Surface temperature trends and variability in New Zealand and surrounding oceans: 1871-2019

M.J. Salinger[1] , H.J. Diamond[2] and J.A. Renwick[1]

[1] *School of Geography, Environmental and Earth Sciences, Victoria University of Wellington, P. O. Box 600, Wellington, New Zealand*
[2] *NOAA/Air Resources Laboratory, College Park, Maryland 20740, USA*

Correspondence: jimbosalinger09@gmail.com ORCID: 0000-0002-5782-1411

Key words: New Zealand, surface temperature trends, temperature variability, sea surface temperature, anthropogenic global warming, CMIP5, Southern Annular Mode, Interdecadal Pacific Oscillation, El Niño Southern Oscillation, volcanic eruptions.

Abstract

We compare homogenised series of maximum, minimum, and mean air temperature averaged over New Zealand (NZ) for the period 1871-2019, with surrounding ocean surface data. Temperatures over the New Zealand Exclusive Economic Zone exhibit an increase (linear trend) of 0.66°C from 1871-2019. As well as the anthropogenic warming signal (identified by CMIP5 simulations), interannual to decadal variability is also examined. Significant volcanic eruptions have caused temporary cooling and the positive trend in the Southern Annular Mode is linked to warming over NZ. The influences of the Interdecadal Pacific Oscillation (IPO) and the El Niño/Southern Oscillation (ENSO) are also evident in the temperature series. All warm years (>+0.45°C above the 1981-2010 normal) occur from 1998 onwards, and all of the nine cold years (<-0.84°C below the 1981-2010 normal) occur prior to 1933. We conclude that the climate teleconnections that cause interannual to decadal variability (ENSO and IPO) are key factors in these results, beyond the anthropogenic warming signal.

1. Introduction

The New Zealand (NZ) region, including the entirety of its Exclusive Economic Zone (EEZ), an area of 4 million km^2, represents a significant area in the southwest Pacific, and is of similar size to the Indian subcontinent. NZ lies in the South Pacific Ocean, largely in the temperate zone, but extending into the sub-Antarctic zone in the south.

This study examines variations and trends in air and sea surface temperature (SST) for New Zealand's Exclusive Economic Zone (EEZ) area using a network of 22 surface air temperature series (NZ22T) and SST from the surrounding oceans in the New Zealand Exclusive Economic Zone, from 1870 to 2019. Land and SSTs are combined to form a combined temperature series (NZEEZT). New Zealand land surface temperature data, which have been adjusted for inhomogeneities, have been demonstrated to be consistent with SSTs from 1870 (Folland and Salinger, 1995). In this paper we document trends and variability in NZ22T combined with Extended Reconstructed Sea Surface Temperature version 5 (ERSST, Huang et al., 2017) for the New Zealand region to NZEEZT on annual to multidecadal time scales. We investigate relationships with anthropogenic global warming (AGW) associated with human-induced increases in atmospheric

Submitted: 28 November 2019
Accepted: 13 November 2020

greenhouse gas concentrations by comparing with temperature series from CMIP5 simulations, with major volcanic eruptions, and with the Southern Annular Mode (SAM), El Niño/Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO).

The extent to which historic temperature data are adequate to describe regional trends and variations over the land and the oceans is an open question. For the land surface, issues arise because artificial changes can be introduced, such as variations in the exposure of thermometers (Parker, 1994), alterations in observing methods and times (Karl et al., 1986) and changes in the environment surrounding climate sites, such as those due to urbanization (Jones et al., 1990; Karl et al., 1993). Sea surface temperature data have also suffered from artificial changes caused mainly by differences in the methods of observation. In the mid- to late nineteenth century wooden buckets were often used to collect seawater and were largely replaced by uninsulated canvas buckets by the early 20th century. A further change to the predominant use of engine intake thermometers occurred in the early part of the Second World War, followed by the development of insulated sea-water buckets (Bottomley et al., 1990; Folland and Parker, 1995). The parametric uncertainty, including measurement and sampling errors, and variability of the (ERSSTv5) dataset is depicted in Figure 1 of Huang et al. (2018). The uncertainties are generally larger in the earlier period (1854–1900) than the latter periods of 1900–50 and 1950–2010. For the area of study in this paper, the uncertainties in SST were less than 0.4°C from 1854-1900, around 0.2°C from 1900-1950, and less than 0.2°C from 1950 to the present.

Previous work on New Zealand land temperature trend has focused on the "seven-station series" (7SS); Mullan et al. (2012) noted that the linear trend in the 7SS was +0.91°C/century in the period 1909-2009. The 95% confidence interval on the calculated linear trend was ±0.29 °C/century. Three global products that apply to land temperature (GISS, NOAA, HadCRU4), over the period 1909-2015 show linear trends of +1.12°C, +1.16°C and +1.03°C/century respectively. A significant contribution to the warming can be attributed to greenhouse gas increases (Dean and Stott, 2009).

Several studies have described temperature variability in the NZ region associated with various climate teleconnections. The Southern Annular Mode (SAM) operates on shorter than annual time scales and describes north-south meandering of the eddy-driven jet over the Southern Oceans and the associated storm track (Kidston et al., 2009). A positive SAM phase is associated on average with temperatures at least 0.5°C above normal throughout western parts of the North and South Islands, resulting from weaker than normal westerly winds. In the negative phase, the SAM shows the opposite, with cooler temperatures in the west of both islands. Kidston et al. (2009) note that these temperature anomalies are much stronger in summer (December-February) than in winter (June-August). The SAM has trended increasingly positive during the 20th century contributing to a warming trend over NZ (Arblaster et al., 2011).

For interannual relationships, Gordon (1986) found that land surface air temperatures in NZ were positively correlated with the Southern Oscillation Index (SOI, Troup, 1965). In the El Niño phase, NZ experiences more frequent and stronger than normal southwesterly winds. This generally results in lower temperatures for New Zealand. The La Niña phase is essentially the opposite of El Niño. New Zealand experiences more northeasterly flows, higher temperatures and air pressure tends to be higher than normal over the South Island. The most notable El Niño years with cooler than normal temperatures occurred in 1905, 1912, 1919, 1941 and 1965. Much warmer than normal years associated with La Niña episodes occurred in 1917, 1971, 1999 and 2018.

Interdecadal climate variability in the Pacific is driven by the IPO (Parker et al., 2007; Power et al., 1999). The partition between recent IPO phases occurred at 1945, 1977 and 1998 (Salinger et al., 2001, Henley et al., 2015). The IPO phases induce decadal variations in NZ climate variability, especially temperature change. Changes in mean annual surface air temperatures from the IPO positive to IPO negative phases (1946-1976 compared with 1930-1945, and 1998-2019 compared with 1977-1997) show accelerated warming over much of the region. During the two later 20th century IPO positive phases regional warming slowed (Salinger and Mullan, 1999).

Finally, explosive volcanic eruptions (Kelly et al., 1996) cause climate impacts for up to 30 months. Examination of six eruption events (Krakatau (1883); Tarawera (1886), Pele, Soufrire and Santa Maria (all 1902); Agung (1963); El Chichon (1982) and Pinatubo (1991)) found good agreement between the spatial patterns of temperature anomalies associated with these events. The composite response shows cooling of just under 0.2°C on average globally; the response is strongest and statistically significant over a 2-year period starting early in the year after the eruption. The total area in which statistically significant departures are found is considerable. Volcanic eruptions in tropical latitudes can be global in their effect, whilst those in temperate latitudes only affect those regions in the eruption hemisphere (Robock, 2003). Robock and Free (1995) conclude that for both hemispheres there is no evidence of an impact of volcanic eruptions on El Niño/Southern Oscillation (ENSO) events. Salinger (1998) documented the impacts of major volcanic eruptions which inject significant amounts of dust and sulphate aerosols into the atmosphere on atmospheric circulation and temperatures for the six major volcanic events above on NZ. The effects commenced rapidly, in the first few months after the volcanic eruption and lasted 24 months on average, with surface temperatures depressed in the region by 0.3°C to 0.4°C from one to 21 months after the eruption. Atmospheric circulation anomaly patterns show more patterns of south westerlies and troughs.

2. New Zealand's temperature data

Land Surface Temperature

Daily maximum and minimum temperature measurements in New Zealand were irregular until 1859, when the Colonial Secretary of the time, Mr Stafford, supplied standard instruments to observers at eight locations. Responsibility for meteorological stations was transferred to Sir James Hector, Director of the Colonial Museum and Geology Department, in 1867, and he introduced unusually uniform and rigorous methods of observation (Hector, 1869). These included the use of Stevenson screens throughout the network, probably the earliest attempt to do this in any country. The temperatures measured used high-quality sheathed thermometers read at 0930 New Zealand Standard Time (NZST) which were regularly checked for calibration. Since then, instruments and observation methods have remained the same except for a change in the definition of NZST from the mean noon fixed at 172°E to use mean noon at 180°, and an observation time change to 0900 NZST. Standard reporting forms and meteorological notebooks for entering the recordings at the time of observation were also introduced. Indeed, every effort was made to make the observations at best international standards, which has lasted to the present.

The concept of New Zealand's seven-station series (7SS) was developed by Salinger (1980, 1981) based on long term stations. Salinger et al. (1992) homogenised temperature for 24 reference climate stations, which included the 7SS as a subset. The homogenisation of climate data is a process of calibrating old meteorological records to remove spurious factors which have nothing to do with the actual temperature change.

Daily maximum and minimum temperatures, using mercury, glass and alcohol in glass self-registering thermometers, were homogenised at these NZ climate stations including 22 stations, termed NZ22T (Figure 1). The homogenisation was necessary because some of these locations had observations at more than one site. These are distributed evenly over the land area of New Zealand, 11 in the North Island, and 11 in the South Island, and is representative of New Zealand regional climate. The two stations not used of the 24 were remote offshore islands far away from the main islands of NZ. Records were screened for inhomogeneities by examining station histories and comparisons were made between neighbouring stations to identify unrecorded site changes or other environmental changes near the climate station sites. Procedures used to homogenise the data (Rhoades and Salinger, 1993) included cumulative sum plots and neighbouring station comparisons. For a few early records where neighbouring stations do not exist, other techniques were used to evaluate the significance of, and make adjustments for, suspected inhomogeneities (Rhoades and Salinger, 1993). This included the estimation of the size and standard error of a change point (discontinuity) in the temperature time series by (i) using manual data before and after the change points, (ii) using monthly data for specified symmetric intervals before and after the discontinuity, and (iii) estimating the most likely change points using the size of the change from an appropriate average.

Mullan et al. (2010, 2012) re-analysed the 7SS over the period 1909-2010 with the key result is that the NZ-wide warming trend from the 7SS series trend is +0.91 °C/century, which is identical to the previous estimate of +0.91 °C/century from Salinger et al. (1992). From 1870-80 10 stations were available, this reduced to six from 1881-1895, seven from 1895-1909, increasing to 14 from 1910–1930, 18 from 1931-1940 then 22 from 1940 onwards. The correlation between 7SS and NZ22T on all time scales starting across all decadal intervals (viz 1871-2019, 1881-2019 etc.) from 1871-2019 is 0.99.

The first conjoint analysis of trends and variability of both land and marine surface temperatures in the NZ region was by Folland and Salinger (1995) with later publications by Folland et al. (1997, 2003). Folland and Salinger (1995) concluded that the observed trend and shorter-term variations in the 7SS are in excellent agreement with those of nearby SST. Folland et al (2003) note *non detrended* standard deviations and correlations with annual land data from eight New Zealand stations, and marine series, are 0.35°C, 0.83 for SST and 0.32°C, 0.85 respectively with night marine air temperature series over the period 1870-1998. Folland et al. (2003) concluded that consistency between the land and marine temperature series both seasonally and interannually is very good. Mullan et al. (2010) found that the spatial pattern in the warming is consistent with changes in SST around NZ. More warming occurred in the north of the country, and less warming in the south.

Sea Surface Temperature

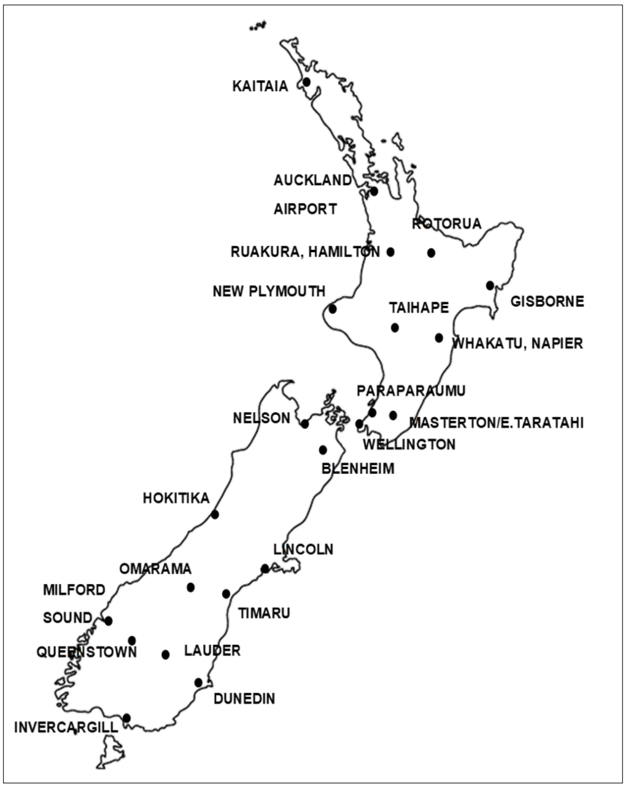

Figure 1: Location of 22 stations to measure land surface temperature (NZ22T) after Salinger (1992). The 7SS is a subset of NZ22T, which includes Mangere (Auckland), Kelburn (Wellington), Masterton, Nelson, Hokitika, Lincoln and Dunedin.

The SST data set used for the NZ region was taken from the ERSSTv5 of Huang et al. (2017, 2018). The monthly global ERSSTv5 has been revised to incorporate a new release of ICOADS release 3.0 (R3.0), a decade of near-surface data from Argo floats, and a new estimate of centennial sea ice from HadISST2. The resulting ERSST estimates have more realistic spatiotemporal variations, better representation of high-latitude SSTs, and ship SST biases are now calculated relative to more accurate buoy measurements, while the global long-term trend remains about the same. These data extend back to 1854. SST data from ERSSTv5 from 2°x2° grid points (83) from within New Zealand's Exclusive Economic Zone (EEZ) (Figure 2) between 32-54°S, 162°E-176°W were averaged to form a monthly ERSST series around New Zealand. The averaging done in the analysis here was an area-weighted average by using the cosine of latitude, given the significant convergence of meridians across the latitude range of 32-54°S.

The accuracy of SST analyses is mostly dependent on how the biases of observations from different instruments are corrected (Kent et al., 2017). Huang et al. (2017) suggested that the globally-averaged SST in the ERSSTv5, is systematically about 0.1°C lower than the previous version, ERSST.v4 (Figure 1, from Huang et al. (2018)-solid black and red lines). The lower SST in ERSST.v5 results from the biases of ship observations adjusted to more accurate or homogeneous buoy observations. The quality-controlled SST data were bin-averaged to 2°x2° grid boxes at a monthly timescale from 1920 to 2016, and globally integrated numbers and area coverages of observations were calculated. The area coverage is a ratio of the total gridbox area containing observations over the total ocean area. Calculations show that numbers of observations are solely from reversing thermometers (RT) attached to Nansen–Niskin hydrographic bottles; conductivity–temperature–depth (CTD RT/CTD) over the timeframe from 1920–40, dominantly from mechanical bathythermographs (MBT) and RT/CTD over 1940–70,

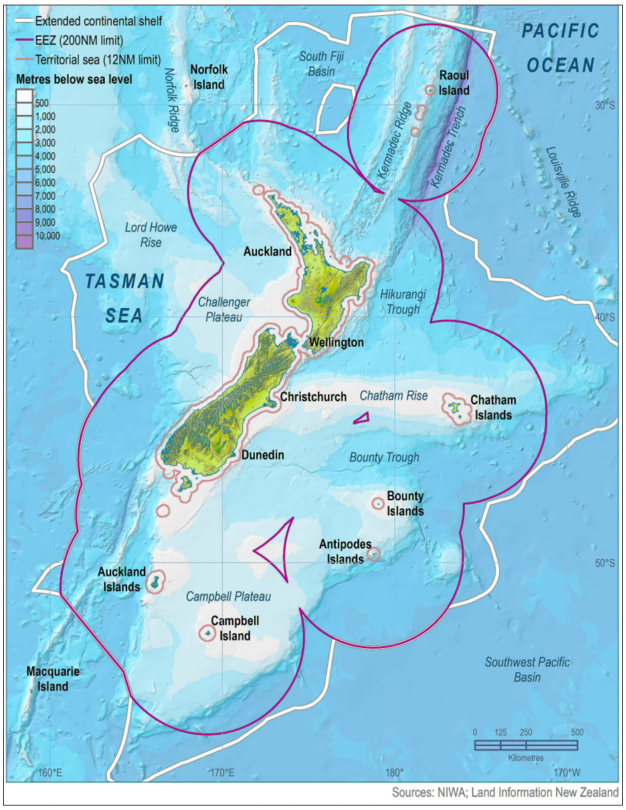

Figure 2: New Zealand's exclusive economic zone. Source: https://www.mfe.govt.nz/publications/marine-environmental-reporting/our-marine-environment-2016-introduction-our-marine

and mostly from expendable bathythermographs (XBT) and RT/CTD over 1970–2010 (as noted in Figure 2a of Huang et al., 2017). Bottomley et al. (1990) found that a monthly 5°x5° SST value is considered usable if it contains at least one quality-controlled data value; and with the ERSSTv5 dataset meeting this threshold at a resolution of 2.5ºx2.5º resolution, we feel confident in the validity of the data prior to 1920. Uncertainties in the ERSSTv5 dataset are generally less than 0.4°C from 1854-1900, around 0.2°C from 1900-50, and less than 0.2°C from 1950 to the present (Huang et al., 2016, 2019).

Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations

CMIP5 experiments with coupled atmosphere-ocean global climate models, most of which were reported on in the IPCC Fifth Assessment Report, Working

Group I, used the average of all suitable CMIP5 model simulations for 1900-2015 which had AGW and natural variability runs (NAT) (B. Mullan pers. comm., for sea surface temperatures for the New Zealand region (35-50°S, 160°E-180°), 13 CMIP5 models were suitable). The methodology is that of Flato et al. (2013). The CMIP5 (AGW) trends and 95% confidence interval are shown in Figure 3. These simulations show the magnitude of the AGW warming signal compared with NAT over time, and do not relate to any time period.

Circulation indices

Indices of variability used were the extended Gong and Wang (1999) SAM index (https://www.esrl.noaa.gov/psd/data/20thC_Rean/timeseries/monthly/SAM/sam.20crv2c.long.data). These were extended for 2012-2019 by regressions with the Marshall (2003) SAM index (https://legacy.bas.ac.uk/met/gjma/sam.html), with a correlation coefficient r = 0.87. The IPO from Henley et al. (2015) (https://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/tpi.timeseries.hadisst11.data) and the SOI (Troup (1965) (http://www.bom.gov.au/climate/current/soihtm1.shtml) were used, all of which extended back to the 1870s. The SAM, SOI and IPO are standardised indices (unit standard deviation).

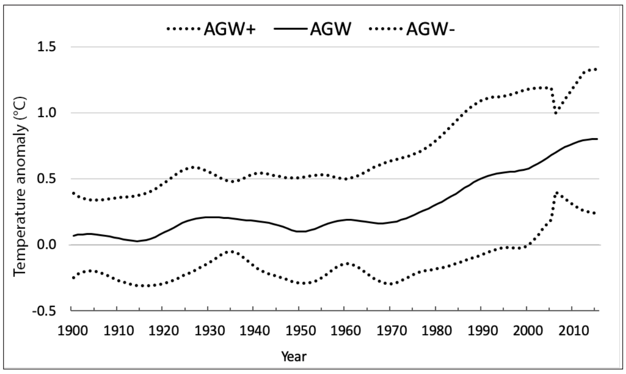

Figure 3: Warming in the New Zealand region (°C), (35-50°S, 160°E-180) from AGW 1900-2015. Time series are CMIP5 (AGW) models (solid) SSTs from 13 CMIP5 (AGW) models (solid) and 95% confidence interval (dotted) (AGW+, AGW-).

Atmospheric circulation patterns over New Zealand were characterized (as in Salinger et al., 2019) by correlating annual values of indices from the Kidson (2000) three regimes (Trough, Zonal and Blocking) for the period 1948-2019 and two of the Trenberth (1976) circulation indices Z1 (west-east zonal circulation) and M1 (south-north meridional circulation) from 1896-2019 (Table 1) with annual temperature anomalies. The values of the latter have been standardised for the 1896–2019 period.

Reanalyses

Two reanalysis data sets, ERA-Interim (Dee et al., 2011) and the Twentieth Century reanalysis (20CR, Compo et al., 2011) were used. ERA-Interim fields were obtained for the period 1979-2019 and 20CR for the period 1871-2014. Monthly mean anomaly fields were calculated as differences from monthly averages over the 30-year period 1981-2010 (used for both reanalyses).

3. Methods

Land and sea surface temperatures

The homogenised land data sets of Salinger et al. (1992) were updated, checked for homogeneity, and combined with the 7SS of Mullan et al. (2010). The pre-1909 records were rechecked with the homogenisations of Salinger (1981), Salinger et al. (1992) and Mullan (2012), by examination of maximum and minimum temperatures with the Rhoades and Salinger (1993) methodology, and careful examination of the limited metadata summary from Fouhy et al. (1992). The re-homogenised data were used to form a continuous monthly series of NZ22T from 1870–2019 with anomalies from the 1981-2010 climatological normal period. Table 2 shows the pre-1909 series adjustments compared with Salinger et al. (1992) and Mullan (2012). The twenty-two station values were averaged. The land and sea surface temperature series were combined to produce a weighted anomaly series from the

Table 1: Definitions of large-scale climate teleconnections, regional circulation indices (Trenberth, 1976) and Kidson (2000) Circulation Regimes affecting New Zealand

	Index	Definition	Wind anomaly (+/- index)
Climate Teleconnections	SAM	The zonal mean sea level pressure difference between 40° and 65°S	Weaker/stronger westerlies over the South Island.
	SOI	Normalised sea level pressure difference between Tahiti and Darwin	Northeast/southwest (over NZ).
	IPO	Pacific decadal SST anomalies - a long-term oscillation of sea surface temperatures in the Pacific Ocean that can last from 20 to 30 years.	West-southwest/east-northeast.
Trenberth Indices	Z1	Pressure difference between Auckland and Christchurch	Measures strength of westerlies over NZ: positive stronger, negative weaker westerlies.
	M1	Pressure difference between Hobart and Chatham Islands	Positive southerly, negative northerly airflow over NZ.
Kidson Regimes	Trough	Frequent troughs crossing the country.	
	Zonal	Highs to the north with strong zonal flow to the south of NZ	
	Blocking	Blocking patterns with highs more prominent in the south.	

1981-2010 period according to the following surface areas (ERSSTv5 4,083,744 km^2, NZ22T 268,680 km^2 or 15:1), where NZEEZT is 15/16*ERSST + 1/16*NZ22T. Vose et al. (2012) addresses this in creating a global combined ocean/land dataset. This dataset is well-recognized and states the following: "The reconstruction process dictates that Land Surface Temperatures (LST) and SSTs should be processed separately and then merged together into a single reconstruction".

There are several reasons for performing separate reconstructions, the first being major differences in spatial coverage between the land and ocean surface (the latter having systematic gaps early in the record). Another motive for separate reconstructions is that LST and SST observations are fundamentally different; a land grid box represents at least one month of daily observations from at least one station, whereas in an ocean grid box observation frequency is quite different. Although the combined series are heavily weighted by the ERSSTv5, it is valid to combine these for the NZ region so as to obtain values representative of all the area NZ has jurisdiction over for its economy, particularly for fisheries. The LST is relevant for the agricultural economy. The work documented by Vose et al. (2012) coupled with the work of Smith and Reynolds (2005) and Smith et al. (2008) document how to merge a land and ocean database as to what has been done in this paper.

Table 2: Adjustments of the pre-1910 time series for the 7SS compared with Salinger et al. (1992) and Mullan (2012) in °C

Time period	Salinger et al. (1992)	Mullan (2012)
1870-1880	-0.08	-0.10
1880-1900	+0.03	-0.09
1900-1910	+0.03	+0.07

Trends, Variability and Extremes

Detrended annual values were also generated for the NZEEZT area by subtracting out linear trends (Mullan et al., 2016) from NZ22T, ERSST and NZEEZT. Temporal relationships with atmospheric teleconnections of variability, using actual and linearly detrended data, were examined as follows: (1) major volcanic eruptions; (2) the

SAM for both trends and annual periods; (3) the SOI for interannual periods, and (4) the IPO for decadal periods. Bivariate correlations were used to identify relationships between both forcing of temperature by AGW, and teleconnections with SAM, SOI and the IPO. Multiple linear regression was used to explore multivariate relationships between NZEEZT and these four factors.

For the analysis of the ERSSTv5 data in the NZ EEZ region we performed a fairly straightforward (averaged over the New Zealand box) for the following 5 timeframes of 1871-1900; 1901-30; 1931-60; 1961-90; and 1991-2019; and examined the distribution of those anomalies (not shown). The distributions do not change significantly, and the variances across all five time periods are all comparable. A consultation with the ERSSTv5 developer (personal communication, Huang, September 2020) concurred with our finding that the SST trend is relatively strong in the NZ region, with the difference between the 1901-1930 and 1990-2019 30-year time periods being at +0.65°C, and, when 20-year averages are used, the difference between the 1901-1920 and 2001-2019 time periods is +0.82°C. This is also confirmed in a study of global SST trends in a prior version of ERSSTv5 (e.g., ERSSTv4), and that analysis indicated that the SST trend from 1901-2014 was relatively strong as well (Huang et al., 2016).

Analogues

To determine circulation features associated with extremely warm and cold years, sea-level pressure and 500hPa height anomalies for the two reanalyses were extracted for the warmest and coldest years in the actual and NZEEZT-AGW series. Anomaly values chosen for the 5th and 95th percentile values respectively (>+0.45°C and <-0.84°C) for the NZEEZT series which yielded 7 warm (1971, 1999, 2001, 2013, 2016, 2017, 2018) and nine (1902, 1903, 1906, 1912, 1919, 1926, 1930, 1931, 1932) cold cases respectively. For the NZEEZT-AGW series, the 5th and 95th percentile values were also chosen ranged from >+0.15°C and <-1.05°C, yielding four warm (1916, 1917, 1962, 1971) and six cold (1902, 1906, 1930, 1931, 1992, 1993) cases respectively. For this sample the four warm years were different, and the cold years the same.

4. Results

Homogenisations

Comparisons of NZ22T with the 7SS from Mullan (2012) and Salinger et al. (1992) show the very small adjustments made during the pre-1909 period (Table 2). These are -0.10°C and -0.08°C lower than Mullan et al. (2012) and Salinger et al. (1992) respectively for the 1870-1880 period, and -0.09°C lower with Mullan et al. (2012) and +0.03°C higher than Salinger et al. (1992) for the 1881-1900 period. For the period 1900–1910 the differences are +0.07°C and +0.03°C compared with Mullan et al. (2012) and Salinger et al. (1992) respectively. From 1909 the series is similar to Mullan et al. (2012) with the use of data from more stations to a maximum of the 22 stations.

Variability

From 1870-1895 temperatures were 0.4°C below the 1981-2010 normal, then decreased to 0.8°C below normal in the early 1900s (Figure 4). It was cooler by a similar amount again in the early 1930s; both these periods being the coolest in the temperature record. During the 1910s, 1920s and 1940s mean temperatures were 0.4°C below normal. Temperatures subsequently were near normal in the 1950s, 1970s and 1980s, with a brief cooler excursion in the 1960s. Temperatures subsequently decreased sharply to around 0.5°C below normal in early 1990s, then increased rapidly to 0.1°C above normal, then averaged 0.4°C above normal for the 2010-2019 period. On an annual basis the impacts of major volcanic eruptions clearly show a decrease in most cases by about 0.5°C for 12 to 18 months from the relevant decadal averages. The six major volcanic eruptions that affected New Zealand climate depressed temperatures briefly between 0.3 to 0.5°C.

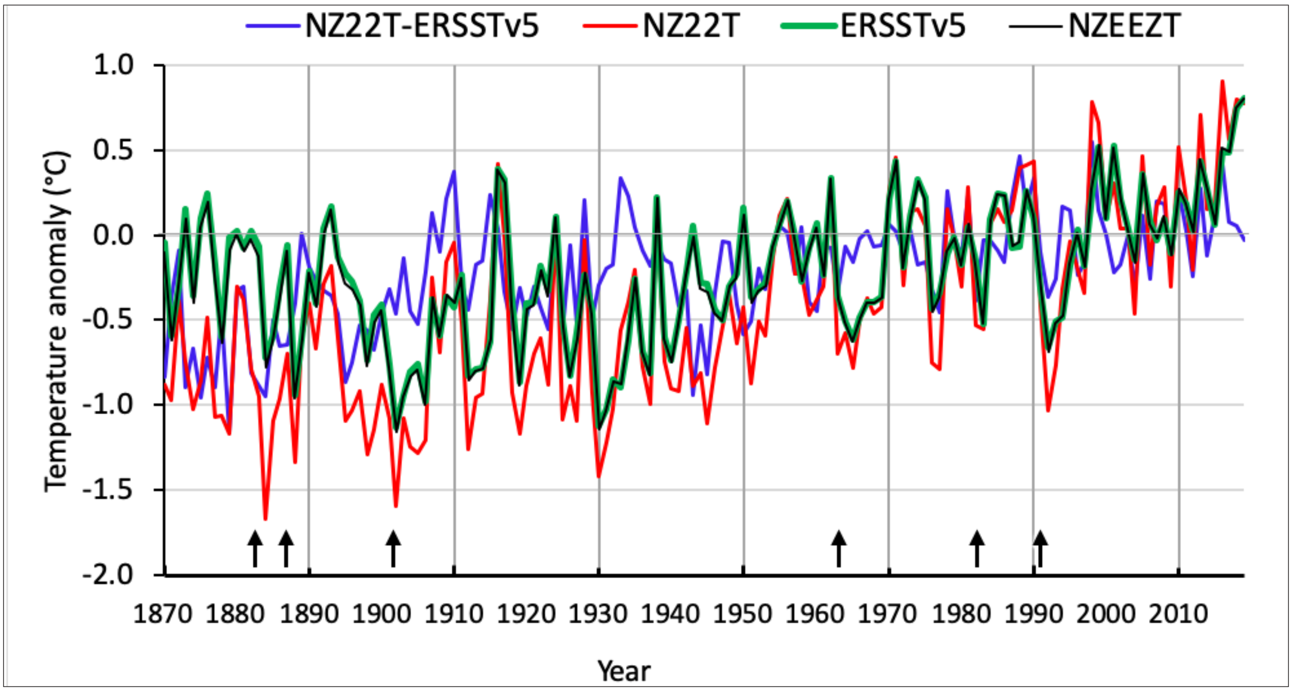

Figure 4: New Zealand temperature 1870-2019 (°C). Values are expressed as anomalies in mean annual temperatures from the 1981-2010 climatological period, for NZ22T(red), ERSSTv5 (green), NZEEZT (black) and the difference between NZ22T and ERSSTv5 (blue). ERSSTv5 is very similar to NZEEZT. The arrows indicate dates of major volcanic eruptions that affected New Zealand climate (August 1883, June 1886, October 1902, April 1963, April 1982 and June 1991).

Table 3 shows serial correlations between atmospheric indices, regional circulation indices and regimes with NZT series, both actual and detrended. SAM and AGW are primary amongst them for the centennial trend. Relationships with regional atmospheric circulation and indices were very significant with both the Z1 and M1 indices and the blocking regime, as well as with related trough regimes (Figure 5 top, Table 3b). Warm (cold) years are associated with more northerly (southerly) airflow over New Zealand with more (less) blocking and fewer (additional) troughing. For the detrended cases associations were highly significant with detrended Z1, M1, blocking and to a lesser extent with zonal regimes. In these cases, warm (cold) years are associated with more northeasterly (southwesterly) airflow and more (less) blocking.

With AGW the most significant climate teleconnection is the SAM (Table 3, Figure 5 bottom) on a centennial scale. On interannual to interdecadal timescales the SOI and the IPO are the most important (Table 3, Figure 5 middle). In the detrended series, the SAM correlation values lower whereas the IPO and SOI correlation values strengthen demonstrating the importance of these on interannual to decadal timescales. For both periods the correlation with the detrended AGW is not significant.

Anthropogenic Regional Warming

The New Zealand regional temperature signal, NZEEZT, shows a highly significant linear warming trend of +0.66°C over the 150-year period ($p<0.01$) between 1870 –2019. The trend in CMIP5 for AGW (Figure 3) shows an increase of 0.67°C representing the magnitude of the warming signal for the 1900-2015 period, compared with increases of 1.16°C, 0.81°C and 0.87°C for NZ22T, ERSST and NZEEZT respectively.

Table 3: Serial correlations between atmospheric indices, regional circulation indices and regimes with New Zealand temperature anomalies using annual means for calendar years for actual and detrended series. Bolded italicized values are significant at the 1% confidence level and bold at the 5% level of significance. (a) 1900-2015, and (b) 1948-2015. Z1 and M1 indices commence in 1896, and Kidson regimes in 1948. AGW comes from the CMIP5 runs. All series, both indices and temperature, have been detrended linearly.

a) 1900-2015

		SAM	SOI	IPO	Z1	M1	AGW	NZEEZT-AGW
Actual	ERSST	***0.49***	***0.38***	***-0.43***	***-0.43***	***-0.38***	***0.47***	***0.85***
	NZ22T	***0.55***	***0.34***	***-0.32***	***-0.36***	***-0.49***	***0.54***	***0.71***
	NZEEZT	***0.51***	***0.38***	***-0.42***	***-0.43***	***-0.41***	***0.50***	***0.84***
	Smoothed NZEEZT	***0.58***	0.04	***-0.43***	***-0.26***	***-0.58***	***0.70***[1]	***0.47***
Detrended	ERSST	***0.23***	***0.47***	***-0.45***	***-0.33***	***0.47***	-0.14	
	NZ22T	***0.28***	***0.47***	***-0.32***	***-0.29***	***-0.62***	-0.05	
	NZEEZT	***0.23***	***0.48***	***-0.44***	***-0.33***	***-0.48***	-0.14	

[1] Correlation between smoothed time series of NZEEZT and AGW from CMIP5 models shown in Figure 3.

b) 1948-2015

	SAM	SOI	IPO	Z1	M1	Trough	Zonal	Block	AGW
Actual NZEEZT	***0.54***	***0.50***	**-0.23**	***-0.43***	***-0.46***	**-0.38**	-0.06	***0.53***	***0.44***
Detrended NZEEZT	***0.37***	***0.60***	***-0.41***	***-0.39***	***-0.54***	**-0.28**	**-0.27**	***0.61***	0.05

Variability

Multivariate analysis demonstrated the relative importance of the climate teleconnections of SAM, ENSO and IPO and forcing via AGW. Table 4 shows the order of importance in affecting NZEEZT is AGW, followed by the IPO, SAM and ENSO as expressed by the SOI. The β values, which compares the strength of the effect of each individual independent variable to the dependent variable (Tiemann and Mahbobi, 2015) are all highly significant and the variance explained by the multiple linear regression is 52.1%. The multicollinearity measures show that the independent variables are not correlated to a high extent in the multivariate analysis (Table 4), even though the individual correlation between AGW and SAM is 0.67. The regression equation is:

$$NZEEZT = -0.482 + 0.67*AGW - 0.46*IPO + 0.149*SAM + 0.143*SOI \quad (1)$$

with a standard error of 0.28. Actual and predicted time series are shown in Figure 6, which shows generally good agreement, although the periods in the 1930s, 1980s and since 2006 are less consistent. The correlation between AGW and filtered NZEEZT (for decadal variability) is 0.70 (Table 3).

Table 4: Multivariate relationships between atmospheric teleconnections (SAM, IPO and SOI) and the AGW forced in NZ temperatures (NZEEZT) 1900-2015. The standardized beta (β ranges from 0 to 1 or 0 to -1), and the closer the value is to 1 or -1, the stronger the relationship. b is the slope of the regression relationship. using annual means for calendar years. Multicollinearity is measured by variance inflation factors (VIF) and tolerance (TOL). A TOL of less than 0.20 or 0.10 and/or a VIF of above 5 above indicates a multicollinearity problem.

	β	b	Std. Error	t	Prob. >t	VIF	TOL
SAM	0.24	0.10	0.03	2.92	0.004	1.67	0.60
IPO	-0.29	-0.46	0.11	-4.03	0.000	1.20	0.83
AGW	0.38	0.67	0.15	4.48	0.000	1.68	0.60
SOI	0.27	0.14	0.04	3.77	0.000	1.23	0.81

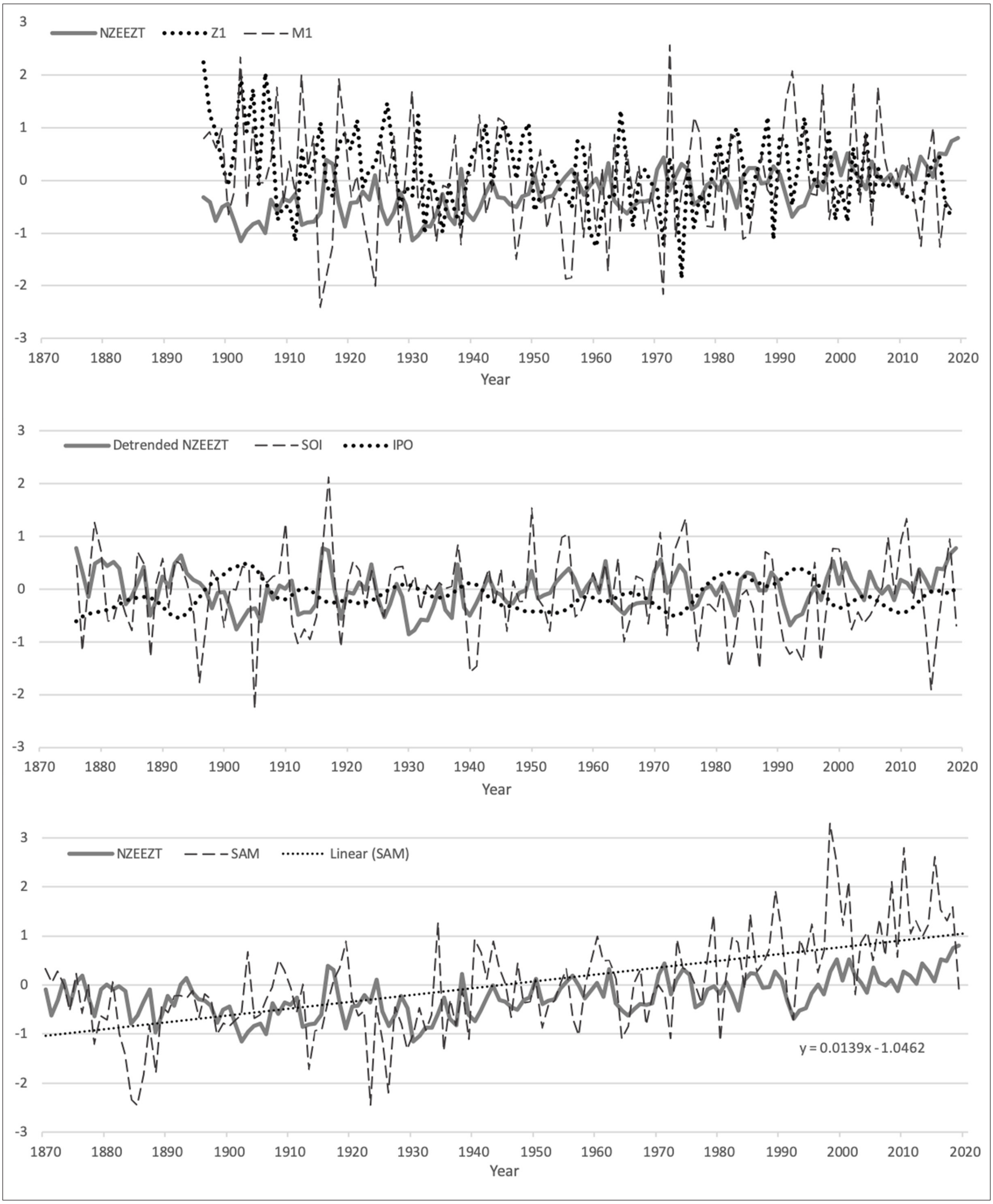

Figure 5: NZEEZT (°C) and circulation indices. Top: NZEEZT (solid), standardised circulation indices Z1 (dotted) and M1 (dashed), 1896-2019 Middle: Detrended NZEEZT (solid), circulation indices SOI (dashed) and IPO (dotted), 1876-2019 and Bottom: NZEEZT (solid) and the SAM (dashed), with a linear fit (dotted) 1870-2019.

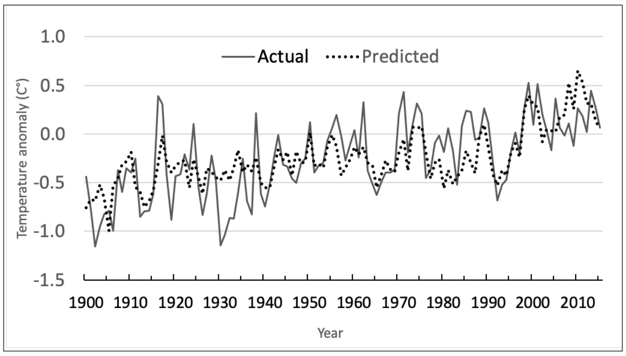

Figure 6: Actual (bold) predicted (dotted) NZEEZT (°C) 1900-2015. The predicted values are from multivariate analysis using the multiple regression equation. NZEEZT = -0.48+0.67*AGW -0.46*IPO +0.10*SAM +0.14*SOI, where AGW is anthropogenic global warming, IPO is the Inter-decadal Pacific Oscillation, SAM is the Southern Annular Mode and SOI the Southern Oscillation Index. The standard error is 0.28°C. R^2 =0.52.

Analogues

As was documented in Salinger et al. (2019), a subset of past analogue annual periods was chosen from both the NCEP and ERA-Interim reanalysis 500 hPa anomaly fields. The analogues were chosen based on the highest anomaly correlation and lowest RMS difference (RMSD) across the New Zealand/Tasman Sea region. In all cases with AGW, the extreme warm years occurred in the period 1998–2019 (Figure 7a, Table 5). A subset of past analogue (similar) annual periods was chosen from both the ERA-Interim (Dee et al., 2011) and 20th Century reanalysis (20CR, Compo et al., 2011). Analogues that exhibited anomaly correlations of at least 0.65 and RMSD of 16 gpm or less were selected. A common 500hPa feature for warm year analogues were positive 20 to 40 geopotential metre (gpm) anomalies to the east of the country. In all cases Z1 and M1 were negative, demonstrating north easterly flow anomalies over NZ. Kidson (2000) weather regimes did not show specific trends over time. In all cases SAM was significantly positive with ENSO in the La Niña state on three occasions. M1 showed northerly airflow anomalies. The cold year analogues were less consistent,

Table 5: Temperature departures (°C), index values and circulation regimes for the warmest and coldest groups of years for actual and detrended NZEEZT. The mean (x̄) and standard deviation (σ) are given for each time period for each index. Bolded values are significant at the 5% level of confidence. All values in the table have been standardised (x̄ = 0, and σ = 1). (a) 1900-2019 and (b) 1948-2019. Z1 and M1 indices commence in 1896.

a) 1900-2019

	NZEEZT	SAM	SOI	IPO	Z1	M1
Actual (x̄±σ)	-0.25±0.4	-0.77±0.9	-0.11±0.8	-0.07±0.2	0.0±1.0	-0.0±0.0.8
Warmest 7	**1.98**	**1.30**	0.61	**-0.70**	-0.92	-0.83
Coldest 9	-1.90	-0.58	-0.15	0.85	0.96	0.64
NZEEZT-AGW	-0.53±0.36					
Warmest 4	**0.29**	-0.90	**1.08**	-0.28	-0.61	**-1.45**
Coldest 6	**-1.25**	-1.22	-0.31	0.26	**1.17**	**0.90**

b) 1948-2019

	NZEEZT	SAM	SOI	IPO	Z1	M1	Trough	Zonal	Block
Actual (x̄±σ)	-0.04±0.35	-0.41±0.9	-0.11±0.8	-0.13±0.3	0.0±1.0	0.0±1.06	0.0±1.0	0.0±1.0	0.0±1.0
Warm 10	**1.51**	0.60	0.59	-0.33	-0.96	-1.46	-0.55	-1.08	0.99
Cold 8	**-1.46**	-0.58	-0.76	0.76	0.23	0.09	0.52	-0.65	-0.63
Detrended	-0.43±0.31								
Warm 6	**0.14**	-0.89	**0.90**	-0.36	**-1.17**	**-1.11**	0.17	**-1.38**	**1.35**
Cold 8	**-0.94**	-0.25	**-1.06**	0.13	0.77	**1.12**	0.35	-0.41	-0.89

but all occurred between 1902-1932, in the early 20th century. In all cases SAM was negative, and in three of the cases significantly so. Either positive height anomalies occurred in the south Tasman Sea or very strong negative 500 hPa anomalies occurred in the Tasman Sea or east of NZ. Neither the SOI nor the IPO show any clear tendency. Although an average of the analogues demonstrates a trend towards more southerly and westerly circulation, this was not dominant.

The warm year analogues changed for the NZEEZT-AGW series (Table 5, Figure 6 and Figure 7b), all being prior to 1972: 1916, 1917, 1962 and 1971. At the 500 hPa level warm years had consistent positive anomalies of 20 to 50 gpm

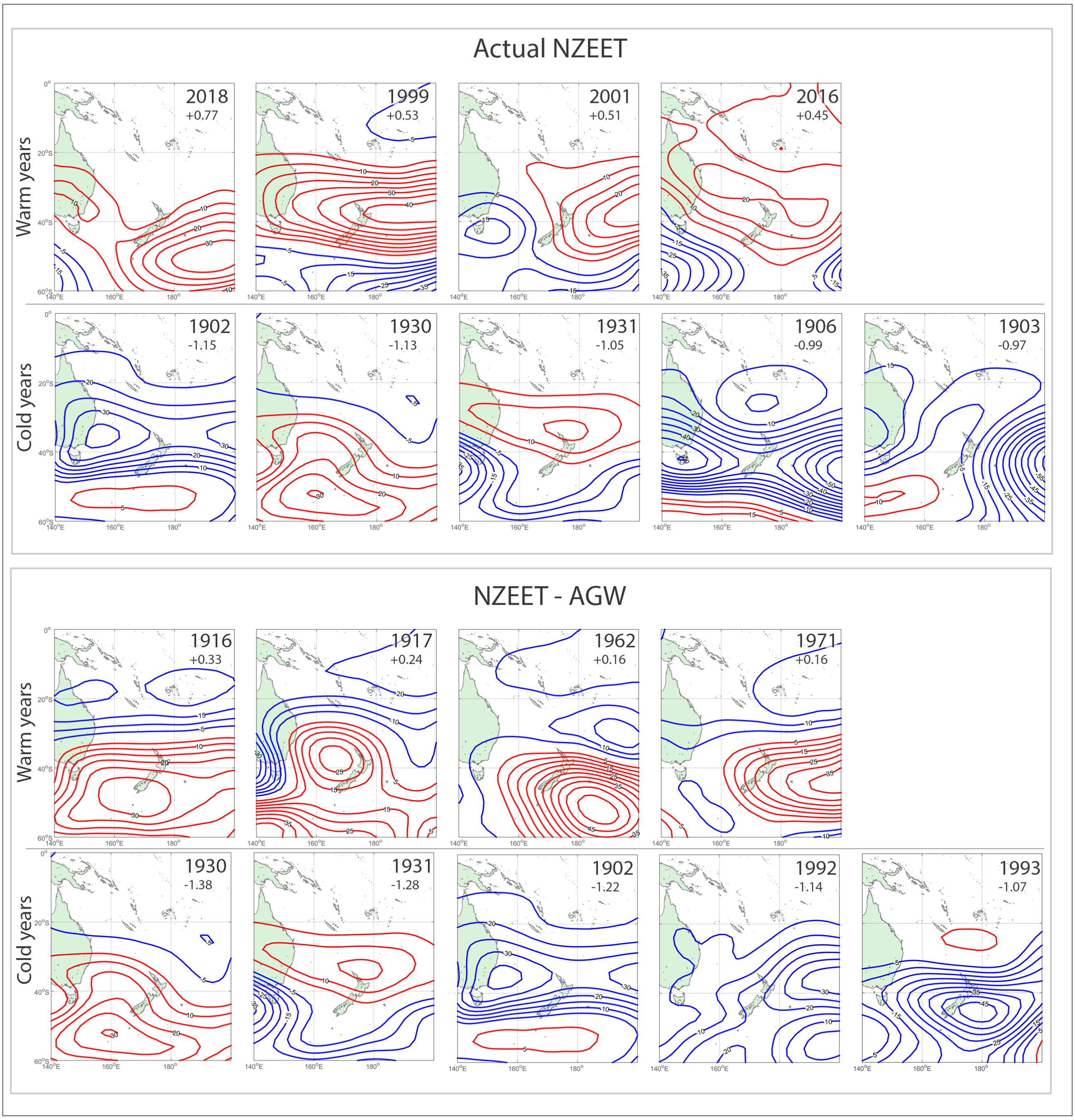

Figure 7: Warmest and coldest 500 hPa height anomalies. Top: NZEEZT years. where NZEEZT was > 0.45°C or < -0.84°C. Bottom: NZEEZT-AGW years where NZEEZT-AGW was > +0.15°C, or < -1.05°C. Source: 20th Century Reanalysis, Compo et al. (2011).

across or east of the South Island. In all cases both Z1 and M1 were negative, the latter strongly so indicating north to northeasterly flow anomalies over NZ. These years had lack of zonal and more frequent blocking circulation regimes. On interannual to interdecadal timescales both the negative phase of the IPO and positive phase of the SOI (La Niña phase) were important. The cold year analogues were similar to those for AGW, except 1992 was present instead of 1903. The 500 hPa patterns were similar. A strong feature was the positive M1 index, with southerly quarter airflow anomalies in the region with no dominance of any of the three circulation regimes. SAM was negative in all cases, the SOI generally neutral and IPO trending positive.

5. Discussion and conclusions

The New Zealand region has high-quality and detailed temperature records, with the introduction of Stevenson screens and precision sheathed thermometers in 1869 which have been operational since that time. Mullan (2012) did not homogenise station temperature series prior to 1909 despite calculating adjustments, comparisons with these with earlier (Salinger et al., 1992) and this work (Table 1) displayed very close agreement from 1870-1908. Such a high quality 148-year record provides a unique opportunity to investigate the climate teleconnections and atmospheric circulation for establishing climate trends and variability.

The cooling impacts of major volcanic eruption events that resulted in depressed regional surface temperatures (0.3-0.5°C) along with strong southwesterly winds is clearly depicted both in annual values and centennial trends (Figures 3 and 4), consistent with the findings of Salinger (1998).

The warming trend in NZEEZT, broadly matches the CMIP5 simulations of AGW (Mullan et al., 2018). The trend from the CMIP5 simulations (Figure 3 CMIP5 modelling) from 1900–2015 is +0.7°C. The additional observed warming of 0.2°C could be a result of the positive SAM trend (Arblaster et al., 2011). This is compatible with Kidston et al. (2009) who showed positive correlations between the SAM index and temperatures over much of the country. The associated anomalous high pressure over the county would also be associated with increased solar radiation.

The IPO as noted by both Power et al. (1999) and Salinger and Mullan (1999), dominated variability on interdecadal timescales. During positive (negative) IPO phases, SST anomalies are negative (positive) in the NZ sector, and similarly with land surface air temperatures (Power et al., 1999). The two IPO phases induce interdecadal variations in NZ climate variability, including temperature changes, with warmer periods, or accelerated warming occurring during negative IPO phases, and slower warming during positive IPO phases.

ENSO is clearly important for NZEEZT on interannual timescales and confirms the conclusions of Gordon (1986) where La Niña years tend to exhibit above average temperatures with more northeasterlies, and El Niño years are cooler than average due to more frequent southwesterly winds.

Figure 8a schematic displays the various climate teleconnections and circulation in operation for warm and cold years. In terms of regional circulation, both negative (positive) values of Z1 and M1 were important in influencing very warm (cold) years. Thus, a more northeasterly circulation predominated in warm years, compared to southwesterly circulation in the cold years. For the extreme warm years, a positive SAM together with northerly quarter circulation were the most important factors. In cold years a negative SAM with westerly quarter circulation were the chief influences.

The blocking in warm year analogues bear this out

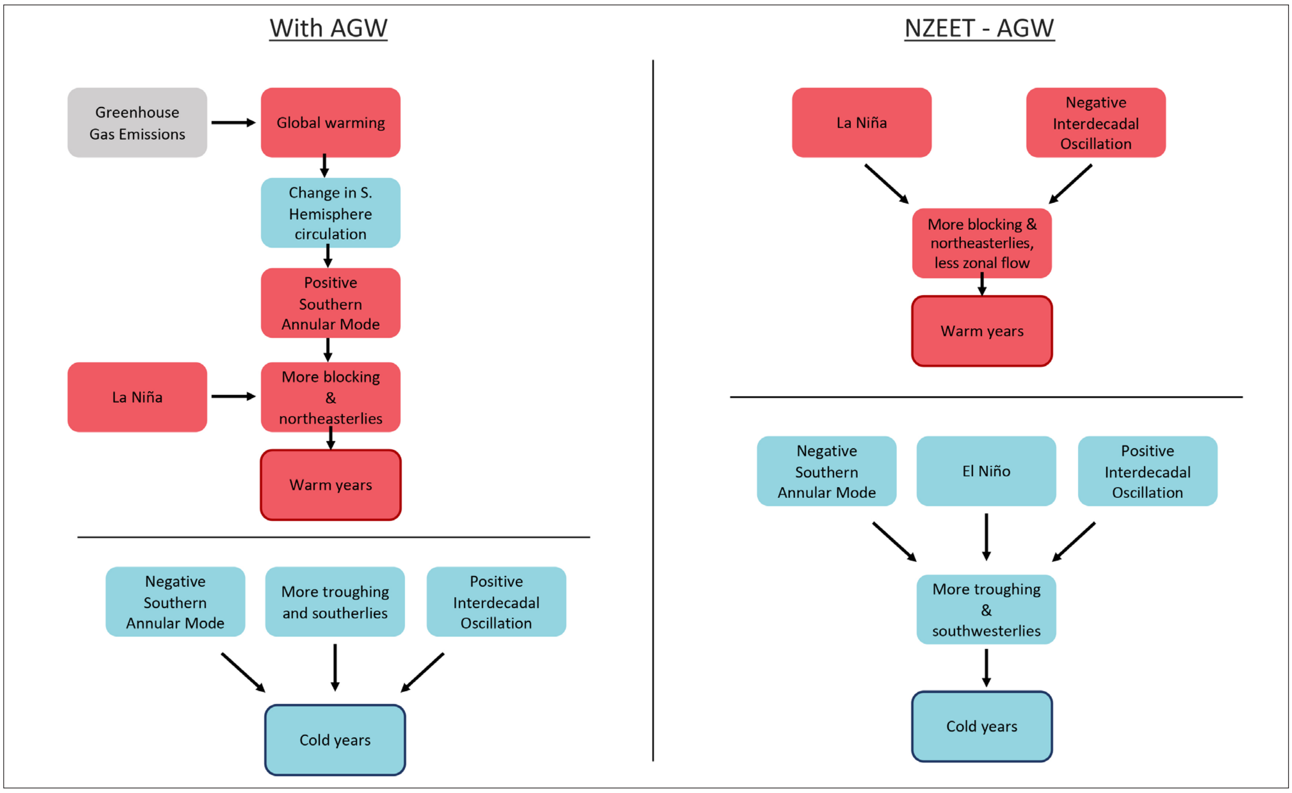

Figure 8: Schematic of likely driving mechanisms for warm and cold years. (a). With AGW, and (b) NZEEZT-AGW.

with 500 hPa anomalies showing very positive height anomalies over and to the east of NZ. These were characterised by a positive SAM and north easterly flow anomalies. The 500 hPa fields for cold analogues were less consistent but generally showed blocking patterns in the south Tasman Sea. There was a southerly quarter 500 hPa field, and more cyclonic type fields. Cold year analogues had strongly negative SAM values.

When NZEEZT values are detrended (Figure 8b), relationships with Z1 are unchanged whereas the relationship with M1 become stronger. The correlation with SAM weakens which supports the link (Arblaster et al., 2011) between trends in AGW and the SAM (Figure 8b). The importance of ENSO in determining cold or warm years increases, whilst IPO associations remain the same for interdecadal variability. Detrended warm year analogues differed somewhat in that 500 hPa blocking area was located further south across the South Island of NZ and to the east. La Niña years were particularly prominent in the warm sample, as was the IPO, with northerly flow strengthened. Lack of a zonal flow and a more prevalent blocking pattern occurred. There was only one common year (1971) between the actual and detrended analogues. In contrast, the actual and detrended cold years are similar, with three being the same: 500 hPa fields of blocking patterns in the south Tasman Sea with a southerly quarter 500-hPa field, or more cyclonic in nature near NZ. This was consistent with the negative phase of the SAM and southerly quarter meridional flow and a tendency towards El Niño episodes.

This study has shown the importance of AGW forcing as depicted by CMIP5 simulations and the SAM in determining long-term warming in the New Zealand region. It is of note that all the warm years >+0.45°C) occurred from 1998 onwards, and all the cold years (<-0.84°C) prior to 1933. Detrending emphasises the role of modes of interannual to decadal variability (SOI and IPO). The cold years (anomaly<-1.05°C) are similar, whereas the warm years (anomaly>+0.15°C) are quite different, apart from one. The consequences of atmospheric circulation in this mode (lack of zonal and more frequent blocking) in the current climate (AGW) would be an extremely warm year.

Acknowledgements

Dr Brett Mullan provided the average results data from the 13 CMIP5 model simulations of climate which had both AGW and natural variability (NAT) over the 1900–2015 period. The differences between AGW and NAT were used to calculate the AGW signal. We also thank the detailed comments of three anonymous reviewers which have significantly improved this paper.

Dedication

Our colleague and good friend Brett Mullan died of cancer on 22 April whilst this manuscript was under review. Brett has been a mainstay of the Meteorological Society of New Zealand contributing strongly over the last 38 years. From 1983 – 1985 he was editor of *Weather & Climate* and the MSNZ quarterly newsletter, and 1996 to 1998 president, as well as serving for many years on the committee. Brett has made incredibly significant contributions and authored seminal papers in meteorology. These include the analysis of Southern Hemisphere climate and circulation variability over interannual (El Niño-Southern Oscillation) to interdecadal (Interdecadal Pacific Oscillation) timescales. The development of relationships with climate variability has been a basis for seasonal climate prediction for New Zealand commencing in the 1990s. He has carried out research into climate change and climate modelling, with particular emphasis on Southern Hemisphere and New Zealand regional effects (Southern Oscillation, greenhouse warming, ocean-atmosphere coupled models and, decadal variability, integrated climate impact models). In particular he has been at the forefront of development of climate change scenarios for New Zealand, leading and completing two major reports for the Ministry for the Environment published in 2008 and 2016 which are widely used as the basis for climate change adaptation and mitigation planning in New Zealand. More recently Brett re-evaluated the calculation of the 7SS, which had been under scrutiny from climate sceptics in New Zealand. Brett led a seminal paper which robustly defended established temperature trends and addressed the criticism. He has made research visits to the UK Hadley Centre for Climate Prediction and Research, and CSIRO Division of Atmospheric Research in Australia. Over the 40-year period Brett's contribution to New Zealand meteorology and climate science and beyond has been substantial, including mentoring to many scientists. He will be missed.

References

Arblaster J.M., Meehl, G.A., Karoly D.J., 2011. Future climate change in the Southern Hemisphere: Competing effects of ozone and greenhouse gases. *Geophysical Research Letters*, Volume 38 (2), L02701 pp. 1-6. https://doi.org/ 10.1029/2010GL045384.

Bottomley, M., Folland, C.K., Hsiung, J., Newell, R.E., and Parker, D. E. 1990. *Global Ocean Surface Temperature Atlas*, 20 + iv pp. and 313 color plates, Her Majesty's Stn. Off., Norwich, UK, 1990.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R.J., Yin, X., . . . Worley, S. J. (2011). The Twentieth Century reanalysis project. Q*uarterly Journal of the Royal Meteorological Society,* 137(654): 1-28. https://doiorg/10.1002/qj.776

Dean, S.M., Stott, P.A., 2009. The effect of local circulation variability on the detection and attribution of New Zealand temperature trends. *Journal of Climate* 22(23), 6217–6229. https://doi.org: 10.1175/2009jcli2715.1

Dee D.P, Uppala S.M, Simmons A.J, Berrisford P., Poli P., Kobayashi S., Andrae U., Balmaseda M.A., Balsamo G., Bauer P., Bechtold P., Beljaars A.C.M., van de Berg L., Bidlot J., Bormann N., Delsol C., Dragani R., Fuentes M., Geer A.J., Haimberger L., Healy S.B., Hersbach H., Hólm E.V., Isaksen L., Kållberg P., Köhler M., Matricardi M., McNally A.P., Monge-Sanz B.M., Morcrette J-J, Park B-K, Peubey C., de Rosnay P., Tavolato C., Thépaut J-N, Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system *Q. J. R. Meteorol. Soc.* 137: 553–597.

Flato G., Marotzke J., Abiodun B., Braconnot P., Chou S.C., Collins W., Cox P., Driouech F., Emori S., Eyring V., Forest C., Gleckler P., Guilyardi E., Jakob C., Kattsov V., Reason C. Rummukainen M.. 2013. Evaluation of Climate Models. In: T.F. Stocker, D. Qin, G.K . Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. http://cmip-pcmdi.llnl.gov/cmip5/

Folland, C.K. and Parker, D.E. 1995. Correction of instrumental biases in historical sea surface temperature data, *Q. J R. Meteorological. Soc*., 121, 319-367. https://doi.org/10.1002/qj.49712152206

Folland, C.K., Salinger, M.J, 1995. Trends in New Zealand and surrounding ocean surface temperature, 1871 - 1993. *International Journal of Climatology* 15, 1195 - 1218.https://doi.org/10.1002/joc.3370151103

Folland C.K.; Salinger, M.J, and Rayner, N. 1997. A comparison of annual South Pacific island and ocean surface temperatures. *Weather and Climate* 17(1): 23-42.

Folland, C.K., Salinger, M.J., Jiang, N., and Rayner, N., 2003. Trends and variations in South Pacific island and ocean surface temperatures. *Journal of Climate*, Volume 16 (17), pp. 2859-2874. https://doi.org/10.1175/1520-0442(2003)016<2859:TAVISP>2.0.CO;2.

Fouhy, E., Coutts, L; McGann, R.P, Collen, B and Salinger, M.J., 1992. South Pacific Historic Climatological Network Climate Station Histories. Part 2: New Zealand and Offshore Islands. NZ Meteorological Service, Wellington, ISBN 0-477-01583-2, 216 p.

Gong, D. and Wang, S., 1999. Definition of Antarctic oscillation index, *Geophys. Res. Lett.*, 26, pp. 459–462. https://doiorg/10.1029/1999GL900003

Gordon, N.D., 1986. The Southern Oscillation and New Zealand weather, *Monthly Weather Review*, 114, 371 – 387. https://doi.org/10.1175/1520-0493(1986)114<0371:TSOANZ>2.0.CO;2

Hector, J., 1869. Meteorological Report, 1868. New Zealand Government Printer, 1869, Wellington, 60pp.

Henley, B.J., Gergis, J., Karoly, D.J., Power, S.B., Kennedy, J., and Folland, C.K. 2015. A Tripole Index for the Interdecadal Pacific Oscillation. *Climate Dynamics,* 45(11-12), 3077-3090. https://doi.org/10.1007/s00382-015-2525-1

Huang, B., Thorne,P.W., Smith, T.M., Liu,W., Lawrimore, J., Banzon,V.F., Zhang, H.M., Peterson, T.C., and Menne, M. 2016. Further Exploring and Quantifying Uncertainties for Extended Reconstructed Sea Surface Temperature (ERSST) Version 4 (v4). *J. Climate*, 29 (9): 3119–3142, https://doi.org/10.1175/JCLI-D-15-0430.1

Huang, B, Angel, W., Boyer, T., Cheng, L., Chepurin, G., Freeman, E., Liu, C., Zhang, H-M, 2018. Evaluating SST Analyses with Independent Ocean Profile Observations. *Journal of Climate*, 31 (13): 5015–5030. https://doi.org/10.1175/JCLI-D-17-0824.1

Huang, B., Menne, M.J., Boyer, T., Freeman, E., Gleason, B.E., Lawrence, J. H., Liu, C. Renne, J., Schreck, C.J., Sun F., Vose, R., Williams, C.N., Yin, X. , and Zhang, H-M. 2019. Uncertainty Estimates for Sea Surface Temperature and Land Surface Air Temperature in NOAA Global Temp Version 5. *Journal of Climate* 33, 1351-1379, https://doi.org/ 10.1175/JCLI-D-19-0395.1

Huang B., Thorne P. W., Banzon V.F., Boyer T., Chepurin

G., Lawrimore J. W., Menne M.J., Smith T.M., Vose R.S., Zhang H-M., 2017. Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5), Upgrades, validations, and intercomparisons. *Journal of Climate*, Volume 30, pp. 8179-8205. https://doiorg/ 10.1175/JCLI-D-16-0836.1

Huang, B, Angel,W., Boyer, T., Cheng, L., Chepurin, G. Freeman, E., Liu,C., Zhang, H-M. 2018. Evaluating SST Analyses with Independent Ocean Profile Observations. *Journal of Climate*, 31 (13): 5015–5030. https://doi.org/10.1175/JCLI-D-17-0824.1

Jones, P. D., Groisman, M, Coughlan, M., Plummer, N., Wang, W. C. and Karl, T. R. 1990. Assessment of urbanisation effects in time series of surface air temperature over land, *Nature,* 347, 169—172. https://doi.org/10.1038/347169a0

Karl, T.R., Jones, P.D., Knight, N., Plummer, N., Razuvayev, V., Gallo, J., Lindesay, J., Charlson, R.J. and Peterson, T.C., 1993. A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature, *Bulletin of the American Meteorological Society*, Volume 74, pp. 1007-1023.

Karl, T.R., Williams, C.N., Young, P.J., 1986. A model to estimate the time of observation bias associated with mean monthly maximum, minimum and mean temperatures, *Journal of Applied Meteorology and Climatology*., Volume 25, pp. 145-159. https://doi.org/10.1175/1520-0450(1986)0252.0.CO;2

Kelly, P.M., Jones, P.D. and Pengqun, J., 1996. The spatial response of the climate system to explosive volcanic eruptions. *International Journal of Climatology* 16(5), 537- 550.

Kent, E.C., Rayner, N.A., Berry, D.I., Saunby, M., Moat, B.I., Kennedy, J.J. and Parker, D.E. 2017. A call for new approaches to quantifying biases in observations of sea surface temperature. *Bull. Amer. Meteor. Soc.,* 98, 1601–1616, https://doi.org/10.1175/BAMS-D-15-00251.1.

Kidson J.W., 2000. An analysis of New Zealand synoptic types and their use in defining weather regimes. I*nternational Journal of Climatology* 20 (3): 299-315. https://doi.org/10.1002/(SICI)1097-0088(20000315)20:3<299::AID-JOC474>3.0.CO;2-B

Kidston, J., Renwick, J.A., and McGregor, J., 2009. Hemispheric-scale seasonality of the Southern Annular Mode and impacts on the climate of New Zealand. J*ournal of Climate*, 22, pp. 4759-4770. https://doi.org/ 10.1175/JCLI-D-11-00474.1

Marshall, G.J. 2003. Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate,* 16: 4134–4143 https://doi.org/10.1175/1520-0442(2003)016<4134:TITSAM>2.0.CO;2

Mullan, A.B., 2012. Applying the Rhoades and Salinger Method to New Zealand's "Seven-Station" Temperature Series, *Weather and Climate*, Volume 32(1), pp. 23-37. https://doi.org/ 10.2307/26169723

Mullan, A. B., Stuart. S. J., Hadfield, M. G., Smith, M.J., 2010. Report on the Review of NIWA's 'Seven-Station' Temperature Series NIWA Information Series No. 78. 175 pp.

Mullan, A. B., Sood, A., and Stuart, S., 2018. Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment Wellington: Ministry for the Environment.https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/Climate-change-projections-2nd-edition-final.pdf

Parker, D.E., 1994. Effects of changing exposure of thermometers at land stations, *International Journal of Climatology*, 14, pp. 1-31. https://doi.org/ 10.1002/joc.3370140102

Parker, D. E., Folland C. K., Scaife,A.A., Colman, A., Knight, J., Fereday, D., Baines, P. and Smith, D. 2007. Decadal to interdecadal climate variability and predictability and the background of climate change. *Journal of Geophysical Research: Atmospheres*, 112 D18115, pp. 1-18. https://doi.org/10.1029/2007JD008411

Power, S., Casey, T., Folland, C. K., Colman, A., and Mehta,

V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, 15, pp. 319-323. https://doi.org/ 10.1007/s003820050284

Rhoades, D. A. and Salinger, M. J., 1993. Adjustment of temperature and rainfall records for site changes, *International Journal of Climatology*., 13, pp. 899-913. https://doiorg? 10.1002/joc.3370130807

Robock, A., 2003. Introduction: Mount Pinatubo as a test of climate feedback mechanisms, in Volcanism and the Earth's Atmosphere, *Geophys. Monogr. Ser*., 139, edited by A. Robock, and C. Oppenheimer, pp. 1–8, AGU, Washington, D. C.

Robock, A. and Free, M.P. 1995. Ice cores as an index of global volcanism from 1850 to the present. J*ournal of Geophysical Research: Atmospheres,* 100 (D6), 11549-11567. https://doi.org/10.1029/95JD00825

Salinger, M. J., 1980. The New Zealand temperature series, *Climate Monitor*, 9, pp. 112-118.

Salinger, M. J. 1981. New Zealand climate. The instrumental temperature record. Unpublished Ph.D thesis, Victoria University of Wellington, 357pp.

Salinger, M. J.; 1998. New Zealand climate: The impacts of major volcanic eruptions. *Weather and Climate*, 18(1) 11-20.

Salinger, M.J., McGann, R.P., Coutts, L., Collen, B., and Fouhy, E. 1992.
South Pacific historical climate network. Temperature trends in New Zealand and outlying islands, 1920-1990. New Zealand Meteorological Service, 46pp, Wellington, New Zealand.

Salinger, M. J., and Mullan, A. B., 1999. New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930–1994, *International Journal of Climatology,* 19, pp. 1049–1071. doi: 10.1002/(SICI)1097-0088(199908)19:10<1049::AID-JOC417>3.0.CO;2-Z

Salinger, M. J., Renwick, J. A., and Mullan, A. B., 2001. Interdecadal Pacific Oscillation and South Pacific climate. *International of Climatology*, 21, 1705–1721. https://doi.org/10.1002/joc.691

Salinger, M.J., Renwick, J., Behrens, E., Mullan, A.B., Diamond,H.J., Sirguey, P., Smith, R.O., Trought, M.C.T., Alexander, L.V., Cullen,N.J., Blair Fitzharris, B., Hepburn, C.D., Parker, A.K. and Sutton, P.J. 2019. The Unprecedented Coupled Ocean-Atmosphere Summer Heatwave in the New Zealand Region 2017/18: Drivers, Mechanisms and Impacts, *Environ. Res. Lett*, 14 (2019) 044023 https://doi.org/10.1088/1748-9326/ab012a.

Smith, T. M., and Reynolds, R. W. , 2005. A global merged land–air–sea surface temperature reconstruction based on historical observations (1880–1997). *J. Climate*, 18, 2021–2036. https://doi.org/10.1175/JCLI3362.1

Smith, T.M., Reynolds, R.W., Peterson, T.C., and Lawrimore, J. 2008. Improvements to NOAA's historical Merged Land–Ocean Surface Temperature analysis (1880–2005). *J. Climate*, 21, 2283–2296. https://doi.org/10.1175/2007JCLI2100.1

Tiemann, T.K. and Mahbobi, M., 2015. *Introduction to Business Statistics with interactive spreadsheets.* 1st Canadian Edition. 124pp. https://open.umn.edu/opentextbooks/textbooks/introductory-business-statistics-with-interactive-spreadsheets-1st-canadian-edition

Trenberth, K. E., 1976. Fluctuations and trends in indices of the southern hemispheric circulation, *Quarterly Journal of the Royal Meteorological Society*, Volume 102 (431), pp. 65-75. https://doi.org/ 10.1002/qj.49710243106.

Troup, A. J., 1965. The 'southern oscillation'. *Quarterly Journal of the Royal Meteorological Society*, 91 (390), pp. 490-506. https://doi.org/10.1002/qj.49709139009

Vose, R. S., and Coauthors, 2012. NOAA's Merged Land–Ocean Surface Temperature Analysis. *Bulletin of the American Meteorological Society*, 93, 1677–1685. https://doi.org/10.1175/BAMS-D-11-00241.1