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Classification of New Zealand Synoptic Weather Types and Relation to the Southern Oscillation Index

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

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

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

Abstract

Obliquely rotated T-mode principal component analysis has been applied to the NCEP/NCAR geopotential height reanalysis data for winter months from 1958 to 1996 over the New Zealand region. A new set of ten representative weather types were identified, with two being the most dominant. The temporal characteristics of the ten synoptic weather types were analysed in relation to different phases of the Southern Oscillation Index (SOI). While weather type–local meteorology relationships were consistent over time, the frequency of some weather types changed significantly with the SOI phases. In general, and relative to "normal" conditions, the frequency changes in El Niño years tended to be more significant than in La Niña episodes.

1. Introduction

Many studies in synoptic climatology have been based on map classification (Kidson, 1997). Apart from purely subjective classification methods (e.g., Lamb, 1950), there are four objective methods: correlation method (Lund, 1963), sums-of-squares method (Kirchhofer, 1973; Blair, 1998), cluster analysis (e.g., Key and Crane, 1986; Kidson, 1994a), and principal component analysis (PCA) (Richman, 1981; Huth, 1996a, b). A comparison of the four objective methods was performed by Huth (1996a). It was found

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

that none of them is indisputably superior. However, Huth (1996a, b) suggested that the obliquely rotated T-mode PCA method is preferable for circulation classification purposes. While in comparison to some other methods the circulation types obtained by T-mode PCA are slightly less separated from each other, the method does provide more stable classes in time and space (i.e., it is less sensitive to changes in grid density and period investigated) and is more efficient in reproducing predefined circulation types known in advance. Also, T-mode PCA is relatively insensitive to the choice of subjectively prescribed parameters (i.e., number of components rotated). Moreover, the undesirable "snowballing" effect which is common to most other methods, appears to be satisfactorily suppressed by T-mode PCA.

Earlier weather type classifications for the New Zealand region were based on subjective methods [refer to Kidson (1994a) for a detailed review]. An objective weather typing approach using cluster analysis (a combination of unrotated S-mode empirical orthogonal function analysis and clustering techniques such as k-means) was first applied to this region by Kidson (1994a), and further used by Kidson (1994b; 1997, 2000) and Kidson and Waterson (1995) for climate studies. From these applications, as noted by Kidson (1997), the use of synoptic map typing has proved helpful in interpreting climate variability, improving the ability to forecast daily temperatures, validating the performance of climate models and indicating the anticipated changes in atmospheric circulation patterns as a result of enhanced greenhouse effect. However, Kidson (1997, 2000) has further concluded that for the New Zealand region synoptic climatological techniques are largely of qualitative value. The main difficulty is that the variability of a climatic element within a synoptic class is typically too large relative to the differences between classes.

The current study aims to determine whether a different weather typing technique would have greater utility for climate studies and evaluations of other environmental parameters such as air quality and human health in the New Zealand region. The present paper reports on a synoptic classification of weather types for the New Zealand region using obliquely rotated T-mode principal component analysis, and discusses the temporal characteristics of the weather types in relation to El Niño-Southern Oscillation (ENSO) events. Urban air pollution levels, human mortality and morbidity in New Zealand are relatively higher in winter than other seasons. Therefore, as the first stage of this study, the analysis was focused on winter months from May to September.

2. Data and methods

2.1 Gridded meteorological data

The gridded meteorological data used to derive the synoptic weather types comprised daily NCEP/NCAR 1000 hPa geopotential height reanalysis at 0000 UTC for the period of May-September from 1958 to 1996. The grid of 2.5°×2.5° mesh was bounded by latitudes 25°S to 50°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 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).

The actual geopotential heights, rather than anomalies, were analysed, as the weather in this region is largely dependent on the relation of the overall air flow (rather than the anomalous flow) with orography (Sturman and Tapper, 1996). An obvious advantage of using the original data for classification is that the results are more readily interpretable.

The climatic mean map for the entire data set is shown in Figure 1. In order to reduce the possible effects of seasonal variability in the geopotential height the classification procedure was performed for each month separately (it needs to be noted that an analysis on the merged data led to a very similar classification and detailed results will be reported elsewhere).

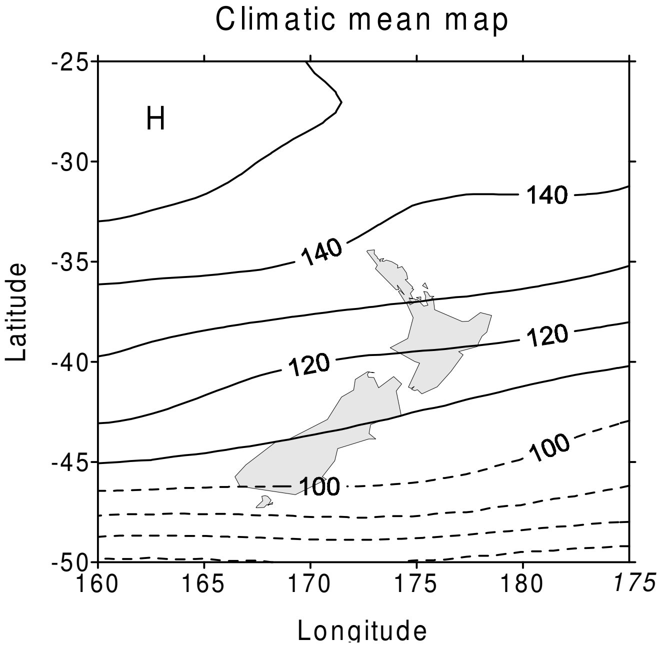

Figure 1. Mean daily NCEP/NCAR 0000 UTC (1200 NZST) 1000 hPa geopotential height reanalysis from May to September, 1958-1996. The contour interval is 10m

2.2 Local meteorological data

The following data from the Auckland Airport meteorological monitoring site were used in the study: wind speed, wind direction, u and v components of wind, air temperature, relative humidity, mean-sea-level air pressure and 24-hour rainfall. The time series of each variable consisted of three hour mean values for the period of 11:00-13:00 NZST on each day in May-September from 1966 to 1996, except rainfall for which there was only one value per day. The choice of the time duration (11:00-13:00 NZST) was to match the geopotential height data.

The local meteorological data were used without distinguishing the month-to-month variations. Removal of seasonal variations or use of standardized data still led to similar results to those reported in this paper.

2.3 Southern Oscillation Index

Monthly values of the Southern Oscillation Index (SOI) for January-December from 1958 to 1996 were based on a revised calculation by the National Climate Center (NCC) of the Australian Bureau of Meteorology. The climate base period is from 1933 to 1992, and the new SOI data are the actual values multiplied by 10 (Allan, 1996).

Following Ropelewski and Jones (1987), the data were smoothed using a five-month running mean. The resulting SOI vaues for May-September were used to define the occurrence of ENSO events (Table 1). A year was defined as a *La Niña* year if at least one SOI value was = 10; similarly, if there was at least one SOI value = -10, the year was defined as an *El Niño* year; in all other cases, the year was defined as a *Normal* year. The results from this definition was consistent with the season-by-season breakdown list of occurrences of ENSO events provided by the USA's National Center for Environmental Prediction (NCEP), which was defined by the sea surface temperature (SST) in a key region of the tropical Pacific along the equator from 150º W to the date line (NCEP, 1999).

2.4 Procedure

First, a daily index of synoptic weather types was established using the stratified gridded meteorological data and obliquely rotated T-mode PCA. Subsequently each weather type was characterized using meteorological variables for the Auckland Airport site in order to display the relationships between synoptic weather types and local meterological conditions. Further analysis determined whether the weather type–local meterology relationships had changed in association with the different SOI phases (ENSO events) defined in Table 1. Finally, frequencies of the weather types were examined with respect to occurrences of ENSO events.

Table 1. Definition of ENSO events for years from 1956 to 1996, according to the five-month running mean SOI values for the period of May-September.

ENSO Event	SOI Phase	Year
El Niño/ Warm	Low SOI phase	1965, 1972, 1977, 1982, 1987, 1991, 1992, 1993, 1994
La Niña / Cold	High SOI phase	1964, 1971, 1973, 1974, 1975, 1988, 1989
Normal	Normal phase	1958, 1959, 1960, 1961, 1962, 1963, 1966, 1967, 1968, 1969, 1970, 1976, 1978, 1979, 1980, 1981, 1983, 1984, 1985, 1986, 1990, 1995, 1996

Without loss of generality, a correlation matrix was used for the PCA analysis. The Promax algorithm (Richman, 1986) was used to obliquely rotate the retained PCs. The similarity of a daily circulation pattern/map to a particular type is expressed by the corresponding PC loading: the higher the loading, the greater the similarity between the type and the pattern for the given day. Therefore, each pattern was classified simply with the type for which it had the highest PC loading (in the absolute sense). Given that each large positive and negative loading for a PC can define two opposite types (Huth, 1996a, b; van den Dool, 1991), a particular number of PCs retained and Promax rotated will yield twice as many synoptic classes.

The choice of the number of PCs to retain is crucial when identifying the underlying dominant weather patterns. In the present study, the number of PCs to retain was determined using a two-step procedure (Jiang, 2000). Firstly, following Cattell (1966) and North et al. (1982), for each month a plot of the eigenvalue and sampling error versus PC-number was used to make an initial choice by excluding those PCs on the sections of the curve with relatively small slope. It was necessary to avoid separating degenerate multiplets from one another while maximising the variance explained by the retained PCs. This procedure indicates three possible options: 6, 7, or 8

PCs to retain. The appropriate (optimum) number was finally decided by comparing the characteristics of the classiftions using the pre-determined various numbers of PCs, following the method developed by Huth (1996b). For all months, retention of the 7th or higher order of PCs resulted in little increase in the communality and maximum loadings of daily weather patterns, but leading to weather types of very small sample sizes. Therefore, it was determined that six PCs should be retained to obtain the final classification.

The next section will discuss the mean type maps of the resulting classification, the meteorological characteristics of the weather types and the temporal characteristics of these weather types in relation to ENSO events.

3. Results and discussions

3.1 Mean type maps of the classification

The Promax rotated T-mode PCA analysis with retention of six PCs resulted in 12 synoptic weather types. Each weather type is characterized by the mean 1000 hPa geopotential height map for the relevant days. The frequencies of the weather types are also discussed briefly.

It is noteworthy that for all five months the first six PCs have similar score patterns (not shown), except that sometimes the high and low centers have opposite signs between different months, and/or very small differences exist in the positions of synoptic centers. A similar situation was also noted by Compagnucci and Salles (1997) when investigating the surface pressure patterns during each month of the year over southern South America. This suggests a strong similarity between the main weather patterns throughout the months examined, although the frequencies of the patterns can differ. Consequently, the mean maps of the classification types were also very similar for the different months. As examples, only the mean maps for July are shown in Figure 2. The monthly frequencies of each type are shown in Table 2.

Table 2. Percentage frequency of the weather types in the classification.

Type	**May**	**June**	**July**	**August**	**September**	**Average**
SWH	42.43	37.95	38.46	31.18	35.64	37.14
NW	20.18	24.02	20.43	25.56	33.08	24.60
H	11.41	10.34	6.87	7.03	6.67	8.46
NE	4.05	4.87	7.20	7.69	8.29	6.42
L	5.54	3.85	4.88	12.49	2.05	5.80
SE	4.05	7.01	8.02	5.21	3.85	5.63
TLE	5.62	1.37	5.29	4.14	3.68	4.04
THE	3.89	4.96	4.22	0.99	2.65	3.34
TO	1.24	2.22	3.14	3.14	2.14	2.38
HL	0.91	3.16	0.99	1.82	1.71	1.71
TO2	0.66	0.17	0.41	0.66	0.26	0.44
HL2	0.00	0.09	0.08	0.08	0.00	0.05

Focusing on the flow regimes and the positions of main synoptic centers, the types were defined as SWH, NE, NW, SE, H, L, TLE, THE, TO, TO2, HL and HL2 and are described briefly as follows:

SWH type: westerly to southwesterly wind dominates most of the grid area; a high centre is located to the northwest of the North Island, over the Tasman Sea. It is the most frequent weather type, with the average frequency being 37% of the total for May-September. The highest frequency is in May, with the lowest frequency in August. The type map is very similar to the climatic mean map shown in Figure 1. Such similarity was confirmed real by inspecting the

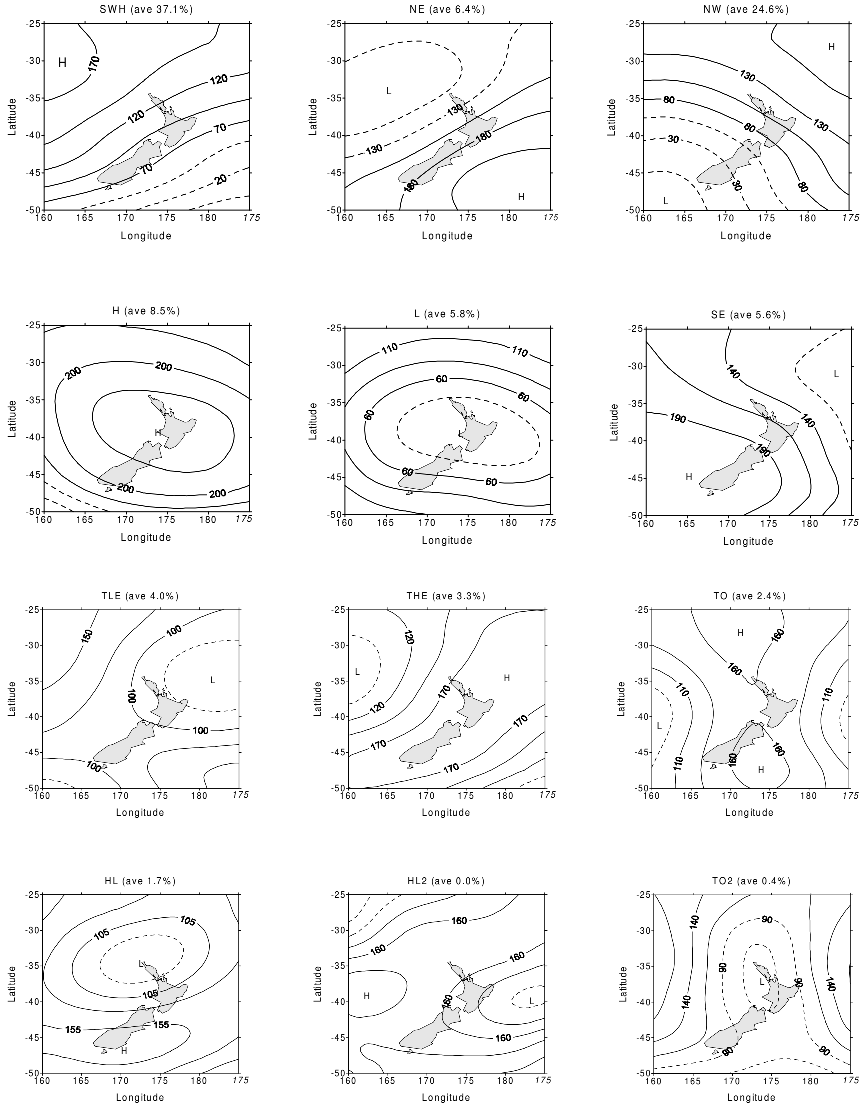

Figure 2. Mean 1000 hPa geopotential height maps for weather types in July (1958-1996). The classification was obtained by obliquely rotating six PCs. The contour interval is 25 m.

actual daily weather maps.

NE type: northeasterly gradient flow dominates most of New Zealand. The type occurs most frequently in July, August and September.

NW type: northwesterly gradient flow dominates the North Island. This is the ssecond most frequent type over the region. Its frequency is considerably higher in September than in other months.

SE type: southeasterly gradient flow dominates the North Island. The highest frequency months are June and July.

H type: a high is centred over the North Island. This type is most frequent in May and June.

L type: a low is centred over the North Island. The frequency of occurrence in August is almost twice that of any other month.

TLE type: an anticyclonic blocking type, with the North Island on the western edge of a low. This type has its lowest frequency in June.

THE type: a transitional type, with the North Island on the western edge of a high. Relatively higher frequencies are found in May, June and July. The lowest frequency month is August.

TO type: a transitional type, with weak pressure gradients over the North Island. Relatively higher frequencies are found in July and August.

TO2 type: a secondary transitional type, with a low center over the North Island. This type seldom occurs, and is thus not further discussed.

HL type: a low center over the northern North Island with its margins dominating the southern North Island; a weak high pressure area is over the South Island. This type has the highest frequency in June.

HL2 type: a secondary type, with a ridge over the northern North Island, oriented southwest to northeast, and a low center to the east of New Zealand. The low frequency of occurrence means that this type is not further discussed.

Therefore, by omitting the two low-frequency types TO2 and HL2 (the relevant days, <0.5% of the total days, were treated as unclassified), this new classification comprises ten main types. The classification procedure was repeated for data subsets covering different sub-grids/domains (but not so small that the synoptic-scale systems can not be identified) and different time periods (e.g., from 1976 to 1996), in an effort to test for the stability of classifications over time and space. It was found that the resulting PC patterns and classifications did not differ substantially over time and space (not shown). This confirms the results of Huth (1996a, b) and others, who have shown that classifications based on obliquely rotated T-mode PCA are stable in time and space.

There exists some degree of similarity between the present classification and those obtained in earlier work, e.g, Kidson (2000). Kidson (2000), based on cluster analysis and using the NCEP/NCAR reanalysis data (Jan 1958 - June 1997), derived a set of 12 daily weather types for the New Zealand region. The NE (6.4%), SE (5.6%) and TLE (4.0%) types in the present classification correspond to Kidson's (2000) *NE* (6.3%), *HW* (5.4%) and *R* (4.7%) types, respectively. However, some weather types from the present study may have *multiple counterparts* in Kidson (2000). For example, the SWH type of the present classification corresponds to Kidson's (2000) *SW* and *HNW* types. These weather types are mainly featured by dominance of southwesterlies over the New Zealand and adjacent areas and a high centred to the west-northwest of the North Island. Preliminary results indicate that the present classification seems able to capture more detailed features such as flow regimes over the New Zealand region. However, more detailed analysis is needed for further conclusion.

*Table 3. Means, standard errors (italic) and coefficients of variation (**bold italic**) of the Auckland Airport meteorological variables by weather types. "Total mean" corresponds to the climatic average level of a variable for all situations rather than a specific weather type.*

Meteorological variable	Weather type										Total mean
	H	HL	L	NE	NW	SE	SWH	THE	TLE	TO	
Mean sea level	1027.5	1009.1	1001.9	1017.9	1017.5	1015.8	1014.1	1016.1	1012.6	1017.5	1015.7
air pressure	*0.1*	*0.6*	*0.2*	*0.3*	*0.1*	*0.3*	*0.1*	*0.4*	*0.3*	*0.4*	*0.1*
(hPa)	***0***	***1***	***1***	***1***	***1***	***1***	***1***	***1***	***1***	***1***	***1***
24-hour rainfall	1.0	7.3	5.7	6.2	4.7	1.2	2.6	8.9	1.7	2.6	3.6
(mm)	*0.2*	*0.6*	*0.2*	*0.4*	*0.1*	*0.1*	*0.1*	*0.7*	*0.2*	*0.3*	*0.1*
	641	***122***	***98***	***184***	***176***	***322***	***164***	***168***	***344***	***228***	***204***
Relative humidity	76.2	84.6	80.8	77.4	78.6	72.5	76.3	81.8	75.6	74.7	77.2
(%)	*0.3*	*0.6*	*0.4*	*0.4*	*0.2*	*0.4*	*0.1*	*0.5*	*0.4*	*0.6*	*0.1*
	14	***11***	***13***	***15***	***14***	***14***	***13***	***14***	***14***	***15***	***14***
Temperature	12.7	13.8	14.7	14.5	15.0	12.0	13.6	14.6	13.5	12.4	13.9
(º C)	*0.1*	*0.1*	*0.1*	*0.1*	*0.0*	*0.1*	*0.0*	*0.1*	*0.1*	*0.1*	*0.0*
	22	***16***	***14***	***16***	***14***	***19***	***16***	***19***	***17***	***17***	***17***
u component of	-0.7	-3.9	3.0	-5.2	0.8	-0.5	4.6	-1.8	0.6	0.7	1.6
wind (m/s)	*0.1*	*0.3*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.0*
	364	***103***	***157***	***72***	***471***	***676***	***84***	***170***	***581***	***396***	***293***
v component of	1.0	-0.3	-2.2	-2.0	-2.6	3.3	2.4	-2.5	3.2	0.9	0.4
wind (m/s)	*0.1*	*0.3*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*	*0.1*	*0.2*	*0.0*
	253	***1744***	***201***	***200***	***149***	***104***	***157***	***138***	***103***	***359***	***1185***
Wind speed	2.8	6.4	6.5	6.9	5.2	5.1	6.6	4.6	5.0	3.2	5.6
(m/s)	*0.1*	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*	*0.0*
	89	***53***	***52***	***52***	***61***	***63***	***56***	***67***	***63***	***89***	***63***
Percent calm (%)	43.7	9.4	6.8	10.4	15.8	16.4	12.0	23.7	17.6	38.7	16.8

3.2 Meteorological characteristics of synoptic weather types

The mean, standard errors and coefficients of variation (CV) of the selected meteorological variables were calculated for each weather type (Table 3). In addition, the same statistics were also calculated for a derived variable, *percent calm*. This was defined as the percent of hours with measured wind speed = 2m/s over the total number of hours within a specific weather type category. Collectively the statistics present a general description of the meteorological conditions associated with each synoptic weather type. The main findings are summarized as follows:

1) Distinctive meteorological conditions are associated with the synoptic weather types (Table 3). For example, in Auckland the H type is often associated with relatively low rainfall and mean wind speed, with light winds on average from the south and relative humidity and air temperature below average levels (the total means). On the other hand, the L type is often associated with above-average relative humidity, rainfall and windspeed. Strong southwesterly winds prevail during days of the most frequent weather type, SWH. The rainfall, relative humidity and temperature are slightly below their climatic averages, while rainfall is marginally higher than its average level. This is consistent with the findings of Hessell (1990).

2) The coefficients of variation (CV) suggest that, among the different weather types, the within-type variability of meteorological conditions is generally similar; the significantly high CV values for rainfall and u and v components reveal high within-type variability for these variables. One-way analysis of variance (ANOVA) indicates that meteorological variables differ significantly (at a less than 0.0001 level) by synoptic weather types. Tukey' s (1953) Honestly Significant Difference (HSD) test further reveals that at least one variable is significantly different between any two weather types (not shown).

3) The H, TO and THE types, especially the H and TO types, have a high probability to be associated with calm (low wind speed) conditions, as indicated by the large percent calm values. On the other hand, as expected, the SWH type together with the L type has very low percent calm values.

3.3 Weather types and ENSO events

Previous studies have shown that ENSO events have significant influences on the weather and climate, and consequently on social and economical conditions and other aspects of New Zealand (e.g., Basher and Thompson,

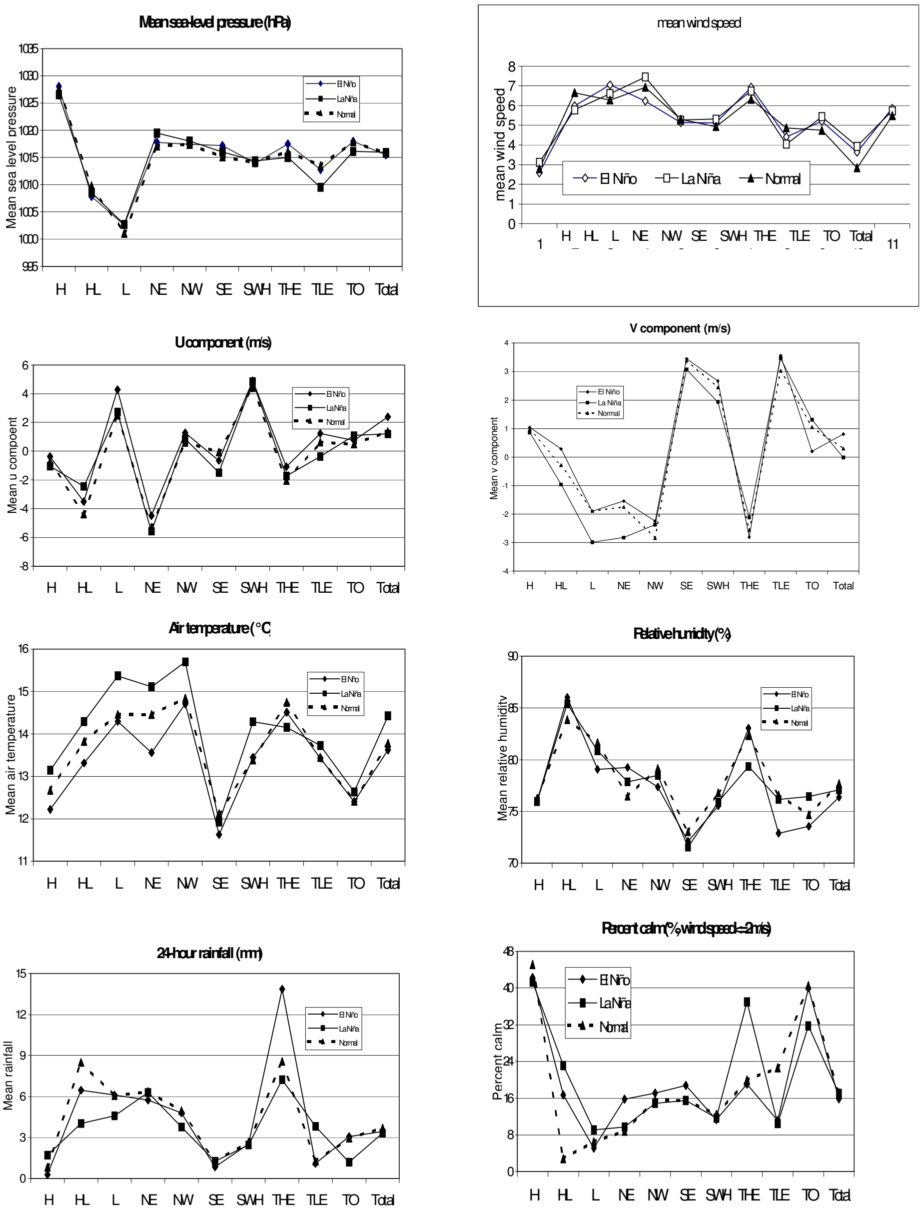

Figure 3. Mean levels of the Auckland Airport meteorological variables for each synoptic weather type corresponding to the El Niño, La Niña, and Normal years. Total corresponds to the climatic mean level of the entire record of a variable despite specific weather types.

1996; Salinger and Mullan, 1999; Hay and Fitzharris, 1988; Fitzharris *et al.*, 1992; Gordon, 1986).

Based on the SOI phases identified in Table 1, the years from 1958 to 1996 were subdivided into three subgroups, namely, El Niño, La Niña and Normal. The distributions of climatic means and coefficients of variation of local (Auckland Airport site) meteorological variables for each synoptic weather type were determined for the El Niño, La Niña and Normal years (Figure 3). It was found that, for a given synoptic weather type, the same meteorological conditions prevailed in Auckland for each of the three phases of the SOI.

Given the above results , the stationarity in the meteorological characteristics of weather types is an important finding. Thus the documented differences in climatic conditions between different SOI phases (e.g., Basher and Thompson, 1996; Salinger and Mullan, 1999) likely result from a change in the frequency of synoptic weather types for the different SOI phases. Figure 4a shows the differences in the relative frequencies of each weather type in El Niño years and La Niña years, from Normal years. The differences were further scaled by the average frequency of each weather type (Table 2) and

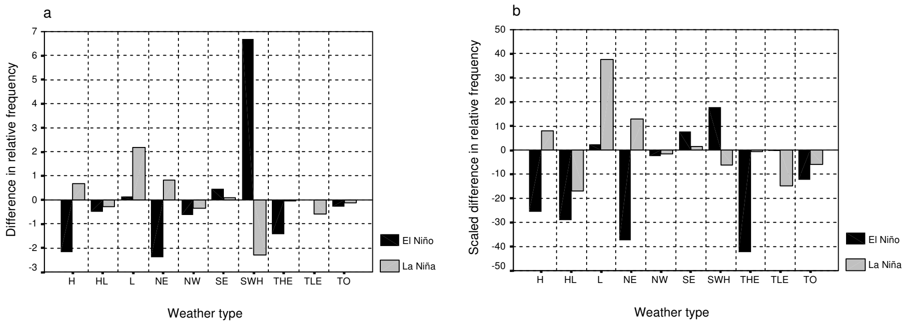

Figure 4: a) Occurrence possibility of weather types to be associated with El Niño, La Niña events. The values are the differences of relative frequencies of weather types in the El Niño and La Niña years from the Normal years for the period of May-September from 1958 to 1996. b) Same as Figure 4a but the differences in relative frequency are scaled by the average frequency for each weather type

shown in Figure 4b, to elicit the relative changes in the frequncies of different weather types. The Mann-Whitney rank sum test was performed for each weather, comparing its relative (yearly) frequencies in El Niño or La Niña years with that in Normal years, in order to determine whether changes in the frequencies are *statistically* significant. The frequency changes during the El Niño events are more significant than that in the La Niña events (Figures 4a, b). Associated with the El Niño years, the main feature is the lower frequencies of the THE, NE and H types accompanied by the higher frequency of the SWH type. During the La Niña years, more frequent L type occurs than the Normal years. These changes in frequencies are statistically significnat at a 0.1 level. The scaled frequency changes for the HL type are also large (Figure 4b), but this change is not statistically significant at the 0.1 level.

Kidson (2000), based on a screening regression analysis, suggested that the monthly frequencies of individual synoptic types are only weakly related to the SOI. However, this study has shown that the frequencies of some synoptic types differ signficantly between different SOI phases. This finding is consistent with some previous studies. During El Niño years, less frequent THE, NE and H types have a potential for leading to less frequent easterly flows, while more frequent SWH type likely contributes to more frequent southwesterlies over New Zealand. Sturman and Tapper (1996) and Salinger and Mullan (1999) have demonstrated that in El Niño years the *mean* southwesterly flow was stronger than normal, while in La Niña years, the *mean* west-southwesterly flow was weaker than normal in the New Zealand area. The frequency change of the L type during La Niña years is also supported by Sinclair *et al.* (1997), who suggested that more cyclones occur over the Australasia region during high SOI phases.

4. Summary

A new synoptic classification has been obtained for the New Zealand region for winter months (May-September) from 1958 to 1996, using an obliquely rotated T-mode principal component analysis as the classification tool, and further disscussed in relation to occurrences of ENSO events. The main points are summarized as follows:

1) For the first time the obliquely rotated T-mode PCA method was used for weather typing for the New Zealand region. Ten representative winter weather types have been identified, with the SWH, NW being the most dominant.

2)Distinctive local meteorological conditions are associated with different synoptic weather types. The synoptic weather type–local meteorology relationship is consistent over different phases of the ENSO cycle.

3) The consistent weather type–local meteorology relationship suggests that it is mainly the changes in the frequencies of synoptic weather types that lead to the significant differences in New Zealand's climate between La Niña and El Niño events. It was found that, between such events significant differences in frequencies of some weather types do occur. In general, the frequency changes in El Niño events (focused on May-September in this study) tend to be more significant than in La Niña episodes.

The availability of the 39-year NCEP/NCAR data has made it possible to establish a long-term index of synoptic weather types for the study area, which can be potentially useful for investigations of the effects of climatic events such as ENSO phenomena on New Zealand's climate. While a detailed comparison between this new classification and Kidson' s (2000) and others is desirable, future work could direct to the improvement of weather typing techniques. For instance, Jiang (2000) has indicated that the use of PCA as both a data reduction tool and a *pre-classification* technique combined with cluster analysis, may provide an improved synoptic classification over both the present and Kidson' s (2000). Applications of this research could be made to a variety of environmental problems that respond at the synoptic scale. For example, the present synoptic index will be used to analyze the the winter air pollution phenomena in cities such as Auckland and Christchurch, and to assess the differential and synergistic impacts of weather, climate and air pollution on human health such as human mortality and morbidity.

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