Introduction

$PM_{2.5}$ refers to tiny particles or droplets suspended in air that are two-and-half microns or less in width ("Fine Particles (PM 2.5)", n.d.). $PM_{2.5}$ not only attenuates atmospheric visibility, but also has major health impacts (Wang, Zhang, Shao & Liu, 2006). Particulate matter originates from a variety of different sources, both natural and anthropogenic. Natural sources include dust storms, pollen, forest fires, sea spray and spores (Koçak, Mihalopoulos & Kubilay, 2007). Sources like fossil fuel combustion, industry, heavy machinery and biomass combustion are key anthropogenic sources of $PM_{2.5}$ (Venkataraman et al., 2018). The government of British Columbia classifies particulate matter into two different categories ("Common Air Pollutants - Province of British Columbia", n.d.):

1. Primary:
    a. Emitted directly into the atmosphere by wood and fossil fuel burning;
    b. Includes pollen, spores and road dust
2. Secondary:
    a. Formed in the atmosphere through chemical reactions involving Sulphur dioxide (SO_2), nitrogen dioxide (NO_2), volatile organic compounds (VOCs) and ammonia (NH_3)

The International Agency for Research on Cancer (IARC) and the World Health Organization (WHO) have deemed particulate pollution as a Group 1 carcinogen (Loomis, Huang & Chen, 2014). Epidemiology studies have shown associations with particulate matter and adverse human health as $PM_{2.5}$ has the ability to penetrate deep into the lungs which can irritate the alveolar wall (Xing, Xu, Shi & Lian, 2016) as well as induce asthma, cardiovascular problems, respiratory infections, lung cancer and mortality (Kloog, Ridgway, Koutrakis, Coull & Schwartz, 2013). The WHO air quality guidelines for $PM_{2.5}$ are 10 µg/m^3 annual mean and 25 µg/m^3 for 24-hour mean (Loomis, Huang & Chen, 2014).

Ucluelet Inlet lies on the west coast of Vancouver Island along the western edge of Barkley Sound (Figure 1), 288 kilometers northwest of British Columbia's capital, Victoria. The closest city, Port Alberni, lies 100km east. Ucluelet experiences an oceanic climate with mild winters (~8°C) and cool summers (~20°C) with abundant precipitation in the winter (3,350 mm/yr); only a little of this in the form of snow ("Canadian Climate Normals 1981-2010 Station Data", 2010). Temperature is usually controlled by the proximity to the Pacific Ocean rather than by direct insolation (Valentine, 1971). During autumn and winter, the land is relatively cool, where moist air is subject to greater instability than in summer, hence leading to more precipitation than in spring and summer (Valentine, 1971). The Ucluelet municipality has a population of around 1,717 ("Census Profile, 2016 Census", 2016)) but due to it being a popular tourist destination, in the summers seasonal workers and visitors tend to increase this population number. Historically, the local population was based on fishing and logging. However, like its neighbour Tofino, Ucluelet has made the transition from a resource-based economy to a year-round tourism based economy (District of Ucluelet, 2012) - with the Pacific Rim Visitor centre welcoming close to 90,000 visitors annually (District of Ucluelet, 2012).

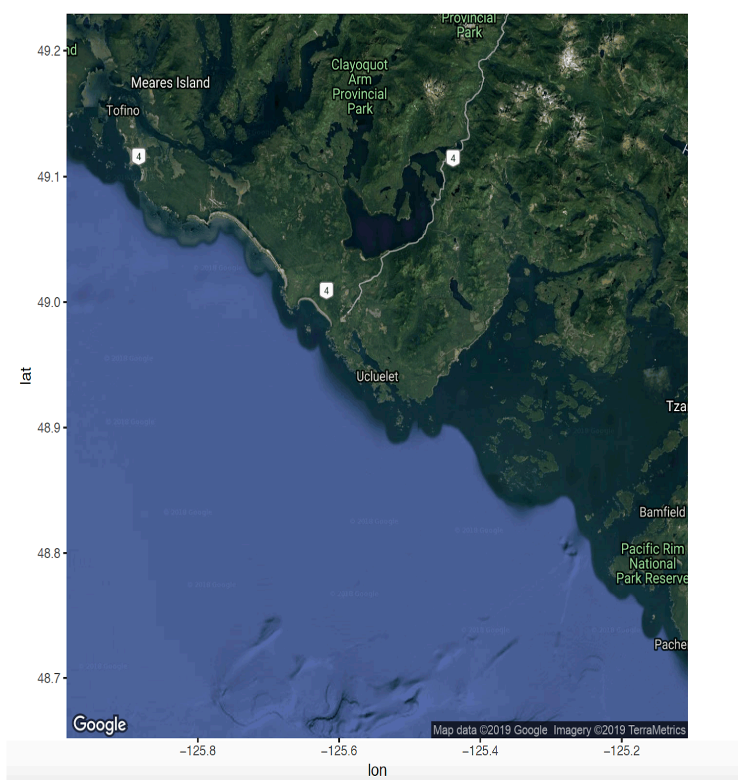

Figure 1: Map of Ucluelet, located on Vancouver Island, British Columbia

Seasonal and Diurnal Variations:

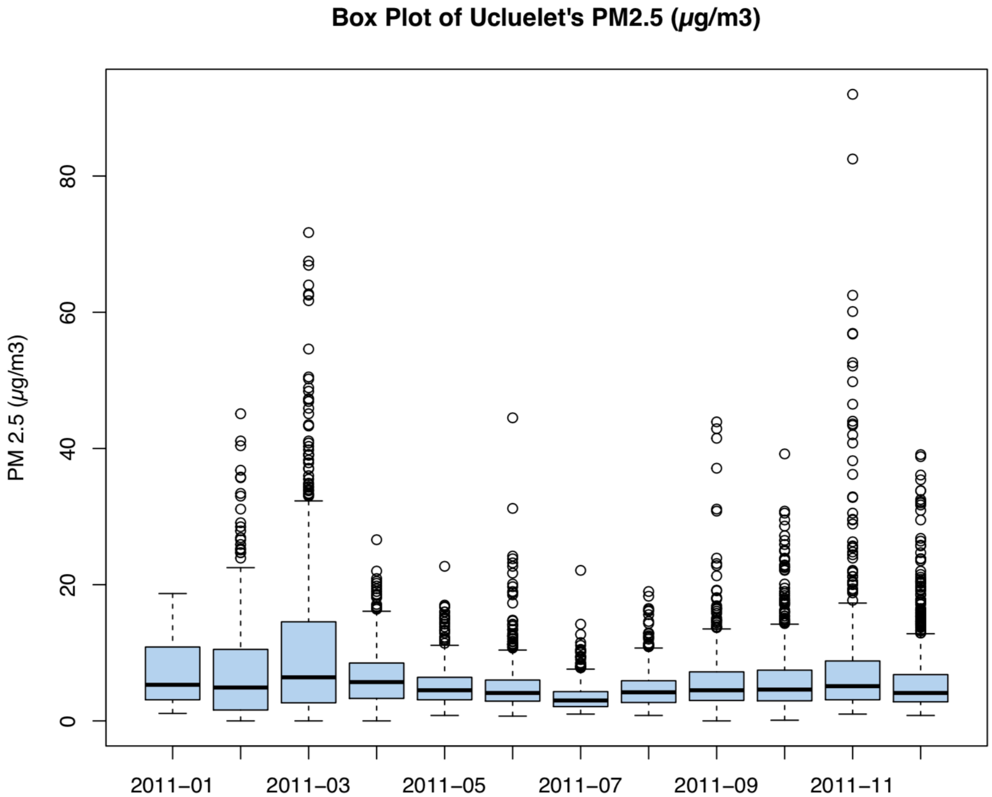

Figure 2: Box plot of PM2.5 data binned by month. Outliers are denoted as circles

Figure 2 is a boxplot which represents a standardized way of displaying concentrations of $PM_{2.5}$ in Ucluelet over the entire year of 2011. The central line represents the median of hourly $PM_{2.5}$ concentrations. Whiskers represent the ranges within 1.5 times the interquartile range, and values falling outside this are considered to be outliers which are denoted by circles. Monthly mean concentrations around 6.19 μg/m^3 and the data is slightly skewed to the right. While the median tends to remain similar month by month, there are quite a few outliers in the data set. March has the highest variability and January has the lowest (data starts on the 29th of January). The data collected shows some patterns of seasonal variations in $PM_{2.5}$ concentrations, with July having the lowest concentrations and November - March showing relatively elevated concentrations.

Figure 3 is a time plot which creates a time series for $PM_{2.5}$ grouped in seasons and figure 4 shows temporal variation of the pollutant concentration in the form of a linear graph to see fluctuations through time in four separate plots that show the diurnal, day of the week and monthly variations for $PM_{2.5}$ concentrations. For the purpose of this study, winter is defined as December, January, February; spring as March, April, May; summer as June, July, August; and autumn as September, October and November (Fig. 3, Fig. 4). The difference in $PM_{2.5}$ concentrations are noticeable through the year. Maximum peak values tend to be higher in the late-winter, early-spring (March) and a decline in concentrations from April to July and increasing again (Fig. 4c). The summer months (Fig. 3) have the lowest average concentration of 4.42 μg/m^3, while autumn has an average of 6.53 μg/m^3, winter average of 6.71 μg/m^3 and an average concentration of 7.49 μg/m^3 for spring. Autumn and spring are the two seasons that have the most peaks in $PM_{2.5}$ concentrations. Looking at figure c. March and November experience the highest peaks in terms of concentration, while July experiences the lowest concentration levels.

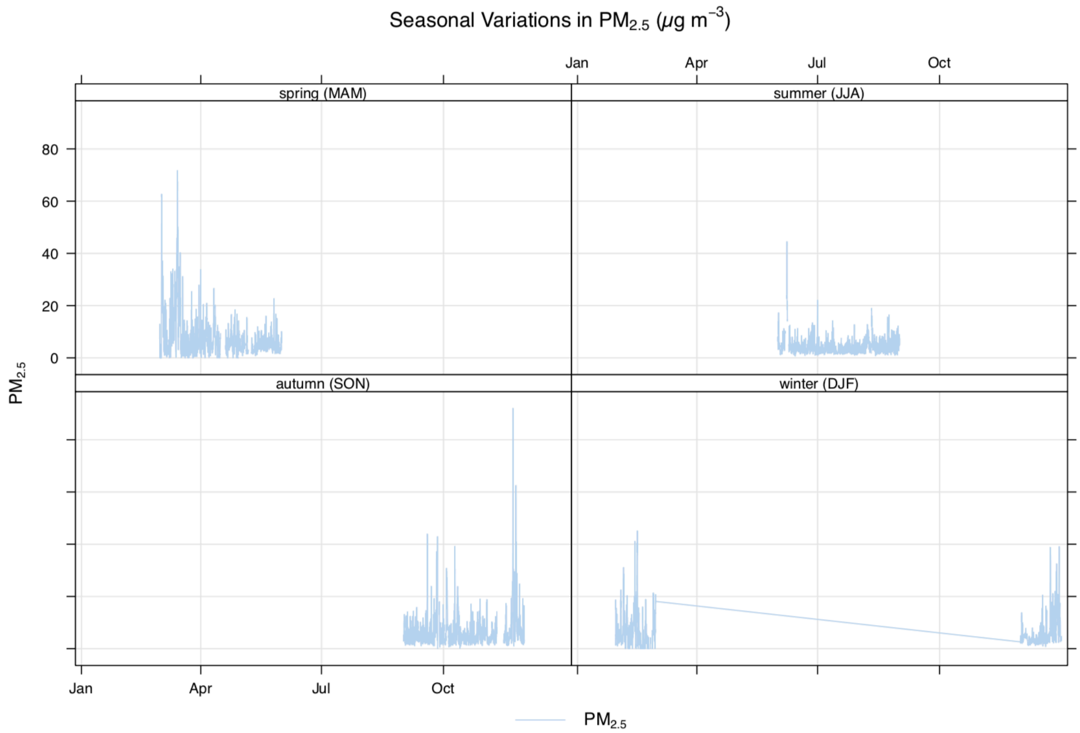

Figure 3: Seasonal variations in PM2.5 for Ucluelet 2011

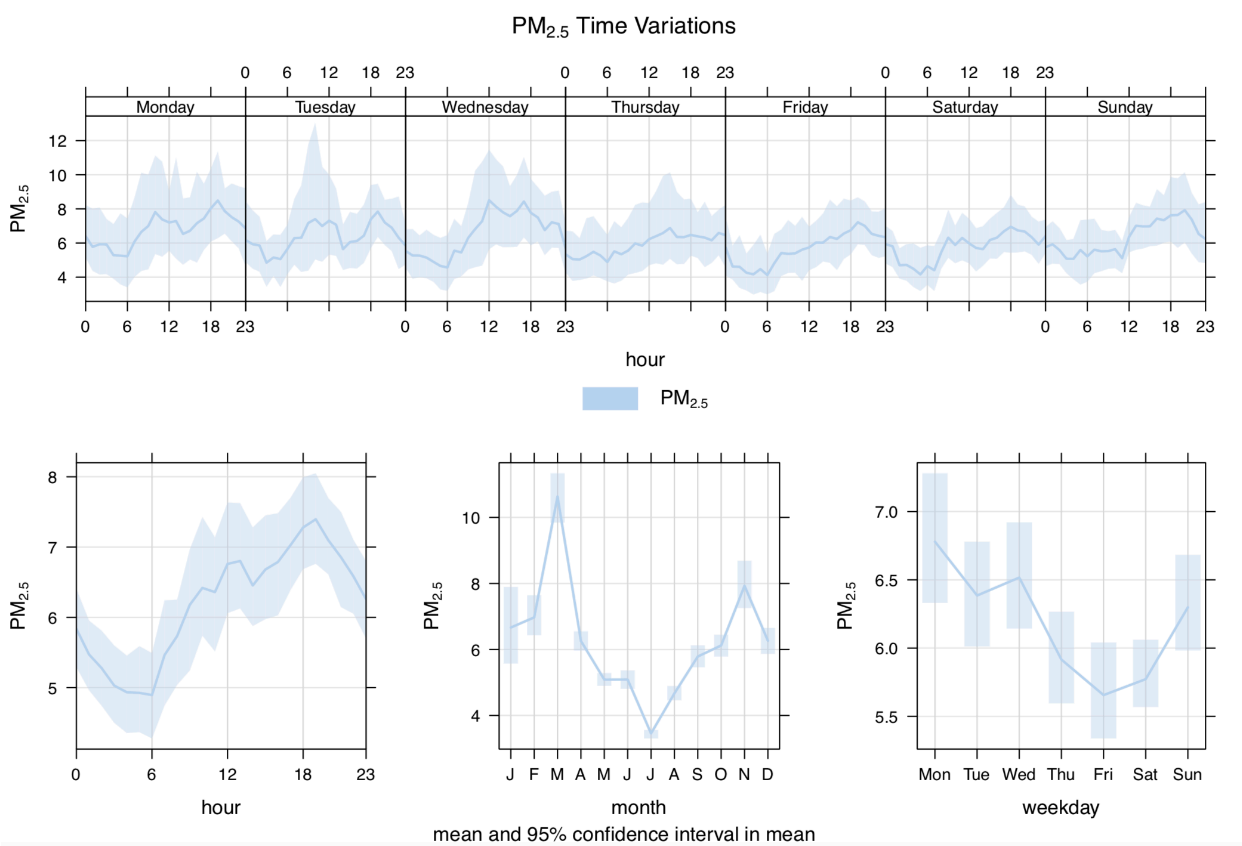

Figure 4: a – Daily variations though the week. b- Hourly variations in PM2.5. c – monthly variations. d- variations in weekday

Diurnal patterns show an increase in concentration though the day and into the night. According to figure 4 b. $PM_{2.5}$ averages are lowest at around 6:00 and gradually increase through the day peaking at around 19:00. Figure 5 is a heat map by hour and weekday, hours 17:00 – 20:00 on Monday see elevated levels of $PM_{2.5}$ and from 12:00 – 19:00 on Wednesdays. Through the night and particularly in the morning concentrations tend to stay relatively low. A stable boundary layer that is present late evening might typically result in higher concentrations. Concentrations start relatively high on Monday and gradually decrease as the week progresses (Fig. 4 a, Fig. 5). While traffic is key source of PM2.5, the lack of peaks during morning rush hour indicates that car emissions are not a key source of pollution for this site. It must also be noted that Ucluelet is relatively remote with a low population density.

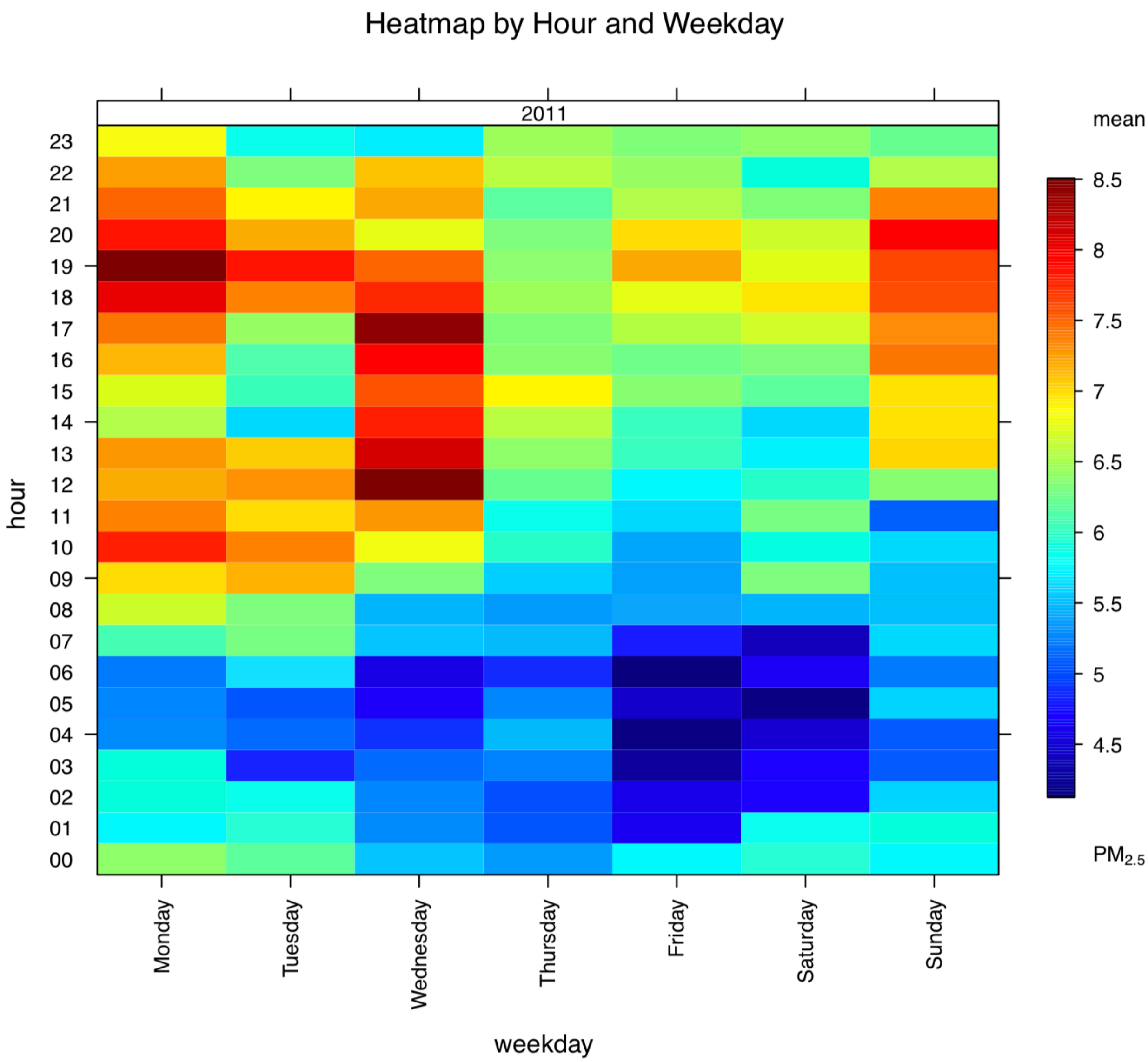

Figure 5: Heatmap of PM2.5 in Ucluelet by hour and weekday

Standards of Exceedances:

The Canadian national ambient air quality standards are prepared under the Canadian Council of Ministers of the Environment (CCME) which allows for air quality assessments by framing a set of standards referred to as the Canada-Wide Standard (CWS). Air quality is assessed by classifying them into three levels: 1) lowest threshold level; 2) middle threshold level; 3) maximum threshold level (maximum tolerable level) (Guidance document on air zone management, 2012). The maximum tolerable level for $PM_{2.5}$ for a 24-hour averaging time is 28μg/m^3 - 98th percentile ambient measurement annually, averaged over three consecutive years, to be achieved by 2015.

Through the year, $PM_{2.5}$ concentrations were mostly below the maximum threshold. According to Figure 6 Ucluelet experienced a few days where $PM_{2.5}$ concentrations exceeded the maximum threshold (denoted by the red data points). Highest value recorded was 92 μg/m^3 on November 22nd at 9:00AM. A 130 out of 7431 air pollution readings exceeded 28 μg/m^3. March saw a cluster of values that exceeded the CWS and October- December had smaller peaks. Lowest frequencies of $PM_{2.5}$ occurred during the summer and autumn months and there is very little variation seasonally and diurnally unlike winter and spring.

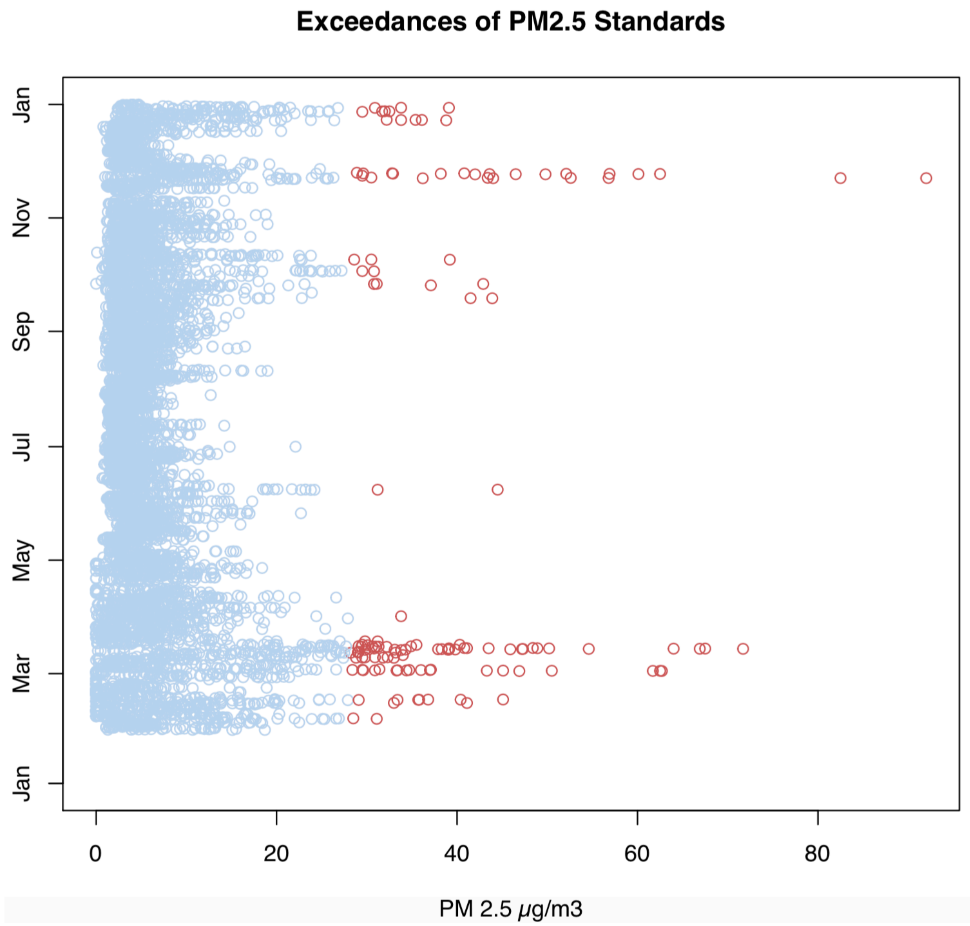

Figure 6: Exceedance Standards of PM2.5 according to CWS

Influence of Meteorology:

General weather forecasts are based on large scale synoptic events as well as forecasts in the mesoscale and microscale. This can have a large effect on Ucluelet due to valley, mountain and ocean effects which may potentially cause stagnation of air in some areas while other regions are able to better disperse pollutants (BC Clean Air Research Fund, 2016). Seasonality could play a role in how much PM2.5 is released into the atmosphere and meteorological conditions could affect how well particulate matter is dispersed (BC Clean Air Research Fund, 2016), for example, in the winter months, wood-burning to warm homes may increase particulate matter or increased vehicular emission in the summer due to an influx of visitors. Venting conditions can also play a role in pollutant dispersal. Days that are anti-cyclonic, calm and clear would experience elevated concentrations compared to cyclonic, windier days.

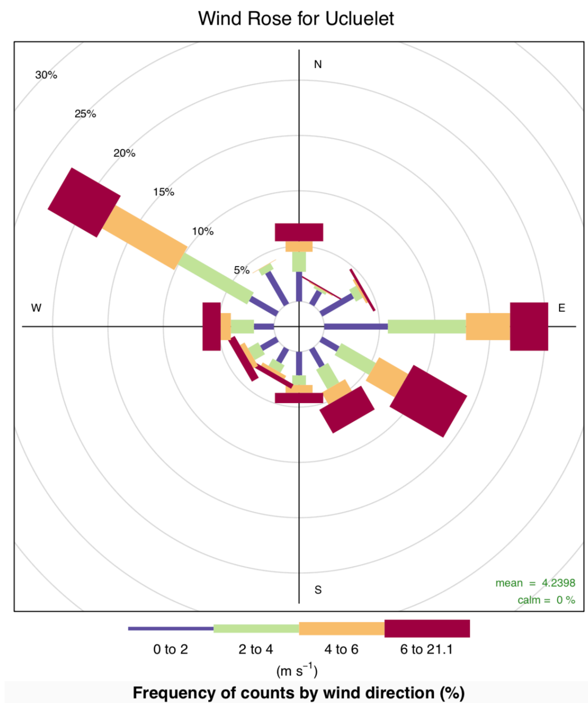

Figure 8: Wind Rose for Ucluelet

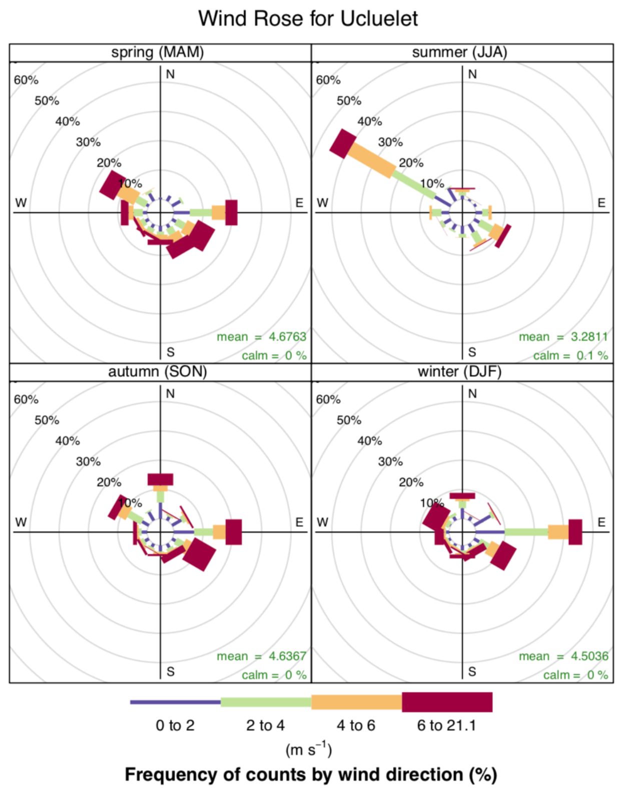

Figure 7: Wind Rose for Ucluelet split by season

To explain the patterns of pollution, wind speed and wind direction can be used to illustrate the effects of meteorology on elevated $PM_{2.5}$ concentrations in Ucluelet. However, due to limited records and missing data within the dataset it is hard to create a sound relationship between the two. Figure 6 is a wind rose chart which plots the frequency of distribution at a location over a specific period of time, in this case the whole of 2011. Presented in a circular format, the wind rose shows the frequency of winds blowing from a

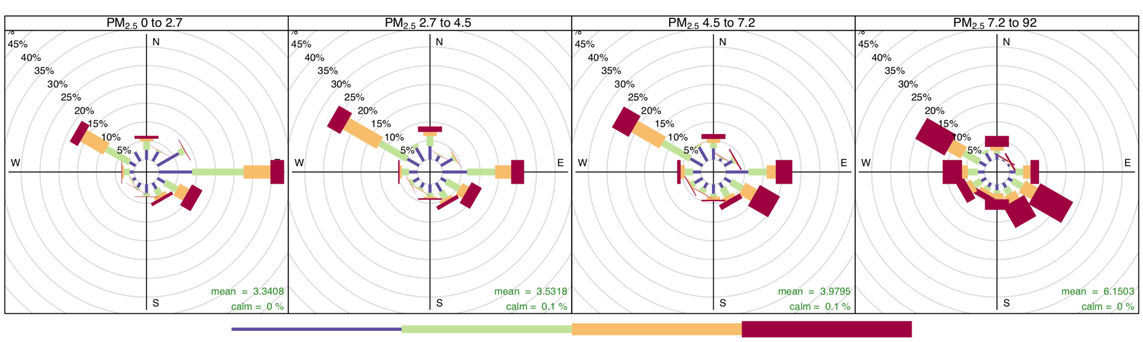

Figure 9: Wind counts by PM2.5 bins

particular direction with each ‘spoke’ highlighting this frequency. Legend at the bottom of the wind rose gives the speed category and the associated colours. Figure 6 shows a majority of the wind blowing from the north-west (23%) and east + south-east (34%) with winds barely blowing from the north-east. A potentially source of pollutants from the north/ north-east could be due to trans-continental pollution coming from Asia.

Figure 7 is the wind rose split by seasons. Summer experienced relatively low speeds with most winds coming in from the north-west. In winter, cool windy air from the east could be responsible for elevated concentrations. Elevated air pollution during the winter months could also potentially come from Port Alberni which lies 200 km east of Ucluelet and is home to multiple wood processing plants which sit by the inlet. Port Alberni is also an inland port (Ucluelet by the mouth of it) which regularly receives large ocean-going cargo vessels. Emissions from these cargo ships can be attributed to increase in PM2.5 in Ucluelet. Higher concentrations of pollution (Fig. 9) have associations with higher wind speeds coming from the south-west quadrant. Looking at wildfire season, according to the British Columbia summary “The 2011 fire season will go down in history as one of the slowest on record. Cool and wet conditions in the spring and early summer months resulted in minimal fire activity” ("Wildfire Season Summary - Province of British Columbia", n.d.) so wildfire as a major source of $PM_{2.5}$ in Ucluelet can be disregarded.

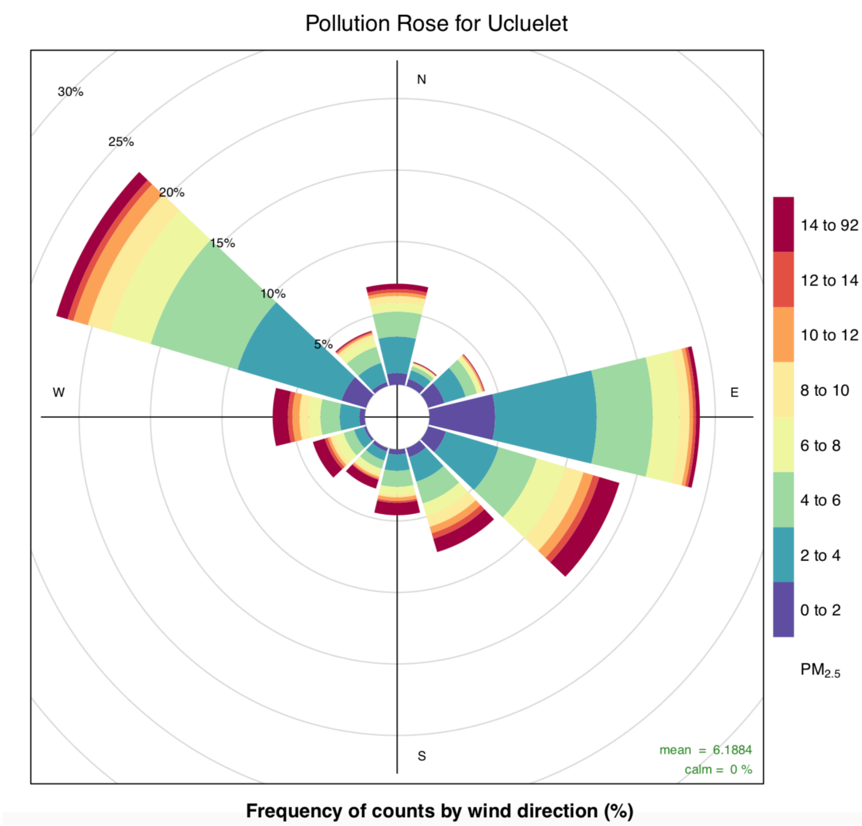

Figure 10: Pollution Rose

The pollution rose (fig. 10) is a wrapper around the wind rose function with the main aim to elucidate the effect of wind direction on the dispersal of $PM_{2.5}$. Radiating ‘spoke’ lengths and colour scheme show the contribution of pollution due to wind from a given direction. Highest pollution is seen in the south-east quadrant (2% 14-92 µg/m^3).

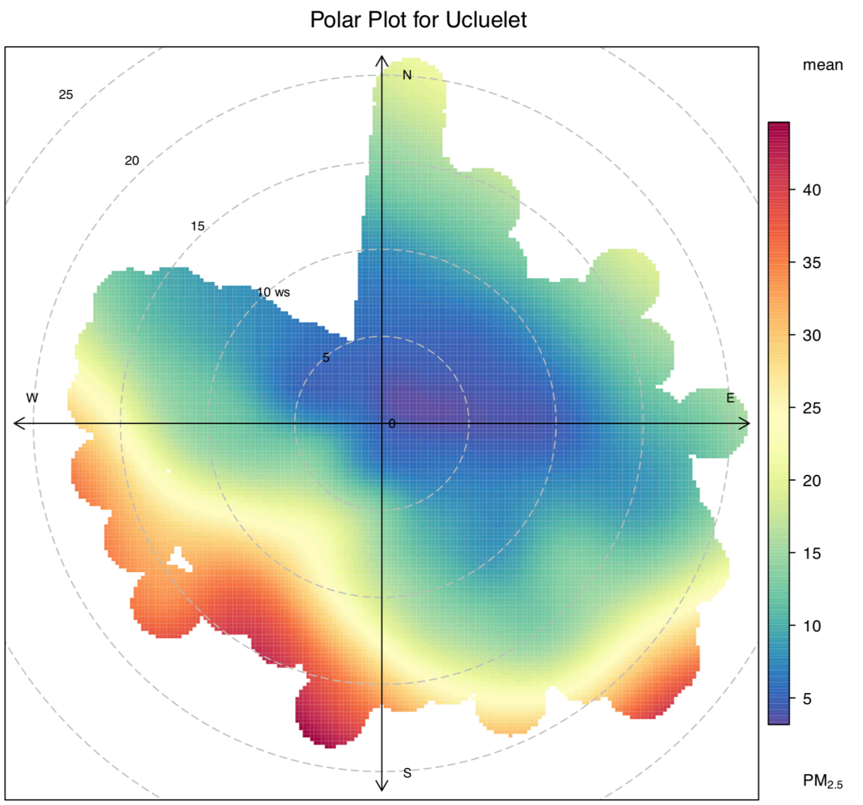

Figure 11: Pollution Intensity Plot

Pollution intensity plots/ polar is a bivariate plot (fig. 11) designed to illuminate the effects of both wind direction and wind speed on the movement of air pollution. This plot highlights a continuous series of tones which reflect the concentration, in this case blue hues indicate lower $PM_{2.5}$ values and vice versa for red. This can be used to help identify the source and spatial distribution of emission dispersion from possible sources. According to figure 11 the south-west quadrant seems to have the highest mean. This highlights that the pollutant is not locally sources as it does not appear at the centre of the plot. Highest concentrations are experienced with south-westerly winds when wind speeds were around 17-19 ms^{-1} and south-easterly winds at around 23 ms^{-1}. However, results would be substantially improved if data came from several air quality monitoring stations.

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