Linking synoptic weather types to daily rainfall in Auckland

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Abstract

This paper provides a probabilistic analysis of the linkage between synoptic weather types and the daily rainfall in Auckland, New Zealand for the period 1962-2008. Under each synoptic type and for each season, the daily rainfall data from the Auckland Airport site are examined and the probability of occurrence of high rainfall events calculated. The effects of different weather types on the chance of having a wet day (with daily rainfall > 1 mm) are modelled using logistic regression and taking into the account of the effect of El Niño Southern Oscillation (ENSO) and Inter-decadal Pacific Oscillation (IPO).

The results show that the synoptic weather types can be meaningfully linked to the rainfall data, conforming well to general meteorological principles. Relatively dry (low rainfall) conditions are associated with anticyclonic weather types and relatively wet (high rainfall) conditions are related to cyclonic states. However, under the influence of the same synoptic type, the average rainfall level and the chance of high rainfall events in Auckland to some degree vary across seasons. Two cyclonic states, associated with a low system centred to the east or west of the South Island, are found to provide much higher probabilities of a wet day in Auckland than other weather types. A change in the phase of ENSO, as indicated by the phase of the Southern Oscillation Index (SOI), is also shown to change the probability of a wet day in Auckland. Compared to the neutral SOI phase, on average, the low (high) SOI

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phase is associated with a 7% (9%) decrease (increase) in the odds of having a wet day. The effect of the IPO is found to be statistically insignificant in this study, with only a 2% decrease in the odds during the positive IPO phase relative to the negative IPO phase. This analysis demonstrates the utility of a synoptic climatological method for environmental studies in the Auckland context.

1. Introduction

Daily rainfall in Auckland is primarily determined by the activity of low pressure weather systems that originate in the Tasman Sea and secondarily influenced by the complexity of the local topography (Hessell, 1988, 1990). During the summer and autumn, storms of tropical origin can also affect Auckland, sometimes resulting in heavy rainfall. The primary purpose of the present study is to provide a probabilistic description of how the typical synoptic weather types over New Zealand are related to the daily rainfall in Auckland.

Weather types can be classified either manually, by objective (computer-assisted) methods, or using a combination of both. Early weather type classifications for the New Zealand region were based on subjective methods (e.g., Sturman *et al*., 1984). An objective weather typing approach using cluster analysis was first applied to this region by Kidson (1994a), and further used by Kidson (1994b, 1996, 1997, 2000) and Kidson and Watterson (1995) for climate studies. The utility of different classification techniques was also explored by Jiang (2000), Jiang *et al*. (2004, 2005) and Jiang (2008, 2010a) for the New Zealand context. In particular, Jiang *et al*. (2004) applied the obliquely rotated T-mode PCA method to the New Zealand region for weather typing during the winter months (May-September) for the 1958-1996 period, and subsequently assessed the consistency of the obtained synoptic weather types with local meteorological conditions in Auckland (as expressed in 24-hour rainfall, air temperature, relative humidity, mean-sea-level air pressure, solar radiation, and wind speed and direction). It was found that different synoptic types are associated with distinctive local meteorological conditions and that the synoptic type-local meteorology relationship is consistent over different phases of the Southern Oscillation Index (SOI). Furthermore, Jiang *et al.* (2005) and Jiang (2008) demonstrated the utility of T-mode PCA-based weather-typing procedures in the study of air pollution climatology during Auckland winters.

Jiang (2010a) recently established a long-term (1958-2008) synoptic climatological index for the New Zealand region using a new objective weather-typing procedure consisting of obliquely rotated T-mode principal component analysis (PCA) followed by convergent K-means clustering [also see Section 2(b)]. It was shown that the frequencies of some synoptic weather types vary significantly on the seasonal, interannual and longer time scales and in relation to different phases of the SOI.

This paper provides a brief evaluation of the Jiang (2010a) classification by conducting an analysis of the synoptic weather type-Auckland rainfall relationship for the period from 1962 to 2008. The rainfall level in this region is known to vary significantly by season and from year to year, and is, to some degree, influenced by the El Niño Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO) (ARC, 2010; Salinger and Mullan, 1999; Sturman and Tapper, 2008). Hence, the effect of the seasonal cycle and phase changes in the SOI and IPO are also considered in this analysis. The data and methods used are described in Section 2, while the results and discussions are presented in Section 3. A brief summary of the analysis is given in Section 4.

2. Data and method

(a) Daily rainfall data

The daily rainfall dataset consists of 24-hour rainfall records from the Auckland Airport site for May 1962-December 2008. This single time series was used to indicate the precipitation condition in the Auckland Region. The rainfall data from the Auckland Airport site were previously used in a few environmental studies for the Auckland region (e.g., Jiang, 2008).

(b) Jiang (2010a) classification index

The Jiang (2010a) classification index was obtained from the daily 0000 UTC (12:00 NZST) NCEP/NCAR 1000hPa geopotential height fields for the New Zealand region using a two-stage objective classification procedure (obliquely rotated T-mode principal component analysis followed by convergent K-means clustering). The index provides a categorization of the daily weather patterns into 12 synoptic types for the period from January 1958 to December 2008. The 12 weather types are illustrated in

Figure 1 and briefly described in Table 1. The general properties of these weather types are detailed in Jiang (2010a).

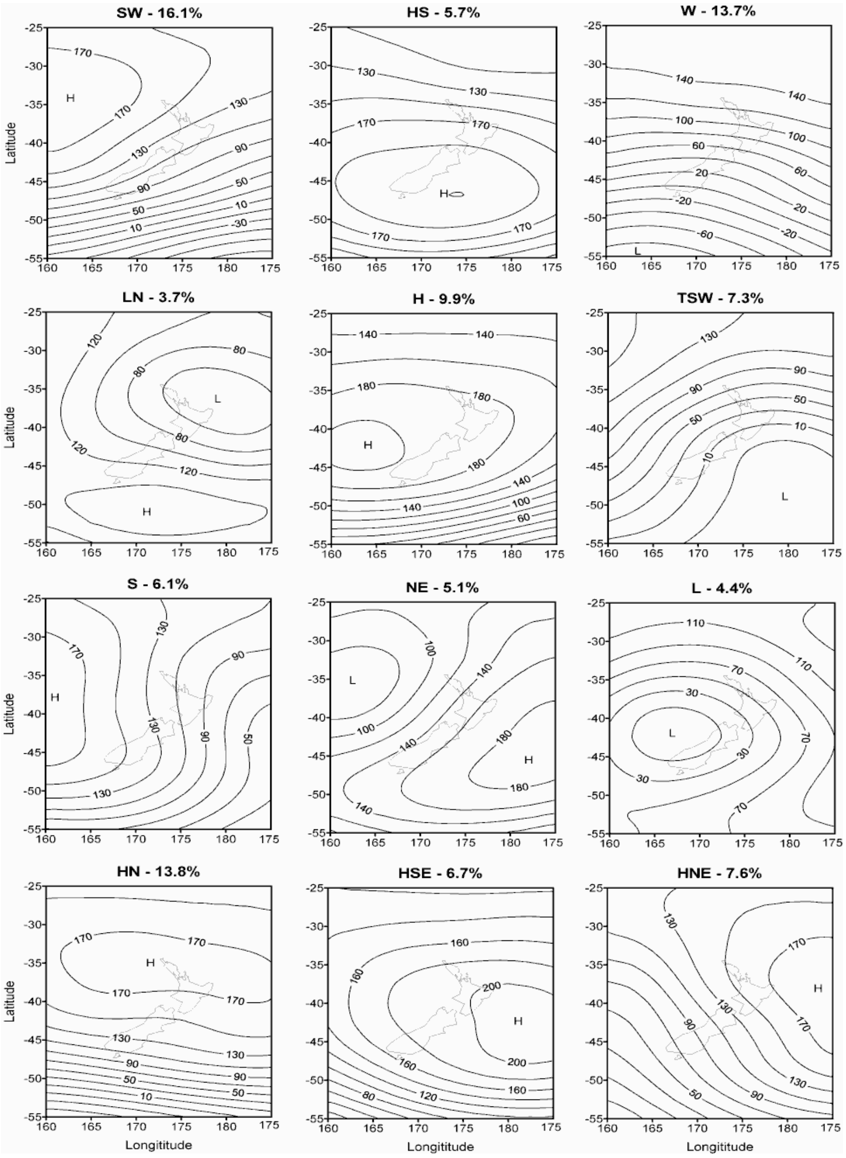

Figure 1: The mean 1000 hPa geopotential height maps and frequencies for 12 synoptic weather types obtained from NCEP/NCAR reanalysis for 1958-2008. The contour interval is 20m. Source: Jiang (2010a).

Type	Frequency (%)	Description
SW	16.1	southwesterly flow; high to the northwest of the country
HS	5.7	blocking type: high near south of South Island; shallow trough to the north of North Island
W	13.7	westerly flow; shallow trough extending from the south
LN	3.7	low near North Island; a blocking high in the southwest
H	9.9	high centred near west of the country
TSW	7.3	southwesterly flow; low/trough to the southeast, tilting southeast-northwest
S	6.1	southerly flow; ridge in the south and trough in the north, both tilting southeast-northwest
NE	5.1	blocking type: northeasterly flow; low/trough to the northwest, high/ridge to the southeast
L	4.4	low near South Island
HN	13.8	zonal flow; high over North Island
HSE	6.7	blocking type: high to the east of South Island
HNE	7.6	high to the east of North Island

Table 1. Description of 12 synoptic weather types. Source: Jiang (2010a).

(c) Definition of SOI phases

The SOI time series was used to indicate the phase changes of ENSO in this study. The definition of the SOI phases is the same as that used in Jiang (2010a). The monthly SOI values for 1958-2008 were obtained from the National Climate Centre (NCC) of the Australian Bureau of Meteorology (Allan *et al.*, 1996). The SOI values were used to allocate each month to an SOI phase: a month was classified to the positive/high SOI phase (La Niña) if SOI > 7, to the negative/low SOI phase (El Niño) if SOI < -7, to the neutral/normal SOI phase (neutral ENSO phase) otherwise.

(d) Definition of IPO phases

We define positive and negative IPO phases based on the IPO index obtained from the Hadley Centre, Meteorological Office, United Kingdom (Folland *et al.*, 1999; Folland *et al.*, 2002). The period of 1977-1998 was classified as a positive IPO phase, while the 1958-1976 and 1999-2008 periods were classified as negative IPO phases.

(e) Methods

The present investigation involved three analytical steps. The first step was to identify the main weather types associated with relatively dry or wet conditions in Auckland by examining the distribution of the rainfall data by synoptic types and across seasons. The second step was to estimate the probability of high rainfall events in Auckland under each synoptic type. The probability was estimated using the Bayesian method as described in Wackerly *et al*. (2008). The third step was to quantitatively assess the average effects of synoptic weather types, seasonality and phase changes in the SOI (thus ENSO) and IPO on the chance of having a wet day in Auckland. The assessment was based on the development of a generalized linear model (GLM; Dobson and Barnett, 2008), as described briefly below.

The GLM approach has become increasingly popular in environmental studies. The class of GLMs generalizes the classical linear regression by allowing the linear model to be related to the response variable (continuous, discrete or categorical) via a link function and the variance of each observation to be a function of its predicted/expected value (Dobson and Barnett, 2008). Through a GLM model, rainfall may be modelled as a continuous quantity or as a categorical outcome. For simplicity, we adopted the latter approach in the present analysis. A logistic regression model (a member of the GLM family) was developed in order to account for the effects of weather types, seasonality and phase changes in the SOI and IPO (as covariates) on the occurrence of wet days in Auckland (as the binary response variable). For practical significance, 1 mm, rather than 0 mm, was used as the cut-off value to define the wet and dry (non-wet) days from the daily rainfall records (note: the use of 0 mm as the cut-off value leads to very similar results to those reported in this paper). That is, letting Y_i indicate a wet or dry day,

$$Y_i = 1 \text{ (a wet day) if rainfall on the } i^{th} \text{ day } >= 1\text{mm}$$

$$Y_i = 0 \text{ (non-wet day) if rainfall on the } i^{th} \text{ day} < 1\text{mm.}$$

Y_i has a Bernoulli (p_i) distribution, where p_i is the expected probability of being a wet day and $i=1, \ldots, N$ (total number of days). The model can be expressed as:

$$\ln p_i/(1-p_i) = x_i^T\beta \quad (1)$$

where x_i^T is the transpose of the data matrix and β the parameter vector [note that there is no *residual* term in Equation (1), as we model the expected probability p_i]. Conceptually, the model may be described as

$$\ln p_i/(1-p_i) = \text{constant} + \text{synoptic type effect} + \text{seasonality effect} + \text{SOI effect} + \text{IPO effect} \quad (2)$$

In order to estimate the parameters in Equation (1), we need to specify a base/reference category for each categorical covariate. For convenience, we defined summer as the base category for the seasonal effect, the SW type as the base category for the synoptic type effect, the neutral SOI phase (neutral ENSO phase) as the base category for the SOI (ENSO) effect, and the negative IPO phase as the base category for the IPO effect. Hence, the effects of the covariates were actually modelled relative to the base categories. The model parameters were estimated using the maximum likelihood method as described in Dobson and Barnett (2008) and implemented within the SAS statistical package (SAS, 2003). It is known that, for a logistic regression model, the exponential transformation of the parameter estimates (e^{β}) can be interpreted as the odds ratio (here, the odds ratio of having a wet day in Auckland compared with the base category). Hence, in this text, the modelled effects of the covariates are described in odds (Section 3).

A few considerations should be noted in relation to the GLM model development. Firstly, no time-dependent terms (linear or non-linear function of time) were included in the regression model, as the trend in rainfall was regarded as insignificant in this analysis. Secondly, omission of the IPO-related terms from the model does not change the estimates of the other parameters. Thirdly, for simplicity, the possible interactions between the different covariates and the effects of type persistence (i.e., lifetime of individual synoptic types) were not considered in the modelling process. This will be considered further elsewhere.

3. Results and discussion

(a) Weather types associated with dry or wet conditions

This subsection identifies the weather types associated with relatively dry (low rainfall) or wet (high rainfall) conditions in Auckland. Figure 2 shows the box plots of the daily rainfall data by weather types for each season. It can be seen that the distribution of daily rainfall under each weather type is consistent with the general meteorological principles (Sturman and Tapper, 2008). Overall, the relatively dry conditions occur under weather types associated with anticyclonic conditions, i.e., HS, H, HN and HSE. These are characterised by easterly or south-easterly winds over Auckland. The relatively wet conditions correspond to cyclonic states NE, L, TSW, W and LN and the transitional type HNE. These are associated with a northerly component in the prevailing airflows over the North Island. The SW and S types, associated with the dominance of cold and dry south-westerly to southerly airflows over the North Island, tend to provide low to moderate rainfall in Auckland.

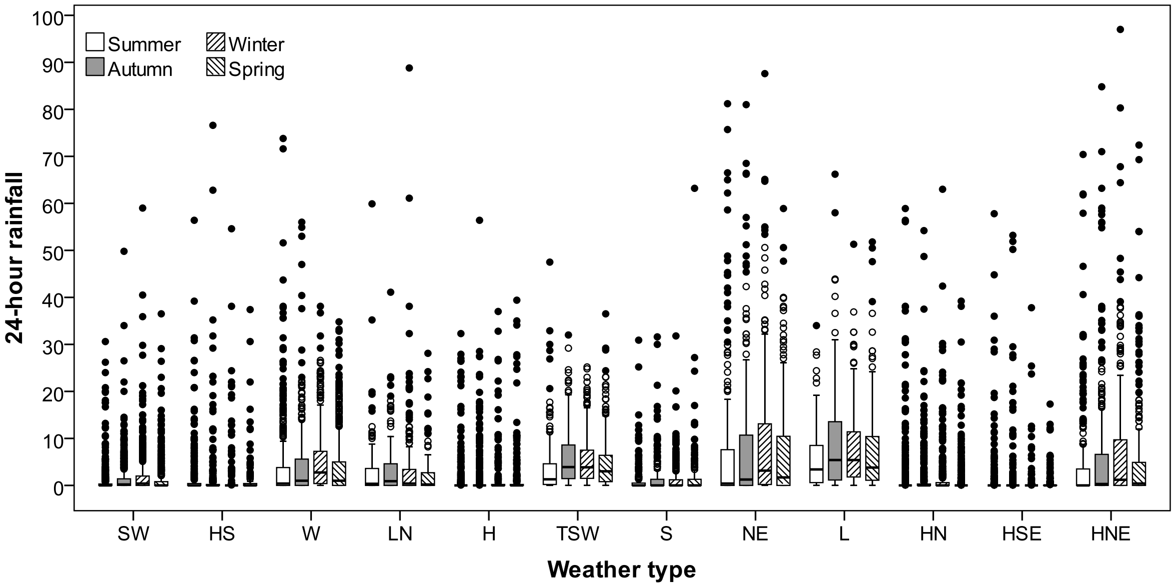

Figure 2. Box plots of the daily rainfall data at the Auckland Airport site by weather types. The bottom of the box: the 25th percentile; the top of the box: the 75th percentile; the horizontal line inside the box: the median; T-bars (whiskers): values that extend to 1.5 times the height of the box from the 25th or 75th percentile; dots: outliers that fall beyond the whiskers.

It is also observed that there exists some degree of seasonal variations in the daily rainfall totals under each synoptic category. In general, a weather type is associated with relatively lower rainfall in summer, but relatively higher rainfall in winter or autumn. Jiang (2010a) noted that there exist seasonal variations in the intensity of synoptic systems over the New Zealand region. Such variations may in part explain the within-type seasonal variations in local rainfall observed in Figure 2. Also, Kidson (2000) and Jiang (2010a) showed that the occurrence of synoptic weather types over New Zealand varies across seasons. Hence, the documented seasonal variations in Auckland rainfall (e.g., Hessell, 1988) may be caused (at least in part) by changes in not only the frequencies but also the air-mass properties (e.g., the intensity of high or low pressure systems) of individual weather types.

In addition, it is noticeable that high rainfall events occur across all weather types. However, the heaviest rainfall events appear to occur under the NE and HNE types, which are associated with warm and moist northerly to north-easterly winds over Auckland. This is consistent with results from Griffiths (2011), who found that annual extreme 1-day rainfalls in the northeast of the North Island (including the Auckland Airport site) were strongly linked to the Kidson NE weather type.

(b) Probability of wet events

This subsection discusses the probability for the occurrence of “wet events” in Auckland associated with each synoptic weather type. A day is classified as a “wet event” if the daily rainfall is in the top 10% of the seasonal daily totals. Under the influence of each synoptic type, the probability of having a wet event in Auckland was calculated (using the Bayesian method) and the results are given in Table 2. Two main points are noted below:

- Overall, the L and NE types, and secondarily the HNE, W and LN types, have relatively high probability of being associated with wet events in Auckland (the estimated probabilities are up to 0.35, 0.27, 0.22, 0.16 and 0.18, respectively). Other weather types, including the S and SW types, provide a very low chance of leading to a wet event in this region.
- The probability of occurrence of wet events varies across seasons. The probability of LN leading to a wet event is the highest in summer (0.18) but the lowest in winter (0.08), while the probability of TSW leading to a wet event is the highest in autumn (0.22) but the lowest in winter (0.11). The L type has a

significantly lower probability of causing a wet event in winter (0.22) than during the other seasons (around 0.30 or higher), but the HNE type has a higher probability in autumn (0.21) and winter (0.22) than in the other seasons.

Overall, it is the wet condition-related weather types identified in Section 3(a) that are more likely to cause high rainfall events in Auckland. These weather types appear to have a lower chance of causing wet events during winter than in other seasons.

Type	summer	autumn	winter	Spring
SW	0.04	0.03	0.03	0.03
HS	0.08	0.06	0.06	0.06
W	0.16	0.14	0.13	0.13
LN	0.18	0.13	0.08	0.12
H	0.04	0.05	0.04	0.06
TSW	0.16	0.22	0.11	0.17
S	0.07	0.05	0.01	0.04
NE	0.26	0.27	0.27	0.26
L	0.30	0.35	0.22	0.29
HN	0.06	0.05	0.05	0.03
HSE	0.04	0.05	0.03	0.03
HNE	0.16	0.21	0.22	0.17

Table 2. Probability of weather types causing wet events in Auckland in different seasons.

(c) Interpretation based on the logistic regression model

The effect of synoptic weather types on the probability of having a wet day (daily rainfall >= 1mm) in Auckland is now examined after taking into account the effect of seasonality and phase changes in the SOI and IPO.

Associated with the logistic regression model, i.e., Equation (1) in Section 2, the exponential transformation of the parameter estimates/coefficients (*βs)* associated with each covariate may be interpreted as the odds ratio of having a wet day in Auckland when compared with the base category. An odds ratio <1 indicates a decrease in the odds of having a wet day, while an odds ratio >1 suggests an increase in the odds of having a wet day. The odds ratio, its significance level and the change (%) in odds relative to the base category are shown in Table 3 for each covariate in the logistic wet-day model. The main points are summarized below:

- Compared with the SW type, there are significant (at the 0.05 level for a Chi-square test) increases in the odds of having a wet day in Auckland for L and TSW, and secondarily for the NE, W, HNE and LN types. For example, the L type provides 736% higher odds of having a wet day in Auckland than the SW type.
- Compared with the SW type, the occurrence of the H, HN, HS and HSE types provides a significant decrease in the odds of having a wet day in Auckland. For example, the occurrence of the HSE type results in a 62% decrease in the odds of having a wet day in Auckland.
- The odds of having a wet day under the S type is the same as that under the SW type, as indicated by the large observed significance level (0.1745).
- Compared with summer, winter and secondarily autumn and spring have the effect of increasing the odds for wet days in Auckland by 28 to 91%.
- The effect of SOI phases is also considerable. Compared with a neutral SOI phase, the negative (positive) SOI phase on average results in a 7% (9%) decrease (increase) in the odds of having a wet day in Auckland. The effect of the phase changes in SOI is marginally significant at the 0.1 level.
- Compared to a negative IPO phase, a positive IPO phase is associated with a 2% decrease in the odds of having a wet day in Auckland. The effect of the IPO is consistent with the general perception that a negative IPO phase contributes to decreased precipitation in some areas of New Zealand (e.g., Salinger and Mullan, 1999). However, the IPO effect is not statistically significant. As noted in Section 2, the inclusion or exclusion of the IPO effect in the logistic regression model does not change the estimates of the odds ratios associated with other covariates.

It can be seen that the GLM (logistic regression) model has quantified the average effects of synoptic types on the daily rainfall in Auckland in a comparative framework. The results are consistent with those in Sections 3(a) and 3(b). It is an important finding that the phase change of the SOI, and thus ENSO, has the potential to shift the probability of having a wet day in Auckland. This is consistent with Jiang (2010a), Jiang *et al*. (2004) and Renwick (2011), who found that the frequencies of some synoptic weather types over New Zealand vary significantly between different phases of the SOI.

Specified base category	Modelled effects	Odds ratio	Significance level (observed p-value)	Change in Odds
SW	H vs SW	0.408	<.0001	-59%
	HN vs SW	0.506	<.0001	-49%
	HNE vs SW	1.975	<.0001	98%
	HS vs SW	0.637	<.0001	-36%
	HSE vs SW	0.377	<.0001	-62%
	L vs SW	8.360	<.0001	736%
	LN vs SW	1.803	<.0001	80%
	NE vs SW	2.902	<.0001	190%
	S vs SW	0.894	0.1745	-11%
	TSW vs SW	7.660	<.0001	666%
	W vs SW	2.931	<.0001	193%
Summer	Autumn vs Summer	1.504	<.0001	50%
	Spring vs Summer	1.280	<.0001	28%
	Winter vs Summer	1.911	<.0001	91%
SOI Neutral	Negative vs Neutral	0.929	0.1064	-7%
	Positve vs Neutral	1.089	0.0845	9%
IPO negative	IPO Positive vs IPO Negative	0.979	0.5674	-2%

Table 3 Odds ratio associated with the effect of each covariate in the logistic regression model.

The utility of a simple logistic regression model may be evaluated by its sensitivity and specificity. The model sensitivity is defined as the proportion of wet days correctly predicted. The model specificity is defined as the proportion of non-wet days correctly predicted. The sensitivity and specificity of the model depend critically on the choice of cut-off probability (which can be specified by the modeller). A Receiver Operating Characteristic (ROC) curve is used to evaluate the predictive power of the model. Such a curve is obtained by plotting sensitivity against 1-specificity for a series of cut-off probability values on the (0, 1) interval (Dobson and Barnett, 2008). The further a curve is to the top left-hand corner, the better its predictive power. The predictive power can be quantified by the area under the ROC curve (AUC). The ROC for the wet-day model is given in Figure 3. The wet-day model has AUC=0.756 > 0.70 (the empirical critical value for significance of model skills) and is thus considered to have useful predictive ability. In other words, the simple logistic regression model demonstrates a promising utility of the synoptic classification defined in Jiang (2010a) for the study of rainfall in Auckland.

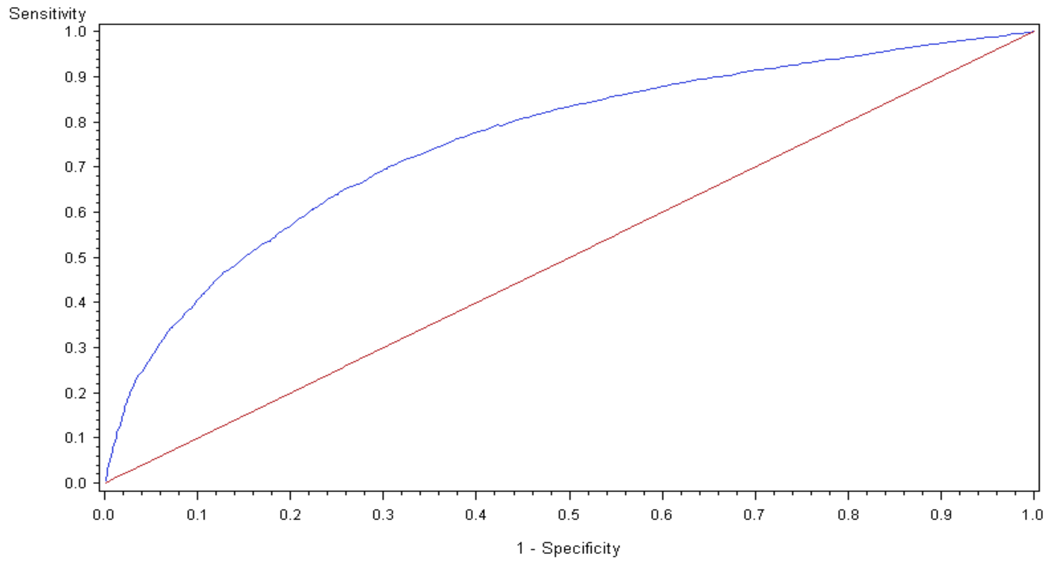

Figure 3. The ROC curve (sensitivity versus 1-specificity; blue curve) of the logistic regression model. Diagonal line (red) indicates the ROC curve of a model with predictive ability no better than chance.

4. Summary and conclusion

This paper provides a probabilistic description of the relationship between synoptic weather types and daily rainfall in Auckland. The analysis was based on the synoptic classification described in Jiang (2010a) and the daily rainfall records (in mm) from the Auckland Airport site for the period 1962-2008. Overall, the synoptic weather types are meaningfully linked to the rainfall data, conforming well to general meteorological principles (e.g., Sturman and Tapper, 2008). The main findings are summarized below:

- The relatively wet (high rainfall) conditions correspond to cyclonic synoptic states and a transitional type with a high centred to the north-east of New Zealand, while relatively dry (low rainfall) conditions are associated with anticyclonic synoptic types with a high centred over New Zealand or to the southeast of New Zealand. It is noted that the average rainfall loads on individual synoptic types tend to vary across seasons, with lower rainfall in summer but higher rainfall in winter.

- Wet events (defined as the daily rainfall in the top 10% for each season) may occur under any of the synoptic types, and the probability for a particular type resulting in a high rainfall event varies across seasons. However, compared with other synoptic types, the wet condition-related weather types are more likely to cause wet events in Auckland. These weather types tend to have a relatively lower chance of causing rainfall extremes in winter than other seasons.
- When compared with other synoptic types, two cyclonic types (L and TSW, which are associated with a low system centred to the east or west of the South Island) are found to have much higher odds for causing a wet day (rainfall>1 mm) in Auckland. If compared with summer, winter and secondarily autumn and spring have the effect of increasing the odds of having a wet day in Auckland.
- On average, the negative (positive) SOI phase results in a 7% (9%) decrease (increase) in the odds of having a wet day in Auckland if compared with the neutral SOI phase. This finding indicates that ENSO has significant effects on the variability of rainfall in Auckland.
- Relative to the negative IPO phase, the positive IPO phase is associated with a 2% decrease in the odds of having a wet day in Auckland, although this impact is not statistically significant.

In conclusion, the present study has demonstrated the utility of the synoptic climatological index defined by Jiang (2010a) for environmental studies in the Auckland context. The application of the GLM approach has also been applied and proved to be a promising tool for a probabilistic analysis of the effect of synoptic weather types on the daily rainfall in this region.

It is recognised that, in the Auckland Region, the local topography causes significant perturbations in the surface wind flows which, in turn, redistribute the observed rainfall (Bradley *et al*., 1997). The greater Auckland region experiences a high degree of spatial variability in rainfall. For example, the (1971-2000) normal annual rainfall totals vary both with elevation and from west to east across the Auckland Isthmus, with the annual rainfall being 1108 mm at the Auckland Airport site (a long-term monitoring site in the southwest of the region), 1286 mm at the

Whenuapei site (in the central region) and 1564 mm at the Warkworth site (with a higher elevation in the north). A limitation of this study, therefore, is the reliance on rainfall measurements from a single site. A direct extension of the present study is to further evaluate the Jiang (2010a) classification with rainfall data from multiple monitoring sites or classifying Auckland days as 'wet' or 'dry'. Consideration of other meteorological variables such as temperature and wind speed could also be made and would provide valuable insights.

Future work (ongoing) could point to an application of the batch self-organizing map (SOM) weather typing method described in Jiang (2010b) and Jiang *et al.* (2011) to the New Zealand context. This method has at least two advantages over the traditional discrete-cluster approach: 1) taking into account the nonlinear variations across the weather maps; 2) the number of weather types can be set arbitrarily large (Jiang *et al.*, 2011). The resultant synoptic classification may be able to reduce the within-type variability in meteorological characteristics such as rainfall.

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