

Effects of meteorological conditions on concentrations of nitrogen oxides in Auckland

N. Jiang^{1,*}, J. E. Hay¹ G. W. Fisher²

¹ *School of Environmental and Marine Sciences, University of Auckland, Auckland, New Zealand.*

² *National Institute of Water and Atmospheric Research, Auckland, New Zealand.*

Abstract

Air quality in Auckland is generally within the national guidelines. But at times, especially in winter, the city suffers from air pollution phenomena such as a brown haze, which is thought associated with high levels of nitrogen oxides. The effects of meteorological conditions on local air quality are quantitatively assessed on a daily basis by determining the relationship between concentrations of nitrogen oxides (NO and NO₂) and several meteorological variables for winter months, from 1990 to 1996. Strong southwesterly winds, the prevalent flow pattern over the region, are associated with good air quality due to enhanced dispersion. Calm, cold conditions lead to the build-up of pollution. Meteorological conditions can explain more variances in NO levels (up to 65%) than in NO₂ levels (up to 26%). For different emission source conditions, the effects of meteorological conditions are consistent for NO levels, but are significantly different for NO₂ levels, suggesting other factors may be important.

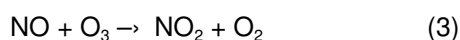
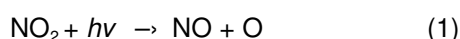
1. Introduction

Auckland is New Zealand's largest city, with about one-third of the country's population. The metropolitan area is situated on a narrow isthmus (Fig. 1), characterized by high population densities, several large industrial areas and high traffic volumes. Air contaminants emitted from the urban area can impact the entire regional airshed (ARC, 1997). Auckland's maritime environment, with its isthmus geography, typically ensures relatively high mean wind speeds. The prevailing winds are westerly and southwesterly, but northeasterly flows are also important (Hessell, 1988). Air quality in this region is generally within the national guidelines. However, recently concern has been raised over a brown haze phenomenon, which degrades local atmospheric visibility. The brown haze can be seen on most light wind days, especially in winter months, and is thought to result from emissions of nitrogen oxides (NO and NO₂) and

* *Corresponding author: Dr N. Jiang, Educational Measurement, NSW Department of Education and Training, Locked Bag 555, Delivery Centre Milperra 1891, Australia. Email: ningbo.jiang@det.nsw.edu.au*

reactions between these pollutants and other air contaminants such as volatile organic compounds (MFE, 1998).

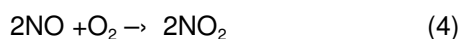
In relation to NO and NO₂, the three rapid reactions of greatest importance are the following (which form the photostationary equilibrium):



Vehicle-emitted nitrogen oxides are mainly in the form of NO. It is ozone which is predominantly responsible for the conversion of NO into NO₂ [primarily through reaction (3)]. The implication of this reaction is that the concentration of nitrogen dioxide can not exceed the concentration of ozone available to carry out the oxidation. This process is generally fast (at a time scale of seconds) and local, and is of great importance in highly polluted areas (Bronnimann and Neu, 1997).

Additional chemistry based on peroxy radicals formed from reactions of hydrocarbons is important in converting NO to NO₂ without consuming ozone, leading to the build-up of enhanced concentrations of ozone. This is a slow and regional process, and strongly influences rural areas. When such ozone-polluted air is advected into urban areas, it encounters freshly emitted NO from vehicle exhausts and thus leading to elevated NO₂ concentrations through reaction (3). This mechanism accounts for some of the summer episodes, often on hot, sunny days.

A second order reaction is suggested for high nitrogen oxides conditions,



This reaction plays no role until NO exceeds certain levels. According to Harrison (1997), however, a detailed analysis in the United Kingdom indicates that, even accounting for the contribution of reaction (4), the above chemistry can not account for the rate of production of nitrogen dioxide in severe pollution episodes.

Variations in concentrations of nitrogen oxides may be partly due to influences of emissions and chemical transformations (e.g., reactions between NO, NO₂ and O₃), but the role of meteorological conditions must also be investigated. Studies undertaken elsewhere (e.g., Uno et al., 1996; McGregor and Bamzeli, 1995; Greene et al., 1999) have indicated that both physical and dynamic properties of the atmosphere play important roles in determining the levels of air contaminants. In Auckland, and New

Zealand generally, such investigations are still very few in number and limited in scope. This makes it difficult to assess the potential adverse effects of air discharges, and consequently limits the development of effective air quality management strategies due to the high degree of scientific uncertainties (MFE, 1998).

Consequently, this study has been initiated in order to assess the role of weather and climatic conditions in determining the levels of nitrogen oxides in Auckland. This paper characterizes the relationships between NO and NO₂ concentrations, and local meteorological conditions. A multivariate analysis was conducted on a daily basis, and focused on weekdays from May to September, when the highest air pollutant concentrations are observed (ARC, 1997). Air quality management implications of the findings are also discussed.

2. Data and Methodology

2.1 Data

Air quality data used are concentrations of NO₂ and NO measured at two long-term monitoring sites, Penrose and Mt Eden, located in central Auckland with a separation of approximately eight kilometers (Fig. 1 and Table 1). The choice of these locations was based on the following considerations: 1) the available records for the two sites are relatively long (>5 years); 2) from 1991, the two sites formed part of the United Nations Global Environmental Monitoring System (GEMS); and 3) the use of data for two locations facilitates examination of weather-induced variability in air quality in the context of different land use types.

The air quality data are available as ten-minute averages. The highest pollution levels at these sites typically occur during the morning rush hour period (7:00-10:00 NZST) on weekdays in winter months (Fig. 2 shows the diurnal variations of hourly NO and NO₂ concentrations). Average pollutant concentrations for the morning rush hour period on weekdays from May to September were used in the present study, to focus on characterizing meteorological effects during the most adverse air quality conditions. The three-hour values were averaged on a daily basis to generate daily morning-rush-hour-average data for each pollutant at each site.

Meteorological data were not available for the air quality monitoring sites. Meteorologi-

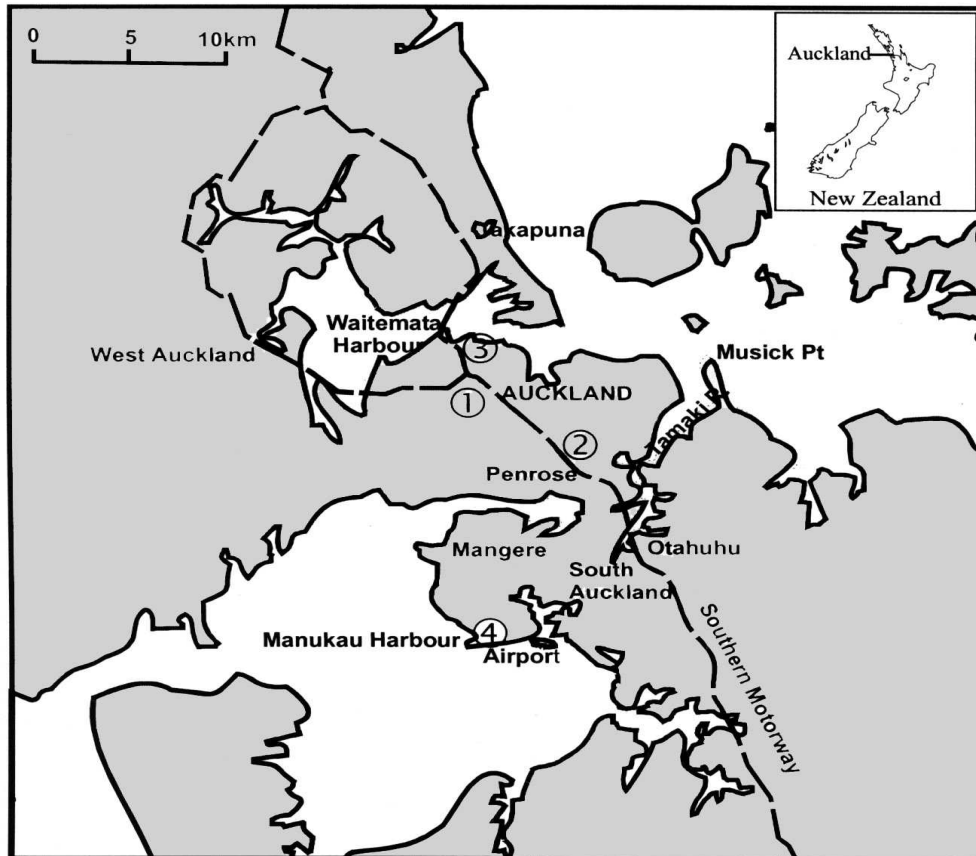


Fig. 1. Locations of monitoring sites in Auckland. 1 and 2 denote respectively the Mt Eden and Penrose air quality monitoring sites; 3 and 4 denote respectively the Auckland City and Auckland Airport meteorological sites.

cal data used in the current study are for two sites, Auckland City and Auckland Airport (Fig. 1), and for the period of May-September from 1990 to 1996. The data for the two meteorological sites were used in combination in an effort to represent the larger-scale weather conditions in the area. For both sites, measurements of hourly wind speed, wind direction, temperature and relative humidity were used. Hourly solar radiation and mean sea-level air pressure data from Auckland Airport were also utilized. The hourly wind vector was converted into its west-east (u) and south-north (v) components. The hourly meteorological data were extracted and averaged for the same three hours of the morning-rush-hour period in order to obtain a daily time series comparable to that for the

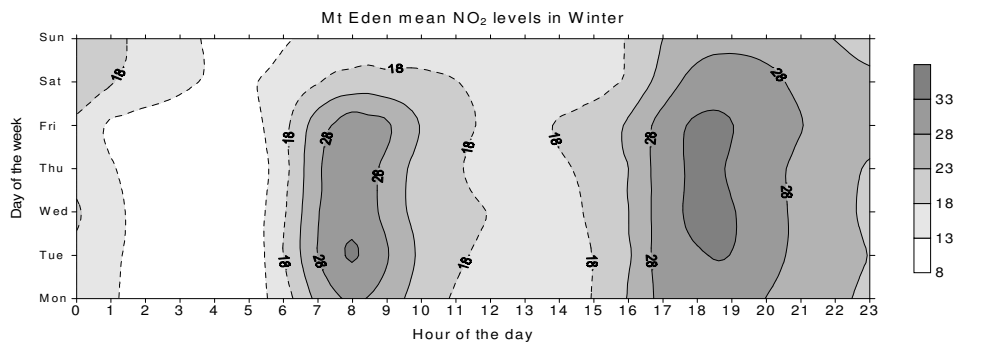
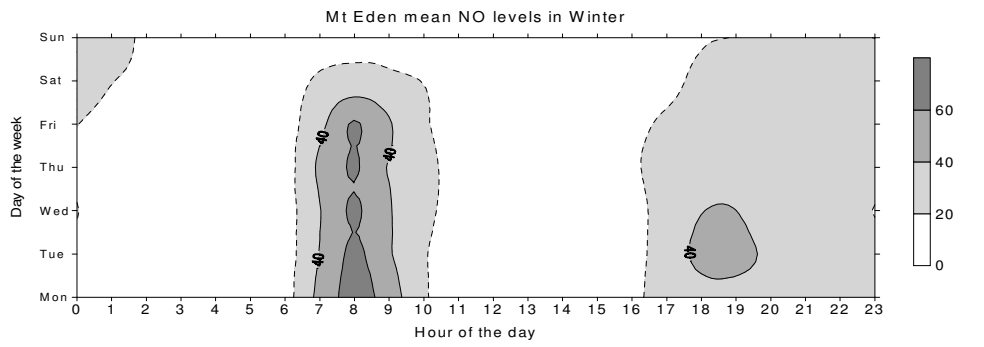
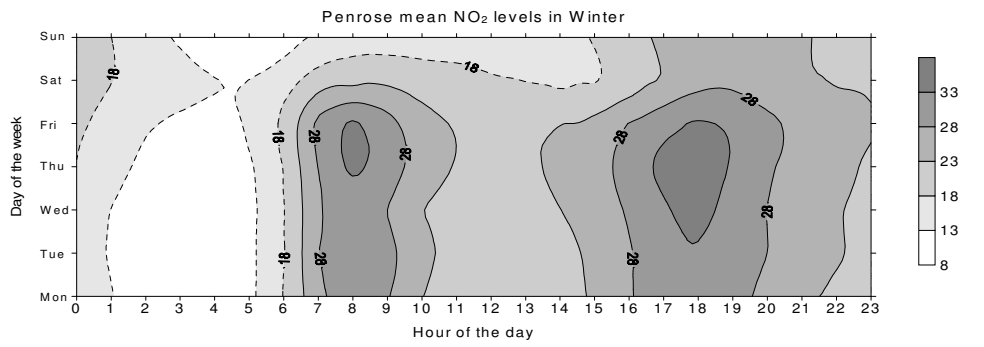
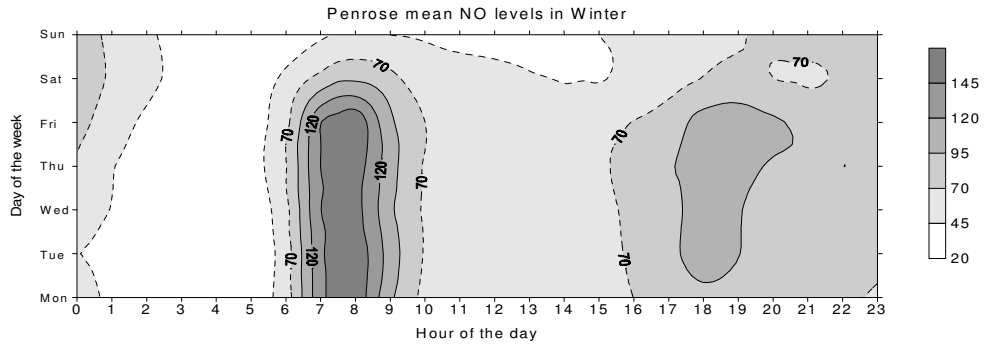
Location	Site details	Period of data
Penrose	Highly traffic impacted site, located approximately 50m northeast of the Auckland Southern Motorway (traffic density of 124,000 vehicles per day). Gt. South Rd (50,000 vehicles per day) is situated about 500m further away to the west. There are main roads within 500m to 1km to the north. No main roads exist within 1km to the east-northeast.	May-Sept., 1990-1996
Mt Eden	Central suburban site, located approximately 30m southwest of Mt Eden Rd (15,000 vehicles per day). Main roads occur to the northeast and northwest within 500m to 1km. No main roads exist within 1km to the southwest. Auckland CBD is to the north.	May-Sept., 1991-1996

Table 1. Site details of the air quality data. The traffic density data (vehicles per day) are from 1997, averaged over five weekdays.

air quality data.

In order to focus the present analysis on the daily variations, the seasonal variations in temperature, relative humidity and solar radiation data were removed by subtracting the corresponding multi-year mean value. This yielded daily anomalies. An alternative method is to subtract 15-day running means from the time series (McGregor and Bamzeli, 1995). This removes variations longer than the synoptic time scale of approximate 15 days. It was found that the choice of approach had little effect on the results reported here.

The resulting daily morning-rush-hour-average data are simply called *average rush hour* data, and used in the analytic procedures that follow. The distributions of the average rush hour data for each variable were determined. Only wind speed and NO data departed significantly from a normal distribution. Therefore, when the analytical methods required that the data be normally distributed (i.e., with normality assumption), the wind speed data were used in the square-root form and NO data were used in the one-fourth-power form [different transformations were chosen due to differences in raw data distributions (Snedecor and Cochran, 1989)]. It should be noted that, although O₃ concentrations and atmospheric stability data are very desirable for studies of nitrogen oxides, such data could not be accessed in the present investigation.



2.2 Methodology

First, the general characteristics of local air quality were investigated by comparing the two-site average rush hour NO and NO₂ data. A rotated principal component (PC) analysis was then undertaken on the average rush hour meteorological data in order to derive a set of new variables (PCs). These PCs were independent of each other, but reflected the underlying covariance among the original meteorological variables. The latter were highly inter-correlated and thus could not be directly used in a regression procedure. A multiple linear regression was subsequently performed on the resulting PCs to determine how air quality varied with the meteorological conditions. Land-use features surrounding each air quality monitoring site were also investigated and summarized for different land-use sectors, namely, four quadrants, starting from the north. These quadrants were considered to represent different emission conditions. The average rush hour air quality data were then stratified in terms of land-use sectors, using wind direction data as an index. Finally, linear regressions between the stratified data and PCs were used to assess the effects of meteorological conditions on local air quality, for different emission sources.

The PCA applied to the meteorological data is similar to that in a P-mode (Richman, 1986), but with some modifications: meteorological parameters at two (rather than one) sites formed the input data matrix. Without loss of generality, the correlation matrix was used for data decomposition in the PCA. Both weekday and weekend average (morning) rush hour meteorological data were used in the PCA analysis (PCA on weekday data only yielded similar results). The number of PCs to be retained was decided following Cattell (1966) and North et al. (1982). A plot of the eigenvalue and sampling error versus PC-number was used for this purpose, keeping in mind that *degenerated multiplets* (PCs) should not be separated from one another and as much variance in the data set as possible should be explained by the PCs retained. Varimax rotation (Richman, 1986) was applied to the retained PCs to facilitate physically meaningful interpretations.

Stratification of average rush hour air quality data by land-use sectors was based on two considerations. Firstly, previous studies have shown that spatial differences in

Fig. 2. Diurnal variations of hourly NO and NO₂ concentrations (ug/m³) in winter at the Penrose and Mt Eden sites in Auckland.

emissions are, to a large extent, consistent with the differences in land use patterns in the pollutant source area (Newton, 1997; Reed and Lewis, 1978). Secondly, advection is an important mechanism in determining pollution levels down wind from an emission source. Hence, for simplicity, the direction of wind can be used as an index to indicate which land areas, or what land use and hence emission sources, will determine the pollutant concentrations at a specific location. Thus, the air quality data at each time point (i.e., day) were stratified with the land-use sector from which wind blew to the site at that time. The wind direction data for the Auckland City site were used as the index for the data stratification. The approach is very simple relative to the complexity of the real world and thus it has limitations. For example, if the flow condition at a location is very different from that in the surrounding areas, the air quality data stratified by wind direction will not be able to reflect the effects of different land uses/emission sources on the local air quality. However, even this simple approach has proved useful in the present investigation.

3. Results

3.1 *Between-site differences in air quality*

The statistics provided in Table 2 show that the air quality at the two sites differed in terms of NO and NO₂ concentrations, despite the small separation distance. The mean, standard deviation and maximum value of pollutant concentrations were generally higher at the Penrose site, except that the maximum NO₂ concentration was higher at the Mt Eden site. It is noticeable that the between-site difference in NO₂ was not as large as in NO.

A correlation analysis was performed in order to identify whether air quality (expressed as average rush hour NO and NO₂ concentrations) at one site was (generally) related to that at the other site. Pearson correlation coefficients revealed: 1) a low yet significant inter-site correlation (0.25, significant at the 0.01 level for a two-tailed t-test) for NO data (transformed); 2) no inter-site correlation (<0.05) for NO₂ data; and 3) as expected, the within-site NO and NO₂ correlation was strong and significant at both locations (>0.50, significant at the 0.01 level for a two-tailed t-test). Therefore, while inter-site correlations did exist, they were low, and inconsistent between pollutants.

	NO ₂		NO	
	Penrose	Mt Eden	Penrose	Mt Eden
Mean	32.3	28.9	134.9	52.0
Standard error	0.7	0.7	5.0	3.1
Standard deviation	16.9	14.0	125.0	63.5
Minimum	0.0	0.0	1.2	0.0
Maximum	84.0	87.0	775.4	426.5

Table 2. Statistics of the average rush hour NO and NO₂ data at two sites in units of ug/m³.

3.2 PCA on meteorological variables

This sub-section presents the results of a Varimax rotated PCA conducted on the average rush-hour (daily) meteorological data, with transformed values used for wind speed in order to meet the assumption of normality. Since two-site (Auckland City and Auckland Airport) data were used, the resulting PCs reflect the dominant meteorological conditions for the study area, within which the air quality monitoring sites are located.

Two PCs were retained. They had dominantly higher eigenvalues than others and explained up to 62% of the total variance. The dominant weather patterns associated with the two Varimax rotated PCs can be described in terms of component loadings (Table 3) as follows:

- 1) *PC1* (SW/NE flow condition): accounting for about 35% of the total variance, had high positive loadings on wind speed, u and v components, and negative loading on relative humidity. It indicated the negative correlation between u and v components and humidity. Days with high positive *PC1* scores implied strong southwesterly (SW) flows with the air relatively drier than normal. These have high frequency in the Auckland region (Hessell, 1988; Sturman and Tapper, 1996). Days with high negative *PC1* scores reflected the opposite meteorological conditions—northeasterlies (NE) with lighter wind speeds and the air typically moister than normal.
- 2) *PC2* (calm/unstable condition): accounting for about 27% of the total variance, had high positive loadings on wind speed and temperature, negative loadings on sea-level air pressure and solar radiation, and modest negative loadings on v

components. It indicated that wind speed co-varied strongly with temperature and air pressure. High positive scores on this PC were associated with days of unstable, cyclonic conditions: high temperature and strong wind, with the warm air often from the north and accompanied by low solar radiation and low air pressure. On the other hand, high negative scores revealed days of calm, anticyclonic conditions: low wind speed, low temperature, with the cold air often

Variable	PC1	PC2
	(SW/NE flow condition)	(calm/unstable condition)
Airport wind speed	0.58	0.67
City wind speed	0.57	0.61
Airport u component	0.77	0.16
City u component	0.76	0.09
Airport v component	0.78	-0.35
City v component	0.75	-0.41
Airport temperature	-0.04	0.90
City temperature	-0.16	0.85
Airport relative humidity	-0.78	-0.05
City relative humidity	-0.75	0.05
Airport solar radiation	0.22	-0.46
Airport sea-level air pressure	-0.09	-0.55

Table 3. Loadings of two Varimax rotated PCs for PCA on the average rush hour meteorological data, May-September, 1990-1996.

from the south and accompanied by high solar radiation and high air pressure. Such conditions can arise from subsidence inversions associated with the slow-eastward-migrating anticyclones which are characteristic of this region's climate (Hurnard, 1980; Power *et al.*, 1992). Often related to such anticyclonic conditions, the calm, cloudless nights can lead to strong radiative cooling of the earth's surface, resulting in low early morning temperatures.

In addition, an oblique (Promax) rotation was also applied to the retained PCs in order to isolate variables that co-varied. The results were very similar to those reported above, confirming that the constraint of orthogonality in Varimax rotation did not have a significant effect on conclusions reached from an analysis of the underlying features in the input meteorological data. Moreover, the choice of transforming or not transforming

wind speed data did not alter the findings.

3.3 Regression of air quality data on meteorological PCs

In order to identify the links between meteorological conditions and air quality, a multiple linear regression analysis was performed for (weekday) average rush hour NO and NO₂ data on the two rotated PCs obtained above. Again, transformed NO data were used so that the assumption of normality could be met.

The Rs and adjusted R-squares reveal the degrees to which the pollutant concentrations varied with the meteorological PCs (Table 4). The adjusted R-square, calculated from the sample R-square by considering the sample size and the number of independent variables (PCs), reflects the goodness of fit of the model in the population and the proportion of the variance in the dependent variable *explained* by the model (Snedecor and Cochran, 1989). The high Rs and adjusted R-square values revealed that variations in pollutant concentrations at both sites were significantly related to the variability in

Dependent	R	Adjusted R-Square	Standardized Coefficients β	
			PC1 (SW/NE flow condition)	PC2 (calm/unstable condition)
Penrose NO	0.74	0.56	0.25*	-0.70*
Mt Eden NO	0.68	0.46	-0.59*	-0.38*
Penrose NO ₂	0.47	0.21	0.27*	-0.40*
Mt Eden NO ₂	0.48	0.22	-0.48*	0.02

Table 4. Regression results on two rotated meteorological PCs. The adjusted R-squares were calculated by formula: $R^2 - p*(1 - R^2)/(N - p - 1)$, with N being the sample size, p the number of independent variables in the regression equation. An asterisk denotes a value is significant at the 0.001 level for a 2-tailed t -test.

meteorological PCs and hence meteorological conditions. However, the importance of meteorological conditions varied between pollutants. The adjusted R-squares showed that the two PCs explain up to 56% of the variance in the transformed NO data, but only around 22% of the variance in the NO₂ data (a regression of air quality data on seven Varimax rotated PCs, which account for over 95% of the total variance in the meteorological data, can explain up to 65% of the variance in NO data and 26% of the variance in

NO₂ data). These differences indicate that NO₂ levels are less dependent of meteorological conditions than are NO levels.

Fig. 3 gives the distributions of predicted values versus observed values of the air quality variables (transformed if necessary) when regressed on two PCs. The predicted values are *adjusted*. Adjusted-predicted values for each air quality variable were calculated from the regression model, without involving the corresponding observed value of the variable in the computation of the model statistics. Consistent with the high Rs and adjusted R-squares, a relatively strong linear relationship between the observed (transformed) and predicted NO data was found for both sites (Fig. 3a, b). But given the comparatively lower Rs and adjusted R-squares, the relationship between the observed

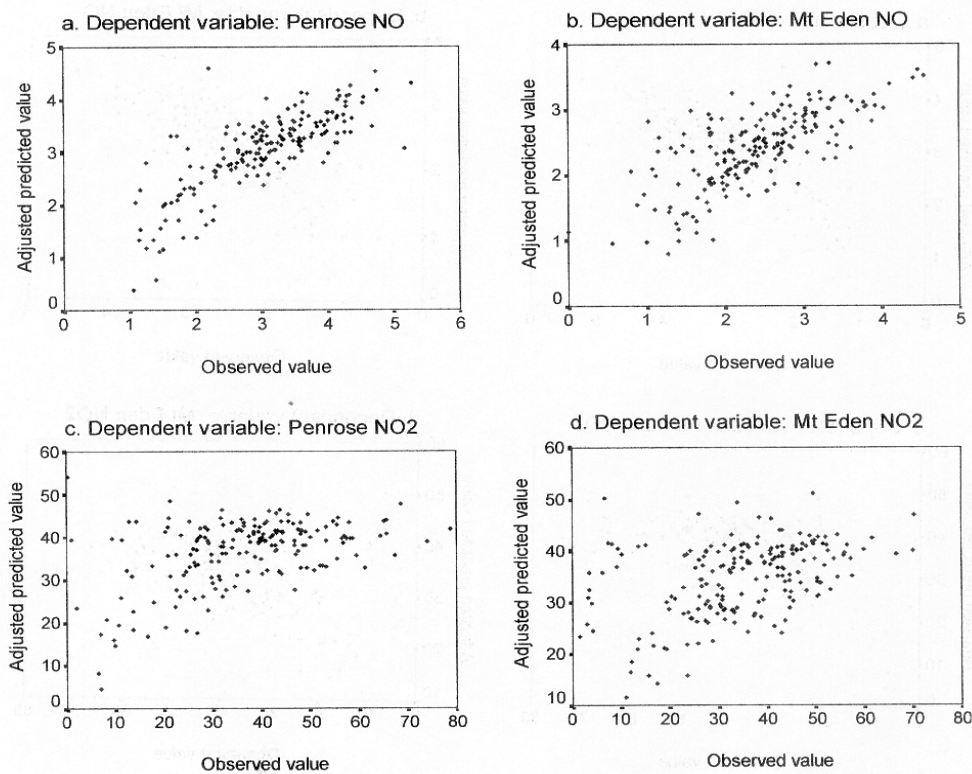


Fig. 3. Scatter plots of adjusted-predicted values of average rush hour pollutant concentrations versus observational values. The regression was performed on two meteorological PCs. Transformed NO data were used.

NO₂ concentrations and the predictions was less clear (Fig. 3c, d). The NO₂ data were significantly underestimated when observed values exceeded a level of around 40 µg/m³. This implies that factors other than meteorological conditions are important in determining the NO₂ levels, or, a non-linear relationship exists (also, the relationship might vary with NO₂ levels).

Standardized regression coefficients (beta weights) were calculated in order to identify the direct correlation between meteorological PCs and air quality (Table 4). The larger the absolute value of a coefficient, the more important the related PC and associated meteorological condition. Three findings are noteworthy:

- 1) A consistent inter-site correlation: the regression coefficients of *PC2*, except for the Mt Eden NO₂, are consistently negative and statistically significant (at the 0.001 level for 2-tailed t-test). This indicated that, regardless of specific site locations (and more importantly, the significantly different overall air quality at the two sites), calm conditions (anticyclonic), with light winds from the south, temperature lower than normal and solar radiation and air pressure higher than normal, were associated with high pollution levels. On the other hand, unstable weather (cyclonic), with warm air often from the north and accompanied by low solar radiation and low air pressure, were related to low pollution levels at the two sites.
- 2) A site-specific correlation: associated with *PC1* and for both NO and NO₂, the regression coefficients are positive for the Penrose site, but negative for the Mt Eden site. This revealed that days with light northeasterlies were associated with relatively high NO and NO₂ concentrations at the Mt Eden site. In this case, a moderate line source (Mt Eden Rd) was located nearby and to the northeast of the monitoring site; the Auckland central business district (CBD), where nitrogen oxides emissions were high (ARC, 1998), was located in the further north (Table 1). On the other hand, given that a strong line source (Auckland Southern Motorway) was situated to the southwest of the Penrose site, the southwesterly wind facilitated transport of air pollutants from the source area to the monitoring site. This highlights that the source-sampler positioning relative to prevailing winds is a major factor happening the dataset.
- 3) Effect of strong southwesterlies: although the Auckland Southern Motorway is located to the southwest of the Penrose monitoring site (Table 1), *PC1* was only

weakly, though positively, related to NO (especially) and NO₂ levels. This revealed that strong southwesterlies, the most dominant flow pattern in this region, were not strongly associated with high pollutant concentrations at the site, despite a strong line source being very close to and upwind of the site (Table 1). In contrast the larger negative correlation between PC2 and the Penrose NO and NO₂ levels implied that calm conditions, with light wind from the south, were related to high pollutant concentrations. These results demonstrate the importance of wind speed in determining local pollution levels, suggesting that *strong* southwesterlies rapidly disperse the emitted pollutants.

For purposes of comparison, regressions of the original NO data were also applied to the meteorological PCs. The violation of the normality assumption resulted in negative predicted values, non-randomly distributed residuals, and less (11 to 19%) variance being explained by the two PCs. Thus, this approach was not adopted.

3.4 Effects of meteorological conditions given different emission characteristics

The preceding results showed that the relationship between air quality and meteorological conditions was typically site-specific, and differed between pollutants. Further investigation was undertaken in order to identify the effects of local meteorological conditions on air quality for different emission source characteristics.

Spatial variations in emissions are generally consistent with differences in land use (Newton, 1997). The four sectors/quadrants surrounding each monitoring site are described in Fig. 4, with the site at the origin and the boundaries orientated west-east and south-north. Emissions from road traffic are identified as the largest anthropogenic source of pollutants in Auckland (over 80% of the anthropogenic emissions of nitrogen oxides are contributed by motor vehicles - ARC, 1998). Hence, the land-use features of the sectors were described mainly in terms of road characteristics. For ease of interpretation, each sector is represented as one of the following: close line source, strong close line source, distant line source, residential area source, and complex sources.

The average (morning) rush hour air quality data were allocated to the land-use sectors by the Auckland City wind direction data; a linear regression of the resulting data

a. Center: Mt Eden Site

<p style="text-align: center;"><i>Distant line source</i></p> <ul style="list-style-type: none"> • Main roads exist about 500m away • Motorway exists about 1000m away • High density commercial buildings 	<p style="text-align: center;"><i>Close line source</i></p> <ul style="list-style-type: none"> • A main road (Mt Eden Rd) exists about 30m away to the northeast, and extends northwards. • Main roads exist within 500~1000m • Motorway exists within 500~1000m
<p style="text-align: center;"><i>Residential area source</i></p> <ul style="list-style-type: none"> • No main road exists to the south-southwest within 1000m • Main roads exist within 500~1000m, to the west-southwest • High density housing 	<p style="text-align: center;"><i>Complex source</i></p> <ul style="list-style-type: none"> • Main roads extend from about 50m away towards the east-southeast • Mt Eden Rd intersects with Esplanade Rd about 100m from the site. • A hill exists in the south-southeast within 500~1000m (Mt Eden Domain)

b. Center: Penrose site

<p style="text-align: center;"><i>Complex source</i></p> <ul style="list-style-type: none"> • Motorway extends from about 80m away, northwestward • Main roads exist within 500~1000m. 	<p style="text-align: center;"><i>Residential area source</i></p> <ul style="list-style-type: none"> • No main road exists to the east-northeast within 1000m • Main roads exist within 500~1000m. • Modest density housing
<p style="text-align: center;"><i>Strong close line source</i></p> <ul style="list-style-type: none"> • Motorway exists about 50m away to the south-southeast • Main roads exist within 500~1000m. 	<p style="text-align: center;"><i>Complex source</i></p> <ul style="list-style-type: none"> • Motorway extends from about 70m away, southeastward • A power sub-station exists within 50m in the southeast. • Main roads exist beyond 500m.

Fig. 4 . Land-use features and names of the four sectors surrounding each air quality monitoring site.

subsets was performed on the two meteorological PCs. For simplicity, only the adjusted R-Squares for sectors with close line and residential area sources, i.e., for conditions of southwesterly and northeasterly winds, are shown in Table 5 and described as follows:

- 1) Consistent effects on NO levels: the high adjusted R-Squares at the two sites, for southwesterly or northeasterly winds, indicated that the NO levels at both sites were significantly related to meteorological conditions, regardless of different emission conditions (either area or line sources).
- 2) Varied effects on NO₂ levels: Adjusted R-Squares varied significantly with wind direction, suggesting that differences in area emissions, in combination with meteorological conditions, had a significant influence on local NO₂ levels. When

	Northeasterlies		Southwesterlies	
	Mt Eden	Penrose	Mt Eden	Penrose
Effective source	Modest close line source	Residential area source	Residential area source	Strong close line source
NO	0.37	0.42	0.50	0.58
NO ₂	0.00	0.35	0.28	0.08

Table 5. Adjusted R-squares for a regression of NO and NO₂ data on the two meteorological PCs, given southwesterly and northeasterly winds.

winds blew from sectors of residential area sources (southwesterlies for the Mt Eden site, northeasterlies for the Penrose site), the adjusted R-Squares were relatively high, reflecting the importance of both sources and meteorological conditions to air quality. On the contrary, when winds blew from sectors with line sources close to the sites (southwesterlies for the Penrose site, northeasterlies for the Mt Eden site) the R-Squares were very small (near zero). This indicates that other factors, rather than meteorological conditions, might be more important in determining local NO₂ concentrations.

4. Summary and Discussion

The effects of local meteorological conditions on NO and NO₂ levels in Auckland have been quantitatively assessed on a daily basis for the morning rush hour period in winter months. The use of air quality data for two sites allowed for consideration of the spatial variability of pollution concentrations and for an examination of meteorology-induced variability in air quality for different emission source strengths and in the context of multiple pollution sources. Although O₃ concentration and atmospheric stability data are important for studies of nitrogen oxides, such data are rather scarce and could not be accessed for the present investigation. The main findings are summarized and further discussed as follows:

- 1) Local meteorological conditions have significant effects on air quality in Auckland. Strong southwesterlies, a dominant flow pattern that often provides enhanced ventilation over the region, help maintain good airshed quality. Calm,

anticyclonic conditions, with light winds often from the south and relatively low (early) morning temperatures, are associated with the build up of high pollution in winter. According to Lenner *et al.* (1983) and Lenner (1987), lower temperatures induce higher NO emission rates from motor vehicles. Therefore, if the weather is cold and calm during the morning rush hour period when traffic volume is relatively high (ARC, 1998), there is a higher potential for pollution events to occur.

- 2) The effects of meteorological conditions differ between pollutants. NO levels are more related to meteorological conditions than NO₂ levels. The effects of meteorological conditions on local NO₂ levels vary with source conditions. Under the effects of residential area sources, NO₂ concentrations are to a considerable extent influenced by meteorological conditions. However, with the effects of close line sources, NO₂ is much less related to meteorological conditions.
- 3) A *weak* correlation between NO₂ levels and local meteorological conditions has also been reported by Hargreaves *et al.* (2000), who investigated the association between seasonal residuals (i.e., with the seasonal cycle being removed) of fortnightly NO₂ records and those of meteorological variables at Rothamsted, UK. Other studies (e.g., Harrison, 1997) suggested that the availability of ozone is important to determine the NO₂ levels in the urban atmosphere [as is consistent with reaction (3) in the Introduction section]; some degree of ventilation may help mixing-in of extra O₃, in order to maintain relatively higher NO₂ levels. During periods of enhanced westerly cyclonic weather (in the Northern Hemisphere), the O₃ levels may increase due to downward transport from the upper troposphere, resulting in increase in NO₂ concentrations (Davies *et al.*, 1992). More locally, Jiang (2000) investigated the distributions of NO and NO₂ concentrations versus wind speeds in Auckland. It was found that the highest mean NO₂ concentrations were not specifically related to the lowest wind speeds (as is the case for NO data), but to a range of 0 to 4 m/s. This implies that some degree of ventilation is needed for high NO₂ levels to occur. However, a more in-depth research is important for further conclusion. For example, O₃ monitoring and related

studies may seek for a better understanding of the NO₂ concentrations in this region.

- 4) Air quality has high spatial variability in this region. Such variability makes it difficult to characterize the regional air quality using single-site data. Meaningful interpretations of air quality data from a single site require knowledge of both meteorological and emission conditions; a comprehensive understanding of the quality of the whole airshed would rely on a study on multi-site data. This implies the need to enhance the current air quality monitoring network in this region, in order to make data available at more sites, and inter-site comparable.

Multivariate approaches, such as rotated PCA, have facilitated an analysis of the air quality-meteorology relationship in Auckland. However, applications of more holistic approaches, such as provided by synoptic climatological methodologies (Jiang *et al.*, 2004), might help further understand the impacts of weather conditions on the quality of the regional airshed. Future work could also point to an extension of this study to the summer season, to a more comprehensive investigation including other pollutants such as ozone and atmospheric stability data, and to understanding of the NO/NO₂/O₃ chemistry in relation to the haze phenomena in Auckland.

Acknowledgments

We are grateful to Dr. Daniela Belberova, NIWA, Auckland and Dr. Harshela Narsey, ESR, Auckland for facilitating access to data. Special thanks go to Dr. John Kidson, NIWA, Wellington for his helpful comments. Thanks also go to Miss Sarah Herman, NSW Department of Education and Training, Australia for the preparation of the final diagrams. This research was funded by the University of Auckland.

References

Auckland Regional Council (ARC), 1998. *Auckland Air Emissions Inventory*. Technical Publication No.91, ISSN 1172-6415.

- Auckland Regional Council (ARC), 1997. *Ambient Air Quality: Monitoring results for the Auckland region 1964-1995*. Technical Publication No.88, ISSN 1172-6415.
- Bronnimann, S., Neu, U., 1997. Weekend-weekday differences of near-surface ozone concentrations in Switzerland for different meteorological conditions. *Atmospheric Environment*, **31**, 1127-1135.
- Cattell, R.B., 1966. The scree test for the number of factors. *Multivariate Behavioral Research* **1**, 245-276.
- Davies, T. D., Kelly, P. M., Low, P. S., Pierce, C., 1992. Surface ozone concentrations in Europe: links with the regional scale atmospheric circulation. *J. Geophys. Res.*, **97 (D9)**, 9819-9832.
- Greene, J.S., Kalkstein, L.S., Ye, H., Smoyer, K., 1999. Relationships between synoptic climatology and atmospheric pollution at 4 US cities. , **62**, 163-174.
- Hargreaves, P.R., Leidi, A., Grubb, H.J., Howe, M.T., Mugglestone, M. A., 2000. Local and seasonal variations in atmospheric nitrogen dioxide levels at Rothamsted, UK, and relationships with meteorological conditions. *Atmospheric Environment*, **34**, 843-853.
- Harrison, R. M., 1997. Urban air pollution in the United Kingdom. In: *Air Pollution in the United Kingdom*. The Royal Society of Chemistry, UK, pp. 11-38.
- Hessell, J., 1988. The climate and weather of the Auckland region. *Miscellaneous Publication*, **115(20)**, New Zealand Meteorological Services, Wellington.
- Hurnard, S.M., 1980. Auckland's Climate. *Miscellaneous Publication*, **161 (1)**, New Zealand Meteorological Services, Wellington.
- Jiang, N., 2000. Quality of the Auckland Airshed. PhD thesis, University of Auckland. UMI's Dissertation Publishing, AAT3112534.
- Jiang, N., Hay, J. E., Fisher, G. W., 2004. Classification of New Zealand Synoptic Weather Types and Relation to the Southern Oscillation Index. *Weather and Climate*, **23**, 3-24.
- Lenner, M., 1987. Nitrogen dioxide in exhaust emissions from motor vehicles. *Atmospheric Environment*, **21**, 37-43.
- Lenner, M., Linqvist, O., Rosen, A., 1983. The NO₂/NO_x ratio in emission from gasoline powered cars: high NO₂ percentage in idle engine measurements. *Atmospheric Environment*, **17**, 1359-1398.
- McGregor, G.R., Bamzeli, D., 1995. Synoptic typing and its application to the investigation of weather air pollution relationships, Birmingham, United Kingdom. *Theoretical and Applied Climatology*, **51**, 223-236.
- Ministry for the Environment (MFE), 1998. *The State of New Zealand's Environment*. Ministry for the Environment, Wellington.
- Newton, P.W., 1997. *Re-shaping Cities for a More Sustainable Future: exploring the link between urban form, air quality, energy and greenhouse gas emissions*. Australian Housing and Urban Research Institute, Melbourne, pp.181.
- North, G.R., Bell, T.L., Cahalan, T.R., 1982. Sampling errors in the estimation of empirical orthogonal functions. *Monthly Weather Review*, **110**, 699-706.
- Power, H.C., de Freitas, C.R., Hay, J.E., 1992. Relative effects of climate and source strength on atmospheric lead concentrations in Auckland, New Zealand. *Theoretical and Applied Climatology*, **45**, 127-138.

- Reed, W.E., Lewis, J.E., 1978. Land use and land cover information and air-quality planning. *Geological Survey Professional Paper*, **1099-B**, United States Government Printing Office, USA.
- Richman, M.B., 1986. Rotation of principal components. *Journal of Climatology*, **6**, 293-335.
- Snedecor, G.W., Cochran, W.G., 1989. *Statistical Methods* (8th Edition). Iowa State University Press, USA.
- Sturman, A.P., Tapper, N.J., 1996. *The Weather and Climate of Australia and New Zealand*. Oxford University Press, Melbourne, pp.476.
- Uno, I., Ohara, T., Wakamatsu, S., 1996. Analysis of wintertime NO₂ pollution in the Tokyo metropolitan area. *Atmospheric Environment*, **30**, 703-713.

Submitted to Weather and Climate April 2002; revised September 2004.