

Classification of synoptic weather types using the self-organising map and its application to climate and air quality data visualisation

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Abstract

The classification and visualisation utility of the self-organising map (SOM) method was explored in the New Zealand context using the NCEP/NCAR geopotential height reanalysis and local (Auckland) meteorological and air quality data. A new synoptic classification was derived from the geopotential height data for the New Zealand region, consisting of 25 types that are self-organised (topologically-ordered) on the SOM plane. The classification has not only reproduced the typical synoptic types previously identified in the literature, but also provided an opportunity to visualise the evolution of eastward-migrating synoptic systems over New Zealand. The topologically-ordered display of synoptic types on the SOM plane facilitated visualisation and identification of the synoptic types/local meteorology/air quality relationships in urban Auckland under a holistic framework. In particular, the projection of ozone (O₃) and NO_x (NO and NO₂) data on the SOM plane provides important insights into how synoptic systems affect local NO_x and O₃ concentrations in urban Auckland. For example, the downward transport (from the upper troposphere/stratosphere) and mixing-in of O₃ under cyclonic conditions and the advection of clean air from open ocean waters under blocking states are two of the main synoptic-scale mechanisms that modulate daily highs and lows of O₃ and NO_x in regional Auckland, bearing in mind that the coupling of local emissions, chemical processes and local meteorology is the major determinant of local air pollution. The results from this study are useful for air quality management in Auckland or similar regions, and also provide a basis for a more comprehensive assessment of the impact of weather and climatic conditions on the quality of the regional airshed.

Keywords: self-organising map (SOM), synoptic type, local meteorology, air quality, data visualisation

1. Introduction

Many map classification techniques can be found in the literature - these can be purely subjective (manual), computer-assisted (objective), or a mixture of both [refer to Jiang (2010a) for details]. The

most commonly-used objective methods include the correlation method (Lund, 1963), the sums-of-squares method (Kirchhofer, 1973), cluster analysis (e.g., Kidson, 2000) and principal component analysis (PCA) (Huth, 1996). Some researchers have

advocated the use of a hybrid procedure for blending manual and objective classifications as complementary methods (e.g., Frakes and Yarnal, 1997). However, such methods generally have fewer applications in practice, mainly due to the demand for extra human labour when dealing with large datasets (Jiang, 2010a). More recently, a two-stage mixed procedure, consisting of obliquely rotated T-mode PCA followed by K-means clustering, was reported in the literature (e.g., Huth, 2001; Jiang et al., 2011a). In recent years, the self-organizing map (SOM) algorithm/method has become increasingly popular in a wide variety of disciplines, including climate research (Jiang, 2010b; Sheridan and Lee, 2011). Hewitson and Crane (2002) have suggested that the use of the SOM to analyse and organise atmospheric circulation data represents a new way of creating synoptic climatology. Ultimately, the most appropriate method(s) for a particular application is largely dependent on the scientist's experience and domain knowledge (Casado et al., 2009).

Several synoptic classifications exist for New Zealand [details in Jiang et al. (2012)]. The major classifications include the synoptic analogues derived by Kidson (1994), Kidson (1997) and Kidson (2000) using cluster analysis (e.g., K-means) and those by Jiang (2000), Jiang et al. (2004, 2005b) and Jiang (2010a) based on weather-typing procedures using T-mode principal component analysis (PCA) or its variants. While these classifications have applications to many environmental problems in New Zealand (e.g., Kidson, 1997; Kidson, 2000; Gosai et al., 2003; Jiang et al., 2005b; Lorrey et al., 2007; Purdie et al., 2011; Jiang et al., 2011b; Griffiths, 2011), to the best knowledge of the

author, there appears to be no application reported in the literature of using the SOM method for the region. Hence, an investigation on the utility of the SOM was undertaken in the New Zealand context.

NO_x and O₃ are interrelated pollutant species that have attracted great public and scientific attention in Auckland. This is in part due to their potential linkage to some public health problems, including the recurrence of a brown haze phenomenon and high prevalence of asthma amongst young children in the region (MFE, 2003; Jiang et al., 2005a; Asher and Byrne, 2006). While variations in NO_x and O₃ concentrations may be influenced by emissions (ARC, 2006a) and chemical processes (e.g., the NO_x/O₃/VOCs chemistry), the role of weather and climatic conditions must also be investigated (Jiang et al., 2005a; Tong et al., 2011). The synoptic type/local meteorology/air quality relationships in Auckland have previously been explored by Jiang (2000), and more recently, Jiang et al., (2005a, b), Khan et al. (2007) and Jiang et al. (2011c), showing that both local meteorology and synoptic circulations have significant effects on local air quality.

This paper extends the studies by Jiang et al. (2004; 2005a, b), Khan et al. (2007) and Jiang et al. (2011c), based on longer data, to demonstrate the potential utility of the SOM method for data classification and visualisation in the New Zealand context. A new synoptic climatological classification was derived from the 53-year NCEP/NCAR geopotential height data (Section 2), which was then linked to the local meteorological and air quality data for urban Auckland (Section 3). The results from this analysis form the

basis of further studies of air quality in Auckland.

2. Data and methods

2.1 NCEP/NCAR geopotential height data

The data used to derive a synoptic climatological index consisted of twice daily (0 and 12 UTC) NCEP/NCAR 1000hPa geopotential height reanalysis for 1958-2010 (Kalnay et al., 1996). The study area covers latitudes 25°S-55°S and longitudes 155°E-170°W at a 2.5°×2.5° resolution (i.e., with a total of 195 grid points). The coverage area was made larger in longitude than most previous studies for New Zealand (e.g., Kidson, 2000; Jiang et al., 2004), so that the eastward migration of synoptic systems would be better captured by taking advantage of the SOM methodology (Jiang et al., 2011c). The data were not standardised so that the subtle changes in weather systems are retained and dealt with by the classification procedure (Jiang et al., 2011a).

2.2 Local meteorological data

Meteorological data were obtained from the Auckland Airport weather station (New Zealand National Climate Database). The dataset consisted of 24-hour rainfall totals and hourly measurements of wind speed, wind direction, air temperature, relative humidity, mean-sea-level air pressure (MSLP) and global solar radiation. The hourly wind vector was converted into its west-east (u) and south-north (v) components. Based on the hourly records, daily average values were calculated for each variable for the period of 1962-2009 (except rainfall for which the 24-hour totals were used). Seasonality was suppressed from the daily values for each variable by subtracting the monthly mean

climatology for 1970-2009, so as to focus on the day-to-day variations in local meteorology (Jiang et al., 2012). The resulting daily anomalies were used to derive local meteorological indices that summarise the typical local meteorological patterns observed in Auckland. It is acknowledged that single-site data may not be fully representative of meteorological conditions at other locations, especially during the summertime when sea breezes develop and the local meteorology becomes more complex. In particular, surface wind conditions at the (elevated) Queen Street monitoring site (Section 2.3) are expected to be (to some degree) different from those at the Auckland Airport. In general, however, studies have shown that meteorological variables at various locations in urban Auckland are highly correlated (Clarkson and Fisher, 2000).

2.3 Air quality data

Hourly pollutant concentration data were obtained from the Auckland Council (Table 1). These include hourly NO₂ and NO concentrations (µg/m³) for the Musick Point and Queen St sites, and hourly O₃ concentrations (µg/m³) for the Musick Point and Sky Tower sites. Based on those records, daily average concentrations were calculated for individual sites and pollutants. These daily averages were used in the present analysis without further treatments (e.g., detrending), mainly for easy interpretation of the results. Removal of trends and/or seasonal variations was attempted but it demonstrated a negligible impact on the findings (patterns) reported in this paper.

Site name	Pollutant	Site type	Data period	Mean	Standard deviation	Minimum	Maximum
Musick Point	NO	Coastal	1999-2009	2.6	5.0	0.0	57.4
	NO ₂	Coastal	1999-2009	8.2	7.4	0.0	51.5
	O ₃	Coastal	1999-2009	41.8	13.1	6.2	99.7
Queen St	NO	CBD	2004-2009	88.9	49.2	2.3	330.9
	NO ₂	CBD	2004-2009	50.9	17.1	3.6	101.0
Sky Tower	O ₃	Elevated	2009 ⁸² 2004	48.3	12.7	16.6	82.5

Table 1. Summary statistics of the pollutant concentration ($\mu\text{g}/\text{m}^3$) data from three sites.

The three selected monitoring sites represent spatially different contexts of land-use types (thus emission conditions) in Auckland (Figure 1). The Musick Point site is situated near the tip of the Musick Point peninsular that extends north into the Hauraki Gulf, with open-ocean waters located to the north and east. Residential houses (of which about 30% have chimneys) are mainly located at the southern end of the peninsular (ARC, 2006b). The Auckland city centre is located to the west (12 km away) of the monitoring site, with the Southern Motorway to the southwest, and the Otahuhu-Penrose industrial area to the south-southwest (11 km away). The sampling inlet at the monitoring site is 15m above ground level. Hence, during westerly, southwesterly or southerly winds, the site is well exposed to Auckland urban emissions (predominantly vehicle and industry-related), but under northerly or easterly flow conditions, measurements of NO_x and O₃ from the instrument are indicative of the regional background

concentrations generally free of human influence (Khan et al, 2007).

Both Queen St and Sky Tower sites are within the Auckland central business area (CBD). Queen St is located in a valley, with a SSW-NNE orientation and sloping gently down to the north. The monitoring site is on the western side of the street and between two traffic light-controlled intersections. All monitoring instruments are installed at a first-floor height and set back by about 3m from Queen Street, so that measurements taken from this site are almost real-time reflecting the nearby road traffic emissions. Airflow canyon/channelling effects are possible at this site due to the existence of tall buildings nearby (ARC, 2006b). The Sky Tower site is not far from Queen St, but with the O₃ monitor installed at about 250m above ground level. The monitor is located on the top level of the Auckland Sky Tower, higher than the top of all surrounding structures and thus well exposed to winds from all



Figure 1. Location of air quality and meteorological monitoring sites.

directions. Due to its high elevation, O_3 concentrations recorded at this site are less influenced by particular ground-level emissions (e.g., NO and NO_2 in individual streets), but largely indicative of the upper-level O_3 concentrations in the urban boundary layer.

2.4 Principal component analysis (PCA)

Meteorological variables are highly inter-correlated with each other. Hence,

rather than using individual variables, in the present study, local meteorological conditions in Auckland have been summarised into local climate indices using the PCA technique described in Jiang et al. (2005a). A P-mode Varimax rotated PCA (Richman, 1986) was conducted on the correlation matrix of the Auckland Airport meteorological variables. The first two leading principal components (PCs), explaining around 60% of the total variance across

those variables, were retained for Varimax rotation. The resulting two rotated PCs were used in this study as local-scale climate indices for Auckland, representing the most dominant local-scale meteorological patterns affecting this area. Certain local meteorological conditions may be under-represented by the two indices. However, the two indices essentially provide a (continuous) solution to the classification of local meteorological conditions (Ding and He, 2004; Jiang et al., 2005b).

2.5 Two-phase batch self-organising map (SOM) classification procedure

The SOM is a non-linear data classification and visualisation method that has become very popular across many disciplines in recent years, including in the field of synoptic climatology (Jiang, 2010b; Sheridan and Lee, 2011). The SOM maps the high-dimensional data points (e.g., weather maps) from the input space onto the nodes (reference vectors, e.g., synoptic types) of a low-dimensional (typically 2-D) map with a topologically-ordered display: similar data items (e.g., weather maps) are projected onto the nearby SOM nodes and dissimilar data items onto the SOM nodes further apart (Kohonen, 2001). In general, SOM mapping may be conducted in two different ways, via a sequential or a batch training algorithm (Kohonen et al., 1996). The batch SOM training algorithm is relatively simple to apply (with no learning rates required), converges fast, and is less (or not) affected by the implementation parameter settings such as the order of data presentation, map initialisation and neighbourhood width (Jiang, 2010b). However, most previous applications of the SOM method in synoptic

climatology were based on the sequential training algorithm.

In this study, a synoptic classification was derived from the geopotential height dataset via a two-phase batch SOM procedure (CP2) detailed in Jiang et al. (2011a). In the first phase, the nodes (reference vectors) of the SOM grid are initialised using the linear method, where a rough estimation of the global patterns is captured by starting off the training with a large initial neighbourhood width that decreases gradually to its researcher-specified minimum value (usually ≥ 1 for data projection) following an iterative process. The second phase involves fine-tuning the SOM mapping and thus obtaining the final data groupings, i.e., SOM nodes. The SOM nodes are initialised with the output reference vectors from the first phase. The training process begins with a small initial neighbourhood width, so that the more localised, non-linear variations among the weather maps are taken into account, i.e., to achieve the local optimum. The number of iterations is set to be large for the second phase, preventing the neighbourhood from shrinking too quickly all the way towards its minimum value, and the training continues until the training process converges. Once the final reference vectors are obtained, each daily weather map is assigned to the SOM node (type) from which it has the smallest squared Euclidean distance.

In the SOM mapping process, a map size (i.e., total number nodes/types on the SOM grid) needs to be assigned. In this study, several SOM map sizes were considered for the geopotential height data. It was found that 5x5 SOM mapping (i.e., having 25 types) is sufficient to reproduce most synoptic types identified in previous studies for

the New Zealand region (e.g., Kidson, 1994; Kidson, 2000; Jiang et al., 2004, 2005b; Jiang, 2010a). To train this SOM, the neighbourhood function was set to “Gaussian” (default), with the neighbourhood width shrinking from 5 to 1 in the first phase within 50,000 iterations, but 2 to 1 for the second phase within 90,000 iterations. A synoptic index/classification was then constructed by allocating each 1000hPa geopotential height map to one of the 25 types on the SOM obtained.

3. Results and discussion

3.1 Local meteorological index – typical meteorological patterns in Auckland

Meteorological conditions in Auckland were summarised with the first two

leading PCs (denoted as PC1 and PC2) from the rotated PCA of the Airport meteorological data (Figure 2). These are used as local-scale meteorological indices for Auckland. The two PCs, together accounting for around 60% (34% and 24%, respectively) of the total variance in the data, mirror the local meteorological patterns identified in Jiang et al. (2005a) for the winter months using shorter meteorological records. As mentioned earlier, the two indices provide a classification of local meteorological conditions in Auckland. As PC loadings are equivalent to correlations between individual meteorological variables and PC time series (Richman, 1986), these PCs can be interpreted as below:

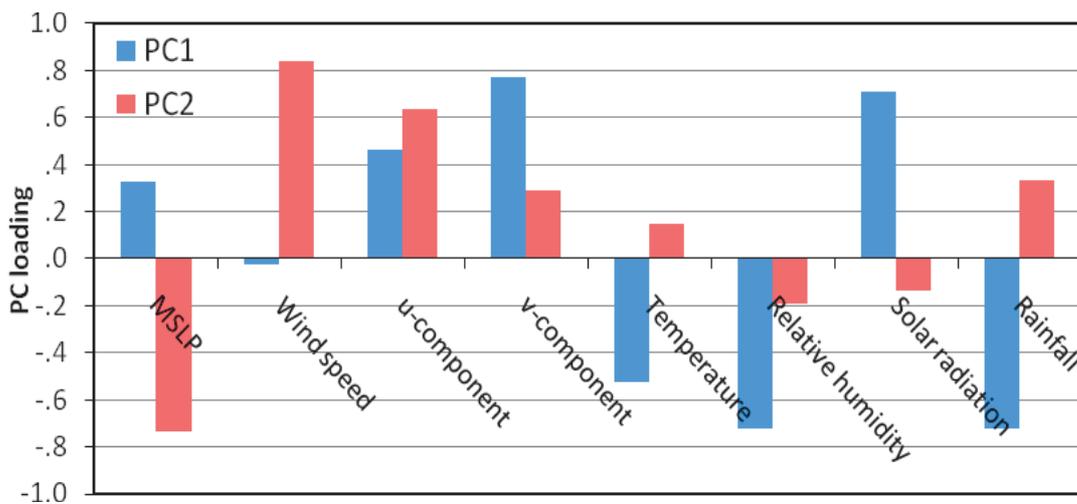


Figure 2. Loadings of the first two PCs from a P-mode Varimax rotated PCA of the Auckland Airport meteorological data.

1) PC1 (SSW/NNE flow condition index) has large positive loadings on v-component and solar radiation and secondarily u-component, but large negative loadings on temperature, relative humidity and rainfall (the loading on MSLP is moderate although positive). Since the PC scores can be positive or negative, this index represents two opposite local weather patterns (expressed as anomalies from

the average conditions; Section 2.2). Days with large positive PC1 scores are characterised by southerly (or southwesterly) airflow conditions, with local weather being relatively colder, drier and sunnier than average conditions. Days with large negative PC1 scores are typical of northerly (or northeasterly) flow conditions, with local weather being relatively warmer,

more humid, wetter and cloudier than average conditions.

2) PC2 (stable/unstable condition index) has large positive loadings on wind speed and u-component, but large negative loadings on MSLP (with only moderately positive loadings on v-component and rainfall). Large PC2 scores indicate the occurrence of two different conditions (expressed as anomalies from the average conditions): a) unstable local conditions (low pressure/cyclonic conditions with a strong westerly wind component) for days with large positive PC2 scores, or b) stable local conditions (high pressure/anticyclonic condition with a light easterly wind component) for days with large negative PC2 scores.

3) However, for days with comparable scores on PC1 and PC2, both PCs together indicate the observed meteorological conditions in Auckland. These represent less typical or more complex local conditions. It is acknowledged that less dominant local meteorological conditions may be under-represented by these two indices.

3.2 Synoptic climatological index – self-organised display of synoptic types on the SOM plane

The resulting synoptic classification (synoptic climatological index) for New Zealand is comprised of 25 synoptic types (Figure 3). This classification has reproduced the typical weather types previously identified by Kidson (2000) and Jiang (2010a) using traditional map classification methods (e.g., K-means). Importantly, in contrast to previous classifications, the SOM-based procedure (CP2) has provided a “self-organised” display of major synoptic situations on the SOM plane/grid: similar types are close to each other, but

dissimilar patterns fall further apart. The westerly trough types are found in the top-right section (e.g., Types 11, 16, 21 and 22), while anticyclonic types (including blocking states) appear in the left and bottom-left sections (e.g., strong anticyclonic types: Types 5, 10 and 9; typical blocking states: Types 2, 3, 4 and 8). The (well-known) dominant south-westerly flow types are near the bottom-right corner of the grid.

The 25 synoptic types have visualised the subtle, nonlinear evolution of eastward migrating synoptic systems over New Zealand. The major transition patterns of synoptic systems are directly identifiable on the SOM plane, characterised by the evolution of synoptic types clockwise along the edge of the grid (Figure 4). The transition patterns are in good agreement with documented local synoptic experience (e.g., Sturman and Tapper, 2008) and those reported in Kidson (2000) and Jiang (2010a) using more traditional analytic methods (e.g., contingency tables).

The frequency of occurrence of the synoptic types is shown on the SOM plane in Figure 3 at the annual level, but in Figure 5 by seasons and Figure 6 by synoptic types. At the annual level, the group size (node size) is less variable (i.e., relatively even) when compared to previous classifications (using conventional methods) for the same region (e.g., Kidson, 2000; Jiang, 2010a). At both annual and seasonal levels, relatively more frequent synoptic types are located at the corners and edges of the SOM grid (Figures 3 and 5; e.g., Types 1, 5, 21 and 25 in Figure 3). However, the occurrence of individual synoptic types does vary considerably with season (Figure 6). The blocking states near the top left-hand corner of

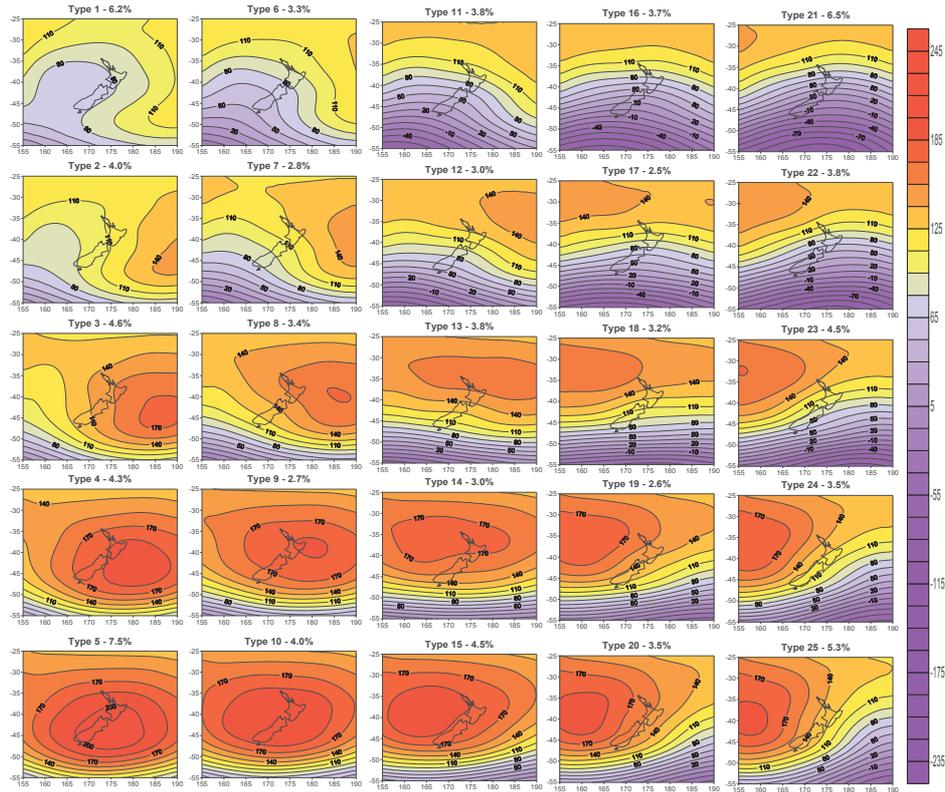


Figure 3. Maps (reference vectors) and frequencies (%) of 25 synoptic types on the SOM plane. Data: twice daily (0 and 12 UTC) 1000hPa NCEP/NCAR geopotential height reanalysis for 1958-2010. Contour interval: 15m.

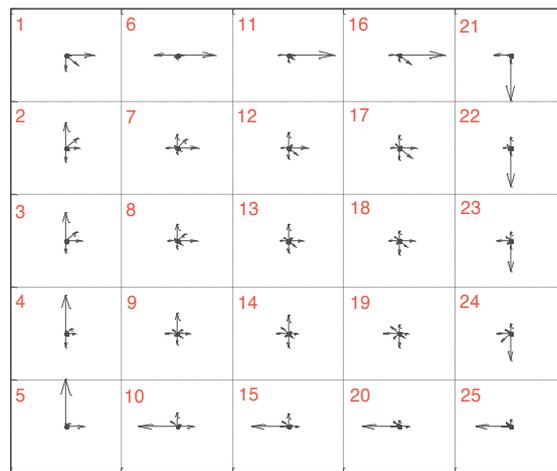


Figure 4. SOM grid overlapped with the forward transition/trajectory pattern of synoptic types. Arrow vectors are expressed as percentages of changes from a given type to a different type after 12 hours over the total number of changes from the source type. A half length or width of the rectangular cell is equivalent to a probability of around 50%.

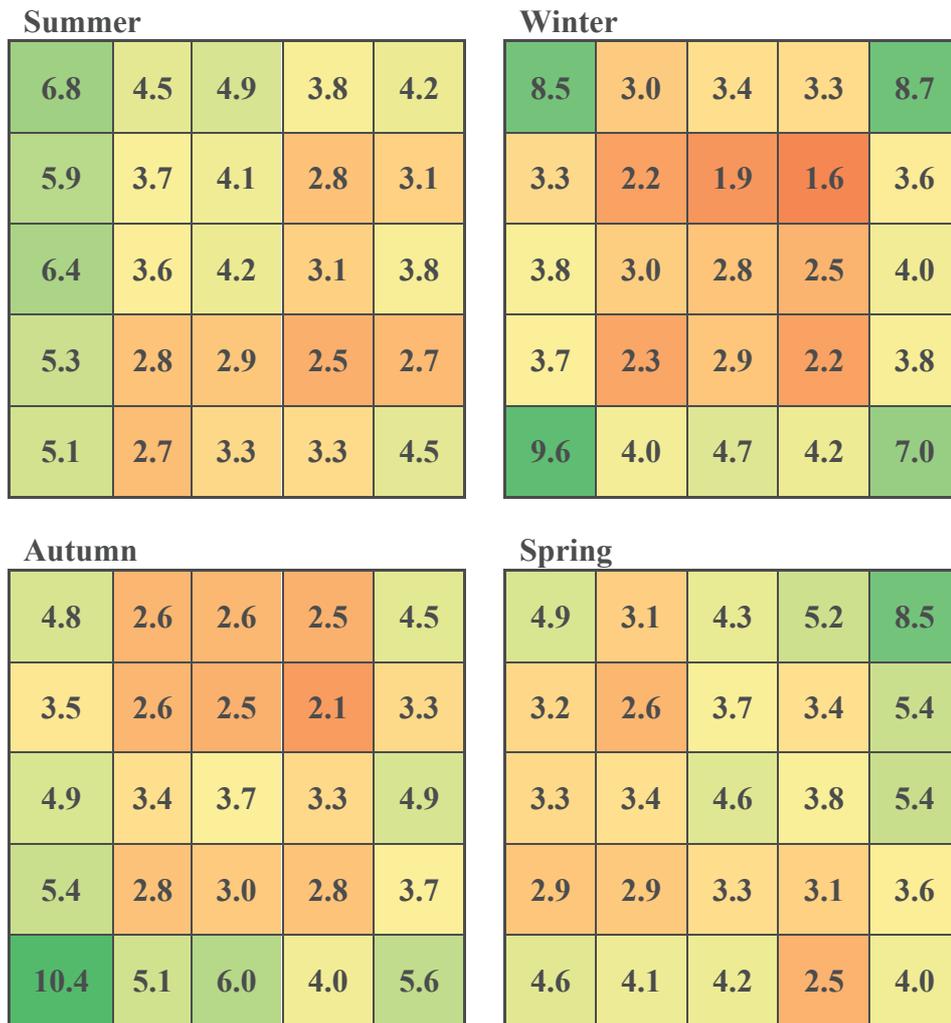


Figure 5. Frequencies (%) of 25 synoptic types in each Austral season plotted on the SOM plane, as in Figure 4. Values are calculated across synoptic types conditional on seasons. Colours are used to highlight low (dark brown) to high (dark green) values.

the SOM are more frequent during summer, while the synoptic types at the four corners of the grid have greater prominence in winter. The westerly trough types near the top-right corner of the SOM show greater prevalence in spring, but those patterns at the bottom-left corner (typical of highs in the south) are more frequent during autumn. Seasonal differences for the transitional types in the middle of the SOM are relatively small compared to other

types. These results are consistent with Jiang (2010a) and Kidson (2000).

3.3 Visualisation of the relationship between local meteorology and synoptic types on the SOM plane.

Understanding the association between local meteorological conditions and synoptic controls is often of interest when dealing with complex environmental issues, such as air

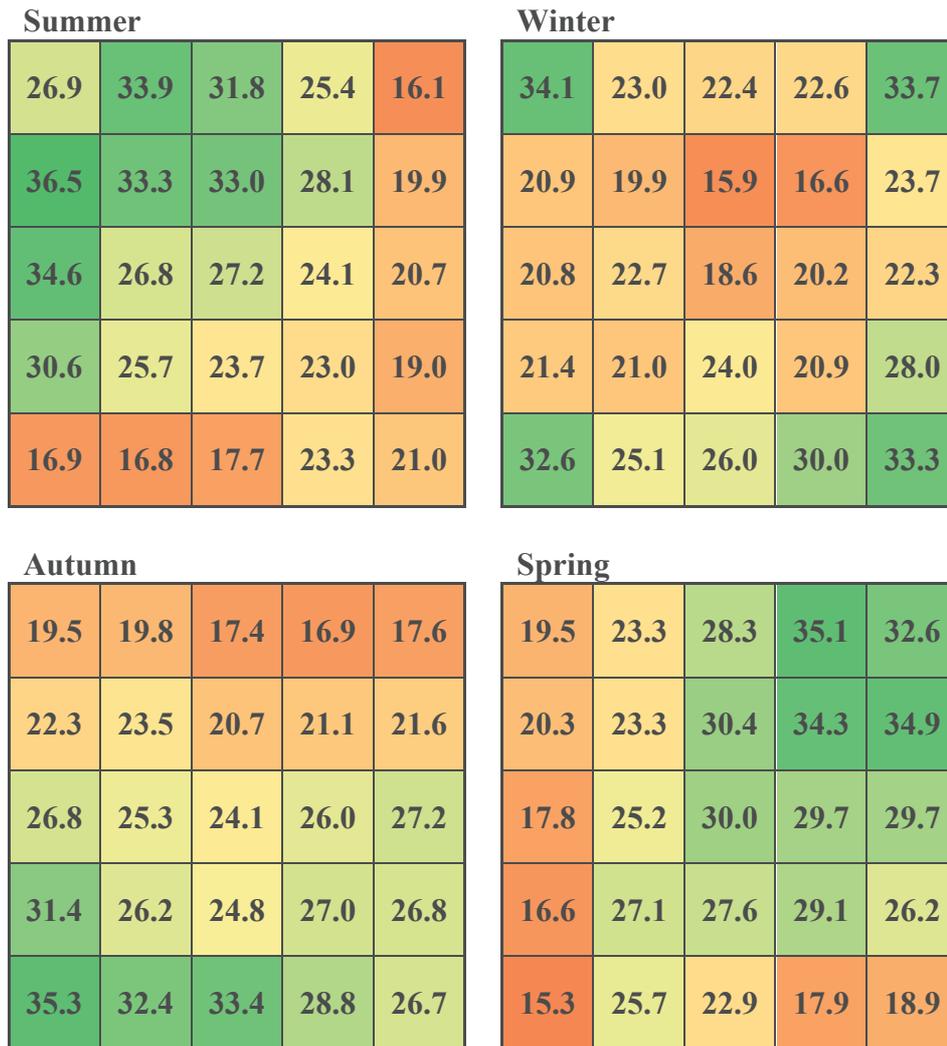


Figure 6. Frequencies (%) of four seasons under each synoptic type plotted on the SOM plane, as in Figure 4. Values are calculated across seasons conditional on synoptic types. Colours are used to highlight low (dark brown) to high (dark green) values.

pollution. In this section, we demonstrate that such across-scale climatic relationships can be transformed into readily recognisable patterns when local meteorological indices (PC1 and PC2) are plotted by synoptic types on the SOM plane (Figure 7). Previous studies (e.g., Jiang, 2000; Jiang et al., 2005a; Carslaw et al., 2007) showed that surface wind plays a significant role in determining the level

of road traffic-related air pollution. Hence, local wind conditions are also plotted by synoptic types on the SOM plane (Figure 8), in order to facilitate the interpretation of results.

As shown in Figure 7, average PC1 (SSW/NNE flow index) and PC2 (stable/unstable condition index) scores vary significantly across synoptic types (p-values < 0.0001 according to

PC1 (SSW/NNE flow condition)					PC2 (stable/unstable condition)				
-0.51	-0.70	-0.60	-0.55	-0.21	0.55	0.33	0.25	0.55	1.40
-0.59	-0.51	-0.24	0.06	0.33	-0.03	-0.26	-0.29	0.22	1.10
-0.54	-0.31	0.10	0.30	0.46	-0.47	-0.76	-0.53	0.04	0.88
-0.21	0.06	0.29	0.43	0.60	-0.65	-0.95	-0.65	-0.05	0.68
0.27	0.42	0.45	0.53	0.55	-0.85	-1.02	-0.69	-0.12	0.46

Figure 7. Mean PC scores by synoptic types on the SOM plane, as in Figure 4. Values in bold are significantly different from zero at the 0.05 level for one sample t-test (allowing for lag-1 serial correlation). Values are coloured from large negative (dark brown) to large positive (yellow).

one-way ANOVA). More importantly, the variation in those average scores manifests as readily distinguishable patterns on the SOM plane. Significant (at the 0.05 level for one sample t-test, allowing for lag-1 serial correlation) negative PC1 scores (NNE flow condition) are found on the synoptic types located in the top-left section. These synoptic types are expected to provide (warm and moist) northerly, northwesterly or northeasterly synoptic flows over Auckland. In contrast, significant positive PC1 scores (SSW flow condition) correspond to synoptic types in the bottom-right section of the SOM grid, which are expected to produce (cold and dry) southerly or southwesterly synoptic flows over most of the country. In general, local winds (Figure 8) are consistent with synoptic flows expected under each weather type, with relatively large wind direction anomalies occurring for Types 16 and 21 and those transitional patterns in the middle of the SOM grid.

On the other hand, significant positive (at the 0.05 level for one sample t-test,

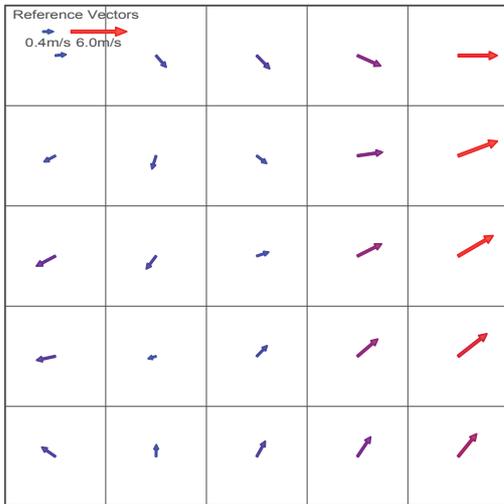
allowing for lag-1 serial correlation) PC2 scores (unstable local conditions) are associated with trough types on the top and right edges (Types 1, 6, 11, 16, 20, 17 and 22 to 25) of the SOM grid. These types are expected to provide cyclonic, unstable conditions over most of New Zealand, typical of westerly synoptic flow components over most of the country. Large negative PC2 scores (stable local conditions) occur on synoptic types that are characterised by an anticyclone over or near New Zealand, providing generally easterly synoptic flow components over the North Island. It is noticed that the average PC scores for a few types are relatively small, i.e., close to zero (insignificant at the 0.05 level for one-sample t-test, allowing for lag-1 serial correlation), indicating the occurrence of more subtle local conditions. Under these synoptic situations, both PC1 and PC2 combine to determine the local response to the synoptic-scale circulations.

In summary, the synoptic classification obtained in the present study provides a

good discrimination of local meteorological conditions in Auckland. The local meteorology-synoptic type relationships displayed on the SOM

plane agree well with general meteorological principles (Sturman and Tapper, 2008) and are also consistent

Local wind (raw data)



Local wind (deseasoned data)

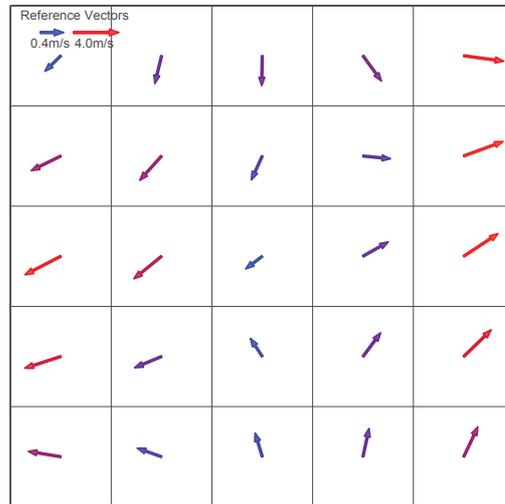


Figure 8. Mean wind vectors (Auckland Airport) by synoptic types on the SOM plane, as in Figure 4. The vectors are reconstructed from daily u and v -components for raw and deseasoned wind data, respectively. An arrow indicates wind direction (north towards top side) and the length of an arrow bar indicates wind speed, as coloured from low (blue) to high (red) speed.

with early studies (e.g., Jiang et al., 2004, 2005b). Synoptic types in general have two types of control effects on local meteorology: a) indicating general flow directions and air mass properties (which interact with local terrain and circulation features); and b) providing background atmospheric stability and ventilation conditions. Such effects facilitate an investigation of the synoptic type-air pollution relationships in the following section.

3.4 Investigating the synoptic control of daily NO_x and O_3 concentrations in Auckland

In this section, we demonstrate the use of the SOM-based synoptic classification for identifying the

relationships between synoptic types and pollutant concentrations for the selected monitoring sites from Auckland (Section 2), including daily NO and NO_2 concentrations at the Queen Street site, O_3 concentrations at the Sky Tower site, and NO , NO_2 and O_3 concentrations at the Musick Point site. The mean pollutant concentrations are curve-plotted by synoptic types in Figure 9, and also contour-plotted on the SOM plane in Figure 10. Again, due to the topologically-ordered display of synoptic types on the SOM grid, the relationships between synoptic types and pollutant concentrations manifest as readily identifiable patterns and trends in Figures 9 and 10 (note: removal of the long-term trend, seasonality and

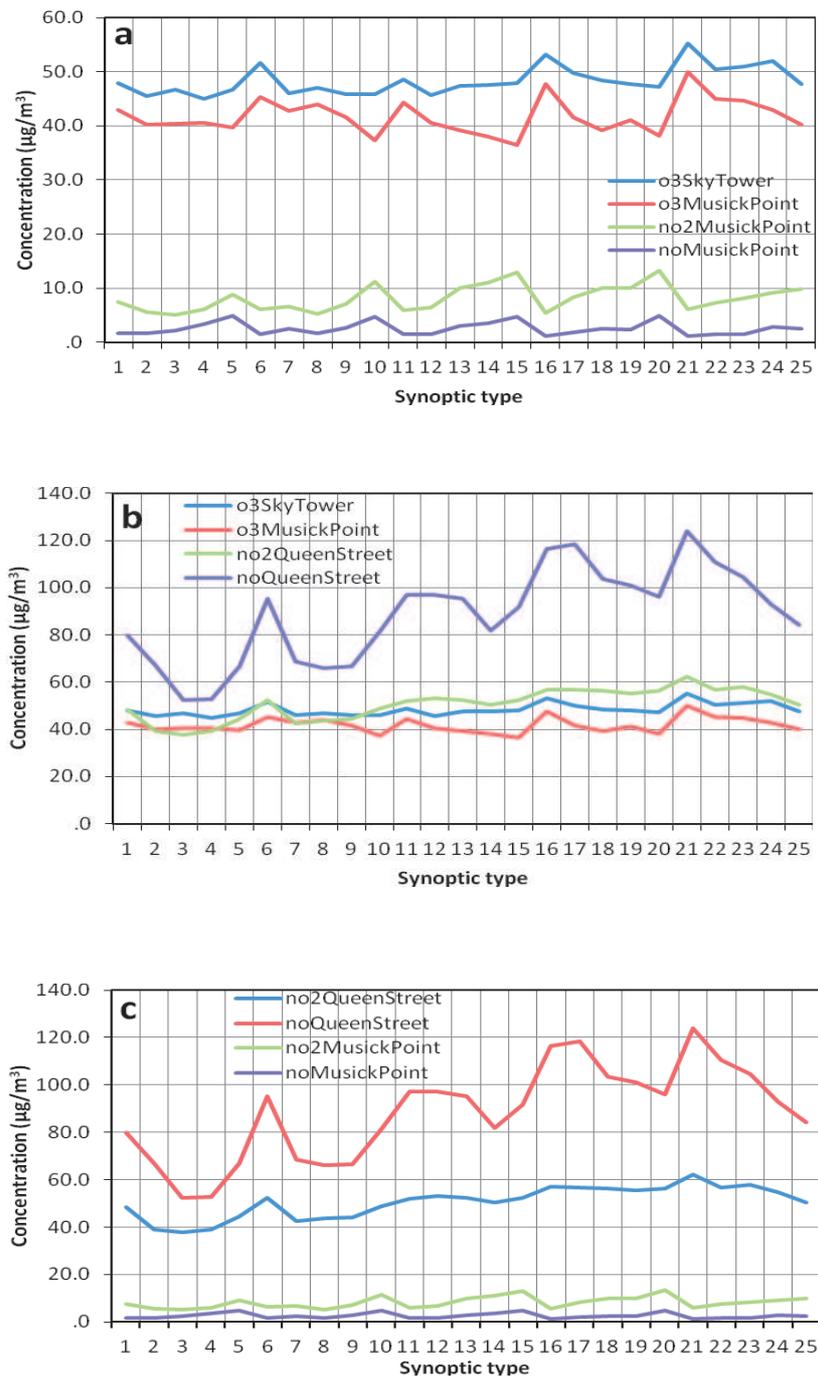


Figure 9. Across-type variations of daily O₃, NO and NO₂ concentrations (µg/m³). Types 1 to 25 are defined the same as in Figure 4. a) O₃ at the Musick Point and Sky Tower sites compared with NO and NO₂ at the Musick Point site; b) NO and NO₂ at the Queen Street site compared with O₃ at the Musick Point and Sky Tower sites; c) NO and NO₂ at the Queen Street and Musick Point sites.

weekly cycle from the NO_x and O₃ data led to similar patterns and trends to those reported here).

3.4.1 Synoptic control of daily NO and NO₂ concentrations at the Queen Street site

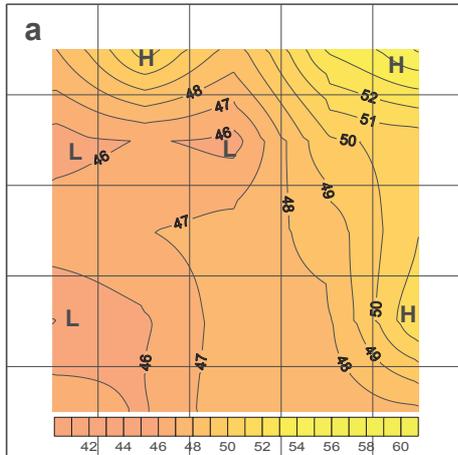
Daily NO and NO₂ concentrations show similar patterns across synoptic types on the SOM plane (Figure 9b; Figures 10c, e). In general, due to proximity to high NO emissions from road traffic, NO₂ concentrations at the Queen Street site can reach, and in most cases exceed, O₃ levels at both the Sky Tower and Musick Point sites, with the exception of Types 2-4 and 7-9 (Figure 9b). This indicates a potential for localised high NO₂ or O₃ events within Auckland city or at downwind locations under favourable meteorological conditions (e.g., under Types 16 and 21).

Cyclonic types, especially those near the top-right corner and right-edge of the SOM grid (e.g., Types 16 and 21 to 23), are associated with high NO and NO₂ concentrations (Figures 10c, e). This finding is consistent with the results of Jiang et al. (2005b), where the cyclonic type/high NO₂ relationship was also reported for the Penrose site (located to the south-southeast of the Auckland CBD). Under high local NO emissions, cyclonic conditions play three competing roles to determine local NO and NO₂ concentrations: 1) the channelling (flow) effect: as Queen Street orientates SSW-NNE, strong westerly to southwesterly (synoptic) flows under the cyclonic types may help entraining (mixing-in) of pollutants from surrounding emission sources (e.g., nearby streets) into the street corridor, leading to high NO and NO₂ measurements (note that surface winds at this site can be different from those at the Auckland Airport, due to strong modification of synoptic flows by tall

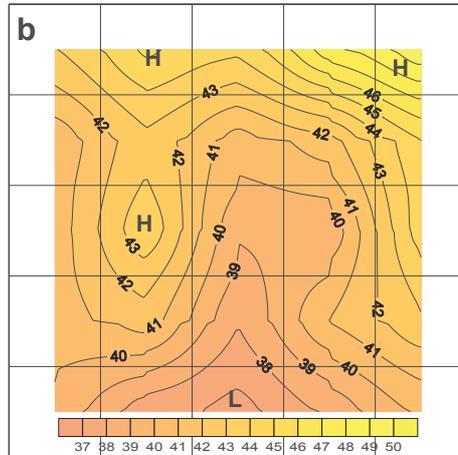
building and street channelling effects); 2) transport and supply of sufficient O₃ (corresponding to high O₃ levels at the Sky Tower site) that enhance NO to NO₂ conversion, contributing to an increase in NO₂ concentrations; and 3) enhanced ventilation/dispersion that helps the removal of pollutants from the site, thus leading to a decrease in pollution levels. Due to the high rate of emissions, the first two roles dominate and lead to elevated NO and NO₂ concentrations at the monitoring site.

In contrast, blocking types near the left edge of the SOM grid are related to low NO and NO₂ (as well as O₃) concentrations. The strong easterly or northeasterly winds under these types facilitate advection of relatively clean (low in NO and NO₂) oceanic air over urban Auckland, helping dilute the highly polluted air in the city corridor. However, the anticyclonic types at the left-bottom edge of the SOM grid are generally associated with moderate NO and NO₂ levels at this site. This is consistent with Jiang et al. (2005b), who reported an anticyclonic type associated with low morning-rush-hour NO₂ concentrations during Auckland winters. These relationships reflect the competing roles of meteorology and chemistry in determining NO and NO₂ concentrations under high local NO emissions (Jiang et al., 2005a). On the one hand, the anticyclonic types provide stable (at times calm) local conditions that suppress ventilation and dispersion of pollutants, leading to elevated concentrations of pollutants due to accumulation effects. On the other hand, the stable local conditions limit the supply of O₃ and thus the NO-to-NO₂ conversion, resulting in moderate NO₂ concentrations (despite the high NO emissions) – this effect appears more significant at the site.

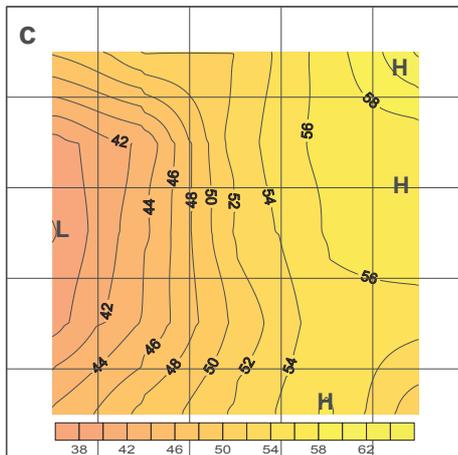
Sky Tower O3



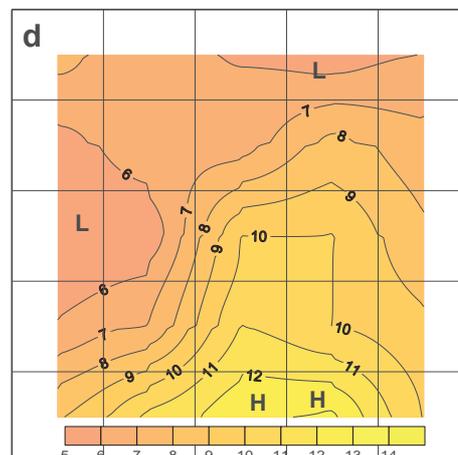
Musick Point O3



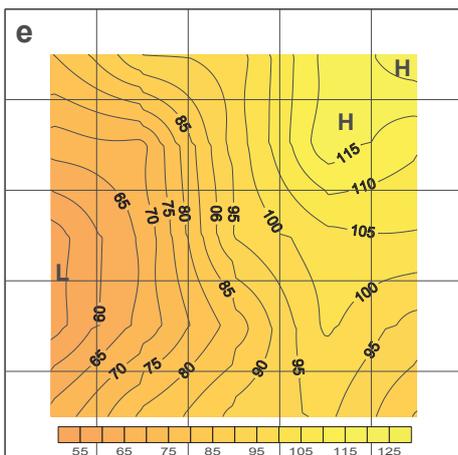
Queen St NO2



Musick Point NO2



Queen St NO



Musick Point NO

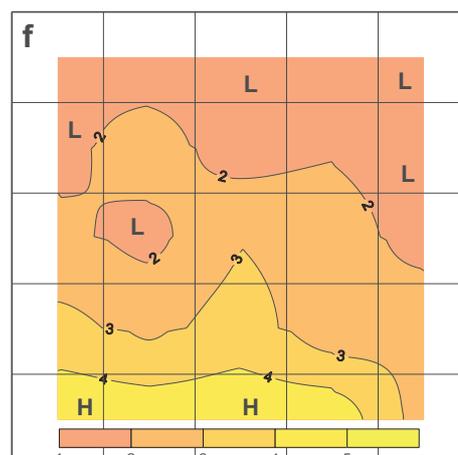


Figure 10. Daily ozone, NO and NO₂ concentrations ($\mu\text{g}/\text{m}^3$) by 25 synoptic types on the SOM plane, as in Figure 4. The patterns are similar when linear trend, seasonality and weekly cycle in daily NO and NO₂ concentrations are removed (not shown).

3.4.2 Synoptic control of daily NO and NO₂ concentrations at the Musick Point site

Concentrations of NO and NO₂ have generally similar across-type variation patterns (Figure 9a; Figures 10d, f), and, as expected, these patterns are out-of-phase with the variation in O₃ concentrations (Figure 10b). Anticyclonic types at the bottom of the SOM grid, typical of strong southerly flows in Auckland (Figure 8), are associated with high NO and NO₂ (but low O₃) levels. This may be interpreted in two ways: a) anticyclonic types provide stable local conditions that limit and suppress pollutant dispersion; and b) the southerly winds facilitate the transport of NO_x upwind from the “Auckland urban plume” where the emitted NO is mostly already converted to NO₂ through O₃ destruction (titration).

In contrast, westerly trough types on the top edge of the SOM, which are typical of unstable local meteorological conditions in Auckland (Figures 7, 8), are related to low NO and NO₂ concentrations (but high O₃ levels), due to enhanced dispersion/ventilation and the intrusion of clean oceanic air. It is notable that blocking types, associated with northeasterly ocean winds, generally correspond to low NO and NO₂ (but high O₃) concentrations at this site. As will be further discussed in Section 3.4.3, measurements under such conditions are determined by the background NO, NO₂ and O₃ concentrations within relatively clean air coming from the northeast quadrant over the open ocean waters (where anthropogenic emissions are generally limited).

In summary, these findings are consistent with those by other studies (Tong et al., 2011; Lee et al., 2012; Khan et al., 2007). For example, Khan et al. (2007) identified a similar correlation between cyclonic/anticyclonic conditions and night-time O₃/NO_x concentrations using short data for the same site. However, it is clear that the relationships identified for the Musick Point site differ to some degree from those for the Queen Street site.

3.4.3 Synoptic control of daily O₃ concentrations at the Sky Tower and Musick Point sites

In general, daily O₃ concentrations have similar across-type variation patterns at the two sites (Figure 9a). Relatively high O₃ concentrations correspond to the trough types at the top edge (e.g., Types 1, 6, 11, 16 and 21, which are associated with northerly surface winds in Auckland – Figure 8) and those at the right edge (e.g., Types 22 and 23, which are related to westerly surface winds in Auckland) of the SOM grid (Figures 10a, b). The possible mechanism is that the unstable conditions associated with these cyclonic types (Figure 7) facilitate downward transport and mixing-in of O₃ from the upper troposphere/stratosphere and advection of less polluted air (low in NO and NO₂ and thus limited O₃ titration) from the open ocean waters to the Auckland urban boundary layer (Tong et al., 2011). In addition, under these cyclonic types, thunderstorms are frequently observed in Auckland (Hessell, 1988; 1990), also potentially contributing O₃ to the regional airshed.

In contrast, the anticyclonic types in the bottom-left section of the SOM grid are generally associated with relatively low O₃ levels – this is especially true for the

(elevated) Sky Tower site (Figure 9a and Figures 10a, b). This is expected, as stable weather conditions (Figure 7) under these synoptic types tend to suppress the dispersion and ventilation conditions and thus limit the supply of background O₃ in the urban boundary layer (Tong et al., 2011; note: if local NO₂ levels are sufficiently high, O₃ production may occur due to disassociation of NO₂ under sunlight). Interestingly, however, the blocking states (Types 2 to 4 and 7 and 8) which provide easterly or northeasterly surface winds in Auckland (Figures 7 and 8), are associated with O₃ minima at the Sky Tower site (Figure 10a) but maxima at the Musick Point site (Figure 10b) on the SOM plane. These seemingly conflicting roles of the same synoptic types can be linked to the differences in site configurations and local emission conditions. On the one hand, O₃ concentrations at the Musick Point site are measured near ground level (15m above the ground), and importantly, due to lack of local NO_x emissions (indicated by low NO levels in Figure 10f), pollutants measured at this site are primarily transported from other ground-level emissions (locations) through meteorological effects (as indicated by the higher NO₂ but very low NO concentrations in Figures 9c and 10d, f). When winds blow from the westerly or southerly quadrants, the air advected from the Auckland “urban plume” is highly O₃-titrated, thus containing relatively low levels of O₃ but high levels of NO₂ (Figure 9a). On the other hand, due to the high elevation of the Sky Tower site (250m above ground level), O₃ concentrations measured at this site are generally less influenced by particular ground-level NO_x emissions (Adeeb and Shooter, 2003), but in some sense indicative of the O₃ levels in the Auckland “urban

plume” as a whole. In other words, weather-related daily variations in O₃ concentrations at this site are mainly due to changes in local stability conditions that determine vertical pollutant dispersion, rather than wind directions that facilitate horizontal transport of pollutants. Consequently, under anticyclonic (blocking) types, the O₃ concentrations in the (less polluted) air advected by easterly or northeasterly winds from the open oceans appear high at the Musick Point site but low at the Sky Tower site. Consistent with this observation, Farcas (1979), Khan et al. (2007) and Adeeb and Shooter (2003, 2004) also reported high O₃ concentrations in the air advected from the open ocean to the Musick Point site. In addition, Figures 10a and b indicate that the O₃ maxima at the Musick Point site are consistently lower than the O₃ minima at the Sky Tower site. That is, the Sky Tower site has generally higher O₃ concentrations than the Musick Point site across different synoptic types (Figure 9a). Consistent with this finding, studies elsewhere also showed that O₃ concentrations generally increase with height, displaying a relatively uniform profile during the daytime due to increased vertical mixing (e.g., Aneja et al., 2000; Cheng, 2000).

In summary, therefore, the synoptic control of regional O₃ concentrations lies in three main mechanisms. Firstly, cyclonic types contribute to increased O₃ concentrations through enhanced ventilation and perhaps the more probable downward transport of O₃ from the upper troposphere/stratosphere. Secondly, anticyclonic types generally limit ozone availability by suppressing the boundary layer dispersion. Thirdly, blocking types provide advection of fresh oceanic air (relatively rich in O₃) over the urban

Auckland land mass, resulting in ground-level O₃ maxima or minima depending on individual site configurations and local emissions. In particular, at the regional scale, downward transport appears to be the main mechanism for O₃ enhancement in the Auckland urban plume (as indicated by the Sky Tower site). The role of cyclonic types may be helpful for interpreting the seasonal behaviour of O₃ concentrations in urban Auckland. For example, the high O₃ levels observed during winter and spring (Adeeb and Shooter, 2004) may result from the increased occurrence of westerly trough types in those seasons (Figure 6; Jiang, 2010a).

It is worth noting that the above results somewhat differ from some previous studies conducted elsewhere (e.g., McGregor and Bamzeli, 1995; Tong et al., 2011). A number of authors reported that anticyclonic types (especially those on hot, sunny and/or calm days in summer) are often associated with high O₃ formation, but cyclonic types (which are typical of cloudy/wet, cool and windy conditions) tend to lead to low O₃ observations (e.g., Comrie and Yarnal, 1992; Greene et al., 1999; Lee et al., 2012). The differences in results are likely due to the vastly different topographies, geographies, emission conditions and climatic features of the areas being studied (Jiang et al., 2005b). For example, Greene et al. (1999) found that the synoptic type/air pollution relationships are substantially different across four cities in the USA. In addition, Comrie and Yarnal (1992) and Lee et al. (2012) showed that the synoptic type/air quality (e.g., O₃) relationships vary across seasons. While such seasonal variations are also possible in Auckland, however, this aspect is beyond the discussion in this paper.

4. Summary and conclusion

This paper has explored the utility of the SOM method for data classification and visualisation in the New Zealand context. A two-phase batch SOM procedure (CP2), as detailed in Jiang et al. (2011a), was used to classify the NCEP/NCAR geopotential height fields for the New Zealand region and the results were further applied to visualise local meteorological and air quality variables for Auckland. The main results are summarised below:

A new synoptic classification has been derived for New Zealand using the SOM methodology, comprised of 25 weather types that are self-organised (topologically ordered) on the SOM grid: similar types are close to each other and dissimilar types fall further apart. The classification has not only reproduced the synoptic types previously identified in the literature, but also provided visualisation of the major evolution paths of migrating synoptic systems over New Zealand.

The classification has facilitated visualisation and identification of the relationships between local and synoptic atmospheric conditions in a holistic framework. In particular, the classification has provided good discrimination of local meteorological conditions in Auckland, consistent with general meteorological principles (Sturman and Tapper, 2008) and previous studies in the literature (e.g., Jiang et al., 2012).

The display of air pollution data on the SOM plane has provided intuitive insights into the synoptic type-air quality relationships in Auckland. In particular, three relationships were identified for O₃ pollution: a) cyclonic types contribute to increase in daily O₃ concentrations due to enhanced

ventilation and probably downward transport of O₃ from the upper troposphere or stratosphere; b) anticyclonic types (with highs centred near or to the east of NZ) generally limit ozone availability by suppressing the boundary layer dispersal conditions; and c) blockings (with the high centred to the east or southeast of NZ and Auckland on the western edge of the anticyclone/ridge) providing advection of fresh oceanic air (relatively O₃-rich due to lack of anthropogenic NO_x emissions over the ocean waters) over the Auckland urban land mass, resulting in ground-level O₃ maxima or minima depending on site configurations and local emissions.

The relationships between synoptic types and NO and NO₂ concentrations are to some degree site-specific. In general, however, blocking types are related to low NO and NO₂ concentrations due to the advection of relatively clean oceanic air over the Auckland land mass. Anticyclonic types have slightly varying effects across the two sites, but in general, contribute to elevated NO and NO₂ concentrations due to reduced dispersion conditions. In contrast, cyclonic types may be associated with high or low NO and NO₂ levels, depending on site configurations and emission conditions.

In conclusion, the SOM method has shown significant promise for the identification of synoptic weather types and the visualisation of climate and air quality data in the New Zealand (Auckland) context. In particular, the new synoptic index derived in this study provides a new tool for examining a wide range of environmental problems in New Zealand, including air pollution, climate variability and change, and their impacts on human health. For example, our future investigation will involve

exploring the relative roles of local meteorology, synoptic circulations and large-scale climate modes in determining the quality of the Auckland airshed. The results from this study may also be useful in air quality management applications in Auckland or similar regions.

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