Modelling emission trends from non-constant time series of PM_{10} concentrations in Christchurch, New Zealand

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Abstract: This paper presents an attempt to model the trend of emissions through analysis of a time series of PM_{10} concentrations in Christchurch, New Zealand. Emissions are not constant over time, but show high seasonality. Fluctuations are removed by creating a time series in which concentrations do not show dependency on ambient air temperature. Remaining meteorological influences are removed through multiple linear regression. Finally, a moving average filter is applied to reveal the low-frequency trend in the residuals of the meteorologically adjusted time series. The modelled trend shows a peak in emissions in 2001–2002 with a steady decrease thereafter.

Keywords: particulate matter; PM_{10}; air pollution meteorology; multiple linear regression; New Zealand; air quality; time series analysis; emissions; home heating.

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Biographical notes: Tim Appelhans graduated with a Diploma in Geography from the Friedrich-Alexander-University Erlangen-Nuernberg in 2005. Since 2006, he has undertaken his PhD in the Department of Geography at the University of Canterbury in Christchurch, New Zealand. The project aims at establishing quantitative and qualitative links between synoptic, regional and local atmospheric processes and air quality in the region of Canterbury, New Zealand. In 2006, he was awarded 'best student presentation' at the annual conference of the New Zealand Meteorological Society. His research interests include general climatology, air pollution climatology/meteorology and mountain geography.

Andrew Sturman holds a personal chair in Geography at the University of Canterbury. He was founding Director of the Centre for Atmospheric Research, and is Author of the *Weather and Climate of Australia and New Zealand* (Sturman and Tapper, 2006) and Editor of *The Physical Environment – A New Zealand Perspective* (Sturman and Spronken-Smith, 2001). He was awarded the inaugural Edward Kidson Medal for research in meteorology and climatology in 2003. He leads research programmes in applied meteorology and climatology (air pollution, wind energy and agriculture), and has taught atmospheric science at the University of Canterbury for many years.

Peyman Zawar-Reza is a Senior Lecturer at the Department of Geography, University of Canterbury. His research interests are in the application of mesoscale modelling to environmental problems such as air pollution dispersion and local winds in mountainous terrain. For his PhD, he focused on the effect of an inner mountain lake in modification of valley flows. As a postdoctoral fellow, he used models such as The Air Pollution Model (TAPM) to study mesoscale circulations prevalent during stagnant synoptic conditions when there is a high potential for air quality to be poor.

1 Introduction

Elevated concentrations of particulate matter less than 10 microns in diameter (PM_{10}) have long been a problem in Christchurch, New Zealand and exceedances of National Environmental Standards (NES) occur regularly. The NES for allowable PM_{10} concentrations is specified at 50 $\mu g\ m^{-3}$ for a 24-hour average between midnight and midnight, with one allowable exceedance per year. In 2013, the NES will be fully implemented and will be a binding national requirement for local and regional authorities, imposing rigorous consequences if violated. Over recent years, Christchurch has experienced an average of around 30–35 days when the NES threshold was exceeded (Aberkane et al., 2005; Zawar-Reza et al., 2005). Therefore, the local environmental authority 'Environment Canterbury' (Ecan) is concerned whether air quality targets set by the NES are likely to be reached in the early part of the coming decade. They are particularly interested to know if their air quality management strategy has been effective in reducing air pollution emissions.

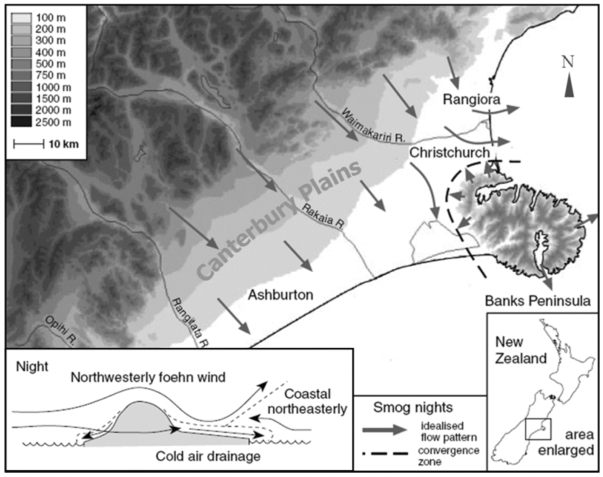
An estimated 80% or more of PM_{10} emissions in Christchurch originate from home heating devices, especially solid fuel burners (Scott and Gunatilaka, 2004). As a result of this, emissions and therewith elevated PM_{10} concentrations are predominantly of concern during winter months (May–August) and within this period are mostly restricted to evening hours. During warmer seasons, anthropogenic contribution to the release of particulates into the atmosphere is restricted to traffic and industrial sources that have little impact on ambient air quality, reflecting New Zealand's low population density (Scott and Gunatilaka, 2004).

Therefore, emissions cannot be considered constant over time. In fact, seasonal variations are such that exceedances almost exclusively occur between May and August. Additionally, even throughout the winter season, variation from day to day is extremely high. The main factor controlling the amount of particulates released into the atmosphere from anthropogenic sources is people's response to changes in ambient air temperature. Poorly insulated old dwellings are widespread, and along with socio-cultural behaviour

patterns shape a preference for traditional home heating practices such as solid fuel burning. A detailed description of socio-cultural factors surrounding traditional home heating practices in Christchurch has been given by Cupples et al. (2007).

Because of Christchurch's maritime climate, temperatures are fairly mild, and even in winter temperatures just below 0°C are mainly restricted to the early morning hours. New Zealand's remote and oceanic location also means that synoptic conditions that control large-scale airflow in the region play a major role in shaping local and regional meteorology. Ambient air temperature in particular is very sensitive to synoptic flow directions and can change dramatically from day to day (even hour to hour). Because of Christchurch's location on the east coast of the South Island (Figure 1), additional regional and local modification of synoptic conditions, such as foehn effects (regionally referred to as the 'Nor'wester' – implying the synoptic flow direction), can exacerbate transitions between atmospheric situations so that the magnitude of differences in temperature from day to day is enhanced. During winter, synoptic weather conditions frequently allow processes within the Atmospheric Boundary Layer (ABL) to promote strong atmospheric stability that coincides temporally with the peak time of daily emission production (Kossmann and Sturman, 2004; Corsmeier et al., 2006). Stable nocturnal conditions within the lower 20–50 m of the ABL are usually associated with descending air motion caused by anticyclonic high pressure systems in the close vicinity of New Zealand. Locally, this large-scale descending motion leads to clear and calm night-time skies and the formation of a surface inversion, which in turn is related to a highly negative surface energy balance and thus, low temperatures (Zawar-Reza and Spronken-Smith, 2005; Oke, 1987).

Figure 1 Overview of study area and schematic representation of idealised low-level airflow in the region during winter smog nights



Source: Kossman and Sturman (2004, modified)

Viewing this from the standpoint of home heating behaviour, it becomes evident that emissions are highly variable on both a seasonal and a daily time scale. This has several implications for any legislative action, as well as any attempt to assess its effectiveness. The problem of high temporal variation at different scales shaped by a high dependency on temperature conditions needs to be accounted for when defining control strategies.

Furthermore, any analysis that tries to identify the effectiveness of control measures is faced with the necessity to successfully account for the effects that meteorological conditions have on PM_{10} concentrations in Christchurch.

Concentrations of ambient air pollutants are generally a result of two factors, the emissions and the dilution/dispersion potential of the atmosphere that these emissions are released into. This paper presents a study that was undertaken to facilitate the identification of emission trends derived from measured PM_{10} concentrations. Following the methodology presented by Wise and Comrie (2005), multiple linear regression analysis is used to identify and remove blurring meteorological influences on PM_{10} concentrations. This approach, however, assumes that emissions are approximately constant over time and that resulting concentrations are being modified mostly by weather conditions. As outlined earlier, PM_{10} emissions in Christchurch cannot be considered constant owing to the influence of temperature. Therefore, this dependency was removed prior to the regression. Finally, a running mean filter is applied to extract the low-frequency trend. This filter is based on the Kolmogorov-Zurbenko filter (KZ filter), which was first introduced to applications in ambient air quality investigations by Rao and Zurbenko (1994) to effectively separate different frequencies within a time series. Numerous studies have subsequently confirmed its usefulness in achieving various objectives within air quality research (e.g., Hogrefe et al., 2003; Ibarra-Berastegi et al., 2001; Porter et al., 2001; Yang and Miller, 2002; Anh et al., 1997; Eskridge et al., 1997).

2 Statistical analysis

2.1 Preparation of the time series

A time series of hourly averaged PM_{10} concentrations from the main air-quality monitoring site located at Coles Place, St. Albans, was analysed to evaluate meteorological influences over the period 1999–2006 (inclusive). As instrumentation changed from a Tapered Element Oscillating Microbalance sampler with the inlet temperature set at 40°C (TEOM) to a Filter Dynamics Measurement System (FDMS) set at 30°C in 2004, a TEOM-FDMS equivalent data set was created by Ecan to ensure a continuous record with the highest possible comparability between the two measurement techniques. Ecan adjusted the recordings obtained from the two instruments using simple linear regression, as part of their quality control process. Although this procedure was undertaken prior to the data being provided to the authors, it is important to be aware that some pre-processing has taken place. For an in-depth description of the calibration technique refer to Scarrott et al. (2008). The time series of PM_{10} concentrations provided by Ecan is shown in Figure 5 (upper panel) along with two other series, which resulted from the statistical analysis outlined in Sections 2.2 and 2.3.

PM_{10} concentrations were averaged on a daily basis for the hours between 5 pm and 12 am. Focus was given to evenings rather than daily averages for two reasons. First, daily averages are problematic when assessing atmospheric stability as positive lapse rates during the day and negative lapse rates during the night tend to cancel each other out so that meteorological influences become obscured. Second, it was found to be the main peak time for concentrations (Figure 2). Wind speed, 1 m air temperature and the vertical temperature difference between 1 m and 10 m, all obtained from the same site

as the PM_{10} concentrations, were chosen to be representative of meteorological conditions. A comparison between observations from Ecan's air quality site and the automated weather station at Christchurch airport are given in Figure 3. Temperature recordings from both sites are very similar. There is little scatter and most observation pairs lie very close to the line of equality ($y = x$) represented by the dashed line. The relationship between wind speed readings of the two sites exhibits higher scatter and shows that wind speeds are generally lower at Coles Place than at the airport. The increased scatter that is observed for wind speeds can be explained by the generally more variable nature of wind recordings. The higher wind speeds observed at the airport are testament to the fact that this site is situated outside of the city limits and is therefore much more exposed than the inner urban air-quality monitoring site. Wind speed and temperature difference represent the intensity of horizontal and vertical mixing within the ABL, respectively. These meteorological variables were averaged over the 5 pm–12 am time period.

Figure 2 Average diurnal cycle of PM_{10} concentrations at Coles Place, St Albans between 1999 and 2006

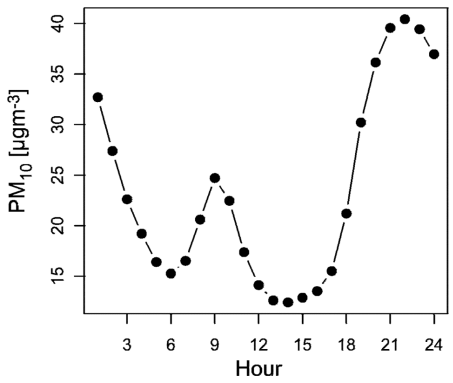
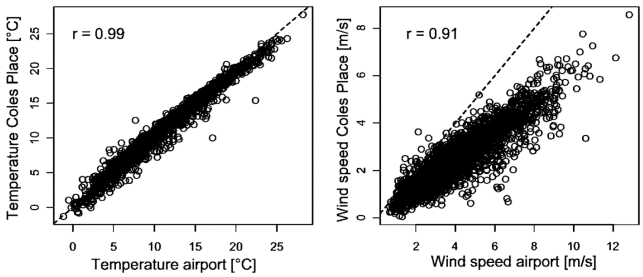


Figure 3 Comparison between observations recorded at Coles Place and Christchurch airport for temperature (left panel) and wind speed (right panel). Correlation coefficients are shown



2.2 Approximation of constant emissions

The identified diurnal maximum of PM_{10} concentrations in the evening hours reflects the above-mentioned fact that by far the largest contribution to PM_{10} concentrations measured in Christchurch originates from home heating devices such as solid fuel burners. This makes emissions very variable, as they are highly dependent on temperature

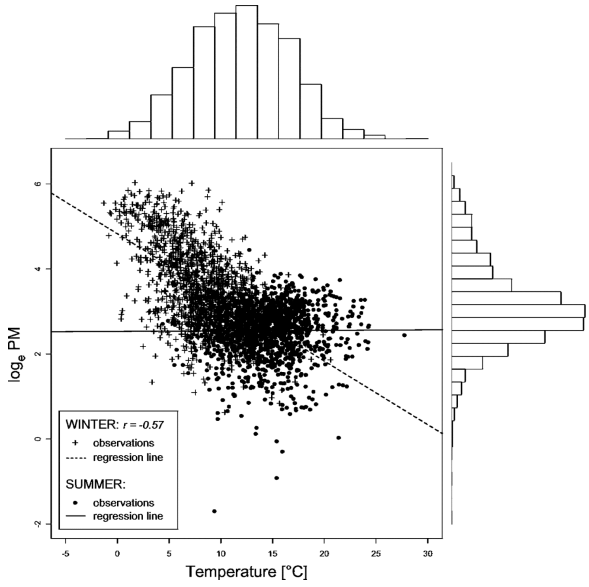
behaviour and can therefore not be considered as constant over time (in comparison with emissions from traffic, which show only little variation over the course of a year). In other words, air temperature is a key cause of PM_{10} emissions in Christchurch owing to its effect on human heating behaviour, whereas wind speed and vertical temperature gradient influence concentrations via their effect on ventilation.

In line with Ott (1990), the distribution of PM_{10} concentrations was found to be log normal and, therefore, values were transformed using the natural logarithm ($\log_e$), achieving a near-normal dataset (see Figure 4 – right panel histogram). Subsequently, the series was split into a winter and a summer season (April–September and October–March, respectively). Figure 4 shows the relationship between the logarithmically transformed PM_{10} observations ($\log_e$ PM) and temperature for both the summer (represented by dots) and the winter (+) seasons. Clearly, no correlation between temperature and PM_{10} concentrations can be found during summer, whereas in winter a clear inverse dependency is observable. Therefore, wintertime observations were regressed against temperature and the calculated linear dependency was removed using the following formula, retaining the maximum variation by recalculating the observed residuals to represent deviations from a zero trend line (in this case the average of the means of PM_{10} concentrations in each season):

$$\text{corr}.\log_e \text{PM} = \cos(\arctan b) * (\log_e \text{PM} - (a + b * \text{TEMP})) + \text{avg}.\log_e \text{PM}.$$

With corr. $\log_e$ PM = natural logarithm of temperature-corrected PM_{10} concentrations, $\log_e$ PM = natural logarithm of original PM_{10} concentrations, TEMP = 1 m air temperature, avg. $\log_e$ PM = mean natural logarithm of original PM_{10} concentrations for each season, a = intercept of the calculated regression and b = slope of the calculated regression.

Figure 4 Correlation between $\log_e$ PM and temperature of the original time series for winter (crosses) and summer (dots). Histograms of the full record for temperature (top) and $\log_e$ PM (right) provide evidence for approximate normality of the data



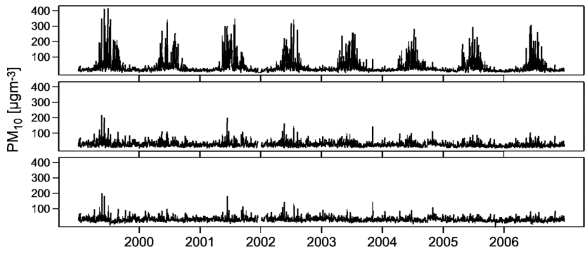
Summertime observations were scaled so that these recordings too are scattered around the overall mean rather than their seasonal average. The data sets were subsequently rejoined into one continuous time series, and this temperature-corrected data set was then taken as the input time series for the multiple linear regression analysis to identify and subsequently remove remaining meteorological influences on PM_{10} concentrations in Christchurch.

2.3 Removal of meteorological influences

To remove the meteorological influences controlling horizontal and vertical mixing, multiple linear regression analysis was performed. The corrected logarithmic PM_{10} concentrations were selected as the dependent variable and regressed against the independent variables of wind speed (which was transformed using the square root to approximate a normal distribution; not shown) and temperature difference. No further significant relationships between atmospheric variables (including wind direction and relative humidity) and PM_{10} concentrations were found. The multiple regression was able to explain 20% of the remaining variance within the PM_{10} concentrations ($r^2 = 0.2$). To avoid mathematical problems associated with non-negativity of antilogarithms, it was decided to obtain residuals after antilogarithms of observed and predicted values were calculated to investigate the variation in concentrations that remained unexplained by the selected meteorological influences. The residuals reveal variations within PM_{10} concentrations owing to factors other than meteorology and thus represent a better approximation of the behaviour of emissions (Wise and Comrie, 2005).

To make residuals comparable with concentrations, they were added to the overall mean of the original (but temperature corrected) measurements. This step is necessary as residuals, by definition, only represent deviations from a calculated series of values – in this case the calculated series of optimal predictions of PM_{10} concentrations based on variations in wind speed and temperature difference – and therefore fluctuate around a zero line (i.e., their sum equals zero). This new data set can now be understood as adjusted PM_{10} concentrations, where meteorological influences, namely 1 m air temperature, wind speed and presence and strength of a temperature inversion, have been removed. Figure 5 shows both the temperature corrected (central panel) and the meteorologically adjusted time series (lower panel).

Figure 5 Time series plots of original concentrations (upper panel), temperature-corrected observations (central panel) and meteorologically adjusted observations (lower panel)



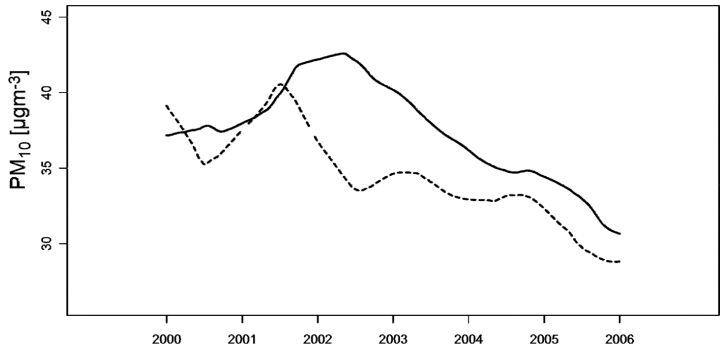
A simple moving average filter (based on the KZ filter described in Rao and Zurbenko (1994)) was applied to both the original and the adjusted PM_{10} data set. A window size of 365 days (evenings) was chosen to average out seasonal fluctuations and two repeated

iterations were run to facilitate interpretation of the trend. As the KZ filter utilises a central moving average, each iteration truncates half the size of the chosen window length from each end of the time series, so that the first filter run effectively cuts one year off the time series and the second run two years (Wise and Comrie, 2005). A comparison of the resulting trends is shown in Figure 6. Only the trends obtained after the second iteration are shown. These lines are highly smoothed (removing fluctuations smaller than 1.4 years) to aid interpretation of the long-term behaviour of PM_{10} concentrations. Rao and Zurbenko (1994) proposed the application of a third iteration to extract the low-frequency trend. However, owing to the short monitoring period and the outlined cut-off effect with each iteration, it was chosen to apply only two iterations to preserve a time span that allows a more solid interpretation of the extracted trend.

3 Results

The original trend for the evening hours (dashed line in Figure 6) follows the trend observed in daily averages (for comparison refer to Aberkane et al. (2005)), reflecting general winter conditions, which are primarily influenced by variations in mean temperatures throughout the winter months. This becomes particularly evident when comparing average concentrations for 2000 and 2001, reflecting, respectively, mild and cold winter conditions. The adjusted trend (solid line in Figure 6) shows an increase in PM_{10} emissions with a peak in 2001–2002. Afterwards, emissions appear to decrease steadily.

Figure 6 Trend comparison between original PM_{10} concentrations (dashed line) and meteorologically adjusted PM_{10} concentrations (solid line)



4 Discussion and conclusions

This research has shown how relatively simple analytical techniques can be used to try and separate the meteorological signal from an air pollution concentration time series, so that trends in emissions can be identified. The results suggest that the trend of PM_{10} emissions in Christchurch peaks in 2001–2002 and shows a gradual decrease since then. This is somewhat contradictory to Ecan's emissions inventories, which suggest a peak in emissions in 1999 and a steady decrease thereafter (Scott and Gunatilaka, 2004). However, emission inventories are only carried out every three years, which makes

comparisons difficult. Furthermore, as described earlier, the statistical approach used by Wise and Comrie (2005) assumes constant emissions, which are subsequently modified by meteorological conditions. This approach has been modified here to allow it to be applied to situations where emissions are not constant. The creation of a time series that is independent of temperature behaviour (which can be interpreted as a rough proxy for seasonality) allows the assumption that emissions are approximately constant over time. In addition, the utilisation of a running mean filter with a window that is larger than seasonal fluctuations further reduces the impact of seasonality of emissions. However, it is a matter of fact that the use of home heating devices is limited to the cold half of the year in Christchurch and, therefore, emissions will always be subject to seasonal variation. A quantification of the expected bias of these results seems impossible at this stage. However, further research, both towards refining the analysis as well as additional in-depth examination of the problem in Christchurch, plus investigation of other areas with similar pollution behaviour, might provide means to enhance the accuracy of the statistical analysis.

This study has presented preliminary results from a wider research programme that aims to establish clear qualitative and quantitative links between meteorology and ambient air quality at various spatial and temporal scales in PM_{10} polluted environments in New Zealand. It is anticipated that other approaches used in further stages of the research programme will help to put the present findings into perspective and provide further confidence in the trends identified here and deliver a clearer picture of emissions behaviour in cities like Christchurch over longer time scales.

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