer in use, but the difficulty of reading off those indications with exactness when the vessel is in considerable motion. The Aneroid, on the contrary, responds in a moment to the change in atmospheric pressure (Dent, 1849, p. 32).

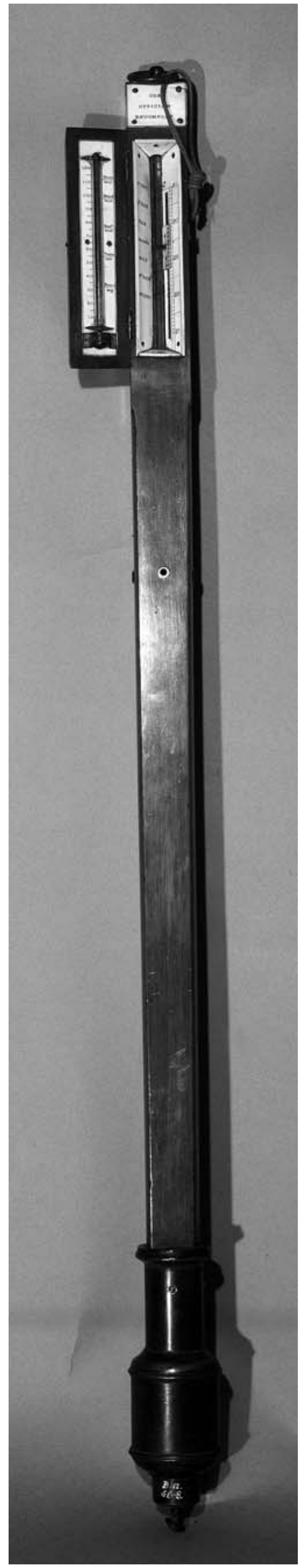

FIGURE 3. Marine stick barometer manufactured by Cox, W. C., Devonport, Devon, ca. 1830. Gimbals would have kept the barometer steady. (©National Maritime Museum, London)

In addition to the marine and aneroid barometers, some ships were furnished with Adie's "sympiesometer" (Fig. 4). Patented in 1818, the sympiesometer (derived from the Greek word for compression) was viewed as an improvement on the air barometer. Sympiesometers were designed to work along similar principles to Robert Hooke's "thermo barometer" which he devised and described to the Royal Society in 1668. Compression took place in a gas-filled reservoir, allowing readings to be taken by means of colored liquid, in this case almond oil, and instead of using air he used hydrogen, placed at the other end of the tube, above the oil. A sliding temperature correction scale enabled the user to adjust the barometric scale to compensate for the effect of the temperature on the oil-filled tube (L'e Turner, 1983).

Officers chiefly wanted advance warning of storms, not an absolute measure of pressure, so this instrument, which prevented the liquid from oscillating, did what was required. Sir John Ross's 1819 *Voyage of Discovery* narrative gives his view on the instrument:

> This instrument acts as a marine barometer, and it is certainly not inferior in its powers; it has also the advantages of not being affected by the ship's motion, and of taking up very little room in the cabin. I am of the opinion that this instrument will supersede the marine barometer when it is better known (Ross, 1819, Appendix p. CXXX).

The sympiesometer had its limitations, however. According to Edward Dent:

> . . . experience has shown, that when this double instrument has been kept long, the included air loses somewhat of its elasticity, hence in process of time, the water stands higher than it ought and therefore indicates the gravity of the atmospheric air to be greater than it really is . . . it is not so generally used on shipboard as the marine mercurial barometer (Dent, 1849, p. 13).

With the introduction of the aneroid barometer and improved marine barometers in the 1850s, the sympiesometer was used more as a supplement, allowing comparisons in readings between instruments on occasions where greater accuracy was required.

Measuring Wind Speed and Direction

The observation of wind force and direction at sea during the 18th and 19th centuries has been given much attention in recent years. Several studies by Wheeler (1988, 1997) have established that Royal Navy officers could generally make reliable estimates of both wind direction and wind force, which were two particularly important observations acquired by recording officers, as these two elements more than any others contributed to the safe handling, speed, and the direction of a sailing ship.

Wind direction was recorded using a 32-point compass and was always from the point of the compass from which the wind was blowing. There might be several wind directions recorded during the day and recording officers would quite often write comments in the register on a change in wind direction and force with an accompanying rise or fall in the barometer.

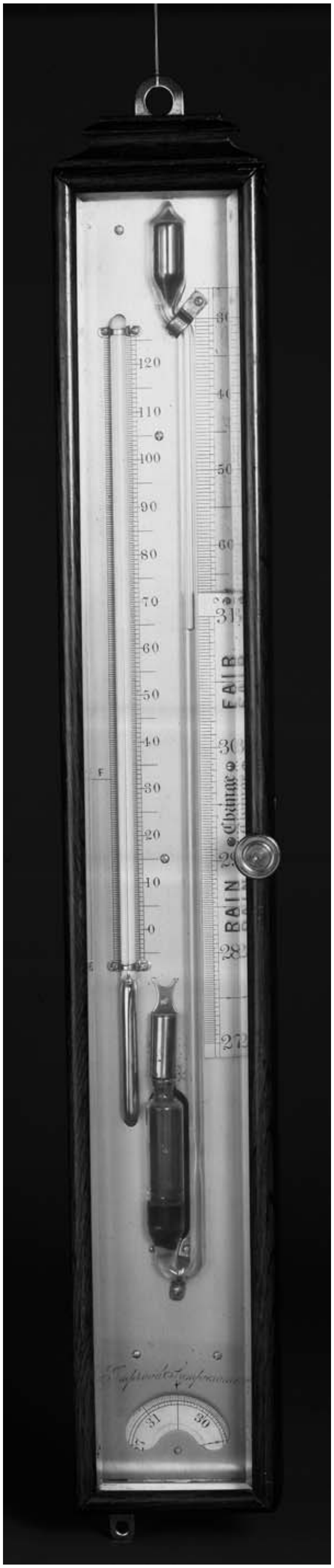

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FIGURE 4. A Sympiesometer barometer, English, ca. 1840. On the left is a Fahrenheit thermometer, 0–120 degrees. On the right is the atmospheric air pressure in equivalent inches of mercury, 27.5–31 inches. Behind this is the temperature correction scale. The pressure scale (2) must be set to the value indicated by the thermometer (1). The semicircular scale at the base of the instrument is an index scale, which is set to the pressure measured as a record for comparison with the next reading. (©National Maritime Museum, London)

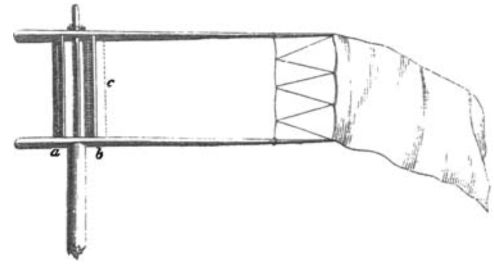


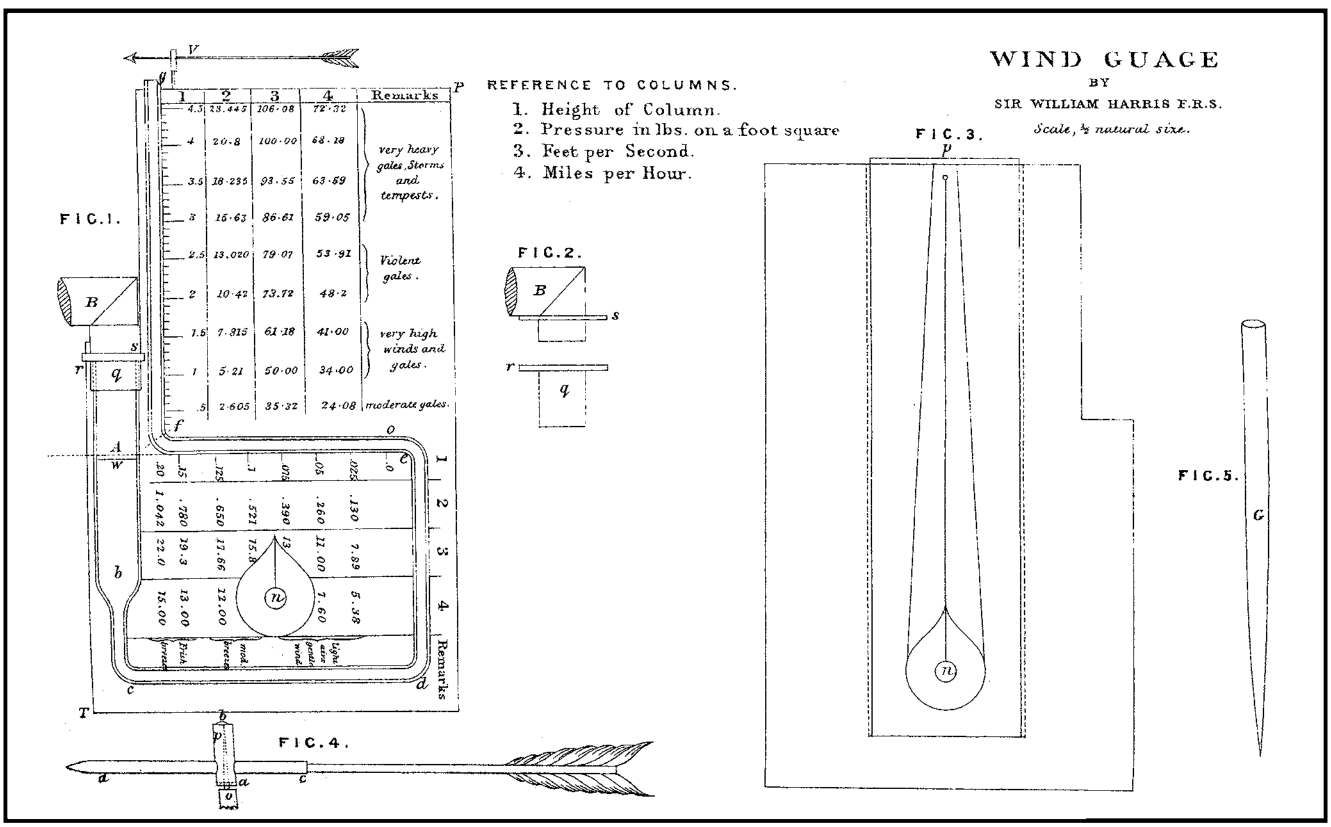
FIGURE 5. Belcher's "Wind Vane" constructed while on board HMS *Assistance*, 1852–1854. The instrument was built in order to "*determine the effect of the direct force of the wind on a thermometer exposed to its full influence, a compared with its opposite, sheltered, b*" (Belcher, 1855, p. 212).

Wind direction was recorded with regard to either magnetic or true (geographical) north. To understand navigation at sea, calculations and corrections were made to allow for magnetic variations. Mariners were well aware that magnetic variation and declination altered both temporally and spatially around the globe and that corrections had to be made to the compass or wind direction observations in order to obtain "true" rather than magnetic readings. With this is mind, magnetic variation was recorded daily to allow these corrections to be made. The magnetic north pole was, during the 19th century as it is today, migrating through the Canadian Arctic islands, making the use of compasses very difficult in this area. In Arctic winter quarters, however, ships' officers would have established true north accurately from astronomical observations.

Where wind force has been recorded in ships' meteorological registers, this has been expressed using Admiral Beaufort's 12-class numerical wind scale, which was first mentioned in his private logbook on 13 January 1806 and later revised in 1807 (Wheeler and Wilkinson, 2004). Officers estimated wind force by observing the state of the sea (if, in Arctic waters, this could be seen among the sea-ice floes) or by the effect of the wind on sails or flags (especially in winter, when ships were usually surrounded by a continuous sheet of shorefast sea ice of up to several meters in thickness).

Some ships may have been furnished with a vane to measure wind direction and Lind's wind gauge to measure wind force. The position of the former was, as far as possible, clear of deflections and eddies from objects of the same height or level and its position with regard to the true north was determined. In registering the wind direction, it would be sufficient to use only 16 points of the compass. Belcher (1855) constructed the wind vane shown in Figure 5 in order to establish the direct effect of the wind on thermometers exposed to, and sheltered from, its full influence.

By the 1850s, Lind's wind gauge or anemometer was considered the only suitable instrument to be used to measure wind speed on ships. The instrument consisted of a J-tube containing liquid with one end bent into a horizontal direction to face the wind (Fig. 6). It was adjusted by filling the tube with water until both legs of the siphon corresponded with zero on the scale. The tube was then held towards the wind with the depression in one leg and elevation in the other to be noted. Force



Malby & Sons, Lith.

FIGURE 6. Anemometer designed by Dr. James Lind, modified by Sir William Snow Harris ca. 1858. In figure one, the tube, q Ab, is made of glass and is about 2.75 inches long. This tube is welded to a second smaller tube, bcdefg, which is bent four times to create a rectangle, ce, and a vertical portion, fg. A funnel-shaped mouthpiece is fitted at the top of tube A and a light arrow-shaped vane, v, is placed on a pivot used to determine the direction of the wind. Tube A is filled with clear water, tinged with liquid carmine, coincident with the horizontal line, Ae. The funnel is turned into the direction of wind and the pressure exerted on the column of water in the tube is measured off against the wind force scale.

of wind on a square foot for different heights of the column of water was used to determine approximate wind speeds (Admiralty Manual; Herschel, 1851, p. 298). Clearly, this instrument would only have been useful when temperatures were above freezing.

Instrument Accuracy and Precision

Very little contemporary written evidence exists regarding the absolute accuracy or the precision (i.e., the repeatability of measurements) of the various meteorological instruments taken to the Arctic on 19th century voyages. Since most of the instruments were supplied by the Admiralty on recommendation from the Royal Society it can be assumed that they would have been calibrated against the best standard of the day by each manufacturer, but not necessarily against any agreed national or international standard prior to the 1850s. Instruments were also very expensive and it was not uncommon for officers to supply or purchase their own set of instruments from reputable instrument makers to take with them.

By the middle of the 19th century, however, with the establishment of the British Meteorological Society (forerunner of the Royal Meteorological Society) in 1850, and subsequently in 1854 of the Meteorological Department of the Board of Trade, there was a growing demand for standardizing meteorological observations. Of particular interest was the demand for standardized weather recording at sea. This culminated in 1853 with the International Maritime Conference, convened in Brussels to coordinate observational methods and logging. Greater emphasis was from this time given to ensuring instruments were tested before and after the expeditions.

Colonel Sabine, FRS, in a letter of 1855 to the Royal Society on the subject of marine meteorological observations, remarked:

> The strict comparability of observations made in different ships may perhaps be best assured, by limiting the examination of the instruments to comparison, which is proposed to make at the Kew observatory, before and after their employment in particular ships. From the nature of their construction, the barometers with which Her Majesty's navy and the mercantile marine are to be supplied are not very liable to derangement, except from such accidents as would destroy them altogether. Under present arrangements they will be carefully compared at Kew before they are sent to the Admiralty or to the Board of Trade; and similar arrangements may easily be made by which they may be returned to Kew for re-examination at the expiration of each tour of service (Sabine, 1855, p. 345).

THERMOMETER ACCURACY

The Admiralty Manual (Herschel, 1851, p. 292) states that "The observer should be furnished with a delicate and accurate thermometer, most carefully compared with a perfectly authentic standard at several temperatures, differing considerably, and of which the freezing point has been most scrupulously verified". Such carefully calibrated thermometers were used for reference only and every other thermometer aboard a given ship was to be compared with this instrument. Other thermometers were sometimes calibrated to the freezing point of water during expeditions.

In general, the thermometers supplied to each ship were tested by either the Kew or Greenwich Observatory prior to an expedition. On board HMS *Assistance*, which wintered in the Northwest Passage from 1852 to 1854, for example, 12 thermometers were supplied; 7 were mercurial (numbered 34, 46, 47), 5 were spirit thermometers (numbered S2, 4, 6, 7, 8), and each was graduated for low temperatures. John Welsh, from the Kew Observatory, remarked on the particular thermometers given to Sir Edward Belcher, the captain of HMS *Assistance*:

TABLE 1

A comparison between alcohol thermometers nos. 1–5 (uncolored) and alcohol thermometers 6–10 (colored with a dye to enable easier reading) conducted by Captain Parry on board HMS *Fury* at Winter Island in 1822 (Source: HMSO, 1882, p. 296).

Thermometer (no.)	1	2	3	4	5	6	7	8	9	10
Temp (°F)	−56	−56	−49	−49	−52	−40	−40	−44	−44	−46

> The mercurial thermometers were after their graduation compared incidentally at two and three different temperatures, and found to agree generally to 0.1° Fahr. They were all placed in melting ice, when it was found that four of them read exactly 32°, the other three viz. No's 34, 46, 47 were about 0.1° too low. The five spirit thermometers were compared at four different temperatures with a standard mercurial thermometer. The comparison at 0° being taken in ice and salt is not very trustworthy. These spirit thermometers cannot by any means be considered as standard, although they are doubtless more trustworthy than most of those usually made (Welsh, 1852, p. 188).

Recording officers appear to have taken a keen interest in ensuring that thermometers were calibrated correctly. Their journals often included descriptions of various "experiments" carried out to determine the accuracy of their instruments. Of particular importance was the determination of the freezing point of mercury and whether this differed according to how pure the mercury was. For example, Captain Parry on board HMS *Fury* in 1822 carried out experiments to study the freezing points of different amalgams of mercury and other metals. "The mixtures were exposed in small thin glass cylinders at steady and natural temperatures". He was aware that pure mercury begins to freeze at –37.90°F but "an amalgam of 100 grains of mercury and 3 grains of tin is firmly frozen at –35.5°F, and an amalgam of 200 grains of mercury and as much silver as it would dissolve was partly frozen after considerable exposure to –35.5°F" (Meteorological Council, 1882, p. 297).

There were also various comparisons made between the mercurial and spirit thermometers, and nearly all recording officers commented on the relative unreliability of their spirit thermometers well below the freezing point of mercury. For example, Parry, whilst making observations at Winter Island in 1821–1822, explained:

> . . . to determine the freezing point of pure mercury, a portion of it was put out into a shallow glass evaporating dish, and placed upon a support consisting of a slender rim of copper, with three glass legs. The bulbs of two spirit thermometers were placed upon each side of the dish, and the bulb of another in the centre of the mercury, the thermometer being attached to the stand, and in a vertical position. These thermometers had been compared frequently with the standard mercurial one, when the temperature was not lower than –30°F, and their respective errors applied at lower temperatures (Meteorological Council, 1882, p. 296).

Parry compared 10 spirit thermometers by placing them in parallel and vertical positions upon a board fixed about 3 feet above the frozen sea surface, each freely suspended by a nail, and found that there was nearly 10° difference between the means of the thermometers filled with the uncolored alcohol and those which were colored, and the greatest difference was 16°F (Table 1). The five uncolored thermometers showed a mean temperature of –52.4°F (–46.9°C) with a standard deviation of 3.1° and the five colored thermometers produced a mean of –42.8°F (–41.6°C) with a standard deviation of 2.4°.

Parry noted that, in his opinion, the temperatures as indicated by the thermometers with the uncolored spirit appeared to be more accurate than the colored ones in which the power of contraction of the

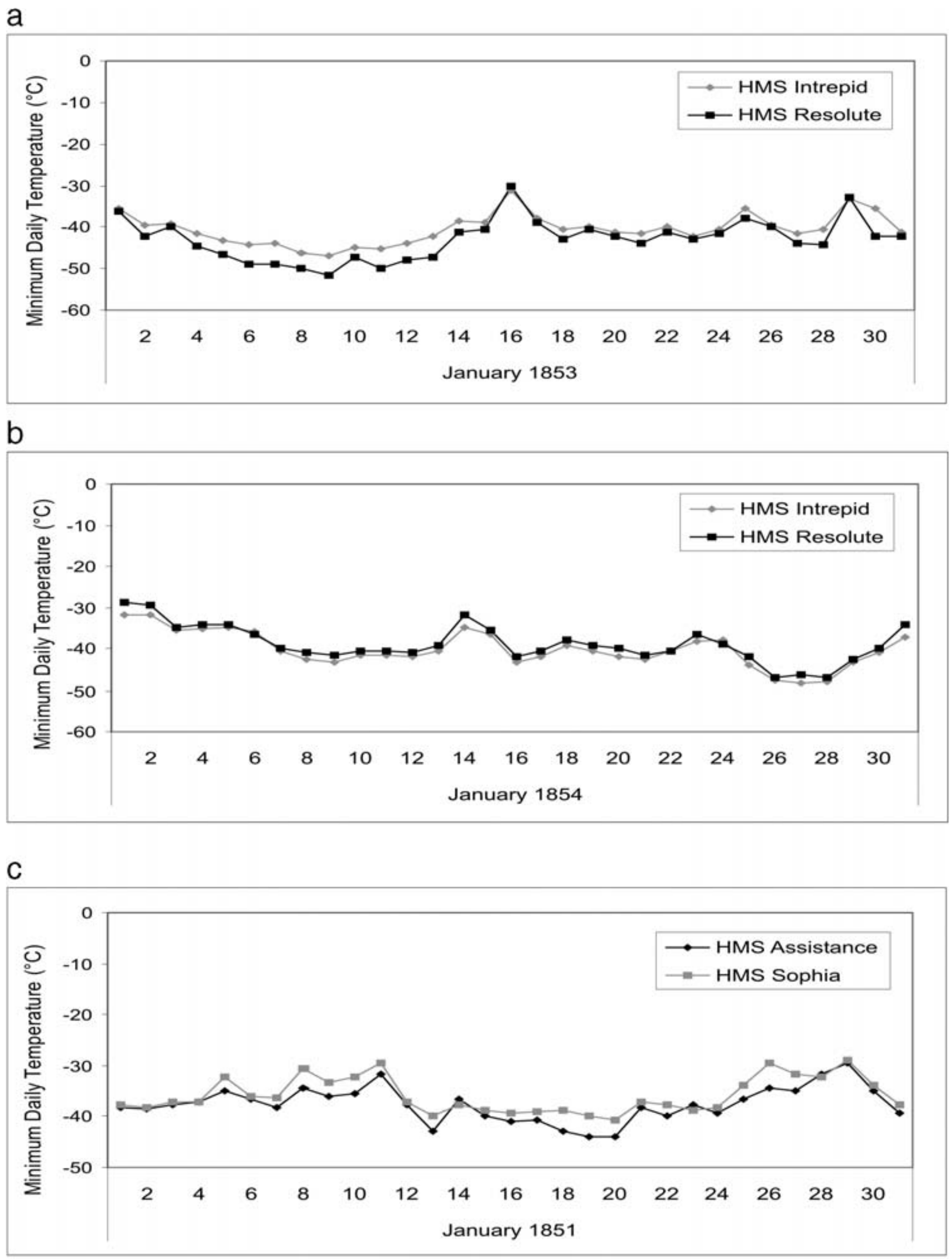


FIGURE 7. Comparison between independently recorded minimum daily temperatures below mercurial freezing point from HMS *Resolute* and *Intrepid* in (a) January 1853 and (b) January 1854; and for HMS *Assistance* and *Sophia* in (c) January 1851.

spirit appeared to diminish and, when suddenly taken from moderate to very low temperatures, most of the coloring matter was left in the upper part of the stem. Parry concluded,

> . . . the great difference between spirit thermometers at very low temperatures renders any dependence upon them, when accuracy is required, very precarious, without a comparison with the mercurial ones, a few degrees above the freezing point of mercury (Meteorological Council, 1882, p. 297).

By the middle of the 19th century, such discrepancies were still present. On 20 January 1853, Captain Elisha Kane on board the American naval ship *Advance* recorded temperatures of –64° to –67°F (–53° to –55°C) as the reduced means of the best spirit thermometers, but he remarked,

> . . . the differences which alcoholic thermometers exhibit at temperatures below the freezing point of mercury are so varying as to require a large amount of comparison, and upon many instruments to determine their proper correction. It was not uncommon for thermometers which had given us correct and agreeing temperatures as low as –40° to show at –60° differences of between fifteen and twenty °F (Kane, 1856, Appendix X1, p. 405).

Despite such differences between thermometers, one spirit thermometer would have been identified as the most accurate (determined by comparison with a standard mercury thermometer just above –37.90°F [–38.8°C]), and its measurements would have been those recorded in the ship's logbook.

A comparison of minimum daily temperatures in January taken on board HMS *Resolute* and *Intrepid*, beset in sea ice about half a kilometer apart in the Canadian Arctic, shows very high correlation coefficients (R) of 0.95 and 0.97 for both 1853 and 1854 (Figs. 7a and 7b). A correlation coefficient of 0.90 also existed between daily minimum temperatures taken onboard the adjacent HMS *Sophia* and *Assistance* in 1851 (Fig. 7c). The mutual consistency of these records implies good instrumental precision, although the measurements may still be in error in an absolute sense, depending on the quality of their calibration.

It should be noted, however, that at least some instruments on most Navy ships were calibrated against established Observatory standards prior to each expedition. Furthermore, on returning from an expedition, each Captain was expected to ensure that all instruments were returned safely to Kew or Greenwich for re-calibration. For example, a Pastorelli marked N19, a ruby colored spirit thermometer kept on board HMS *Resolute*, was recalibrated at Kew Observatory and the following errors were found: at –37.9°F, –0.9, and at 12°F, +0.4. A red spirit thermometer was returned by Captain Penny of *Lady Franklin* in October 1851 to the Kew Observatory, when its corrections were found to be as follows: at –38°F, –0.7, at 12°F, +0.5, at 22°F, +0.5, and at 32°F, +0.4 (Meteorological Council, 1880, p. 142). This instrument was thus validated as a very accurate thermometer.

BAROMETER ACCURACY

Recording Officers were well aware that, for a given sea-level pressure, the length of the mercury column was not constant, but varied to some extent according to the temperature of the mercury, the height of the instrument above sea level, and the latitude. A thermometer was usually attached to the barometer in order to make the necessary thermal corrections. Mercury barometers have a temperature coefficient of nearly 0.2 hPa $°C^{-1}$, so it was important to ensure that their thermometers responded to ambient temperature changes in the same fashion as the barometer.

Traditionally, barometer thermometers were mounted with their bulbs within the frame of the barometer so that the thermal time-constant of each was about the same. An alternative was to mount the thermometer in a short tube of mercury having the same cross-sectional area as the barometer's tube, and shielded with the same materials as the barometer's frame (Middleton and Spilhaus, 1953).

Observers were aware that the aneroid barometer was less accurate than a mercury barometer. Changes in the elasticity of the metal that compressed or contracted with a change in pressure would result in inaccurate readings, so correction tables were issued with the instrument or calibrated against a mercurial barometer (McConnell, 1988).

Routine and Logging of Meteorological Observations

The British Admiralty were quite clear on the importance of recording weather at sea. Contemporary literature such as *The Admiralty Manual of Scientific Enquiry* (Herschel, 1851, 2nd edition) gave specific guidance as to the preferred methods of observing and recording. Meteorological registers were to be regarded as official documents. They were, as far as possible, required to be complete and, in the event of missing observations, no attempt was to be made to fill in or falsify later any blank entries.

Entries made in the register or logbook at the time of observation were ideally to be made by one person and, where this was not possible, a comparative study was recommended to be undertaken to ensure that those recording would observe in a similar way. Observations were not to contain reduction or correction of any kind and any interruptions to the continuity through changes in the instruments themselves or their positioning or exposure was seen as "exceedingly objectionable and ought to be sedulously avoided" (Admiralty Manual; Herschel, 1851, p. 282). Observations were to be made regularly throughout the day and, at the very least, at the hours of 3 a.m., 9 a.m., 3 p.m., and 9 p.m. On voyages of discovery, however, it was recommended that observations should be made at the hours of 3, 6, and 9 a.m., noon, 3, 6, and 9 p.m., and midnight.

The majority of meteorological registers followed a similar format. A typical page from the meteorological register of *HMS Assistance* in December 1850 is shown in Figure 8. On the left-hand page, observations were made of: (a) atmospheric pressure, using a mercurial or aneroid barometer or sympiesometer; (b) temperature of the air and sea and, during Arctic overwintering, the temperature on deck or onshore; (c) wind direction and force (using Beaufort's scale); (d) weather (using Beaufort's notation); (e) precipitation; and (f) types of clouds. The opposite page was reserved for "Remarkable Observations". Here, observers recorded any notable instances of unusual weather or the occurrence of squalls, storms, or cyclones. "Such also are those occasions of which the attentive observer will not fail to take advantage, when particular meteorological sequences of cause and effect stand out in unusual prominence, or when opportunity is offered for the exact or approximate determination of some datum of scientific interest" (Admiralty Manual; Herschel, 1851, p. 316).

Above all, instructional documents impressed upon the recording officer the importance of keeping an accurate, daily account of the weather. The reasons behind keeping such an account were twofold: that "of all branches of physical knowledge, being that on which the success of voyages and the safety of voyagers are most immediately and unceasingly dependent, a personal interest of the most direct kind is infused into its pursuit at sea"; and that, furthermore, "It is to the regular meteorological register, steadily and perseveringly kept throughout the whole of the voyage, that we must look for the development of the great laws of this science" (Admiralty Manual; Herschel, 1851, p. 281).

Exposure, Siting, and Housing of Instruments

While the accuracy and precision of 19th century meteorological instruments was important to obtaining useful measurements of Arctic weather and climate, the exposure of instruments, the setting in which they were placed, and how they were housed and sheltered from the elements was also of considerable importance to their scientific value and comparability.

THERMOMETER EXPOSURE

In the Arctic and elsewhere, in order to obtain an accurate reading of air temperature, it was particularly critical that thermometers were situated in a free-air stream rather than in pockets of air that might be warmer or colder than the surroundings. The need to screen or cover instruments from both solar and terrestrial radiation was also recognized from the earliest expeditions and was discussed in the various contemporary guidance notes issued to observers. "External thermometers at night should be screened from the sky, so as to annihilate all loss of heat by upward radiation; a light frame of double wire-gauze will perhaps be found a secure and efficient protection from both injury and obnoxious influences" (Royal Society, 1839).

It was also understood that temperature observations differed depending on the placement of the thermometers. For example, at Winter Harbour on Melville Island, Captain Parry remarked on 26 October 1819:

> . . . by a register of the temperature of the atmosphere, which was kept by Captain Sabine at the observatory, it was found that the thermometer invariably stood at least from 2 to 5°F, and even on one or two occasions 7°F higher on the outside of the ships, than it did on shore, owing, probably to a warm atmosphere created around the former by the constant fires kept up on board.

On 14 February 1820, he wrote,

> In consequence of a comparatively warm atmosphere which was always floating around the ships, the thermometer on board by which the temperature was noted every two hours, usually stood 2 to 5° higher than that fixed on shore, in consequence of which circumstance, the whole of the temperatures in our meteorological

Date	Hour	Temp Air	Temp Lower Deck	Barom	Therm	Aneroid	Therm	True Winds Directn.	Force	W.	Remarks
Saturday 14th Decr 50	2	-27	47	29.71	40	29.72	41	NW	4	bc	
	4	27	52	29.69	40	29.71	38	"	7	cq	Heavy drift.
	6	23	52	29.73	40	29.71	37	NNW	6	cmq	
	8	21	52	29.73	40	29.72	36	"	5	cm	
	10	21	54	29.77	49	29.75	34	"	4.7	oq	
	12	23	55	29.77	52	29.75	45	"	6	q	Heavy drift.
	2	22	55	29.78	50	29.76	45	"	"	c	
	4	22	55	29.82	52	29.81	45	"	"	c	
	6	21	55	29.84	52	29.83	45	"	"	cm	Heavy drift
	8	20	51	29.85	50	29.86	45	NW	"	m	
	10	21	51	29.85	50	29.86	46	"	"	—	
	12	22	51	29.88	49	29.88	45	"	"	bc	— do —
Sums		270	630	942	564	564	572	NW	6	cmq	
Means		22.5	52.3	29.785	47	29.779	42.7				
Sunday 15th Decr 50	2	-23	51	29.90	46	29.89	43	NW	6	cq.	
	4	22	51	29.91	44	29.89	40	"	7	"	
	6	23	51	29.90	42	29.90	38	"	"	bq	
	8	21	49	29.90	42	29.90	38	"	5	"	Heavenly bodies clear.
	10	20	49	29.93	50	29.94	42	"	6.7	"	
	12	20	51	29.94	51	29.94	45	"	5.6	"	
	2	20	50	29.97	50	29.98	46	"	5	b	
	4	21									
	6	21	55	29.99	50	29.98	44	"	3	bm	
	8	21	55	29.99	50	29.98	46	"	2	bc	
	10	21	52	29.98	50	29.98	45	"	2	c	
	12	19	51	29.99	49	29.98	45	"	"	"	
Sums		252	566	1039	524	10.36	472			c	
Means		-21	51.4	29.940	44	29.939	42.9	NW	3.7	bcq.	

> journals, may be taken at least 2 or 3 lower than those actually registered (Meteorological Council, 1879, p. 257).

Curiously, this does not appear to be the case according to Belcher, on board HMS *Assistance* some years later.

> From the autumn of 1852 to the summer of 1853 the records used are those of the observatory on shore and comprise hourly observations. The matters registered on shore coincided so nearly with those made by the best instruments on board, read two hourly, that I had no misgivings as the perfection of the observations, and consequently of the attention of those entrusted with their record (Belcher, 1855, p. 306).

It was not until the 1850s that standardizing the exposure of thermometers was resolved through the introduction of louvered screens in the form of the Glaisher or Stevenson screen. These screens minimized the transfer of heat by radiation, while offering as little resistance as possible to the natural movement of air (Middleton, 1966). From this time, screens were mounted at a standard height of 1.25 m above the ground and, in areas of snow accumulation, could be moved up or down to be kept at the same height above the snow.

Recording officers were also aware not to touch or breathe on the thermometers and, in particular, during Arctic nighttime observations, to be especially careful not to expose the thermometer to heat from the observer's lantern. M'Dougall, Master on board HMS *Resolute*, noted in his journal:

> . . . the registration was worse than useless, for by the time the observer had succeeded in detecting the whereabouts of the fluid and the corresponding degree, the radiation of the heat from the lamp which was necessarily close, had affected the temperature of the immediate atmosphere which proved to be as much as 2° in half a minute (M'Dougall, 1857, p. 178).

Officers used instructions from those who supplied the instruments as to the preferred siting of observatories both onboard ship and, in particular, where and how to site instruments when ships were in Winter Quarters. As Belcher described in his journal:

> Various other observations were carried out by myself at the instance of Mr Glaisher of the Royal Observatory, Greenwich who supplied, by authority of the Admiralty, a most valuable suite of thermometers and other instruments and spared no exertion to afford valuable information and suggestions for their management (Belcher, 1855, p. 140).

During winter months, observations continued to be taken on board ship but, in addition, an observatory was usually set up onshore. No uniform structure was provided by the Admiralty to house the various instruments placed onshore. Most were constructed from whatever materials were available on board. Consequently, the shelter designs varied from a "house" built from wood to more makeshift shelters, such as a canvas tent or upturned boat. Sir John Ross noted in his journal when onboard *Victory*:

> . . . (the) men were severally instructed to read off the degrees shown by Fahrenheit's thermometer, which was placed on the ice, in a canvas tent, at a convenient distance from the ship. Its altitude was registered every hour and at the same time direction and force of wind, and the state of the weather (Ross, 1835, Appendix 2).

Captain Belcher, onboard HMS *Assistance*, remarked:

> Today the thermometers have been placed under the small boat, inserted and suspended to our driver boom affording a free current of air through them, at four feet above the floe edge. They are registered at the hours of eight, twelve and four; the standard spirit and minimum every two hours (Belcher, 1855, p. 22).

Regardless of the materials used to construct the shelter, officers would ensure, as far as possible, that the design of the shelter would not influence the instrumental readings. It was understood that temperatures varied according to where and how the thermometers were located; for example, it was commonly believed that shade temperatures were reasonably comparable if they were always taken on a north-facing wall. In the inhospitable conditions experienced during an Arctic winter, this was not always possible; nevertheless care was taken to ensure that thermometers were located above the ground and shaded from direct exposure to sunshine or that reflected by the sea. The instruments were also guarded from direct precipitation so that the bulbs would not become wet and were generally placed out of any warm or cold air currents. On board, thermometers were often placed at various positions around the ship, for example on deck or in the upper and lower cabins. Thermometers recording outside temperatures on deck would be completely detached from the ship's side and fully exposed to the external air.

BAROMETER EXPOSURE

The marine barometer on board was normally suspended on a gimbal frame out of the sunlight, as near to amidships and in a place as little liable to sudden changes of temperature and gusts of wind as possible (Admiralty Manual; Herschel, 1851).

Barometers kept onshore during winter months were ideally to be placed in an area subject to as little variation of temperature as possible and in a good light. For night observations or periods of winter darkness, an arrangement would be made for placing a light screened behind a sheet of white paper (Royal Society, 1839).

Conclusions

The meteorological records of the 30 or so British Navy ships that overwintered in the Canadian Arctic islands during the early to mid-19th century (Fig. 1) are of particular significance, because these data represent the earliest detailed baseline of direct historical data against which modern and future climate trends in this part of the Arctic can be assessed.

During the 19th century, a range of meteorological instruments was available to the officers of Royal Navy ships, many loaned from the Royal Observatories at Greenwich or Kew. Each instrument was accompanied by instructions and guidance on maintenance and

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FIGURE 8. Typical page from the meteorological journal of HMS *Assistance*, December 1850, kept by Captain Ommanney. The page is split into observations made on 14 and 15 December 1850. The second column shows the time of observation, made at 2-hourly intervals, beginning at 2 a.m. and ending at midnight. The third and fourth columns show air and lower deck temperatures, the fifth and sixth columns show barometric pressure with attached thermometer reading followed by an aneroid barometer with attached thermometer reading. True wind direction and its force and prevailing weather were expressed using Beaufort's notation. The right-hand side of the page is used for additional atmospheric or astronomical remarks. At the end of each day, sums and means are calculated for each variable.

calibration. Instructions concerning the most suitable instruments and observational methods became more formalized in 1839, when the Royal Society produced guidelines on the instruments and methods used to record the weather.

The Royal Navy's ordered and disciplined daily regime lent itself well to ensuring regular scientific observations. Recording officers on the Arctic expeditions also took a clear interest in ensuring that instruments were calibrated carefully. Individual instruments on most Navy ships were calibrated against established Observatory standards prior to and after each expedition.

Little contemporary written evidence exists regarding the absolute accuracy or the precision of meteorological instruments taken to the Arctic, but some calibration data are available to assess typical instrument errors between 32° and –38°F. Our comparison of minimum daily temperatures from four overwintering ships in 1853 and 1854 shows very high correlation coefficients (Fig. 7). The mutual consistency of these records implies good instrumental precision. Although the absolute accuracy of temperatures recorded below the freezing point of mercury is in doubt, those above this point are relatively accurate especially as the calibration point of 32°F is approached.

Specific guidance on the preferred methods of observing and recording were codified in, for example, the *Admiralty Manual of Scientific Enquiry* (Herschel, 1851). Meteorological registers were regarded as official documents that were, as far as possible, required to be complete and no attempt was to be made to fill in missing data.

There are clear opportunities to investigate meteorological parameters, climate variability, and synoptic pressure patterns in the Canadian Arctic during the 19th century using the data from the ships located in Figure 1. Overland and Wood (2003) have already used temperature data from these ships' registers in quantitative analyses of the onset and length of the summer melt season and compared them with modern meteorological observations from the Canadian Arctic.

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