Weather and Climate, **25**,(2005),43-69

Synoptic weather types and morning rush hour nitrogen oxides concentrations during Auckland winters

N. Jiang[1,*], J. E. Hay[2], G. W. Fisher[3]

[1] *NSW Department of Education and Training, Australia*

[2] *John E. Hay & Associates, Auckland, New Zealand*

[3] *Endpoint, Auckland, New Zealand.*

Abstract

A synoptic climatological approach is applied to the study of weather air quality relationships in Auckland. Ten synoptic weather types are identified using a new, two-stage classification scheme that consists of obliquely rotated T-mode principal component analysis (PCA) followed by K-means clustering via Varimax rotated S-mode PCA. The weather types are analysed in relation to local meteorology, and to nitrogen oxides concentrations at two monitoring sites. Two anticyclonic weather types, characterised by calm, cold and relatively humid morning rush hour local conditions, are related to both high regional pollution and severe pollution episodes. Weather types associated with strong and persistent local west-southwesterly winds help maintain good regional air quality due to enhanced ventilation. Under unstable cyclonic synoptic types, characterized by moderate to strong northerly winds, warm, humid, cloudy and rainy local conditions, emissions from the Auckland Central Business District can have significant air quality impacts on downwind residential areas. It is also suggested that the synoptic determinants of solar radiation intensities as well as temperatures appear important in controlling morning rush hour nitrogen oxides conversion chemistry. The weather type-air quality relationships vary to some extent from site to site due to the coupling of local meteorology and spatial variations in major emission sources. The findings demonstrate that the weather typing approach is not only capable of reflecting the effects of conditions associated with both emissions and local meteorology, but also provides an integrated evaluation of the impacts of synoptic circulation on both regional meteorology and air quality.

Keywords: synoptic climatology, t-mode principal component analysis, k-means clustering, rush hour, nitrogen oxides, air quality

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

1. Introduction

Air quality in Auckland is generally within the national guidelines. However, at times, especially in winter months, the city suffers from air pollution phenomena such as a brown haze that degrades local atmospheric visibility and may also do harm to humans and environmental health (ARC, 1997). The brown haze is thought to be associated with emissions of nitrogen oxides (NO and NO_2) and reactions between these pollutants and other air contaminants such as volatile organic compounds (Jiang et al., 2005). Identification and understanding of the contributory factors to elevated nitrogen oxides concentrations in Auckland is now an important scientific and policy issue.

Variations in nitrogen oxides concentrations may be partly due to influences of emissions and chemical transformations (e.g., reactions between nitrogen oxides and ozone - Jiang et al., 2005), but the role of atmospheric conditions must also be investigated. However, in Auckland, and New Zealand generally, such investigations are still very few in number and limited in scope. Studies undertaken elsewhere (e.g., Uno et al., 1996) have indicated that both the physical and dynamic properties of the atmosphere, on time scales from hours to days, can play an important role in determining the levels of air contaminants. The surface wind field is important for the transport and dispersion of pollutants and atmospheric stability can determine the extent to which pollutants are diffused within the planetary boundary layer. By influencing reaction rates, meteorological conditions such as humidity, temperature and solar radiation also influence both the chemical and physical processes involved in the formation of secondary pollutants. Indirectly, weather and climatic conditions affect air quality by influencing human activities and consequently the emissions of pollutants (Davis and Gay, 1993a).

The meteorological parameters that influence air quality are often closely interrelated with each other, and are strongly modulated by the synoptic-scale circulation, as manifested by the passage of fronts, cyclonic systems and anticyclones. This has prompted the popular application of synoptic climatology to the investigation of short-term variations in air quality (e.g. McGregor and Bamzelis, 1995; Kalkstein and Corrigan, 1986; Davis and Gay, 1993a, b; McKendry, 1994; Zelenka, 1997; Shahgedanova *et al.*, 1998; Greene *et al.*, 1999; Comrie and Yarnal, 1992; Heidorn and Yap, 1986; Muller and Jackson, 1985; Comrie, 1992). A classic synoptic climatological analysis first involves determining the dominant and recurring categories of atmospheric circulation and subsequently understanding how external environmental or meteorological parameters relate to the resulting categorization (Barry and Perry, 1973). Implicit in this is the assumption that particular modes of atmospheric circulation produce distinctive environmental conditions at particular localities. The advantage of a synoptic approach to air pollution climatology is that it allows for the consideration of numerous interrelated variables within a holistic framework.

Such a holistic examination of the role of weather and climatic conditions in determining the levels of nitrogen oxides in Auckland has been undertaken. As part of this project, Jiang et al. (2005) examined the relationship between Auckland morning rush hour nitrogen oxides (NOx) concentrations and several meteorological variables (as local meteorology indicators) for winter months (May-September). They found that the prevalent southwesterly winds help maintain good air quality due to enhanced dispersion, while calm, cold local conditions lead to the build-up of air pollution. The present paper investigates the relationship between synoptic circulation, local meteorology and NO and NO_2 concentrations in Auckland. A synoptic climatological analysis was conducted on a daily basis, and focused on the morning rush hour period on weekdays in May-September. This is when the highest air pollutant concentrations are observed (Jiang, 2000). As described in the following section, the synoptic climatology was developed using a new, two-stage weather typing method involving obliquely rotated T-mode principal component analysis (PCA) followed by a convergent K-means clustering via Varimax rotated S-mode PCA. The approach allows for an analysis of the local and regional response of air quality to synoptic weather patterns in different land use/emission contexts. In addition, the synoptic control of extreme local meteorological conditions that are directly related to air quality - wind speed, temperature, solar radiation, relative humidity and rainfall - is also analysed within a synoptic climatological framework.

2. Data and Methodology

2.1 Air quality data

The study uses concentrations of NO_2 and NO measured at two long-term monitoring sites, Penrose and Mt Eden, in Auckland between 1991 and 1996 (Figure 1 and Table 1). The choice of these locations was based on the following considerations: 1) the available records are relatively long (records from other sites are too short and not suitable for a synoptic climatological analysis); 2) since 1991, the two sites have formed part of the United Nations Global Environmental Monitoring System (GEMS). Using data for two locations facilitates examinations of the relationship between weather conditions, land use and air quality. Although ozone (O_3) is directly related to the nitrogen oxides chemistry (Jiang et al., 2005), ozone data were unavailable for the present study.

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 (Jiang et al., 2000). Therefore, as in Jiang et al. (2005), the original air quality data were extracted and averaged for the morning rush hour on a daily basis to

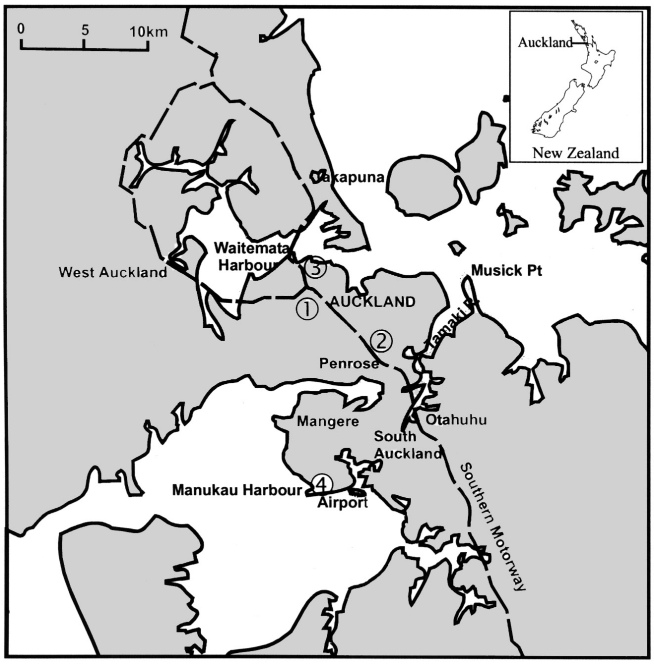

Figure 1. Locations of monitoring sites in Auckland. 1 and 2 denote respectively the Mt Eden and Penrose air quality monitoring sites; 3 denotes the Auckland CBD; and 4 the Auckland Airport meteorological site.

generate daily time series for each pollutant at each site. Only data for weekdays from May to September were used so as to focus on characterizing meteorological effects during the most adverse air quality conditions. Further standardization was applied to allow for an appropriate comparison of pollutant concentrations between months. Following Davis and Gay (1993b), the standardization was accomplished by converting each daily observation into a z-score by subtracting the

Location	Site detail
Penrose site	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.
Mt Eden site	Suburban residential 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 3 km to the north.

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

overall monthly mean concentration from each daily value and dividing by the overall standard deviation (with weekend data excluded in the calculation). Hence, each standardized value represents the number of standard deviations by which a given observation departs from the monthly mean (normal) concentration.

2.2 Local meteorological data

Meteorological data were not available for the air quality monitoring sites. However, correlations of meteorological data from seven weather stations over Auckland show a high degree of spatial agreement in meteorological conditions, except for on some summer days when local land/sea breezes become dominant in this region. Therefore, the current study uses the meteorological data for the Auckland Airport site as a proxy of the regional meteorological conditions, given that more weather elements are measured and longer records available for this site. The meteorological data are for the same period as the air quality data (May-September, 1991-1996). These include hourly measurements of wind speed, wind direction, dry bulb air temperature, dew point, relative humidity, solar radiation and mean sea level air pressure, and 24-hour rainfall totals. 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 morning rush hour in order to obtain a daily time series comparable to the daily air quality data, except rainfall for which there was only one value per day. Atmospheric stability data are very desirable for air quality studies, but such data were not available for this analysis.

In order to focus the present analysis on the daily scale, anomalies of the resultant (daily morning rush hour) temperature, dew point and solar radiation data (significant monthly variations exist in these variables) were calculated by applying a 15-day running mean filter to remove variations longer than the synoptic time scale of approximate 15 days (McGregor and Bamzelis, 1995).

2.3 Gridded meteorological data

The gridded meteorological data used to derive the synoptic weather types comprises daily NCEP/NCAR 1000 hPa geopotential height reanalysis at 0000 UTC for the same period as the air quality and local meteorological data. The grid of 2.5°×2.5° mesh is bounded by latitudes 25°S to 55°S, and longitudes 160°E to 175°W.

The NCEP/NCAR geopotential height reanalysis is available for both 0000 UTC and 1200 UTC. The analysis time of 0000 UTC corresponds to local noon time 12:00 NZST. It was chosen for the present study because emissions are generally higher during the daylight period, and at this time and in this region of the Southern Hemisphere, radiosonde coverage is more comprehensive than at other times of the day (Kidson, 1994a). Although the chosen time is outside the morning rush hour period, such a time difference should not cause any significant deviation in conclusions of this analysis, given that local atmospheric circulation patterns such as land/sea breezes are insignificant in winter [in contrast, they may play an important role on some summer days - Hessell (1988)]. The climatic mean map for the entire dataset is characterized by prevalent westerly flows over the New Zealand and surrounding areas, similar to that shown in Jiang et al. (2004).

2.4 Methodology

A synoptic climatological approach was taken in this analysis. First, obliquely rotated T-mode PCA (Huth, 1996a) and a combination of Varimax rotated S-mode PCA (Richman, 1986) and convergent K-means cluster analysis (Kidson, 1997) were used to derive a daily index of synoptic weather types based upon the NCEP/NCAR gridded 1000hPa geopotential height reanalysis for the New Zealand region. Subsequently the weather types were characterized by Auckland Airport meteorological data, and air quality data at the two monitoring sites, with synoptic situations associated with above, or below, normal pollution levels being identified. Finally, weather conditions that are directly related to regional air quaity were analysed within a synopitc climatological framework.

Weather typing, rather than an air mass-based approach, was used in this study as the former has been used successfully in other New Zealand studies (e.g., Kidson, 2000; Jiang et al., 2004). There are many weather typing techniques available in the literature. Huth (1996a) compared widely used methods and suggested that the obliquely rotated T-mode PCA method is preferable for circulation classification purposes. He also noted that the map groupings based on rotated T-mode PCA are less separated from each other than those obtained by other methods, while the convergent K-means method provides groupings that are best separated. Jiang et al. (2004) has demonstrated the utility of obliquely rotated T-mode PCA for synoptic weather classification in New Zealand. In the present study, we introduce a new two-stage procedure for map classification. The first stage involves a pre-classification process. As in Jiang et al. (2004), the daily weather maps were classified through obliquely rotated T-mode PCA, to pre-define the dominant weather patterns within the dataset. The actual geopotential heights, rather than anomalies, were analysed so that the results are readily interpretable and the maps that are similar to the climatic mean pattern can also be classified (Huth, 1996b). A correlation matrix was used for the PCA analysis and the Promax algorithm applied to obliquely rotate the retained PCs (Richman, 1986). The number of PCs to retain was determined through the same method used by Jiang et al. (2004). Consequently, the first five leading PCs, accounting for about 91% of the total variance, were retained and rotated, leading to 10 pre-classification types. In the second stage, the convergent K-means clustering procedure was used to optimally redistribute the type membership of daily maps (MacQueen, 1967) so as to define the final, compact clusters. The mean maps of the pre-classification clusters were used as seeds (prototypes) to start the clustering iteration.

Importantly, the K-means clustering was conducted on the principal component scores of a Varimax rotated S-mode PCA. The PCA contributes to the effectiveness of K-means clustering in at least two respects: firstly, it reduces the orginal high dimension data to a small set of PCs with orthorgonality, with the contribution from small-scale variability and noise effectively ignored (Kidson, 1994a); secondly, Ding and He (2004) mathematically proved that principal components are the continuous solutions of the discrete cluster membership indicators in the K-means clustering method, i.e., the PCA dimension reduction automatically performs data clustering according to the K-means objective function. In the present study the S-mode PCA was based on the correlation matrix of spatially standardized data. The standardisation was applied to each daily map. This to some extent removes the intensity effects of synoptic systems (Kidson, 1994a). The PCA analysis resulted in the retention of five PCs, accounting for around 87% of the toal variance. The PCs were Varimax rotated and the PC scores were then weighted by the square root of their eigenvalues (sum of squares of Varimax rotated PC loadings) – weighted PC scores correspond to map projections in the low dimension space. The similarity between a daily map and a cluster was measured by Euclidean distance between the set of five daily PC scores and the cluster centriod (mean) scores.

3. Results and Discussion

3.1 Synoptic weather types and average local meteorological conditions

The frequencies and mean 1000 hPa geopotential height maps for the resulting ten synoptic weather types are shown in Figure 2. The weather types are arbitrarily designated as SWH, NEH, NWH, SEH, H, SWL, HLE, NWL, TO and HLW, for easy reference. All of these ten weather types have their counterparts in the earlier classifications based on other weather typing techniques, for example, Jiang et al. (2004), Kidson (1994a) and Kidson (2000). In other words, the present analysis has reproduced weather types identified in previous synoptic climatological studies. The mean maps for the pre-classification clusters are almost identical to those shown in Figure 2, except that small

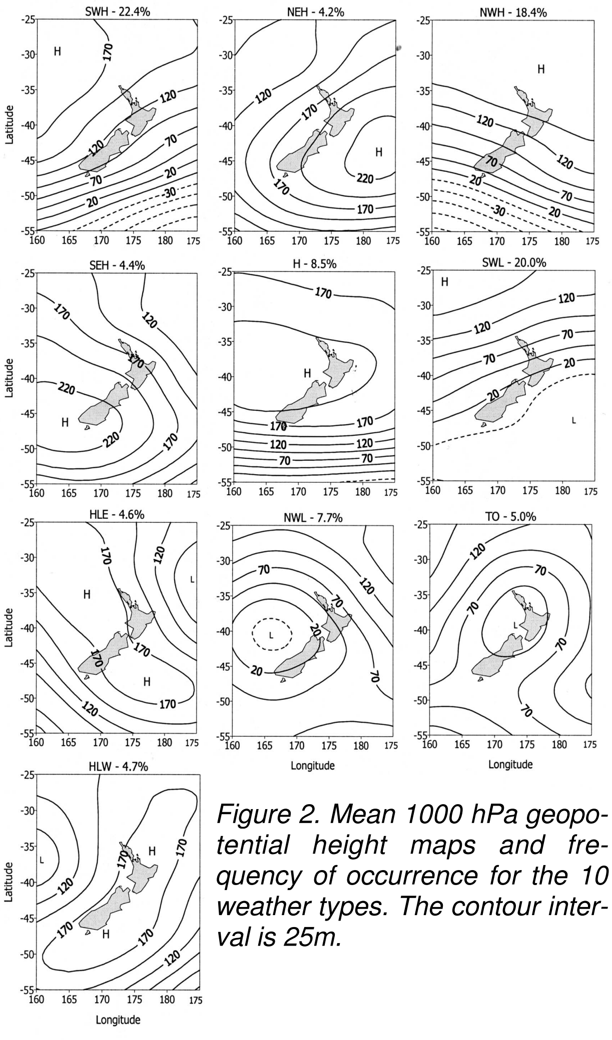

Figure 2. Mean 1000 hPa geopotential height maps and frequency of occurrence for the 10 weather types. The contour interval is 25m.

differences may exist in the positions of some synoptic centres. This indicates that the convergent k-means clustering did not change the cluster centroid locations significantly, but redistributed the memberships of daily maps to form compact clusters. As expected, the final cluster groupings resulting from the two-stage classification procedure were found more consistent than that obtained from the obliquely rotated T-mode PCA method alone (i.e., from the pre-classification stage). The detail on this is to be reported elsewhere since the primary purpose of the present paper is to relate the classification to air quality in Auckland, and there is also limitation of space.

Table 2 provides the means and F-ratios (analysis of variance - ANOVA) of the selected meteorological variables for the ten synoptic weather types, based on the daily (morning rush hour) meteorological data. Statistics were also calculated for a derived variable, *percent calm*. This was defined as the percent of times with wind speed less than or equal to 1m/s (rush hour average) over the total number of days within a specific type category. This variable, together with solar radiation and actual wind speed, was considered indicative of atmospheric stability. Collectively the statistics present a general description of local meteorological characteristics associated with each synoptic type. For the Auckland area the main findings of this analysis are summarized as follows:

1) Distinctive meteorological conditions are associated with each synoptic type. The large F-ratios from one-way ANOVA indicate that all meteorological variables differ significantly (at a 0.05 level) between synoptic weather types. Tukey's (1953) Honestly Significant Difference (HSD) test reveals that at least one variable is significantly different (at a 0.05 level) between any two weather types. This confirms a significant coupling between synoptic-scale circulations and daily meteorological conditions, consistent with the findings of Jiang et al. (2004) who have shown a temporally consistent correlation between synoptic categories

and weather elements in the study area.

2) The HLW and H types, characterized by an anticyclone/high pressure ridge centred over New Zealand (Figure 2), are typical of light winds, large percent calm values, above average relative humidity, below

Meteorological variable	Weather type										Total mean	ANOVA F-ratio
	SWH	NEH	NWH	SEH	H	SWL	HLE	NWL	TO	HLW		
Mean sea level air pressure (hPa)	1015.0	1022.2	1019.2	1019.6	1023.8	1005.8	1018.7	1006.9	1003.9	1020.6	1014.4	90.5
Wind speed (m/s)	5.1	4.0	3.3	4.8	2.1	6.9	3.4	5.2	4.7	2.1	4.6	32.1
u component of wind (m/s)	3.1	-3.3	0.7	-1.5	-0.6	5.2	-0.5	-1.2	-1.1	-0.6	1.4	73.9
v component of wind (m/s)	1.6	0.6	-1.1	3.9	1.0	1.2	2.8	-4.0	-2.2	-0.0	0.4	42.4
Dry bulb temperature deviation (ºC)	0.2	0.0	-0.1	-1.8	-1.5	0.6	-1.9	1.6	1.5	-1.0	0.0	20.1
Dew point deviation (ºC)	-0.2	0.0	0.3	-2.3	-0.9	0.1	-2.7	2.2	2.3	-0.8	0.0	25.1
Relative humidity (%)	84.1	88.4	88.5	83.4	90.4	82.6	82.0	90.5	92.0	89.3	86.3	20.7
24 hour rainfall (mm)	2.7	8.5	4.9	1.2	1.2	5.4	1.9	6.6	3.7	6.3	4.4	5.9
Solar radiation deviation (W/m^2)	-0.2	-8.0	-5.9	-1.3	11.9	4.8	16.3	-9.8	-8.0	2.3	-0.0	5.4
Percent calm (%)	7.8	12.8	11.8	5.0	26.9	1.6	11.9	4.2	4.3	30.2	9.8	na

Table 2. Means and ANOVA F-ratios for the Auckland Airport meteorological variables by weather types, May-September, 1991-1996. "Total mean" corresponds to the climatic average level of a variable. The ANOVA F-ratios are all significant at a 0.05 level.

normal temperature and dew point and above normal solar radiation. The HLW type provides above average 24-hour rainfall in contrast to the H type under which little rain is observed. Often these weather types are related to development of night time and early morning atmospheric inversions due to the anticyclonic subsidence and nocturnal radiation cooling (Tapper and Sturman, 1996). Secondarily, the NWH, NEH and HLE types, under which Auckland is dominated by a periphery of a high pressure ridge/anticyclone (the later two are anticyclonic blocking patterns), are locally associated with marginally below-average wind speed and above-average percent calms. The NWH and NEH types featured relatively humid, rainy and cloudy weather, in contrast with the HLW type that corresponds to colder, drier and sunnier than normal local conditions. Weak elevated inversions may be observed under these situations.

3) The cyclonic types, SWL, NWL and TO, represent situations when Auckland is located in the periphery/centre of a cyclone/low pressure trough. They have the lowest percent calms and moderate to strong wind speeds, suggesting highly unstable local conditions. The two most prominent types, SWH and SWL, are relatively more persistent in time and correspond to the strongest westerly to southwesterly winds (and below average percent calms and relative humidity, but normal solar input), thus providing excellent ventilation.

3.2 Weather type-air quality relationships

Relationships between synoptic weather types and air quality could be expected due to the coupling between synoptic weather types and local meteorological conditions and the important roles of local meteorology in determining local air quality (Jiang et al., 2005). A one-way ANOVA on the daily air quality data was performed to determine whether the synoptic climatology produces statistically distinct air quality regimes in Auckland. The results confirm that pollution levels vary significantly (at a 0.05 level) between synoptic weather types for both NO and NO_2, indicating a significant impact of synoptic-scale circulation on local air quality.

Average values of standardized NO and NO_2 concentrations were calculated for each synoptic weather type and a one-sample t-test performed to determine if the average pollutant concentrations for each synoptic type are significantly different from zero. As shown in Figure 3, positive values represent above normal pollutant concentrations. Asterisks indicate that the t-test for the site identifies mean concentrations statistically different from zero at a 0.05 level, and vice versa. A few features are noteworthy:

1) For some synoptic types the weather type-air quality relationship differs

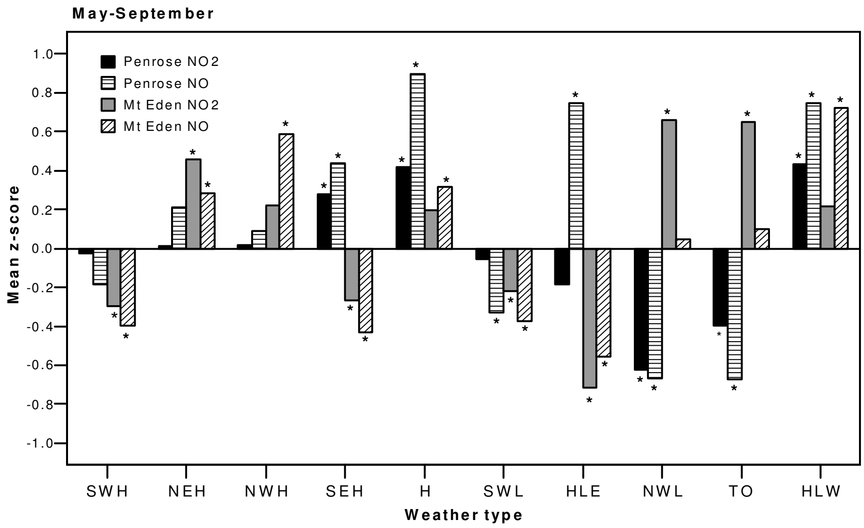

Figure 3. Variations of standardized NO and NO_2 concentrations, by synoptic weather types and for each monitoring site. Departures that are significantly different from zero at the 0.05 level, as defined by a one-sample t-test, are indicated by an asterisk.

between monitoring sites. This is likely caused by the coupling effects of emission source-sampler positioning and transport of pollutants by prevailing winds under particular synoptic weather patterns. For example, given that the SEH type is related to moderate but persistent south-southeasterly winds (cold and less humid) in Auckland, the associated NO and NO_2 concentrations are above normal at the Penrose site as a strong line source (Auckland Southern Motorway) exists upwind of the monitoring site (Table 1). Conversely, the pollution levels are below normal at the Mt Eden site because the main nearby emission sources are located downwind under this synoptic situation. A similar feature could also be observed for the HLE type which is locally characterized by cold, dry and sunny weather and modest southerly wind. The significantly high NO concentration (above normal) may be caused by high solar input that intensifies the disassociation of NO_2 to NO.

It is noteworthy that the NWL and TO types, characterized by unstable cyclonic conditions, moderate to strong northerly winds and above normal temperature (Table 2), are associated with significantly above normal NO_2 concentrations at the Mt Eden site. This is mainly due to the immediate transport of nitrogen oxides (mostly NO_2) from the Auckland CBD by the favourable wind regimes. The very high NO_2 concentrations may also be related to the coincident low solar input that limits the disassociation of NO_2 to NO. In previous studies (e.g., McGregor and Bamzelis, 1995) it was suggested that during periods of enhanced westerly cyclonic weather, ozone levels may be elevated due to downward transport from the upper troposphere. If this occurs in Auckland, the increased O_3 may be able to enhance the conversion of NO to NO_2 in the CBD where the emissions of NO are usually high. In addition, a weather-emission rate interaction may exist - under the humid, cloudy and even rainy conditions of the NWL and TO types there could be more people using cars and a higher chance of traffic congestion in the central city traffic corridors, resulting in higher rates of vehicle emissions and thus increased overall pollution loads (Jiang, 2000). However, this signal is not as strong for the Penrose site, and in-depth investigations are needed.

2) In general, the anticyclonic HLW and H types are associated with above normal pollutant concentrations, though not all are statistically significant. This is because under these synoptic types, as noted earlier, Auckland is subject to relatively weak winds and a high probability of stable planetary boundary layer conditions (Table 2) that limit ventilation and suppress vertical mixing heights. The NWH and NEH types are to a lesser extent related to above normal pollution levels, as the relatively higher wind speed helps pollutant transport and dispersion [but this factor could be compounded by a possible increase in road traffic emissions due to the humid, cloudy and rainy weather conditions (Jiang, 2000)]. On the other hand, the SWL and SWH types, characterized by strong west-southwesterly winds that favour pollution transport and dispersion, generally relate to below normal pollutant concentrations due to enhanced ventilation. However, a between-site difference described above is also noticeable. For example, on days of the H type, which is characterized by light southerly winds, the NO and NO_2 concentrations at the Mt Eden site are not statistically significant, though above normal. The main emission sources are located downwind of this site (Table 1). Such between-site differences are not as obvious for the HLW type, likely due to the associated wet weather that may have caused increases in vehicle emissions at an area scale. Otherwise, the between-site differences, though physically explainable, have complicated the common weather-air quality interaction signals.

3) Higher NO (other than NO_2) levels correspond to weather types associated with above normal solar radiation and below normal temperature

and dew point (e.g., HLW), while higher NO_2 concentrations are observed under weather types characterized by the opposite local conditions (e.g., NWL). Such relationships are stronger at locations where major emission sources exist nearby and upwind under specific synoptic types. These results indicate a holistic effect of weather conditions on the NO/NO_2 conversion-related chemistry (Jiang et al., 2005). For example, as discussed earlier, high solar input can result in higher NO (standardised) levels by enhancing the disassociation of NO_2 to NO, and vice versa.

The upper 25% of days for the standardized NO and NO_2 concentrations were examined to identify the relationships between synoptic weather types and extreme pollution episodes. In Table 3 the relationship is expressed as a ratio of the percentage of days in the upper 25% for NO and NO_2 to the overall percentage of occurrence of the particular type. Hence, values greater than *one* indicate that the synoptic type is more likely to be present on days of high pollution levels than expected (Greene *et al.*, 1999). Three features are noteworthy. Firstly, the ratios associated with the HLW and

		SWH	NEH	NWH	SEH	H	SWL	HLE	NWL	TO	HLW
Overall frequency (%)		22.4	4.2	18.4	4.4	8.5	20.0	4.6	7.7	5.0	4.7
Frequency of upper 25% days (%)	Penrose NO_2	24.5	4.3	24.5	3.6	10.8	19.1	1.4	2.2	2.2	7.5
	Penrose NO	15.8	5.8	25.2	6.5	19.4	8.6	5.8	2.9	1.4	8.6
	Mt Eden NO_2	16.8	6.5	27.2	0.9	6.5	12.0	0.0	14.0	9.3	6.7
	Mt Eden NO	18.6	3.7	30.9	0.9	9.4	9.3	0.9	8.4	4.7	13.0
Ratio of upper 25% days	Penrose NO_2	1.1	1.0	1.3	0.8	1.3	1.0	0.3	0.3	0.4	1.6
	Penrose NO	0.7	1.4	1.4	1.5	2.3	0.4	1.3	0.4	0.3	1.8
	Mt Eden NO_2	0.7	1.5	1.5	0.2	0.8	0.6	0.0	1.8	1.9	1.4
	Mt Eden NO	0.8	0.9	1.7	0.2	1.1	0.5	0.2	1.1	0.9	2.8

Table 3. Relationship between synoptic weather types and high pollution events in Auckland. The ratio is expressed as a ratio of the percentage of days in the upper 25% for NO and NO_2 to the overall percentage of occurrence of the particular weather type.

NWH types are generally high for both monitoring sites (though not all are statistically significant), indicating these two types are more likely to be associated with days of extremely high pollutant concentrations at the area scale. This is consistent with the earlier results that mean pollutant concentrations for these synoptic types are in general above normal (Figure 3). The H type, however, though associated with above normal mean pollution levels, is related to high pollution events at the Penrose site but not at the Mt Eden site (where main emission sources are downwind). Secondly, the SWL and SWH types have generally low relationship ratios (< 1). Thus, these weather types, compared with others, have a lower probability of being related to high pollution levels. Thirdly, the NWL and TO types have large ratios for the Mt Eden NO_2, consistent with the significantly above normal mean NO_2 concentrations shown in Figure 3. This further highlights the significant air quality impact of the Auckland CBD on downwind residential areas.

In summary, the above findings illustrate that local air quality can be related to synoptic weather types. The weather-air quality relationship may differ between sites due to the coupling of local meteorological conditions such as wind, temperature, solar input, humidity and rainfall associated with specific synoptic types, and spatial variations in emission sources relative to a monitoring site. Examination of the synoptic weather types that are most highly correlated with extreme pollution events have provided additional information on the linkages between mean pollution conditions, synoptic types and land use (emission sources) in urban Auckland. The analysis has provided a detailed insight into the synoptic control of air quality within a holistic framework, supplementary to Jiang et al. (2005) who examined the local meteorology-morning rush hour NOx concentrations relationship.

3.3 Synoptic controls on extreme meteorological conditions

Meteorological conditions play a critical role in local and regional air quality. This section investigates the influence of synoptic weather types on meteorological conditions associated with poor air quality conditions. Jiang et al. (2005) indicated that, if the weather is cold and calm during the morning rush hour period when traffic volume is relatively high, there is a higher potential for pollution events to occur. Wind speed is most important in determining the transport and dispersion of pollutants in Auckland (Jiang, 2000). Lower temperatures induce higher NOx emission rates from motor vehicles (Lenner *et al.*, 1983; Lenner, 1987). Below normal early morning temperatures are often associated with inversions due to strong radiative surface cooling and air subsidence during calm, cloudless nights under slow-eastward-migrating anticyclones (Sturman and Tapper, 1996). Solar radiation inputs influence NOx chemistry and formation of secondary pollutants such as O_3 (Jiang et al., 2005). Precipitation cleanses the air of particulates (aerosols) through wet deposition (Davis and Gay, 1993a), but may also increase the overall emission rate due to the higher probability of traffic congestion on main busy roads (Jiang, 2000). These factors are generally non-anthropogenic, but can influence the overall airshed quality in Auckland.

Hence, similar to the pollution events analysis described earlier, relative relationship ratios were also calculated for the upper and lower 25% of days for each meteorological variable, by synoptic type (Table 4). By analysing the larger ratio values (though not all are statistically significant), tentative conclusions can be reached as to the extreme conditions associated with each synoptic type. In general, extremely light winds (calm), cold and humid conditions correlate to weather types associated with poor air quality, but windier and less humid conditions correspond to weather types that help maintain good air quality. For example, the synoptic types associated with extremely low wind speeds and low early morning temperatures include the two clusters with poor mean air quality levels (HLW and H). This is consistent with the findings of Jiang et al. (2005) and confirms that wind

		SWH	NEH	NWH	SEH	H	SWL	HLE	NWL	TO	HLW
Overall frequency (%)		22.4	4.2	18.4	4.4	8.5	20.0	4.6	7.7	5.0	4.7
Frequency of upper 25% days (%)	Wind speed	28.3	3.0	6.5	3.0	0.9	42.2	1.7	8.7	4.8	0.9
	Dry bulb temperature	22.6	4.3	18.3	0.9	5.2	21.7	0.9	15.2	7.4	3.5
	Dew point	17.9	3.5	20.1	1.7	5.7	17.9	0.4	17.5	12.2	3.1
	Solar radiation	20.0	1.7	17.5	1.7	15.0	19.2	9.2	6.7	4.2	5.0
	Relative humidity	15.3	4.4	24.9	2.2	16.2	6.6	2.2	11.8	10.5	6.1
	24 hour rainfall	10.7	6.0	25.6	0.6	1.8	29.2	1.8	12.5	4.8	7.1
Frequency of lower 25% days (%)	Wind speed	16.1	4.8	25.7	2.2	20.4	5.7	7.0	2.6	4.3	11.3
	Dry bulb temperature	17.0	3.5	20.4	10.0	17.8	7.8	11.7	2.2	1.7	7.8
	Dew point	20.5	4.4	13.1	12.2	13.5	16.6	11.8	1.3	0.0	6.6
	Solar radiation	22.5	5.0	33.3	0.8	5.0	7.5	1.7	13.3	6.7	4.2
	Relative humidity	30.1	1.7	10.9	6.6	3.5	34.1	8.3	2.2	0.9	1.7
	24 hour rainfall	25.6	4.2	14.9	10.1	11.9	14.9	6.0	2.4	4.2	6.0
Ratio of upper 25% days	Wind speed	1.3	0.7	0.4	0.7	0.1	2.1	0.4	1.1	1.0	0.2
	Dry bulb temperature	1.0	1.0	1.0	0.2	0.6	1.1	0.2	2.0	1.5	0.7
	Dew point	0.8	0.8	1.1	0.4	0.7	0.9	0.1	2.3	2.4	0.7
	Solar radiation	0.9	0.4	1.0	0.4	1.8	1.0	2.0	0.9	0.8	1.1
	Relative humidity	0.7	1.0	1.4	0.5	1.9	0.3	0.5	1.5	2.1	1.3
	24 hour rainfall	0.5	1.4	1.4	0.1	0.2	1.5	0.4	1.6	1.0	1.5
Ratio of lower 25% days	Wind speed	0.7	1.1	1.4	0.5	2.4	0.3	1.5	0.3	0.9	2.4
	Dry bulb temperature	0.8	0.8	1.1	2.3	2.1	0.4	2.6	0.3	0.3	1.7
	Dew point	0.9	1.0	0.7	2.8	1.6	0.8	2.6	0.2	0.0	1.4
	Solar radiation	1.0	1.2	1.8	0.2	0.6	0.4	0.4	1.7	1.3	0.9
	Relative humidity	1.3	0.4	0.6	1.5	0.4	1.7	1.8	0.3	0.2	0.4
	24 hour rainfall	1.1	1.0	0.8	2.3	1.4	0.7	1.3	0.3	0.8	1.3
Description of extreme meteorological conditions		Maybe windy dry	Maybe cloudy rainy	Cloudy, maybe calm humid rainy	Cold and dry	Calm cold sunny humid	Windy low humidity, maybe rainy	Cold low humidity sunny, maybe calm	Warm cloudy, maybe humid rainy	Warm humid, maybe cloudy	Calm cold, maybe humid rainy

Table 4. Relationship between synoptic weather types and extreme meteorological events in Auckland. The ratio is expressed as a ratio of the percentage of days in the upper or lower 25% for the meteorological variables to the overall percentage of occurrence of the particular weather type.

speed and, to a lesser extent, temperature are important factors in morning rush hour NOx variations. However, the HLE type is also associated with low temperatures and light winds, but not with high pollution levels, except for NO at the Penrose site (due to the coupling effect of solar radiation and upwind emissions). These results further highlight the benefits of a synoptic climatological approach to air quality analysis, since the wind speed-temperature-air quality relationship is confounded by correlations between air quality, solar radiation, relative humidity, rainfall, pollution chemistry and local emissions. Further examinations of the meteorology-air quality relationships could be conducted for each synoptic weather type using partitioned datasets. However this requires larger data sets than are presently available.

4. Summary and Conclusion

A synoptic climatological approach has been applied to air quality problems in the Auckland context. The dominant weather types have been identified and related to local meteorology and air quality. The analysis has been focused on the morning rush hour in winter months when pollutant concentrations are typically high in this region. The use of air quality data from two sites, and of both NO_2 and NO concentrations, has facilitated examination of meteorologically-induced variability in air quality in the context of land use and hence spatial variations in emissions. The main findings are summarized as follows:

1) Ten representative weather types have been identified for the New Zealand region, using a new two-stage classification scheme (T-mode PCA followed by K-means clustering via S-mode PCA). All types have counterparts in previous analyses and are associated with distinctive local meteorological conditions. Although the thermodynamic variables, such as wind, temperature, and relative humidity, were not used explicitly to determine the synoptic weather types, they are associated collectively and distinctively with each synoptic category. This is very significant due to the limitation of data availability, including the absence of meteorological data at the air quality monitoring sites (the air quality monitoring network used at the time of this study, especially at the

long-term sites, did not have the meteorological monitoring component).

2) Two anticyclonic weather types are associated with high regional pollution and locally severe pollution episodes, as the relatively stable boundary conditions suppress vertical mixing as well as transport and dispersion of pollutants. The westerly to southwesterly flow types, which are relatively more persistent in time and characterized by strong local winds, help maintain good air quality due to enhanced ventilation. These results are somewhat different from studies elsewhere. For example, McGregor and Bamzelis (1995) indicated that cyclonic conditions are most effective in producing non-severe pollution conditions, while they also found that high level NO and NO_2 concentrations are related to anticyclonic types in Birmingam, UK. However, Shahgedanova et al. (1998) examined the air pollution synoptic climatology in industrial Moscow, and found that extremely cold anticyclonic conditions in winter result in low NO_2 levels. Such differences between studies are likely caused by the different complexity and nature of land use and thus emission sources and their interactions with local meteorology and climatology within different urban cities. This was highlighted by the study of Greene et al. (1999) who examined the synoptic climatology-atmospheric pollution relationships at four US cities and found that the cities have substantially different relationships.
3) The cyclonic types, characterized by unstable boundary layer conditions in Auckland, are not necessarily associated with low pollutant concentrations, but can actually provide significantly high NO_2 concentrations downwind from the significant source area - the Auckland CBD. This highlights the significant impacts of such sources on downwind residential areas, and may also indicate the possible effects of downward transport of ozone from the upper troposphere on local nitrogen oxides concentrations.
4) The weather type-air quality relationship varies from site to site due to

the coupling effects of local meteorological conditions such as wind regimes, rainfall, humidity, temperature and solar input, and variations in major emission sources surrounding each monitoring site. Such interactions indicate that, in a synoptic approach to air quality problems in urban regions, it is important to consider the effects of different patterns of land use (thus emissions) to seek a physically meaningful assessment of the air quality impacts of weather conditions. This is significant because of the spatial and temporal complexity of emission sources in urban areas and their interactions with meteorology and the modified urban environment, which is not sufficiently addressed except for in the work by Shahgedanova et al. (1998).

5) In addition, solar radiation may be important in determining morning rush hour nitrogen oxides concentrations in Auckland. Implied in this is a holistic effect of synoptic weather conditions on NO/NO_2 chemistry (Jiang et al., 2005), which in turn could affect the overall pollution loads and production of secondary pollutants such as ozone in the Auckland airshed. Also, it appears that weather-emission rate interactions may play an important role in determining Auckland's nitrogen oxides concentrations, as weather conditions can modulate road traffic conditions, subsequently total vehicle emission loads.

This analysis has confirmed that the weather typing approach is not only capable of reflecting the effects of local conditions associated with both emissions and local meteorology, but also provides an integrated evaluation of the potential impacts of synoptic weather on the regional meteorology and air quality. This demonstrates the utility of a synoptic approach, specifically the new two-stage weather map classification procedure, for air quality studies. This study has not only confirmed the results in Jiang et al. (2005), but also provided further insight into the complex weather-air quality relationship within a holistic framework. Although exploratory in nature, the results and approach described here could be useful for studies of extensive environmental problems that respond at the synoptic scale. For example, the weather type-air quality relationship identified could be indicative of possible changes in regional air quality potentials in relation to ENSO episodes and the Interdecadal Pacific Oscillation (Folland et al., 2003; Salinger and Mullan, 1999). Jiang et al. (2004) showed that the relationship between synoptic weather types and local meteorology is consistent over time, while the frequency of some synoptic types changes significantly with the SOI phases. The method and findings can also be used to develop a weather forecast-pollution potential warning system for the study area, and to investigate the differential and/or synergistic impacts of climate and pollution on human health (such as mortality), for example, in Auckland and Christchurch. Future work could also point to an extension of this study through the use of longer datasets and other pollutants such as ozone, and through the application and validation of the new classification scheme in a broader context.

Acknowledgments

We are grateful to Dr. John Kidson, Dr. Jim Renwick, and Dr. Daniela Belberova, NIWA, New Zealand for facilitating access to relevant meteorological data; to Dr. Harshela Narsey, ESR, New Zealand for facilitating access to air quality data; to Dr. Radan Huth, Department of Climatology, Institute of Atmospheric Physics, Czech Republic for providing materials on weather typing using T-mode principal component analysis; to Prof. Howard Bridgman, School of Environmental and Life Sciences, University of Newcastle, Australia and unknown referees for useful 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), 1997. *Ambient Air Quality: Monitoring results for the Auckland region 1964-1995.* Technical Publication No.88, ISSN 1172-6415.

Barry, R. G. and Perry, A. H., 1973. *Synoptic Climatology Methods and Applicati*ons, Methuen, London, 555pp.

Comrie, A.C., 1992. An enhanced synoptic climatology of ozone using a sequencing technique. *Phys. Geog.*, **13**, 53-65.

Comrie, A.C. and Yarnal, B., 1992. Relationships between synoptic-scale atmospheric circulation and ozone concentrations in metropolitan Pittsburgh, Pennsylvania. *Atmos. Environ.*, **26B**, 301-312.

Davis, R. E. and D. A. Gay, 1993b. An assessment of air quality variations in the Southwestern USA using an upper air synoptic climatology*. Int. J. Climatol.*, **13**, 755-781.

Davis, R. E. and D. A., Gay, 1993a. A synoptic climatological analysis of air quality in the Grand Canyon National Park. *Atmospheric Environment*, **27A**, 713-727.

Ding, C. and He, X., 2004. *K-means clustering via principal component analysis*. Proceedings of the 21st International Conference on Machine Learning, Banff, Canada, 2004.

Folland, C. K., Salinger, M. J., Jiang, N., Rayner, N. A., 2003. Trends and variations in South Pacific island and ocean surface temperatures. *Journal of Climate,* **16**, 2859-2874.

Greene, J. S., Kalkstein, L. S., Ye, H., Smoyer, K., 1999. Relationships between synoptic climatology and atmospheric pollution at 4 US cities. *Theoretical and Applied Climatology*, **62**, 163-174.

Heidorn, K. C. and Yap, D., 1986. A synoptic climatology for surface ozone concentrations in southern Ontario, 1976-1981. *Atmos. Environ.*, **20**, 695-703.

Hessell, J., 1988. *The climate and weather of the Auckland region*. Miscellaneous Publication 115(20), New Zealand Meteorological Services, Wellington.

Huth, R., 1996a. An intercomparison of computer-assisted circulation classification methods. *Int. J. Climatol.,* **16**, 893-922.

Huth, R., 1996b. Properties of the circulation classification scheme based on the rotated principal component analysis*. Meteorol. Atmos. Phys.*, **59**, 217-233.

Jiang, N., 2000. *Quality of the Auckland Airshed*. PhD thesis, University of Auckland. UMI Publication Number AAT 3112534, ISBN 0-496-60046-7, ProQuest Information and Learning Company, pp.292.

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,** 3-23.

Jiang, N., Hay, J. E., Fisher, G. W., 2005. Effects of meteorological conditions on concentrations of nitrogen oxides in Auckland. *Weather and Climate*, **24**, 15-34.

Kalkstein, L. S. and Corrigan, P., 1986. A synoptic climatological approach for environmental analysis: assessment of sulfur dioxide concentrations. *Ann. Assoc. Am. Geogr.*, **76,** 381-395.

Kidson, J. W., 1994a. An automated procedure for the identification of synoptic types applied to the New Zealand region*, Int. J. Climatol.*, **14,** 711-721.

Kidson, J. W., 1997. The utility of surface and upper air data in synoptic climatological specification of surface climatic variables. *Int. J. Climatol.*, **17**, 1-15.

Kidson, J. W., 2000. An analysis of New Zealand synoptic types and their use in defining weather regimes*. Int. J. Climatol.*, **20**, 299-316.

Lenner, M., 1987. Nitrogen dioxide in exhaust emissions from motor vehicles. *Atmospheric Environment,* **21**, 37-43.

Lenner, M., Linqvist, O., Rosen, A., 1983. The NO_2/NOx ratio in emission from gasoline powered cars: high NO_2 percentage in idle engine measurements, *Atmospheric Environment*, **17**, 1359-1398.

MacQueen, J., 1967. Some methods for classification and analysis of multivariate observations. *Proc. Fifth Berk. Symp. Math. Stat. Prob***., 1,** 281-297.

McGregor, G. R. and Bamzelis, 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.

McKendry, I. G., 1994. Synoptic circulation and summertime ground-level ozone concentrations at Vancouver, British Columbia. *J. Appl. Meteorol.*, **33**, 627-641.

Muller, R. A. and Jackson, A. L., 1985. Estimates of air quality potential at Shreveport, Louisiana. *J. Clim. Appl. Met.*, **24,** 293-301.

Richman, M. B., 1986. Rotation of principal components. *Journal of Climatology*, **6**, 293-335.

Shahgedanova, M., Burt, T. P., Davies, T. D., 1998. Synoptic climatology of air pollution in Moscow. *Theoretical and Applied Climatology*, **61**, 85-102.

Sturman, A. P. and Tapper, N. J., 1996. *The Weather and Climate of Australia and New Zealand*. Oxford University Press, Melbourne, pp.476.

Tukey, J. W., 1953. *The problem of Multiple Comparisons*. Dittoed manuscript, 396pp. Department of Statistics, Princeton University, New Jersey.

Uno, I., Ohara, T., Wakamatsu, S., 1996. Analysis of wintertime NO_2 pollution in the Tokyo metropolitan area. *Atmospheric Environment*, **30**, 703-713.

Zelenka, M. P., 1997. An analysis of the meteorological parameters affecting ambient concentrations of acid aerosols in Uniontown, Pennsylvania. *Atmospheric Environment,* **31**, 869-878.

Submitted to Weather and Climate February 2005, revised August 2005.