WEATHER & CLIMATE

JOURNAL OF THE METEOROLOGICAL SOCIETY OF NEW ZEALAND (INC.)

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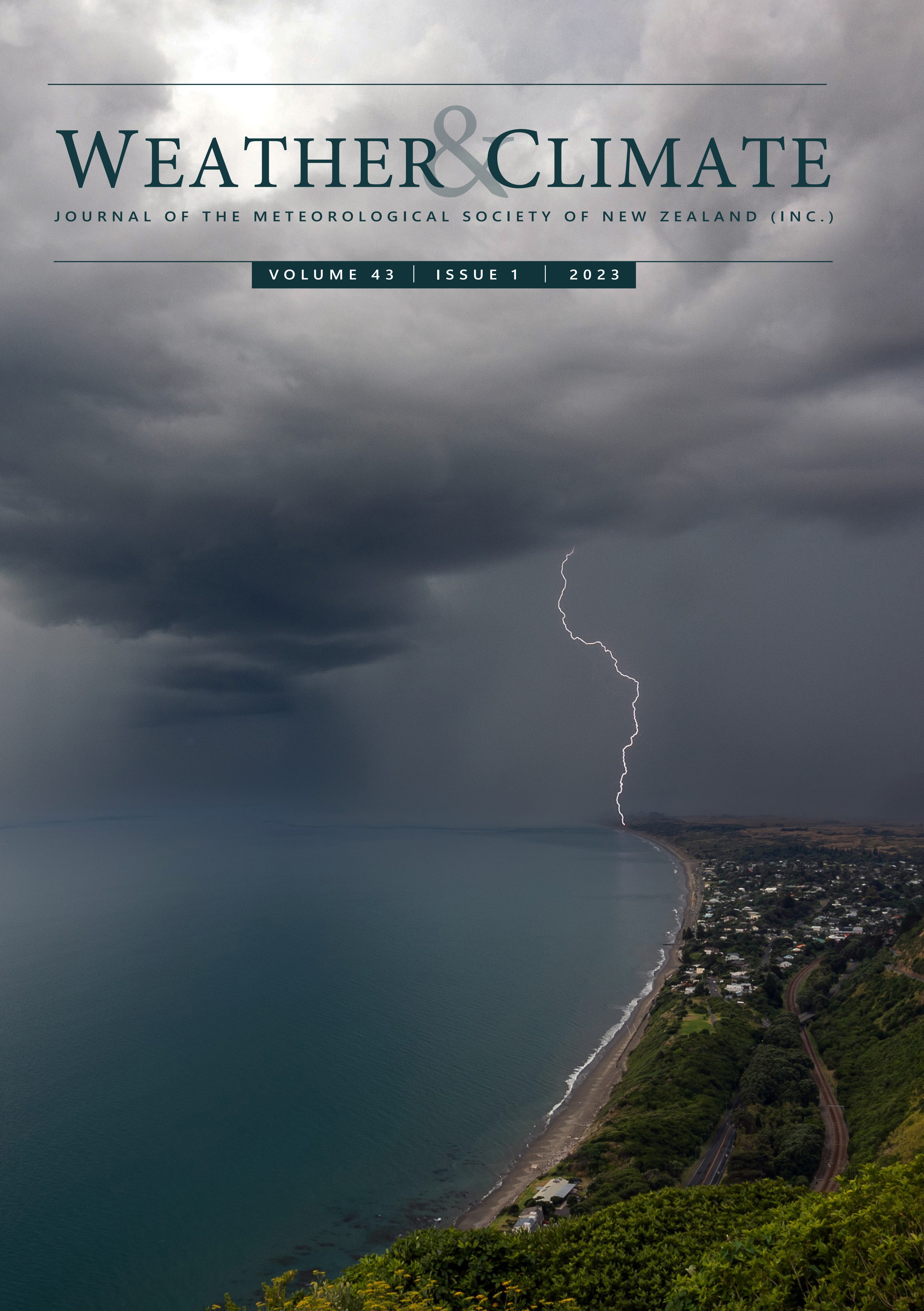

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COVER IMAGE Brendon Doran

"On 29 January 2023 there was a storm visible coming down the Kāpiti Coast on the Metservice rain radar. I drove up from Porirua to the Paekakariki Hill Road lookout and set up my camera, watching the sky get darker to the north. I managed to capture one bolt of lightning on camera."
Winner 2023 Meteorological Society Photo Competition

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Contents

Condensation nuclei data off the west coast of New Zealand

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ABSTRACT

From 2005 to 2013, air sampling across the SW Pacific between Nelson, New Zealand and Osaka, Japan was undertaken by New Zealand's National Institute of Water and Atmospheric Research (NIWA) from MV *Transfuture5*, a 60,000 tonne bulk carrier owned and operated by Toyofuji Shipping Company. An average of two sampling voyages a year were carried out; on eight of these voyages aerosol sampling instrumentation was available to take on the ship. Condensation nuclei (CN) were measured using a TSI 3010 condensation particle counter (CPC). The aerosol data collected from 30°S through to Osaka have been analysed and the results previously published (Bromley et al, 2018).

This paper discusses the data collected during the earlier section of the voyages from Port Nelson (41.35°S to 30°S). Sudden large increases in CN concentrations were detected on several voyages, in particular when the wind pattern was off the North Island of New Zealand, or from the Australian east coast. Back trajectories were compiled to examine possible sources of the enhanced CN concentrations, which included human activities, oil and gas commercial industrial activities and volcanic eruptions. Advection of aerosols into the coastal areas will cause enhanced signatures in the size distribution, composition and optical depths and can strongly influence the radiative coupling between ocean and atmosphere by scattering and absorbing solar radiation.

1. INTRODUCTION

Condensation nuclei (CN) are very small hygroscopic particles upon which water vapour can condense to form a liquid. They range in size from 0.001 micrometre (μm) to 0.1μm in diameter. By comparison a human hair is around 50μm. Water requires a non-gaseous surface to make the transition from a vapour to a liquid. The particles continue to coalesce until they are large enough to become cloud or rain droplets. The size and number of particles is important in determining the effect they have on atmospheric conditions.

Oceans constitute one of the single largest sources of atmospheric aerosols (and therefore CN). Estimates have shown that around 30% of the total natural aerosol flux to the atmosphere is of marine origin and in the range 1000 to 2000Tg per year (Prospero et al, 1983; Andreae, 1995; Xiao, H-W et al, 2018; Bromley et al, 2018). In the marine atmosphere, the smaller nanometre (nm) sized particles originate from atmospheric oxidation of precursor gases to form secondary particles. They come from natural and anthropogenic sources such as dimethyl-sulfide, sulfur dioxide, ammonia, oxides of nitrogen and organic VOC precursors such as isoprene, momterpenes and gloxal in a process known as gas-to-particle conversion. This particle size dominates the number distributions. Sub-micrometre aerosols act as cloud CN in marine stratocumulus clouds (Charlson et al, 1987), influencing the droplet size distribution (Fitzgerald, 1991). The larger micrometre sized particles originate from natural and anthropogenic sources and include dust or clay; soot from fires, combustion engines and factories; sea salt from wave spray, and bubbles breaking; and sulfates from volcanoes. These larger particles can interact with CN of gaseous origin. This particle size dominates the volume and mass distributions (Ayers et al, 1997).

Long-range transportation of aerosols and their precursors can produce high aerosol concentrations over oceans many kilometres from any land mass. Bodhaine et al (1981) showed that aerosols sampled in the Arctic had probably originated in Europe and possibly North America and Asia. Biomass burning in southern Africa has been detected in the results at Cape Grim in Tasmania (Andreae et al 2009). At Lauder in New Zealand, Liley and Forgan (2009) found that the austral springtime peak in aerosol optical depth measurements could be related to enhanced aerosols in the middle and upper troposphere and that much of this enhancement was from advection of tropical biomass burning products. Hoppel et al (1990) showed mineral aerosols from continental and arid regions are transported by winds to remote ocean locations. During the Pacific Exploratory Mission-Tropics B (PEM-Tropics B) campaign in 1999, air masses sampled for carbon monoxide in the northeastern tropical Pacific were strongly influenced by urban and industrial sources, and through the use of back trajectories they frequently originated from the Eurasian continent (Staudt et al, 2016). While aerosols are transported in the same air masses as gases, the size and chemistry of the aerosol may be shorter lived. There may also be in situ production and evolution of the aerosol size spectrum through processing during transportation such as in situ oxidation, aerosol-cloud interaction and washout-rainout.

This paper focuses on the condensation nuclei measurements recorded during eight ship voyages off the west coast of the North Island of New Zealand from 2006-2013, and the transportation of aerosols from various sources into this region of the Tasman Sea.

2. AEROSOL SAMPLING

Transfuture5 (TF5) is a 200m-long, 60414 tonne bulk carrier owned and operated by Toyofuji Shipping Company based in Japan (Figure 1). It operates a southbound voyage from Japan to Australia then New Zealand and a northbound voyage from Nelson, New Zealand directly to Osaka, Japan. It was during these return voyages that the air sampling was undertaken by New Zealand's National Institute of Water and Atmospheric Research (NIWA). The data were collected as part of the Ships of Opportunity (SOOP) programme, operated through the Centre for Global Environment Research at Japan's National Institute for Environmental Studies (NIES) led by Dr Y. Nojiri (http://soop.jp).

Figure 1: Bulk carrier *Transfuture5*.

NIWA's air sampling on TF5 was centred on a steel shipping container attached to the top deck (deck 13) which is 36.2m above the sea. The container was located centrally 70m from the bow and 20m aft of the crews' quarters and bridge complex. The primary activity was the collection of large air samples for later analysis of various greenhouse gases for concentration and stable isotope measurements; additional instrumentation was taken on some of the voyages including continuous aerosol monitoring equipment. Also on board was an atmospheric laboratory operated by NIES, which monitored several atmospheric and meteorological parameters.

The NIWA aerosol sampling intake was a 5m, ¼" diameter copper tube located two metres above the top of the container. The CN data were measured using a TSI model 3010 CPC. It detects particles from ten nanometres to greater than three micrometres with a nominal particle range up to 10,000 particles per cubic centimetre (particles/cm^3). The CPC will record higher values but the accuracy of the particle count decreases due to particle coincidence. The CPC operates by passing a 1.0 litre per minute (l/min) air sample through a heated n-butanol alcohol reservoir. The alcohol evaporates into the air sample to create a flow saturated with alcohol vapour. The sample flow is then cooled, causing the alcohol vapour to supersaturate and condense onto the particles in the sample to create droplets large enough to be detected using a light scattering technique. The particles then pass through a 780nm laser beam that causes light to be scattered as the beam hits the particles. The scattered light is collected by optical lenses and focused onto a photo detector that converts the light signal into an electrical pulse, which is proportional to the particle count. The CPC was connected to a computer, with data logged as a thirty-second average (UTC timing).

Global Position System (GPS) data were logged continuously at one-minute intervals for use in the later analyses to determine the location the sample or concentration was taken. NIWA staff recorded current meteorological conditions and commented about any atmospheric conditions they considered could be significant in interpreting the results.

Meteorological trajectories use observed data from weather stations throughout the world to create models of the atmosphere. By selecting a position and height for a sample of air, the models can determine where the parcel has been (backward trajectory) or will go (forward trajectory). The use of trajectories is a commonly used method in atmospheric chemistry to track the movement of atmospheric chemicals, gases and aerosols. The back trajectory model used in this research was HYSPLIT, with the duration generally set at 48 hours, vertical motion calculation method was model vertical velocity and the meteorology was the NCAR/NCEP CDC1 reanalysis file.

For the two voyages in 2013, the opportunity was taken to install a second aerosol instrument on board the vessel. A GRIMM aerosol spectrometer operates on the principal of orthogonal light scattering of a single particle. A 1.2 l/min air sample is collected into a sample cell, where the particles of various sizes pass through a light beam produced by a laser diode. The scattered light is collected at approximately 90° by a mirror and transferred to a photo diode. The signal from the diode travel to a multi-channel pulse height analyser for size classification. The pulse height analyser then classifies the signal transmitted in each channel to give a count output. The GRIMM used (model 1.107) can separate the particles into 31 size bins ranging from 0.25 to 32µm. Figure 2 shows the relationship between the various types of particle instruments and the main sources of particles.

3. DATA COLLECTION, VALIDATION AND INITIAL INTERPRETATION

Eight voyages were completed with the CPC instrument on board the vessel. These were:

- 7th - 18th August 2006 (Aug 2006)
- 27th May - 7th June 2007 (May 2007)

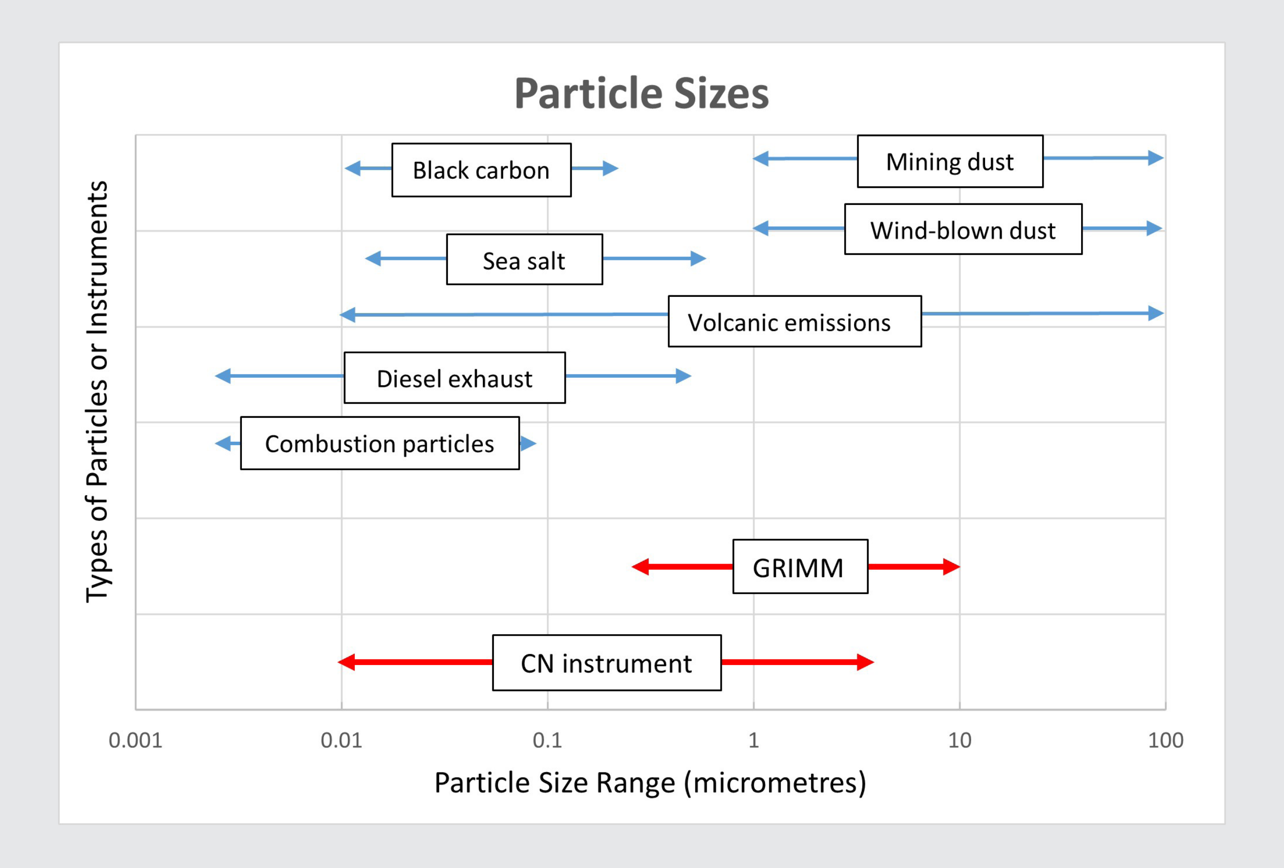

Figure 2: Particle type size range (blue arrows) and instrument measurement range (red arrows).

- 26th April - 7th May 2008 (April 2008)
- 30th August - 11th September 2008 (Aug 2008)
- 27th October – 7th November 2009 (Oct 2009)
- 5th – 17th June 2012 (June 2012)
- 27th February – 10th March 2013 (Feb 2013)
- 21st May – 2nd June 2013 (May 2013)

The GRIMM instrument was available for only the last two voyages (February and May 2013).

Validation of the data was undertaken using the following techniques. The CN data (from the CPC) were checked and any invalid data removed. Data were invalidated when any local sources of contamination were known (such as exhaust emission when the wind was over the stern of the vessel and bringing the stack emissions to the sampling intake, lifeboat engine testing, and the mid-Pacific crew barbeque). A metadata file was created detailing the reasons for the removal or non-use of any data. A comparison of the CN data collected in the open ocean areas against that normally expected in pristine maritime areas was used to indicate if there was any possible instrument fault, along with checks of the zero level before and after each voyage to determine drift during the voyage.

The position data (from the GPS) were checked for validity. Where there were gaps in the NIWA record, alternative sources (NIES instrumentation or ship data) were used to obtain a continuous record. The data were interpolated to generate thirty-second positions to coincide with the timing of the CN data.

This paper discusses only data collected off the west of the North Island from Port Nelson (41.35°S) to 30°S; the CN data collected from 30°S through to Osaka has been the subject of an earlier publication (Bromley et al, 2018). The ship's track off the west coast of New Zealand is shown in Figure 3.

The voyages were sorted into those that had similar weather patterns, particularly emphasising the direction of the winds. This resulted in four voyages having west or south-west winds from the Tasman Sea (August 2006, May 2007, June 2012 and May 2013), three with easterly flow off New Zealand (May 2008, August 2008 and February 2013). The October 2009 voyage had winds from both east and west directions.

The data from the three voyages with easterly flow off the land were then analysed further. The May 2008 and February 2013 voyages both had short periods of high concentrations at intervals, whereas the August 2008 voyage showed a longer period of high concentration from 40° S to 38° S, followed by generally even, low concentrations after this period. (Figure 4).

Figure 3: TF5 voyage track after leaving Port Nelson.

The data from the other voyages with the general southwest flow are not discussed in this paper; the recorded CN values were low and steady, typical of values occurring in clean "background" Southern Ocean areas, with no recent influence from landmasses.

4. TRANSPORTATION OF AEROSOLS FROM ANTHROPOGENIC SOURCES

The investigation into the possibility of aerosols with an anthropogenic particulate source started following the analysis of the August 2008 voyage. This voyage showed high CN counts off the coastline between south of New Plymouth (parallel to Palmerston North) through to south of Hamilton (offshore from Kawhia). At the time of these higher counts, the vessel was travelling northwest some 100 to 250 kilometres offshore. The CN data (Figure 5) showed a long period of higher concentrations but little short-term variability, during the early hours of 31 August.

The meteorological conditions at the time were dominated by an area of high pressure moving across New Zealand from the west, followed by an approaching front (Figure 6). This system had been giving cooler southerly winds over the North Island since 28th August with the centre crossing over the country on 30th August. As the anti-cyclone moved over the country the winds over the North

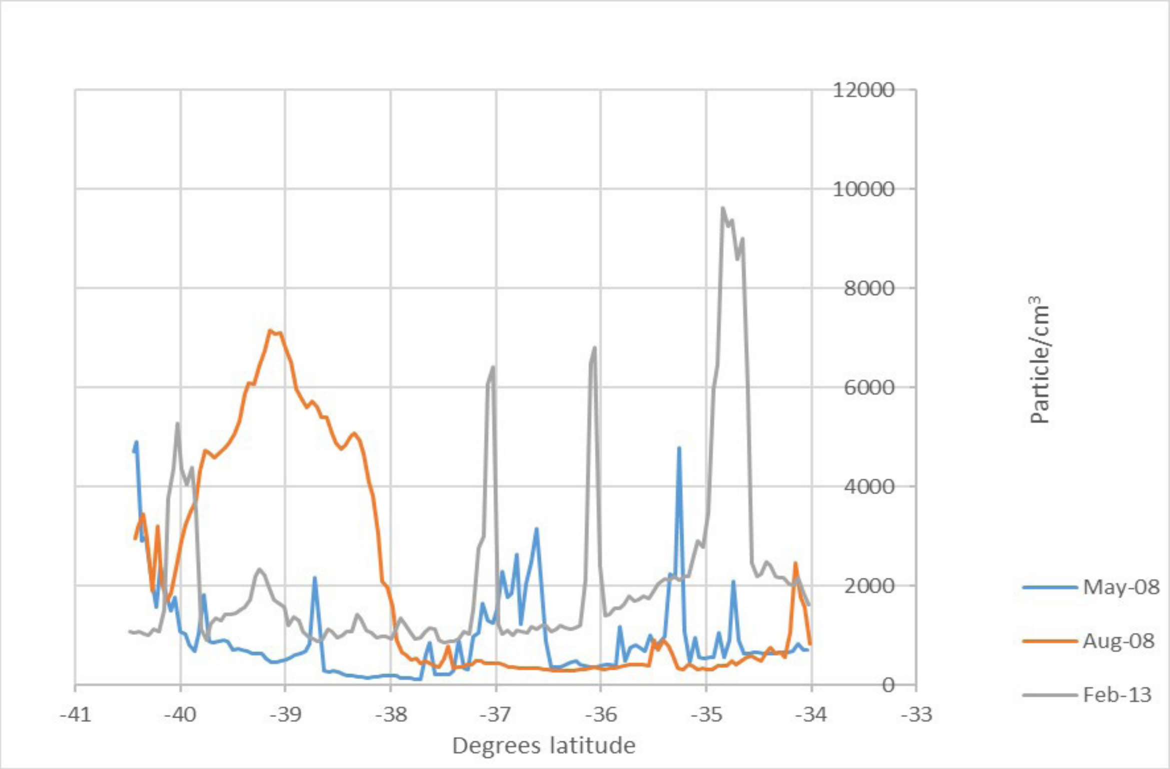

Figure 4: Data from voyages with easterly flow off New Zealand.

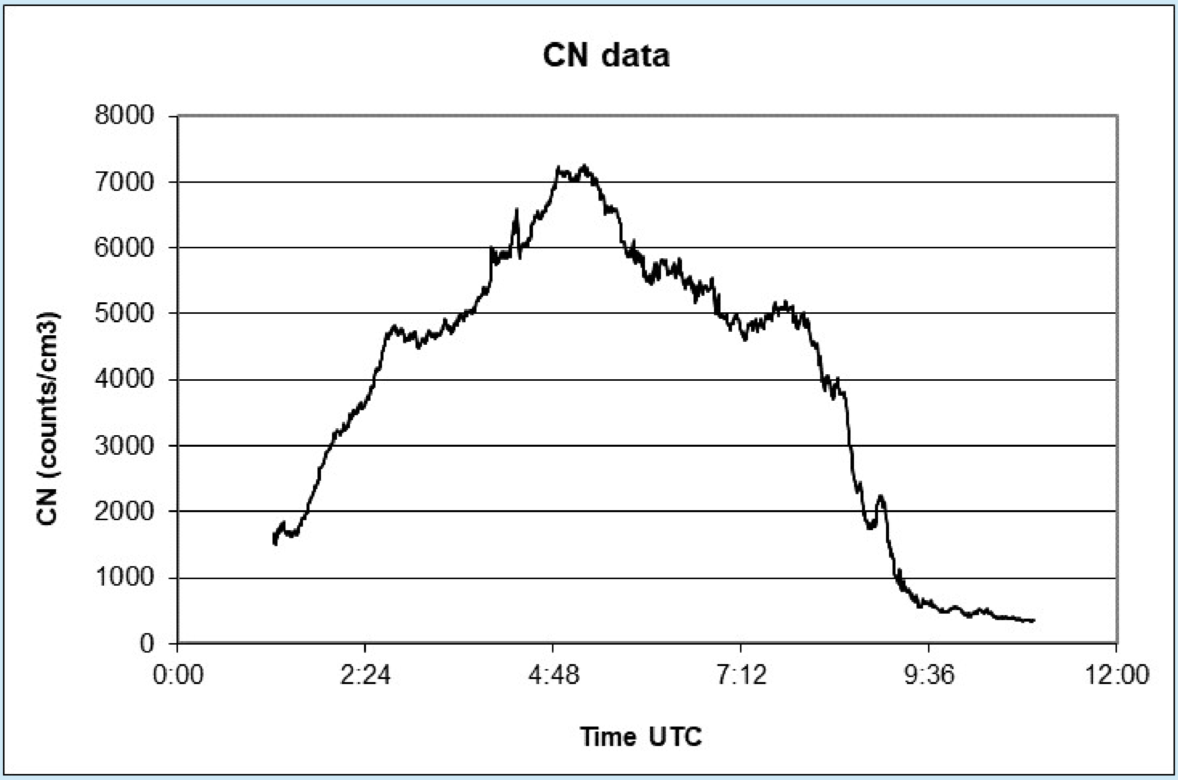

Figure 5: CN data through early hours of 31 August 2008.

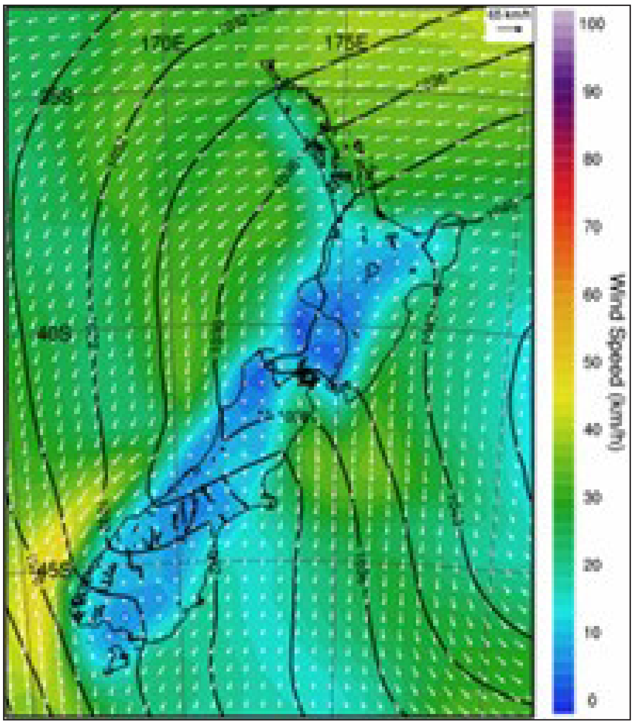

Figure 6: Surface pressure analysis and wind speed for 0600 UTC, 30 August 2008 (NZ Convective Scale model NIWA).

Island veered from southerly to easterly to northeasterly. Sea wave conditions along the ship's track were relatively slight and recorded as being less than 1m.

The southerly wind direction through 28 and 29 August resulted in minimum temperatures dropping to less than 5°C in many centres before rising to around 10°C as the northeasterly was established, with maximum temperatures varying from 13°C to 16°C. At these levels, homes will require some form of heating.

Two-day back trajectories using HYSPLIT were generated from three ship positions - the start of the CN increase (blue), maximum CN values (red) and the end of the period of elevated CN concentration (green). These trajectories all show that the sampled air had crossed over the northern and central North Island in the preceding 24 hours (Figure 7).

There are no CN or similar aerosol data collected on the mainland of New Zealand but particulate data are available, mainly PM_{10}. These data can be used as an indicator of the variation in particle concentration in the air. Hourly particulate data in the Auckland and Waikato regions were obtained from Auckland Council and Environment Waikato for a number of sites in their regions (no hourly data were available from the Taranaki area). PM_{10} is particulate matter less than 10µm in diameter. The PM_{10} trends were similar over the entire region. Figure 8 shows raised concentrations of PM_{10} during the preceding day for both Auckland (station Glen Eden) and the Waikato (stations Hamilton and Te Kuiti) regions. Using the information from the back trajectories, the timing of the increase in urban PM_{10} correlates with the period of high CN concentrations recorded on the vessel the following day.

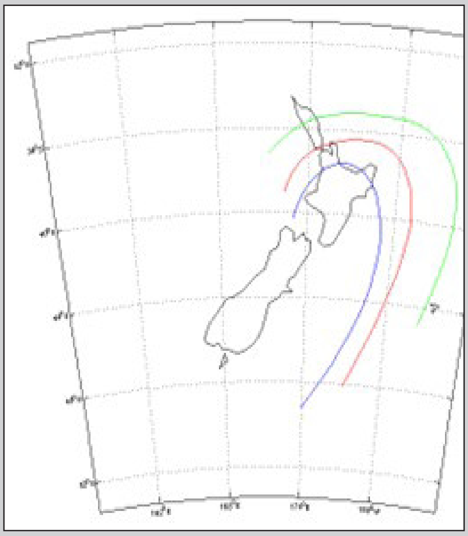

Figure 7: 48-hour back trajectories for the period of the CN increase. The start of the CN increase (blue), maximum CN values (red) and the end of the period of elevated CN concentration (green).

This information indicates that the probable source for this period of high CN concentration was the burning of fossil fuels to heat homes (peaks at night) and emissions from vehicles (peaks during the day), as these are two of the main sources of PM_{10}. It also shows that emissions from one area can be transported to a location some considerable distance away by the wind patterns. This was the only voyage where there was a large increase in CN over a long period. Shorter periods of high concentrations were observed on other voyages.

5. TRANSPORTATION OF AEROSOLS FROM AN INDUSTRIAL SOURCE - USING PARTICLE COUNT AND CN DATA

The February 2013 voyage was the first voyage undertaken with the two aerosol instruments allowing for a closer investigation of the CN data. A period of high concentrations of CN was seen in these data on the 27th February 2013 (see Figure 4) while the vessel was passing through the Taranaki Bight (40°S) area, followed by three

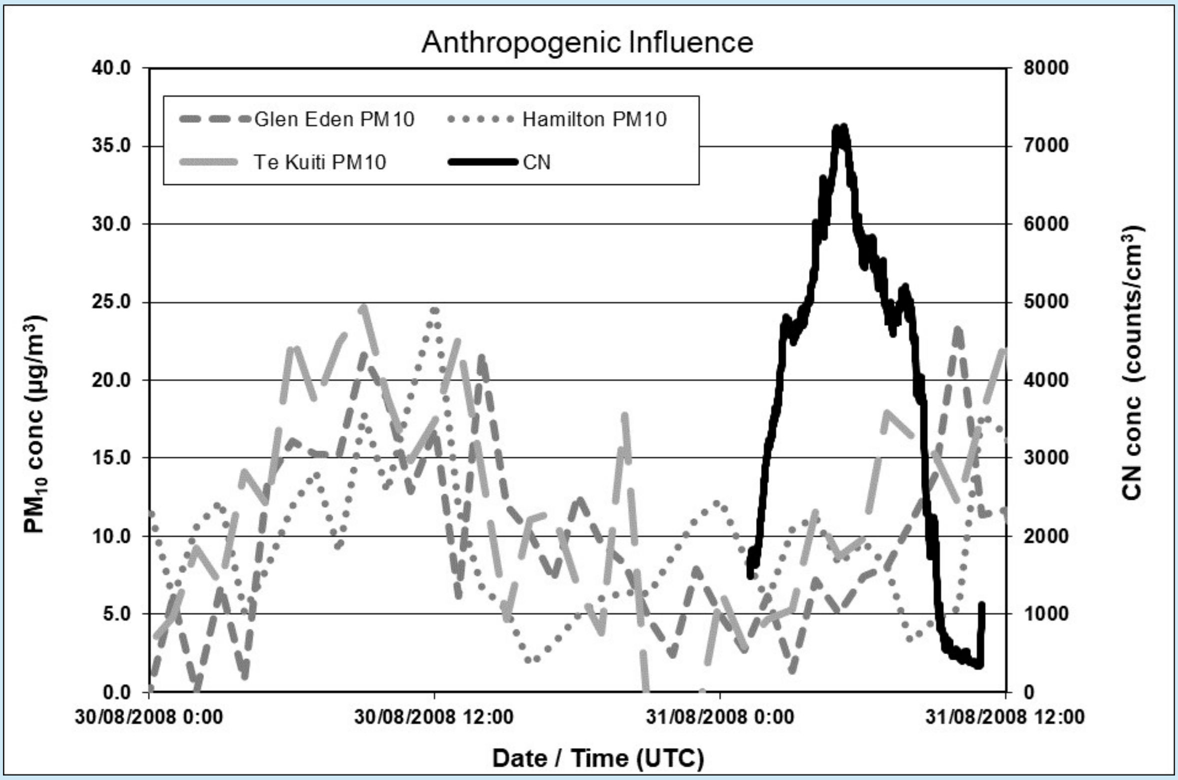

Figure 8: PM_{10} data from New Zealand towns and CN data from TF5.

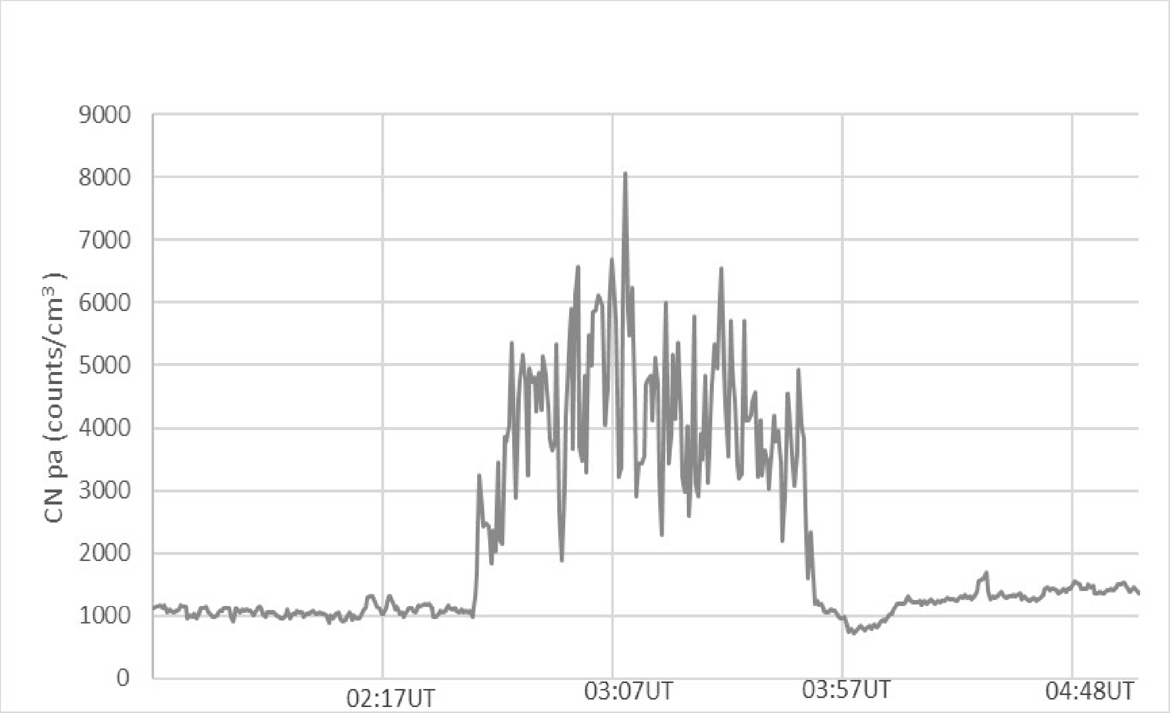

Figure 9: CN increase off the South Taranaki Bight (40°S) during 27 February 2013.

short-lived peaks further north at 37°S, 36°S and 34.7°S, and these data were investigated further. Figure 9 below shows the CN increase off the Taranaki Bight in detail. The CN data showed a marked increase starting at 0236 and ending at 0352 UTC, when the vessel was travelling between the latitudes of 40.15°S and 39.82°S. The data are also "spiky" indicating a probable variable source, or possible variability in the vertical mixing/transport.

Back trajectories over a 48-hour period were calculated around the Taranaki area for the start and end of the period when the CN concentration increased (Figure 10). This showed that winds had been light at the time of the increase of CN and the predominant direction was from the area south of Mt Egmont/Taranaki to the east of the ship's track. Wind observations from the ship position through the period of increased CN concentration indicated light easterlies prevailing.

In this vicinity there are a large number of oil and gas facilities, both on land and sea, which have flares associated with them. The yellow marks indicate the location of some of the oil and gas facilities in the area. The vessel at this time was within 60km of the nearest of these facilities.

Data from both the GRIMM and the CN instrument are plotted in Figure 11. Prior to the CN increase, the wind had been from the west at 7 – 10mps, and the GRIMM data shows mostly steady particle numbers over all sizes, with higher numbers in the two smallest bin-sizes. At the time of the sudden increase in CN at 0236UT, the wind changed to easterly at 5-10mps; a slight increase, with some spikiness is noted in the GRIMM data as well. The drop in GRIMM counts could possibly be due to a lull/change in wind at this time, marking reduced transport across all sizes. The position of the ship at this point indicates it had moved north of the area of windblown particles from

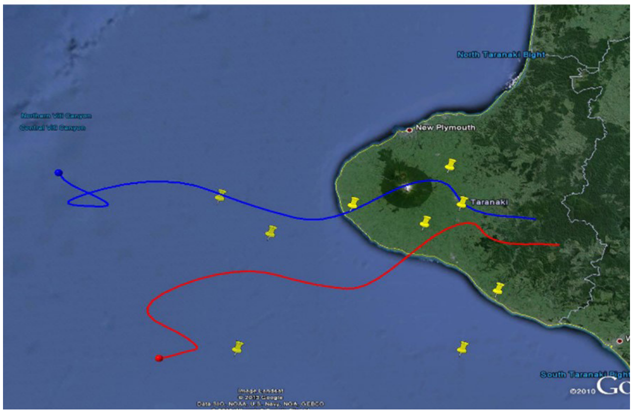

Figure 10: 48-hour air back trajectories from start of CN increase (red) to end of increase (blue). The yellow marks indicate the location of known oil and gas facilities in the area.

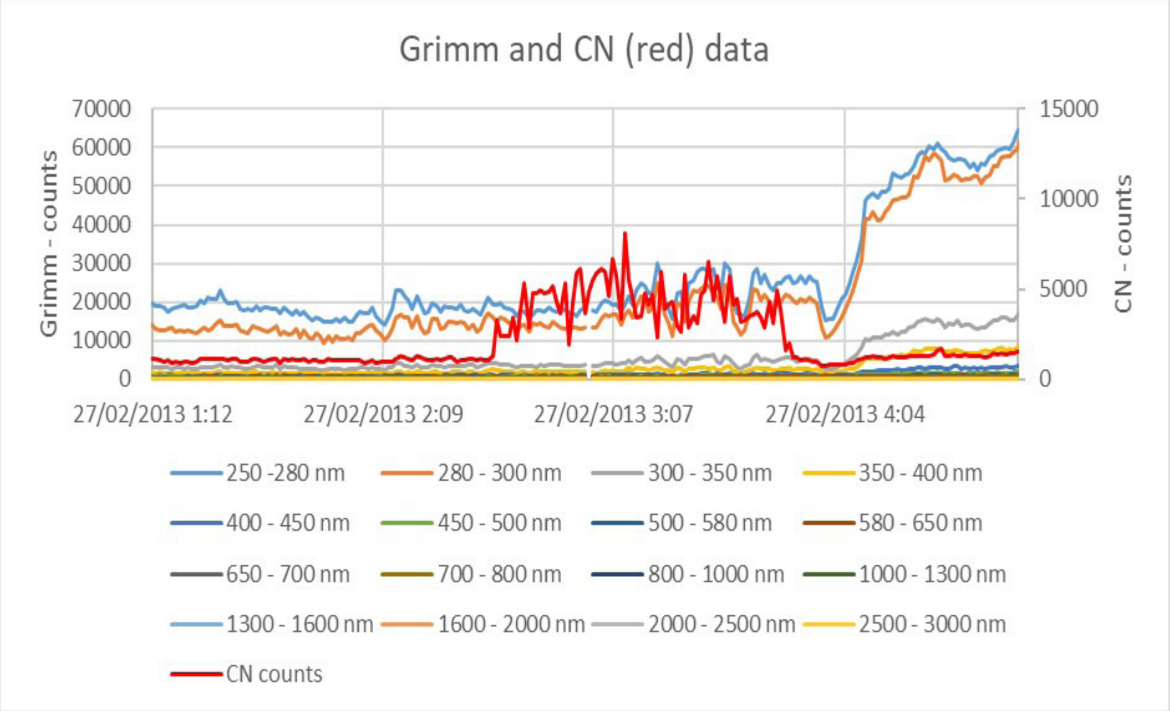

Figure 11: CN and Grimm data collected as ship passed west of South Taranaki Bight.

the oil field and into cleaner air. Further on, the GRIMM counts over larger bin sizes again increased significantly, coinciding with an increase in wind speed to 25mps and possibly some variability in vertical transport and mixing. This would be due to increased larger sea salt particles in the atmosphere produced by spume drops torn from sea-wave crests under the stronger winds. The CN instrument counts also increased slightly, although the largest particles are not in its range of measurement.

The short duration of the sudden increase of the spiky CN values while the ship was traversing the area immediately downwind of the area of the Taranaki oil field, the light easterly flow across the field, and then an equally sudden decrease in CN when the ship moved north of the field indicates emissions from the field are leading to enhanced secondary aerosol formation through that period. The spikiness is likely a mixture of a variable influence of the plumes from the flares and a degree of in - situ nucleation occurring.

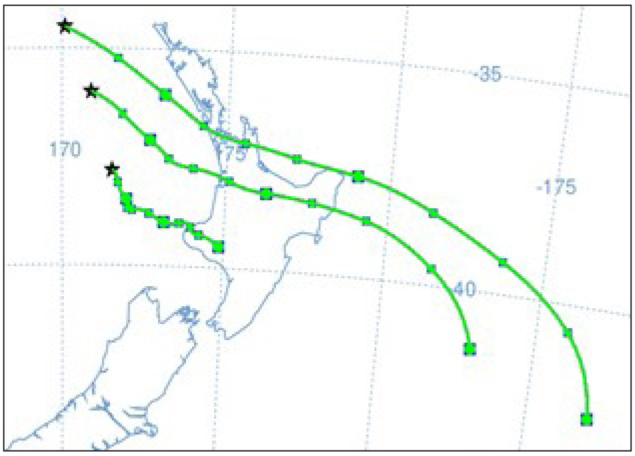

Figure 12: HYSPLIT air trajectories passing over New Plymouth, Hamilton and Auckland 27 February 2013.

As the ship continued tracking north, three more sharp CN spikes were recorded at 37°S, 36.1°S and 34.8°S (see Figure 4). HYSPLIT back trajectories from the position of maximum of the spikes were calculated and are shown in Figure 12, and indicate the high CN concentrations almost certainly originate from the urban areas of New Plymouth (first peak), Hamilton city (second peak) and then Auckland city (third peak).

5. TRANSFUTURE5 VOYAGE APRIL - MAY 2008

The April-May 2008 Transfuture5 voyage experienced four occasions where measured CN data showed sudden relatively short-lived increases as the ship travelled north off the west coast of the North Island (Figure 4). On 26 April, shortly after leaving Nelson port CN numbers increased to more than 5000 particles/cm^3 between latitudes 40.4°S to 38.75°S, off the Manawatu area (Figure 13); the data was seen to be spiky, indicating a likely variable source. The wind flow was light to moderate from the northeast.

From February, volcanic activity at Mount Ruapehu in the central North Island had been reported and from mid-April this had increased, with visible plumes of ash and gas emissions being emitted into the atmosphere in varying amounts. This suggests that the measured increase of particles of variable amounts was from the volcanic plume emitted from Ruapehu some 8 hours earlier. A backward air trajectory plot (Figure 14) supports this with the track passing directly over the mountain.

As the ship continued sailing further north, a large area of high pressure was moving away to the east of New

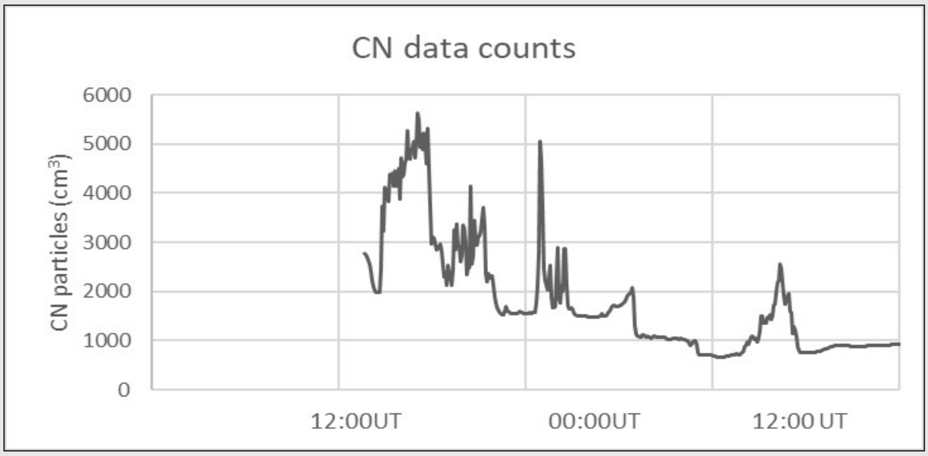

Figure 13: Recorded CN data between 40.4°S and 38.75°S, 26-27 April 2008.

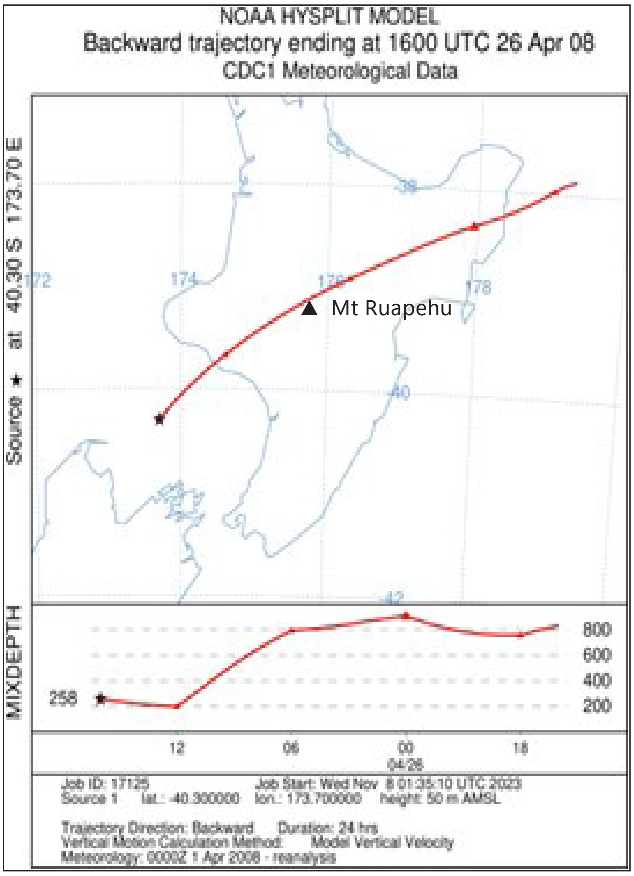

Figure 14: Back trajectory passing over Mt Ruapehu.

Zealand, with a ridge over the North Island maintaining a northeasterly flow over the North Island and over the Tasman Sea close to land. A low in the central Tasman Sea was moving east and bringing a north to north-westerly flow further offshore from the North Island (Figure 15).

Three periods of CN increase were recorded as TF5 moved further north and west: the first was a spike at 38.8°S, followed by a more lengthy spikey increase between 37.7°S – 36.5°S, and a third occurrence between 35.8°S – 34.7°S. Back trajectories (shown in Figure 16) indicate that the southern of the three increases was anthropogenic pollution from the Auckland city area, blown out into the Tasman Sea by the NE flow from the ridge (green trajectory).

The back trajectory from the second increase in CN (39.7°S – 36.5°S, yellow trajectory) indicated flow from the NNW; the likely source of the particles is from the continuously erupting volcano on uninhabited Matthew Island, some 500km east of Noumea, New Caledonia. The third (blue) back trajectory from the third CN increase shows a NW airflow around the low pressure centre moving eastwards across the mid-Tasman Sea towards the north of the North Isalnd. This indicates air from just north of Brisbane city and the heavily populated Gold Coast area on

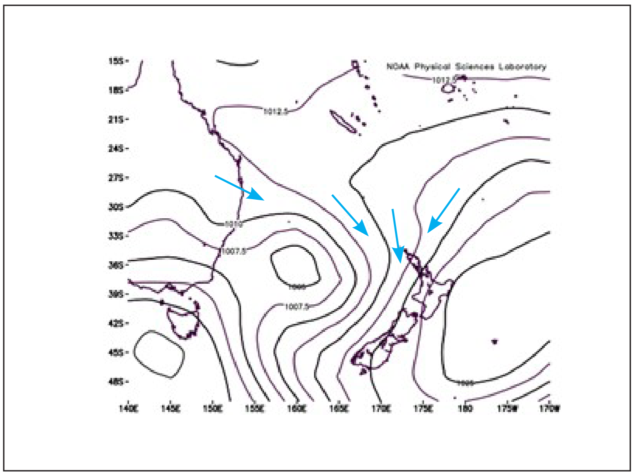

Figure 15: MSL pressure 00 UT 27 April 2008 (NCEP/NCAR reanalysis). Blue arrows indicate general windflow direction.

the Australian east coast, and the CN increase is most likely to be composed of particles from human activity from the large built-up area e.g. industrial, traffic, home heating emissions etc.

6. SUMMARY

This research has shown that aerosols of anthropogenic and volcanic sources have been detected off the coastline of the North Island of New Zealand. Similar patterns have also been detected as the vessel travelled past some of the other islands in the Pacific (most significantly at New Caledonia) and also as the vessel approached Japan (Bromley et al, 2018). The amount of aerosols and the areas where they have been blown to are small compared to events measured in the more heavily populated and industrialised Northern Hemisphere but they still affect weather and climate in the New Zealand region.

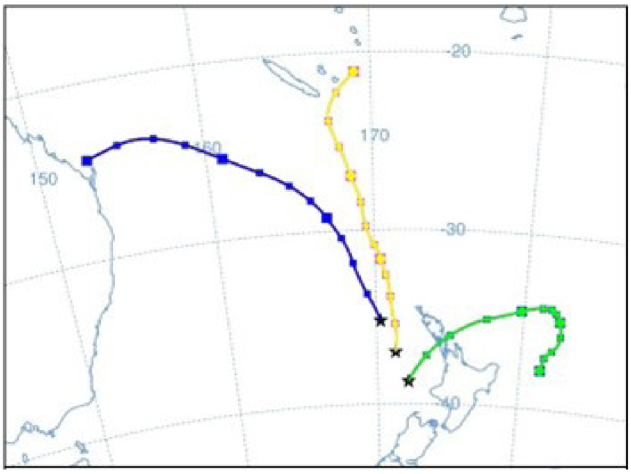

Figure 16: Back trajectories from source positions of areas of increased CN counts April 2008 voyage.

CN are important because the variation in concentration, source and size contributes to weather and climate predictions at local, regional and global levels. Atmospheric aerosols are one of the largest sources of uncertainty in the current understanding of climate change (Boucher et al, 2013). They influence the world's climate in two main ways: direct and indirect forcing. The direct forcing mechanism is where aerosols reflect sunlight back into space, thus acting to cool the planet. Conversely, aerosols of a sooty nature absorb some of the sun's energy, which can lead to local atmospheric heating and changes in stability and convective patterns in nearby regions. The indirect forcing effect is where aerosols act as cloud condensation nuclei that can cause clouds to be more reflective and longer lasting. Aerosols from large or long-lasting eruptions that enter the stratosphere (eg those of El Chichon, Pinatubo and the recent Hunga Tonga-Hunga Ha'apai) have also caused cooling periods that typically last a year or two.

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- Toyofuji Shipping Company
- Officers and crew of Transfuture5
- Dr Nojiri and Shigeru Kariya (NIES)
- Ross Martin (NIWA)

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REFERENCES

Andrae, M. (1995). Climate effects of changing atmospheric aerosol levels. *Environmental Science*, Vol. 16: 347-398.

Andrae, M. (2009). Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions. *Atmos. Chem. Phys.*, Vol 9: 543-556.

Ayers, G.P., Cainey, J.M., Gillett, R.W. and Ivey, J.P. (1997). Atmospheric sulphur and cloud condensation nuclei in marine air in the Southern Hemisphere. *Phil. Trans. R. Soc.* Lond B 352, 203-211.

Bodhaine, B.A., Harris, J.M. and Herbet, G.A. (1981). Aerosol light scattering and condensation nuclei measurements at Barrow, Alaska. *Atmospheric Environment* Vol. 15, No 8: 1375-1389.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S.K., Sherwodd, S., Stevens, B. and X.Y. Zhang. (2013). Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boscung, a. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bromley, A.M., Harvey, M.J., Gray, S.A. and McGregor, J. (2018). Condensation nuclei and aerosol optical depth measurements through the western Pacific Ocean. *Weather & Climate*, Vol 38, Issue 1: 38-57.

Charlson, R., Lovelock, J., Andrae, M. and Warren, Stephen G. (1987). Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* 326, 655-661.

Fitzgerald, James W. (1991). Marine aerosols: A review. *Atmospheric Environment* Vol. 25: Issues 3-4: 533-545.

Hoppel, W.A.,Fitzgerald, J.W., Frick, G. M., Larson, R.E. and Mack, E.J. (1990). Aerosol size distributions and optical properties found in the marine boundary layer over the Atlantic Ocean. *Journal of Geophysical Research* pp 3659-3686.

Lawson, SJ, Selleck, PW, Galbally, IE, Keywood, MD, Harvey, MJ, Lerot, C, Helmig, D, Ristovski, Z (2015) Seasonal in situ observations of glyoxal and methylglyoxal over the temperate oceans of the Southern Hemisphere. *Atmos. Chem. Phys.* 15, 223-240.

Liley, J.B., and B.W. Forgan (2009), Aerosol optical depth over Lauder, New Zealand. *Geophys. Res. Lett.*, Vol. 36, Issue

Prospero, J.M., Charlson,R.J., Mohnen, V., Jaenicke, R., Delany, A.C., Moyers, J., Zoller, W. and Rahn,K. (1983). The atmospheric aerosol system: an overview. A.G.U.:*Reviews of Geophysics* Vol 21, 1607-1629.

Staudt, A.C., Jacob, D.J., Logan,J.A., Bachiochi, D., Krishnamurti,T.N.andSachse,G.W.(2016).J.*Geophys. Res: Atmospheres 106*. doi:10.1029/2001JD-900078.

Xiao, H.-W., Xiao, H.-Y., Shen, C.-Y., Zhang, Z.-Y., Long, A.-M. Chemical Composition and Sources of Marine Aerosol over the Western North Pacific Ocean in Winter. *Atmosphere* 2018, 9, 298. https://doi.org/10.3390/atmos9080298

Regional ocean grid refinement and its effect on simulated atmospheric climate

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ABSTRACT

In this work we analyse the impact of including a regional, high-resolution ocean model on simulated atmospheric climate in a coupled earth system model. The resolution of the regional, nested ocean model is approximately 0.2° compared to the ~1° resolution of the global ocean model within which it is embedded and this work complements previously published work on ocean circulation and marine heatwaves using this setup, referred to as the New Zealand Earth System Model, NZESM. After a brief discussion of the wider model setup, the persistent Southern Ocean warm bias in climate models and the validation data sets used, we show the effects of the altered ocean physics on air temperature, precipitation and evaporation, latent and sensible surface heat balances, westerly winds, the storm track and the effect on total cloud amount. Overall we find that the NZESM provides a better representation of regional atmospheric climate compared to its parent model – UKESM1 – although this improvement is not universal. For example, although the NZESM shows better agreement in surface air temperature within the nested ocean region, there is also some deterioration in the agreement at higher southern latitudes where the seasonal sea ice edge coincides with a transition from negative to positive correlation between air temperature and cloud amount. The lack of additional model tuning in the NZESM after the nested ocean model's inclusion largely accounts for the presence of these improvement-deterioration pairs with respect to observations. The reader is encouraged to read the paper of Behrens et al. (Behrens et al, 2020) before this one since it provides much additional information which will aid understanding. This study aims to provide a high-level reference ontology for how changing one aspect of the ocean physics in a coupled model can impact simulated atmospheric climate.

1. INTRODUCTION

This paper examines the effect on simulated atmospheric climate of altered ocean physics in a coupled Earth System Model by comparing outputs from a control model, UKESM1-0-LL (Sellar et al, 2020) ('UKESM1') and the New Zealand Earth System Model, NZESM (Williams et al, 2016). This work is a companion, description paper to previous oceanographic studies (Behrens et al, 2020, 2022), focusing on multi-year, annual means. The physical oceanography of the NZESM is described in detail in (Behrens et al, 2020) and the only difference to UKESM1 is the inclusion of an embedded high-resolution ocean model in the New Zealand region, which allows the model to simulate ocean eddies rather than parameterising them.

Climate models' representations of Southern Ocean climate are subject to some persistent biases in the literature and a warm bias with respect to observational products is one of the best known. What this means in practice is that, in general, climate models do not represent the surface temperature of the Southern Ocean and its overlying atmosphere as well as other regions. The interested reader is referred elsewhere for an in-depth historical review of this using data from the last three Intergovernmental Panel on Climate Change Assessment Reports (Beadling et al, 2020). The goal of improving our understanding of the climate of the Southern Ocean and Antarctica – New Zealand's 'Deep South' – is the driving goal of the New Zealand Government's Deep South National Science Challenge, and indeed the NZESM itself (Williams et al, 2016).

Southern Ocean biases in coupled climate models are typically two-fold, manifesting in a persistent surface warm bias of the Southern Ocean (e.g. Yool et al, 2021) and in a large shortwave cloud radiative effect bias in the overlying atmosphere (e.g. Varma et al, 2020). In coupled models these biases are inherently connected in that, for example, an ocean surface that is too warm will also result in an atmospheric radiation bias which in turn will affect cloud formation, and so on. The Southern Ocean biases in the precursor to UKESM1, HadGEM2-ES, – results from which were submitted to the 5th Coupled Model Intercomparison Project (CMIP5) (Taylor et al, 2012) – are discussed in detail elsewhere (Hawcroft et al, 2016). In the results section below, we focus on changes to

1. Air temperature and surface heat flux.
2. The hydrological cycle.
3. Westerly winds and the storm track.

The impact of tropical cyclones on New Zealand and mid-latitudes in general is the subject of a separate indepth study (Williams et al, 2023). The main aim of this work is to act as a standard, relatively brief reference for future work on the atmospheric climate of the NZESM and as such seasonal variability of the discussed variables is deliberately not included so as to strike a balance between maximising the number of meteorological variables shown whilst remaining relevant to the general reader.

2. MODELS AND VALIDATION DATASETS

The atmospheric component of the models used here is the 'Global Atmosphere Model, Version 7.1' – GA7.1 (Walters et al, 2019) – configuration of the Unified Model. It uses a semi-implicit, semi-Lagrangian dynamical core (Wood et al, 2014), the SOCRATES radiation scheme, based on (Edwards et al, 1996), shallow and deep mass-flux-based convection - e.g. (Gregory et al, 1990) - and sub-gridscale boundary layer turbulence e.g. (Brown et al, 2008). The models also simulate explicit tropospheric and stratospheric chemistry (Archibald et al, 2020).

The configuration of the NZESM described here includes a two-way nested, high-resolution ocean model in the New Zealand region whilst keeping all other aspects of the ocean model unchanged. This nesting has been achieved using the Adaptive Grid Refinement In Fortran – AGRIF – method (Debreu et al, 2008) and has improved the nominal ocean grid resolution from 1° to 0.2°, making it 'eddy permitting', rather than small-scale eddies needing to be parameterised (Hewitt et al, 2020). Previous studies using similar ocean model nesting methods have addressed radioactive isotope dispersal (Behrens et al, 2012) and the ocean circulation of the Agulhas current off southern Africa (Biastoch et al, 2008) for example. A 2019 study gives a further example of how this nesting procedure affects model results when a regional nest at five times higher resolution than that one it is embedded within (the same as the NZESM), albeit at a significantly higher base resolution than UKESM1 (Schwarzkopf et al, 2019).

The ocean model used is NEMO version 3.6 (Gurvan et al, 2022), which contains the MEDUSA ocean biogeochemistry simulator version 2.1 (Yool et al, 2013) and is coupled to the sea ice model CICE version 5.1.2 (Hunke et al, 2017; Ridley et al, 2018). In the nested ocean model, the ocean diffusivity and viscosity are different to the global model and the integration time step is reduced from 2,700s to 900s. The AGRIF formulation is described in detail elsewhere (Behrens et al, 2020).

Throughout this work we compare 20-year annual means (1989-2008) of climate model output to observational and reanalysis products of temperature, precipitation and evaporation, heat fluxes, zonal winds and total cloud amount. The models runs are started in 1950 to enable model spin-up to occur and both models start from initial conditions from a UK Met Office simulation (Tang et al, 2019), which was itself run from 1850. We use data from the ERA5 reanalysis (Hersbach et al, 2020), surface heat flux data from the Objectively Analyzed Air–Sea Heat Fluxes data set (Yu et al, 2007) – hereafter 'OA flux' – and cloud cover from the International Satellite Cloud Climatology project, ISCCP (Rossow et al, 2004; Rossow et al, 1999).

3. RESULTS

3.1 Temperature and surface heat balance

3.1.1 1.5m temperature

Figure 1 shows annual mean 1.5m air temperature for UKESM1 and the NZESM compared to the ERA5 reanalysis (Hersbach et al, 2020).

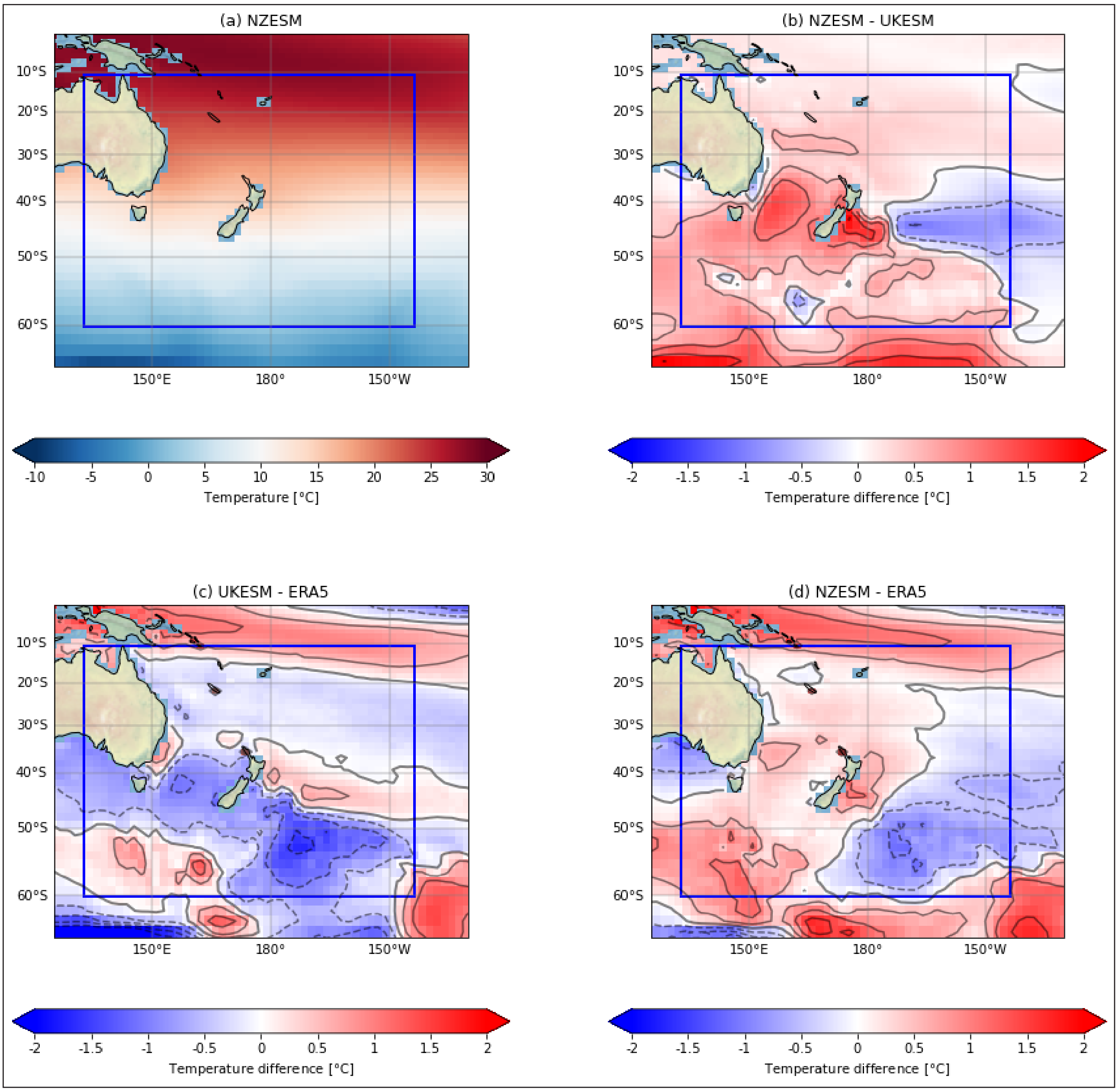

Figure 1: 1.5m annual mean air temperature (°C) for: (a) NZESM (b) NZESM - UKESM; (c) NZESM - ERA5 reanalysis; (d) UKESM - ERA5 reanalysis. All data shows annual means for 1989-2008. The region defined by the blue rectangle denotes the location of the high-resolution nested ocean model, i.e. 'the AGRIF region', after the method used to implement it (Behrens, 2020; Behrens et al, 2020; Debreu et al, 2008). Negative (positive) contours are shown as dashed (solid) lines.

The ocean data in (Behrens et al, 2020) uses the EN4 climatology for sea surface temperature (Good et al, 2013) and therefore this serves as an interesting comparison to a previous analysis of, ostensibly, the same quantity but with a different 'ground truth' data set.

The agreement with the ERA5 reanalysis is improved in the NZESM in some regions (e.g. Tasman Sea, east of New Zealand) and degraded elsewhere (higher latitudes to the south of Australia). The steady state atmosphere results shown in Figure 1 are analogous to the SST data shown in the paper describing the oceanography of this model pair (Behrens, 2013) where detailed information regarding ocean current changes and their effects on surface temperature and salinity, for example, is given.

The warming seen in the NZESM around -60°S in Figure 1(b) is also visible at even higher southern latitudes. This is shown elsewhere (Behrens et al, 2020) and later in this study in relation to the effect of the AGRIF region on the storm track, Figure 12(c) where the NZESM exacerbates the Southern Ocean warm bias already present in UKESM1. This is most notable in the warming of the southern Indian Ocean in the NZESM cf. UKESM1 – Figure 9(a) in the 2020 study detailing the physical oceanography of this model pair (Behrens et al, 2020). These 'far field' changes can be attributed to ocean circulation changes which increase the southward heat flux in the ocean which, over time, bring the surface atmosphere into this new, warmer equilibrium state. This combination of a localised improvement accompanied by an associated deterioration elsewhere is often encountered in climate model development where new physical parameterisations are included without any additional model tuning. The tuning of climate models has its own extensive literature and the interested reader is referred elsewhere (Hourdin et al, 2017; McNeall et al, 2020; Schmidt et al, 2017).

3.1.2 Temperature as a function of pressure

Figure 2 shows zonal mean temperature profiles for the region shown in Figure 1.

The tropospheric warming signal in the NZESM is clearly visible in Figure 2(b), as is the accompanying stratospheric cooling, which is thermodynamically required in order to achieve overall energy balance (Pisoft et al, 2021). Due to the warming in the NZESM's low-to-middle-atmosphere, the tropopause is raised by up to ≈130m (Figure 3). Figure 3 shows the tropospheric pressures for the models and the difference between the tropospheric heights.

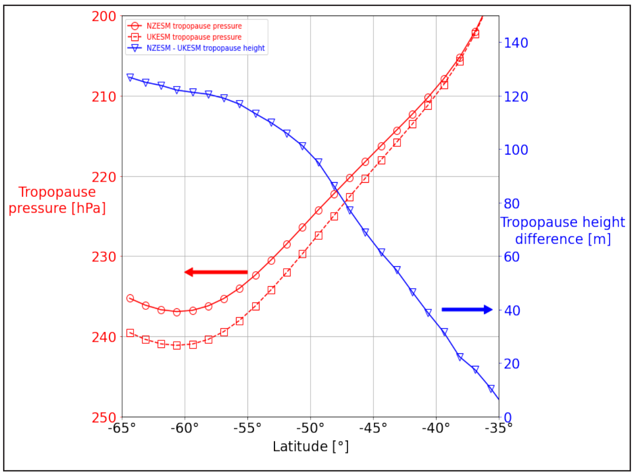

Figure 3: Tropopause pressures in Figure 2 (red) and the tropopause height difference (blue).

Although this is only ~1% of the total height of the tropopause in this region it has been shown that the global warming signal for 20°N – 80°N has been ≈ 50 – 60m per decade for the period 1980-2020 (Meng et al, 2021) and so this response of the lower stratosphere is far from trivial and reflects the importance of coupled modelling in understanding seemingly disparate aspects of the earth system under climate change.

The agreement between the tropospheric temperatures in the NZESM versus the reanalysis data is markedly

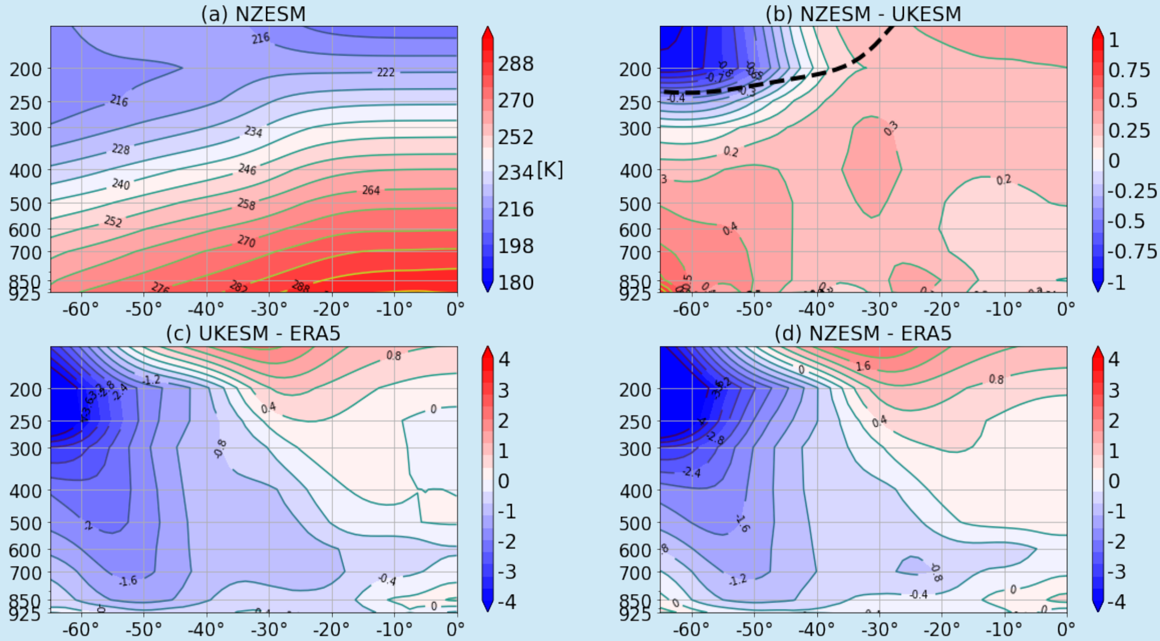

Figure 2: Temperature as a function of pressure: (a) NZESM, (b) NZESM - UKESM (c) NZESM - ERA5 reanalysis, (d) UKESM - ERA5 reanalysis. All data is for 1989-2008 and the thick dashed line in (b) shows the NZESM tropopause in this region.

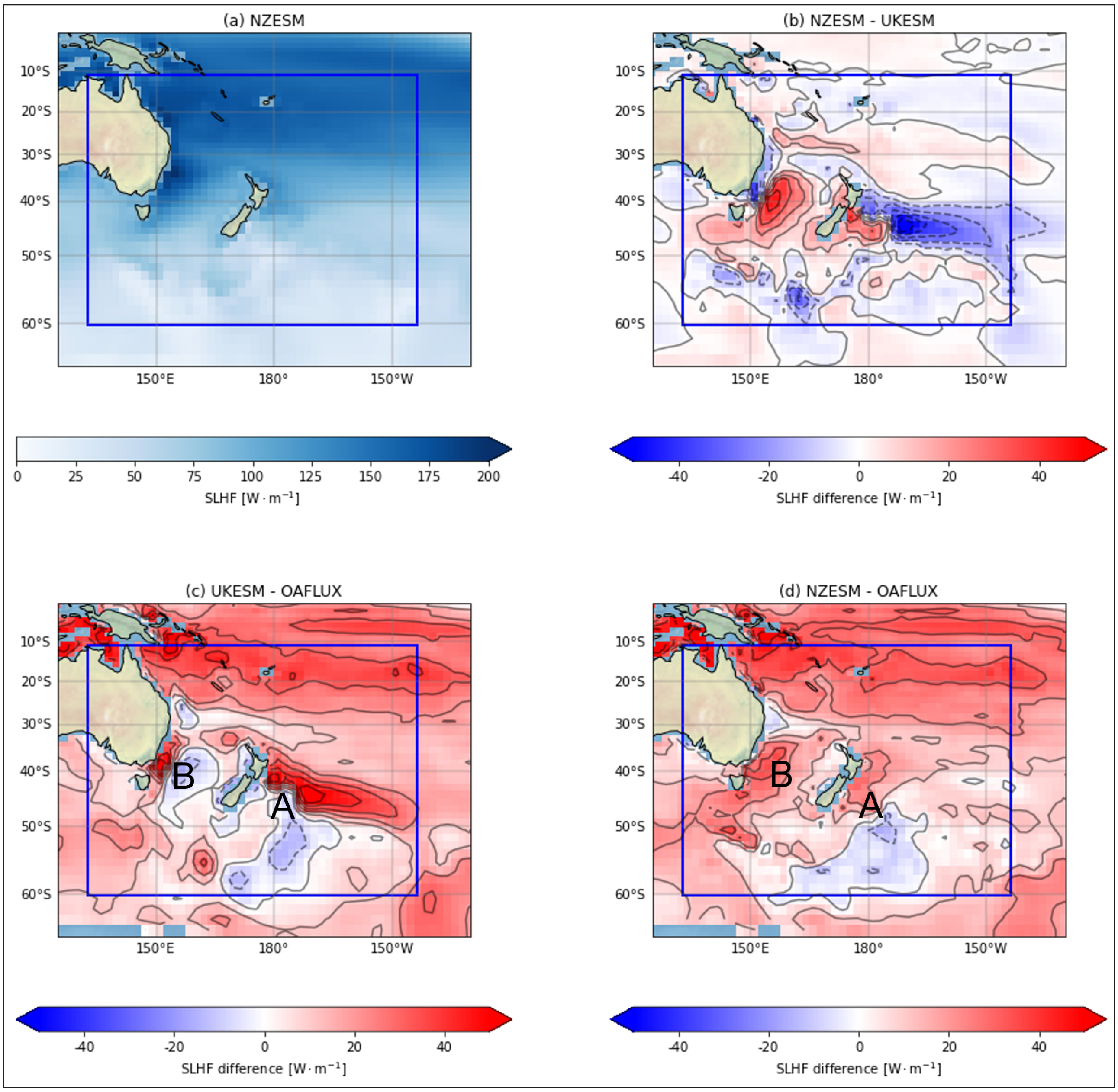

Figure 4: Surface latent heat fluxes (W · m^{-2}) for the models and with respect to the OA flux data set (Yu et al, 2007). (a) NZESM (b) NZESM - UKESM; (c) NZESM - OA flux; (d) UKESM - OA flux.

improved in the mid-to-lower troposphere. There is some deterioration in the agreement in the stratosphere but this is of much smaller extent that the formerly mentioned improvement.

The general warming observed in the NZESM is primarily due to increased southward heat transport by the eddy-permitting ocean, which is discussed in detail elsewhere (Behrens et al, 2020, 2022). This of course not only affects the surface temperature but the structure of the surface heat balance.

3.1.3 Surface heat balance

Figures 4 and 5 show the surface latent and sensible heat fluxes respectively for the models versus the OA flux data set (Yu et al, 2007).

The anomalies' spatial responses in Figures 4 and 5 is - as expected - very similar to temperature response in Figure 1. In both cases, the model-reanalysis data agreement is improved in the NZESM; this is particularly striking in the case of the sensible heating, which shows significantly improved model-reanalysis agreement to the east of New Zealand. The improvement to model-data agreement in this region can be attributed to the decrease in SST in this region in the NZESM, thereby reducing upward heat

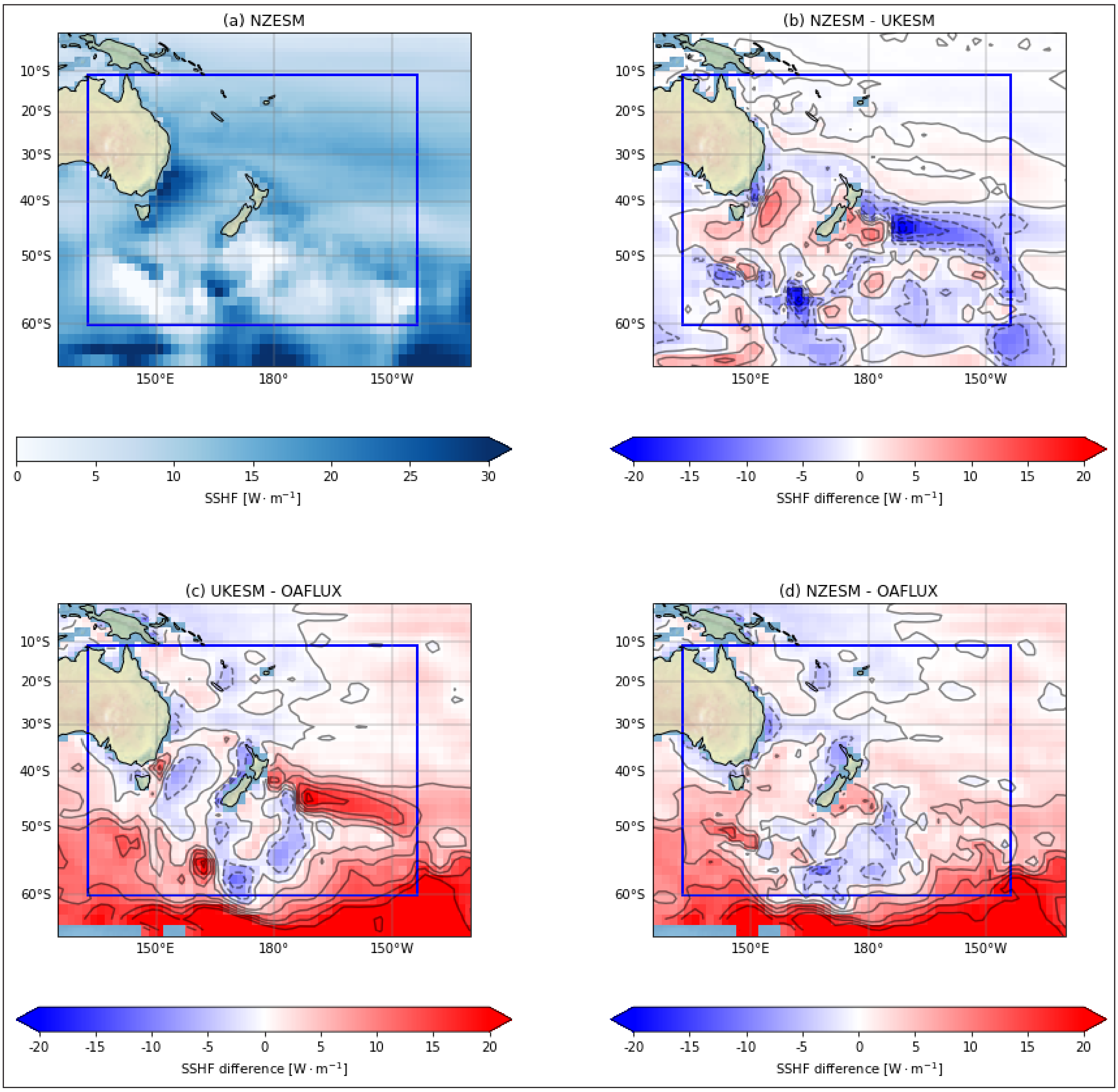

Figure 5: Surface sensible heat fluxes (W · m^{-2}) for (a) NZESM (b) NZESM - UKESM; (c) NZESM - OA flux; (d) UKESM - OA flux.

flux and the positive bias seen in Figure 5(c). The wider relationship between temperature, clouds and radiation is a topic of ongoing research by many authors and represents a 'grand challenge' of coupled climate modelling (Hoem et al, 2022; Hyder et al, 2018; Luo et al, 2023; Varma et al, 2020).

The significant positive sensible heat bias in both models at higher southern latitudes (outside the AGRIF region) is indicative of the warm bias in that region however the agreement within the boundaries of the eddy-permitting ocean is encouraging, illustrating that improved ocean circulation has beneficial effects on atmospheric climate in this coupled framework. In the case of the latent heating there are some areas of improvement – in the region of convergence of the Southland and East Auckland Currents; 'A' in Figure 4(c,d) – and deterioration – Tasman Sea and the south east coast of Australia in particular; 'B' in Figure 4(c,d). That said, there is a clear overall improvement in the model-data agreement in Figure 4.

3.2 Precipitation, evaporation and cloud amount

The hydrological cycle is now considered by examining precipitation, evaporation, total evapotranspiration and total cloud amount. Firstly, Figure 6 shows the annual mean total precipitation fluxes for the models against ERA5

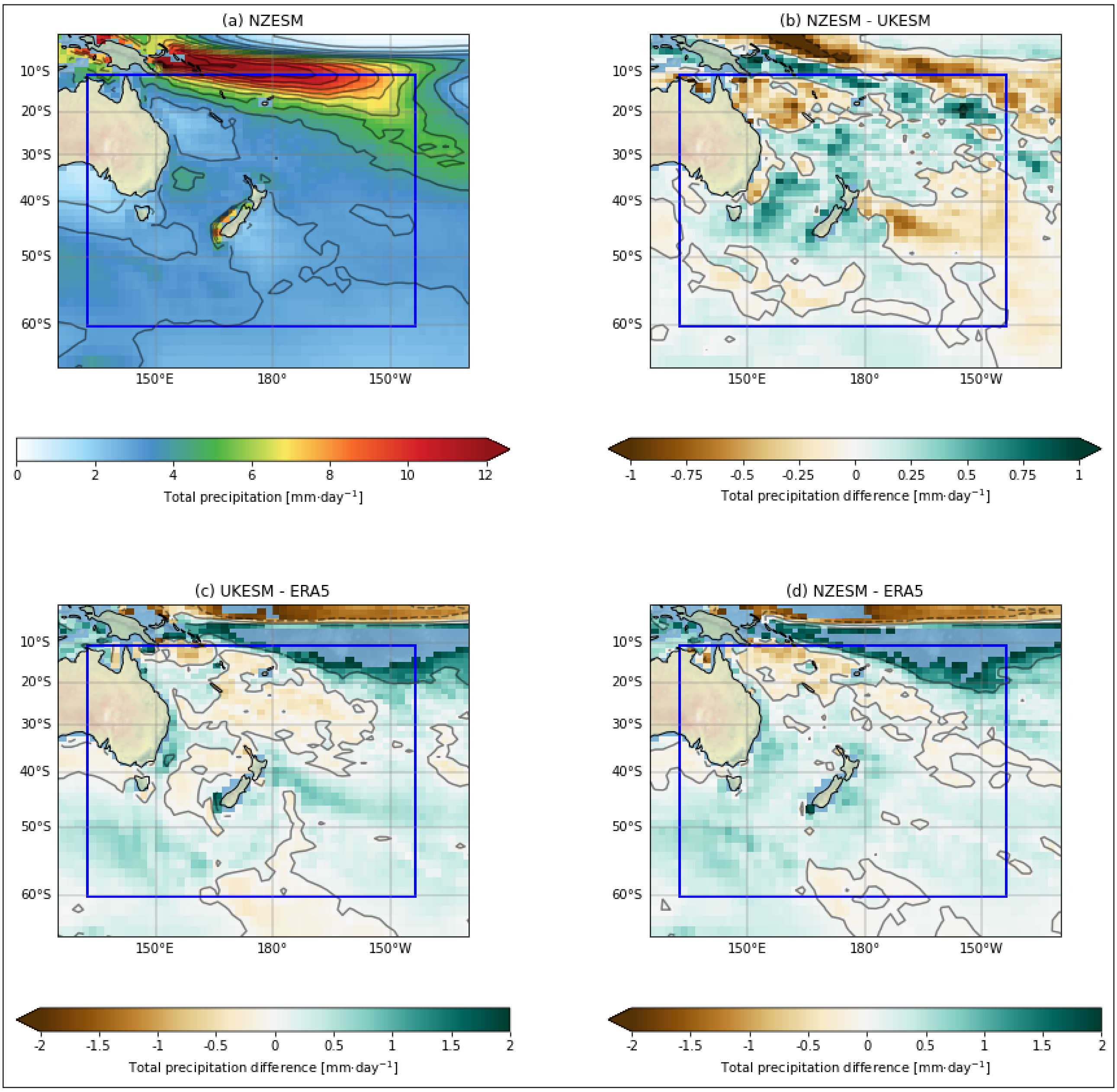

Figure 6: Total precipitation (mm · day^{-1}) for (a) NZESM, (b) NZESM - UKESM, (c) UKESM - ERA5, (d) NZESM - ERA5. Contour levels for levels for all plots are at integer values and for (c) and (d) values over 2mm · day^{-1} are masked to aid visual interpretation.

reanalysis data.

Figure 6(b) shows that the largest changes to the total precipitation come from the South Pacific Convergence Zone – SPCZ – in the northern and eastern portions of the region studied. This region of intense precipitation inclines south-eastwards from the Maritime Continent and is displaced southward in the NZESM cf. UKESM1. This is evidenced by drying in the far northeastern portion and the moistening immediately south thereof in Figure 6(b) and also in the drying signal which occurs in a narrower band in Figure 6(d) with respect to ERA5 cf. Figure 6(c). We also see a general drying to the east and a moistening to the west of New Zealand, which is anti-correlated to the 1.5m temperature changes observed in Figure 1(b) and that the NZESM reduces both wet and dry biases close to New Zealand.

Figures 7 and 8 show sea to air evaporation flux and precipitation minus evaporation *(P - E)* for the model and ERA5 respectively.

Overall, the pattern of changes in the NZESM cf. UKESM1 in the evaporation are of the same sign as the precipitation but larger in magnitude, so $\Delta E > \Delta P$ – compare Figures 6(b) and 7(b). This means that overall changes to surface evapotranspiration – i.e. $\Delta(P - E)$ – are of the opposite

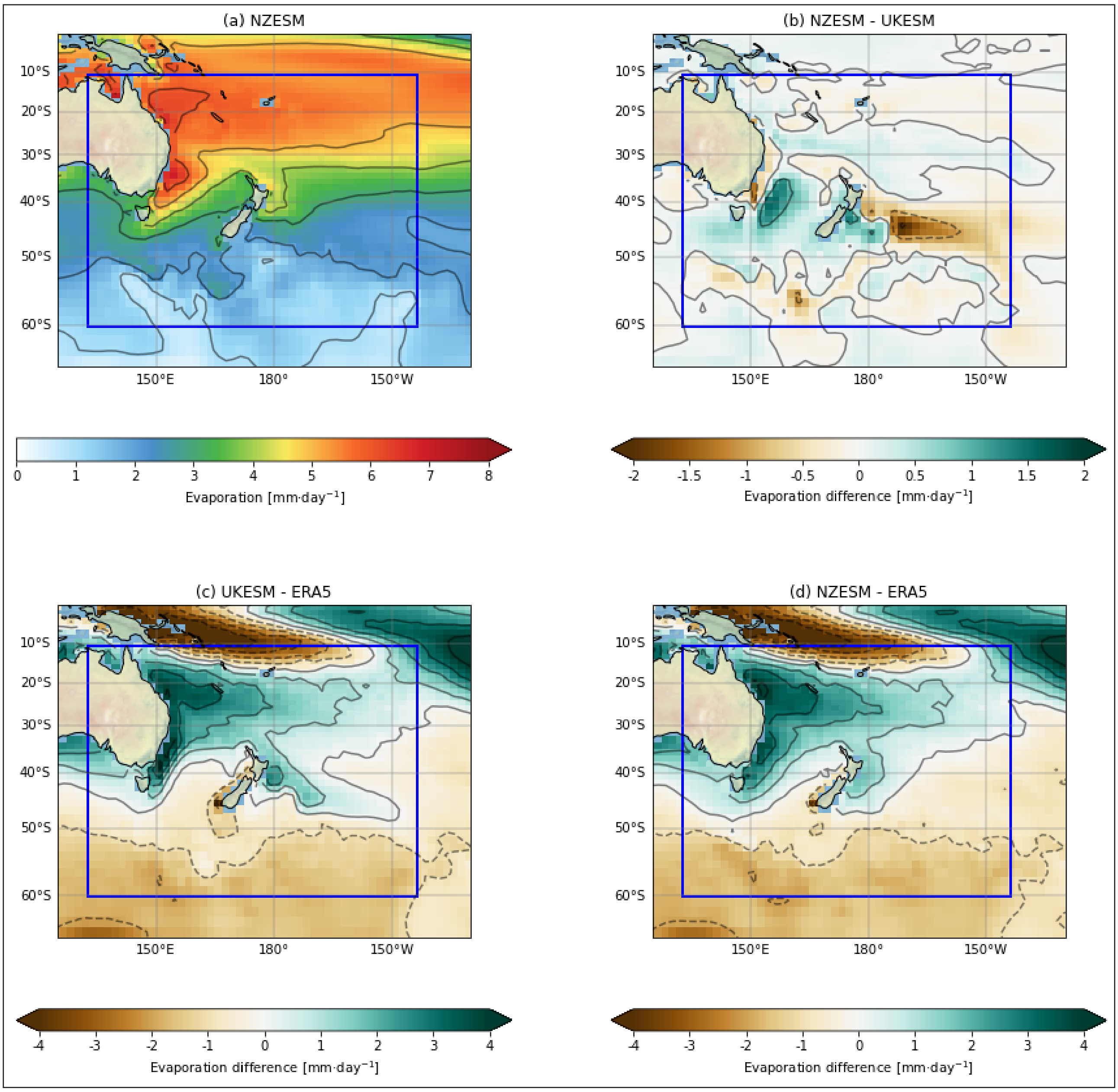

Figure 7: Sea to air evaporation (mm · day^{-1}) for (a) NZESM, (b) NZESM - UKESM, (c) UKESM - ERA5, (d) NZESM - ERA5. Contour levels for levels for all plots are at integer values.

sign to changes in precipitation. Precipitation changes are often considered in isolation in model sensitivity studies and this can have counter-intuitive effects on, for example, surface ocean composition and circulation where regions of increased precipitation could exhibit *increased* salinity and density, in spite of the increased water input from rainfall.

3.2.1 Cloud amount

Figure 9 shows the response of the total cloud amount in the models (Bodas-Salcedo et al, 2011) as defined by the International Satellite Cloud Climatology Project, ISCCP (Rossow et al, 1999).

Figure 9(b) shows that there is a general increase in cloud in the NZESM to the east of New Zealand. The reverse seen in the SPCZ and around the Tasman Sea. At mid-latitudes, the sign of this change is anti-correlated with the temperature change – Figure 1(b), Figure 10 below – and in the SPCZ there is a clear relationship between the reduction in total cloud and the amount of precipitation, Figure 6(b). At higher latitudes, the sign of the relationship between increasing temperature and cloud cover is reversed and there is clear increase in total cloud amount in the vicinity of the maximum sea ice extent.

In each ocean grid-box, the prognostic, overlying sea ice

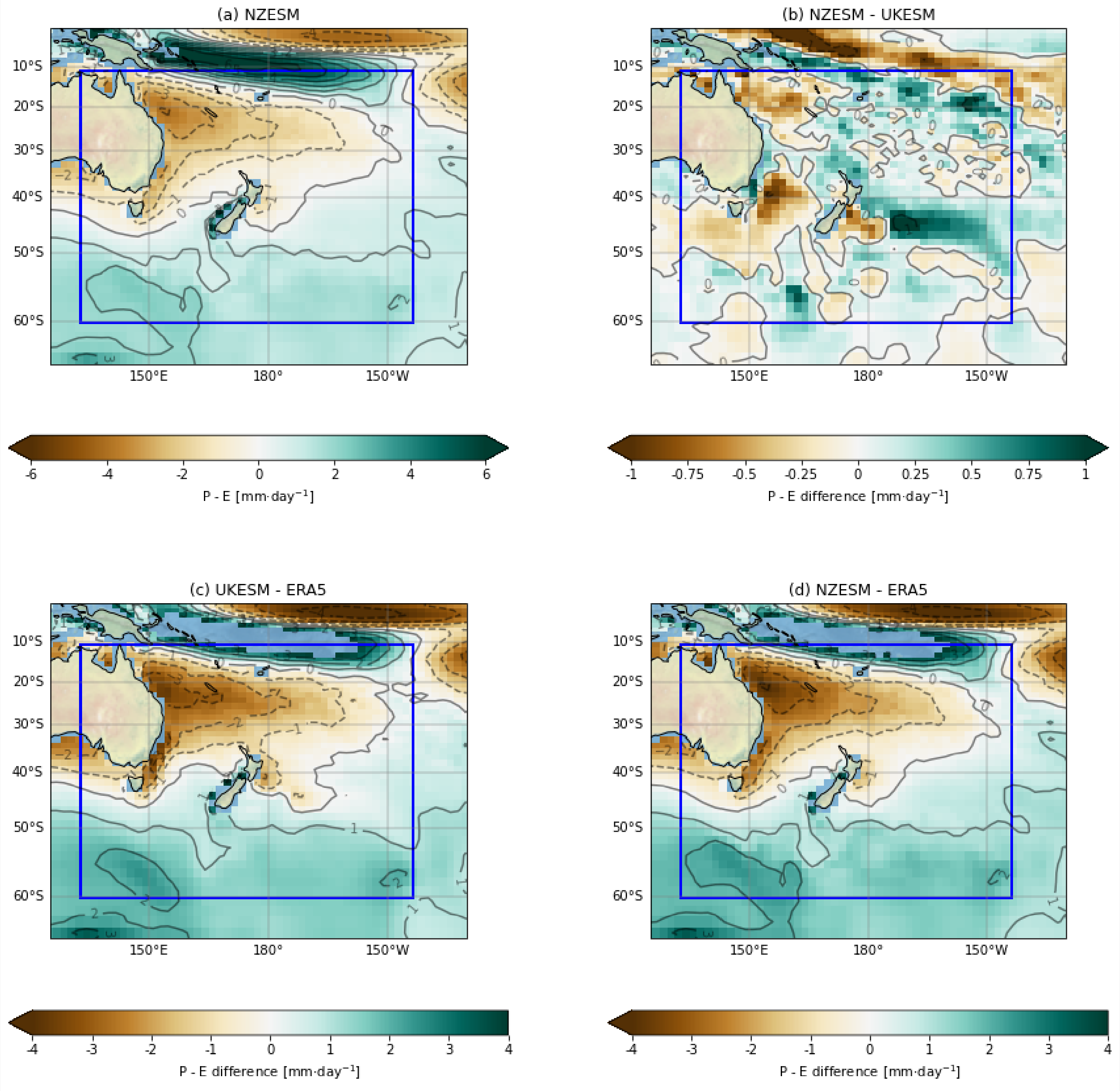

Figure 8: $P - E$ (mm · day^{-1}) for (a) NZESM, (b) NZESM - UKESM, (c) UKESM - ERA5, (d) NZESM ERA5. Contour levels for levels for all plots are at integer values and for (c) and (d) values over 4mm · day^{-1} are masked to aid visual interpretation.

coverage ranges from 0% to 100% and the 15% contour at maximum monthly coverage – September in these models – is often used in the literature as a proxy for maximum extent (Kwok et al, 2009). The yellow lines in Figure 9(b-d) show this contour level for the two models. These intra-model differences notwithstanding, the differences between the models and the observations are an order of magnitude larger, Figure 9(c,d). Therefore the changes made in the NZESM do not make any notable difference to the overall agreement between the models and observations and hence significant model observation disagreement remains.

Due to the warming in the NZESM around -60°, the sea ice retreats southward and allows increased potential evaporation from the ocean surface, thus favouring increased cloud cover. This complex behaviour illustrates the utility of using a coupled climate model to study ocean-ice-atmosphere interactions since in an atmosphere-only climate model configuration, the relationship between sea ice retreat and cloud cover could not be examined at all.

Figure 10 shows the Pearson correlation coefficient between the total cloud amount and the 1.5m temperature for the extra-tropics and is indeed negative everywhere except for some small, isolated patches to the south and east of Australia and a very clear positive signal south of

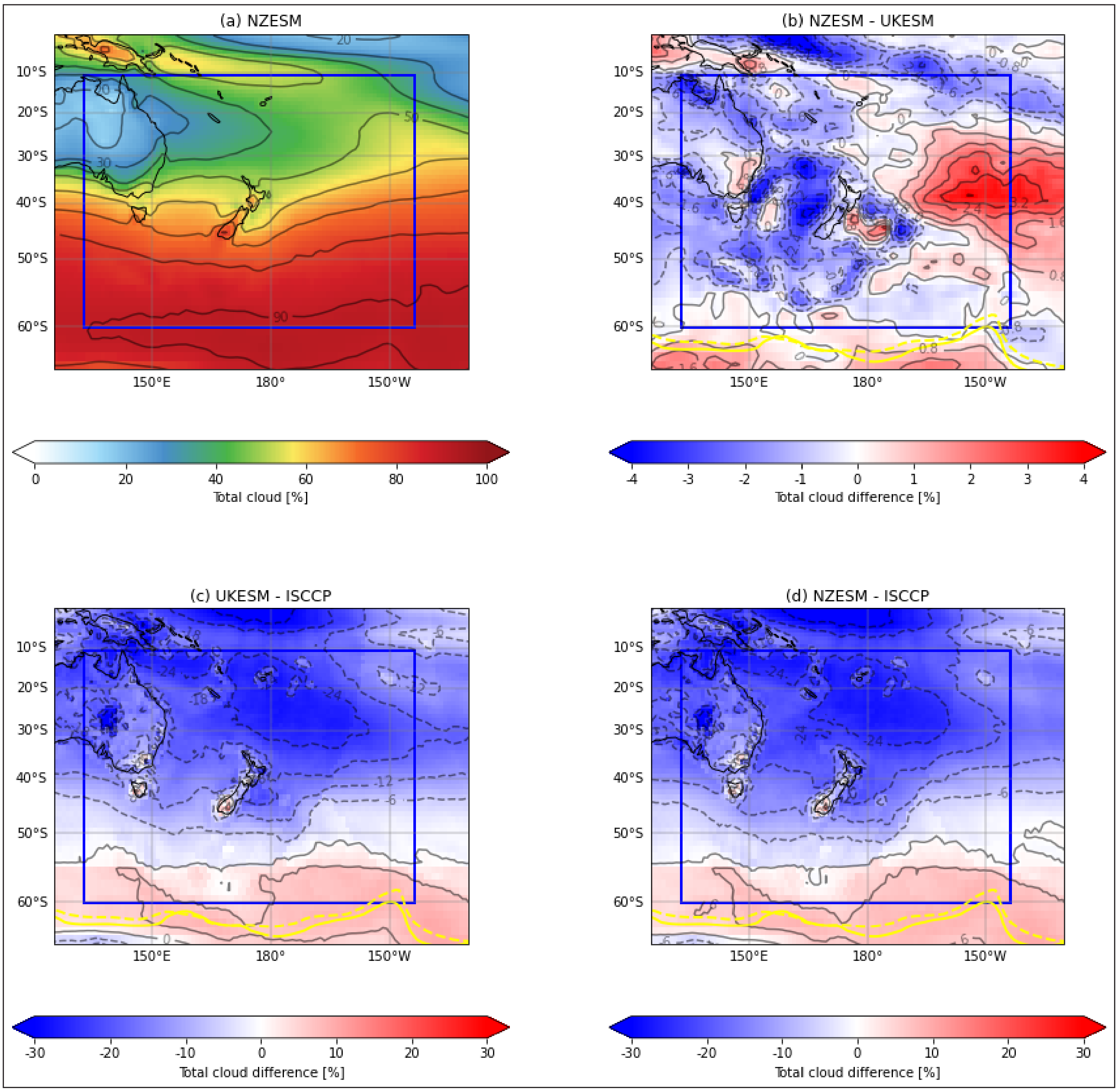

Figure 9: Total cloud for (a) the NZESM, (b) NZESM - UKESM, (c) UKESM - ISCCP, (d) NZESM - ISCCP. Figure (b-d) show 15% grid-box coverage contours of September sea ice cover for UKESM1 (dashed line) and the NZESM (solid line), which is a commonly-used measure of sea ice extent (Kwok et al., 2009) (see main text in S3.2). Observed cloud amount data is from the International Satellite Cloud Climatology Project, ISCCP (Rossow et al., 1999).

the sea ice edge – cf. Figure 9(b-d). Figure 10 is only shown for the extra-tropics to remove the complicating factors of widespread deep convection in the inter-tropical and South Pacific convergence zones.

3.3 Zonal wind and the storm track

3.3.1 Zonal wind

New Zealand's climate is primarily maritime-driven, for example the prevailing westerlies which drive the high rainfall in the South Island's West Coast (Reid et al, 2021). Before examining the position of the storm track, we study the zonal component of the wind. Figure 11 shows this for the same region considered above.

In Figure 11(a) the dominance of the westerlies (i.e. positive u values) is clearly visible and the jet is easily identifiable at around 200hPa and 30°S.

Figure 11(b) shows that there is a small but non-negligible southward shift of the jet in the NZESM and (c), (d) show improvement in model-reanalysis agreement north of ≈ 30°S. This is a further illustration of how improved model physics in one area of a coupled earth system model can have 'downstream' improvements in other

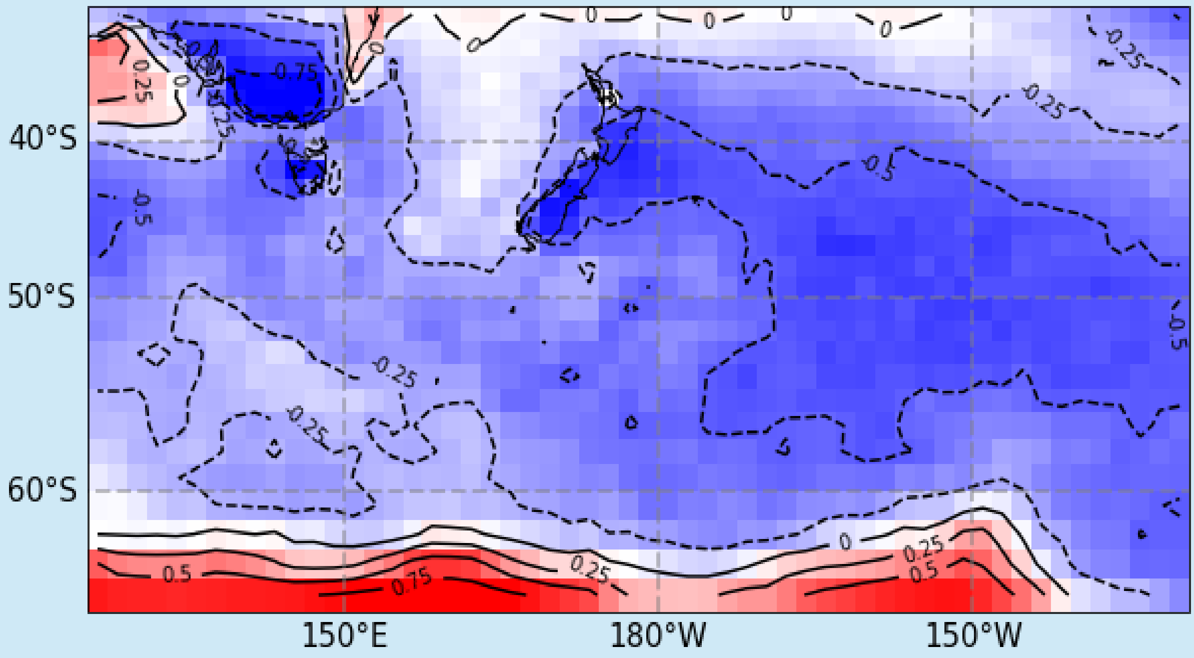

Figure 10: Pearson's correlation coefficient between 1.5m air temperature and total cloud amount for the NZESM.

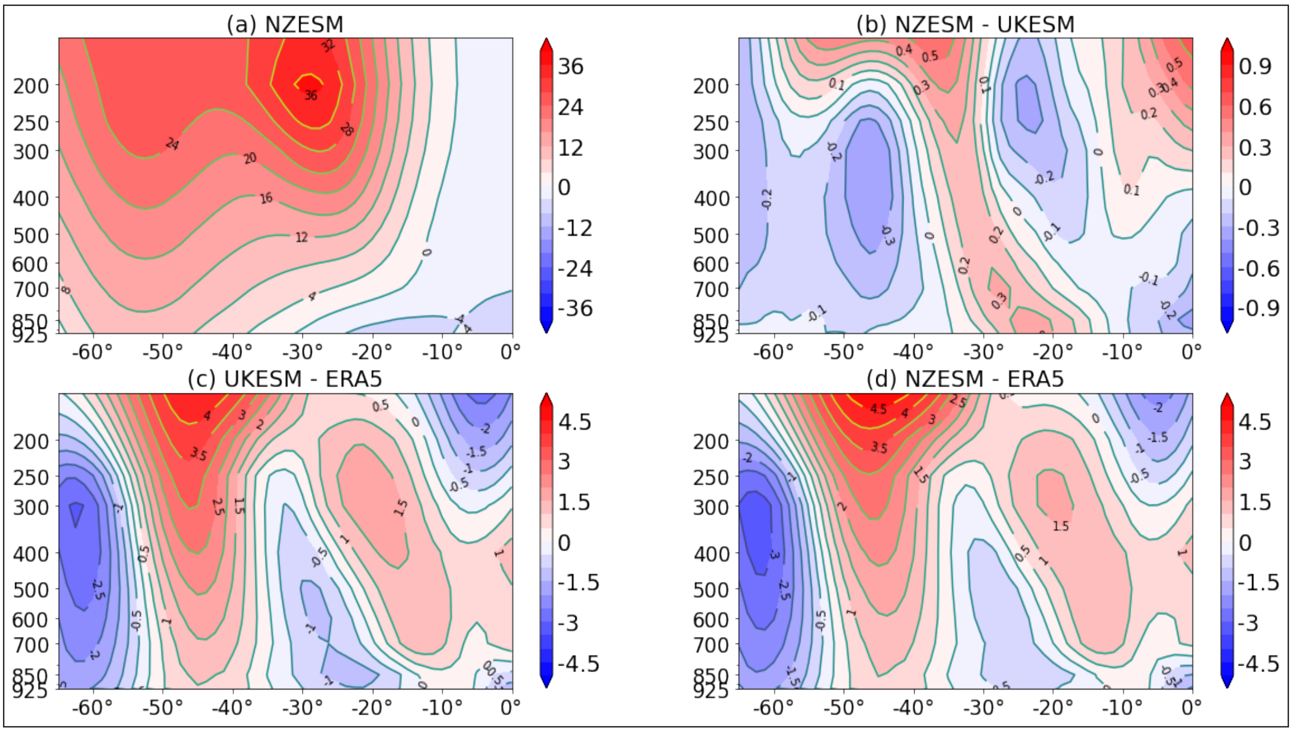

Figure 11: Zonal mean zonal wind (m · s^{-1}) for: (a) NZESM (b) NZESM - UKESM; (c) NZESM - ERA5 reanalysis; (d) UKESM - ERA5 reanalysis.

areas. There is some evidence of model-data deterioration at high southern latitudes which, unsurprisingly, coincides with the decreased fidelity of the air temperature fields considered above.

3.3.2 *Storm track*

Using the stormTracking package (https://github.com/ecjoliver/stormTracking) we have generated maps of the number of unique cyclones – N_c – detected in simulated air pressure data, Figure 12. As its input, this software uses pressure at mean sea level at six-hourly intervals throughout the 20 year period. The algorithm is split into detection and tracking scripts and is based on a previous study of ocean eddy tracking (Chelton et al, 2011). At each time step, the pressure field is scanned for isolated lows which are then followed through time until they are deemed to have terminated. This Lagrangian-style method allows systems to be followed through time whilst at the same time allowing the number of storms encountered within each grid box to be counted and hence allowing the formation of cyclone density maps, as shown here. An application of this method to tropical cyclones affecting New Zealand can be found elsewhere (Williams et al, 2023) in which a detailed description of the tracking method is included.

Figure 12 shows two main features of the N_c distribution in the NZESM :

1. A general weakening of the storm storm track at latitudes affecting New Zealand, around 30-50°S.
2. Strengthening at higher latitudes, particularly to the north and east of the Ross Sea.

What these changes amount to is a general southerly movement of the storm track and this is particularly evident to the east of New Zealand. Comparing this behaviour with Figure 12(c) shows that there is a general relationship between SST and storm activity; the decrease in SST to the east of New Zealand, for example, is accompanied by a decrease in storm activity. We also see a correspondence south of 60°S where the increase in SST is accompanied by an increase in storm activity.

Although this relationship appears to apply on synoptic scales, it is not universal. For example the NZESM shows an increase in the SST in the immediate vicinity of NZ whilst the storminess shows some evidence of decreasing. This behaviour is somewhat isolated however and may be due to land-sea heat capacity contrast. A more detailed exploration of the models' storm climatologies and how they are predicted to change over the course of the 21st century is the subject of separate work (Williams et al, 2023) and a further study of the midlatitude storm track – addressing for example the relationships between wind, latent heat loss and SST and cloud cover – is currently underway.

4. CONCLUSIONS

In this work we have studied the regional atmospheric climate around New Zealand. We have used historical simulations of the period 1989-2008 using configurations of a coupled earth system model with (Behrens et al, 2020)

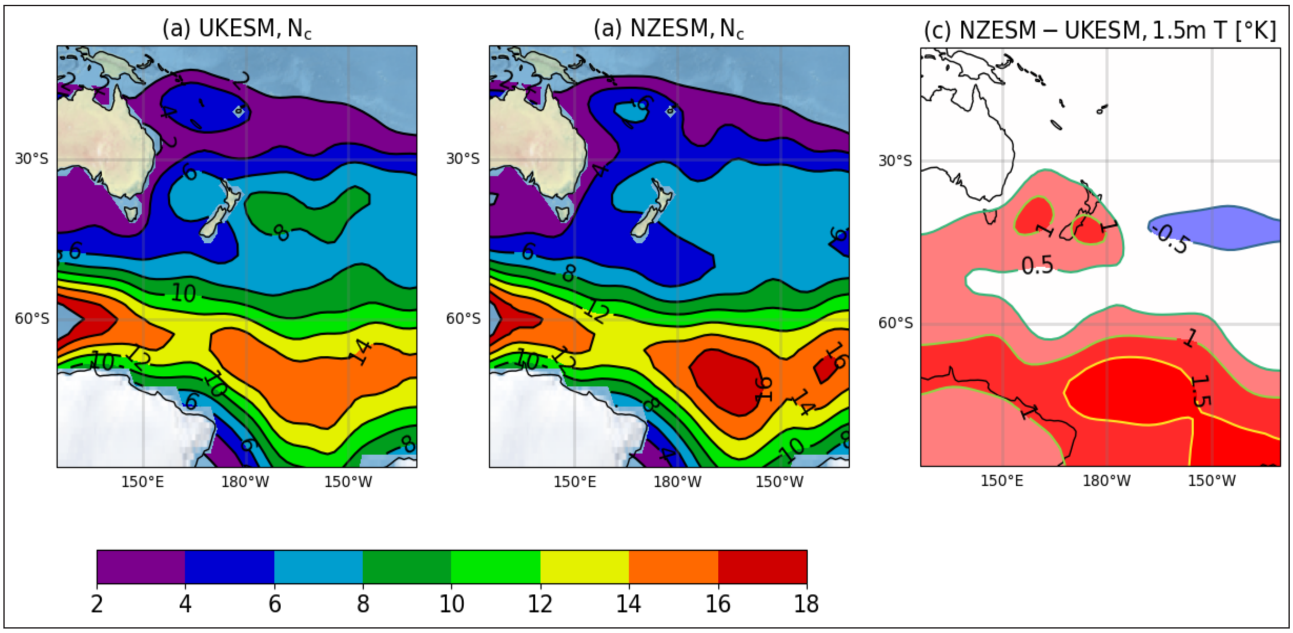

Figure 12: (a) UKESM N_c (b) NZESM N_c (c) NZESM - UKESM 1.5m air temperature difference; all with $\sigma = 2$ in the Gaussian smoothing calculations. The data in (a), (b) is obtained from the stormTracking software and uses the mesoscale feature tracking capability described in (Chelton et al, 2011) by firstly identifying and then following each individual system through time. The number of unique cyclone tracks in each gridbox are then counted in each grid box and smoothed using a Gaussian kernel standard deviation of 2 in the SciPy software (Virtanen et al., 2020). Without this additional smoothing the data are too noisy to enable a reasonable interpretation of the differences between the data sets and since the smoothing reduces the absolute value of N_c the numerical values of the contours are somewhat arbitrary. As a rough guide, the $\sigma = 2$ smoothing reduces the raw N_c values by approximately a factor of 2. The data in (c) is the same as in Figure 1(b) with a southward extension to better illustrate the relationship with the storm track.

and without (Sellar et al, 2019, 2020) a nested, regional ocean model, the introduction of which improves several aspects of model-observation agreement. As is always the case when model physics is altered in the absence of additional model tuning however, the observed changes are not all beneficial. The state-of-theart UKESM1 model was used extensively in the recent 6th Assessment Report of the Intergovernmental Panel on Climate Change and to our knowledge this paper is among the first to consider how a nested ocean model impacts atmospheric climate in a coupled simulation framework.

We have split the analysis into three sections. Firstly we examined the air temperature at the surface and aloft and how this affects surface heat balance. Next, the hydrological response, and finally the effect on the westerly wind structure and the storm track are investigated.

The 1.5m air temperature closely mirrors the improvements seen in the equivalent plots shown in (Behrens et al, 2020). This is of course expected since the data presented are multi-decadal annual means for the same model pair. Above the boundary layer, the NZESM exhibits tropospheric warming and stratospheric cooling, the former of which leads to a general improvement in model-reanalysis agreement and a raising of the tropopause height by an amount comparable to the climate change signal over recent decades. The surface heat balance biases (latent and sensible) are improved in the NZESM cf. UKESM1 with respect to observations and this is particularly striking in the latter.

The SPCZ dominates the precipitation signal and shows a southward shift in the NZESM. The NZESM also shows reduced wet and dry biases close to New Zealand. Evaporation changes are generally of the same sign as the precipitation changes, but larger in magnitude, meaning that $\Delta(P - E)$ is of the opposite sign to ΔP in some areas. The first-order effect of the NZESM's high-resolution ocean is to increase total cloud cover to the east of New Zealand and to decrease it over the Tasman sea and the SPCZ. These cloud changes are generally anticorrelated with surface temperature changes at mid-latitudes, but the reverse is seen at high latitudes near the seasonal sea ice edge. This has been quantified by the inclusion of a map of the correlation coefficient between temperature and cloud cover which makes this assertion explicit.

The structure of the westerly winds shows some improvement in the NZESM and the storm track is shifted south due to the increased eddy-induced warming introduced by the high-resolution ocean. A companion paper on tropical cyclones and their predicted changes through the coming decades is available (Williams et al, 2023) and work to better understand the shift of the mid-latitude storm track is underway. Future work using this nesting methodology on other similarly-related model pairs, as well as this same model pair in different regions would be of significant interest. Additionally, nesting of a high-resolution atmosphere within the global, coupled model would complement the longstanding history of regional atmosphere modelling in New Zealand, e.g. (Ackerley et al, 2012).

APPENDIX

A NZESM computational run-time configuration

Given the significant computational expense of Earth System Models, it is very important to optimise the build and runtime configuration of the component model executables to achieve best efficiency. Ideal setups depend on the characteristics of the target high-performance computing (HPC) platform, such as the number of CPU cores per node, CPU architecture, choice of compilers and libraries, as well as the interconnect that is used for communicating data between the processes that run the model in parallel, and the storage system.

The NZESM consists of separate executables for the atmosphere (Unified Model) and ocean (NEMO) components, which are coupled using the OASIS library (Craig et al, 2017). CPU cores on the HPC need to be distributed between these components to match their respective runtime between data exchanges as closely as possible, as any wait times will reduce efficiency. With the atmosphere model requiring many more cores than the ocean model to handle its much larger computational expense, just enough resources should be assigned to the ocean so that the atmosphere does not need to wait for data to arrive. OASIS comes with a timing feature to help find the right balance.

The Unified Model and NEMO use the Message Passing Library (MPL) for distributed parallel computing, where finding an optimal CPU core count for a given science configuration typically involves trade-offs between runtime and computational efficiency ('strong scaling'). While assigning more cores will speed up computation and thus achieve a higher number of model years per wall clock time interval, communication overheads become more and more important with increasing core count and reduce computational efficiency, as relatively more time needs to be spent on non-science related computation. It is usually advisable to start with a miminum number of cores that allows the model to meet runtime expectations at reasonable efficiency, especially on a busy HPC, where smaller core counts can lead to shorter queuing times and thus higher overall throughput. If communication overhead is still small and if there is enough capacity on the HPC, core counts can be increased to reduce runtime without suffering much efficiency loss ('linear scaling').

Both the Unified Model and NEMO impose constraints on how CPU cores can be used for parallel computing with the 'domain decomposition' approach, which can prevent configurations from using all available cores on the assigned HPC nodes and thus impact efficient resource utilisation.

The Māui HPC that was used for this work comes with 40 Intel Skylake CPU cores per node. The original core count configuration of NZESM was readjusted for Maui to minimise atmosphere/ocean runtime imbalance, minimise the number of unused cores on the nodes, and maximise MPI parallelisation efficiency. This led to a 28% node count reduction from 32 nodes to 23 with only a modest 5% increase in runtime from 7.7 hours per model year to 8.1 hours per model year. Overall computational resource utilisation by the NZESM was thus reduced by 24%.

ACKNOWLEDGEMENTS

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REFERENCES

Ackerley, D. et al. (2012). Regional climate modelling in New Zealand: Comparison to gridded and satellite observations. In: *Weather and Climate* 32.1, pp. 3–22. http://www.jstor.org/ stable/26169722.

Archibald, A. T. et al. (2020). Description and evaluation of the UKCA stratosphere–troposphere chemistry scheme (StratTrop vn 1.0) implemented in UKESM1. In: *Geoscientific Model Development* 13.3, pp. 1223–1266.

Beadling, R. L. et al. (2020). Representation of Southern Ocean Properties across Coupled Model Intercomparison Project Generations: CMIP3 to CMIP6. In: *Journal of Climate* 33.15, pp. 6555–6581. https://doi.org/10.1175/JCLI-D-19-0970.1.

Behrens, Erik (2013). The oceanic response to Greenland melting: the effect of increasing model resolution. en. PhD thesis.

Behrens, Erik (2020). erikbehrens/NZESM1: *First release of the NZESM* (ocean+sea ice code). Version v1.0. https://doi.org/10.5281/zenodo.3873691.

Behrens, Erik et al. (2012). Model simulations on the long-term dispersal of 137Cs released into the Pacific Ocean off Fukushima. In: *Environmental Research Letters* 7.3, p. 034004.

Behrens, Erik et al. (2020). Local Grid Refinement in New Zealand's Earth System Model: Tasman Sea Ocean Circulation Improvements and Super-Gyre Circulation Implications. In: *Journal of Advances in Modeling Earth Systems* 12.7. https://doi.org/10.1029/2019MS001996.

Behrens, Erik et al. (2022). Projections of future marine heatwaves for the oceans around New Zealand using New Zealand's earth system model. In: *Frontiers in Climate* 4, p. 798287.

Biastoch, Arne et al. (2008). Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation. In: *Nature* 456.7221, pp. 489–492.

Bodas-Salcedo, Alejandro et al. (2011). COSP: Satellite simulation software for model assessment. In: *Bulletin of the American Meteorological Society* 92.8, pp. 1023–1043.

Brown, AR et al. (2008). Upgrades to the boundary-layer scheme in the Met Office numerical weather prediction model. In: *Boundary-Layer Meteorology* 128.1, pp. 117–132.

Chelton, Dudley B. et al. (2011). Global observations of nonlinear mesoscale eddies. In: *Progress in Oceanography* 91.2, pp. 167–216. https://doi.org/10.1016/j.pocean.2011.01.002.

Craig, Anthony et al. (2017). Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0. In: *Geoscientific Model Development* 10.9, pp. 3297–3308.

Debreu, Laurent et al. (2008). AGRIF: Adaptive grid refinement in Fortran. In: *Computers & Geosciences* 34.1, pp. 8–13.

Edwards, J. M. et al. (1996). Studies with a flexible new radiation code. I: Choosing a configuration for a large-scale model. In: *Quarterly Journal of the Royal Meteorological Society* 122.531, pp. 689–719. https://doi.org/10.1002/qj.49712253107.

Good, Simon A et al. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. In: *Journal of Geophysical Research: Oceans* 118.12, pp. 6704– 6716.

Gregory, D. et al. (1990). A Mass Flux Convection Scheme with Representation of Cloud Ensemble Characteristics and Stability-Dependent Closure. In: *Monthly Weather Review* 118.7, pp. 1483–1506.

Gurvan, Madec et al. (2022). *NEMO ocean engine*. Version v4.2. https://doi.org/10.5281/zenodo.6334656.

Hawcroft, Matt et al. (2016). Southern Ocean albedo, inter-hemispheric energy transports and the double ITCZ: global impacts of biases in a coupled model. In: *Climate Dynamics* 48.7-8, pp. 2279–2295.

Hersbach, Hans et al. (2020). The ERA5 global reanalysis. In: *Quarterly Journal of the Royal Meteorological Society* 146.730, pp. 1999–2049.

Hewitt, Helene T et al. (2020). Resolving and parameterising the ocean mesoscale in earth system models. In: *Current Climate Change Reports* 6, pp. 137–152.

Hoem, Frida S. et al. (2022). Strength and variability of the Oligocene Southern Ocean surface temperature gradient. In: *Communications Earth & Environment* 3.1, p. 322.

Hourdin, Frédéric et al. (2017). The Art and Science of Climate Model Tuning. In: *Bulletin of the American Meteorological Society* 98.3, pp. 589–602.

Hunke, Elizabeth et al. (2017). CICE, *The Los Alamos Sea Ice Model*, Version 00.

Hyder, Patrick et al. (2018). Critical Southern Ocean climate model biases traced to atmospheric model cloud errors. In: *Nature Communications* 9.1. DOI: 10.1038/s41467-018-05634-2.

Kwok, R. et al. (2009). Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. In: *Geophysical Research Letters* 36.15. DOI: https://doi.org/10.1029/2009GL039035.

Luo, Fengyun et al. (2023). Origins of Southern Ocean warm sea surface temperature bias in CMIP6 models. In: *npj Climate and Atmospheric Science* 6.1, p. 127.

McNeall, Doug et al. (2020). Correcting a bias in a climate model with an augmented emulator. In: *Geoscientific Model Development* 13.5, pp. 2487–2509.

Meng, Lingyunetal. (2021). Continuous rise of the tropopause in the Northern Hemisphere over 1980 & 2013; 2020. In: *Science Advances* 7.45, eabi8065.

Pisoft, Petr et al. (2021). Stratospheric contraction caused by increasing greenhouse gases. In: *Environmental Research Letters* 16.6, p. 064038.

Reid, Kimberley J. et al. (2021). Extreme rainfall in New Zealand and its association with Atmospheric Rivers. In: *Environmental Research Letters* 16.4, p. 044012.

Ridley, Jeff K. et al. (2018). The sea ice model component of HadGEM3-GC3. 1. In: *Geoscientific Model Development* 11.2, pp. 713–723.

Rossow, W. B. et al. (2004). The international satellite cloud climatology project (ISCCP) website: An online resource for research. In: *Bulletin of the American Meteorological Society* 85.2, pp. 167–172.

Rossow et al. (1999). Advances in understanding clouds from ISCCP. In: *Bulletin of the American Meteorological Society* 80.11, pp. 2261–2288.

Schmidt, Gavin A. et al. (2017). Practice and philosophy of climate model tuning across six US modeling centers. In: *Geoscientific Model Development* 10.9, pp. 3207–3223.

Schwarzkopf, F. U. et al. (2019). The INALT family – a set of high-resolution nests for the Agulhas Current system within global NEMO ocean/sea-ice configurations. In: *Geoscientific Model Development* 12.7, pp. 3329–3355.

Sellar, Alistair A. et al. (2019). UKESM1: Description and evaluation of the UK Earth System Model. In: *Journal of Advances in Modeling Earth Systems* 11.12, pp. 4513–4558.

Sellar, Alistair A. et al. (2020). Implementation of U.K. Earth System Models for CMIP6. In: *Journal of Advances in Modeling Earth Systems* 12.4. https://doi.org/10.1029/2019MS001946.

Tang, Yongming et al. (2019). MOHC UKESM1.0-LL model output prepared for CMIP6 CMIP historical. DOI: 10.22033/ESGF/CMIP6.6113.

Taylor, Karl E. et al. (2012). An overview of CMIP5 and the experiment design. In: *Bulletin of the American Meteorological Society* 93.4, pp. 485–498.

Varma, Vidya et al. (2020). Improving the Southern Ocean cloud albedo biases in a general circulation model. In: *Atmospheric Chemistry and Physics* 20.13, pp. 7741–7751.

Virtanen, Pauli et al. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python" In: *Nature Methods* 17, pp. 261–272.

Walters, David et al. (2019). The Met Office Unified Model global atmosphere 7.0/7.1 and JULES global land 7.0 configurations. In: *Geoscientific Model Development* 12.5, pp. 1909–1963.

Williams, Jonny et al. (2016). Development of the New Zealand Earth System Model: NZESM. In: *Weather and Climate* 36, pp. 25–44. https://www.jstor.org/stable/26779386.

Williams, Jonny et al. (2023). Coupled atmosphere-ocean simulations of contemporary and future South Pacific tropical cyclones. In: *EGUsphere* 2023, pp. 1–31.

Wood, Nigel et al. (2014). An inherently mass-conserving semi-implicit semi-Lagrangian discretization of the deep-atmosphere global non-hydrostatic equations. In: *Quarterly Journal of the Royal Meteorological Society* 140.682, pp. 1505–1520. https://doi.org/10.1002/qj.2235.

Yool, A. et al. (2013). MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. In: *Geoscientific Model Development* 6.5, pp. 1767–1811.

Yool, A. et al. (2021). Evaluating the physical and biogeochemical state of the global ocean component of UKESM1 in CMIP6 historical simulations. In: Geoscientific Model Development 14.6, pp. 3437–3472.

Yu, Lisanetal. (2007). Objectively Analyzed Air–Sea Heat Fluxes for the Global Ice-Free Oceans (1981–2005). In: *Bulletin of the American Meteorological Society* 88.4, pp. 527–540.

Notes from the forecast room: Wellington snow event 10 August 2023

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KEY WORDS
Meteorology, Wellington, snowfall

ABSTRACT

Snow is a relatively rare event in the Wellington region, and there are subtleties in forecasting all aspects of it (timing, spatial distribution, and the level it falls to). For most residents of the Wellington region, snow is of novelty value, but it can occasionally prove a nuisance when it threatens the Remutaka Road Summit. The key synoptic ingredients for snowfall in the Wellington region are discussed.

A recent Wellington snow event on 10 August 2023 is then used as a real-world example, to examine whether all meteorological ingredients were present, including a comparison to observations. This note was written because there was a high level of forecaster interest in this snowfall event, due to synoptic complexity.

1. INTRODUCTION

It is difficult to get snow in Wellington. Even on the surrounding hills, we may only see it a few times a year, and there are some winters where the local hills never see snow.

Our snow challenges are common to most coastal locations in New Zealand – we have a lot of relatively mild sea between us and our source of cold air, and our source of cold air is quite a long way away. This combination allows for a lot of potential modification of incoming polar outbreaks, which means that only the very coldest bursts tend to be of interest.

This is not our sole difficulty though: even when we can access cold air from either Antarctica or the Southern Ocean quickly enough to minimise modification, we need the remainder of the atmosphere to play its part.

One typical factor that can spoil our snow is if the wind direction in the lower levels of the atmosphere is southwesterly. In these setups, we have seen snow to low levels elsewhere, even on the West Coast of the South Island, but Wellington finds itself orographically sheltered by the South Island landmass and ranges. The result can be clear, crisp days, but perhaps a sense of squandered opportunity.

The weather situation in August 2019 (Figure 1) saw the South Island's West Coast experience some of its coldest

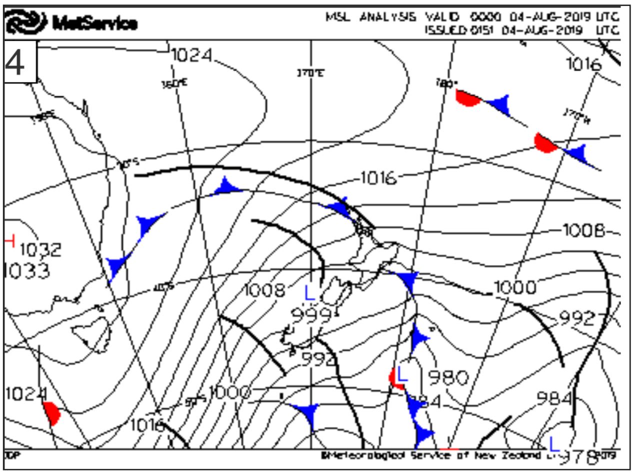

Figure 1: Mean sea level pressure analysis at noon 4 August 2019, showing a cold southwesterly outbreak over New Zealand. No snow was observed in Wellington during this event.

August days on record, with snow down to 200m above sea level (asl). Even though the same airmass affected Wellington, the southwesterly flow prevented any showers from reaching the region.

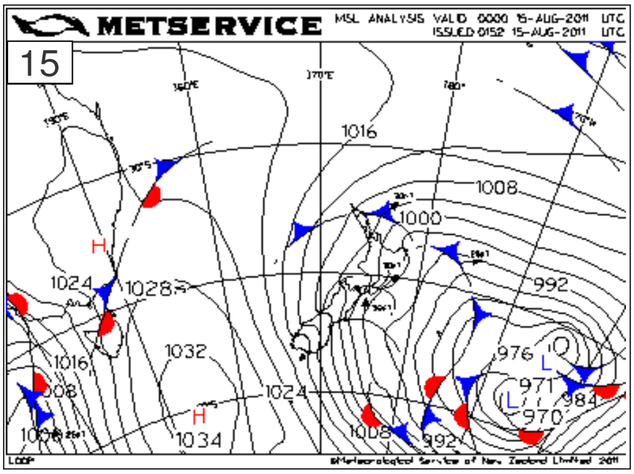

Figure 2: Mean sea level pressure analysis at noon 15 August 2011, showing a very cold southerly outbreak over New Zealand. This event produced significant snow in Wellington.

If the wind direction in the lowest levels of the atmosphere is direct southerly, any sheltering is removed, and abundant showers reach Wellington (Figure 2).

However, we need more ingredients than just especially cold air and a southerly wind direction – and for this we must investigate the full vertical reaches of the atmosphere.

To produce snow, atmospheric processes must be creating snowflakes. For this to happen, there must be sufficient moisture at levels in the atmosphere where snowflake production is accelerated. This happens inside a temperature range which is usually referred to as the dendritic zone – where temperatures are between around -12°C and -18°C. Typically in winter snow situations like this, these temperatures occur between approximately 2000m and 4000m asl.

It is reasonably common for Wellington to experience both very cold southerlies and showers, but with the showers themselves not deep enough to be good snow producers due to insufficient moisture in the dendritic zone. In these setups, Wellington finds itself dendritically deprived, and we miss out on snow again. This often happens during the latter part of cold events as the atmosphere slowly stabilises while cold air remains at the surface.

There are additional critical factors higher in the troposphere. In these regions we are primarily sleuthing for anything that can give us significant upward motion. Upward motion is the true essence of operational meteorology – the thermodynamic processes acting on rising air lead to condensation of water vapour, clouds and ultimately: precipitation.

In the mid-levels (approximately 3000m to 7000m), upward motion is typically driven by cyclonic vorticity advection (CVA). As per quasi-geostrophic theory, an increase in CVA with height promotes upward motion in the atmosphere. Cyclonic vorticity itself can be found near the axis of troughs, and the advection of it occurs downstream of the trough.

We can start to put all the synoptic ingredients together by looking at a recent event in August 2023. This event did not bring snow to extremely low levels but was notable in producing some large totals above 500m asl in the Wellington region.

2. METEOROLOGY OF THE 10 AUGUST 2023 WELLINGTON SNOW EVENT

On 10 August 2023, a cold airmass had been entrenched over the lower South Island for a few days, and a developing low pressure system to the east was expected to advect cold air towards Wellington. The primary cold front was forecast to lie from approximately Napier to Raglan, at midday on the 10th (Figure 3).

Freezing levels (not shown) were forecast to lower to around 800-900m over the Capital and remain static for many hours – a good start. Usually for Wellingtonian eyes to light up, we'd need to see a freezing level lower than around 1200m. Snow can fall significantly lower than the free air freezing level. This is because in the absence of thermal advection, the melting effect, which is usually an order of magnitude less than sublimation, can become

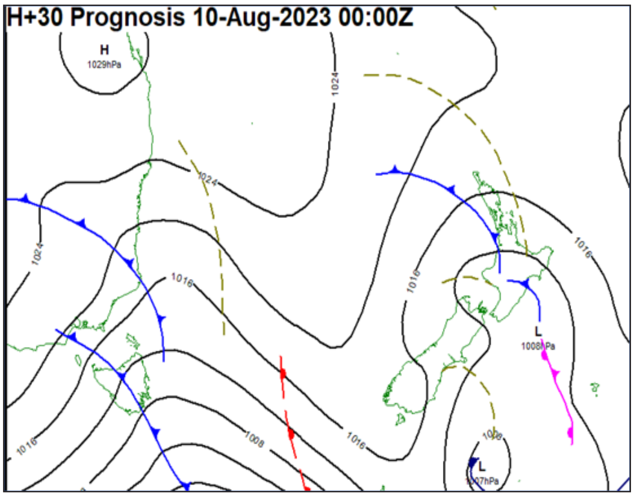

Figure 3: Mean sea level pressure prognosis for noon on 10 August 2023.

the primary mechanism for cooling the atmosphere. The melting effect is the processes of snowflakes melting as they fall, progressively cooling the surrounding air, and allowing subsequent snowflakes to fall even lower.

We can split this event into two halves: what comes with the cold front, and what comes after the cold front.

With the cold front:

At the time that the cold front was close to Wellington itself (about 6am), forecasters analysed a following trough sitting just to the south of Wellington (Figure 4).

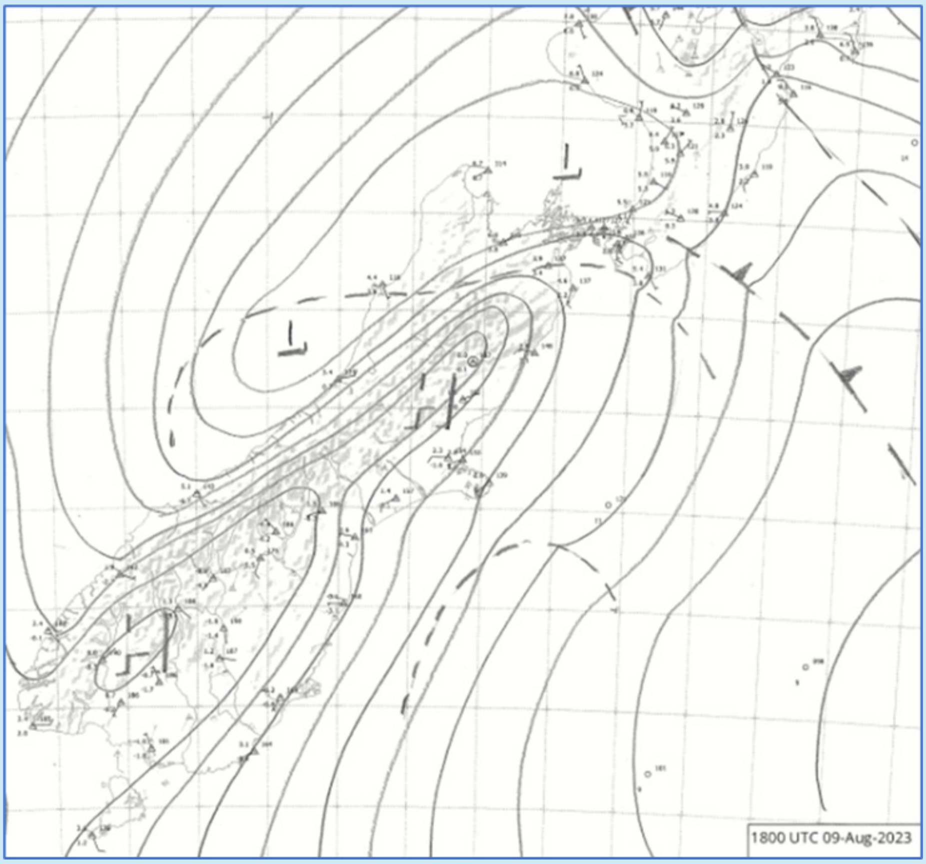

Figure 4: Hand-drawn mean sea level pressure analysis at 6am 10 August 2023.

At this time, forecast models indicated robust upward motion (not shown) along the surface front and trough. Surface fronts and troughs are associated with surface convergence, which leads to low-level upward motion. The upward motion can be enhanced through a greater depth of the atmosphere if we have further factors in favour.

In this event, strong cyclonic vorticity advection (Figure 5) was in play in the middle atmosphere (500hPa) as the upper trough approaches Wellington. This was the main driver of upward motion through the middle atmosphere.

Additionally, the relatively “slack” pressure gradient east of New Zealand under the broad trough indicates that this is a mature, slow-moving system which is very close to being “vertically stacked”. Vertically stacked lows are defined to be in the same position at all heights of the atmosphere, not tilted with height. They are slow moving and this assists the relatively long lived low freezing levels mentioned prior.

The gauge corrected radar accumulations are useful to see what happened around dawn on 10 August 2023 (Figure 7).

During this time, is it likely that snow was falling and settling over the southern Remutaka Range – and sleet was reported in Karori at a height of 200m asl. Figure 6 clearly shows the largest rainfall accumulations were confined to the southern part of the Wellington region during the first half of this event, due to the stalled front. Measured rainfall totals in low lying gauges were five times higher than for areas further north during this period. For example, around 25mm in Karori compared with 5mm in various locations near Upper Hutt.

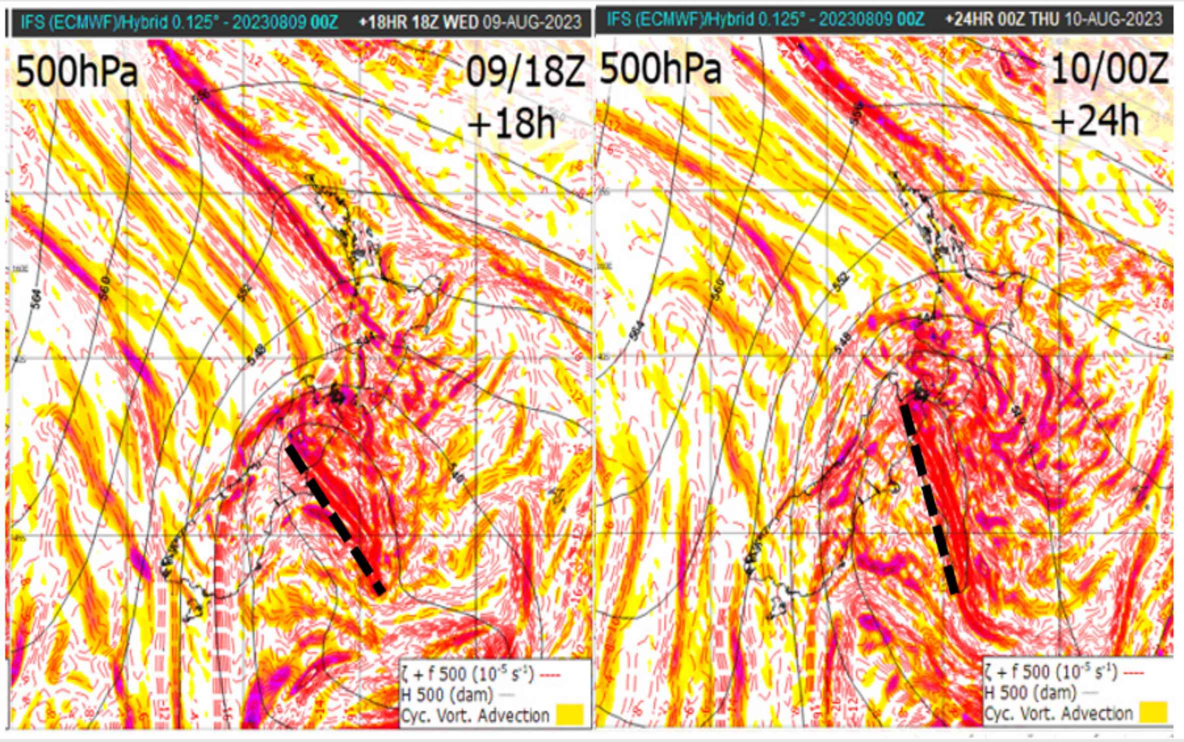

Figure 5: ECWMF 500hPa modelled fields identifying cyclonic vorticity (marked with black line) at 6am 10 August (left) and advecting towards Wellington at noon 10 August 2023 (right).

Figure 6: Identifying a few locations of interest in this event.

After the cold front:

For the second half of the event, the surface low gradually moves eastwards and allows a showery, strong southerly wind flow to push continuously through Wellington.

Of course, when we're looking at showers, we are very interested in these becoming deep enough to reach the aforementioned dendritic zone. There are various ways we can do this, but one important contributing factor is the 500hPa temperature field. If this is sufficiently cold, it can enhance the buoyancy of rising air from below, and again assist with our all important upward motion.

The modelled 500hPa temperature at midnight 10 August 2023 was still expected to be colder than -30°C, still being close to the axis of the cold upper trough (Figure 8). We would not expect showers to ease or become shallower until that cold trough has moved away from Wellington, and this proved to be the case (Figure 9).

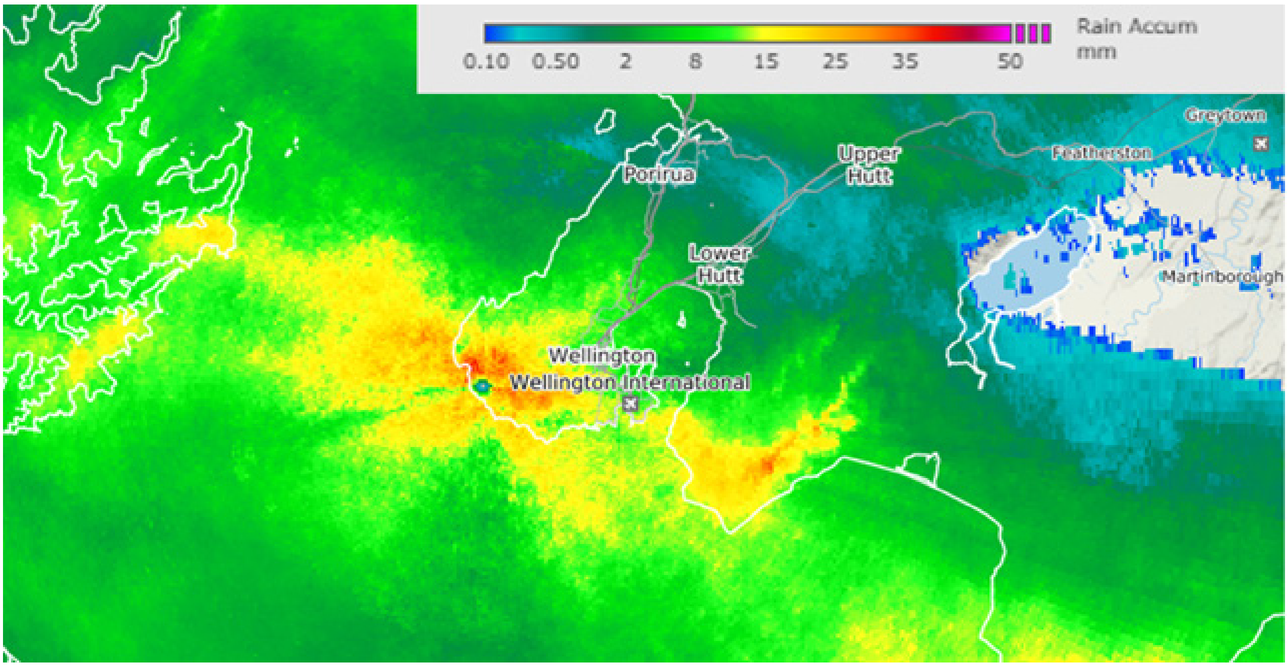

Figure 7: Wellington radar gauge corrected accumulations for 3 hours between 4am and 7am 10 August 2023. Orange colours indicate totals 15-25mm, with red colours indicating totals of 25-40mm.

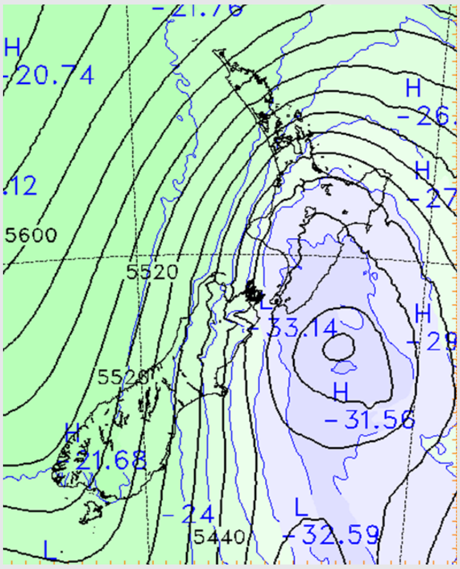

Figure 8: The modelled 500hPa temperature at midnight 10 August 2023. Blue colours depict 500hPa temperatures below -30°C.

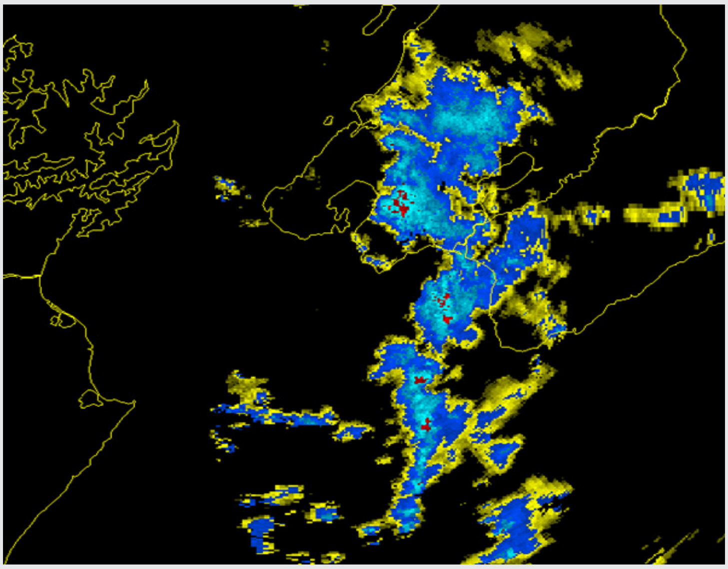

Figure 9: A radar snapshot shortly after midnight 10 August 2023 shows heavy showers tracking into the Remutaka Range, bringing snow to some higher parts of the ranges.

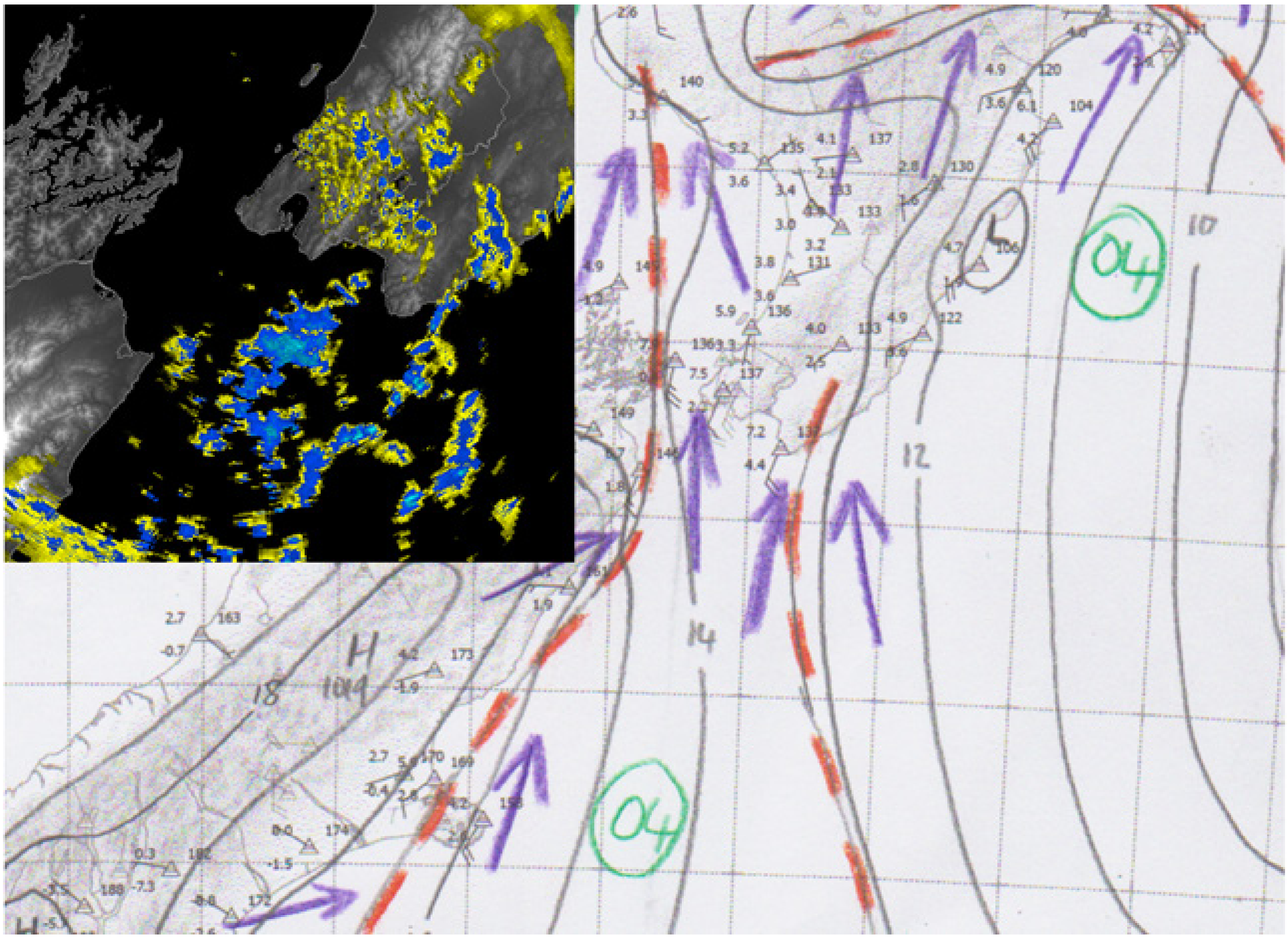

Figure 10: Surface analysis valid at 9pm on 10 August 2023 showing isobars, generalised wind flow (purple arrows) and analysed surface troughs (red dashed lines). Green numbers represent wet bulb potential temperatures.

During the post-frontal period, the precipitation was characterised by more meridionally oriented troughs within the broad southerly flow. These would enhance surface convergence and lead to periods of more organised showers. Outside of these troughs, showers would tend to be more sporadic. Figure 10 shows an indicative image of this period.

Two weather stations illustrate the divisions of this event effectively (Figures 11a, 11b). Kelburn (MetService), at 120m asl and Orongo Swamp (GWRC) at 420m asl. Both stations are at elevations where all precipitation would have fallen as rain. Kelburn received 28mm of rain from 3am on 10 August 2023 until 7am on 11 August 2023, and Orongo Swamp 33mm in the same time period, which are comparable amounts. However, Kelburn saw around 85% of its rainfall fall during the stalled frontal period, and just afterwards (up until 10am on 10 August). In contrast, Orongo Swamp received much of its rainfall during the post-frontal period, during prolonged showery conditions, leading to a more even distribution of its rainfall over time.

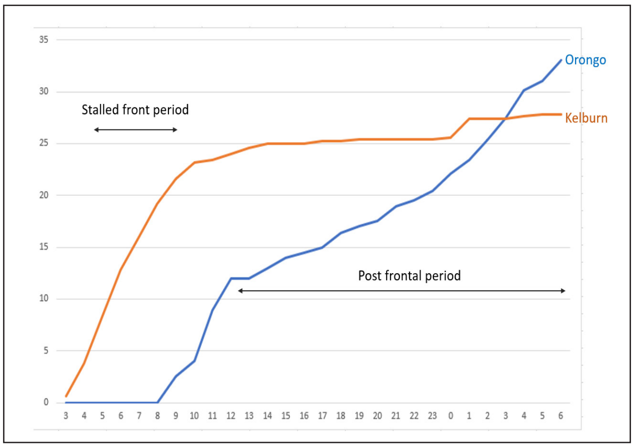

Figure 11a: Rainfall accumulation (mm, vertical axis) from 3am on 10 August to 6am on 11 August (horizontal axis) for Kelburn and Orongo Swamp weather stations.

3, OBSERVATIONS

In comparison to the rain observation network, there is a relative lack of direct, real-time snow observations through

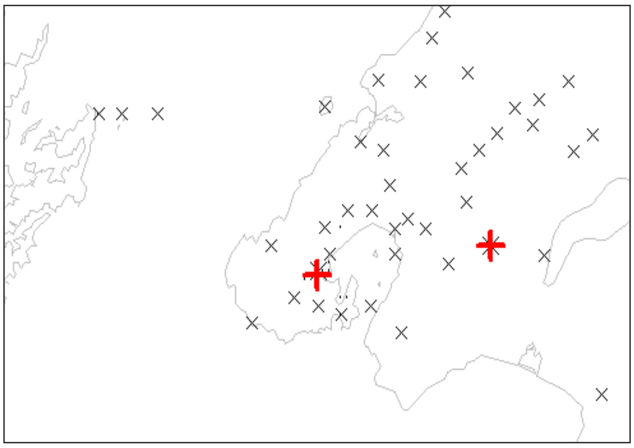

Figure 11b: Red crosses mark the location of Kelburn (left) and Orongo Swamp (right).

the Wellington region. Sometimes, field observations are the only way to gain feedback on an event. A former Meteorological Society member, Tom Adams, and his canine assistant Katla, mounted an expedition to assess the snowfall the following morning (11 August 2023). Tom measured 10-15cm of snow on Mt Climie in the Remutaka Range (Figure 13), at an elevation of approximately 900m asl with the smallest accumulations extending down to around 500-600m asl.

4. SUMMARY

This article is an overview of the most important factors relevant to Wellington snowfall, and then compared against a recent event. It has only really scratched the surface, but the author hopes it will elucidate some details. In this era, forecasters have access to a lot of sophisticated, highly derived NWP output. During the forecasting process, this guidance should be balanced with a physical understanding of the situation to assist in appropriate decision making.

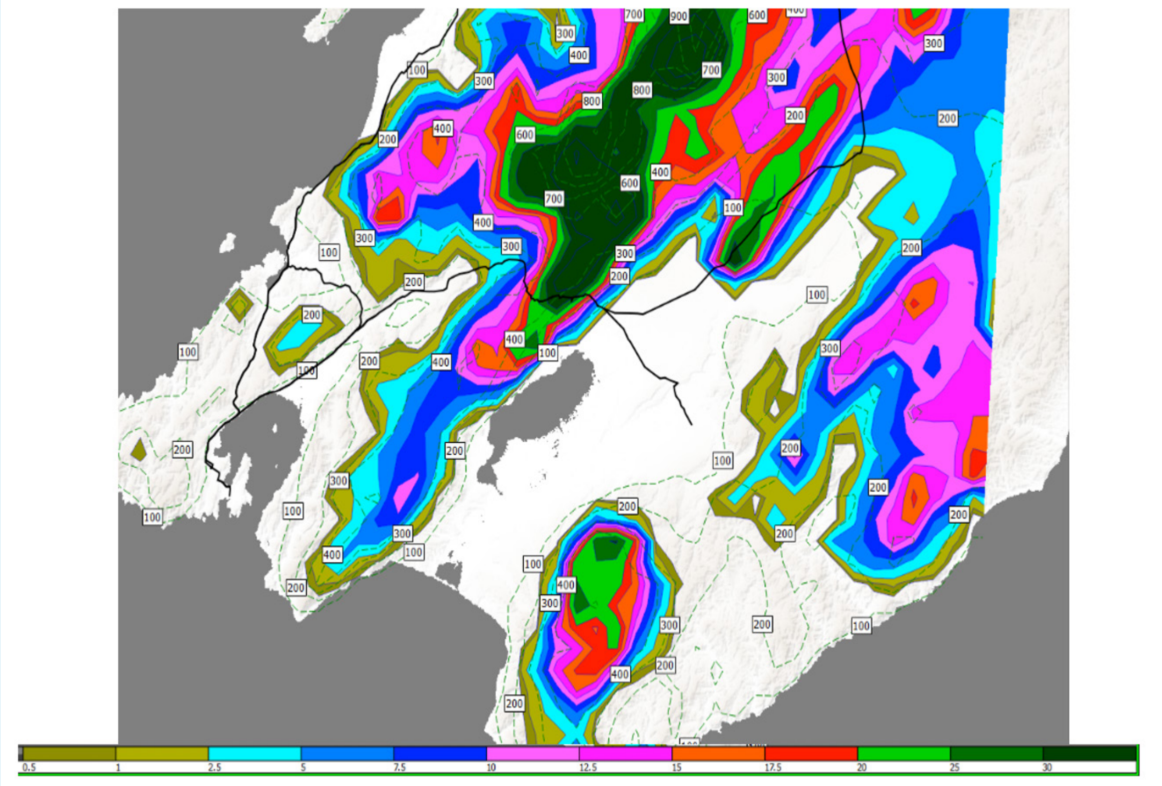

Figure 12: Derived snow accumulation guidance from an ECMWF IFS WRF 1.5km model. This shows 24hr snow accumulations (cm) up to midnight 10th August 2023.

Shadings depict snow accumulation. Black lines are State Highways and dashed, labelled lines depict the model terrain heights (metres asl).

In operational environments, forecasters must assess this type of guidance and filter for the plausible and implausible. For example, in this case, the accumulations over the Remutaka Range and Tararua Range may be given more credibility than some of the spurious looking accumulations at near-sea level in the Wairarapa.

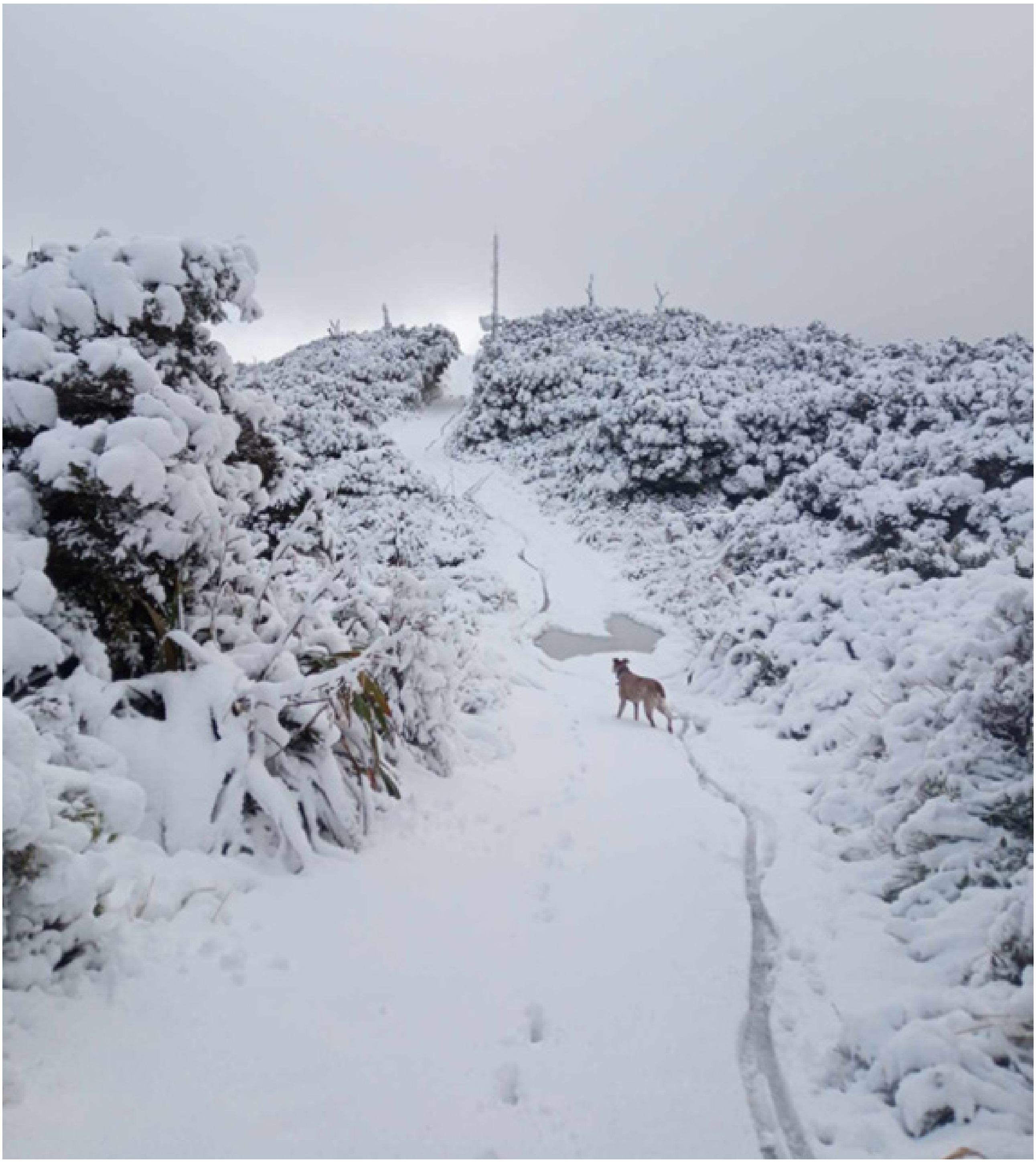

Figure 13: Katla and snowfall on Mount Climie, Remutaka Range. Photo credit: Tom Adams.

Book review

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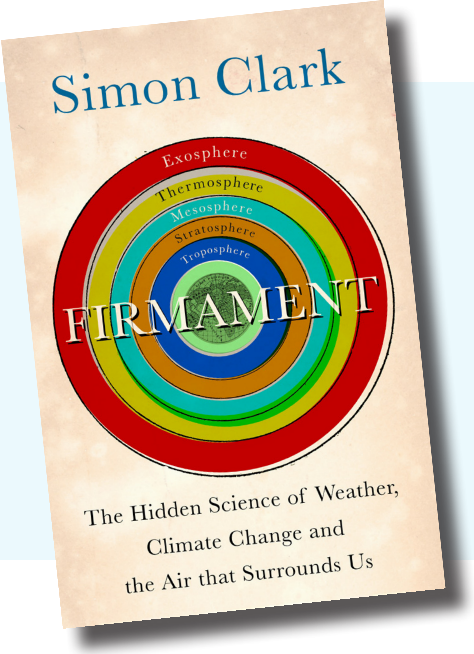

Simon Clark. 2023.

Firmament: The Hidden Science of Weather, Climate Change, and the Air that Surrounds Us

London: Hodder & Stoughton.
253 pp. 12 illustrations.
ISBN 978 1 5293 6231 2 (paperback) £10.99.

Part history of science, part science communication, *Firmament* is a fascinating survey of atmospheric science from antiquity to the present day.

Simon Clark holds a PhD in atmospheric physics from the University of Exeter; his research examined stratosphere-troposphere coupling over the Arctic. He started a YouTube channel in 2010, which initially focused on giving advice to students from disadvantaged backgrounds on the application process for Oxford and Cambridge (Clark completed a master's degree at University of Oxford). Upon moving to Exeter his YouTube output shifted to videos about science, mostly focused on physics of the atmosphere. Since finishing his PhD he has worked full-time as a science communicator. His YouTube channel has accrued 460,000 subscribers and over 40 million views.[1]

The first chapter, "Idea," charts the shifting conceptualisations of the atmosphere from antiquity through the invention of the thermometer and barometer in the early modern period to present-day knowledge of the troposphere's lapse rate. The chapter contains the extraordinary story of James Glaisher, a pioneering meteorologist who, in 1862, assisted by aeronaut Henry Coxwell, undertook manned balloon flights to determine the characteristics of the upper atmosphere, on behalf of the British Association for the Advancement of Science. A tangled valve line caused the balloon to rise uncontrollably; Glaisher lost consciousness during the ascent, while Coxwell just managed to avert disaster by releasing the valve, causing the balloon to begin descent, before he too lost consciousness. It is believed the pair may have reached as high as 37,000ft – without oxygen or any kind of heating beyond thick clothing.[2]

The second chapter, "Birth," expands on the previous discussion by describing the structure of the stratosphere, mesosphere, thermosphere, and exosphere. First, however, Clark describes how ice core samples are used to map the past climate; he establishes for the reader that the atmosphere has varied greatly in chemical composition

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[1] https://www.youtube.com/@SimonClark.

[2] This flight was the subject of the 2019 film *The Aeronauts*, although Coxwell is replaced by a fictional character.

and temperature over the course of its history. Clark then describes the technological advances that made it possible for upper reaches of the atmosphere to be studied – weather balloons could only rise so high (the current record is 53 km), so it took the invention of liquid-fuelled rockets in the 1920s to penetrate the mesosphere and above.

Chapter three, "Wind," takes us on a journey through debates about the nature and origin of storms. The view handed down from antiquity was that weather developed in situ. Daniel Defoe's *The Storm* (1704), which recognised that stormy weather reported across Europe in late November 1703 was attributable to a single storm that moved across the region, was one of the first works to challenge this notion of in situ development. The discussion then takes us from Benjamin Franklin's investigation of a storm in 1743 through William Redfield's recognition of the cyclonic nature of lows in 1831 to William Ferrel's formulation of the equations of motion in 1858.

Chapter four, "Fields," introduces the notion of a meteorological field. Having discussed in the previous chapter how Ferrel connected changes in pressure to wind, Clark highlights how the ideal gas law links pressure changes to temperature variations. To explain the origin of temperature changes he describes the radiative balance of the earth and in turn accounts for the troposphere's lapse rate. He concludes with a discussion of air parcel theory and static stability. He points out the contrast between the often unstable troposphere and the highly stable stratosphere – vertical motion is a common feature of the former, but almost entirely inhibited in the latter.

In chapter five, "Trade," Clark gives an account of how the trade winds have been understood over the course of history. He discusses Edmond Halley's remarkably accurate description of the global wind circulation, which was published in 1686. Halley attributed the cause of the trade winds to the movement of the sun across the sky: the sun would heat up a section of the atmosphere, causing the pressure to fall and air to rush in from the east towards the area of low pressure. In 1735, George Hadley challenged Halley's theory of the trade winds, instead arguing that air in the tropics, owing to an excess of heat, is forced to rise, which causes air to converge from the north and south to replace the rising air. Hadley also got part of the way to accounting for the Coriolis effect. Clark finishes the chapter by explaining how Gaspard-Gustave Coriolis' contribution in 1835 addressed the shortcomings in Hadley's theory.

Chapter six, "Distance," explains the role of the subtropical and polar jet streams in the genesis of weather systems. Clark rightly attributes the discovery of the mid-latitude jet stream to Japanese meteorologist Wasaburo Ooishi, whose upper air studies in the 1920s documented the phenomenon long before the winds were "discovered" by Allied aviators during the Second World War – Ooishi's trouble was that he published his results in Esperanto, which limited the circulation of his work amongst the meteorological community. He also explores Gilbert Walker's early 20th century statistical investigations of the monsoon in India, which led Walker to recognise a connection between El Niño Southern Oscillation (ENSO) and the monsoon. Clark then segues Walker's observations into a discussion of Jacob Bjerknes' articulation in 1969 of the physical processes that drive ENSO.

> The characters and historical episodes Clark selected are entertaining and instructive and he deftly (at times, even poetically) weaves the historical narrative in and out of the discussion of scientific concepts.

In chapter seven, "Forecast," Clark details the progress in weather forecasting from Robert Fitzroy in the UK during the 1860s, Cleveland Abbe in the US during the late 19th century, Vilhelm Bjerknes and the Bergen School of Meteorology in Norway during the early 20th century, through to Lewis Fry Richardson's attempt at numerical weather prediction (NWP) in 1922 and its ultimate realisation by electronic computer with the work of Jule Charney and John von Neumann during the 1950s. In the course of this discussion Clark explains concepts like pressure gradient force, geostrophic flow, air masses/fronts, the primitive equations, and chaos theory.

Chapter eight, "Vortex," focuses on the stratospheric polar vortex and its effects on surface weather. Through an account of Richard Scherhag's investigations in 1952, Clark explains the process of sudden stratospheric warming and details its effects on the behaviour of the polar vortex.

Finally, in chapter nine, "Change," Clark describes how we came to recognise that climate change was possible. He identifies Chinese scholar Shen Kuo, who wrote in the late 11th century, as one of the first to recognise the possibility of climate change, and then explains James Hutton's late 18th century thesis of glacier retreat and Louis Agassiz's mid 19th century postulation of past ice ages. Clark details James Croll's 1864 theory that ice ages are caused by changes in the Earth's orbit, and the more successful variant of the theory developed by Milutin Milanković during the 1920s and 30s. Noting, however, that Croll-Milanković orbital cycles only explain temperature variation on timescales of tens of thousands of years, Clark goes on to account for temperature changes over tens or hundreds of millions of years by tracing the evolution of the idea that the atmosphere acts as an insulator from Jean-Baptiste Fourier in the 1820s, through to Eunice Newton Foote in 1856 and John Tyndall in 1859, who demonstrated the greenhouse effect experimentally. He explains how the global carbon cycle accounts for temperature variation on geological time scales, and then discusses Charles Keeling's discovery in the late 1950s of increasing carbon dioxide concentration in the atmosphere. Finally, Clark describes the emergence of a global scientific consensus on the problem of anthropogenic climate change and offers a short summary of the predicted consequences of climate change.

> I enjoyed this book. It is a great demonstration of how the history of science can serve as a tool of science communication.

I enjoyed this book. It is a great demonstration of how the history of science can serve as a tool of science communication. The characters and historical episodes Clark selected are entertaining and instructive and he deftly (at times, even poetically) weaves the historical narrative in and out of the discussion of scientific concepts. At points along the way I worried the book was suffering from poor organisation – reading over the chapter summary above one might feel that the topics were jumbled together with little logical structure. By the time I had got to the end of the book, however, these doubts had fallen away: Clark brings the historical and scientific stories together nicely in the end.

Most of the cast of historical characters will be familiar to historically inclined atmospheric scientists or historians with an interest in the history of meteorology. But Clark is not claiming to have produced an original work of history of science. Nevertheless, I was impressed by his sensitivity to the way in which women, people of colour, and other historically marginalised groups were excluded (or if not excluded, written out) of the history of atmospheric science in the 19th and 20th centuries. I was also glad to see him acknowledge the ways in which meteorology benefited from the expansion of the European empires – both in money and data. Furthermore, although much of his historical narrative focuses on the contribution of individual scientists, he is clear that these achievements need to be understood in their broader social context:

> While individuals may make remarkable accomplishments, propelling our understanding of the natural world forward, these accomplishments are enabled only by circumstance. The wealth of a nation, the availability of particular materials, the quality of education given to the general populace – broader societal factors position and enable their contributions … James Croll and William Ferrel, in particular, [benefited from] scientific textbooks and journals being made widely available in the nineteenth century. Any history of science is truthfully a history of these societal factors (p. 173).

These issues are often neglected by scientist-historians in their accounts of the development of their fields. These facets ought to endear Clark's book to historians of science.

Firmament is an entertaining, informative read. I don't know if atmospheric science is all that "hidden" these days, but those still in the dark will find themselves enlightened by the end of this book. It ought to be accessible to a motivated lay reader, yet it also contains historical anecdotes and context that atmospheric scientists will find of interest. Clark's book is also an excellent introduction to the problem of anthropogenic climate change. His book ends with an urgent plea for societal action: the "atmospheric giant" has been "happy to keep us safe and warm, fed and watered. In return, we must now use the collected knowledge of the past 500 years to keep it on our side" (p. 196).

Book review

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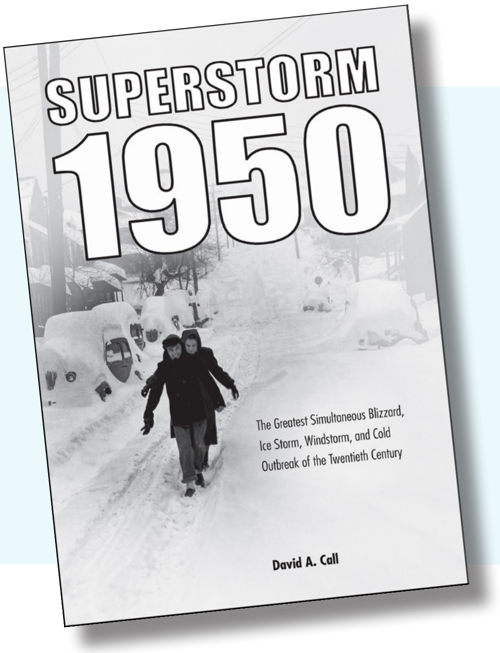

David A. Call. 2023.

Superstorm 1950: The Greatest Simultaneous Blizzard, Ice Storm, Windstorm, and Cold Outbreak of the Twentieth Century.

West Lafayette, Indiana: Purdue University Press.
248 pp. 36 illustrations.
ISBN 978 1 6124 9797 6 (paperback) US$25.99.

In late November 1950 much of the eastern United States was impacted by one of the most intense and destructive mid-latitude cyclones of the 20th century. This cyclone, which is often referred to as the Great Appalachian or Thanksgiving storm, brought numerous severe weather hazards including snow, ice, wind, flooding, and cold, with many records being broken. It was the costliest weather disaster when it occurred, and only two storms affecting the mainland since (both hurricanes) have exceeded the loss of life caused by the 1950 cyclone.

David Call is an Associate Professor of Geography and Meteorology at Ball State University. Call teaches courses in meteorology and physical geography, including a storm chasing class in which he takes students on the hunt for tornadoes. His research investigates the impacts of winter weather. In *Superstorm 1950* the author's broad background is brought to bear to produce a study of interest to a wide range of scholars including meteorologists, geographers, historians, emergency managers, and policy makers. Call examines every aspect of the storm, from the meteorological background through the various weather impacts to the present-day significance of the storm.

The first chapter sets the scene by comparing life in the 1950s to 21st century America. Chapter two provides the meteorological background to the storm, while chapters three through eight document in detail the many impacts of the storm, organised according to phenomenon (snow, ice, flooding, etc.). Chapter nine discusses the significance of the storm to the history of science, in particular its impact on the development of numerical weather prediction (NWP). Finally, the last chapter examines the concept of a "superstorm" and speculates on the impacts a comparable storm would have today.

Towards the end of November 1950 an anomalously cold air mass developed over western Canada and began moving southeastwards. On 22 November the cold air started to arrive over the northern Great Plains of the United States. Unimpeded by any mountain ranges, the cold air continued to spread south over the next several days, breaking November records for low temperatures from Ohio down to Florida. The surface analysis in the top left of Fig. 1 depicts the situation on 24 November 1950 of cold air spreading across the central United States following a cold front. Note, the low-pressure system at the northern border of the United States is not the superstorm – the northern low-pressure system filled before the superstorm developed further south.

The low that was subsequently to become Superstorm 1950 first appears on the 1230 UTC 24 November chart (Fig. 1, middle left), with a central pressure just under 1016 mb. Over the next 12 hours the depression deepened (Fig. 1, bottom left). This didn't greatly concern forecasters at the time as the east coast of the United States is a well-known location for cyclone development. Usually, such a depression would move up the coast following the Gulf Stream or out to sea. However, this cyclone surprised both the forecasters and public by moving inland to the northwest.

Conditions in the upper troposphere were ripe for rapid subsequent development of the depression. An unusually intense upper cold pool was located over the Ohio Valley, west of the surface depression – a favourable set-up for further development. Furthermore, the polar jet associated with this upper cold pool was located unusually far south for November (over southern Alabama and Georgia) and was unusually strong. In addition, an upper-level ridge over Maine and New Brunswick, located to the west of a surface anticyclone over Labrador, helped to intensify the latter. This intense anticyclone was responsible for blocking the progress of the depression to the northeast, instead directing it northwestwards.

The favourable upper air conditions caused the cyclone to undergo explosive cyclogenesis – to "bomb."[1] By 1230 UTC 25 November (Fig. 1, top right) the cyclone's central pressure had fallen to 992 mb – a drop of 16 mb over the preceding 12 hours and 26 mb over the preceding 24 hours. Meanwhile, Caribou, Maine, under the influence of the anticyclone set a November record for high pressure at 1024 mb. The extreme pressure gradient generated between the high- and low-pressure centres brought hurricane-force winds across the northeastern United States on 25 November.

A new low developed on Saturday morning near Erie, Pennsylvania, and moved west-southwest over Cleveland, Ohio. For a time, this new low coexisted with the existing intense low, but soon it took over as the primary centre. The central pressure of the new depression fell rapidly – though not fast enough to still call it a bomb – while the former bomb low decayed. As the storm drifted further southwest in Ohio it deepened further reaching a minimum of 978 mb over northern Ohio early on 26 November. Dayton, Ohio, set a record for lowest November air pressure at 983.7 mb, less than 24 hours after Caribou reached its November high pressure record.

> In *Superstorm 1950* the author's broad background is brought to bear to produce a study of interest to a wide range of scholars including meteorologists, geographers, historians, emergency managers, and policy makers.

By the morning of Sunday 26 November the worst of the storm was over. The cold air had wrapped completely around the low, occluding the warm air; the surface low had moved under the upper-level low, an unfavourable position for further development; and the high-pressure system over Labrador was weakening and moving towards Greenland (see 1230 UTC 26 November chart, Fig. 1, bottom right). Over the next 24 hours the storm filled, and no longer posed a serious threat. However, the cold air persisted, and further light snow and rainfall caused problems. It would be a week before settled, warmer weather returned to the eastern United States.

Superstorm 1950 had a widespread destructive impact across much of the eastern United States. Damage ran into the hundreds of millions of 1950 dollars (equivalent to at least US$1 billion today) and 353 people were killed. To briefly summarise some of these impacts, record-breaking snow affected eastern Ohio, western Pennsylvania, and West Virginia (see Fig. 2); it is the worst snowstorm to have affected the Ohio Valley according to the Regional Snowfall Index. In Pennsylvania, heavy rain caused flooding, especially on the West Branch of the Susquehanna River – this would have been the worst flooding of 1950 had there not been further flooding a week later owing to saturated soil and swollen rivers caused by the superstorm. In west central Pennsylvania, in places like Clearfield and

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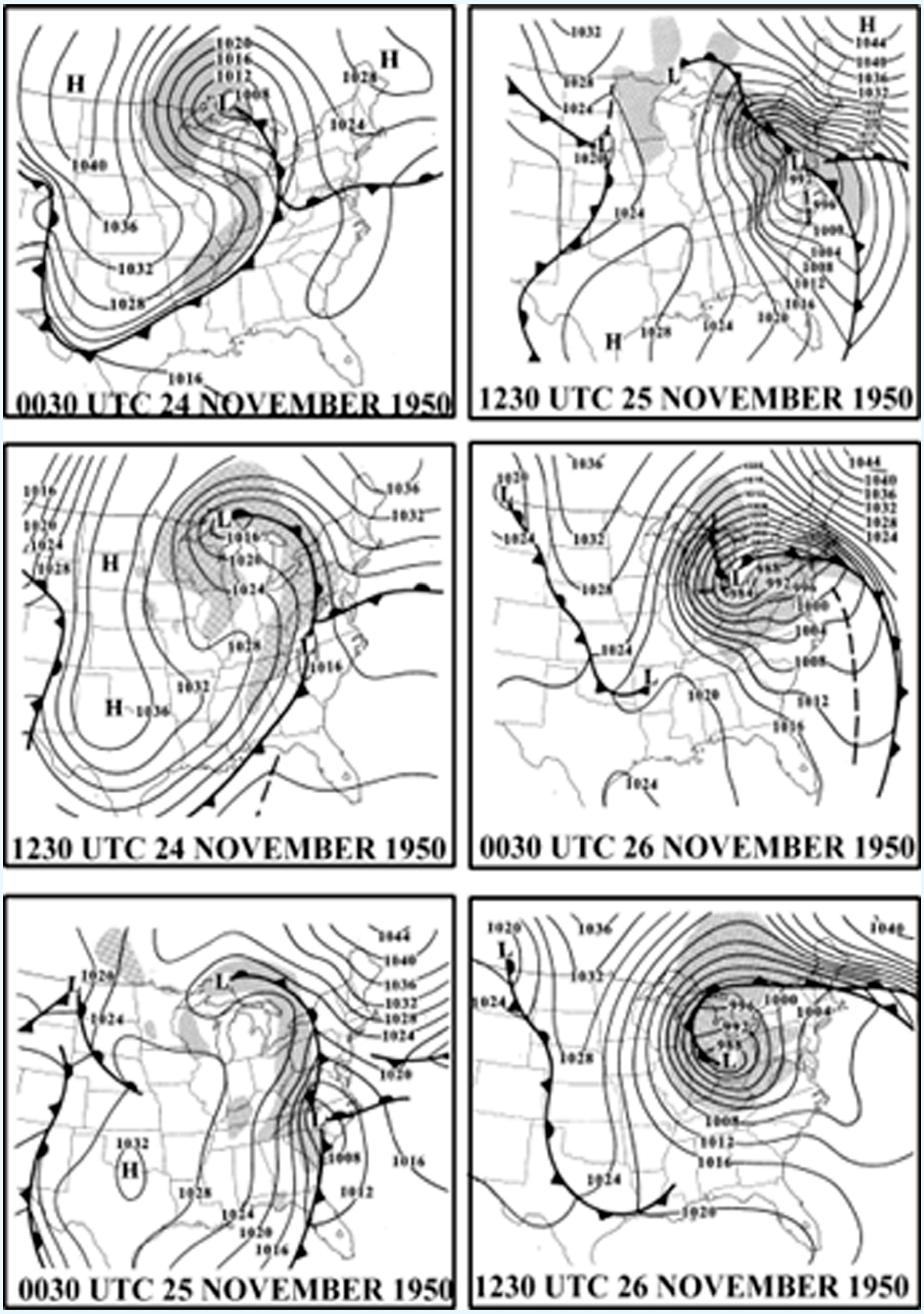
[1] A "bomb" is a rapidly intensifying mid-latitude cyclone that, according to Fred Sanders' and John Gyakum's (1980) criteria, deepens by at least 24hPa (mb) in 24 hours (at 60°N/S).



0030 UTC 24 NOVEMBER 1950

1230 UTC 25 NOVEMBER 1950

1230 UTC 24 NOVEMBER 1950

0030 UTC 26 NOVEMBER 1950

0030 UTC 25 NOVEMBER 1950

1230 UTC 26 NOVEMBER 1950

Figure 1: Surface analyses of Superstorm 1950. The storm first appears on the 1230 UTC 24 November chart (middle left), located just south of the triple point between the cold, warm, and occluded fronts. The depression rapidly deepens and moves to the northwest. Typically, cyclones progress up the east coast or out to sea, but in this case an intense anticyclone to the northeast blocked the superstorm's progress, forcing it inland. From Kocin and Uccellini (2004, p. 348). (© American Meteorological Society. Used with permission.)

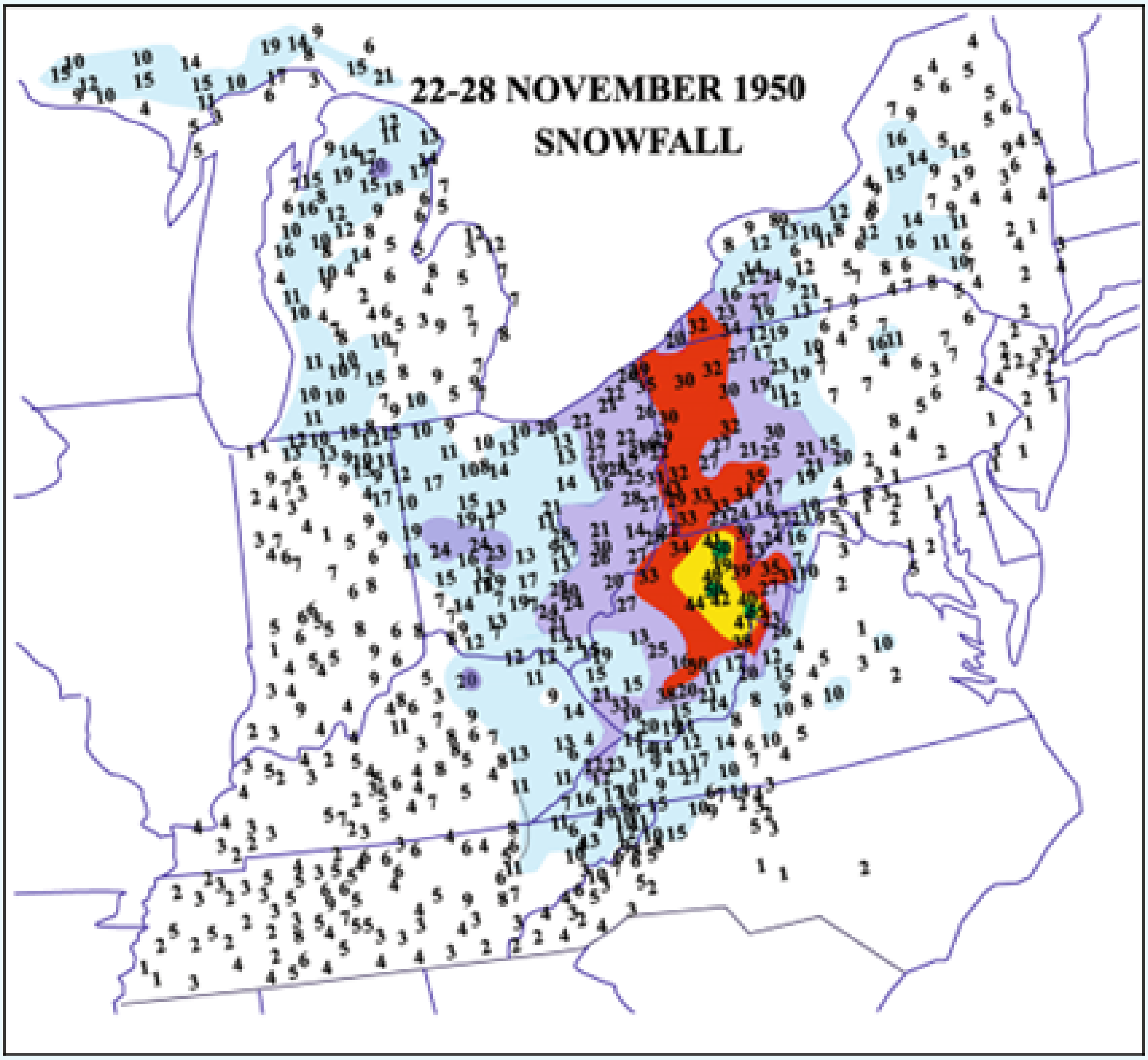


Figure 2: Cumulative snowfall (in.) across the northeastern United States for 22-28 November 1950. Coloured shading represents increments of 10in. (25cm) for amounts of 10in. (25cm) and greater. The heaviest snowfall (red, yellow, and green) occurred in eastern Ohio, western Pennsylvania, and West Virginia. From Kocin and Uccellini (2004, p. 347). (© American Meteorological Society. Used with permission.)

Altoona, precipitation fell as freezing rain, which destroyed the electricity grid. Finally, the windstorm in the northeast was widespread and severe. The destruction wrought by the wind was compared to the Great Hurricane of 1938 with many areas experiencing gusts to hurricane strength.

Superstorm 1950 was poorly forecast. Call argues that a bust forecast was probably unavoidable given that in 1950 meteorological science was in a juvenile stage of development, and there were few upper air observations and little data over the oceans and polar regions. He does note, however, that there was an analogue storm, the 1913 White Hurricane, which forecasters could have drawn upon in their prognoses. In the end, he argues, even if the storm had been well predicted:

> it is unlikely that the forecasts would have been heeded. Weather forecasts in 1950 were given nowhere near the credence of those today. And even if the forecasts had been heeded, the magnitude of the weather was so extreme that government officials could not have done much to prepare (p. 33).

Arguably, today, courtesy of the great advances in meteorological theory, remote sensing, and NWP, meteorologists and emergency management officials are faced with the reverse problem: the public has become so accustomed to reliable, timely warnings that there is a tendency to view weather as less of a hazard than it has been for previous generations. While improvements in forecasting have allowed the public to prepare for storms well in advance, society remains vulnerable to severe weather.

Chapters three through eight, which make up just over half the book, examine in detail the effects of the storm, namely snow, freezing rain, flooding, wind, and cold temperatures. All but one of these chapters are relevant to New Zealand's experience of mid-latitude cyclones – chapter five is on freezing rain, which is an extremely rare phenomenon in any of the populated parts of New Zealand. Of the effects studied, the flooding and wind damage could be said to be of similar magnitude to severe storms in New Zealand history – though it should be noted that in the last 100 years our most destructive storms tended to be ex-tropical cyclones (e.g., the 1936 storm, the 1968 Wahine storm, the 1988 Cyclone Bola, and the 2023 Cyclone Gabrielle), whereas Superstorm 1950 was a classical frontal wave. Although New Zealand also experiences disruptive snow and cold with outbreaks from the Southern Ocean (e.g., the 2006 snowstorm, 2011 polar outbreak), these events are typically more severe in the United States owing to the continental character of their climate.

In cataloguing the many different impacts of the superstorm, Call is sensitive to the uneven way in which the storm's effects were experienced. Race, gender, and class shaped peoples' experience of the storm. African Americans, especially in the South, were overrepresented in the fatalities from the storm; poverty among African Americans was extremely high in 1950 and many died from exposure owing to inadequate heating in their dwellings or in fires started by faulty heating systems. Men were also overrepresented in fatality statistics; many died from heart attacks triggered by overexertion while attempting to clear fallen snow.

As is often the case during natural disasters, there were many stories of survival, self-sacrifice, and community spirit. Call also weaves into the narrative some more light-hearted anecdotes. For example, in Wheeling, West Virginia, a bottled gas dealer enjoyed 15 minutes of local and national fame when he offered the use of his home-made flamethrower to melt snow. The city manager gave the experiment his blessing and the flame throwing went ahead. The experiment was a flop: only a small area about the size of a newspaper was successfully melted. More successful, however, were the efforts of electricity workers in Pennsylvania. Desperate to free their lines from the burden of accumulated ice, they took to short-circuiting sections of the lines – the heat generated from shorting they hoped would melt the ice. This apparently worked for all but the most elevated sections of the lines.

I must say I found these chapters dry and hard going at times. The author seems to have relied heavily on newspaper reportage in working up his narrative of the effects of the storm. There is nothing wrong with this per se, but I was left wondering if the story could not have been rendered livelier through quotations from first-hand accounts of people affected by the storm. In the end, these reservations may simply be attributable to my professional interests – meteorology and history of science. Geographers and emergency managers, for example, might find these sections of the book more engaging. Social historians, on the other hand, are likely to be underwhelmed.

The final two chapters I found much more interesting. Chapter nine examines the impact of Superstorm 1950 on the history of meteorological science.

At the Institute for Advanced Study in Princeton, New Jersey, meteorologist Jule Charney and mathematician John von Neumann were leading the Meteorology Project to undertake NWP by computer for the first time in history. While waiting for their own navy-funded computer to be built at Princeton, the Meteorology Project travelled to Aberdeen, Maryland, in March 1950 to use the army's Electronic Numerical Integrator and Computer (ENIAC) to conduct their initial NWP efforts. The scientists were pleased with their initial experiments and encouraged for the future. Seven months later the superstorm occurred. The scientists at Princeton were affected by the superstorm, with winds at nearby Trenton gusting over 100 mph (161 km/h), causing extensive damage and knocking out power to much of the town and university. The unusual severity and track of the storm, as well as the fact it was poorly forecast, inspired the modellers to use it as a key case study to test their models. If their early NWP models could predict this storm, so the modellers' logic went, then surely they could predict more garden-variety weather systems. Norm Phillips, another Meteorology Project member, developed a simple two-level model building on Charney's work. In 1951 he tested this by hand-calculating values for Superstorm 1950 – this was the first time the storm was used to test a model. The results, published in *Journal of Meteorology,* were mixed and Phillips recommended introducing another vertical level and modifying some assumptions.

By 1952 the Princeton computer was up and running, offering vastly superior performance to the ENIAC. In 1953 Charney and Phillips published a paper outlining how a two-and-a-half-dimensional model outclassed a two-dimensional model for Superstorm 1950. A year later Charney showed a three-level model improved the forecasting of the magnitude of the superstorm, though the location was still wrong. In 1958 Phillips used a model with a stream function to forecast the superstorm. The model was a great success; Phillip's two-layer model, focused on wind fields rather than temperatures, was a major improvement on the traditional geostrophic approach. Later in life, Phillips credited his and Charney's work modelling the superstorm as leading to the formation of the Joint Numerical Weather Prediction Unit (JNWPU) in 1954. The JNWPU was a collaboration between the United States Weather Bureau, air force, and navy. They began issuing forecasts in 1955, although these were not of a usable quality. However, by 1958 computer models were successfully able to forecast future weather. Superstorm 1950 was used by the modelling community as a key case study to test their models for the next 50 years.

The other interesting dimension to Superstorm 1950's role in the history of science was its contribution to storm surge modelling. In the 1960s N. Arthur Pore and William S. Richardson at the National Weather Service's (NWS) Techniques Development Laboratory began developing storm surge models using the superstorm as a test case. Superstorm 1950 was of value because of its unusual intensity and track. Winds that generated the storm surge came from the east/southeast instead of from the more typical northeast direction; the timing of the storm coincided with a spring tide; and the intensity of the storm generated record high tides along the northeastern coastline.

Call's concluding remarks of this chapter neatly capture that fascinating interplay of chance, social necessity, and ingenuity which so often lies at the heart of periods of rapid progress in science:

> The weather disruptions caused by Superstorm 1950 were severe, but generally short-lived. The storm, however, lived on within meteorology. Its fortuitous timing meant that it played a large role in developing and perfecting meteorologists' and computers' understanding of the atmosphere … Ultimately, while Superstorm 1950 killed hundreds and caused hundreds of millions of dollars in damage, countless lives and dollars have been saved since then due to the improved accuracy of weather forecasts. The quality of these forecasts is directly attributable to this storm (p. 176).

The final chapter of the book examines how changes in society since 1950 have modified the effects of cyclones of similar severity to Superstorm 1950. Call notes that while progress has been made in improving race relations, reducing poverty, and addressing gender inequity, the effects of a similarly severe storm would still be felt unevenly across society. Although technological changes have increased societal resilience in some areas, society remains susceptible to several hazards. Improvements in automobile technology and snow removal equipment has reduced their susceptibility to stalling and other mechanical failures. Tires have also improved making for better traction on snowy surfaces. Flood protection systems have reduced the risks of riverine flood damage. Record cold would be less of a hazard to life due to public education around carbon monoxide poisoning and better home insulation and heating systems. Tremendous improvement in forecasting has also greatly reduced disruption caused by severe storms by allowing the public and emergency managers to prepare for various weather impacts well in advance. On the other hand, society remains vulnerable to ice storm damage, if not more vulnerable given the greater dependence on electricity today. Coastal flooding would also likely be worse due to a combination of explosive growth of the coastal population and property values, sea level rises associated with climate change, and the loss of coastal wetlands. Wind damage would probably be similar in terms of physical effects, but greater in cost due to increases in property values. Crop damage would also be worse in terms of costs because of the increase in crop yields.

Finally, Call argues for the adoption of the term "Superstorm" to describe intense mid-latitude cyclones. He motivates the use of this term by discussing the challenges of communicating Hurricane Sandy in 2012. When Sandy transitioned from a hurricane to a mid-latitude cyclone, the NWS began referring to it as "post-tropical storm Sandy" and forecasting responsibilities were handed over from the National Hurricane Center to the Hydrometeorological Prediction Center, an office more than 1000 miles away. The "post-tropical" label was one largely unknown to non-meteorologists. Call argues that while the public understand hurricanes are serious storms, according to the NWS label

Sandy was no longer a hurricane, yet it was still a severe storm of which the public needed to be vigilant. To add to the confusion, the Federal Emergency Management Agency continued to refer to it as Hurricane Sandy after the system had transitioned, which was technically incorrect and potentially misleading as the heavy snow that accompanied Sandy is not an impact normally associated in the public imagination with a hurricane.

These communication challenges around former tropical cyclones echo the experience of New Zealand meteorologists. MetService has cycled through a range of labels over the years – e.g., "ex-tropical cyclone," "former tropical cyclone." Today the practice is to refer to transitioned tropical cyclones as "Cyclone …," simply dropping the term "tropical" from the name. Call makes the case for the term "Superstorm" as a way of clarifying the communication of severe post-tropical storms as well as for severe depressions that develop in the mid-latitudes. He proposes a general definition of a "Superstorm" as:

> a midlatitude cyclone that causes record conditions in multiple disparate meteorological hazards over a large area. Superstorms also cause significant societal impacts via loss of life, destruction of property, or general disruption (p. 185).

He goes on to discuss more specific criteria for a storm to meet the threshold of a superstorm. These are somewhat American centric and would require reinterpretation were they to be applied to the New Zealand region.

Call's advocacy of the term "Superstorm" to clarify communication of severe mid-latitude cyclones should be situated within a broader debate about the best practice for communicating severe weather in the 21st century. An approach gaining currency amongst hydrometeorological organisations around the world, with support and encouragement from the World Meteorological Organization, is "impact-based forecasts/warnings," which are typically conveyed graphically with the inclusion of colour to indicate impact severity. Advocates for impact-based forecasts/warnings argue that traditional hazard-based forecasts/warnings often fail to adequately communicate to the public the risks associated with weather hazards as they focus on phenomenon intensity (e.g., X mm of rain per hour) rather than the societal impacts of the phenomenon (e.g., flooding of a state highway during rush hour). MetService has begun to move in the direction of impact-based warnings through the introduction of formal colour-codes in its Warning System in 2019. Warnings are categorised into Orange or Red "depending on the expected severity and impact of the event," with Red being reserved for only the most severe/impactful storms (MetService, 2023). Arguably, even before the introduction of these new warning categories MetService was already taking an impact-based approach by adhering to slightly different warning criteria for various phenomena across different regions based on known regional weather vulnerabilities (e.g., lower wind thresholds for northeast winds in Auckland, lower rain thresholds in Southland and eastern Otago). This is a growing area of research internationally as well as in New Zealand (for a New Zealand study see Potter et al. 2021).

Overall, I enjoyed this book. It is a valuable addition to the literature on historical storms. The study is multifaceted, which ought to make it of interest to a diverse range of readers. I personally got the most out of early chapter dealing with the meteorological background, and the last two chapters which discussed, respectively, the significance of the storm to the history of science and to present-day efforts in meteorology, science communication, and emergency management to respond to superstorms. I found the middle chapters less stimulating, but as noted above this may simply reflect my professional background. With severe storms becoming increasingly the norm in a warming climate, Call's thoroughly researched, eminently readable study is a timely contribution which ought to be read by scientists, policy makers, and anyone else who is grappling with the pressing questions of New Zealand's – and the world's – future climate.

REFERENCES

Kocin, P. J. & Uccellini, L. W. (2004). *Northeast Snowstorms*. Boston, Ma.: American Meteorological Society.

MetService. (2023). *Warnings & Watches*. Available: https://www.metservice.com/warnings/home [14 June 2023].

Potter, S., Harrison, S., Kreft, P. (2021). The Benefits and Challenges of Implementing Impact-Based Severe Weather Warning Systems: Perspectives of Weather, Flood, and Emergency Management Personnel. *Weather, Climate, and Society*, 13(2): 303-314.

Sanders, F., Gyakum, J. (1980). Synoptic-Dynamic Climatology of the "Bomb." *Monthly Weather Review*, 108(10): 1589-1606.

Book review

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James Renwick. 2023.

Under the Weather. A Future Forecast for New Zealand.

Harper Collins Publishers, Auckland, New Zealand.
320 pp.
ISBN 978 1 7755 4172 1 (paperback) $40.00.
ISBN 978 1 7754 9203 0 (e-book) $21.00.

New Zealanders are used to diurnal and day-to-day variability in our weather but the ferocity of recent extreme events, such as Cyclone Gabrielle in February 2023, has taken many by surprise. Scientists have since confirmed that climate change had a role in the severity of Gabrielle (Borenstein, 2023). The Ministry for the Environment (2023) also reports that there is a growing body of evidence that extreme weather events in New Zealand, such as heavy rainfall and flooding, will increase in frequency and severity. This is a daunting prospect. It raises many questions about climate change at the personal level, including: Is climate change already happening now? Is there anything we can do? Is it already too late to make a change?

For the lay person, it can be difficult to obtain credible articles about the science of climate change that are also palatable. Newspaper articles can be too simplified, we know social media contains both information and misinformation, and scientific reports are full of jargon and very specialised. What is really needed is a book that is readable but also relevant, relatable, and scientifically rigorous. *Under the Weather. A Future Forecast for New Zealand* by Professor James Renwick is such a book.

Under the Weather is presented in a format that is easy to read. I purchased the paperback; it is also available as an e-book. The book is typeset with ample margins and a larger font, which is easy on the eyes. Renwick has presented the information in 16 chapters: none is very long and each can be read separately, as a stand-alone 'essay'. The jargon is kept to a minimum and, where it is necessary, it is explained in a conversational manner. Renwick has included autobiographical anecdotes throughout the book and shares his personal points of view. This makes the book far more relatable than most science publications—it feels like a conversation with the author, not a textbook. I think this book will appeal to many readers. That includes the general reader, teachers, university students, and scientists for whom climate change is not their area of expertise. It explains concisely and clearly how we know that the climate has already changed, why climate change is important to our daily lives, what our future will look like, and what we can do about it.

Renwick's fascination with weather and climate began during his childhood in Canterbury, New Zealand. He has 40 years' experience in atmospheric science and climate research and has worked at the New Zealand

Meteorological Service and National Institute of Water and Atmospheric Research. He is currently a Professor at Victoria University of Wellington. Renwick was awarded the prestigious Prime Minister's Science Communication Prize in 2018 and is a Companion of the Royal Society of New Zealand Te Āparangi. He was a lead author for the 4th and 5th Assessment Reports, and a convening lead author for the 6th Assessment Report, of the International Panel on Climate Change. In 2019, he was appointed to the New Zealand Climate Change Commission, to advise Government on national responses to climate change.

> *Under the Weather* speaks to the reader at the personal level, explains how scientists know that climate change is real, and why climate change is already important to our daily lives.

Under the Weather focuses on issues related to climate change for New Zealand and its geographical neighbourhood, the waters and island nations of the South Pacific. It is divided into four parts. 1) 'The Global' sets the broad context including the geological and historical climate record. 2) 'The Local' describes and explains the climate of New Zealand and its oceans. 3) 'The Forecast' digs down into the outlook for New Zealand and the South Pacific for the near future, based on "the climate change that is already locked in" (p6). The response so far is also addressed. 4) 'Where to From Here' looks at best- and worst-case scenarios for the future and actions that could be taken at global, local, and personal levels. In a concluding chapter, Renwick poses the question "Can we really halt climate change?" and answers with "a cautious, but hopeful, yes" (p298). A list of useful websites is provided for readers who want to learn more.

But what about the sceptics? In a recent interview for the Medical Assurance Society's online magazine (2021), Renwick said that "you can't win an argument with someone who's opposed to the science of climate change, because it's not about the science". In the misinformation age, you need to connect on a human level, to find out "what people are afraid of, what they hold dear, what they wish for" (Medical Assurance Society, 2021). *Under the Weather* speaks to the reader at the personal level, explains how scientists know that climate change is real, and why climate change is already important to our daily lives. I suggest it is a good place to start reading if you are undecided or lean towards being a sceptic.

There are no graphs or tables in the book; that might disappoint some readers. I found it refreshing to just read and not have to look at diagrams. I would have liked to have seen an author's photograph inside the back cover. Renwick is the go-to person for local media when they want an expert to comment on climate change. Many readers in New Zealand will have seen him being interviewed on TV; some will have heard him speak at their local hall. A photograph would have helped readers identify the book with the person. I enjoyed the autobiographical anecdotes throughout the book. I would have also loved to have seen some biographical photographs, such as a young Renwick out in a howling nor'wester flying his home-made kite.

Under the Weather is very readable, with a relatable style and rigorous scientific content. I highly recommend it to people who want to learn more about climate change, particularly as it relates to New Zealand.

REFERENCES

Borenstein, S. (2023). Scientists Say Climate Change Worsened Cyclone Gabrielle in New Zealand. *The Diplomat*. Oceania. https://thediplomat.com/2023/03/scientists-say-climate-change-worsened-cyclone-gabrielle-in-new-zealand/. [1 September 2023].

Medical Assurance Society. (2021). *The misinformation age: how to talk about science in a time when it's never been more important*. Medical Assurance Society. https://on.mas.co.nz/issues/july-2021/the-misinformation-age/. [4 September 2023].

Ministry for the Environment. (2023). *The science linking extreme weather and climate change*. Ministry for the Environment. https://environment.govt.nz/news/the-science-linking-extreme-weather-and-climate-change/. [1 September 2023].

2023 Meteorological Society of New Zealand Photo Competition

THEME: Stormy weather

WINNER: (Cover image) Ben Cloke - Lightning strikes the Kāpiti Coast, Wellington

SECOND PLACE: Lisa McClelland - storm approaching Thornbury in Southland, January 2023.

THIRD PLACE: Anjali Thomas - storms about to engulf the main divide, seen from Foggy Peak, Porters Pass, March 2023.

HIGHLY COMMENDED:
Allan McGregor - Mount Gold, Wanaka.

HIGHLY COMMENDED:
Ben Noll - A sun break over a stormy Tasman Sea, Muriwai.

HIGHLY COMMENDED:
Brenda Richardson - Waikato evening looking east from Hamilton as a spectacular storm cloud catches the sunset.

HIGHLY COMMENDED:
Jenny Newstead - a rainy July evening in central Dunedin, seen through the windscreen.

HIGHLY COMMENDED:
Brendan Gully - glorious evening storm over Kāpiti Island.

HIGHLY COMMENDED:
Dion Ayers - Ocean Mail Point, Chatham Islands.

HIGHLY COMMENDED:
Elizabeth Soal - Oamaru Harbour, May 2023.

HIGHLY COMMENDED:
Grant Udy - decaying storm clouds at sunset.