Condensation nuclei data off the west coast of New Zealand

A. M. Bromley and S. A. Gray

National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand

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)

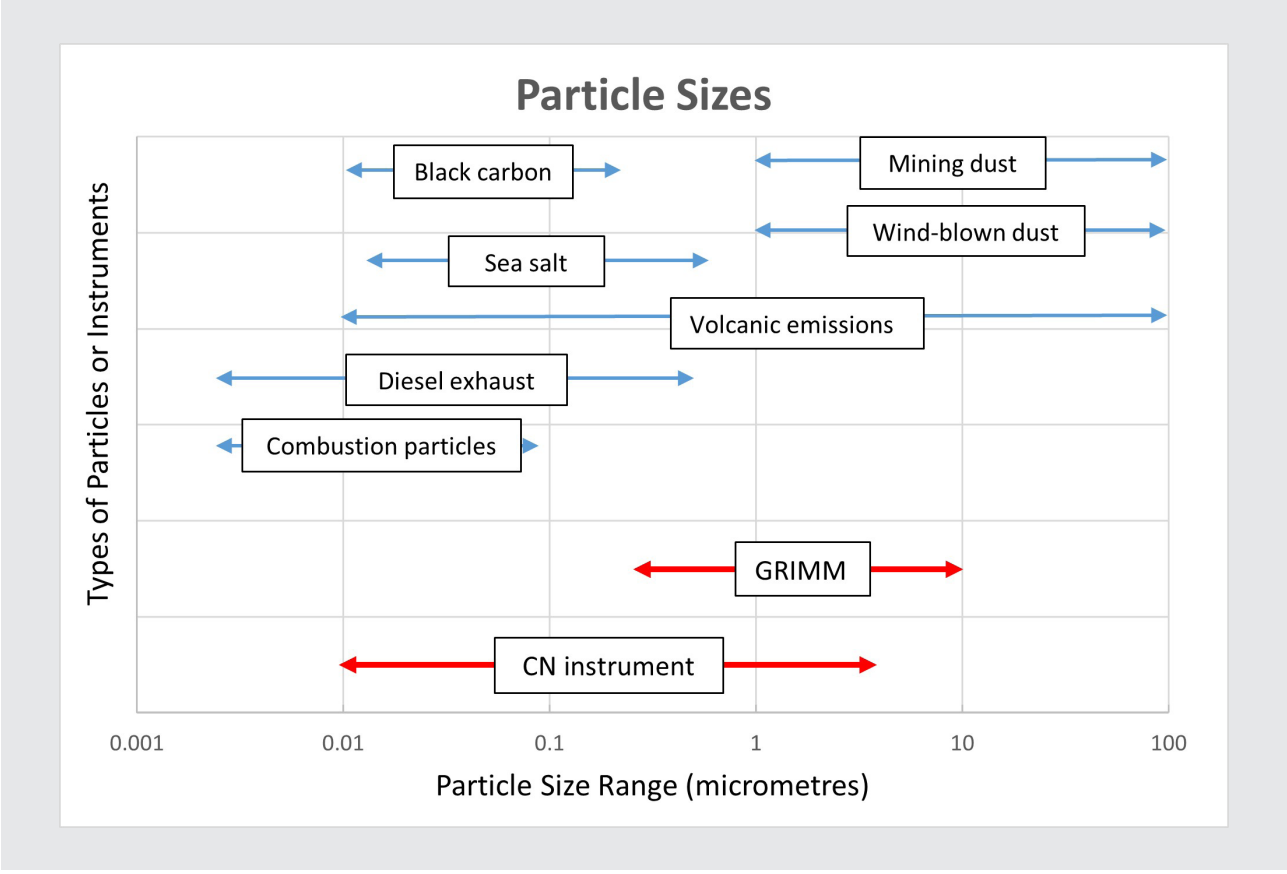

Figure 2: Particle type size range (blue arrows) and instrument measurement range (red arrows).

- 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

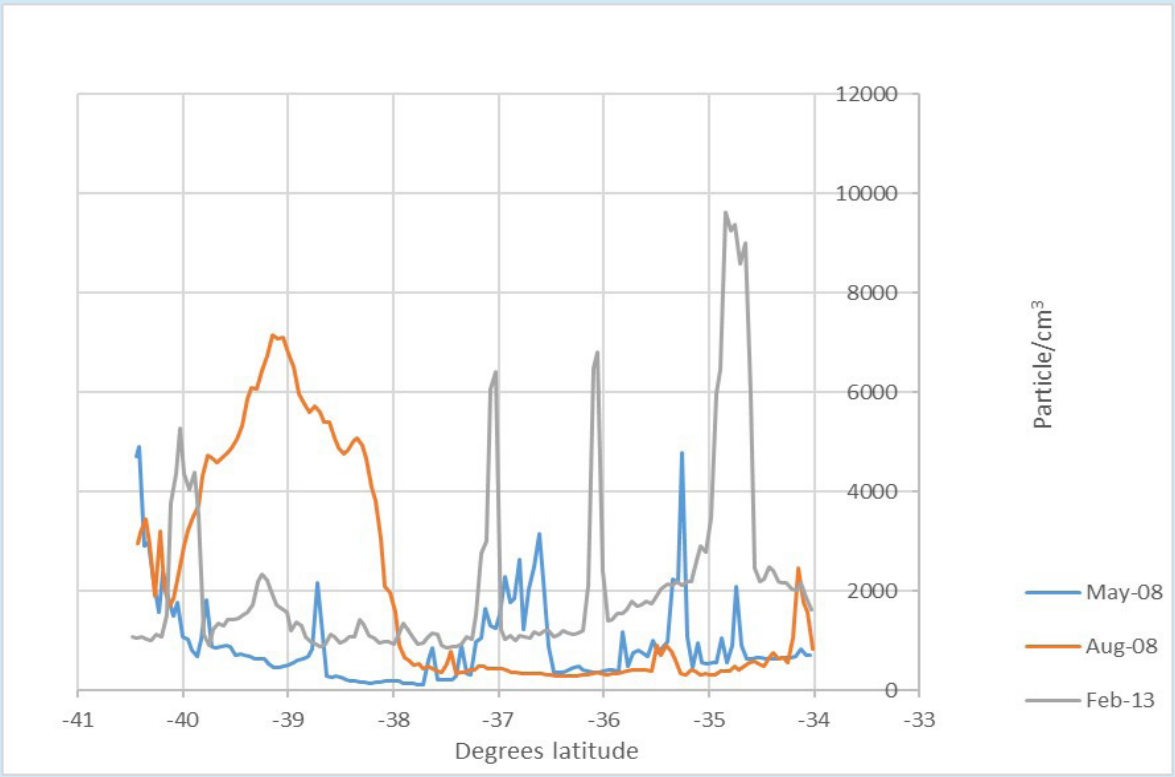

Figure 4: Data from voyages with easterly flow off New Zealand.

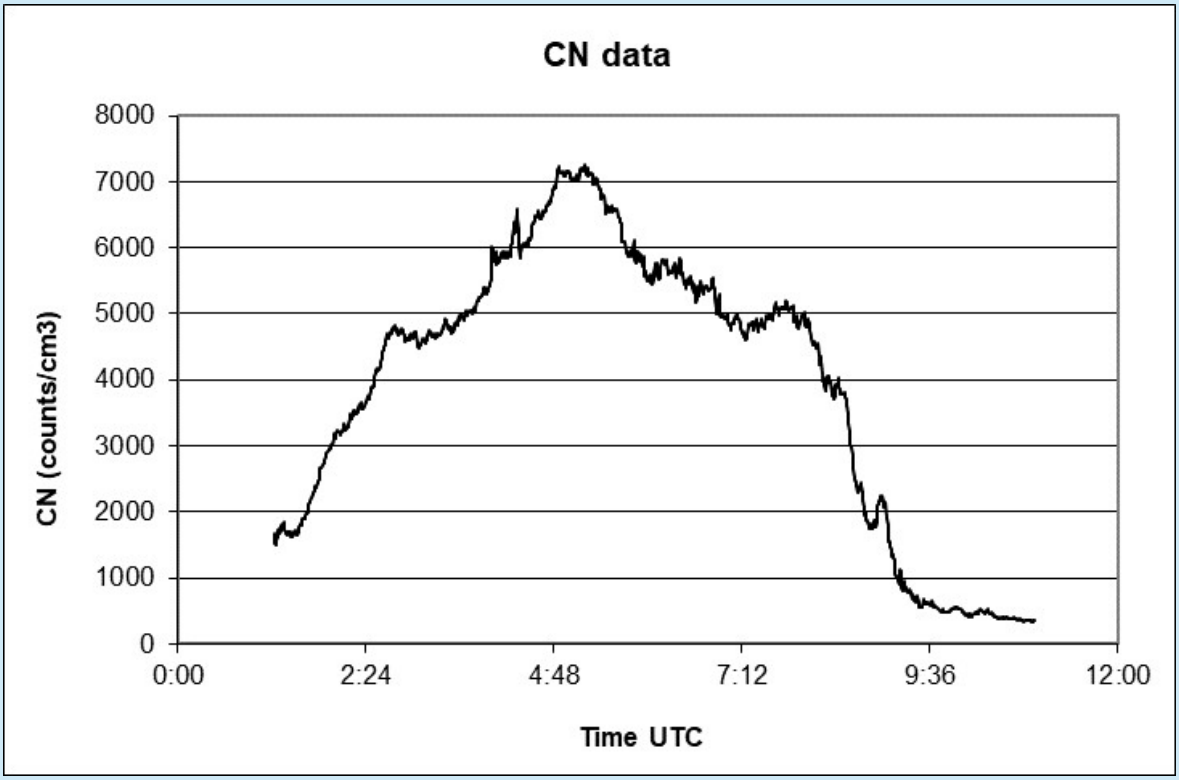

Figure 5: CN data through early hours of 31 August 2008.

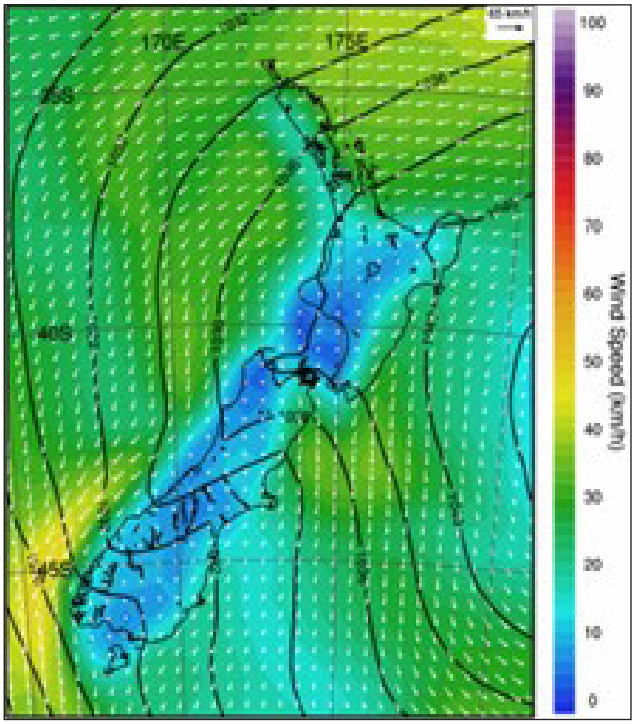

Figure 6: Surface pressure analysis and wind speed for 0600 UTC, 30 August 2008 (NZ Convective Scale model NIWA).

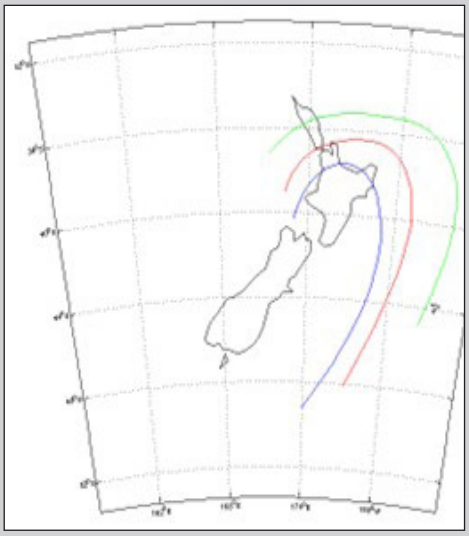

Figure 7: 48-hour back trajectories for the period of the CN increase. The start of the CN increase (blue), maximum CN values (red) and the end of the period of elevated CN concentration (green).

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.

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

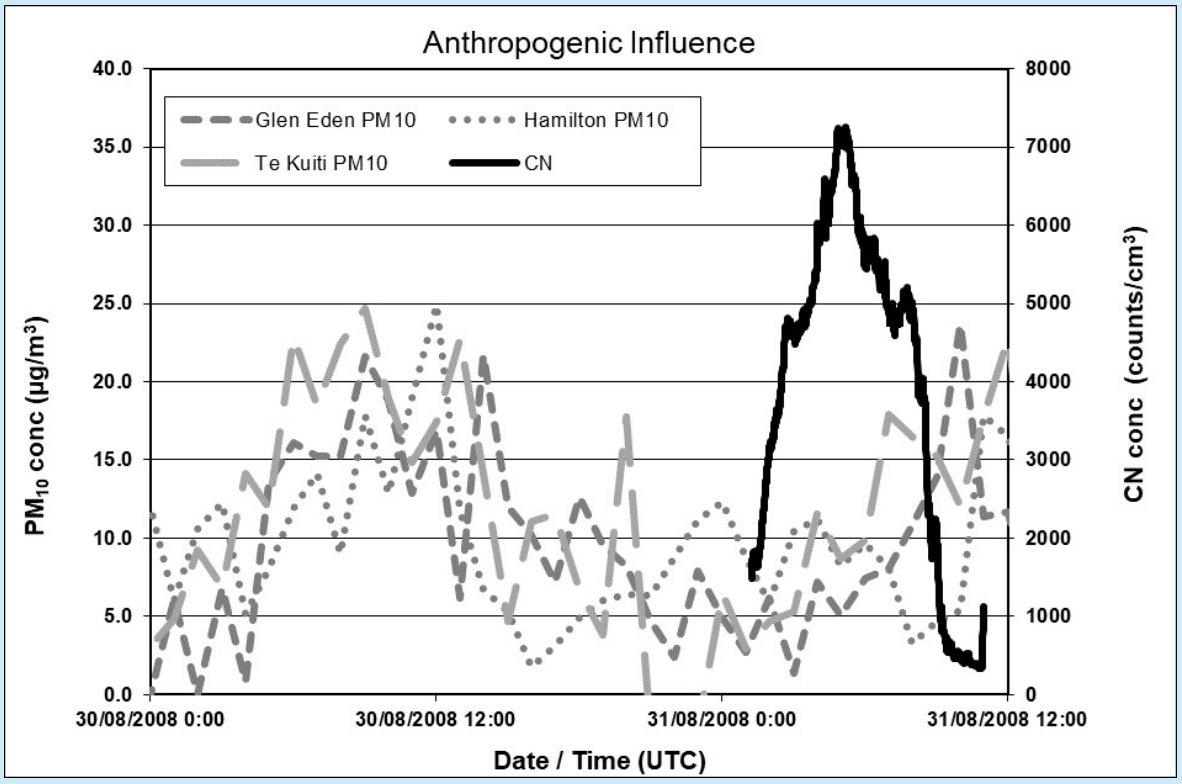

Figure 8: PM_{10} data from New Zealand towns and CN data from TF5.

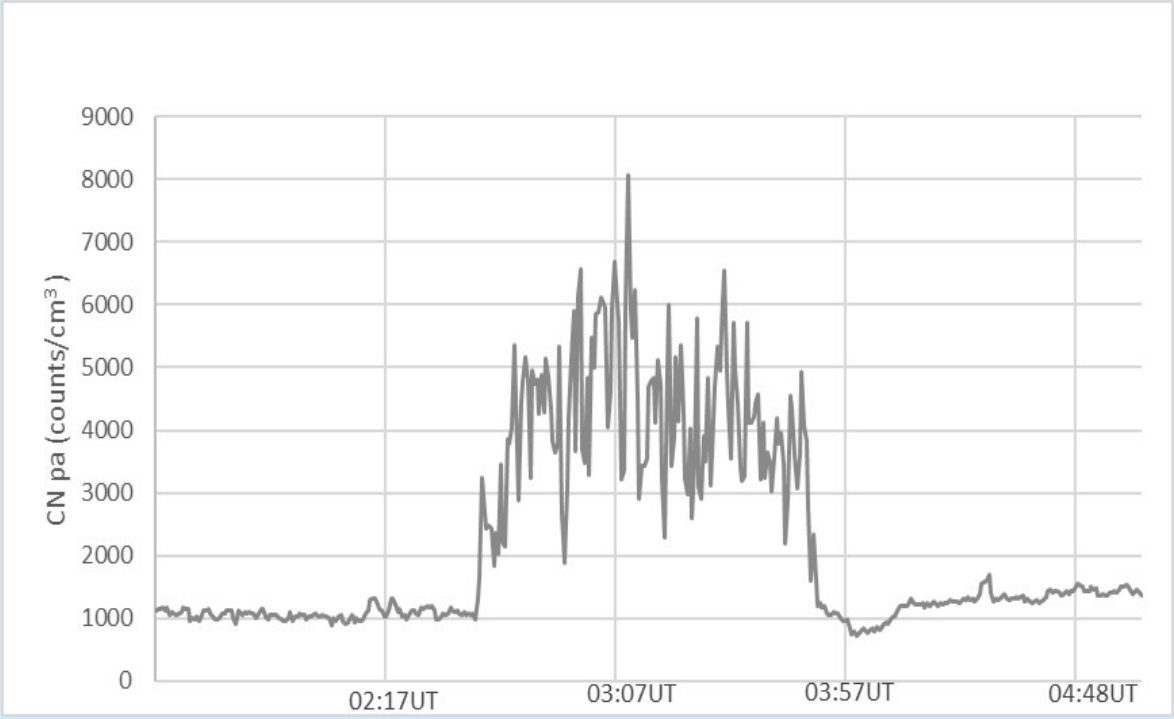

Figure 9: CN increase off the South Taranaki Bight (40°S) during 27 February 2013.

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

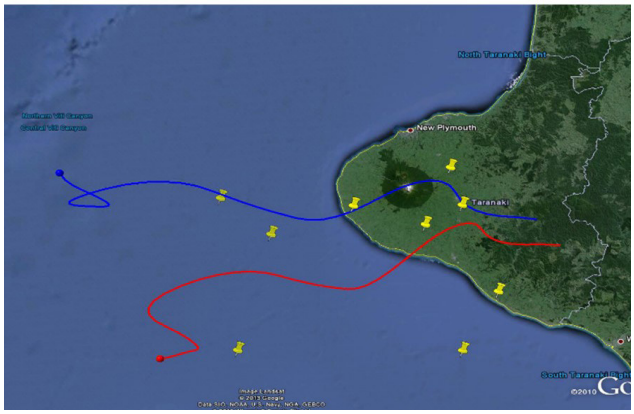

Figure 10: 48-hour air back trajectories from start of CN increase (red) to end of increase (blue). The yellow marks indicate the location of known oil and gas facilities in the area.

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

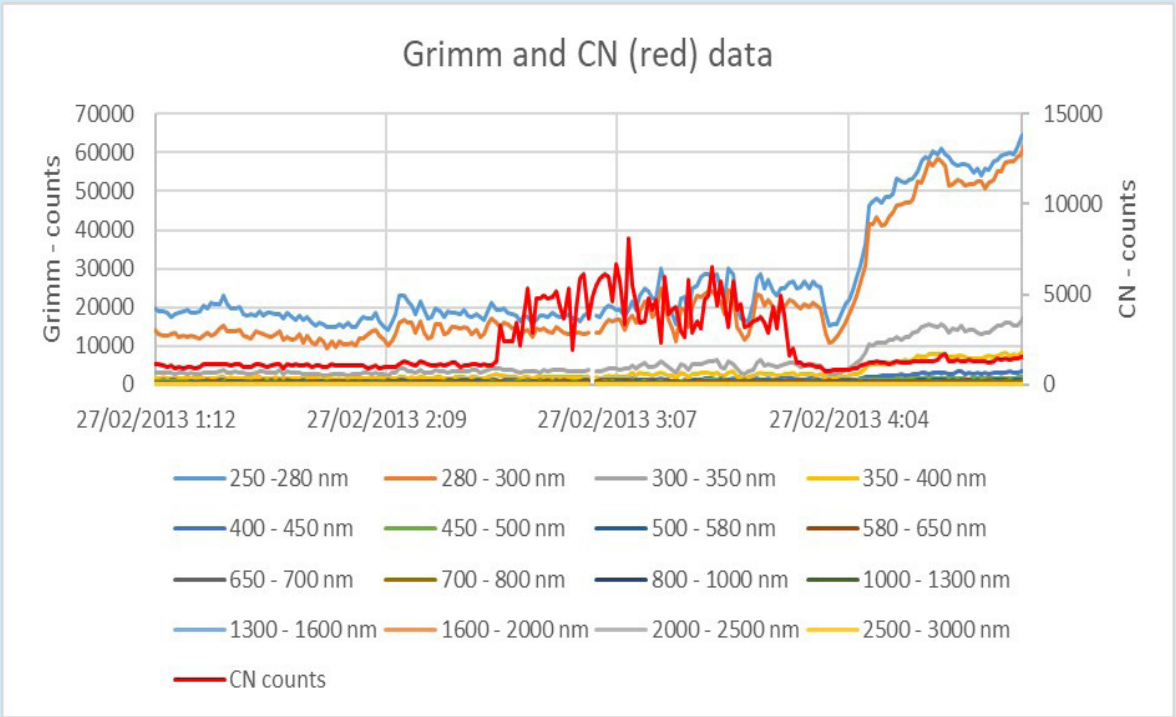

Figure 11: CN and Grimm data collected as ship passed west of South Taranaki Bight.

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.

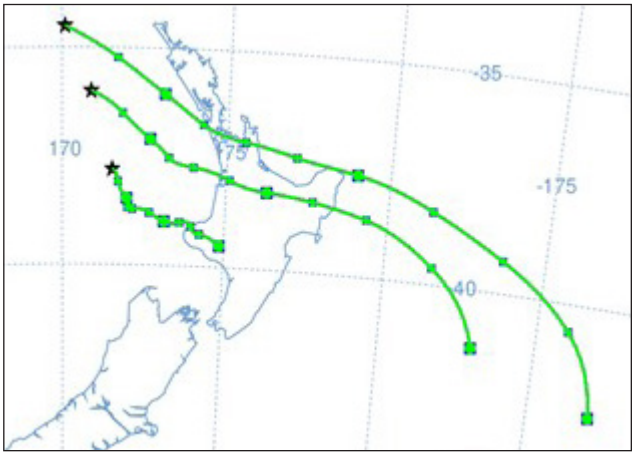

Figure 12: HYSPLIT air trajectories passing over New Plymouth, Hamilton and Auckland 27 February 2013.

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

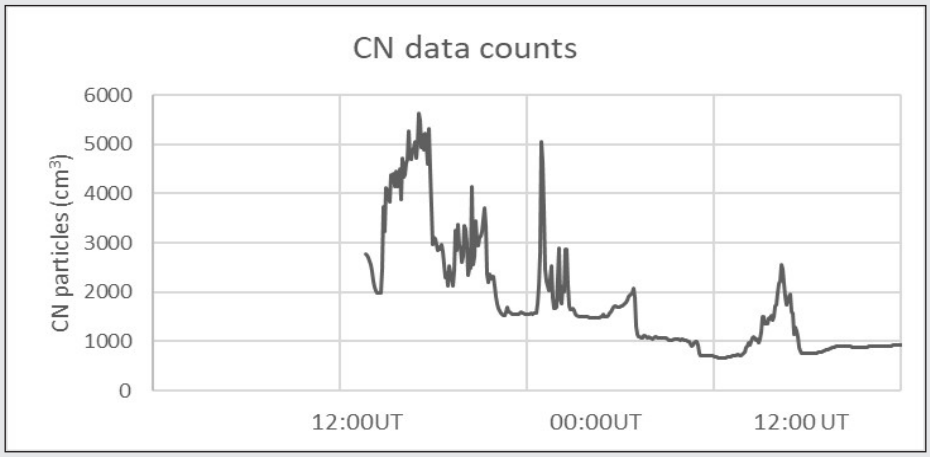

Figure 13: Recorded CN data between 40.4°S and 38.75°S, 26-27 April 2008.

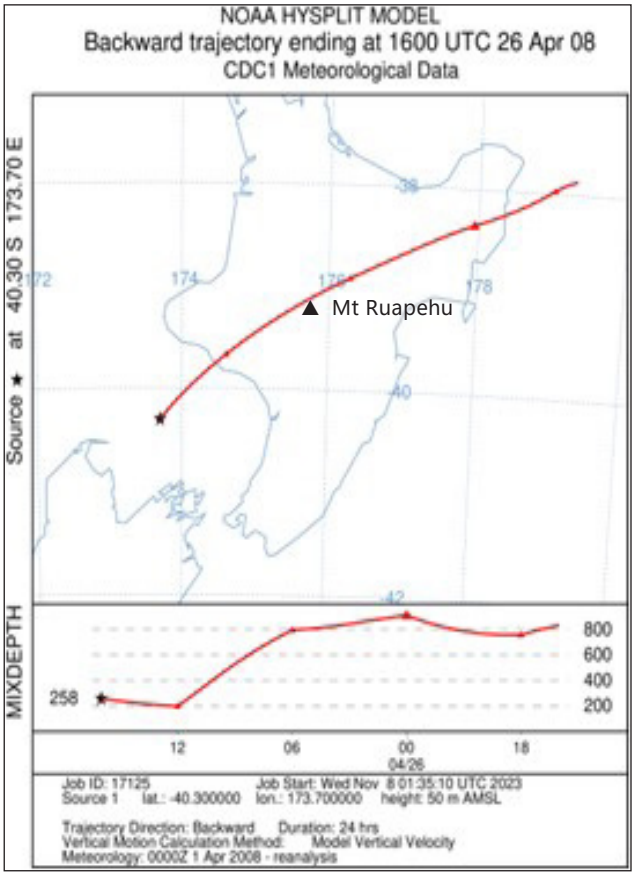

Figure 14: Back trajectory passing over Mt Ruapehu.

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

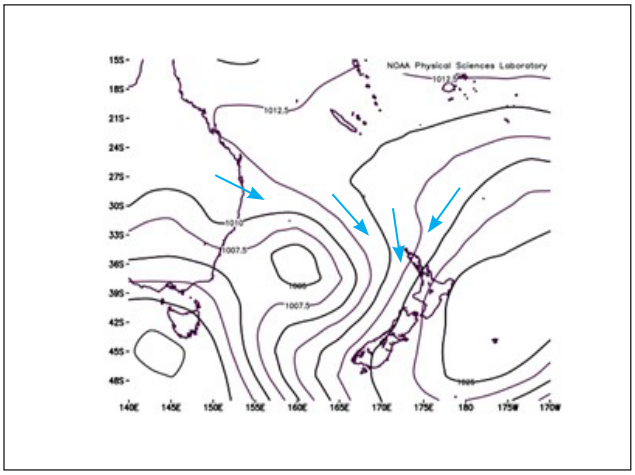

Figure 15: MSL pressure 00 UT 27 April 2008 (NCEP/NCAR reanalysis). Blue arrows indicate general windflow direction.

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.

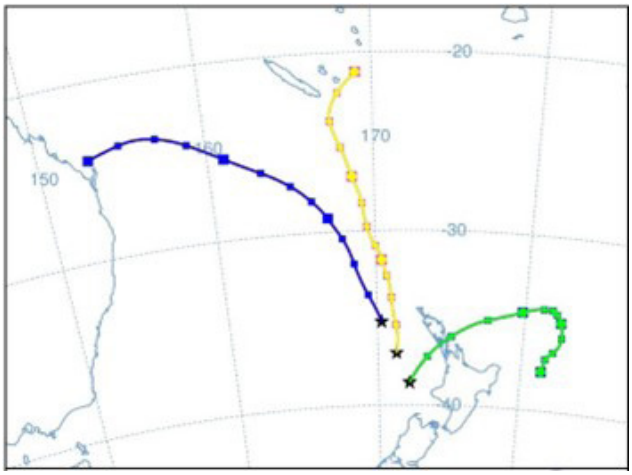

Figure 16: Back trajectories from source positions of areas of increased CN counts April 2008 voyage.

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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