The "Dirty Weather" diaries of Reverend Richard Davis: Insights about early Colonial-era meteorology and climate variability for Northern New Zealand, 1839-1851

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Abstract

Reverend Richard Davis (1790–1863) was a Colonial-era missionary stationed in the Far North of New Zealand who was a key figure in the early efforts of the Church Mission Society. He kept meticulous meteorological records for the early settlements of Waimate North and Kaikohe, and his observations are preserved in a two-volume set in the Sir George Grey Special Collections at the Auckland Central Library. The Davis diary volumes are significant because they constitute some of the earliest land-based meteorological measurements that were continually chronicled for New Zealand.

The diary measurements cover nine years within the 1839–1851 timespan that are broken into two parts: 1839–1844 and 1848–1851. Davis' meteorological recordings include daily 9 AM and noon temperatures and mid-day pressure measurements. Qualitative comments in the diary note prevailing wind flow, wind strength, cloud cover, climate variability impacts, bio-indicators suggestive of drought, and notes on

extreme weather events. “Dirty weather” comments scattered throughout the diary describe disturbed conditions with strong winds and driving rainfall.

The Davis diary entries coincide with the end of the Little Ice Age (LIA) and they indicate southerly and westerly circulation influences and cooler winter temperatures were more frequent than today. A comparison of climate field reconstructions derived from the Davis diary data and tree ring-based winter temperature reconstructions are supported by tropical coral palaeotemperature evidence. Davis’ pressure measurements were corroborated using ship log data from vessels associated with iconic Antarctic exploration voyages that were anchored in the Bay of Islands, and suggest the pressure series he recorded are robust and can be used as ‘station data’. The Reverend Davis meteorological data are expected to make a significant contribution to the Atmospheric Circulation Reconstructions across the Earth (ACRE) project, which feeds the major data requirements for the longest historical reanalysis – the 20th Century Reanalysis Project (20CR). Thus these new data will help extend surface pressure-based re-analysis reconstructions of past weather covering New Zealand within the data-sparse Southern Hemisphere.

1 Introduction

New Zealand was one of the last places permanently settled on Earth (Wilmshurst et al. 2011) and meteorological records there do not extend back in time with regularity prior to the early 1860s (Fouhy et al. 1992). Qualitative climate and weather observations for New Zealand first came from exploratory voyages that entered waters around the country (Banks, 1768–1771). Subsequently, the increased number of colonial settlers and supply ships arriving during the late 18th and early 19th century (Chappell and Lorrey, 2013) coincided with the earliest written accounts that documented local weather and climate conditions. These observations were often included in regular channels of communication to and from ‘newly found territory’, and some provide the first instrumental measurements of the physical environment. Early colonial-era settlers of New Zealand were very keen to understand the character of climate and weather for agricultural purposes (Holland and Mooney, 2006; Holland et al., 2009). Despite frequent mention of weather conditions in reports or diaries, however, observations were irregularly timed, sporadically spaced, and sometimes contained little quantitative data.

A key improvement for documenting New Zealand’s weather and climate occurred in the early 1850s with several fledgling observatories established within military fortifications (Fouhy et al. 1992). Instrument-based meteorological observations were recorded by the Royal Engineers in Auckland three times daily, and they constitute some of the earliest known ‘modern day’ long-term data for New Zealand. The Royal Engineers meteorological observations for Auckland also temporally overlap and merge with early-to-mid 1860s instrumental observations (Hessell, 1988) that were initiated in an orderly fashion and overseen by James Hector as part of the Geological Survey of New Zealand (Dell, 2013). The network Hector set up is essentially the precursor to the present day New Zealand Meteorological Service’s observing stations, with the long-term observations held by the National Institute of Water and Atmospheric Research (NIWA).

Australasian weather and climate accounts prior to the mid 1850s are sparse in general (Gergis, 2008; Holland et al., 2009; Gergis et al. 2009; 2010; Ashcroft et al., 2012; 2014). As such, additional information that can improve our understanding of past weather and climate for the region are important. Of significance, all types of historic weather observations are being sought by the Atmospheric Circulation Reconstructions across Earth (ACRE) initiative (Allan et al., 2011), which is recovering, digitizing and feeding old synoptic pressure observations into the 20th Century Reanalysis Project (20CR), a reanalysis without data input from radiosondes, aircraft or satellites (Compo et al., 2011, Cram et al., 2015). In this regard, there is a prominent opportunity to link New Zealand historic weather observations with massive data assimilation undertaken by supercomputers to provide realistic representations of regional atmospheric circulation spanning the Southwest Pacific and wider Southern Hemisphere. That effort is posed to make a significant contribution to our understanding of past weather and climate change.

As part of a search to identify early weather observations for New Zealand that could be supplied to the ACRE initiative, the National Register of Archives in New Zealand yielded a reference for an historic weather diary that was kept by Reverend Richard Davis, a missionary who lived north of Auckland (Lorrey et al., 2011a; 2011b). In this study, we have analyzed that record and we demonstrate the value of the meteorological observations that Reverend Richard Davis kept. To date, the Davis weather diary is the earliest reported quantitative meteorological account for New Zealand that was continuously kept over multiple years. We provide an analysis and modern climatological context for the Davis weather diary data (Figure 1), and are able to quantify conditions he experienced to deduce similarities and differences in weather and climate relative to today.

2 Background on Reverend Richard Davis and the climate of Northland, New Zealand

2.1 Richard Davis biographical notes

According to his memoir, written by friend and correspondent Reverend John Coleman, Reverend Richard Davis (born 18 January 1790, Dorset, England; died 28 May 1863, Waimate North, New Zealand) was associated with the Church Mission Society (CMS) of England. He spent much of his time in northern New Zealand and was stationed for significant periods of time in the settlements of Waimate North (Figure 1 and Figure 2) and Kaikohe in Northland. In 1831, Davis arrived at Waimate North and established a farm. Davis was also ordained a deacon in Waimate North in the mid-1840s. He was a prolific writer and observer of the natural environment, evidenced by hundreds of letters sent back to England and the CMS that included commentary on physical geography and astronomy (noting the occurrences of comets and the *Aurora australis*). Davis also documented social perspectives of Colonial era settlers and interactions of Europeans with Māori, as well as general activities that occurred near the settlements of Russell, Marsden Vale, Kawakawa and Paihia (Coleman, 1865).

2.2 Physical geography and climate of Northland

Northland is a long peninsula of land that extends southeast-to-northwest (~34.425°S – 36.325°S) from north of the Auckland Isthmus to the most northern extent of New Zealand (Figure 2). The region contains multiple deep-water harbors that intersect the coastline which were prized (though treacherous at times) during the Colonial era for anchorage, including Hokianga and north Kaipara in the west, and Whangarei, Bay of Islands, and Whangaroa in the east. In general, the Northland peninsula varies in breadth from 35 to 95km, and most of the densely settled locations are positioned at low elevations in close proximity to the sea. Topography can be variable, and local relief in some areas can exceed 500m over a 1km horizontal span, though in most cases it is only of the order of a couple hundred meters (Orange, 2012).

Chappell (2013) recently updated the climatology for the Northland region, and basic information contained therein is similar to Moir et al. (1986). In summary, the region has a mild, humid, and windy climate. Austral summers are warm and humid and winters are mild, with only a few sites receiving a couple of light frosts per year. Mean annual temperatures range between 14°C and 16°C (Figure 2), with eastern and northern locales being generally warmer than western and southern sites. The prevailing atmospheric circulation over Northland is from the southwest, particularly in winter and spring, but during summer the winds increase from the easterly quarter, especially in eastern districts to equal that from the southwest. This seasonal wind flow change arises from the changing location of the subtropical ridge (high pressure belt), which shifts further south in summer and early autumn relative to winter and spring (Figure 2). In addition, sea breezes add to the proportion of easterlies in eastern areas in summer and early autumn. Spring is generally the windiest season, except in exposed places such as Cape Reinga, where winter tends to be the windiest period. Summer and autumn usually have the greatest number of calm days (with mean daily wind speed <31 km/hr).

Rainfall is typically plentiful all year round in Northland, with sporadic very heavy falls. Annual rainfall totals range from 1200 mm in low-lying coastal areas, to 2000 mm at higher elevations. Areas north of Kaitaia receive considerably less rainfall than further south. Dry spells may occur in summer and autumn, but they are generally not long-lived (average dry spell duration is 20 days). Rainfall in Northland predominantly occurs when there is a stationary anticyclone to the east or southeast of New Zealand, and humid northeasterly winds cause significant rain over Northland. Also, extra-tropical depressions or ex-tropical cyclones that pass over Northland on average once or twice per year may cause torrential rain and damaging winds (Lorrey et al., 2013b). Cold, showery weather occurs in Northland with southwesterly and southerly winds, following the passage of a depression from the northwest or west. Easterly winds associated with an anticyclone to the south of Northland may also cause showery weather. Fine weather in Northland mainly occurs when an anticyclone moves slowly over the North Island, and during phases of anticyclone replacement (which typically last two to three weeks during summer). Most parts of Northland receive about 2000 hours of sunshine per year, with northern and eastern areas recording more sunshine hours than western and southern areas. It can be very windy in exposed areas, and occasionally Northland experiences gales, sometimes in association with the passage of depressions of tropical origin (Chappell, 2013).

3 Data and Methods

3.1 Location and "rescue" of the Reverend Richard Davis Diary

A key word search of the term 'meteorology' within the New Zealand National Register of Archives in 2008 (now called the Community Archive: National Register of Archives and Manuscripts; thecommunityarchive.org.nz) yielded the Davis Diary entry (Ref # NZMS 14, NZMS 378 held by Auckland Central Library, Tamaki Pataka Korero). This source was considered as an important prospect to follow through on because the entry for the Davis diary was one of only a few search items that mentioned meteorological tables. Details for the Davis Diary showed it was held by the Auckland Central Library (ACL), and a viewing to assess the quality of the meteorological measurements (in terms of physical state of the document, temporal completeness, legibility, and content) was undertaken. The collective components of the Davis meteorological diary numbered in the thousands in terms of entries and comments, and these are outlined in the results section. We describe the scanning and transcription procedure in the supplement.

3.2 Corroborating Davis' observations and comparative information

To examine the validity of the barometric pressure observations made by Davis, we also corroborated his measurements during days when available ship log data from the Bay of Islands were available. Three voyages from the 'heroic' era overlapped Davis' observations for short time spans; The *HMS Erebus* (Capt. Ross; Great Britain), The *USS Vincennes* (part of the US Exploring Expedition 1838-1842 lead by Capt. Wilkes) and two corvettes from a French expedition; the *Astrolabe* and the *Zelee* (Capt. Dumont D'Urville). Pressure data for times when these ships were anchored in the Bay of Islands and verification of historic ship tracks was supplied by ACRE through Dr. Rob Allan and Dr. Philip Brohan at the UK Met Office (UKMO). We consider the shipboard measurements were reliable because the barometers onboard would have been calibrated to the highest institutional standard. While no metadata exist about how the barometric measurements may have been regularly checked, it is likely that Reverend Richard Davis took the opportunity to periodically compare his observations with those from ships in port at Russell, Bay of Islands. For the comparison between the pressure series, we show the data in native format (keyed; and in inches of mercury) and then discuss differences relative to measurement site elevations. We also include pressure data one day prior to and after departure from port. For comparison to present day, temperature measurements were converted from Fahrenheit to Celsius and pressure measurements recorded in inches of mercury were converted to hectopascals. The Davis pressure measurements are not corrected for temperature, altitude or gravity.

Comparative daily meteorological records from the NIWA climate database for Kaikohe and Waimate North come from sites that are positioned close to where Davis resided between 1839-1851. The closest high-quality daily meteorological observations for the modern period that correspond to the site Davis was located at come from the Virtual Climate Station Network (VCSN; Tait et al., 2006), which is a 5km^2 gridded field that includes 13 variables from interpolated from station data (see Supplement for more details). The VCSN data set provides 9AM pressure, daily maximum temperature (Tmax) and daily minimum temperature (Tmin) amongst other variables. Hourly meteorological measurements for the Far North are relatively sparse; however some do exist for Kaikohe, which overlaps one of Davis' observation locations, and it is very close to the Waimate North site. In order to extract added value from the Davis weather diary aside from describing his twice-daily temperature series, both of Davis' temperature recordings were transformed to be equivalent to VCSN Tmax and Tmin using an established relationship between the VCSN daily extremes and 9AM and noon temperature measurements from Kaikohe (established using all available data between 1972-2012). Tmax and Tmin were then derived from the Davis diary recordings, and were subsequently used to derive Tmean. So as to not introduce an interdependence element to the derived VCSN reconstruction, we were also able to produce a time series of 9AM temperatures independently for the VCSN grid using 9AM vapor pressure and the Antoine equation[1],[2]. We also used monthly mean pressure measurements from nearby sites (Whangarei and Kerikeri) for comparative purposes (see Supplement for regression equations).

The Davis reconstructed temperatures were compared to extant tree ring proxy data sourced from the Past Global Changes (PAGES) Australasia database. These data have recently been collated for the purpose of undertaking global temperature reconstructions and were already standardized (Neukom and Gergis, 2012) using five different standardization techniques. We have used the 'signal free' (Melvin and Briffa, 2008) chronology produced by Neukom and Gergis (2012) for three cedar (*Libocedrus bidwillii*) tree ring records to establish new, significant correlations to austral cool season (and winter) temperatures (Lorrey, unpublished) from Takapari, Moa Park and Flanagan's Hut (original chronologies from Xiong and Palmer, 2000) to corroborate the Davis diary winter observations. The relationship between cedar tree rings and temperature was established via correlating the standardized signal free chronologies to the closest VCSN grid at a monthly level, then aggregating monthly temperatures into seasonal and longer composite averages and re-running the correlations to achieve the strongest correlation. This exercise clearly indicated that the cedar tree ring growth is sensitive to austral cold season and winter temperatures. The regression equations from these correlations allowed the standardized index

[1] 9AM vapor pressure is independently derived from Tmax and Tmin.

values to be transformed to a quantitative temperature, which was then converted to an anomaly relative to the modern period (1972–2010).

The collective temperature anomaly reconstructions from the Davis diary and the tree ring–based temperature conditions for 1839–1843 and 1848–1851 were fed into the Past Interpretation of Climate Tool (PICT) to derive local, southwest Pacific and Southern Hemisphere climate fields, following the approach used by Lorrey et al (2013a). The PICT reconstruction approach is essentially a modern analog spatial field method that uses detrended gridded local and global data (Tait et al., 2006; Kalnay et al., 1996) to assess what the local atmospheric circulation would have been like based on terrestrial palaeoclimate data. A reconstructed temperature anomaly for a proxy site is first compared directly to detrended climatological temperature quintiles for a corresponding grid point. All of the analog seasons that fall within each quintile are then selected and composited with equal weighting to produce mean geopotential height patterns, which are based on detrended daily NCEP1 reanalysis data (Kalnay et al. 1996) The fact that several sites can then be compiled into an ensemble, and that each of the proxies will have different analogs selected helps to provide weighting toward the most commonly selected analog seasons. The synoptic types are classified according to Kidson (2000) and later Renwick (2011) based on the daily output, and relies on the assumption of stationarity for local climatic responses to incident circulation in the maritime climate of New Zealand (i.e. when it is more southerly, it is cooler than normal, and vice versa for more northerly atmospheric circulation conditions). Full details of the PICT method, the significance testing of the synoptic type changes and differences of the mean geopotential height patterns relative to modern are described further in Lorrey et al. (2013a). This approach was used to a) provide a comparative national-scale context for the temperature anomalies recorded by Davis and b) provide a wider atmospheric regime context for the observed temperatures. These results are brought to bear in the discussion to contextualize the mean climate conditions recorded by Reverend Davis.

4 Results

4.1 Components of the Davis diary and 'dirty weather' comments

Reverend Richard Davis' weather diary consists of two parts: 1839–1844 and 1848–1851. A partial year of weather observations were made by Davis for both 1844 and 1851 and we have transcribed them; 1844 is not considered further in this study because it constitutes less than half a year of observations. The temporal break in the diary corresponds to the time when Davis was ordained as a Deacon and left Te Waimate Mission Station to establish Kaikohe Mission Station. The diary break also marks a period when tumultuous activity occurred in Northland that relates to the onset of the Maori Land Wars (King, 2003). There is mention by Davis in his personal diary of an insurrection in Kaikohe being "crushed" in January 1846. To our knowledge, the collective observations and measurements made by Davis comprise the earliest historic land-based meteorological register for New Zealand that has survived to date. It significantly pre-dates other informal weather observations for New Zealand that come from personal diaries as noted by previous researchers (Holland and Mooney, 2006). However, it is possible that earlier missionaries (i.e. Samuel Marsden, who resided in New Zealand from 1816), military personnel, or people involved in agriculture and viticulture (i.e. the viticulturist James Busby; who is mentioned by Davis as having provided him with 50 grape plants on 8 December 1835) could have kept similar quantitative records that are even older.

The two Davis diary components collectively contain >13000 meteorological measurements and local environmental observations. Quantitative instrumental observations include 9AM and 12 noon temperature and noon pressure recordings. Qualitative observations include daily wind direction, which are divided into eight basic compass bearings relative to true north, and an additional category termed 'variable' (where multi-directional wind flow was noted). Climatology for the instrumental measurements and qualitative observations (both temporal intervals integrated) are presented below (Figure 4). The comments column within the meteorological register includes mention of frost, ice, hail, wind strength, relative rainfall, cloud, snowfall, thunder, lightning, sunsets, and wildlife behavior (including bio-indicators about migratory waterfowl and insect life).

The Davis diary also includes 67 remarks about "dirty weather" spread throughout the two-volume meteorological register. Davis commonly associated dirty weather with atmospheric circulation from northern and eastern quadrants and in connection to southerly quadrant flow. Rainfall was common during days characterized as having dirty weather, with strong, blustery winds and low cloud cover. The general indication is that the dirty weather remarks made by Davis were indicative of generally gloomy conditions.

4.2 Pressure

4.2.1 Davis' barometer

Analysis of Davis' personal diary entries (Davis, Richard: Letters and Journals, 1824–1863, MS-1211, sourced from Hocken Heritage Collections, Dunedin, New

Zealand) was undertaken to try and gain knowledge about the type of barometer he used, where it was purchased, how he received it and how it may have been calibrated. A mention of the word 'barometer' is made five times in Davis' personal diary. Two of the entries associated with that word are:

- 9 February 1836: In a letter to Rev. W. Jowett in London (clerical secretary of the CMS), a request was made for Davis' friend Nicholas Broughton to obtain a barometer and send it to New Zealand (MS-1211, Vol. 1, p. 118).
- 11 April 1839: A comment is made by Davis about inclusion of three months of barometer and thermometer data with the letter to Rev. W. Jowett (MS-1211, Vol. 2, p. 9).

Contact with archivists at the CMS of England did not yield any leads about the purchase of the barometer Davis used. We have also made an enquiry with the Clarke Family in Northland (George Clarke was a fellow missionary with Davis at Te Waimate), as well as Heritage New Zealand, who are the curators of the mission house that Davis was based at (to no avail). We do know that a friend of Davis who is mentioned in his letters, Mr. Nicholas Broughton, lived at Swanyard in Holbourn Bridge, London. A census from that era indicates many skilled tradesmen who participated in the manufacture of chronometers, timepieces and ship instruments circa 1835 (The Horological Foundation, 2015) resided in Holbourn Bridge, which included a hive of barometer makers who were based locally. It seems likely that Mr. Broughton would have purchased equipment there. We recognize that observers in the early to mid 1800s had access to multiple types of barometers (see Jones et al. 1997 for an example); however metadata about calibration and correction of the Davis barometer are lacking. A common type of barometer made in the mid-1830s that was highly portable was a mercury ‘wheel’ barometer of ‘banjo’ morphology. Davis mentions a ‘screw’ as part of the metadata associated with his observations, which is consistent with that type of equipment. There are no other entries that indicate what instrument he had and how the instrument was calibrated.

4.2.2 Comparison of Davis pressure measurements with ships at anchorage

Prior to discussing the observed climatology and extreme pressure values, we outline a corroboration of Davis pressure measurements. Several ships of exploration transited through New Zealand waters or were based in New Zealand on military operations report being anchored east of Waimate North and Kaikohe in the Bay of Islands (Figure 2). Three separate occasions in 1840 are used to compare the Davis pressure measurements to parallel observations made on British, American and French vessels (the *HMS Erebus*, the *USS Vincennes*, and the *Astrolabe* (and *Zelee*), respectively; Data provided from ACRE by Rob Allan, UKMO). As such, the Davis pressure series and the shipboard observations comprise a measurement pair (n=29) that can be examined to see a) how inland/upland station pressure and ‘near sea level’ pressure compare and b) to determine how the Davis pressure measurements (see Figure 3 top panel) compare in general to other reference series. The common pattern of variability for the aggregated ship data and Davis measurements and their correlation are significant (r=0.93; Figure 3, middle panel). The Davis daily pressure observations are consistently offset lower than those reported by all of the shipboard observations (by an average of -0.64±0.10 inches of mercury). This negative pressure measurement offset of -0.64 inches of mercury corresponds to the altitude increase from the harbour where the ships were anchored to the altitude of the site where

Davis' land-based measurements were made (Figure 1). The variance for the Davis and shipboard pressure measurements is also similar (0.19 and 0.25, respectively). As such, we consider the pressure measurements recorded by Reverend Davis to be a robust indication of surface pressure at both sites where he was located, and note that these measurements can be employed as station data which are not corrected for temperature, gravity or reduced to sea level.

4.2.3 Climatology of pressure measurements

The monthly climatology for noon pressure indicates an annual cycle with lower pressure in austral winter and spring and the highest average pressure for late summer and autumn (Figure 4). Davis's pressure measurements indicate an annual mean value of 1016.47 hPa (when adjusted to sea level), which is similar to average annual values for modern measurements recorded at nearby stations (Kerikeri Aero, 1016.85 hPa; Whangarei Aero, 1016.81 hPa) of equivalent latitude. Across the year, Davis' meteorological diary indicates the highest pressures were most frequent from January-April, with a decrease to the lowest values in winter (Figure 4; Table 1). Seasonal average pressures recorded by Davis also compare similarly to modern pressure values for autumn, but suggest summer pressures in the early-mid 1800s were higher than present for summer, and lower than present for winter and spring. There are significant intra-seasonal and inter-annual variations in the pressure observations recorded by Davis (Figure 3), which can be attributed to the wide range of synoptic weather systems he witnessed (supported by qualitative descriptions of clouds, precipitation, wind direction and wind strength). Davis also notes some key occurrences of unusually low pressures associated with specific storms (See Figure 3), which are discussed below along with other observations of weather extremes.

Davis also made comments about unusually high pressures during the first five months of 1848, and he suggested that the screw on the bottom of the barometer might have been adjusted without his knowledge to cause an artificial inflation of pressure observations by 4/10ths of an inch. This particular period corresponds to the re-initiation of observations being made after a key temporal break in his meteorological diary. We discuss the context of these 'high' pressure anomalies noted by Davis in the discussion.

4.3 Temperature

4.3.1 Temperature recordings and thermometer metadata

Davis recorded twice-daily (9AM and noon) temperature at the Te Waimate mission house grounds and Kaikohe (Figures 1 & 4), and several comments related to temperature recordings are made by Davis in his writings to others and in his personal diary. Davis also made sporadic observations about soil temperature and contrasted temperature measurements in the direct sunlight as well as in the shade. The general commentary from Davis (below) suggests that the thermometer was kept in a ventilated shed in the shade.

- 4 November 1833: "Today the thermometer stood at 80 in the shade; this I have never known it to do before since I have been in the country." (MS-1211, Vol. 3, p. 70).
- 9 November 1833: "In the shed the thermometer stood at 78; plunged into the garden soil in the sun it stood at 110." (MS-1211, Vol. 3, p. 70)

- 18 January 1834: “Thermometer stood at 82 in the shade and at 125 in the sun.” (MS-1211, Vol. 3, p. 75)

We note here that there could be some issues with regard to radiation errors (Nakamura and Mahrt, 2005) for these temperature measurements in the absence of metadata about where the thermometer was positioned in the shed, which is not a standard type of enclosure (Parker, 1994), and we also assume Davis used a mercury-in-glass instrument.

4.3.2 Climatology and extremes from 9AM and noon temperature

9AM and noon temperatures recorded by Davis (Figure 4, Table 1) ranged from a maximum in January to a minimum in July (19.3°C to 8.9°C for 9am; 22.2°C to 11.4°C for noon). Mean 9AM vapor pressure and the Antoine equation were used to derive a local 9AM temperature from the VCSN relative humidity values (instantaneous) to compare to climatic means calculated from the Davis diary[2]. Mean annual 9AM temperature (based on only the years with fully complete measurements; 1839-1843; 1848-1850) indicates an average of 14.4°C, which is 2°C lower when compared to a VCSN average 9AM temperature of 16.4°C (Table 2). Monthly 9AM temperature variance was greatest for December and lowest for March in the Davis record. The 9AM temperature derived from the VCSN grid closest to the Waimate and Kaikohe sites also indicates that Davis’ measurements of maximum extreme monthly 9AM temperature were categorically cooler than those observed during the modern era (1972-2012). In addition, many of the 9AM minimum extreme

[2] This was done because the VCSN temperature data include minimum and maximum values that can occur at any time during a day rather than a set time. Tmean can be calculated from those categories; however, use of Tmean, Tmax or Tmin to compare to Davis 9AM temperature creates an interdependence issue when subsequent correlation exercises will employ 9AM Davis data to reconstruct Tmean anomalies relative to present day.

temperatures appear cooler than present day, with the exception of February-April, June and October (Table 2).

4.3.3 Tmax, Tmin and Tmean derived from Davis temperature measurements

Comparisons between local high-resolution hourly temperature measurements at Kaikohe and the corresponding Kaikohe VCSN grid were used to generate correlation functions for Tmax and Tmin, where use of noon and 9AM temperatures as measured by Davis were converted to Tmax and Tmin respectively. This was done so the Davis diary measurements could be directly compared to a modern VCSN-based climatology representative of the Waimate North and Kaikohe sites where Davis took temperature measurements. The fidelity of the correlation functions (and therefore the VCSN reconstructed temperatures from the Davis diary) are better for noon temp and Tmax than for 9AM temp and Tmin. In addition, correlations are strongest for the austral cool season (Tmax vs. noon $r > 0.75$ for Apr – Oct inclusive; Tmin vs. 9AM $r > 0.65$ for Apr-Aug inclusive) than for the warm season (Tmax vs. noon $r < 0.75$ for Nov-Mar inclusive; Tmin vs. 9AM $r < 0.53$ Sep-Mar inclusive; See Supplmentary Materials for more details).

The comparison of reconstructed Tmean, Tmax, Tmin, and diurnal range from the Davis diary relative to VCSN statistics are presented in Table 3. We note specific occurrences when more than ±0.5°C difference exists between the reconstructed Davis monthly temperature values and the VCSN, but do not attach any significance to these differences due to the large discrepancy in sample size for the individual monthly correlation functions, because of the associated errors in this style of reconstruction, and because of the limitations on the metadata for the thermometer Davis used. Nevertheless, Tmax, Tmin and Tmean for December, January and March (and Tmax and Tmean for November) appear warmer in the Davis record relative to present day, while May-August are categorically cooler. Diurnal temperatures were only relatively different (warmer) for January in the Davis record. Qualitative observations made by Davis about extremes related to temperature, such as snowfall, ice, and frost are brought to bear in the discussion about the realism of these differences.

4.4 Rainfall

Qualitative comments by Reverend Davis about rainfall were summed from the daily observations and indicate ~34% of all days had some form of precipitation (Figure 5). Comments about fine, dry and/or calm conditions were aggregated and tallied and indicate 38% of the time constituted absence of rain. Consecutive dry day stretches (as noted by no mention of significant precipitation) documented by Davis topped out at 18 days duration (days 207-224) during late July-mid August 1839. That is slightly longer than the maximum interval of 13 consecutive dry days that occurred during August 1987 as indicated by rain data from the VCSN grid point that corresponds to Davis' site. Overall, the climatology of rainfall (derived from aggregating days with all rain key word indicators) shows December and January were the driest months, while June, July and August were the wettest months that Davis experienced (Figure 5). This is very similar to what the VCSN data indicate for the grid point that corresponds to Davis' site (with January and February being the driest months, and June-August being the wettest). The opposing annual trends for wet vs. dry days also lends to the same assertion. By proportion, 'dirty weather' was most frequent during

July, and least frequent in December. Comments about cloud cover suggest greater frequency of cloudy skies from January-May, and less so during July-December; however this general pattern (Figure 5) may be skewed by the fact that clouds may have not been mentioned during rainy days.

4.5 Winds

The general wind direction recorded by Davis was used to develop a wind climatology (Figure 4; Table 4) that can be used to gauge the local conditions he experienced, including how incident atmospheric circulation changed through the seasons. This analysis can also be used to determine whether there are differences in the frequency of general prevailing winds during Davis' time relative to present day. Davis mentions 'variable' or squally/disturbed conditions ~11% of the time, with almost twice as frequent occurrence during summer than other seasons (Figure 6). On an annual basis via percentage, southerly, southwesterly, and westerly winds were most common (constituting ~50% of all entries). Grouped by direction quarter, westerly winds were most frequent (and more so during spring) and easterlies were least frequent across the year (Table 4). In addition, the departures from the annual mean climatology indicates Davis experienced more frequent easterlies during summer (with reduced westerly frequency) and diminished easterly flow in spring. Relative to modern wind direction frequencies for Northland (Chappell, 2013), southerly quarter winds were more frequent across the year during Davis' time at Waimate North and Kaikohe - at the expense of diminished easterly quarter winds in particular.

4.6 Weather Extremes

4.6.1 Thunder, lightning, floods and gale winds

Davis made several observations regarding extreme types of weather, including thunder and lightning, hail, frost, ice and floods. Comments about thunder are greatest in October and January and least frequent in March. There is no mention of lightning during August-November, with highest frequency of comments in March and June. In general, lightning and thunder are poorly correlated in the Davis diary, typically because remarks about thunder were commonly made when it was 'off in the distance'. Commentary related to 'rivers in flood' that are mentioned in the Davis diary indicates that December was the most common month when floods happened, followed by February and November (Figure 6). Davis also makes mention of 'gale' winds which are interpreted here as blustery stronger-than-normal winds that lasted for a substantial time during the day. The climatology of those comments (Figure 6) indicates a general rise in frequency beginning at the end of summer, culminating in October.

4.6.2 Ex-tropical cyclone of 1 March 1840

A significant commentary about an extreme weather event was made by Reverend Richard Davis at the end of the February 1840 meteorological diary register and also in his personal diary. Davis wrote about sustained strong winds with heavy rain that wrought damage to a fence he had recently installed on his farmland. The personal diary entry mentions 'a hurricane' and the meteorological diary comment section specifically indicates that anomalous low pressure influenced the Waimate site, with a minimum pressure in native format of 28.09 inches (28.73 inches when adjusted to sea level) recorded close to midnight on 1 March 1840. Davis remarks that the "mercury rebounded rapidly to 29.22 inches (29.86 inches when adjusted to sea level) by noon the following day" as the storm passed. When the adjusted sea-level pressure recordings are converted to hectopascales, the antecedent and follow-on conditions from the low pressure anomalies are close to 1011 hPa, which are reasonable values for late summer-early autumn when compared to present day values for early March. The adjusted low pressure anomaly of 28.73 inches (973 hPa) recorded at midnight 1 March 1840 by Davis is significant in that it, along with preceding and following high pressures and general wind direction changes, are akin to a signature of an ex-tropical cyclone interaction, which are well documented for Northland (Lorrey et al., 2013b). The suggestion from the qualitative and quantitative measurements made by Davis is that he experienced a direct hit or near miss of an ex-tropical cyclone, which passing over or close to Waimate North on 1 March 1840. An assessment of the South Pacific Enhanced Archive for Tropical Cyclone Research (Diamond et al., 2012) does not show a track interacting with New Zealand in 1840; however d'Aubert and Nunn (2012) note a significant storm that impacted Fiji and the Cook Islands in late February 1840 which may have exited the tropics and subsequently made landfall in Northland as a decaying storm system. Future work will focus on the other extreme pressure values recorded by Davis, which may have a polar rather than a tropical origin.

4.6.3 Extreme temperatures

A comparison of the monthly average Tmean, Tmax and Tmin, 9am average, minimum single-day and maximum single-day extreme temperatures are shown for the Davis diary with reference to the VCSN for the same location (Table 2 & 3). For the mean extreme high monthly values, the Davis diary is categorically cooler across all months relative to present day by an average of -2°C. For 9 AM single day maximum 9AM temperatures, none of the extreme values from the Davis diary exceed extreme temperatures for the modern era. On average across the year, the VCSN 9AM single-day extreme high temperatures for each month are 2.9°C±1.6°C higher than those Davis recorded, with significantly larger differences in the monthly 9AM extreme relative to the modern era in March-May and July-September (Table 3). However, it is interesting to note that for extreme 9AM temperatures, the modern period has some occurrences of colder mornings for February-April, June and October relative to the time Davis was residing in the Far North.

4.6.4 Frost, ice, hail and snow

Several qualitative remarks related to cold temperatures and frost can be found in Davis's personal and meteorological diaries. Davis's sent a letter to John Coleman dated 21 June 1834 (Coleman, 1865: 180): "Last night was our first night of frost this year. The ice this morning was the thickness of a shilling" (approximately 1.2mm thick). Davis again mentions ice in the meteorological diary on 15 July 1839 indicating "ice ¼ inch thick" (6.35mm), presumably observed on the surface of the millpond at the Waimate North site. Frost is noted 106 times by Davis spanning nine years. His observations suggest no frosts occurred during November-March and that the frostiest month was July, with more than half of the frost events occurring in winter (June-August).

Hail was also observed by Richard Davis for all seasons except summer (Figure 6), with a peak occurrence in winter (July), dropping away to no hail accounts in December. Snowfall was also mentioned in the Davis meteorological diary once as an isolated event spanning two days for 30–31 July 1849. For the two days of snow that were mentioned, Davis's meteorological diary comments are:

- (30 July 1849) Hail storms. This morning the southern hills and Poutahi covered with snow.
- (31 July 1849) This morning the hills were again covered with snow.

In a personal letter to a friend in England, Davis also affords a parallel description (Coleman, 1865: 350):

- (30 July 1849) The hills were covered with snow, the first ever seen by the natives inhabiting this part of New Zealand. The Putahi (sic) was also covered.
- (31 July 1849) This morning the hills were again white with snow.

Contrary to widely held belief that it never snows in northern New Zealand, there are six historic accounts of frozen precipitation for Auckland/Northland (Figure 7a & 7b) that can be brought to bear for reference. Two of the events (1939 and 2011) are noted as having delivered at least some light snow to high elevations. Geographic coverage of eyewitness accounts for the occurrence of frozen precipitation including snow (and/or sleet and/or graupel) related to six historic Auckland/Northland events (Figure 7a) suggests the 1849 snow seen by Davis may have been akin to the 1939 event, which saw snowfall on isolated ridges as far north as Cape Reinga, with the next closest analog being the 2011 event. The similarities and diagnostics for these analogs are brought to bear in the next section.

5 Discussion

5.1 How similar or different are Reverend Davis' weather observations of the early Colonial era from today?

The Reverend Davis meteorological diary from Waimate North and Kaikohe contains years of continuous daily instrumental and qualitative observations for several key variables. The most notable components of this diary are quantitative measurements of temperature and barometric pressure (Figure 3). A comparison of the barometric pressure from Waimate North to reference series from ships (Figure 3) suggest the Davis' pressure measurements can be used as station data. When compiled into a climatology and compared to reference data series derived from the VCSN, there are elements of the Davis meteorological register that undeniably indicate he was making faithful measurements of local conditions. The annual cycle pattern is evident in all three instrumental data sets, and their patterns are phase locked in terms of the timing of the peaks and troughs seen in modern climatology records. The relative temperature changes for the 9AM and noon temperature climatology (Table 2; Figure 4) between summer and winter are also quite similar to the modern era, with a change of ~10°C between summer and winter. The distinctions of the Davis diary observations with respect to modern times, however, are observed for the overall offsets in mean monthly temperatures and some of the daily temperature extremes (Tables 1-3).

5.2 Can we corroborate the general indications of past temperature anomalies noted in the Davis diary and determine their cause?

Recent work of the Australasia palaeoclimate research community has gathered high-resolution climate proxy data (Neukom and Gergis, 2012) and made it available in a centralized database (Kaufman et al., 2014). There is thus an opportunity to examine some of those proxy data, which in the case of New Zealand constitute tree ring chronologies, alongside the reconstructed temperatures for 1839–1851 (exclusive of the missing years between the diary components) based on Reverend Davis's observations. Collectively, the Davis diary anomalies and corresponding tree ring reconstructed anomalies for winter temperatures can be integrated in PICT (see Lorrey et al., 2014 and pict.niwa.co.nz for details of the reconstruction technique and prior application) to provide greater context for the local conditions Reverend Davis experienced in his lifetime.

The Davis diary mean winter temperatures (-0.9°C) are comparable to anomalies for *Libocedrus* tree ring-based reconstructions from Takapari (-1.9°C), Moa Park (-0.36°C) and Flanagan's Hut (-0.90°C) (See Xiong and Palmer, 2000 for chronology details). The resulting synoptic type changes that would have caused colder winter temperatures for all sites, as indicated by the PICT-based reconstructed climate fields, would have been driven by an increase in 'Trough' types (Kidson, 2000), a reduction in 'highs' over the country (the "H" zonal type of Kidson, 2000) and a reduction of 'Blocking' synoptic types that typically are known for increasing the frequency of northerly quarter flow (Kidson, 2000). There are clear 'differences in opinion' amongst the proxy data with regard to what the specific change in frequency of occurrence for individual synoptic weather types may have been for 1839–1851 (Figure 8). However the integration of all sites together shows confidence in the reconstructed regional atmospheric circulation field (z1000) in the New Zealand sector, with increased lows to the east of the country and over the Chatham Islands (Figure 9). This regional atmospheric circulation pattern would have produced more frequent S and SW winds with cooler-than-normal temperatures for New Zealand (Figure 9).

Moreover, a projection of anomalous temperatures for the SW Pacific, that is a result of the integrated New Zealand tree ring reconstructions, with the Davis instrumental temperature observations suggest an El Niño-like pattern existed for the mean winter climate state during 1839–1851 (Figure 9). Those signals are corroborated against existing coral palaeotemperature reconstructions (albeit annually resolved; see Delong et al., 2012 and Dunbar et al., 1994) that indicate the integration of the Davis temperatures with the tree ring data and their collective 'opinion' about the tropical Pacific mean climate state is robust. Looking further afield at the wider Southern Hemisphere z1000 field (Figure 10) the atmospheric circulation is characterized by an anomalous high pressure in the Bellinghausen Sea paired with a low pressure east of the Drake Passage. This configuration has a spatial pattern similar to what is observed for the Pacific-South American mode (PSA; Mo and Paegle, 2001). Overall, the indication from the PICT spatial field projections are that at least two key teleconnections and climate drivers may have had an important influence on the 'dirty weather' that Reverend Davis observed during 1839–1851. Some parts of the observed pattern (Figure 9 & 10) are similar to what has been implicated for mean summer conditions based on 22 equilibrium line altitude temperature reconstructions for the LIA (Lorrey et al., 2013a). The integration with tree ring evidence also lends to an interpretation that the Davis meteorological diaries provide a crucial eyewitness account for the end of this recent but (locally) poorly understood climate episode.

5.3 How different are the mean and extreme conditions observed by Davis relative to today?

5.3.1 Temperatures and the presence of ice

The direct 9AM temperature comparison of the VCSN and the Davis recordings suggest that categorically the 9AM average temperature and the most extreme 9AM temperature that Davis experienced was colder than the modern era (Table 2). The transformation of the Davis diary 9AM and 12 noon temperature recordings to be directly comparable to the VCSN modern climatology of daily mean temperature and temperature extremes (Tmax, Tmin and Tmean) indicates the most significant differences were colder daily mean and daily extreme temperatures for May-August. These anomalies are congruent with wider climate change syntheses that have recognized long-term warming trends in minimum temperatures (Pittock and Wratt, 2001). The Davis diary also suggests that average monthly temperatures were relatively warmer for November-March, with the clearest signature of warm anomalies for December and January (Table 3). However, we recognize that some of the climatological results for summer and winter appear consistent with findings related to poor thermometer ventilation and/or exposure (Nicholls et al., 1996). In the context of climate driver associations, proxy evidence of past El Niño Southern Oscillation (ENSO) activity indicates swings occurred between El Niño and La Niña episodes in the early-to-mid 1800s when Davis was making observations (Gergis and Fowler, 2009). This probably means the climatological mean values presented here 'blend' successive ENSO events (and anomalies for Northland) via the averaging process. It may be likely that one particularly strong El Niño and/or a protracted event could skew this perception. While we have opted to not analyze the individual seasonal climate anomalies from the Davis diary in this study, future work looking further afield using Australian weather diary records could prove fruitful for integration, corroboration and delineation of past ENSO teleconnections and activity.

The documentation of surface ice on two separate occasions by Reverend Davis appears unusual. The 15 July 1839 ice event indicates temperatures at 9AM were 4.4°C. This is not the coldest 9AM temperature noted by Davis. Omission of other ice comments may indicate something to the effect that observations of ice as a phenomenon may have been sporadic, infrequent, confounded with frost, or only noted for highly significant events. The alternative is that the conditions for ice formation and/or persistence into the early morning may have only been amenable during the days when Davis noted its presence where he was living. The 9AM temperatures from the Davis diary indicate an extreme low value of 1.7°C occurred on 8 July 1850, which is clearly colder than the temperature on 15 July 1839. In consideration of the fact that early morning temperatures are typically colder than those at 9AM, our VCSN-based Tmin reconstructed temperature of -1.4°C for 8 July 1850 suggests that freezing temperatures at nighttime (and associated surface ice formation) probably occurred episodically during the early Colonial era in Northland. While little photo-documentary information about freezing cold and past ice presence in Northland exists, evidence from other undiscovered historic weather journals might shed more light on this phenomenon. Moreover, traditional Maori knowledge has suggested surface ice formation in the recent past that coincided with the early part of the instrumental observation period may have been more frequent than the present day (King et al., 2008), and that sentiment is congruent with palaeoclimate proxy interpretations.

5.3.2 Snowfall (frozen precipitation)

It is difficult to compare the atmospheric conditions related to the historic Northland snowfall events. Extended reanalysis integrations that are meaningful for New Zealand are not available yet for 1868, and in general past daily weather depictions are data sparse within the 20th Century reanalysis for the pre-1950 interval (Cram et al., 2015). The 1904 snowfall analog cannot be fairly compared to the other analogs due to data sparseness (and this sentiment is probably applicable to the 1939 analog because of high latitude data sparseness). However there are similarities in terms of the geopotential spatial field signatures of the 1939, 1976, and 2011 events (Figure 7b). A significant 'low' anchored south of the Chatham Islands extending to the fringe of the Ross Sea (which was potentially blocked to the east) and a strong 'high' over southeast Australia and Tasmania are common to those three analogs. The general atmospheric circulation pattern for each of the snowfall events facilitated a corridor of strong southerly air drawn off of the Antarctic continent fringe that was transmitted to northern New Zealand. The connection of modern day events that overlap the satellite-observation period which have a similar depiction in reanalysis data indicate the 30-31 July 1849 event was probably of similar origin.

5.4 Pressure observation metadata

In the Davis diary, there is a written note underneath January 1844 (before January 1848) that states:

- "Note: in the following pages, from Jan. 1 1848 to August the 1st 1848 the barometer was caused to range 40 parts of an inch higher than usual from an alteration having been made in the bottom stopper screw by some unknown

> hand. This was not found until August 2 1848. The month of July was arranged in copying."

The range of pressure observations that were made during the January-June interval in question appear higher than normal relative to the rest of the record. We have no reason to not trust the metadata comment by Reverend Davis found in the diary. As such, we have corrected the first six months of data in 1848 by subtracting 4/10^{ths} of an inch of pressure prior to converting the measurements to hectopascales and analyzed these data according to the corrected version. Future work that will see those measurements integrated into the International Surface Pressure Databank (ISPD) (Cram et al, 2015) will mean the scale of the pressure adjustments can be tested in subsequent reanalyses and this will afford an additional opportunity to examine the Davis pressure series (including means, variability and extremes) in more detail.

6. Conclusions

The observations in Reverend Richard Davis's two-volume meteorological diary represent some of the oldest surviving instrumental observations from the Colonial era in New Zealand. The data in this historical register are not as comprehensive as the observations subsequently taken by the Royal Engineers in Auckland during the early to mid 1850s (thrice daily), or those from James Hector's fledgling meteorological service network of the late 1860s. However it is fitting that Davis should be recognized as having made some of the most significant and earliest contributions to New Zealand meteorology and climatology. The extent and breadth of the observations as well as their general antiquity suggests Reverend Richard Davis probably deserves the title of New Zealand's first meteorologist.

When Davis' temperature observations are transformed to be comparable to modern day VCSN Tmean, Tmax and Tmin observations, it appears as though temperatures were categorically cooler during winter when he was resident in the Far North. The wind observations that are provided by Reverend Davis also suggest southerly-quadrant flow was more frequent than present day. The timing and descriptions of monthly and seasonal climate anomalies, when compared to tree ring and coral proxy data (Figures 8-10) suggest a connection to ENSO and potentially the PSA existed for New Zealand climate during the mid 19th century. It is likely that these two climate drivers guided some of the local anomalies and synoptic variability that Reverend Davis observed. With the addition of new data fed into an extended reanalysis, the depiction of past conditions will be clearer, and these hypotheses can be tested more rigorously.

Extreme temperature values, potentially linked to a subtly different mean climate state (Mann et al., 2009), suggest Davis experienced a relatively higher proportion of what are normally uncommon occurrences of frost and rare events (freezing, ice, snow) that do not typify the modern climate and weather of Northland. Overall, the 'dirty weather' comments Davis penned with his extensive instrumental observations provide an eyewitness account of the Little Ice Age conclusion in New Zealand. The LIA culmination is notoriously indicated by historic photos and paintings of ice margin positions with juxtaposed moraines along the Southern Alps margin to the south of where Davis lived that unequivocally show glaciers were much more extensive relative to today (Chinn et al., 2012). Extended evidence from the Southern Alps using equilibrium line altitude-based summer temperature reconstructions

(Lorrey et al., 2013a) similarly suggest generally cooler conditions existed during Davis's time in the Far North, with other proxy evidence demonstrating seasonal variability – including both cold and warm temperatures – was associated with enhanced ENSO activity (Fowler et al., 2012). As such, the anomalies of colder winters and warmer summers on average during Davis' time are not unexpected, and this evidence enriches our understanding that early settlers may have faced significant climate anomalies (such as drought and deluge) that New Zealanders continue to grapple with today.

The 'discovery' of this meteorological gem in a local archive raises the interesting point that future prospects for historic climate work in New Zealand are numerous. There are clear indications that historical documents contain instrumental weather observations and some of these observations overlap and even antedate the Davis diary, based on initial investigations about ships that transited into New Zealand waters during the Colonial era (Chappell and Lorrey, 2013). Our expectation is that extension of historic climate work utilizing a range of documentary archives will enrich the knowledge about the range of natural weather and climate variations that are possible, and this endeavor is requisite for contextualizing past-to-present historic trends and for making adequate preparations for future changes.

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Figure Captions

Figure 1. (top, left) Print of a photomechanical portrait of Reverend Richard Davis taken c. 1860, from the file print collection, Box 16. Ref: PAColl-7344-97, Alexander Turnbull Library, Wellington, New Zealand sourced from http://natlib.govt.nz/records/23073407 (top, right) a digital scan of the Davis meteorological diary for July 1849 which also includes commentary about dirty weather and snow (bottom) The Waimate North mission house in the Far North of New Zealand where Davis lived.

Figure 2. Map of Northland, New Zealand including major points of interest in Reverend Richard Davis' meteorological diary. The inset map shows New Zealand's location in the Southwest Pacific and a box around the Northland region. The base map displays the median annual temperature for the region, based on the 1981-2010 climatology period (temperature legend on right). The top bar plot shows monthly rainfall (1985-2010 period) and the bottom bar plot shows monthly temperature (1985-2010 period) for Kaikohe, with frost day occurrences (triangles) inset on the temperature plot.

Figure 3. (top) Monthly pressure observations from the Reverend Richard Davis (RRD) meteorological diary for 1839-1843. Number on x-axis denotes month of each year. Circles represent values that are 1.5 to 3 times the interquartile range away from the middle 50% of all of the data, while stars represent extremes are more than 3 times the interquartile range away (middle) comparison of pressure observation in inches mercury from RRD relative to ship data in the Bay of Islands for the same day (bottom) RRD pressure observation vs. expedition measurements (leader noted in

parenthesis) from USS Vincennes (Wilkes), the corvettes Astrolabe & Zelee (D'Urville) and the HMS Erebus (Ross). There are 29 pairs of daily observations and so the x-axis simply shows the comparisons of Davis' record to the three ships in a sequence with the specific intervals noted.

Figure 4. (top) Climatology of 9AM temperature and noon temperature and pressure measured by Reverend Richard Davis at Waimate North and Kaikohe (means for 1939-1843 and 1848-1851 inclusive). (bottom) seasonal wind climatology (% frequency observation) for the same sites and interval.

Figure 5. Climatology of qualitative observation for 'dirty weather' rain days and 'dry' days (left hand scale) vs. 'dirty weather and cloud (right hand scale) percentage of days per month in the Reverend Davis' meteorological diary.

Figure 6. Climatology of qualitative observation for 'gale' winds and frost days (left hand scale) with flood and hail (right hand scale) percentage of days per month in the Reverend Davis' meteorological diary.

Figure 7a: (top, left) Distribution of historic frozen precipitation events (snowfall, sleet and graupel) for northern New Zealand. (bottom, left) Reported elevations for the eyewitness accounts above plotted by latitude, with demarcation lines separating the minimum estimated settling elevation for frozen precipitation for each event. The diamond colors note evidence for distinct events: red – 2008, green – 1976, orange – 1868 & 1904, grey – 2011, blue – 1939. The maroon (encircled) diamond indicates the 30-31 July 1839 event recorded by Reverend Davis for the Putahi volcanic cone when he was living at Waimate North.

Figure 7b. 500hPa wind strength and streamlines for the aforementioned snowfall events, courtesy of the 20th Century reanalysis v2.

Figure 8: (Top) Frequency of New Zealand synoptic types (X-axis) during austral winter as determined by an ensemble composite of reconstructions from three tree ring proxy sites and the Reverend Richard Davis weather diary for 1839 CE - 1851 CE. Grey bars indicate climatological frequencies in terms of percentage (Y-axis, left), box and whiskers indicate distribution of anomalies in terms of change in frequency (Y-axis, right) indicated by the ensemble reconstruction. The black horizontal line in each box is the median bound by the 25th and 75th percentile while whiskers are 5th and 95th percentile. Synoptic type abbreviations follow Kidson (2000; See Supplementary Materials for full details). (Bottom) Heat map of New Zealand synoptic type (X-axis) frequency changes with respect to climatology for individual site members (Y-axis) of the ensemble composite for 1839 CE - 1851 CE. Significance of synoptic type frequency changes was assessed using a Monte Carlo approach. 10000 simulations of synoptic type evolution were realized based on Markov chains constrained by the observed frequency and transition probabilities between Kidson's (2000) synoptic types observed during the modern reanalysis era (1972-Present). Circles and stars represent anomalies significant at the 90th and 95th level, respectively. Figures generated using the Past Interpretation of Climate Tool (PICT) courtesy of National Institute of Water and Atmospheric Research (NIWA). See Lorrey et al. 2014 and http://pict.niwa.co.nz for details.

Figure 9: (top, left) June-August (JJA) geopotential height anomaly at 1000hPa (z1000) over the New Zealand region for 1839 CE - 1851 CE determined by an ensemble composite of reconstructions from three tree ring proxy sites (Moa Park, Takapari and Flanagan's Hut) and the Reverend Richard Davis weather diary . Anomaly height is in meters. Reanalysis data is courtesy of the National Centers for Environmental Prediction (NCEP). Confidence intervals (90th and 95th) are noted with black (dashed and solid) contour lines. (top, right) Temperature anomalies for JJA as reconstructed using the selected analog circulation patterns from 4 sites for 1839 CE - 1851 CE. Temperature anomalies are degrees Celsius. (bottom) JJA sea surface temperature (SST) anomaly over the Southwest Pacific region for 1839 CE - 1851 CE determined by an ensemble composite of reconstructions from four proxy sites. Temperature anomaly is in C. SST reanalysis data is courtesy of the Hadley Centre (HADSSTa v3). Confidence intervals (90th and 95th) are noted with black (dashed and solid) contour lines. Supporting temperature reconstructions for years corresponding to the New Zealand data and associated errors are shown as purple symbols on the map to denote locations of reconstructions and alongside the SSTa scale with associated 1 standard deviation errors. The SSTa reconstructions are based on coral Sr/Ca from the Great Barrier Reef (triangle), New Caledonia (circle) and Fiji (square) in Delong et al., (2012) and from d18O for the Equatorial Pacific at the Galapagos Islands (hexagon) after Dunbar et al., (1994). Base figures were generated using the Past Interpretation of Climate Tool (PICT) courtesy of National Institute of Water and Atmospheric Research (NIWA). See Lorrey et al. 2014 and http://pict.niwa.co.nz for details.

Figure 10. July-August geopotential height anomaly at 1000hPa (z1000) over the Southern Hemisphere for 1839 CE - 1851 CE determined by an ensemble composite of reconstructions from the Reverend Davis diary temperatures and three tree-ring proxy data series (same as Figure 9). Anomaly height is in meters. Reanalysis data is courtesy of the National Centers for Environmental Prediction (NCEP). Confidence intervals (90th and 95th) are noted with black (dashed and solid) contour lines. Figure generated using the Past Interpretation of Climate Tool (PICT) courtesy of National Institute of Water and Atmospheric Research (NIWA). See Lorrey et al. 2014 and http://pict.niwa.co.nz for details.

Figure 11. Pressure series for the second half of the Reverend Richard Davis meteorological record showing adjusted and unadjusted (clear/white boxes) pressure series for January – June 1848. Circles represent values that are 1.5 to 3 times the interquartile range away from the middle 50% of all of the data, while stars represent extremes are more than 3 times the interquartile range away

Table 1. Monthly average 9AM temperature, Noon temperature and Noon pressure from the Reverend Richard Davis meteorological diary converted from Fahrenheit to Celsius and inches of mercury to hectopascales.

Thermometer 9am	January	February	March	April	May	June	July	August	September	October	November	December
1839	17.4	18.4	18.4	14.8	12.4	10.4	9.1	9.3	11.7	12.7	16.2	15.6
1840	17.9	18.4	18.1	16.8	12.5	11.0	10.2	9.5	10.7	14.0	14.6	20.5
1841	21.0	18.5	18.3	14.4	11.7	8.8	8.2	10.0	11.6	15.5	16.3	18.4
1842	20.6	19.4	17.4	15.4	11.0	8.8	8.1	8.3	11.2	13.2	16.6	18.0
1843	18.5	19.0	17.6	14.9	11.5	9.4	8.6	10.2	11.8	13.0	16.1	18.8
1848	19.8	18.5	17.7	15.5	12.8	11.6	10.3	11.0	12.2	12.8	16.7	19.1
1849	19.0	19.3	19.1	15.9	13.0	9.9	9.6	9.2	12.1	14.3	16.0	18.7
1850	20.5	20.8	18.4	14.7	12.2	10.4	7.2	10.5	11.9	13.4	16.6	18.3
1851	20.5	20.9	19.5	13.8	12.7	10.4	9.2	10.1	12.9			
Average	19.5	19.2	18.3	15.1	12.2	10.1	8.9	9.8	11.8	13.6	16.1	18.4

Thermometer noon	January	February	March	April	May	June	July	August	September	October	November	December
1839	21.6	22.5	22.0	19.0	15.1	13.6	12.1	12.1	14.4	15.9	19.0	19.6
1840	21.7	20.7	21.3	19.3	16.4	14.0	12.5	11.9	13.0	17.5	17.3	24.7
1841	25.1	22.4	21.0	17.4	14.6	12.3	11.3	12.5	14.6	18.2	18.3	20.5
1842	23.4	22.5	20.7	17.4	14.3	11.5	11.5	11.6	14.7	15.9	19.3	21.5
1843	21.1	21.4	20.5	16.8	14.1	12.2	11.2	12.9	14.6	14.8	18.6	21.2
1848	21.5	20.0	19.5	17.4	14.0	13.3	13.0	12.7	13.6	14.8	18.8	20.7
1849	20.9	20.8	20.6	17.6	14.3	11.6	10.9	10.9	13.6	15.7	17.4	20.6
1850	22.2	21.6	19.6	16.0	13.8	11.6	9.1	11.8	13.6	15.0	18.3	19.6
1851	22.2	22.7	20.6	15.6	14.3	11.9	11.2	12.1	14.7			
Average	22.2	21.6	20.7	17.4	14.5	12.5	11.4	12.1	14.1	16.0	18.4	21.0

Barometer noon	January	February	March	April	May	June	July	August	September	October	November	December
1839	990.7	994.9	997.4	997.3	999.9	994.6	990.3	993.0	997.4	991.5	992.8	992.7
1840	996.6	993.9	994.8	992.8	994.7	992.7	994.9	987.8	993.0	998.2	993.1	1000.1
1841	992.5	995.1	997.8	996.7	996.1	990.9	992.7	996.2	997.9	995.7	991.8	988.7
1842	996.5	997.9	997.0	992.5	990.8	990.4	993.5	992.8	994.5	987.7	990.6	994.1
1843	992.7	999.0	998.3	996.0	998.1	991.7	991.5	992.6	988.9	986.7	993.4	996.3

1851	993.6	996.3	990.0	999.7	992.9	988.3	988.3	989.3	992.0			
Average	998.1	998.5	999.1	998.4	996.2	992.6	992.1	993.2	994.2	993.7	994.0	996.0

Table 2. VCSN-equivalent temperatures from the Davis diary for 9AM mean, 9AM extreme minimum and 9AM extreme maximum values with reference to VCSN 9AM temperature data.

9am mean	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Davis	19.3	19	18.1	15.3	12.1	10	8.9	9.7	11.7	13.6	16.1	18.4
VCSN	19.8	20.3	19.5	17.7	15.6	13.7	12.7	13.1	14.1	15.1	16.6	18.5
Difference	-0.5	-1.3	-1.4	-2.4	-3.5	-3.7	-3.8	-3.4	-2.4	-1.5	-0.5	-0.1
Davis era	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder

9am extreme min	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Davis	11.1	13.9	12.2	5.6	5.6	3.9	1.7	2.2	5.6	8.3	8.9	8.9
VCSN	11.2	9.9	9.7	2.9	6.3	2.1	3.9	5.2	6.5	5.9	9.7	9.2
Difference	-0.1	4	2.5	2.7	-0.7	1.8	-2.2	-3	-0.9	2.4	-0.8	-0.3
Davis era	colder	warmer	warmer	warmer	colder	warmer	colder	colder	colder	warmer	colder	colder

9am extreme max	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Davis	26.7	24.4	23.9	21.1	19.4	20	15.6	16.1	16.7	21.1	22.2	24.4
VCSN	27.5	26.3	27.3	24.8	23.8	21.5	19.8	21.1	21.9	22.8	24.3	24.9
Difference	-0.8	-1.9	-3.4	-3.7	-4.4	-1.5	-4.2	-5	-5.2	-1.7	-2.1	-0.5
Davis era	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder	colder

Table 3. VCSN-equivalent average monthly Tmin, Tmax, Tmean and diurnal temperature range based on Reverend Davis 9AM and Noon temperatures compared to modern climatology. Bold (italic) highlighting indicates warmer (colder) differences of more than 0.5°C for Davis observations relative to the present.

Davis - reconstructed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tmin(C)	14.5	14.7	14.1	12.0	9.1	7.0	6.0	6.4	7.8	9.4	11.4	13.6	10.5
Tmax(C)	24.4	24.1	22.8	19.5	16.5	14.5	13.5	14.1	16.0	18.1	20.4	23.0	18.9
Tmean(C)	19.5	19.4	18.5	15.7	12.8	10.7	9.8	10.3	11.9	13.8	15.9	18.3	14.7
Diurnal range	9.9	9.4	8.7	7.6	7.4	7.4	7.6	7.4	8.2	8.7	9.0	9.4	8.4

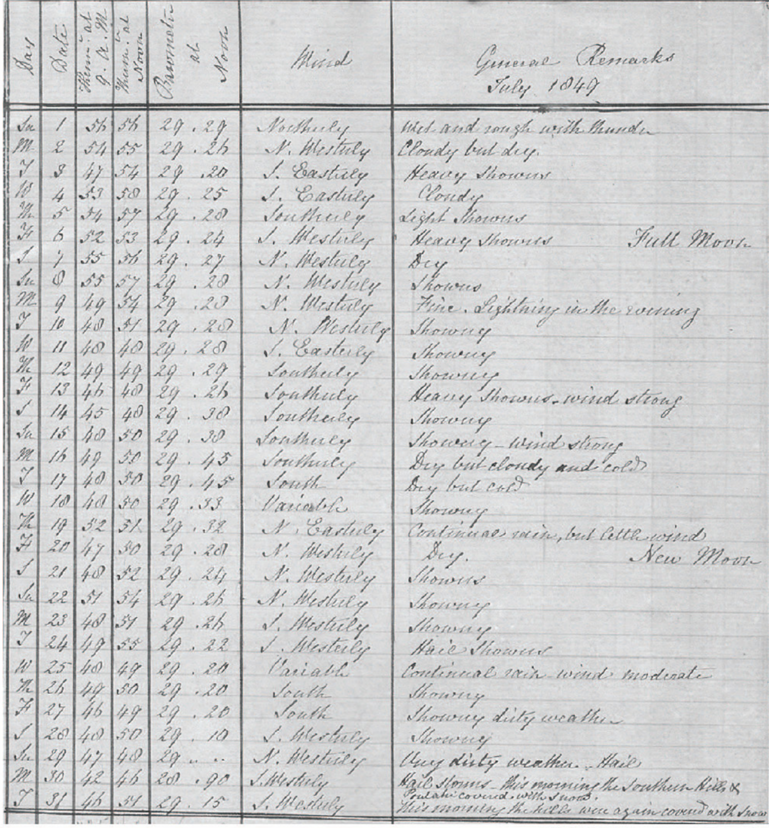
VCSN modern	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tmin(C)	14.0	14.5	13.5	11.8	9.9	8.0	7.1	7.3	8.3	9.4	10.9	12.7	10.6
Tmax(C)	23.3	23.7	22.2	19.8	17.3	15.2	14.5	14.8	16.2	17.6	19.5	21.6	18.8
Tmean(C)	18.6	19.1	17.9	15.8	13.6	11.6	10.8	11.1	12.2	13.5	15.2	17.1	14.7
Diurnal range	9.3	9.2	8.7	8	7.5	7.2	7.3	7.5	7.9	8.2	8.6	8.9	8.2

Davis era difference	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Tmin(C)	0.5	0.2	**0.6**	0.2	*-0.8*	*-1.0*	*-1.1*	*-0.9*	-0.5	0.0	0.5	**0.9**	-0.1
Tmax(C)	**1.1**	0.4	**0.6**	-0.3	*-0.8*	*-0.7*	*-1.0*	*-0.7*	-0.2	0.5	**0.9**	**1.4**	0.1
Tmean(C)	**0.9**	0.3	**0.6**	-0.1	*-0.8*	*-0.9*	*-1.0*	*-0.8*	-0.3	0.3	**0.7**	**1.2**	0.0
Diurnal range	**0.6**	0.2	0.0	-0.4	-0.1	0.2	0.3	-0.1	0.3	0.5	0.4	0.5	0.2

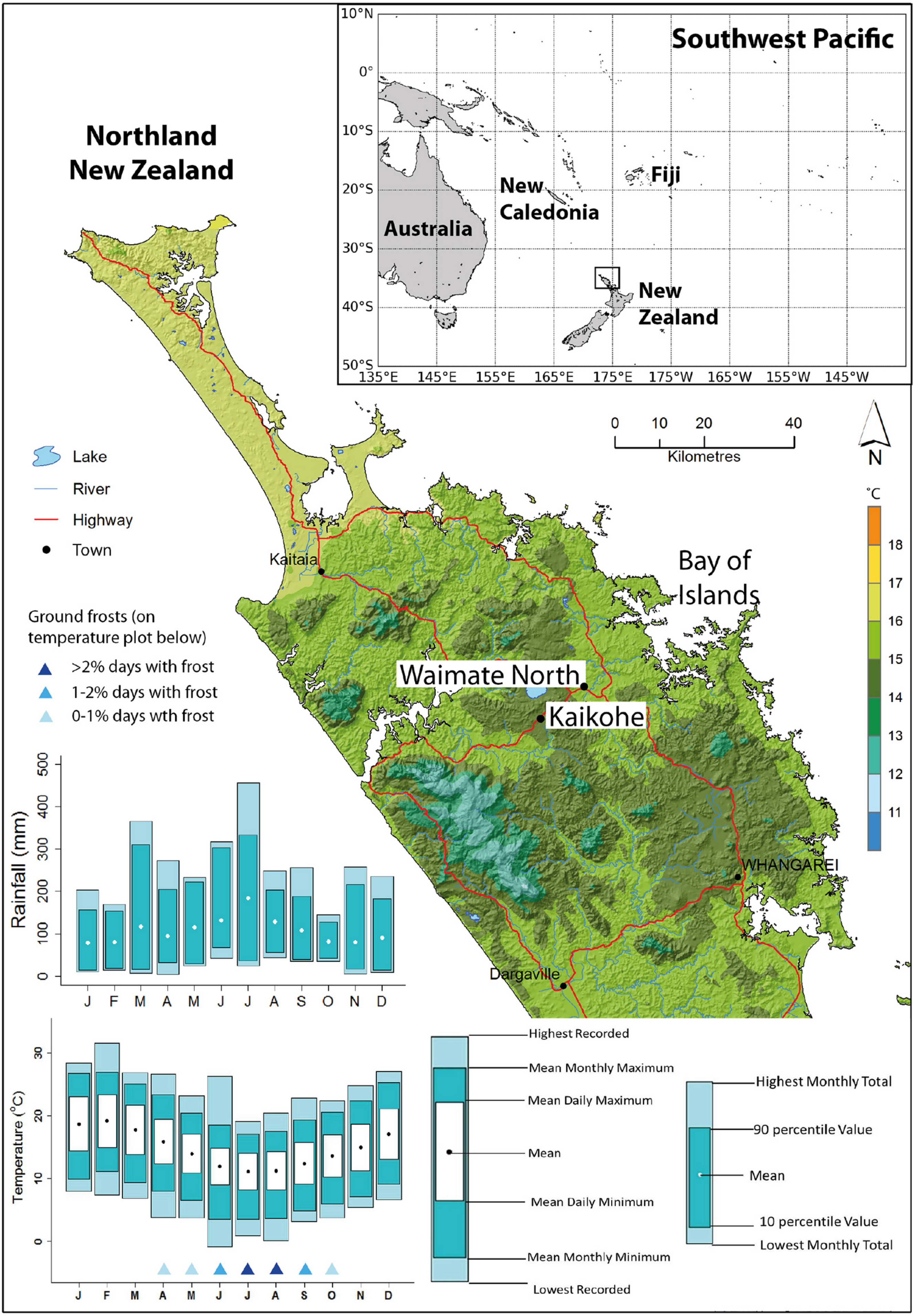
Table 4. Percentage frequency per month (and averaged by season) for qualitative wind direction observations by Reverend Richard Davis for the entire span of his observations.

Month	N	NE	E	SE	S	SW	W	NW	VRB
Jan	11.1	2.9	10.0	5.0	14.3	16.8	14.7	6.5	18.6
Feb	10.2	5.9	11.4	13.0	16.5	12.2	9.1	5.5	16.1
Mar	7.9	4.3	16.1	12.2	15.4	14.3	12.2	6.5	11.1
Apr	8.9	5.2	7.4	9.3	24.4	15.6	11.5	9.6	8.1
May	7.9	3.6	4.3	5.7	21.9	20.4	13.6	14.7	7.9
Jun	13.0	2.2	6.3	9.3	15.9	15.9	17.8	12.2	7.4
Jul	9.7	5.7	4.3	11.1	19.0	12.2	15.4	12.2	10.4
Aug	10.0	4.7	6.1	13.3	13.6	17.9	16.1	9.0	9.3
Sep	12.1	7.1	8.8	6.7	12.9	10.8	17.1	12.9	11.7
Oct	9.3	2.4	6.5	5.2	13.7	16.5	23.8	16.1	6.5
Nov	17.1	7.9	3.8	3.8	10.0	13.8	21.3	12.1	10.4
Dec	7.7	8.5	11.3	4.8	12.5	13.7	17.7	7.3	16.5
AVG	10.4	5.0	8.0	8.3	15.9	15.0	15.9	10.4	11.2
SON	12.8	5.8	6.3	5.2	12.2	13.7	20.7	13.7	9.5
DJF	9.7	5.7	10.9	7.6	14.5	14.3	13.8	6.4	17.1
MAM	8.2	4.4	9.3	9.1	20.6	16.8	12.4	10.3	9.0
JJA	10.9	4.2	5.6	11.2	16.2	15.3	16.4	11.1	9.0

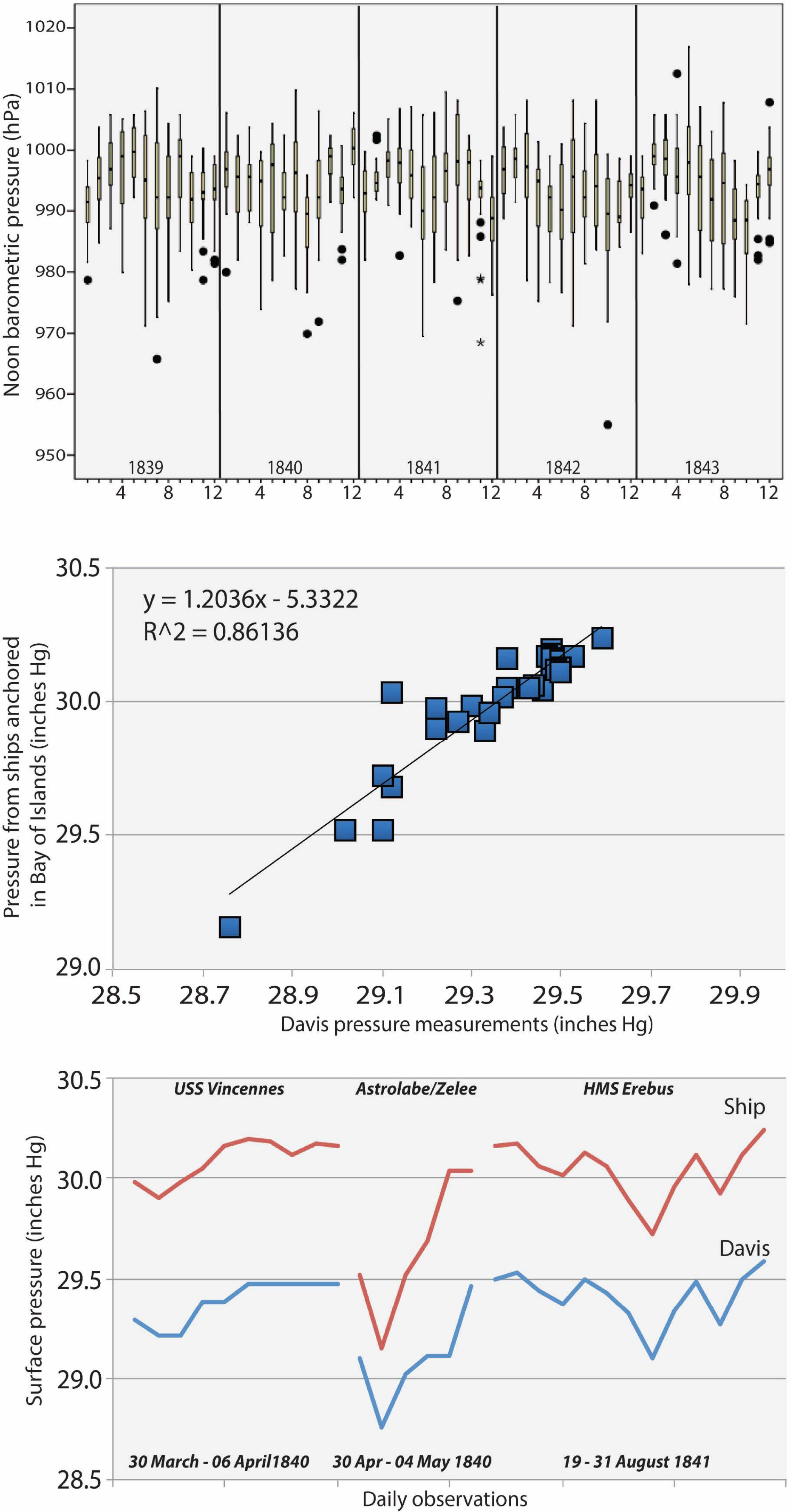
The Rev. Richard Davis,
Father of Mrs. Joseph Matthews and
Mrs. William Gilbert Puckey.
Arrived in Bay of Islands August 15, 1824.



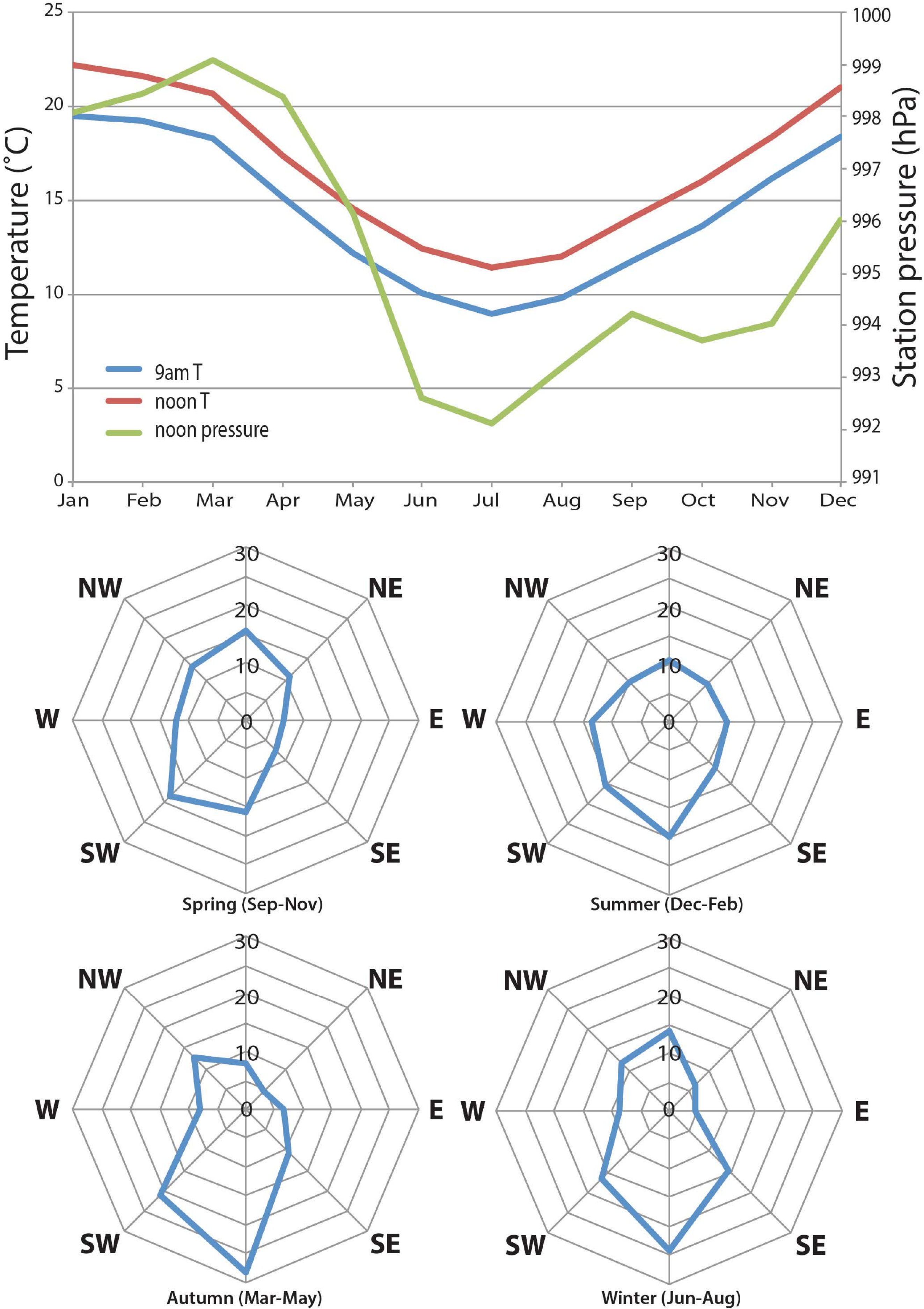
Day	Date	Therm. at 9 A.M.	Therm. at Noon	Barometer at Noon	Wind	General Remarks July 1849
Su	1	56	56	29.29	Northerly	Wet and rough with thunder
M	2	54	55	29.26	N. Westerly	Cloudy but dry.
T	3	47	54	29.20	S. Easterly	Heavy Showers
W	4	53	58	29.25	S. Easterly	Cloudy
Th	5	54	57	29.28	Southerly	Light Showers
F	6	52	53	29.24	S. Westerly	Heavy Showers Full Moon
S	7	55	56	29.27	N. Westerly	Dry
Su	8	55	57	29.28	N. Westerly	Showers
M	9	49	54	29.28	N. Westerly	Fine. Lightning in the evening
T	10	48	51	29.28	N. Westerly	Showery
W	11	48	48	29.28	S. Easterly	Showery
Th	12	49	49	29.29	Southerly	Showery
F	13	46	48	29.26	Southerly	Heavy Showers - wind strong
S	14	45	48	29.38	Southerly	Showery
Su	15	48	50	29.38	Southerly	Showery - wind strong
M	16	49	50	29.45	Southerly	Dry but cloudy and cold
T	17	48	50	29.45	South	Dry but cold
W	18	48	50	29.33	Variable	Showery
Th	19	52	51	29.32	N. Easterly	Continual rain, but little wind
F	20	47	50	29.28	N. Westerly	Dry. New Moon
S	21	48	52	29.24	N. Westerly	Showers
Su	22	51	54	29.26	N. Westerly	Showery
M	23	48	51	29.26	S. Westerly	Showery
T	24	49	55	29.22	S. Westerly	Hail Showers
W	25	48	49	29.20	Variable	Continual rain wind moderate
Th	26	49	50	29.20	South	Showery
F	27	46	49	29.20	South	Showery dirty weather
S	28	48	50	29.10	S. Westerly	Showery
Su	29	47	48	29	N. Westerly	Very dirty weather. Hail
M	30	42	46	28.90	S. Westerly	Hail storms. This morning the Southern hills & [illegible] covered with snow.
T	31	46	51	29.15	S. Westerly	This morning the hills were again covered with snow



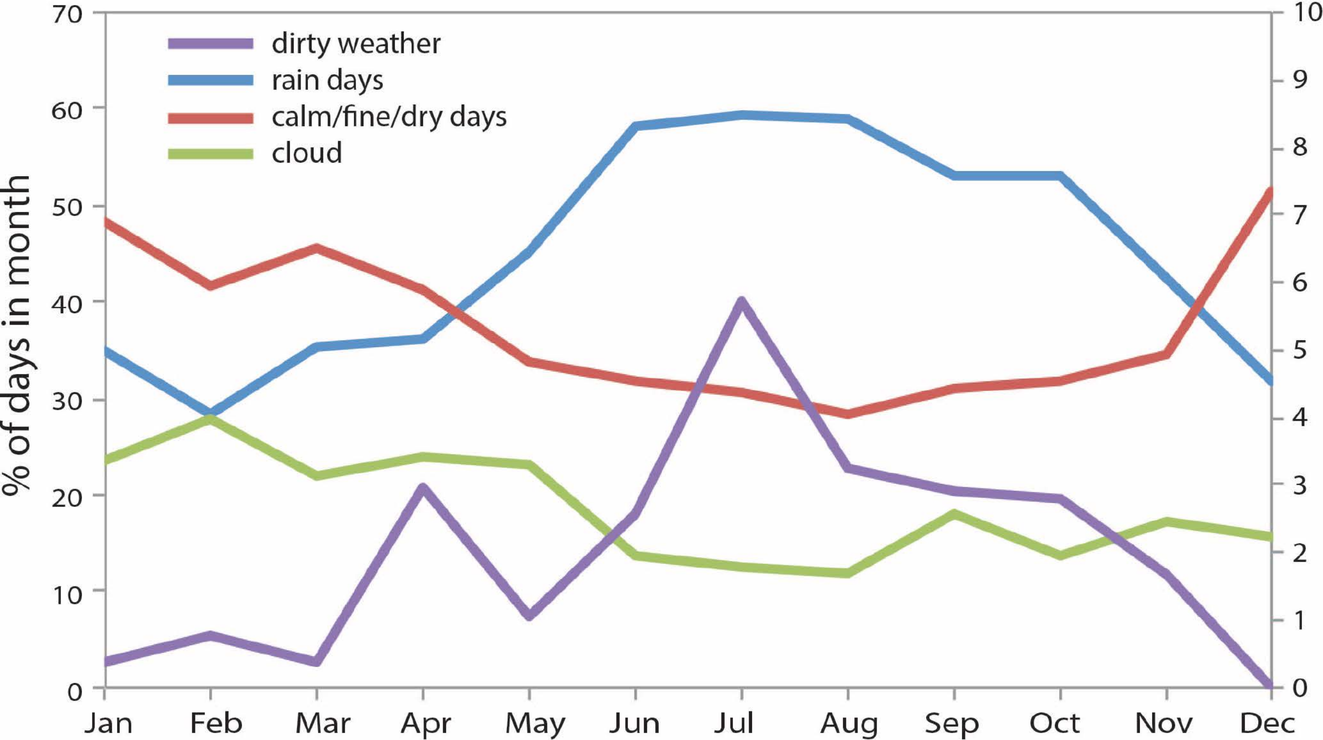
Northland
New Zealand
Southwest Pacific
Australia
New Caledonia
Fiji
New Zealand
10°N
0°
10°S
20°S
30°S
40°S
50°S
135°E
145°E
155°E
165°E
175°E
175°W
165°W
155°W
145°W
Lake
River
Highway
Town
0
10
20
40
Kilometres
N
°C
18
17
16
15
14
13
12
11
Kaitaia
Bay of Islands
Waimate North
Kaikohe
WHANGAREI
Dargaville
Ground frosts (on temperature plot below)
>2% days with frost
1-2% days with frost
0-1% days wth frost
Rainfall (mm)
500
400
300
200
100
0
J F M A M J J A S O N D
Temperature (°C)
30
20
10
0
J F M A M J J A S O N D
Highest Recorded
Mean Monthly Maximum
Mean Daily Maximum
Mean
Mean Daily Minimum
Mean Monthly Minimum
Lowest Recorded
Highest Monthly Total
90 percentile Value
Mean
10 percentile Value
Lowest Monthly Total

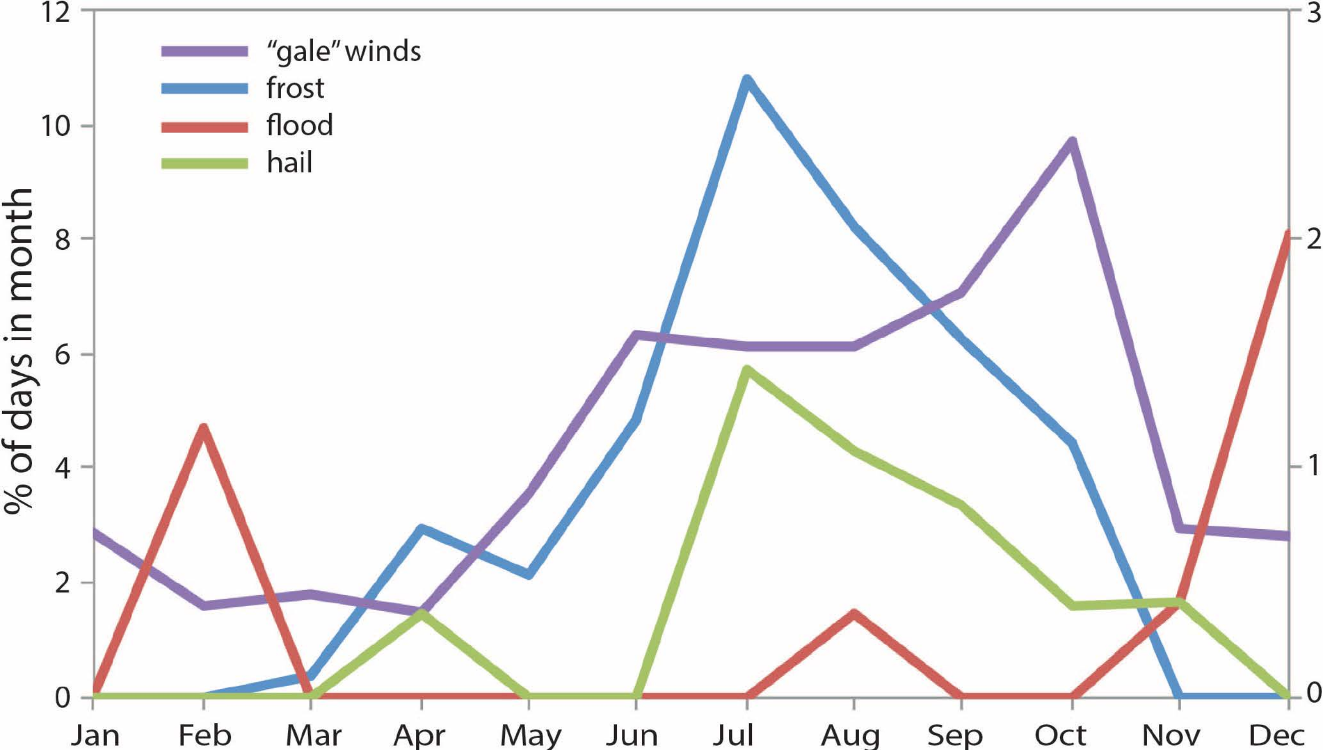


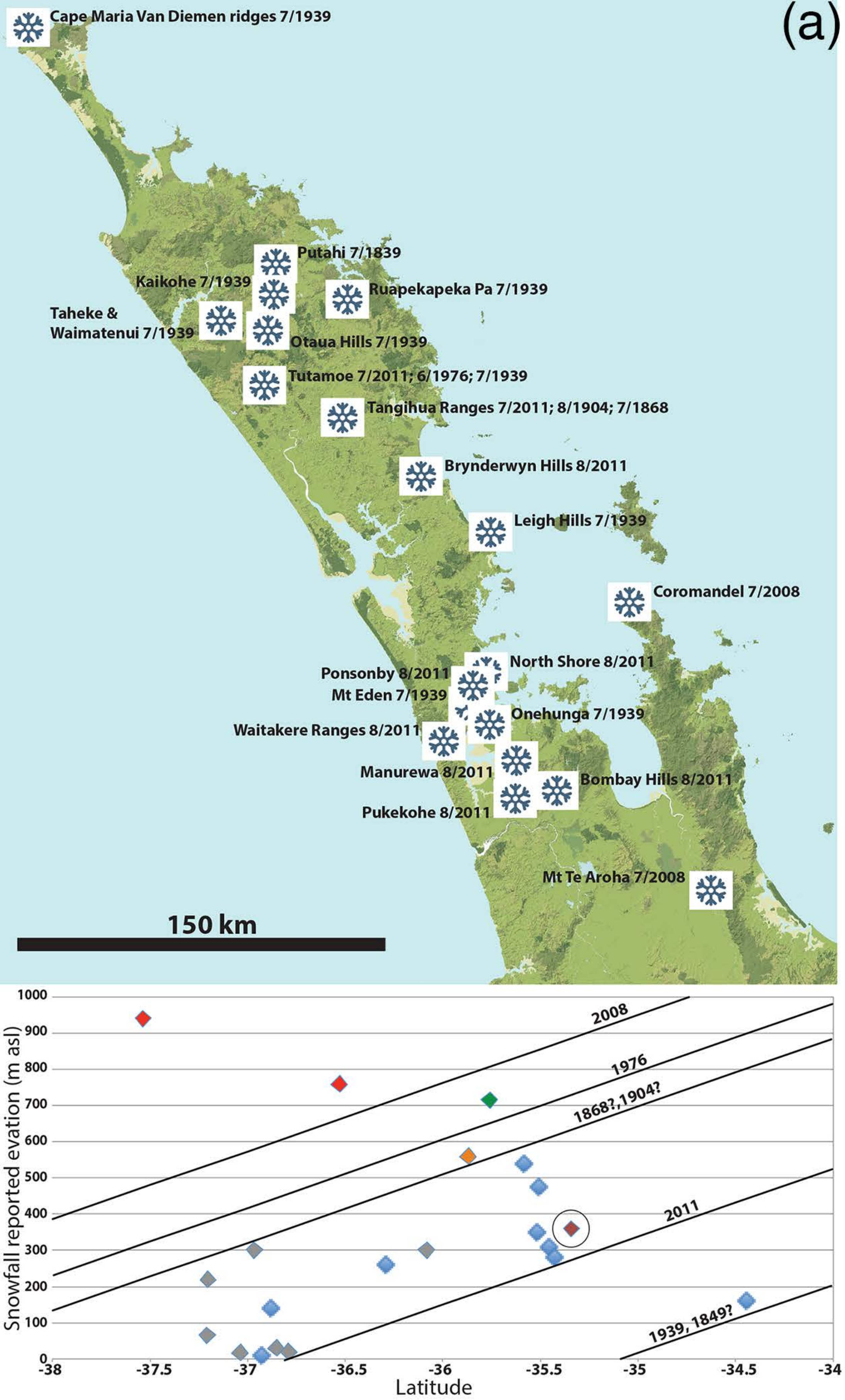
Noon barometric pressure (hPa)
1020
1010
1000
990
980
970
960
950
1839
1840
1841
1842
1843
4
8
12
y = 1.2036x - 5.3322
R^2 = 0.86136
Pressure from ships anchored in Bay of Islands (inches Hg)
Davis pressure measurements (inches Hg)
30.5
30.0
29.5
29.0
28.5
28.7
28.9
29.1
29.3
29.5
29.7
29.9
USS Vincennes
Astrolabe/Zelee
HMS Erebus
Ship
Davis
Surface pressure (inches Hg)
30 March - 06 April1840
30 Apr - 04 May 1840
19 - 31 August 1841
Daily observations

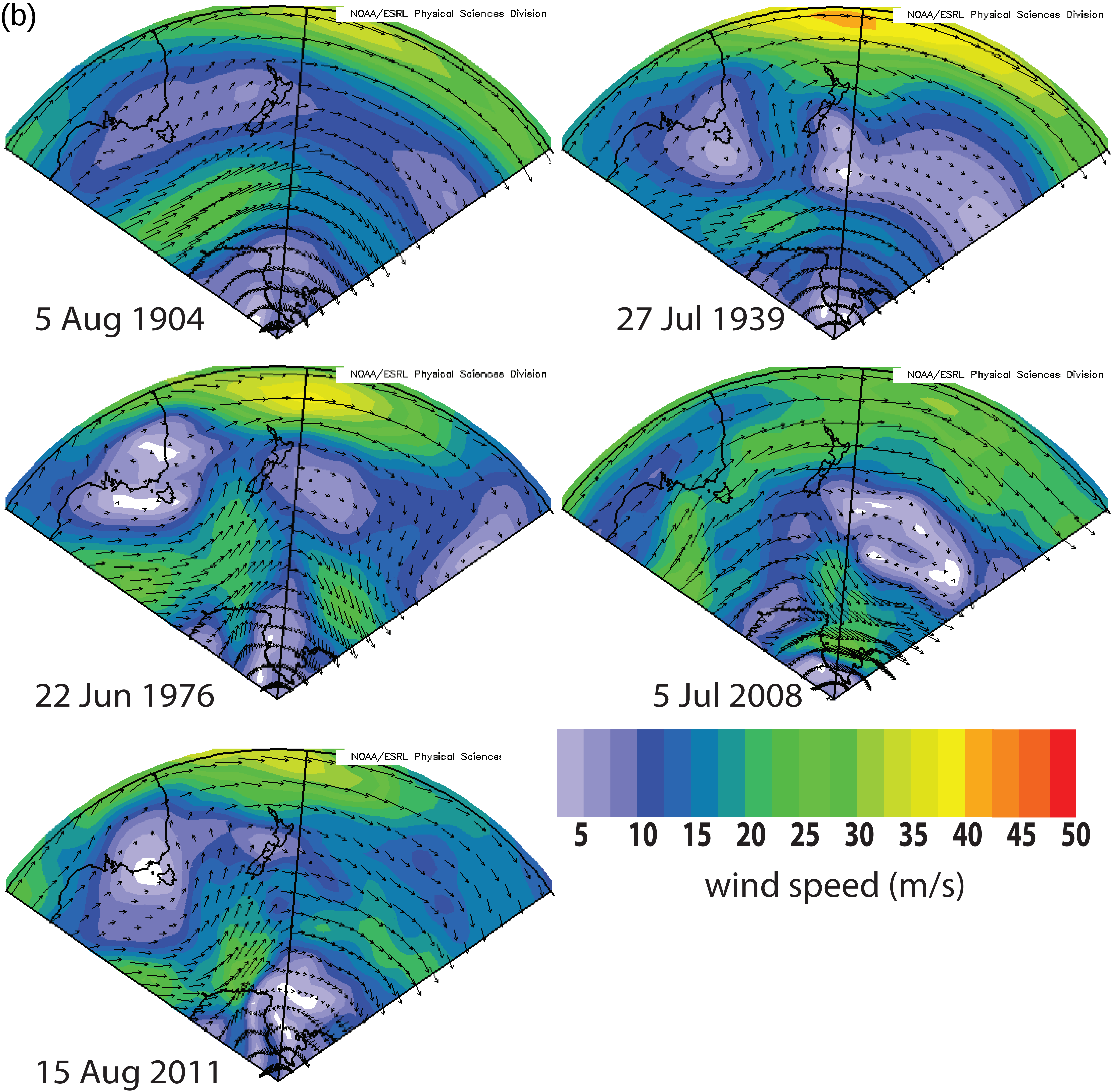


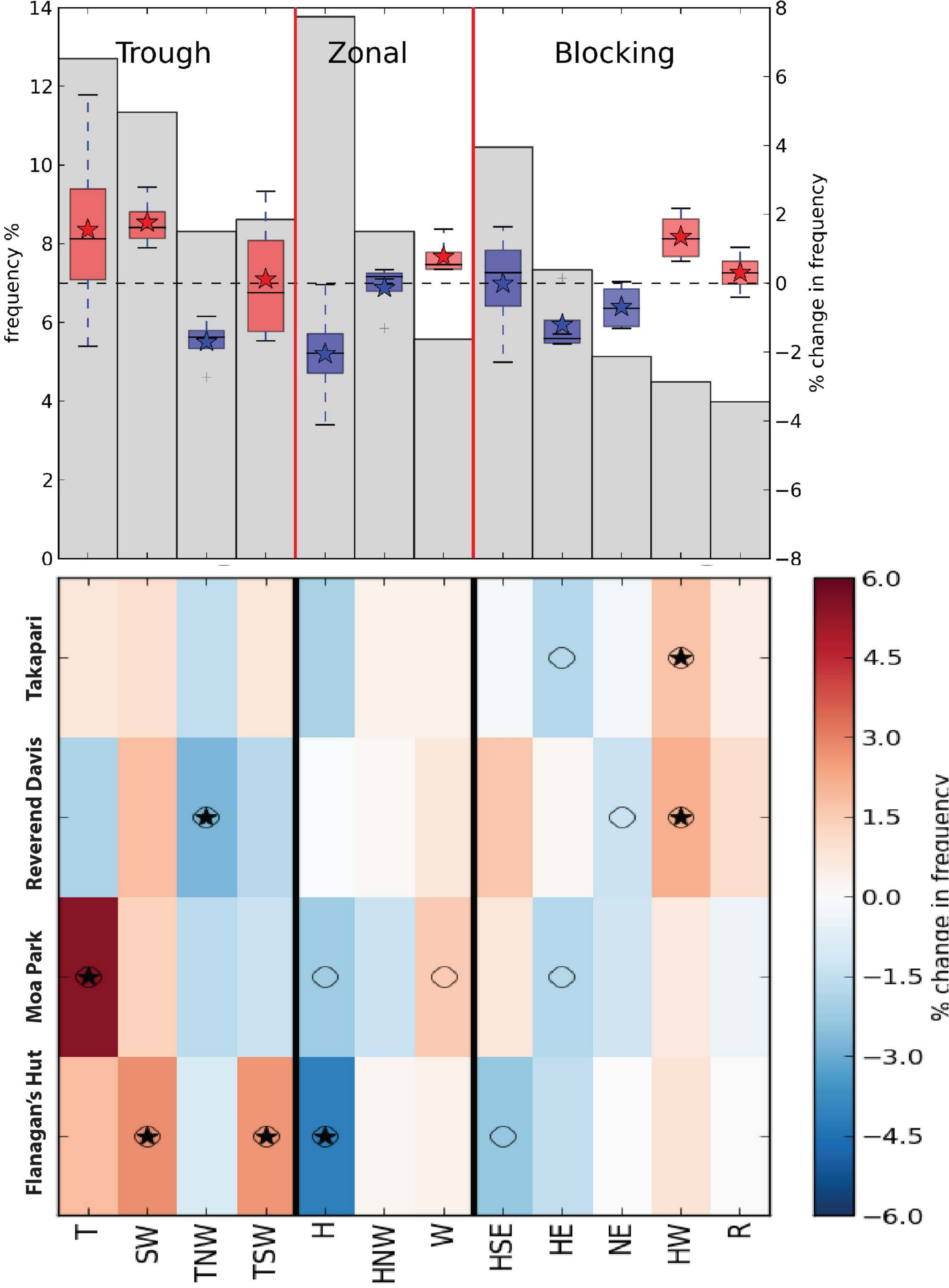
Temperature (°C)
Station pressure (hPa)
9am T
noon T
noon pressure
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Spring (Sep-Nov)
Summer (Dec-Feb)
Autumn (Mar-May)
Winter (Jun-Aug)
NW
NE
W
E
SW
SE


dirty weather
rain days
calm/fine/dry days
cloud
% of days in month
70
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

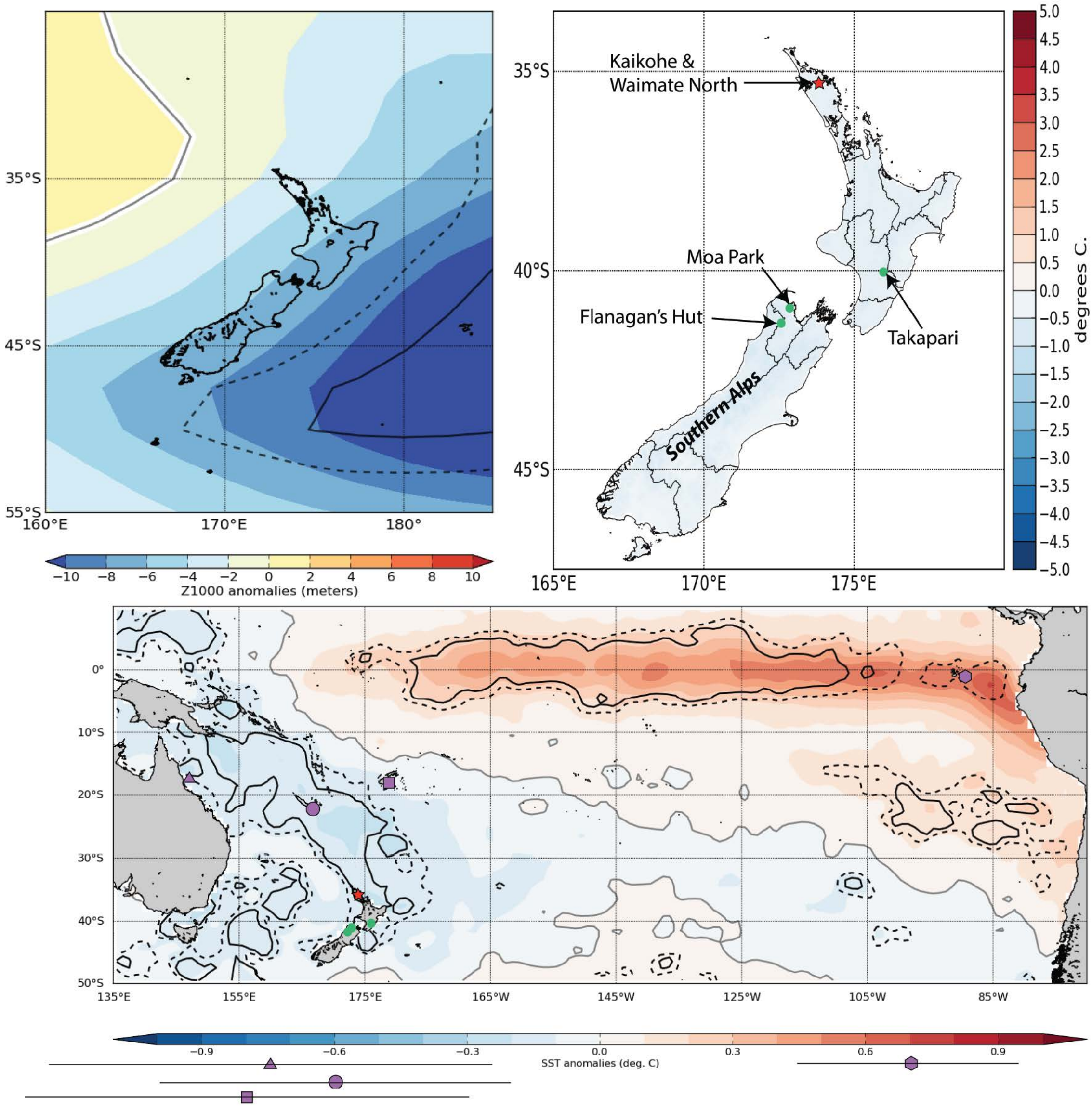

"gale" winds
frost
flood
hail
% of days in month
12
10
8
6
4
2
0
3
2
1
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


(a)
Cape Maria Van Diemen ridges 7/1939
Putahi 7/1839
Kaikohe 7/1939
Ruapekapeka Pa 7/1939
Taheke & Waimatenui 7/1939
Otaua Hills 7/1939
Tutamoe 7/2011; 6/1976; 7/1939
Tangihua Ranges 7/2011; 8/1904; 7/1868
Brynderwyn Hills 8/2011
Leigh Hills 7/1939
Coromandel 7/2008
North Shore 8/2011
Ponsonby 8/2011
Mt Eden 7/1939
Onehunga 7/1939
Waitakere Ranges 8/2011
Manurewa 8/2011
Bombay Hills 8/2011
Pukekohe 8/2011
Mt Te Aroha 7/2008
150 km
2008
1976
1868?,1904?
2011
1939, 1849?
Snowfall reported evation (m asl)
0
100
200
300
400
500
600
700
800
900
1000
-38
-37.5
-37
-36.5
-36
-35.5
-35
-34.5
-34
Latitude

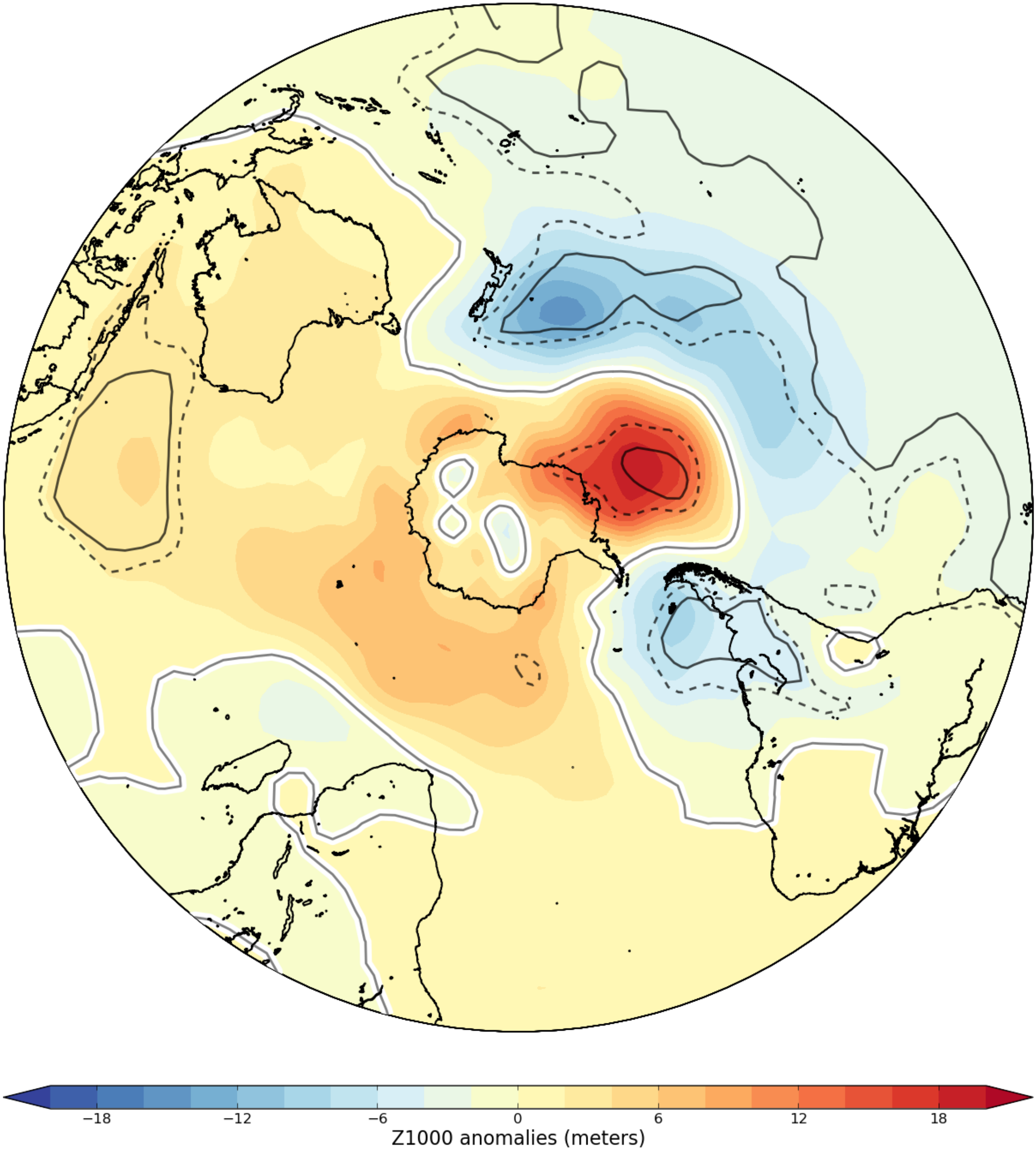

(b)
NOAA/ESRL Physical Sciences Division
5 Aug 1904
NOAA/ESRL Physical Sciences Division
27 Jul 1939
NOAA/ESRL Physical Sciences Division
22 Jun 1976
NOAA/ESRL Physical Sciences Division
5 Jul 2008
NOAA/ESRL Physical Science
15 Aug 2011
5 10 15 20 25 30 35 40 45 50
wind speed (m/s)



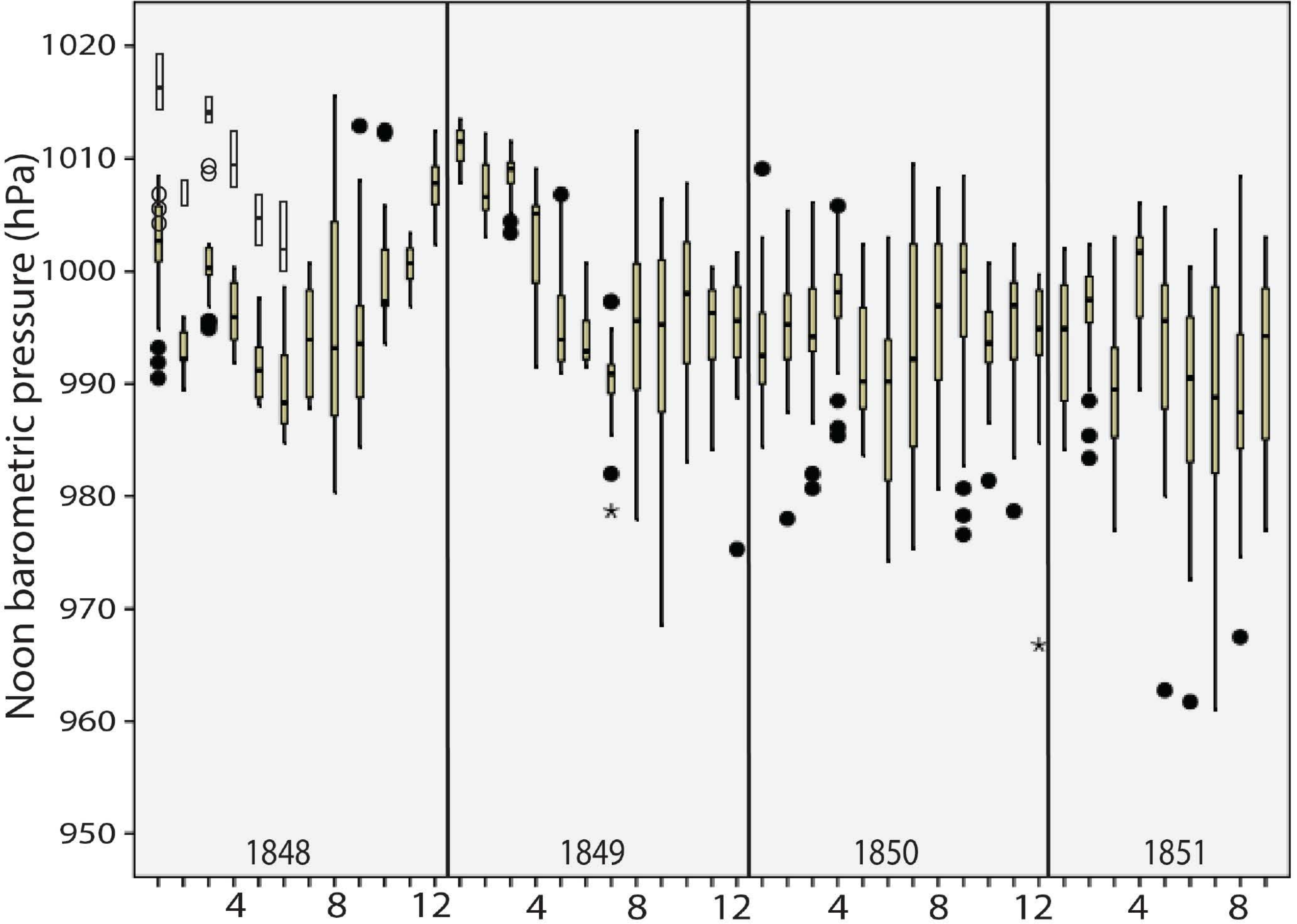
Trough
Zonal
Blocking
frequency %
% change in frequency
Takapari
Reverend Davis
Moa Park
Flanagan's Hut
T
SW
TNW
TSW
H
HNW
W
HSE
HE
NE
HW
R
6.0
4.5
3.0
1.5
0.0
−1.5
−3.0
−4.5
−6.0



35°S
45°S
55°S
160°E
170°E
180°
−10 −8 −6 −4 −2 0 2 4 6 8 10
Z1000 anomalies (meters)
Kaikohe &
Waimate North
Moa Park
Flanagan's Hut
Takapari
Southern Alps
40°S
165°E
175°E
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 −0.5 −1.0 −1.5 −2.0 −2.5 −3.0 −3.5 −4.0 −4.5 −5.0
degrees C.
0°
10°S
20°S
30°S
50°S
135°E
155°E
165°W
145°W
125°W
105°W
85°W
−0.9 −0.6 −0.3 0.0 0.3 0.6 0.9
SST anomalies (deg. C)



−18
−12
−6
0
6
12
18
Z1000 anomalies (meters)



Noon barometric pressure (hPa)
1020
1010
1000
990
980
970
960
950
1848
1849
1850
1851
4
8
12
4
8
12
4
8
12
4
8