STATISTICAL DOWNSCALING AND TELECONNECTIONS: ENSO AND PDO TELECONNECTIONS AS A SOURCE OF WITHIN-TYPE PRECIPITATION VARIABILITY IN BRITISH COLUMBIA

by

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Abstract

The Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) strongly influence atmospheric circulation over Western North America and therefore play a major role in modulating surface climate. This study represents an extension of Stahl et al. (2006a) in which a PCA – based approach was used to develop a synoptic climatology of mean sea level pressure patterns for the period 1948-2003 and in which relations between winter climate and major climate indices (PDO and ENSO) were explored. For both ENSO and PDO teleconnections, the synoptic analysis demonstrated that surface regional climate anomalies were linked to changes in both (a) the frequency of surface circulation types and (b) within-type variations.

As the influence of major climate indices on the magnitude of within-type variability is not well understood, and is crucially important to the success of downscaling efforts, this study explores the nature of such variability in major winter precipitation producing types. Descriptive precipitation statistics are calculated for each synoptic type and compared between teleconnection phases for 56 years of data and for several key stations across British Columbia. Preliminary results suggest that teleconnections are responsible for a significant component of within-type precipitation variability and that this arises as a result of systematic differences in meteorology within types as expressed by such variables as vorticity, vertical velocity, precipitable water and geopotential heights. Based on these findings, creating of synoptic sub-types based upon teleconnection indices is proposed as a method for improving downscaling from GCMs by accounting for within-type variability associated with teleconnections.

The downscaling methodology presented in this study assumes that GCM output, consisting of daily weather patterns and long-range teleconnection indices, can be used to classify the daily patterns into synoptic sub-types based upon the teleconnection indices, given mean precipitation amounts established for each type based on the historic record, downscaling scenarios can be calculated for any station in BC. In order to validate this approach, the statistical model was tested on the historic record using a bootstrapping approach. When repeated many times, this provides a statistically robust means of model assessment.

The performance of a "basic" model, which employs the thirteen synoptic types of Stahl et al. (2006a), is assessed. The modelling methodology performs generally well for most of BC, but varies by region. The best model performance is found along the coast where precipitation amounts are the greatest, reflecting the consistent precipitation climatology of the region. The performance of three additional models, which utilise PDO, ENSO and PDO / ENSO subtypes, is contrasted with the basic model. It is discovered that the model using PDO / ENSO sub-types affords the greatest improvement over the basic model, with improvements varying in different regions of British Columbia.

This study suggests that accounting for teleconnection indices can improve downscaling efforts; however, further research and development is recommended before an operational tool can be produced.

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Dedication

This thesis is dedicated in loving memory to my father, Robert Grant Asplin, who left the world peacefully on March 15th 2006.

Chapter 1

Introduction

1.1 – Study Context

Precipitation variability is a key element of hydroclimatology that is apt to be affected by climatic change in many parts of the world. Variability is manifested in precipitation intensity, distribution, precipitation event frequency, and long-term climatic trends. With the pending threat from climatic change comes an urgent need to gain a better understanding of precipitation variability, and to develop methods to predict possible future precipitation regimes arising from climate change. Global Circulation Models (GCMs) are widely used to model climatic changes; however, they operate at spatial scales too large to effectively model changes in local precipitation climates.

One of the primary tasks of present day climate change research is to develop statistical downscaling models that permit output from GCMs to be downscaled to spatial scales appropriate for local climate change impact assessment. Statistical downscaling has been used widely in efforts to predict changes in local climates arising from global warming in mid-latitude regions such as France (Garbrecht and Rossel, 2000), the United Kingdom (Wilby, 1997, 2002), Canada (Lapp et al., 2002), Brazil (Robertson et al., 2004), and Germany (Enke et al., 2005). Downscaling efforts in mid-latitude regions

tend to focus upon using large-scale atmospheric circulation variables and climate indices as predictor variables; however, some schemes also employ surface climate variables.

There are many different types of methods of statistical downscaling based upon weather typing, regression, and weather generators. One such method for examining precipitation variability and subsequently predicting future precipitation regimes is to classify output from GCMs into daily synoptic types using the circulation-to-environment approach of Yarnal (1993). Days within each of these types are assumed to have similar meteorological properties, hence producing similar precipitation amounts and spatial patterns. Previous studies have used this approach to downscale GCM output to regional scales to investigate climate change (Kidson et al., 1995; Lapp et al., 2002) and for precipitation prediction (Saunders and Byrne, 1999).

Synoptic typing is generally accepted as an effective method in downscaling GCM output (Wilby et al., 2004); however, there are two significant limitations to this approach. Firstly, this approach assumes that every day within a given synoptic type will have the same meteorological characteristics. This is incorrect because the nature of synoptic typing is to match like days with each other; hence, within-type variability is inevitable. Secondly, this approach has generally ignored the meteorological processes contributing to within-type variability. Upper-level atmospheric circulation exerts a significant control on surface climate, and is especially important to precipitation formation. The primary atmospheric mechanisms responsible for precipitation formation over mid-latitude regions operate at synoptic scales; therefore, any significant variability at higher levels is apt to be reflected as within-type variability in precipitation climate (Gershunov, 1998).

Precipitation variability is an important element in the hydroclimate of British Columbia (BC). Spatial and temporal precipitation variability can impact many activities in BC, such as hydroelectric power generation, winter recreation activities, agriculture, and domestic water supplies. Orographic modulation of synoptic flows in the lower troposphere is a key source of spatial variability in mountainous regions. The precipitation climatology can vary widely within a given region with local-scale rainshadows and areas of precipitation enhancement. The complex topography of BC therefore suggests a high degree of variability in precipitation intensities and distributions about the province. Temporal variability in precipitation in BC arises primarily from dynamic atmospheric conditions as they oscillate between states, some more favourable for precipitation formation than others. Long-term temporal variability in atmospheric circulation patterns has been linked to atmosphere-ocean teleconenctions (Yarnal, 1984; Yarnal and Leathers, 1988; Mantua et al., 1997; Shabbar et al., 1997).

Two well-documented teleconnections affect interannual upper-level atmospheric circulation patterns over BC: the Pacific Decadal Oscillation (PDO), and the El Niño Southern Oscillation (ENSO). The former describes an oscillation in sea surface temperature (SST) anomalies in the Pacific Basin, oscillating between warm and cool modes on a decadal scale, with each mode lasting approximately 15 to 23 years (Mantua, 1997). This effectively produces two different climate regimes over BC, each with unique upper-level circulation patterns and subsequent surface climate regimes. ENSO describes a year-to-year variation in tropical SST anomalies that modulate surface atmospheric conditions, which subsequently affect upper-level atmospheric circulation over North America. Furthermore, the interaction of the PDO and ENSO teleconnections

is known to enhance the modification of upper-level circulation. This can result in significant year-to-year variation in the upper-level circulation conditions, and subsequently the surface climate of BC (Gershunov and Barnett, 1998; Gershunov et al., 1999).

Teleconnection influences are demonstrated to be important controls on upperlevel circulation; however, little research has been done on teleconnection induced within-type variability in upper-level circulation and the subsequent effect on the precipitation climatology of BC. This study attempts to address the problem of withintype variability and the exclusion of important meteorological processes by investigating the role of teleconnection influences upon upper level circulation. This is performed by stratifying the 13 synoptic types of Stahl et al. (2006a) into sub-types based upon teleconnection conditions, and by creating complementary composites of corresponding upper-level circulation conditions. Within-type variability of a given synoptic type can then be assessed and linked to corresponding within-type precipitation anomalies in the precipitation record of BC.

Under the assumption that teleconnections exert a significant control on withintype variability, and given that GCMs can predict the state of synoptic circulation and teleconnection indices, it is therefore proposed that methods of statistical downscaling from GCMs can be improved upon using synoptic types that are stratified by teleconnection phases. This study hypothesizes that applying synoptic sub-types based upon PDO and ENSO conditions to the methodology of Saunders and Byrne (1999) can better capture within-type variability, and subsequently can lead to an improve in

statistical downscaling efforts. A downscaling exercise forecasting precipitation in BC based upon synoptic sub-types will test this hypothesis.

1.2 – Literature Review

1.2.1 – Synoptic Climatology and Typing Schemes

Barry and Perry (1973) defined synoptic climatology as "concerned with understanding local or regional climate by examining the relationship between local weather elements and the circulation of the atmosphere of that area."

Synoptic climatology is a powerful analytical branch of climatology, and can be employed in studies involving atmosphere-ground interactions (Yarnal 1985). The main three steps in developing a synoptic climatology are: classification of synoptic atmospheric circulation (commonly called *synoptic typing* or *map pattern classification*), assessment of synoptic types with local weather patterns, and lastly, analysing the interaction between local weather patterns and the main study elements.

The classification method employed can greatly affect the number and nature of classes, and have a profound effect on the outcome of the study. Synoptic classifications schemes vary in sophistication and range between purely subjective and objective approaches (Yarnal 1993; Frakes and Yarnal, 1997). Subjective classification allows the researcher to examine the weather charts and assign synoptic classifications manually. This captures common and important meteorological phenomena; however, because of the subjectivity of this method, it is not easy to reproduce, even by the original researcher (Yarnal, 1993). Subjective classification is also very tedious and time-consuming. Objective classification methods are statistical methods, and can easily be applied to large

amounts of data, and re-created and re-applied to new data.

Objective classification schemes include the Kirchhofer sum-of-squares (Kirchhofer, 1973), the Lund correlation method (Lund, 1965), principal components analysis (Yarnal, 1985), and recursive partitioning (Cannon et al., 2002). These methods can promptly classify large amounts of data with ease; however, they are not completely objective in that they require arbitrary classification thresholds. Slight variations in these thresholds have been shown to significantly alter the number and frequency of synoptic types identified (Key and Crane 1986; Frakes and Yarnal, 1997). Hybrid classification schemes that use subjectively selected synoptic 'key days' have been found to address the major problems of manual classification (time, inability to replicate the classification), and of correlation (threshold limits, and arbitrary synoptic type selection (Frakes and Yarnal, 1997).

Cannon et al. (2002) presents a method of synoptic map classification that uses recursive partitioning trees to classify gridded synoptic circulation data into synoptic types. Surface climate data are used to guide the classification process, and the resultant synoptic types are better able to represent the links between surface climate and upperlevel circulation. Furthermore, the guided classification process requires fewer user decisions to determine the number of map classes to be used.

With the advent of higher-powered computers, classification by EOF and a combined method of PCA and k-means clustering have become commonplace in synoptic climate studies (Kidson, 1994; Kidson, 1995; Murphy and Jackson, 2004; Stahl et al., 2006a, Stahl et al., 2006b; McKendry et al., 2006). Kidson (1994, 1995) conducted synoptic classification by obtaining the EOFs from daily 1000 hPa analyses, and

classifying each day on the basis of pattern correlation between the EOFs and mean EOF for each class using cluster analysis. Murphy and Jackson (2004) utilized PCA and k-means cluster analysis to investigate synoptic controls that create favourable thermal conditions for pine beetle populations in BC. Stahl et al (2006b), in a related study, emphasised that considerable care should be exercised when selecting the number of clusters. It should be noted that some statistical methods have been shown to fail outright in some classification schemes, producing random chance classifications that do not represent real meteorological conditions (Blair, 1998).

Synoptic classification methods have been developed that are based upon neural networks (artificial intelligence), such as Kohonen Mapping (Kohonen, 1990; Murtagh, 1995). These methods are complex and computationally intensive; however they are very effective tools for synoptic classification. Kohonen Mapping also referred to as self-organizing feature mapping (SOFM), uses artificial neural networks to classify data. The classification system is trained by fitting the classes to the observations, a process known as unsupervised training. Next, each item in a multidimensional dataset is assigned to a cluster center, and these are subsequently ordered by their proximities. The cluster centers are then arranged into a grid to yield final classifications.

1.2.2 – Statistical Downscaling

The basic premise of statistical downscaling is to estimate a predictant variable y from a predictor variable x. A linear empirical model is constructed by expressing y as f(x) = ax + e where a is a coefficient. It is typical to assume that e is drawn from a normal distribution with zero mean and standard deviation s; however, e may come from a non-

normal distribution as well. Randomness in f(x) stems from randomness in e, therefore producing different y values from the same x. (Von Storch, 1999). A raw downscaling scheme generally excludes random variability in y; however, this can be addressed by more advanced schemes that include variance inflation (Von Storch, 1999).

Many studies have used statistical downscaling in efforts to predict changes in local climates arising from global warming in mid-latitude regions such as New Zealand (Kidson et al., 1995), France (Garbrecht and Rossel, 2000), The United Kingdom (Wilby, 1997, 2002), Canada (Lapp et al., 2002), Brazil (Robertson et al., 2004), and Germany (Enke et al., 2005). Statistical downscaling methods are advantageous compared to regional climate models due to lower computational requirements, and allow for easy generation of multiple climate scenarios so that climate change uncertainties may be In contrast, there are many concerns with statistical downscaling. better studied. Statistical downscaling has focused upon mid-latitude regions, thus methods have not been widely used in tropical or semi-arid regions. The effectiveness of these methods also depends on the availability of relatively abundant surface climate data. This is an important limination of statistical downscaling whereas this is not a requirement for regional climate models (Wilby, 2004). Finally, resulting concerns about data homogeneity have tended statistical downscaling methods to be biased to low altitude regions.

Wilby (1994) identified three important limitations of statistical downscaling. First, most weather classification schemes are inherently parochial because of regional and local-scale factors, such as topography or ocean/land distributions, that characterize the weather of any given region. Secondly, downscaling approaches seldom capture

climate variability at all temporal or spatial scales. Wilby (1994) demonstrated that mean daily precipitation probabilities, wet-day amounts and persistence can be well represented, but variations in the interannual rainfall totals were not modelled to the same standard at either of the two reference sites. Thirdly, and perhaps the most serious obstacle to the confident application of downscaling, many instances of the relationships between the prevailing weather patterns and associated meteorological properties are not constant in time. Statistical relationships developed for the present day climate may not hold under the different forcing conditions of possible future climates (Wilby et al., 2004).

Wilby and Wigley (2000) identified many different predictor variables and techniques used in statistical downscaling of precipitation from GCM output. Commonly used predictor variables include 500 hPa heights, vorticity, specific humidity, wind direction, cloud cover, thicknesses, sea-level pressure, relative humidity, SST anomalies, monthly precipitation, and teleconnection indices. Downscaling techniques that have been used include weather classification, semi-stochastic regression and resampling, neural networks, regression, canonical correlation analysis (CCA), kriging, and stochastic and stochastic-dynamic methods. Wilby (2004) classified these methods into three main categories of statistical downscaling methods: weather typing, weather generators, and regression methods.

Weather classification methods group days into a number of discrete synoptic types, which are classified manually, or objectively, and the relationship between predictors and predictand within each synoptic type is used to predict future climate. Other weather-typing methods include fuzzy classification (Enke et al., 2005), and self

organizing maps (Kohonen, 1995). These methods yield physically interpretable maps, are versatile, and can be easily used to analyse extreme events. Their main drawbacks are that they may not capture within-type variations in surface climate, and also may be insensitive to future climate changes (Wilby, 2004).

Weather generators are models that replicate the mean and variance of a local climate variable, but not observed sequences of events. These models represent precipitation occurrence via Markov processes for wet/dry transitions, and Probability of Precipitation (Robertson et al., 2004). Weather generators are effective at generating sub-daily information, as well as for spatial interpolation of model parameters using landscape variables. Training weather generators with large-scale atmospheric parameters allows them to be employed in statistical downscaling applications; however, arbitrary changes to model parameters are required in order to predict future climate. This may yield unexpected effects upon secondary climate variables. In addition, weather generators often underestimate persistence and temporal variability of precipitation (Wilby, 2004).

Regression methods encompass methods ranging from multiple linear regression models, such as the 'Statistical Downscaling Model' (SDSM) (Wilby, 2002), to complex methods utilizing neural networks. Other methods include Singular Value Decomposition and Canonical Correlation Analysis (Widmann et al., 2003). Regression methods are straightforward to apply using readily available software, and also afford the researcher the option to use few or many predictor variables. The drawbacks of regression methods are that they assume linearity, normality of data, and may poorly represent observed variance and extreme events (Wilby, 2004). This is of particular

concern for precipitation downscaling efforts.

Regression-based statistical downscaling from GCMs has been extensively employed to develop synoptic climatologies for climate change scenarios (Lapp et al., 2002; Wilby, 2002). Lapp et al. (2002) examined future precipitation scenarios as developed by synoptic downscaling from the Canadian Centre for Climate Modelling and Analysis first version of the Canadian Global Coupled Model (CCCma CGCM1). Seven synoptic types were manually classified from continental-scale 500 hPa geopotential heights, and were employed in a stepwise linear regression scheme to predict precipitation. It was revealed only one synoptic type could be significantly linked to precipitation, thus likely ignoring subtle but important influences from the other synoptic types.

Linear regression methods may perform better if they are designed to better account for local climates. Wilby (2002) presented the SDSM, which calculates statistical relationships based upon multiple linear regressions between large-scale GCM output, and local-scale climate. The SDSM normalizes observed and predicted variables using 1961-1990 climate normals to prevent large differences between observed and GCM-simulated conditions from violating the statistical assumptions associated with SDSM.

Wilby et al. (1998) compared various methods of statistical downscaling including weather classification and 'weather generator' methods. They concluded that statistical downscaling methods based upon upper-level circulation conditions performed better than the weather generator-based methods at both local and regional scales. Lapp et al. (2002) showed that regression methods can fail to include subtle, but important

precipitation characteristics of synoptic types used in the model. Salathé (2003) suggested that scaling large-scale precipitation to local sites using ratios based upon climatological normals and forecast values is an effective way to downscale precipitation; however, this method may fail to adequately capture long-term effects from climate change.

Saunders and Byrne (1999) presented a weather-typing downscaling methodology that utilises methods of synoptic climatology in downscaling precipitation from global circulation models. They employed the Kirchhofer classification scheme to classify normalized 50 kPa geopotential heights to develop a synoptic catalogue. The individual synoptic types were then used to generate synthetic precipitation regimes based upon synoptic type frequency. This method is straightforward, is easy to replicate, and makes use of historical synoptic type frequencies. The shortcomings of this method are that it fails to capture precipitation variability within each synoptic type, and requires arbitrary modification to predict future climate scenarios.

McKendry et al. (2006) tested how effective synoptic types are in assessing future climate scenarios in BC by typing GCM output and comparing synoptic type frequencies and properties to those obtained by Stahl et al. (2006a). They were able to adequately recreate the synoptic record of BC, but recommended caution and further research as they found that the GCM output tended to be biased towards warmer synoptic types in the winter. They also stated that the influence of teleconnections must be better characterized in GCMs as they offer a means of long-range predictability. Furthermore, orographic influences need to be better characterized so that synoptic types derived from GCM output better match those produced from the NCEP reanalysis project. Incomplete or inadequate synoptic classifications may hinder downscaling efforts. Saunders and Byrne (1999) stressed that any days deemed unclassifiable may be significant precipitation producers; therefore, it may be necessary to alter the classification scheme to ensure all days are classified. Brinkmann (2000) supported the need to properly account for missing days. Brinkmann (1999) utilized a modified classification scheme in an effort to better capture small-scale circulation features that are important controls upon surface climate anomalies. Furthermore, she stressed that the spatial extent of the study window must include all areas that contain significant circulation features that influence the meteorology at a given location.

Buishand et al. (2003) investigated the temporal aggregation level best suited for statistical downscaling by comparing monthly and daily precipitation downscaling models. Generalized Linear Models were developed to describe rainfall occurrence, with wet-day precipitation amounts and the monthly precipitation totals. Daily models resulted in larger regression coefficients and smaller standard errors than monthly models; however, this study only managed to explain a small proportion of the variance in daily precipitation. The proportion of explained variance is greater in the monthly model because of persistence in the predictor variables.

1.2.3 – Synoptic Atmospheric Circulation over BC

Changes in large-scale atmospheric circulation patterns cause different synoptic weather patterns to prevail over BC, influencing precipitation and temperature patterns (Yarnal, 1984; Moore and McKendry, 1996; Shabbar et al., 1997; Stone et al., 2000; Graham and Diaz, 2001; Stahl et al. 2006a). The most recent and complete synoptic

climatology for BC is described by Stahl et al. (2006a). Thirteen synoptic types were generated for the period 1948 to 2003 using principal components analysis and an unsupervised k-means cluster analysis. Substantial teleconnection-related variability was identified in the surface climate, and in the synoptic type frequencies, especially during the winter months (December to February).

In an earlier study, Yarnal (1984) presented a synoptic climatology that examined fluctuations in thermal and moisture trends in BC and Washington for the period covering 1948 - 1977. The Kirchofer technique was employed to produce 18 different synoptic classifications, further classified as 'cyclonic' or 'anticyclonic.' It was discovered that four types accounted for roughly two-thirds of all winter days. These types all show steep pressure gradients, which correspond with the perturbed state of the winter climate along the Pacific coast. Furthermore, the synoptic types were described as either being warm or cold in nature. Wet synoptic types represent the southeastern quadrant of the Aleutian Low, with positive vorticity advecting subtropical moisture onto the coast of BC. An increase in the intensity, or westward shifting of the Aleutian Low gives rise to a ridge over north-western North America, bringing drier mean conditions to the region (Yarnal 1984).

Warmer (greater thickness between pressure levels) atmospheric conditions tend to correspond with lower annual precipitation totals. The 500-1000 hPa thickness over the eastern North Pacific and BC coast has oscillated between higher thicknesses (warm) and lower thicknesses (cool) conditions at periods of approximately a decade. This corresponds with identified trends in surface temperatures at Quillayute, Washington, and Annette, Alaska (Yarnal, 1984). A notable warming trend is present from the mid-1950's

and is reciprocated with a cooling trend from the mid-1960's to the mid-1970's. Synoptic typing linked the higher (lower) surface temperatures in the 1950s (1960s) to (greater) 500 hPa heights and revealed a thinner (thicker) 500-1000 hPa layer. Yarnal (1984) also suggested that changes in warm synoptic type frequency can be linked to annual variations in mean 500 hPa heights.

Moore and McKendry (1996) used Kirchofer correlation-based synoptic typing to investigate the relationship between ocean-atmosphere teleconnections and snow pack levels throughout BC. Frequencies of synoptic types were calculated for each winter during the study period with positive snow pack anomalies from 1966 to 1976 correlated with two specific synoptic types. It was also shown that the deepening of the climatological Aleutian Low, characteristic of El Niño conditions, is associated with widespread light snow pack conditions. This indicates the prevalence of overall drier conditions over many parts of BC during El Niño conditions.

1.2.4 – Within-type variability

Within-type variability is identified as one of the critical problems arising within the field of synoptic climatology (Yarnal, 1993). In the process of synoptic classification, weather maps representing particular days are lumped into a finite number of classes or types. Naturally, all days forming members of a particular synoptic type are not identical. Within-type variability is characterized by variations between individual weather maps making up a synoptic type, and can arise from seasonal effects, or small-scale circulation features not visible at the spatial scale of the synoptic classification scheme (Brinkmann, 1999).

Identification of discrete categories of pressure patterns, or synoptic types, presents several problems to those who wish to use them for analysis. Firstly, the atmosphere displays a continuum of variability, and so defining strict boundaries between classes is difficult and each synoptic type may encompass a variety of atmospheric and surface conditions. Secondly, pressure systems can have variable intensities and decisions must be made whether to include small-scale circulation features (Brinkmann, 1999; Brinkmann, 2000). Finally, there may be seasonal variability in type characteristics, or seasonal within-type variability, as winter weather systems tend to be the most intense due to greater equator-pole energy differences (Barry and Perry, 2001).

1.2.4.1 – Within-type Variability in the Surface Climate of BC

Many studies have examined within-type variability in one or many meteorological variables for BC (Yarnal, 1984; Stahl et al, 2006a). Significant withintype variability is discernable over BC between atmospheric thickness regimes governed by teleconnections (Yarnal, 1984). The linkage of significant within-type variability to atmosphere-ocean teleconnections is intriguing in that it suggests that seemingly similar atmospheric circulation patterns may have significantly different dynamic meteorological properties between different phases of a given teleconnection.

Significant within-type variability can be identified through analysis of type frequencies and meteorological variables. Yarnal (1984) identified significant differences in precipitation in given synoptic types between different years, but was unable to detect any significant differences synoptic type frequencies. Yarnal (1985) identified significant variations in 500 hPa geopotential height, but they are not entirely explained by synoptic

type frequency. Regression analysis showed that only 38% of the variation in smoothed mean 500 hPa height was associated with changes in warm synoptic type frequency (significant at the 0.01 level). Greater mean 500 hPa height values were observed during the early (warm) years of the study, and lesser mean heights are observed in the later (cool) years of the study. This shows systematic within-type variability in atmospheric thickness that corresponds with changes in surface temperatures.

Long-term means can be significantly affected by climate regime shifts associated with the PDO. Ramage (1983) suggested that if the atmosphere undergoes significant regime shifts, then separate statistical tests should be performed on populations of data for each regime. This will allow for the characteristics of each atmospheric regime to be examined separately, and reduce within-type variability found in long-term synoptic climatologies. Since teleconnections are well documented to control the intensity and spatial distribution of precipitation, precipitation data should be analysed by teleconnection phase. Statistical analysis can then be performed to determine if significant within-type variability in precipitation is indeed occurring between phases of a particular teleconnection.

1.2.4.2 – Within-Type Variability in Upper-Level Circulation

Upper-level within-type variability is a key element within many previous studies (Gershunov, 1998; Wilby, 1998; Brinkmann, 1999; Brinkmann, 2000; Wilby and Wrigley, 2000). A positive relationship exists between positive vorticity variability and daily precipitation, as well as vorticity and wet-day occurrence (Wilby, 1998). Within-type variability in surface climate is linked to higher low-level synoptic wind velocities

during rain-producing weather episodes resulting in stronger uplift, particularly in mountainous terrain (Wilby and Wrigley, 2000). Furthermore, Gershunov (1998) argued that the occurrence and intensity of heavy precipitation events depend upon dynamic upper-level atmospheric circulation conditions.

Brinkmann (1999) demonstrated that significant within-type variability can be present in surface classifications, and can arise from small variations in the prevailing synoptic conditions. Within-type variability was found within synoptic types based upon 700 hPa geopotential heights over the Lake Superior Basin. Warm and cold subtypes were distinguished within each synoptic type, and the 700 hPa height patterns associated with each were analyzed. Composite difference maps identified small-scale circulation features that accounted for much of the temperature variability. Brinkmann (2000) concluded that within-type variability can be reduced using a version of the same synoptic classification scheme that is modified to better capture small-scale circulation features. Subjective modification of a classification scheme can reduce within-type variability, but should be a prerogative of the original researcher whenever possible.

Stahl et al. (2006a) identified systematic differences in mean precipitation between different teleconnection phases. They suggested that the primary cause of the within-type variability of precipitation in BC is subtle teleconnection-induced changes in upper-level atmospheric dynamics that may significantly alter the intensity, trajectories, and precipitation potential of cyclonic storms in the Northeast Pacific Ocean. A case study examined whether teleconnections induced within-type variability in meteorological conditions in the synoptic types. Days within an important precipitationproducing synoptic type were grouped into synoptic composites by teleconnection phase.

Composites of upper-level meteorological variables, such as 500 and 700 hPa geopotential heights, and 700 hPa relative vorticity were also created for comparison. Within-type variability is identified in the magnitude and spatial location of precipitation and temperature anomalies within several synoptic types, including several synoptic types responsible for much of the winter precipitation in the region.

1.2.5 - Teleconnections and Climate Variability

Numerous studies have identified significant teleconnection-induced variation in synoptic atmospheric circulation features in many regions of the world (Yarnal, 1984; Yarnal, 1985; Kidson, 1994; Kidson, 1995; Brinkman, 1999; Brinkman 2000; Stahl et al., 2006a; Stahl et al., 2006b). Teleconnections have also been linked to variability in large-scale synoptic flow over BC and Western North America (Yarnal, 1984; Yarnal, 1985; Mantua et al., 1997; Shabbar et al., 1997; Gershunov; 1998; Stone et al., 2001). It is also documented that teleconnections influence the frequency of synoptic types (Sheridan, 2003; Stahl et al., 2006a). Teleconnection influences are also cited as a source of small-scale precipitation variability in BC (Dunkley, 1999; Jakob et al., 2003).

Stahl et al. (2006a) suggested that teleconnections influence synoptic climatologies by changing the frequency of synoptic types during a particular phase of a climate index (such as ENSO). Interannual fluctuations in precipitation appear to be closely related to synoptic type frequencies. Wet winters are found to have increased numbers of synoptic types showing southerly flows, and dry winters are subject to higher occurrences of dry synoptic types with more variable flow patterns. The wettest winters

at a given station are found to occur when that station is both within a wet regime and an above average number of wet synoptic types occur.

Teleconnection indices have clear explanatory power for some surface variables in certain regions and seasons for the present global climate, but it remains unclear as to what extent the same indices may be used to downscale future climates. The capability of GCMs to handle teleconnections such as PDO and ENSO is weak, but it is improving. One drawback to their use is that global warming may alter SST anomalies and teleconnection influences may change (Wilby 1998). Kidson (1995) emphasised the need to better understand teleconnection influences and develop the ability to discriminate between climate change and teleconnection influences so that changes in SST anomaly patterns can be properly assessed.

Wilby (1998) used teleconnection indices in an attempt to improve the performance of a precipitation regression model. Three models were tested, one using vorticity as the only predictor variable, the second using vorticity and the Northern Atlantic Oscillation Index (NAOI), and the third using vorticity, NAOI and SST anomalies. The third model yielded the best model performance, with stronger improvements occurring in areas that are strongly influenced by the NAOI. This shows that the inclusion of low-frequency predictors does slightly enhance simulations of low-frequency precipitation variability.

1.2.5.1 – The Pacific Decadal Oscillation

The PDO is a large-scale, atmosphere-ocean teleconnection that is characterized by an interdecadal oscillation between warm and cold SST anomalies in the northern and

eastern tropical regions of the Pacific Ocean. It is characterized by a striking pattern of widespread atmospheric circulation and climate variability that is detectable in many different regions of the Pacific Basin (Mantua et al., 1997; Graham and Diaz, 2001). Minobe (1997) identified an average return period of 23 years for the PDO with a full period of oscillation ranging from 50 to 70 years. Furthermore, tree ring growth rate analysis identifies a 150-year oscillation in the strength of the PDO, with increased intensity noted during the 20th century (Biondi et al., 2001).

Variability in large-scale atmospheric circulation features that control the climate of BC is linked to the PDO (Mantua et al., 1997; Shabbar et al., 1997; Stone et al., 2000). The polar jet stream, the Aleutian Low, and the Canadian High vary in mean position and intensity. During positive PDO conditions (warm phase), the mean jet stream pattern is meridional and is shifted northward. This results in a deepening of the Aleutian Low, and enhancement of the Canadian High, producing strong southwesterly synoptic flow. Negative PDO conditions (cold phase) result in a strengthened zonal polar jet stream that is shifted to the south, and results in a weaker Aleutian Low and a westward displaced Canadian High.

Precipitation and temperature variability in North America has been strongly linked to the PDO (Mantua, 1997; Shabbar et al., 1997; Cayan et al., 1998; Stone et al., 2000; Biondi et al., 2001). It has been found to account for 20% - 50% of the variance of annual precipitation in parts of Western North America (Cayan et al., 1998), and to influence regional temperatures and cyclonic development (Graham and Diaz, 2001). The PDO is also known to be an important dynamic element in the historical climate of the Pacific Basin (Biondi et al., 2001).

The PDO has a significant impact on the climate of BC, with contrasting temperature and precipitation anomalies clearly linked to different phases of the PDO. A proclivity for strong southwesterly flows during positive PDO conditions advects warm, moist air onto the North BC and Alaska coastline, resulting in positive precipitation anomalies. Warm, humid air is advected over the remainder of BC; however, an enhanced anticyclone dominates BC, resulting in less precipitation occurring (Mantua et al., 1997). During negative PDO conditions, positive precipitation anomalies in southeastern BC are attributed to the enhanced zonal jet stream. Near normal precipitation is received along the coast (Shabbar et al., 1997; Dunkley, 1999; Jakob et al., 2003).

Stahl et al. (2006a) investigated the impacts of the PDO on the spatial distribution and intensity of precipitation anomalies in BC. Positive PDO conditions yield negative precipitation anomalies throughout most of BC except for some neutral anomalies in the Georgia Trench, and positive anomalies on the Queen Charlotte Islands and at stations on Vancouver Island. Negative PDO conditions show very strong positive precipitation anomalies in the Okanagan and Kootenay regions, and Northern BC. Negative anomalies are observed over the Queen Charlotte Islands and at stations on the northwest part of Vancouver Island; however, no significant anomalies are observed in the Georgia Trench or in Central BC. Neutral PDO yields positive precipitation anomalies along the coast and at some stations in Northern BC. Negative anomalies are present in the Okanagan Region, and neutral anomalies occur in the Kootenay Region.

1.2.5.2 - The El Niño Southern Oscillation

The El Niño Southern Oscillation exerts an important control on interannual climate variability in BC. Anomalous pooling of warm or cool surface water caused by a reversal in the Walker Circulation disrupts deep-ocean cold-water convection. This affects the location of significant atmospheric convection, and alters synoptic circulation throughout the Pacific Basin. ENSO oscillates on an annual to bi-annual time scale; thus, synoptic circulation patterns can differ greatly between consecutive years (Barry and Carleton, 2001).

The effect of ENSO on the polar jet stream is the most notable atmospheric impact over BC. During an El Niño, the polar jet stream diverges into two branches, with the weaker branch flowing over northern BC, which creates a large ridge over BC that is favourable to the development of anticyclonic conditions over southern BC. Pacific cyclones tend to follow the jet stream branches, bringing above-normal precipitation to California, and northern BC. During La Niña conditions, an enhanced polar jet stream follows a zonal flow pattern across the eastern Pacific Ocean. This increases baroclinicity, sheer vorticity, and favours the formation of Pacific cyclones that impact BC (Shabbar et al., 1997; Jakob et al., 2003).

Stahl et al. (2006a) linked significant precipitation anomalies in BC to ENSO. Similar patterns to those found in the PDO case are observed within the like phases (e.g. negative PDO and La Niña). Negative precipitation anomalies persist during El Niño conditions at most of the stations in BC; however they are not as large as those corresponding to positive PDO. Precipitation is greatly enhanced throughout the

province during La Niña conditions over those found during negative PDO, except at stations within the Georgia Trench and along the west coast of Vancouver Island. In particular, stations in the Cariboo-Chilcotin region of BC show a much larger positive precipitation anomaly.

ENSO impacts on atmospheric circulation and climate are most discernable during the winter months (Cayan et al., 1998; Gershunov, 1998). Many studies have used SOI values for DJF because they reflect the mature stages of the given ENSO event (Shabbar et al., 1997). Spencer and Slingo (2003) suggested that comparing climatic responses to the SOI at the same time creates an artificial correlation because the impacts of ENSO upon atmospheric circulation are usually delayed by several months from the onset of the ENSO event. They recommended employing SOI values from the preceding summer months (June to September) so that the delayed response in atmospheric circulation is accounted for.

Linearity is a common misconception of the atmospheric response to the ENSO phenomenon (Gershunov, 1998; Wu and Hsieh, 2003). Wu and Hsieh (2003) compared geopotential height anomalies between ENSO phases. They found that the presence of anomalies is not linearly related; that is, an anomaly present in a warm-phase year does not necessary disappear or reverse polarity in a cold-phase year. This suggests that a non-linear signal may also be detected within synoptic types and their variability.

1.2.5.3 – Teleconnection Interactions

There is a growing emphasis on the importance of the interaction of the ENSO and PDO teleconnections. A general consensus is that the effects of ENSO tend to be amplified greatly when the PDO is in phase with ENSO, and that the strength of the PDO

may be directly correlated with the strength and phase of ENSO (Gershunov et al., 1999; Gershunov and Barnett, 1998). In addition, El Niños (La Niñas) are more likely to occur during positive (negative) PDO conditions. (Gershunov, 1997; Shabbar et al. 1997; Dettinger et al. 1998; Cayan et al. 1998). The effects of in-phase teleconnection conditions on upper-level atmospheric dynamics are particularly important as it may contribute significantly to within-type variability of surface climate.

The interaction of PDO and ENSO effects upon upper-level dynamics is linked to Aleutian Low and Pacific cyclone intensification (Graham and Diaz, 2001). They found major changes in winter storm climate over the North Pacific, but found that the trend in storm intensity appears to be associated with slow changes in background climatic conditions and the PDO rather than the noted increased frequency of ENSO events. They also suggested that Pacific cyclogenesis may be intensifying, and may lead to increasingly variable synoptic flow conditions that would affect the frequencies of modified synoptic types, and therefore the synoptic climate of BC.

1.3 - Study Objectives and Research Outline

This study will expand on the case study reported by Stahl et al. (2006a) and investigate whether significant within-type variability exists within important winter precipitation-producing synoptic types in BC. It will identify within-type variability within different phases of PDO and ENSO, and investigate the effect on precipitation by analyzing changes in upper-level meteorological conditions. It will then be possible to draw a conclusion regarding whether teleconnection-induced within-type variability exists within precipitation-producing synoptic types in BC. A product of this research
will be a seasonal precipitation-forecasting model that incorporates synoptic type frequencies and within-type variability of precipitation by teleconnection phase to downscale precipitation forecasts from GCM output. It is then possible that this method may be replicated and used for similar studies in other mid-latitude regions.

The objectives of the study are as follows:

- Describe the synoptic climatology of the winter precipitation of BC
- Investigate the nature of within-type variability in the primary precipitation producing types
- Investigate teleconnections as a source of within-type variability
- Develop and test a weather-type-based downscaling model that incorporates teleconnection-based synoptic sub-types

This study will utilize the circulation-to-environment approach (Yarnal, 1993), so that precipitation patterns may be compared with variations in synoptic atmospheric circulation. Gridded daily atmospheric circulation data are then compared and classified into one of many possible categories with a synoptic typing procedure, using principal component analysis (PCA). This classification process yields a number of classes, each containing days with similar circulation patterns. It is then possible to average the daily data together to calculate average circulation conditions, referred to as a synoptic composite, and to determine the variability within a class. The daily synoptic classifications are then applied to different meteorological variables so that the nature of other corresponding meteorological variables can be examined within each class.

Based upon the review of the literature, a statistical downscaling method based upon weather classification is preferred. Weather-classification downscaling methods afford

better physical linkages between surface climate and the atmosphere, and do not eliminate important influences as is the case with regression methods. Furthermore, teleconnections have been found to impact synoptic type frequencies (Yarnal, 1984; Stahl et al., 2006b), and within-type variability (Brinkmann, 1999; Stahl et al., 2006b); therefore, a weather-classification-based statistical downscaling method that incorporates synoptic type frequencies and teleconnection indices is employed by this study.

This study is broken into three analytical components. First, precipitation statistics within each synoptic type are examined for within-type precipitation variability across the different phases of ENSO, PDO and ENSO/PDO. This analysis will allow for types with significant teleconnection within-type variability to be identified and is discussed further in Chapter 3. The second component of this study seeks to better understand within-type variability in upper-level meteorology. Within-type variability of the upper-level meteorological conditions within a given synoptic sub-type can then be assessed so that a better understanding of how teleconnections influence upper-level meteorology can be determined. The results and discussion of this analysis are presented in Chapter 4. The third component of this study proposes a method for improving statistical downscaling of precipitation forecasts from GCM output by using a modified version of the synoptic downscaling methodology of Saunders and Byrne (1999). The results and discussion of this exercise are found in Chapter 5.

Chapter 2

Data and Methodology

2.1 – Data

Three data sets encompassing the period 1948-2003 are exploited in this study. Upper-level meteorological data were retrieved from archives maintained by the NOAA-CIRES Climate Diagnostics Centre (CDC) and originate from the National Center for Environmental Prediction (NCEP) Re-analysis project. The spatial resolution of these data is a 0.5° x 0.5° (latitude and longitude) grid, encompassing the Northeast Pacific Ocean, BC, and neighbouring provinces and states. The variables included were mean sea-level pressure (MSLP), 500 hPa and 700 hPa geopotential heights (gph), 700 hPa vertical velocity, and precipitable water.

Geopotential heights are simply the observed height at which a standard pressure level is found in the atmosphere. Geopotential height gradients can be used to describe the nature and magnitude of the geostrophic wind, and resultant synoptic flow. Vertical velocity (Pa/s) represents vertical motion in the atmosphere, and is represented by the change in pressure over unit time as a parcel of air moves upward or downward in the atmosphere. Since pressure values decrease with height, negative values indicate upward motion, and positive values indicate atmospheric subsidence. Precipitable water W

$$W = \int_{z=0}^{Z_{top}} \rho_{v} dz \tag{2.1}$$

represents the limit to which amount of precipitation that may form in the atmospheric column (Stull, 2000). It is the vertically integrated mass of water vapour per unit area in the water column (kg/m²), and is calculated from the density of water vapour ρ_{v} , and the change in height *z* in the atmosphere, *dz*.

Spatial variations in the surface climate of BC were established from the Environment Canada climate stations network; 44 stations have records of daily precipitation (P) data in the study period. It should be noted that these stations are distributed somewhat unevenly with more stations in southern BC (Figure 2.1).



Figure 2.1: Study area and stations with complete data records

Finally, standard large-scale atmospheric or sea surface temperature based indices describing climate variability in the Pacific Region were utilised: the PDO from Mantua (2005), and SOI and ENSO from Redmond (2005). The PDO phase is determined by averaging the monthly PDO index values for each season. The year is classified as a positive (negative) PDO phase if the index is above (below) 0.5 (-0.5). Seasons not exceeding these thresholds are classified as having 'neutral PDO' conditions. The phase of the ENSO is determined by using the time averaged SOI value for the period covering the preceding June to September, reflecting the delayed ENSO response in winter atmospheric circulation (Spencer and Slingo, 2001). ENSO years are classified as La Niña (El Niño) if the SOI is above (below) 0.5. Years with SOI values that fall between these thresholds are classified as ENSO neutral.

2.2 – Synoptic Typing and Compositing

2.2.1 – Synoptic Typing

A set of synoptic circulation types, or simply 'synoptic types', was classified from daily MSLP data, and then related to precipitation across BC. MSLP grids from 1948-2003 were subjected to a common pattern recognition scheme using principal component analysis (PCA) and a subsequent unsupervised k-means cluster analysis on the components scores of the retained components (Dahni and Ebert, 1998).

Synoptic Typer 2.0, an IDL application (Interactive Data Language software) by the Australian Bureau of Meteorology (Dahni, 2003), was used to conduct the synoptic classification. Synoptic Typer 2.0 determines the eigenvalues for the daily MSLP grids from 1948 to 2003 (20455 days). The first six eigenvectors explain 91% of the variability

and were retained. K-means cluster analyses were then performed on the component scores for 9 to 20 clusters. A 13-cluster solution was chosen as a reasonable compromise between the number of clusters and cluster homogeneity.

The output consists of a catalogue of daily circulation classifications for each day of the study period. The occurrence frequencies of the synoptic types, their persistence, their seasonal variability, and transition characteristics can be derived from this catalogue. The resulting synoptic climatology can be visualized with MSLP composites that are created by averaging the MSLP grids of all days within each synoptic type.

2.2.2 – Synoptic Compositing

Synoptic compositing of dynamically relevant variables (such as vertical velocity and vorticity) was conducted in order to provide meaningful meteorological explanation of precipitation variations associated with-in type variability of surface map types. Upper-level meteorological data are available at six-hour intervals (00Z, 06Z, 12Z, 18Z); however, in order to maintain consistency with the temporal and spatial scales reflected in the synoptic classification, composites were based on averages of the data from all four observation times.

Daily 500 hPa and 700 hPa geopotential heights, 700 hPa vertical velocities, and precipitable water values were extracted from the NCEP-NCAR datasets and then paired with existing daily synoptic type classifications of Stahl et al. (2006a). Geopotential heights at 500 hPa were used because they are a good representation of average tropospheric circulation conditions. The data were then grouped into DJF seasons, and then each season classified by the phase of the PDO and the ENSO. MSLP maps were

then averaged to produce synoptic composites that represent the average MSLP conditions for each synoptic type.

Each variable within the NCEP dataset was then averaged to create composites for each phase of the PDO and ENSO, resulting in six composites for each synoptic type (positive PDO, negative PDO, Neutral PDO, El Niño, Neutral ENSO, La Niña). The data were then subjected to a similar compositing procedure, except these data were only used where PDO and ENSO are in phase with each other. This produced three additional composites for each synoptic type (Positive PDO/ El Niño, Neutral PDO/Neutral ENSO, Negative PDO/La Niña) resulting in a set of surface and upper-level composites for each synoptic sub-type.

The 'relative difference equation' is applied within an IDL script to calculate relative vorticity ζ

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$
(2.2)

for the period of record where $\frac{\partial v}{\partial x}$ and $\frac{\partial u}{\partial y}$ represent the change in magnitude of wind vectors v and u along the x and y plains respectively. Relative vorticity composites for each subtype are then calculated for each daily map grid, classified as per the synoptic catalogue, and then composited into synoptic sub-types for all teleconnection conditions.

The complete sets of surface and upper-level meteorological sub-type composites permit the investigation of within-type variability within each synoptic type. The subtype composites can be contrasted within each synoptic type to visually identify notable or even subtle changes in upper-level circulation conditions. Any notable variations in upper-level circulation can be contrasted to atmospheric circulation modification already attributed to teleconnections in the literature. Variations in upper-level conditions can then be related to corresponding variations in surface climate.

The strongest teleconnection signals in atmospheric circulation are often observed in the winter months (December to February); therefore, the composites used in this analysis are limited to contain days from the period of December to February (DJF).

2.3 – Statistical Downscaling: Seasonal Precipitation Model

The final step in the analysis involved the testing of a simple downscaling model based on mean precipitation values associated with each synoptic type. The approach rests on the fact that GCMs provide both daily weather patterns and teleconnection indices. On this basis, GCM output can be classified into synoptic types (which may be further sub-divided into teleconnection based sub-types). Given mean precipitation amounts established for each type based on the historic record, precipitation scenarios can be calculated for any station in BC.

A downscaling technique is derived from the methodology presented in Saunders and Byrne (1999). A seasonal precipitation total can be calculated by summation of synthetic monthly precipitation data. Multiplying the mean precipitation by the mean seasonal frequency generates a synthetic monthly precipitation value for each synoptic type. Synthetic monthly precipitation totals are then found by summation of the monthly total found for within each synoptic type, and DJF seasonal totals by summation of the monthly totals. Teleconnections are included in this methodology by further classification of the synoptic types into synoptic sub-types by PDO, ENSO and

PDO/ENSO indices, and the calculation of their respective mean frequencies and mean precipitation amounts.

Model 0 uses the original synoptic types to estimate total precipitation P_{ym} using:

$$P_{ym} = \left[\sum_{i=1}^{13} (\lambda_i P_i)\right]$$
(2.3)

where P_{ym} is the monthly total precipitation for year _y and month _m, λ_i is the average monthly frequency of type *i* and P_i is the mean precipitation for type *i*.

Model 1 incorporates sub-types based upon PDO conditions, and predicts P_{ym} using:

$$P_{ym} = \left[\sum_{p=1}^{3} \sum_{i=1}^{13} (\lambda_{pi} P_{pi})\right]$$
(2.4)

where λ_{pi} is the average monthly frequency of sub-type pi and P_{pi} is the mean precipitation for sub-type pi. There are three sub-types for each synoptic type.

Model 2 incorporates sub-types based upon ENSO conditions, and predicts P_{ym} using:

$$P_{ym} = \left[\sum_{E=1}^{3} \sum_{i=1}^{13} (\lambda_{Ei} P_{Ei})\right]$$
(2.5)

where λ_{Ei} is the average monthly frequency of sub-type Ei and P_{Ei} is the mean precipitation for sub-type Ei. There are three sub-types for each synoptic type.

Model 3 incorporates sub-types based upon PDO/ENSO conditions, and predicts $P_{\rm ym}$ using:

$$P_{ym} = \left[\sum_{B=1}^{9} \sum_{i=1}^{13} (\lambda_{Bi} P_{Bi})\right]$$
(2.6)

where λ_{Bi} is the average monthly frequency of sub-type Bi and P_{Bi} is the mean precipitation for sub-type Bi. There are nine sub-types for each synoptic type.

Yarnal (1993) suggested two essential components to effective model validation: a measure of model error, and a measure of the model's 'goodness of fit' to observed data. He presented Willmott's index of agreement d

$$d = 1 - \left[\frac{n(RMSD)^2}{\sum_{i=1}^{n} (|P_i| + |O_i|)^2}\right]^{1/2}$$
(2.7)

as a 'goodness-of-fit' measure (Willmott, 1981; Willmott 1982), where P_i and O_i are the modelled and observed values on day *i*. Values of *d* can range value from 0 to 1, with better model performance being represented by large values of *d*. There is no set threshold for *d* to reach for a model to be considered valid, as it is the prerogative of the researcher to decide how well a model performs. A measure of the error in the model is gained through the root-mean-squared-difference (*RMSD*)

$$RMSD = \left[\frac{1}{n}\sum_{i=1}^{n} (P_i - O_i)^2\right]^{1/2}$$
(2.8)

Furthermore, *RMSD* may be broken down in to systematic (*RMSD_s*) and unsystematic (*RMSD_u*) components. *RMSD_s*

$$RMSD_{s} = \left[\frac{1}{n}\sum_{i=1}^{n} (P_{i}^{*} - O_{i})^{2}\right]^{1/2}$$
(2.9)

represents error that is introduced by the model and should be relatively small in magnitude. It is calculated in a similar manner to *RMSD* except that P_i^* is substituted for

the predicted value P_i from the model. $P_i^* = a + b O_i$ where *a* and *b* are the coefficients associated with ordinary sum-of-squares linear regression between O_i and P_i . *RMSD*_u

$$RMSD_{u} = \left[\frac{1}{n}\sum_{1}^{n} (P_{i}^{*} - P_{i})^{2}\right]^{1/2}$$
(2.10)

represents unsystematic error that is present in the data. Subsequent model versions may be deemed an improvement over former versions if $RMSD_u$ is found to decrease. Yarnal (1993) suggested using $RMSD_u$ and $RMSD_s$ if the goals of model performance evaluation are to select a model from a suite of models, or decide whether or not a model may be improved by tuning.

The statistical model was tested on the historic record using a bootstrapping approach. Bootstrapping is a statistical method that estimates the distribution of a particular variable by sampling by random replacement from within the original dataset. This allows for strong estimates of population parameters, such as mean, median, proportion, correlation coefficient, or regression coefficient (Efron, 1979). For the purpose of model validation, a random dataset is generated by bootstrapping and then is used in conjunction with the model validation statistics of Willmott. When repeated many times, this procedure provides a statistically rigorous means of model assessment.

Reserving ten randomly selected DJF seasons containing daily precipitation records yields a model validation dataset. To ensure robustness of the model validation process, a bootstrapping technique is applied to generate 100 separate validation datasets each containing ten randomly selected seasons of precipitation data. This process is repeated for all 44 stations, which ensures that the model is validated spatially as well. The mean and standard deviation of each model validation statistic are then calculated.

The mean and standard deviation of the model validation statistics of models 1 to 3 are compared to those of model 0 to determine if any performance improvements are gained by using synoptic sub-types.

In order to better assess the spatial performance of the modelling technique, model performance will be assessed separately within six different winter climatic regions in BC (Figure 2.2).



Figure 2.2: BC divided into six winter climatic regions

The regions are South Coast, Okanagan, Kootenays, Cariboo-Chilcotin, North Coast and Northern BC. The climates of the North and South Coast Regions are characterized by frequent precipitation events from Pacific Cyclones, resulting in a very wet and mild climate. In contrast, the Okanagan Region is much drier because it is in the rainshadow of the Coast Mountains. The Kootenay Region is influenced by southwesterly flows, and consequently receives more precipitation than the Okanagan Region, and can receive significant amounts of snow during the winter. The Cariboo-Chilcotin Region is relatively drier than coastal areas, and is subject to influence from both Arctic and Maritime air masses. This results in a wide range of temperatures and winter precipitation is primarily snow, but the occurrence of rain associated with warm air masses is not uncommon. The Northern BC – Yukon region is the coldest on average during the winter, and receives nearly all of its winter precipitation as snow.

Chapter 3

Exploring Within-Type Variability in Winter Precipitation in BC

3.1 - Within-type Variability in Precipitation

Within-type mean precipitation intensity anomalies are presented for the different phases of ENSO and PDO in Figure 3.1 with all synoptic types showing some degree of mean precipitation intensity variability.



Figure 3.1: Precipitation within each type by ENSO (left) and PDO (right) phase

Types 3, 6 and 9 through 13 are identified as important winter precipitation producing synoptic types due to their seasonal dominance in winter, and ability to produce precipitation (Stahl et al., 2006a). Types 9 and 10 through 12 exhibit the greatest

variability arising from the different phases of ENSO. Types 3, 6 and 10 exhibit the highest precipitation intensity variability by PDO phase. Types 10, 11 and 12 exhibit significant variability in precipitation intensities by ENSO and PDO; therefore, when ENSO and PDO are in phase, it is expected that these types will exhibit the highest levels of within-type variability of precipitation. Type 3 (9) varies primarily by PDO (ENSO) and is expected to show the greatest within type variability between opposite PDO (ENSO) phases.

3.2 – Exploratory Analysis of Within-Type Variability of Precipitation

Within-type variability appears to be driven by low-level long-term variability generated by the PDO, and erratic short-term interannual variability generated by ENSO. Therefore, further investigation of within-type variability is warranted within precipitation records. Precipitation statistics are calculated within each synoptic sub-type of each teleconnection, and for PDO/ENSO like-phase synoptic sub-types. The statistics are then contrasted within each teleconnection for the presence of within-type variability. Within-type variability is identified by shifts in means or standard deviations of the precipitation data between teleconnection phases.

The precipitation record at Powell River is selected for a case study for two reasons: 1) Powell River is influenced by multiple orographic influences, situated on the windward slopes of the Coast Mountains and in the rainshadow of Vancouver Island; 2) there are at least 30 days with precipitation within each of the nine PDO/ENSO synoptic sub-types. The mean and standard deviation of precipitation within each synoptic type, and within each teleconnection phase are calculated (figure 3.2). It should be noted that

symmetric bars showing standard deviation are normally not used to assess precipitation because they do not adequately represent the skewed distribution of precipitation data, and they are utilised here for exploratory analysis only.





Figure 3.2: Mean precipitation and standard deviations for each phase of PDO, ENSO and PDO/ENSO for Powell River by synoptic type.

It is evident that notable within-type variability at Powell River can be attributed to teleconnection influences. Precipitation analysis by PDO phase shows that within-type variability is characterized by large changes in standard deviations, especially in types 6, 8, 9, and 11, and by subtle to moderate variations in mean precipitation values in all synoptic types. Negative PDO conditions tend to enhance precipitation in types 1, 6, and 12, and reduce precipitation in type 9. Positive PDO conditions enhance precipitation in types 8 and 11, and decrease precipitation in types 10 and 12. Types 3, 7 and 11 experience an increase in precipitation during positive or negative PDO conditions.

The phase of ENSO also produces notable changes in precipitation standard deviations in types 3, 6, 8, 11 and 13; however, changes in mean precipitation values are less pronounced than they are in the PDO case. La Niña enhances precipitation in types 1, 3, 6, 8 and 11, and lessens it in types 9 and 13. El Niño decreases precipitation in every synoptic type except for type 9 where a slight increase is noted and types 7 and 13 where no noticeable change occurs.

Analysis by in-phase teleconnection conditions yields within-type variability for many of the synoptic types. Negative PDO and La Niña enhance precipitation in types 1, 3, 5 through 8, 11 and 12, and weaken precipitation in types 9, 10 and 13. Positive PDO and El Niño only enhance precipitation in types 3 and 8 while types 2, 4, 9, 10 and 12 experience decreases in precipitation.

These results suggest that teleconnections account for a significant amount of within-type variability at Powell River. In-phase teleconnection conditions appear to influence the greatest number of synoptic types, with nine synoptic types showing some degree of systematic within-type variability. Examining within-type variability by only

the ENSO or PDO yields variability in fewer synoptic types (5 and 4 respectively); however, the magnitude of precipitation variability in these types is greater than the variability identified by in-phase teleconnections. The majority of the 13 synoptic types exhibit within-type variability during in-phase teleconnection conditions, thus suggesting that within-type variability impacts precipitation events more regularly during in-phase teleconnection conditions. Fewer synoptic types exhibit within-type variability during ENSO and PDO events; however the variability is more extreme in nature. This suggests that during ENSO and PDO events, significant precipitation variability at Powell River is attributed to infrequent extreme precipitation events.

It should be noted that the sample size of a sub-type based upon only one of the teleconnections is much larger than the sample size of an in-phase teleconnection sub-type. Given the inability of the precipitation record of Powell River (and all of BC) to capture multiple oscillations of the PDO, this is identified as an unavoidable source of error within this study.

3.3 – Assessing Significance in Within-Type Variability in Winter Precipitation-Producing Synoptic Types

Testing for statistically significant differences between precipitation datasets is difficult as precipitation data are influenced by serial correlation, i.e. date values are not independent. Furthermore, precipitation tends to follow the gamma distribution, thus standard statistical tests that assume normality, such as Student's t test, are not appropriate for assessing significance. The Kolmogorov-Smirnov test (Monahan, 2001) is proposed as a means for identifying significant within-type variability. It is a nonparametric, distribution-free statistical test that, under the assumption of independence between the two datasets being tested, tries to determine if two datasets differ significantly. The precipitation data distributions within important winter precipitationproducing synoptic types (types 3, 6, 9, 10, 11, 12 and 13) are tested for significant differences between teleconnection phases using the Kolmogorov-Smirnov test (table

3.1).

Table 3.1: P-Values from the Kolmogorov-Smirnov test for differences between for precipitation distributions at Powell River by teleconnection phase. Significant differences are indicated by * (p < 0.05) or ** (p < 0.01).

	Phase	Туре	Туре	Туре	Туре	Туре	Туре	Туре
		3	6	9	10	11	12	13
PDO	Neutral vs.	0.202	0.000**	0.803	0.115	0.013*	0.187	0.561
	Positive							
	Neutral vs.	0.076	0.717	0.255	0.383	0.806	0.530	0.226
	Negative							
	Positive vs.	0.035*	0.000**	0.170	0.703	0.086	0.114	0.103
	Negative							
ENSO	Neutral vs.	0.027*	0.000**	0.631	0.012*	0.004**	0.970	0.002**
	El Niño							
	Neutral vs.	0.082	0.000**	0.183	0.207	0.025*	0.249	0.001**
	La Niña							
	El Nino vs.	0.483	0.665	0.433	0.264	0.024*	0.178	0.006**
	La Niña							
	Neutral / Neutral	0.276	0.000**	0.921	0.007**	0.019*	0.270	0.348
	Vs. Positive / El							
PDO	Niño							
&	Neutral / Neutral	0.434	0.265	0.390	0.730	0.341	0.516	0.056
ENSO	vs. Negative / La							
	Niña							
In	Positive / El	0.158	0.000**	0.326	0.278	0.351	0.134	0.092
Phase	Niño vs.						1	
	Negative / La							
	Niña							

Significant within-type variability is identified at Powell River within types 3, 6, 10, 11 and 13. Type 6 exhibits strongly significant within-type variability identified at the p = 0.01 level within all 3 teleconnections. Type 11 exhibits significant within-type variability between ENSO phases at the p = 0.01 and = 0.05 levels, and at the p = 0.05

level within PDO and PDO/ENSO. Type 13 exhibits strong within-type variability within ENSO (p = 0.01). Type 10 exhibits significant within-type variability between ENSO (p = 0.05) and PDO/ENSO (p = 0.01), and Type 3 shows within-type variability within PDO (p = 0.05), and ENSO (p = 0.05). No significant within-type variability is detected within type 9 or type 12.

3.4 – Summary

Thirteen synoptic types characterize the synoptic climate of British Columbia, each with its own unique pattern of temperature and precipitation anomalies. Types 9 through 13 occur most frequently during the winter and are responsible for the majority of winter precipitation. A wide range of precipitation intensity is revealed when precipitation intensities are analyzed by ENSO phase; however, variability is not present in every synoptic type. When synoptic type precipitation is analyzed by PDO phase, moderate precipitation intensity variability is shown to exist within all of the synoptic types. These findings suggest that ENSO influences on precipitation are erratic, and thus may account for a lesser proportion of systematic within-type variability. PDO influences on precipitation are more consistent than ENSO, and appear to shift the precipitation climatology of the synoptic types.

An exploratory analysis of within-type precipitation variability at Powell River shows that several synoptic types exhibit notable within-type variability while others do not. Statistical significance is assessed for the precipitation distributions within each synoptic type between teleconnection phases using the Kolmorgorov-Smirnov test. Significant within-type precipitation variability is identified at Powell River in types 3, 6, 10, 11 and 13. This shows that significant teleconnection-induced within-type variability exists within a number of important winter precipitation-producing synoptic types at Powell River. Furthermore, it provides evidence suggesting that a significant degree of within-type variability in precipitation can be linked to teleconnections.

It is proposed that teleconnection influences upon upper-level atmospheric circulation, and subsequent effects upon upper-level precipitation formation mechanisms drive within-type precipitation variability. Therefore, in the following chapter, an examination of teleconnection influences upon upper-level precipitation formation mechanisms is conducted in order to provide further insight into this within-type precipitation variability.

Chapter 4

The Nature of Within-type Variability

4.1 – Introduction

Interannual variability in winter precipitation patterns in BC has been strongly linked to the PDO and ENSO (Dunkley, 1999; Jakob et al., 2003; Stahl et al., 2006a). It is likely that within-type variability in precipitation is due to atmospheric circulation changes associated with various teleconnection phases; however the nature of atmospheric within-type variability is not well known. In particular, teleconnection impacts on precipitation formation mechanisms and factors such as upper-level divergence, vertical motion, precipitable water, and positive vorticity advection (PVA) are poorly understood. An investigation of within-type variability within upper-level meteorological variables will provide insight into how teleconnections influence precipitation formation mechanisms; and subsequently precipitation anomalies.

This analysis will focus on the four synoptic types with the highest propensity for producing winter precipitation in BC: types 3, 9, 10 and 12. Within-type variability in upper-level circulation within types 3 and 12 will be assessed by different PDO and ENSO phases respectively. Types 9 and 10 exhibit similar degrees of precipitation variability for either teleconnection; therefore, within-type variability arising from both teleconnections (PDO and ENSO in phase) will be investigated within these types.

Notable differences in upper-level circulation between teleconnection phases can then be linked to precipitation anomalies.

4.2 - Results

In this section, sub-type composites of 500 hPa and 700 hPa geopotential heights, 700 hPa vertical velocity, 700 hPa relative vorticity, and precipitable water are examined within each synoptic type for notable, or even subtle differences.

4.2.1 – Type 3 by PDO



Figure 4.1a: Type 3 DJF SLP (hPa) and 500 hPa gph (m) for PDO



Figure 4.1b: Type 3 DJF 700 hPa Relative Vorticity (s⁻¹) and 700 hPa Vertical Velocity (Pa/s) for PDO



Figure 4.1c: Type 3 DJF 700 hPa Precipitable Water (kg/m^2) and 700 hPa gph (m) for PDO

Type 3 is characterized by a moderate surface low that is centred at 56°N, 137°W, and stretches over the Alaska Panhandle along a NW – SE axis. MSLP values at the centre of the low range from 1000 to 1002 hPa, with the surrounding isobars showing a moderate pressure gradient and a west-northwest flow over the northeast Pacific Ocean. The flow then veers towards the north, producing a westerly flow over the coast of BC. Warm, moist marine air is advected over BC by the westerly flow, resulting in significant precipitation occurring in many parts of BC.

During Neutral PDO conditions, the 500 hPa and 700 hPa gph composites show a predominantly zonal flow pattern over southern BC of moderate flow strength. Geostrophic flow is weaker in the north where the pressure gradient is less. There is a weak trough located to the west of the Alaskan Panhandle that corresponds with the SLP pattern. The prominent surface-level low-pressure zone of type 3 shows marked baroclinicity created by sharp coastal temperature gradients and strong upper-level flow. There is apparent high pressure over Alberta and east of the study region.

The upper-level trough and surface low correspond with a significant centre of positive vorticity at 700 hPa. It is centred at 54°N 140°W and is stretched along a NW-SE axis, with mean maximum values of 2.6×10^{-5} s⁻¹. Two relatively weak zones of negative relative vorticity are centred at 58°N 120°W and at 43°N 113°W, with mean maximum values of -0.2×10^{-5} s⁻¹ and -1.4×10^{-5} s⁻¹ respectively.

The vertical velocity composite shows a strong zone of upward vertical motion centred over Central Vancouver Island, 49°N 124°W, with a mean maximum value of approximately -0.22 Pa/s. This zone of vertical velocity corresponds with the eastern part

of the positive vorticity zone, and is consistent with frontal uplifting. Lastly, there is a north-south gradient in precipitable water.

The positive PDO MSLP composite shows a circulation pattern that resembles the original type 3 composite, but with some notable differences. Firstly, there appears to be a consistent 50 m increase in 500 hPa and 700 hPa geopotential heights throughout the study region indicating a greater average thickness. Secondly, the pressure gradient is weaker at 500 hPa and 700 hPa, indicating weaker geostrophic flow. Thirdly, the zone of positive vorticity is slightly weaker, with a mean maximum value of 2.4×10^{-5} s⁻¹. It is now centred at 54°N 136°W and is not stretched as per the original type 3. The inland zones of negative vorticity have strengthened to -0.6×10^{-5} s⁻¹ over northeastern BC, and to -1.6×10^{-5} s⁻¹ over the Northwest United States. Lastly, the zone of upward vertical motion over Vancouver Island is larger and is shifted approximately 2° to the north.

Circulation conditions within the negative PDO sub-type are notably different than those found in the positive PDO sub-type. The 500 hPa and 700 hPa gph circulation patterns follow a NW-SE zonal flow pattern with mean height values approximately 75m lower those found during positive PDO conditions. Furthermore, the flow appears to be stronger over the Pacific, which may lead to increased upper-level divergence and enhanced cyclogenesis.

The above-noted increase in upper-level divergence is complemented by an intensification of the large stretched zone of positive vorticity, with mean maximum values greater than 2.8×10^{-5} s⁻¹. In addition, significant positive vorticity protrudes notably further into BC than during the positive PDO case. The enhanced positive vorticity appears to be balanced by enhanced negative vorticity over Northeastern BC.

The zone of upward vertical motion has shifted towards the southeast; however, the mean intensities are very similar to those observed on the positive PDO composites. The precipitable water composite shows a similar pattern to that found during positive PDO conditions. There is a subtle intrusion of higher precipitable water values southwest of Vancouver Island in the positive PDO precipitable water composite that are not present in the negative PDO case. It is depicted by a slightly merdional pattern in precipitable water contours, resulting in a northward protrusion of higher precipitable water values.

4.2.2 – Type 12 by ENSO



Figure 4.2a: Type 12 DJF SLP (hPa) and 500 hPa gph (m) for PDO



Figure 4.2b: Type 12 DJF 700 hPa Relative Vorticity (s⁻¹) and 700 hPa Vertical Velocity (Pa/s)for ENSO



Figure 4.2c: Type 12 DJF 700 hPa Precipitable Water (kg/m^2) and 700 hPa gph (m) for ENSO

The MSLP composite for type 12 shows a significant low-pressure centre over the Northeast Pacific and a significant centre of high pressure over the northwest United States. The MSLP at the center of the low is approximately 982 – 986 hPa, and the pressure gradient is strong over much of the Northeast Pacific Basin. Type 12 clearly represents strong cyclones.

During neutral ENSO conditions, the 500 and 700 hPa gph composites show a significant trough and ridge system controlling the circulation over the entire region. The trough, located over the Northern Pacific Ocean, gives rise to a large surface low pressure zone located at 55°N 146°W with a minimum MSLP value of 982 hPa. A weak upper-level ridge is situated over Eastern BC and Alberta, and yields anticyclonic conditions. The 700 hPa relative vorticity composite shows a significant zone of positive relative vorticity that is associated with the surface low. It is centred at 53°N 142°W, and has a mean maximum value of 2.4×10^{-5} s⁻¹, and produces PVA over coastal sections of BC. Negative vorticity features exist at 57°N 124°W, and 43°N 114°W, with mean maximum values of -1.2×10^{-5} s⁻¹ and -2.0×10^{-5} s⁻¹ respectively. The vertical velocity composite shows a strong zone of upward vertical motion centred south of Vancouver Island, 48°N 125°W, with a mean maximum value of approximately -0.26 Pa/s.

During El Niño conditions, the 500 and 700 hPa gph composites show an identical circulation pattern. The mean surface low associated with the trough has weakened with a mean central minimum MSLP value of 986 hPa. The positive relative vorticity feature at 700 hPa is shifted approximately 5° to the east, and is less stretched than during neutral ENSO conditions. The vertical velocity composite is identical in intensity and pattern to that found for neutral ENSO conditions. The precipitable water

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composite shows a similar pattern, but it is shifted to the north, which results in greater precipitable water being available further north.

During La Niña, the 500 and 700 hPa gph composites show a more profound trough and ridge. The centre of the surface low has shifted approximately 4° to the north of its mean position; however, the low appears to have expanded in size because the other isolines remain stationary. There are remarkable differences in 700 hPa relative vorticity. The centre of positive vorticity is weaker and is stretched over a NW-SE gradient. This results in PVA penetrating further east into BC. The centre of vertical velocity is shifted southward by approximately 2°. This results in less PVA over much of BC than during neutral ENSO conditions.

4.2.3 – Type 9 by PDO / ENSO



Figure 4.3a: Type 9 DJF SLP (hPa) and 500 hPa gph (m) for ENSO/PDO


Figure 4.3b: Type 9 DJF 700 hPa Relative Vorticity (s⁻¹) and 700 hPa Vertical Velocity for ENSO/PDO (Pa/s)



Figure 4.3c: Type 9 DJF 700 hPa Precipitable Water (kg/m²) and 700 hPa gph (m) for ENSO/PDO

A deep low-pressure centre (982 hPa) located at 59°N 146°W is the distinguishing feature of type 9. This represents a significant zone of baroclinicity over the Northeast Pacific Ocean that is caused by the interaction of warm, humid air with cold Arctic air from out over the relatively warm waters of the Northeast Pacific Ocean. The presence of strong baroclinicity is further reinforced by the presence of a significant upper-level trough and strong geostrophic flows. Other notable features of type 9 include strong high pressure over Idaho, and moderate high pressure that extends over Alberta and Northeastern BC.

The 500 hPa and 700 hPa gph composites show a predominantly westerly flow, changing to southwesterly flow over coastal BC. The flow follows an anti-cyclonic curvature pattern over Northern and Eastern BC. A significant trough exists over the coast of Alaska, and it is complemented by a large centre of positive vorticity located at 57°N 148°W, with a mean maximum value of 3.2×10^{-5} s⁻¹. A negative relative vorticity centre at 46° N 117° W attaining a maximum value of $2.0 - 2.2 \times 10^{-5}$ s⁻¹ corresponds with the anti-cyclonic curvature in the geostrophic flow. A strong zone of upward vertical velocity is situated over Vancouver Island (50°N 127°W), and has a mean maximum value of approximately -0.28 Pa/s.

The MSLP, 500 hPa and 700 hPa gph composites show circulation patterns for El Niño/positive PDO conditions that are identical to those found during neutral/neutral conditions. There are notable differences in 700 hPa relative vorticity, and vertical velocity. The centre of positive vorticity is shifted to the west by approximately 3°. In addition, strong positive vorticity stretches to the southeast, which produces increased PVA over BC. The stretched zone of positive vorticity shifts the centre of upward

vertical velocity 3° southward. Furthermore, the mean maximum value has intensified to approximately 0.32 Pa/sec. Two strong zones of negative relative vorticity are centred at 59°N 123°W and at 45°N 116°W, with mean central values of $-0.2x10^{-5}$ s⁻¹ and $-2.2x10^{-5}$ s⁻¹ respectively.

There is no discernable difference in 500 hPa and 700 hPa circulation patterns between neutral/neutral and negative PDO / La Niña conditions; however, geopotential heights are approximately 50 m lower during negative PDO/La Niña conditions. The characteristic surface low is slightly weaker, but does not deviate in location from neutral/neutral conditions. The positive vorticity centre is significantly more intense than neutral/neutral conditions, with a mean maximum intensity of 3.8×10^{-5} s⁻¹; however, it has not shifted in location. Despite the intensification, PVA actually decreases over BC, with NVA dominating most of the province. Negative vorticity over Alberta, Idaho and Eastern Washington is more intense than during neutral PDO/ENSO conditions.

4.2.4 – Type 10 by PDO and ENSO



Figure 4.4a: Type 10 DJF SLP (hPa) and 500 hPa gphs (m) for ENSO/PDO



Figure 4.4b: Type 10 DJF 700 hPa Relative Vorticity (s⁻¹) and 700 hPa Vertical Velocity (Pa/s) for ENSO/PDO



Figure 4.4c: Type 10 DJF 700 hPa Precipitable Water (kg/m^2) and 700 hPa gph (m) for ENSO/PDO

Type 10 is one of the most important precipitation-producing types, and shows the greatest amount of frequency variability. A very large low-pressure centre that affects most of the study region is the key circulation feature of type 10. It is centred at 49°N 155°W and has a mean minimum MSLP of 986 hPa. There is a strong southwesterly flow over BC indicating the presence of a low-level jet stream, and this type is strongly associated with 'Pineapple Express' rain events that can impact coastal BC during the winter months. This corresponds to warm temperature and high precipitation anomalies throughout the province.

Geopotential height composites at 500 and 700 hPa for neutral PDO/ENSO conditions show a prominent trough is situated on a north-south axis to the west of the Alaska Panhandle, and is characteristic of the Aleutian Low. The large MSLP low-pressure feature of type 10 is accompanied by a well-developed zone of positive relative vorticity centred at 154°W and 48°N, with mean maximum intensities ranging from $2.4 - 2.6 \times 10^{-5}$ s⁻¹. Two relatively weak zones of negative relative vorticity are centred over Northeastern BC, and the Washington-Oregon-Idaho. A zone of upward vertical motion exists in the eastern half of the positive vorticity zone, and represents frontal lifting.

There are striking differences between mean meteorological conditions and conditions present during positive PDO / El Niño conditions. The 500 and 700 hPa GPH composites show a significantly stronger ridge of high pressure situated over most of BC. The trough of low pressure associated with the Aleutian Low is shifted westward, and is noticeably deeper with mean minimum heights of 5250 m at 500 hPa and 2700 m at 700 hPa. Strengthened upper-level divergence over the ocean is reflected by an increase in the 700 hPa relative vorticity, with a maximum mean value of 2.7×10^{-5} s⁻¹. The zone of

upward motion south of Vancouver Island is shifted approximately 2° to the west, thus reducing its presence over BC.

During negative PDO conditions, meteorological conditions appear to resemble mean conditions, but there are five noticeable differences in upper-level circulation at the 500 and 700 hPa levels: 1) Mean geopotential heights are approximately 50 m lower than mean conditions over much of the region. 2) The minimum height values (centre of the trough) are 50m greater than mean conditions. 3) 700 hPa relative vorticity shows a maximum value of 2.2×10^{-5} s⁻¹, 0.2×10^{-5} s⁻¹ less than mean conditions. 4) The trough at the 500 and 700 hPa levels is shifted to the east, and is oriented along a SW to NE axis. 5) There is strong zonal circulation at the 500 hPa level.

4.3 - Discussion of Upper-Level Variability

Stratifying synoptic types into sub-types based upon teleconnection phase reveals remarkable within-type variability of upper-level atmospheric circulation. The greatest deviations from normal upper-level circulation conditions are found when the PDO and ENSO teleconnections are in phase with each other. The range of within-type variability is found to be much greater than what is found by analysis of a single teleconnection influence, which reflects the interaction of the teleconnections. The spatial patterns are also unique in that some composites show irregular patterns. This reflects a non-linear response in atmospheric circulation to in-phase teleconnection influences, further reinforcing the importance of in-phase teleconnection influences. The 500 hPa geopotential composites show a notable contrast in the mean jet stream pattern between teleconnection phases. Positive (negative) PDO and El Niño (La Niña) conditions tend to produce a meridional (zonal) jet stream pattern. The ridgetrough pattern in the jet stream intensifies (weakens) and shifts westward (eastward) during positive (negative PDO) and El Niño (La Niña) conditions. Furthermore, a southward-displaced jetstream is inferred from decreases in geopotential heights at 500 hPa and 700 hPa, ranging on average from 50 to 75 m during negative PDO and La Niña.

Within-type variability in upper-level circulation is accompanied by significant variability in the dynamic meteorology at other levels. A significantly stronger (weaker) centre of positive vorticity associated with the Aleutian Low is depicted on the 700 hPa relative vorticity composites during El Niño (La Niña). Furthermore, the intensity of the negative relative vorticity associated with the Canadian High also varies, with significantly stronger (weaker) negative relative vorticity during positive (negative) PDO and El Niño (La Niña). Stronger (weaker) values of upward vertical motions over coastal BC are noted during negative (positive) PDO and La Niña (El Niño).

Precipitable water values do not appear to vary much between teleconnection phases, or between synoptic types. This is not surprising given the immense capacity of the ocean to moderate air temperature and absolute humidity, and subsequently precipitable water values. Notable surges of higher precipitable water values are noted on composites during positive PDO and El Niño, which are likely reflecting stronger northward advection of warm, moist air by the enhanced positive vorticity advection of the deepened Aleutian Low.

4.3.1 - Variability in Upper-level Precipitation Formation Mechanisms

Positive vorticity advection, upward vertical motion, and precipitable water are primary factors in precipitation formation (Vasquez, 2002); therefore, positive (negative) precipitation anomalies should correspond with upper-level changes that are favourable (unfavourable) to precipitation development. Vorticity advection is controlled by the degree of baroclinicity and upper-level divergence and surface convergence in the atmosphere. Upward vertical motion is directly related to upper-level divergence and positive vorticity advection. Upper-level divergence is greatest during negative and neutral PDO conditions, and baroclinicity and upward vertical motion appear to increase simultaneously. Upper-level divergence is weakest during positive PDO conditions, and this is reflected by weaker upward motion. Notable changes in upper-level divergence, vertical velocity, and positive vorticity will affect precipitation formation processes; thus, within-type variability in upper-level circulation is apt to produce within-type precipitation variability.

The regional jet stream pattern (zonal versus meridional), relative vorticity, and the nature of vertical motion in the atmosphere are key controls on precipitation. During negative PDO and La Niña conditions, the eastward displacement and stretching of the Aleutian Low, and the resultant strong zonal flow, tend to enhance precipitation formation mechanisms, leading to positive precipitation anomalies in parts of BC. Strong zonal flow enhances upper-level divergence, leading to enhanced relative vorticity and vertical motions. Positive PDO and El Niño conditions are characterized by a meridional jet stream pattern over BC, which can persist throughout positive PDO conditions for extended periods of time. Precipitation formation mechanisms are negatively affected,

particularly over southern BC, during positive PDO conditions. This is attributed to stronger ridging aloft, and a subsequent 25% decrease in mean maximum upward vertical motion over the region.

El Niño and positive PDO conditions do not negatively affect all precipitation scenarios, and can in fact lead to the infrequent occurrence of extreme precipitation events. Meridional flow tends to be strongly enhanced during El Niño, and can also lead to the occurrence of strong low-level jets, also referred to as 'warm-air conveyor belts,' that can bring very warm, humid air to BC, with high amounts of precipitable water. This situation is commonly referred to as a 'Pineapple Express', and can produce long periods of heavy precipitation along coastal BC. This implies that very extreme precipitation events are more likely to occur during El Niño and Positive PDO conditions, despite lower average precipitation over much of the region.

4.3.2 – Linking Within-Type Variability in Precipitation Formation Mechanisms to Precipitation Anomalies

Within-type variability in upper-level meteorological variables is linked to corresponding within-type precipitation variability. Strong positive precipitation anomalies within types 3 and 12 can be linked to upper-level within-type variability attributed to positive PDO conditions. This is attributed to greater geopotential heights and a thicker 1000-500 hPa layer, which would increase the capacity of the offshore airmass to hold water. Enhanced PVA, in conjunction with a protrusion of higher precipitable water values off the coast of BC, thus favors enhanced precipitation intensities.

Positive precipitation anomalies occur within type 10 during negative PDO and La Niña. A weakened and shifted Aleutian Low is identified by lower GPH values and a decrease in relative vorticity values. Furthermore, the mean position of the Aleutian Low is stretched and shifted 5° to the east, resulting in significant positive vorticity penetrating into northern BC. The zonal upper-level circulation conditions will likely strengthen the jet stream due to continuous west-to-east flow enhancement from the Coriolis force. This will increase upper-level divergence and shear vorticity, and will result in greater baroclincity over the region. Enhanced cold air advection over the North Pacific from Alaska will further increase baroclinicity. These factors will likely lead to greater upward vertical motion and cyclogenesis, thus, more resultant precipitation.

Strong negative anomalies exist within type 10 during Positive PDO and El Niño conditions throughout most of BC. A meridional jet stream pattern, and enhanced upperlevel divergence enhances a westward-shifted Aleutian Low. Strong PVA transports very warm, moist air northward, enhancing cyclogenesis over the North Pacific Ocean; however, the strong cyclones rapidly succumb to the strengthened Canadian High, which is shifted westward over BC. Evidence of weakened cyclones striking BC is evident with mean upward vertical velocity values 25% lower over most of BC.

Type 9 exhibits a strong negative precipitation anomaly during both La Niña and El Niño conditions, with above average precipitation during ENSO neutral years. The negative precipitation anomaly during La Niña years is likely explained by a decrease in PVA and upward vertical velocity over BC. The negative anomaly during El Niño conditions is more difficult to explain, as upper-level circulation conditions appear identical to those found during neutral ENSO conditions.

Positive anomalies in type 12 during La Niña years and negative anomalies during El Niño years both appear to be strongly controlled by relative vorticity. During La Niña, the Aleutian Low is stretched on a SE-NW axis and produces significant PVA over coastal BC. During El Niño years, the Aleutian low intensifies but also contracts, resulting in negative vorticity over most of BC. This results in a reduction in precipitation intensity despite similar vertical velocity values between La Niña and El Niño.

There are interesting relationships between precipitation variability and precipitable water variability. Slightly more precipitable water appears to be available along the coast of BC during positive PDO conditions, yet negative precipitation anomalies exist over much of BC. Conversely, lower precipitable water is found during negative and neutral PDO years despite positive precipitation anomalies. It is likely that upper-level precipitation formation mechanisms are enhanced (weakened) during negative (positive) PDO; therefore, more (less) precipitation falls, resulting in lower (higher) average precipitable water remaining in the atmosphere.

Upper-level circulation patterns can be linked to the corresponding precipitation anomalies of each basic synoptic type. Positive precipitation anomalies in the interior regions of BC found in type 3 are linked to strong westerly flows over much of BC. Strong westerly flows are normal along the coast during the winter, and precipitation anomalies do not deviate from normal. Large positive precipitation anomalies along coast regions of BC in type 9 are linked to strong Pacific cyclones, indicated by the low MSLP values. Negative precipitation values in the north are likely due to the predominance of NVA. Precipitation is above normal at all stations within type 10,

resulting from strong southwesterly flows, strong PVA, and strong upward vertical velocities. In type 12, precipitation anomalies are positive only in southern BC. This phenomenon is linked to strong PVA and upward motion present only over southern regions of BC.

4.4 – Summary

Mean synoptic circulation conditions (Figure 4.5) are compared with changes in synoptic circulation attributed to teleconnections (Figures 4.6 and 4.7).



Figure 4.5: Mean winter synoptic circulation conditions over the Northeast Pacific Basin



Figure 4.6: Mean winter synoptic circulation conditions over the Northeast Pacific Basin or positive PDO / El Niño



Figure 4.7: Mean winter synoptic circulation conditions over the Northeast Pacific Basin for negative PDO / La Niña

Subtle variations in MSLP composites are complemented by notable changes in mean upper-level circulation conditions between teleconnection phases. Known teleconnection controls on upper-level circulation features are discernable in the 500 hPa and 700 hPa composites. Geopotential heights are 50-75 m greater during positive PDO (El Niño) conditions than during negative PDO (La Niña). Enhancement (weakening) of the Aleutian low during El Niño (La Niña) is identifiable by increased (decreased) relative vorticity values within the synoptic types. No significant changes are detected in precipitable water, suggesting within-type precipitation variability arises from changes in precipitation formation factors rather than changes in atmospheric moisture. This corresponds with a previous study that links variability in precipitation to variability in relative vorticity (Wilby, 1998).

There is sufficient evidence to suggest that teleconnections exert a significant control upon within-type precipitation variability. Teleconnections as a source of withintype variability can be further examined with a statistical downscaling modelling exercise using historical precipitation data and teleconnection indices. In the next chapter, withintype variability is captured by the downscaling model via the use of synoptic sub-types classified by teleconnection conditions.

Chapter 5

Downscaling Winter Precipitation Forecasts Using Synoptic Sub-Types

5.1 – Analytical Overview

In this chapter, a modelling exercise is conducted to determine whether statistical downscaling of precipitation can be improved by accounting for the teleconnectioninduced within-type variability highlighted in previous chapters. Four models based upon the methodology presented in chapter 2 are run, each using a different set of synoptic types. Model 0 uses the basic 13 synoptic types of Stahl et al. (2006a), and models 1, 2 and 3 employ PDO, ENSO and PDO/ENSO sub-types respectively. In the model, the mean precipitation values (a constant for each model) for each type are multiplied by the monthly frequency of each type to arrive at a total monthly precipitation estimate. The models are run for all 44 stations for all 56 years, and then compared with observed values using the validation statistics of Willmott (1981).

The validation statistics employed are Willmott's index of agreement'd', *RMSD*, *RMSDu and RSMDs*. A 'bootstrapping' procedure is applied to the dataset to compensate for the limited period of record (56 DJF seasons). Ten randomly selected DJF seasons are reserved as a validation dataset, with the remaining seasons used to estimate mean synoptic type frequencies and precipitation for use in the model. This procedure is repeated 100 times and the mean and standard deviation of the model validation statistics are then calculated for each station. The mean and standard deviation of the model validation statistics for the sub-type models (models 1, 2 and 3) can then be contrasted with those of model 0.

5.2 – Results

5.2.1 – Model 0: Basic Synoptic Types

The validation statistics for model 0 suggest good model performance, with mean d values greater than 0.70 at 43 out of 44 stations. Mean values of d range from 0.67 (+/-0.04) at Tatlayoko Lake to 0.96 (+/-0.01) at Estevan Point. Standard deviation values for d range from 0.02 to 0.08, with the smallest standard deviations associated with the highest values of mean d.

Model performance is assessed within each region by examining mean d (table 5.1). The best model performance values are found within the North Coast, South Coast, and Kootenay regions, with the highest values of d found over the Queen Charlotte Islands, and Vancouver Island. The weakest performance is found in Northern BC and the Okanagan Region, with mean d values ranging between 0.7 and 0.8. The weakest model performance is found at Tatlayoko Lake, where d = 0.66.

			Moon of	Standard Deviation	Maan d	Standard Deviation	Model 3 Relative	n % Chango
Station Name	LAT	LONG	Model 0	Model 0	Model 3	Model 3	Mean d	Mean d
Saanichton CDA	48.69	-123.59	0.921	0.020	0.932	0.022	0.011	1.19%
Shawnigan Lake	48.64	-123.62	0.933	0.017	0.943	0.021	0.010	1.04%
Victoria Int'l A	48.64	-123.42	0.928	0.017	0.940	0.020	0.012	1.25%
Comox A	49.71	-124.9	0.937	0.016	0.937	0.017	0.000	-0.01%
Nanaimo A	49.05	-123.87	0.936	0.015	0.938	0.019	0.002	0.26%
Estevan Point	49.38	-126.55	0.964	0.010	0.963	0.015	-0.001	-0.10%
Pachena Point	48.71	-125.1	0.957	0.012	0.962	0.016	0.005	0.50%
Powell River	49.87	-124.55	0.925	0.016	0.923	0.020	-0.002	-0.16%
Abbotsford A	49.02	-122.36	0.937	0.017	0.953	0.017	0.016	1.67%
Agassiz CDA	49.24	-121.76	0.932	0.017	0.946	0.018	0.014	1.53%
Vancouver Int'l A	49.19	-123.18	0.937	0.014	0.944	0.017	0.007	0.74%
South Coast Mean			0.937	0.016	0.944	0.018	0.007	0.72%
Hedley	49.35	-120.07	0.734	0.041	0.732	0.057	-0.002	-0.25%
Joe Rich Creek	49.85	-119.12	0.831	0.028	0.840	0.043	0.009	1.11%
Okanagan Centre	50.05	-119.46	0.727	0.038	0.755	0.049	0.028	3.85%
Oliver	49.16	-119.56	0.712	0.039	0.728	0.056	0.017	2.36%
Penticton A	49.46	-119.6	0.786	0.034	0.796	0.048	0.010	1.23%
Princeton A	49.46	-120.51	0.823	0.030	0.848	0.038	0.025	3.05%
Westwold	50.47	-119.75	0.756	0.039	0.761	0.058	0.005	0.62%
Okanagan Mean			0.767	0.036	0.780	0.049	0.013	1.71%
Grand Forks	49.02	-118.46	0.809	0.026	0.822	0.038	0.013	1.56%
Creston	49.09	-116.51	0.852	0.029	0.868	0.036	0.016	1.91%
Fauquier	49.87	-118.06	0.845	0.021	0.857	0.026	0.012	1.44%
Kaslo	49.91	-116.91	0.902	0.018	0.914	0.021	0.013	1.40%
South Slocan	49.45	-117.52	0.872	0.022	0.886	0.029	0.013	1.51%
Warfield	49.1	-117.75	0.873	0.026	0.878	0.038	0.005	0.61%
Fernie	49.48	-115.07	0.880	0.028	0.903	0.030	0.023	2.64%
Golden A	51.29	-116.98	0.759	0.044	0.774	0.046	0.015	1.96%
Kootenav Mean			0,849	0.027	0.863	0.033	0.014	1.63%

Table 5.1: Mean d: model 0 vs. model 3 (n = 100)

n Starten Kriger			Mean d	Standard Deviation of d	Mean d	Standard Deviation of d	Model 3 Relative	% Change
Station Name	LAT	LONG	Model 0	Model 0	Model 3	Model 3	Mean d	Mean d
Smithers A	54.82	-127.18	0.863	0.028	0.876	0.027	0.013	1.52%
Tatlayoko Lake	51.67	-124.4	0.669	0.041	0.681	0.054	0.011	1.70%
Wistaria	53.82	-126.21	0.766	0.030	0.794	0.034	0.028	3.68%
Barkerville	53.06	-121.51	0.889	0.020	0.897	0.026	0.008	0.88%
Fort St James	54.45	-124.25	0.787	0.029	0.823	0.033	0.036	4.55%
Prince George A	53.89	-122.67	0.873	0.022	0.889	0.025	0.016	1.84%
Quesnel	53.02	-122.51	0.822	0.030	0.820	0.038	-0.002	-0.24%
Vavenby	51.57	-119.77	0.818	0.028	0.826	0.038	0.008	1.03%
Chilcotin-Cariboo	Mean		0.811	0.028	0.826	0.034	0.015	1.87%
Port Hardy A	50.68	-127.36	0.954	0.011	0.955	0.011	0.001	0.07%
Quatsino	50.53	-127.65	0.957	0.011	0.960	0.012	0.003	0.33%
Langara	54.25	-133.05	0.962	0.010	0.964	0.015	0.002	0.25%
Sandspit A	53.25	-131.81	0.952	0.012	0.953	0.017	0.001	0.11%
Bella Coola	52.37	-126.68	0.894	0.023	0.897	0.028	0.004	0.40%
North Coast Mea	n		0.944	0.013	0.946	0.017	0.002	0.23%
Fort St John A	56.23	-120.74	0.778	0.039	0.806	0.045	0.028	3.53%
Dease Lake	58.42	-130.01	0.792	0.029	0.804	0.039	0.012	1.55%
Fort Nelson A	58.83	-122.59	0.757	0.034	0.765	0.051	0.008	1.04%
Watson Lake A	60.11	-128.82	0.828	0.031	0.833	0.042	0.005	0.60%
Whitehorse A	60.71	-135.06	0.770	0.036	0.767	0.050	-0.003	-0.44%
Northern BC-Yuk	on Mean	× ,	0.785	0.034	0.795	0.046	0.010	1.26%

Table 5.1 continued: Mean d: model 0 vs. model 3 (n = 100)

Mean *RMSD*, *RMSD*^u and *RMSD*^s values are high in the South Coast and North Coast Regions, and are generally lower in the Kootenay and Cariboo-Chilcotin Regions (Table 5.2). Mean *RMSD* values are lowest in Northern BC and the Okanagan (Appendix B). The highest (lower) values of *RMSD* tend to be found in wetter (drier) parts of the province. This reflects the nature of the precipitation regimes within BC, but also indicates strong spatial correlation among *RMSD* values. Changes in *RMSD*, *RMSD*^u and *RMSD*^s are therefore examined by examining percent change.

Table 5.2: Mean <i>RMSD</i> : model 0 vs. model 3 (n	n = 100)
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			Mean RMSD	Standard Deviation of RMSD	Mean RMSD	Standard Deviation of RMSD	Model 3 Relative decrease in	% Change Mean
Station Name	LAT	LONG	Model 0	Model 0	Model 3	Model 3	Mean <i>RMSD</i>	RMSD
Saanichton CDA	48.69	-123.59	97.3	10.0	91.3	12.6	-6.1	-6.2%
Shawnigan Lake	48.64	-123.62	123.7	12.7	115.2	17.9	-8.6	-6.9%
Victoria Int'l A	48.64	-123.42	91.6	9.0	85.0	11.4	-6.6	-7.2%
Comox A	49.71	-124.9	106.9	11.1	105.7	12.0	-1.3	-1.2%
Nanaimo A	49.05	-123.87	105.1	9.3	103.4	12.9	-1.7	-1.6%
Estevan Point	49.38	-126.55	169.5	19.0	169.8	11.7	0.3	0.2%
Pachena Point	48.71	-125.1	188.4	22.9	177.0	27.0	-11.4	-6.0%
Powell River	49.87	-124.55	92.9	8.6	95.3	33.5	2.3	2.5%
Abbotsford A	49.02	-122.36	120.2	13.7	107.8	20.1	-12.5	-10.4%
Agassiz CDA	49.24	-121.76	137.9	14.2	128.0	12.4	-9.9	-7.2%
Vancouver Int'l A	49.19	-123.18	94.6	9.0	90.0	15.0	-4.6	-4.8%_
South Coast Mean			120.7	12.7	115.3	16.9	-5.5	-4.5%
Hedley	49.35	-120.07	58.6	3.8	58.6	11.5	-0.1	-0.1%
Joe Rich Creek	49.85	-119.12	64.8	4.5	64.4	20.9	-0.3	-0.5%
Okanagan Centre	50.05	-119.46	71.6	4.1	70.9	4.7	-0.7	-1.0%
Oliver	49.16	-119.56	64.1	3.4	63.7	7.6	-0.4	-0.7%
Penticton A	49.46	-119.6	42.9	2.7	42.5	4.7	-0.4	-0.8%
Princeton A	49.46	-120.51	55.7	4.1	53.1	7.9	-2.6	-4.7%
Westwold	50.47	-119.75	54.7	3.8	55.7	5.3	0.9	1.7%
Okanagan Mean			58.9	3.8	58.4	8.9	-3.3	-2.9%
Grand Forks	49.02	-118.46	69.2	3.9	68.0	4.3	-1.2	-1.8%
Creston	49.09	-116.51	75.9	6.0	72.8	5.0	-3.2	-4.2%
Fauquier	49.87	-118.06	79.1	4.6	76.9	16.6	-2.2	-2.8%
Kaslo	49.91	-116.91	86.7	6.6	82.8	19.9	-3.9	-4.5%
South Slocan	49.45	-117.52	99.5	6.8	95.9	12.1	-3.6	-3.6%
Warfield	49.1	-117.75	89.1	7.2	90.2	6.3	1.0	1.1%
Fernie	49.48	-115 .07	135.1	12.6	125.6	7.3	-9.5	-7.0%
Golden A	<u>51.2</u> 9	-116.98	90.3	7.5	95.1	6.0	4.9	5.4%
Kootenay Mean			90.6	6.9	88.4	9.7	-2.1	-2.1%

		an sana	Mean	Standard Deviation	Mean	Standard Deviation	Model 3 Relative	% Change
Station Name	LAT	LONG	RMSD Model 0	of RMSD Model 0	RMSD Model 3	of RMSD Model 3	decrease in Mean RMSD	Mean RMSD
Smithers A	54.82	-127.18	47.8	3.9	46.9	5.6	-0.8	-1.7%
Tatlayoko Lake	51.67	-124.4	113.5	5.7	111.1	3.7	-2.4	-2.1%
Wistaria	53.82	-126.21	70.8	3.6	66.6	5.0	-4.2	-5.9%
Barkerville	53.06	-121.51	87.2	5.9	84.3	5.6	-2.9	-3.3%
Fort St James	54.45	-124.25	72.7	3.9	68.6	7.2	-4.0	-5.5%
Prince George A	53.89	-122.67	49.7	3.5	47.0	5.9	-2.8	-5.6%
Quesnel	53.02	-122.51	59.7	3.9	61.2	8.1	1.5	2.6%
Vavenby	51.57	-119.77	52.4	3.1	52.0	9.1	-0.4	-0.7%
Chilcotin-Caribou Mean		69.2	4.2	67.2	6.3	-2.0	-2.4%	
Port Hardy A	50.68	-127.36	108.1	10.8	108.3	10.5	0.2	0.2%
Quatsino	50.53	-127.65	148.5	15.9	143.7	17.2	-4.8	-3.2%
Langara	54.25	-133.05	76.4	8.2	73.5	5.0	-2.9	-3.8%
Sandspit A	53.25	-131.81	79.4	7.8	78.6	5.9	-0.8	-1.0%
Bella Coola	52.37	-126.68	170.7	14.5	170.6	10.4	-0.1	-0.1%
North Coast Mean			116.6	11.4	115.0	9.8	-1.7	-2.1%
Fort St John A	56.23	-120.74	46.5	3.2	44.6	3.9	-1.9	-4.1%
Dease Lake	58.42	-130.01	43.3	2.3	42.9	3.4	-0.4	-0.9%
Fort Nelson A	58.83	-122.59	36.5	2.1	36.0	3.6	-0.5	-1.3%
Watson Lake A	60.11	-128.82	38.7	3.0	38.1	4.1	-0.6	-1.6%
Whitehorse A	60.71	-135.06	28.9	1.8	29.0	2.5	0.0	0.1%
Northern BC – Yuko	on Mean		38.779	2.5	38.1	3.5	-1.2	-1.6%

Table 5.2 continued: Mean *RMSD*: model 0 vs. model 3 (n = 100)

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5.2.2 - Model 1: PDO Sub-Types

Model 1 performs similarly to model 0, and does not yield any significant improvement in model performance (Figure 5.1). Mean d values obtained from validation of model 1 do not show any significant improvement over those for model 0; however some noticeable small improvements are detected at many stations. No further validation of model 1 is pursued.



Figure 5.1: Mean *d* for Model 1

5.2.3 - Model 2: ENSO Sub-Types

Model 2 performs similarly to model 0, and does not yield any significant improvement in model performance (Figure 5.2) Mean *d* values obtained from validation of model 1 do not show any significant improvement over those for model 0. Similarly to model 1, a very small degree of improvement is detected at many stations; however, it is not enough to be considered a significant improvement. No further validation of model 2 is pursued.





Figure 5.2: Mean d for Model 2

5.2.4 – Model 3: PDO/ENSO Sub-Types

Model 3 shows a notable improvement over model 0 at 38 out of 44 stations through increases in mean d with the largest improvement being +0.04 at Estevan Point. The remaining 6 stations show no improvement or a slight deterioration in performance (Figure 5.3a). The standard deviation of the 100 d values, resulting from the 100 validation runs, tends to decrease at many stations in model 3. This reflects an improvement in the consistency of the model to perform at a certain level, regardless of the value of d.

There is a complementary improvement in mean RMSD values at 36 stations, with little change or slight increases occurring at the other eight (figure 5.3). The magnitude of the changes in RMSD is considerable, with the greatest being a -10% change at Abbotsford Airport. Other notable improvements are found at Victoria Airport (-7%) and Agassiz (-7%). Increases are detected at Golden, Warfield, Westwold, Powell River, Quesnel, Estevan Point, Whitehorse, and Port Hardy with the largest increases

occurring at Golden (+5%) and Quesnel (+3%). The standard deviations for the RMSD statistics decrease at most of the stations, but increase slightly at stations that experience an increase in mean RMSD.



Figure 5.3: Mean d and RMSD (mm) for all stations, Model 3 vs. Model 0 (n = 100)

To further evaluate the performance of model 3, the $RMSD_u$ and $RMSD_s$ statistics for model 3 are contrasted with model 0 (figure 5.4).



Figure 5.4: Mean *RMSDs* and *RMSDu* (mm) for all stations, Model 3 vs. Model 0 (n = 100)

 $RMSD_s$ is the model-induced error and $RMSD_u$ is the unsystematic error present in the data. It is discovered that the $RMSD_u$ values for both models 0 and 3 closely match the RMSD values, and are similar in magnitude at each station. This is complemented by

a wide range of $RMSD_s$ values for both models, with the majority of stations exhibiting relatively small values of $RMSD_s$. The $RMSD_s$ values are found to decrease dramatically for some stations, and increase slightly at others. This suggests that model 3 may decrease systematic error at the majority of the stations, while having less effect on systematic error at others. Normally, large $RMSD_s$ values suggest that further tuning of the model may reduce error; however, in this case, a longer period of record of data may be more beneficial.

5.3 – Spatial Patterns in Model Performance

Using the mean d and *RMSD* values, interpolated surface maps are generated for the study area. Figure 5.5 shows interpolated mean d values for model 0, and changes in model performance between model 0 and model 3.



Figure 5.5: Spatial patterns of mean d in model 0 and model 0 vs model 3

Figure 5.6 shows the mean *RMSD* surface for model 0, and changes in mean RMSD between model 0 and model 3.



Figure 5.6: Spatial patterns of mean RMSD (mm) and model 0 vs. model 3

The improvements afforded by model 3 over model 0 vary significantly throughout different regions of BC (Figure 5.7).



Figure 5.7: Model 3 vs Model 0 mean d and standard deviation by region (n = 100)

The greatest model improvement is found at Fort St. James (+0.036) within the Cariboo-Chilcotin Region. Deteriorations in model performance are found at six stations, and are generally small with the greatest deterioration in model performance occurring at Whitehorse, YK (-0.0034).

Model 3 affords a significant degree of improvement over model 0 at all stations within the South Coast Region, with the exception of 3 stations where only minor improvements are observed. The greatest improvements are found at Abbotsford Airport (± 0.015), Agassiz CDA (± 0.014), and Victoria Airport (± 0.011). Powell River Airport, Comox Airport, and Pachena Point experience a slight deterioration in model performance (≥ 0.01). All stations within the Kootenay and Cariboo-Chilcotin Regions experience some degree of model improvement. Mixed results are found in Northern BC where improvements range from a large improvement at Fort St. John (± 0.03) to a slight decrease at Whitehorse, YK (-0.01). Only minor improvements in model performance are detected within the North Coast Region (≤ 0.01).

5.4 – Discussion

The best overall performance of model 0 is found along the coast of BC, which is the wettest part of the province (mean d > 0.90 for all but one station). These areas receive much of their annual precipitation through winter storms. It is likely the model performs well in these areas because of several favourable factors. Firstly, higher frequencies of synoptic types tend to produce precipitation in these areas. Secondly, the occurrence of precipitation in these areas within a given synoptic type is more consistent. Finally, there is more contrast in mean precipitation values between synoptic types. The model performs generally well in the Kootenay Region with mean *d* values ranging from 0.76 to 0.90. The variable nature of the model performance is likely attributed to local orographic modulation by the topographic relief in this region. The Kootenay Region of BC is wetter than most parts of BC (except coastal regions); therefore, it is possible that the same favourable factors that account for the successful model performance in coastal areas may be exerting an influence in the Kootenay region.

The Okanagan Region is the driest of the regions and yields variable model performance results with mean d values ranging from 0.71 (Oliver) to 0.83 (Joe Rich Creek). The Okanagan Region is a high plateau region, and on average is the driest of the six regions. The combination of less consistent precipitation with orographic modulation likely explains why model performance in this region is modest.

Stations within the Cariboo-Chilcotin Region show mixed performance results; however, the range is much greater than the other regions. The highest mean d value is 0.89 (Barkerville) with the lowest being 0.67 (Tatlayoko Lake). Barkerville is located in the central part of the Cariboo Plateau, and may not be influenced as strongly by orographic modulation of precipitation. In contrast, Tatlayoko Lake is located on a topographically complex area on the leeward side of the Coast Mountains, and its precipitation regime is apt to be strongly modulated by orographic influences and channelling of air. Tatlayoko Lake is also located on the boundary of where cold arctic air may clash with warm, moist Pacific air, thus adding another degree of uncertainty to the problem.

The Northern BC-Yukon region shows modest model performance with mean d values ranging from (0.77 Whitehorse) to 0.83 (Watson Lake Airport). The influence of

Arctic air probably plays a significant role in modulating the precipitation potential of a given synoptic type. The frequency of warm, wet synoptic types with strong southwesterly flow are also important because these can sometimes advect warm air into Northern BC even during the winter months. Lastly, this region is also topographically complex; therefore precipitation is subject to orographic modulation.

Models 1 and 2 exhibit no significant improvements over model 0. This is unexpected given the degree to which precipitation has been shown to vary between teleconnection phases (Stahl et al., 2006a). The PDO has been found to control the frequencies of synoptic types affecting BC (Stahl, et al., 2006a); however, ENSO is more strongly linked to precipitation variability. It is therefore possible that the modified synoptic type frequencies are not sufficient to improve precipitation downscaling if ENSO enhancements upon upper-level circulation features are excluded. Likewise, model 2 does not include the important background signal of the PDO, which accounts for significantly modified synoptic type frequencies.

An interesting array of changes in model performance is afforded by model 3. Mixed improvements occur in the South Coast, Okanagan and in Northern BC, yet little improvement was gained at stations in the North Coast Region. Model 3 did not yield any significant improvements for stations for which model 0 yielded excellent model performance (mean d >0.95). This would account for the lack of improvements in the North Coast Region, as the performance of model 0 was exceptionally good within this region.

In the Okanagan Region, there are notable improvements at three stations (Princeton, Oliver, Okanagan Centre), but a slight deterioration occurs at Hedley. It is

difficult to explain why Princeton, Oliver, and Okanagan Centre, all on the leeward side of mountains, experience an improvement when Hedley is also located in a mountain valley. It is possible that the orientation of the valley may line up with the prevailing winds of a particular synoptic type. In this case, only minor orographic modulation of precipitation would occur, and the model would be expected to perform better.

The mixed performance of model 3 is probably due to orographic influences and precipitation climatology. The nature of how a particular synoptic type or sub-type interacts with topography surrounding a given station is not accounted for in any way. This would suggest poor model accuracy in areas where orographic enhancement or rainshadow effects dominate the precipitation regime. Such an area is the Georgia Trench in the South Coast Region. There is significant model deterioration at stations within the Trench (Powell River, Comox Airport). This is likely due to different surface wind patterns arising from teleconnection influences that alter the degree of orographic enhancement. Furthermore, within-type variability of winds within each synoptic type may also contribute to variability in orographic enhancement.

5.5 – Summary

Statistical downscaling of precipitation in BC from GCMs can be improved using synoptic sub-types based upon both the PDO and ENSO. Mean d values obtained from model 0 show that the downscaling methodology presented in this study is effective at estimating precipitation in BC. When the models using synoptic sub-types are employed, it is discovered that model 3 affords significant improvement while models 1 and 2 yield little improvement over model 0. Model 3 yields improvements in mean d at 36 stations,

and decreases in *RMSD* at 38 stations. Only nominal decreases in performance are detected at the remaining stations.

The modelling methodology appears to work best in wet, coastal regions of British Columbia, which is likely due to the persistent precipitation climatology of the region. This is reflected by the performance of the coastal stations in model 0 as many of them have mean d > 0.90. Model 3 offers little improvement over model 0 for stations that have model 0 mean d = 0.95. The methodology is reasonably effective in other regions of BC; however its performance varies by region.

The improvements of model 3 are mixed in nature in the South Coast, Okanagan and in Northern BC, and little improvement was gained at stations in the North Coast Region. Stations in northern BC show a wide range of improvements in model 3, reflecting considerable effectiveness of the methodology to handle the highly variable climate of this region. Improvements are mixed in the dry Okanagan Region of BC, ranging from moderate to very small improvements, and some stations exhibit no change. This reflects a lower confidence in the precipitation statistics of each synoptic sub-type arising from lower precipitation intensities and overall the lower frequent occurrence of precipitation in the region.

Chapter 6

Discussion and Conclusions

6.1 – Discussion

This research was motivated by the desire to test an improved method that could be used for "downscaling" of GCM output for the development of spatially resolved precipitation scenarios. The assumption underlying this work was that the major climate indices/teleconnections represent a significant source of "within-type" variability in synoptic typing methods. Major objectives for this work outlined in Chapter 1 were to:

- Describe the synoptic climatology of the winter precipitation of BC
- Investigate the nature of within-type variability in the primary precipitation producing types
- Investigate teleconnections as a source of within-type variability
- Develop and test a weather type based downscaling model that incorporates teleconnection-based synoptic sub-types

Classification of synoptic types by teleconnection indices reveals that significant within-type variability exists within each synoptic type that makes up the synoptic
climate of BC. A case study performed at Powell River identified within-type variability in several important winter precipitation-producing types. Precipitation statistics generated within each teleconnection phase show considerable amounts of precipitation variability in the winter synoptic types depending on teleconnection conditions. The Kolmogorov-Smirnov test reveals that significant within-type variability exists within at least one phase of the PDO, ENSO and PDO/ENSO for types 6 and 11. Types 3, 10 and 13 exhibited significant within-type variability for at least one teleconnection. No significant within-type variability was identified for types 9 or 12. Variability in upperlevel atmospheric circulation can be linked to significant anomalies in surface climate, and offers insight into the nature of the anomalies. Within-type variability is present within all levels of the atmosphere, suggesting teleconnections influence many important meteorological variables responsible for precipitation formation.

An examination of composites depicting within-type variability in upper-level atmospheric circulation in synoptic types 3, 9, 10, and 12 yields some novel results. Firstly, it is discovered that there are variations in the location and the nature of the strengthening (weakening) of the Aleutian Low associated with El Niño (La Niña). This alters the magnitude of positive vorticity advection, and thus affects precipitation formation. Secondly, there appears to be stronger ridging present at 500 hPa during positive PDO and El Niño, and more zonal flow during La Niña and negative PDO. A mean flow pattern showing a ridge dominating at 500 hPa will result in reduced upper-level divergence, leading to weaker or downward vertical velocity, thus hindering precipitation formation. Zonal flow will result in the opposite effect, making

precipitation formation more favourable. This is in general agreement with other published research that has examined the effects of ENSO and PDO upon storm tracks.

The performance of the modelling technique varies significantly with respect to location, with the best performance found in wet coastal regions. This shows that the downscaling methodology employed may not be sophisticated enough to model seasonal precipitation throughout all regions of BC; however, it may be quite effective in other similar mid-latitude regions around the world. There are several possible factors that likely influence the performance of the model, including precipitation climatology, topography, and how weather associated with particular synoptic types interacts with topography. The interaction of synoptic flow within the complex topography of BC reduces the models effectiveness in areas; thus, further model refinement must account for orographic influences.

The spatial patterns of within-type variability are strongly controlled by orographic influences upon the various synoptic flow patterns of each synoptic type and sub-type. Precipitation anomalies at a particular location fluctuate in nature between synoptic types, and within synoptic types between teleconnection phases. Small-scale variations in intensity and duration of precipitation events represented by synoptic subtypes are important facts of local precipitation climates. Such variations are attributed to the relatively poor performance of the model at Tatlayoko Lake, a climate station located within rugged mountainous terrain. Finally, a synoptic pattern that fluctuates rapidly between synoptic types throughout the season is likely to cause high variability in precipitation in areas of complex topography because different synoptic types produce different wind patterns, and interact with topography in many different ways.

Accounting for within-type variability using teleconnection indices improves GCM downscaling efforts. Model 3 yields a notable improvement in performance over model 0 in all parts of the province with only a few exceptions. The greatest improvements are found among stations within the South Coast, Kootenay and Cariboo-Chilcotin regions. This shows that seasonal precipitation can be better forecast from mean precipitation and synoptic type frequencies if a sub-type approach using both PDO and ENSO climate indices is applied. This is strong evidence that the PDO and ENSO are significant sources of within-type variability in the synoptic climatology of BC.

Sub-types that subdivide the synoptic types by both PDO and ENSO test the interaction between the teleconnections. The teleconnection effect is significantly enhanced within some synoptic types, and some sub-types even exhibit significant variations in circulation patterns. The jet stream appears to be strongly influenced by the interaction of teleconnection effects, thus increasing the magnitude of changes in relative vorticity and vertical velocity. Modifications upon relative vorticity by teleconnection-induced changes in upper-level circulation directly impact vertical velocity and PVA, important precipitation formation factors (Wilby, 1998). Precipitable water values over BC do not vary much between the different synoptic types and sub-types. This confirms that within-type variability in precipitation arises from changes in atmospheric circulation and interaction with topography.

This study shows that atmospheric circulation responses to in-phase teleconnection conditions are highly irregular, and suggests a non-linear atmospheric response to teleconnection signals. Non-linear responses in precipitation within-type variability are discovered in a case study that examines precipitation within-type

variability at Powell River BC. Firstly, the occurrence and nature of within-type precipitation variability varies between synoptic types. Secondly, the nature of the variability in a given synoptic type is not necessary opposite for opposite phases of teleconnections (e.g. within-type variability may be positively impacted for both phases of a particular teleconnection). It is very likely that teleconnections that affect other parts of the world may also have non-linear within-type variability responses. Non-linear responses in precipitation variability can be captured in GCM downscaling by using large-scale climate indices and synoptic sub-types to account for within-type variability.

6.2 – Conclusions

This study demonstrates that variability in upper-level meteorology attributed to teleconnections governs subsequent variability in lower-level synoptic flows. These flows are represented in BC by 13 synoptic types, each type exhibiting significant within-type variability in precipitation. Upper-level circulation variability arising from teleconnection effects is an important control on seasonal variability for two reasons: 1) Within-type variability in upper-level circulation will directly effect precipitation formation mechanisms, thereby enhancing or hindering normal precipitation processes. 2) Variability in upper-level circulation patterns will create variability in lower-level circulation as well. The subsequent interaction of these modified lower level circulation patterns will introduce more precipitation variability to surface climates.

It is therefore concluded that teleconnections influences upon upper-level precipitation formation mechanisms control within-type variability in precipitation in BC.

Furthermore, downscaling methods based upon teleconnection indices are effective at better predicting the future precipitation climate of BC.

6.3 – Future Research

The downscaling methodology employed in this study presents a fundamental framework for future downscaling exercises in BC or other mid-latitude regions using gridded synoptic-scale upper-level data, and surface climate data. Creating synoptic sub-types by teleconnection phase for various upper-level meteorological variables yields significant changes in mean upper-level circulation. It is therefore recommended that future downscaling exercises incorporate upper-level meteorological variables into the modelling process. The first such variable that should be included is relative vorticity, which is an important control on precipitation formation and has been used extensively in similar exercises (Wilby, 1998).

There are many sources of error within this study that must be addressed in future research. Firstly, the temporal scale (daily) does not capture the evolution and movement of cyclones very well. Another drawback is that the constrained study region does not allow upstream upper-level circulation conditions to be included in the classification process. Furthermore, the advection of moisture into the region from afar by low-level warm-air conveyor belts is also not handled well. These events are infrequent, but are very important precipitation-producing events that should be better captured by this study. The interaction of modified flows synoptic with the complex topography of BC generates further within-type variability that must also be addressed. Finally, the spatial assessment of within-type variability of precipitation is limited because station densities are low throughout most of BC.

Future studies concerning the precipitation climate of BC will improve efforts in downscaling seasonal precipitation forecasts from Global Circulation Models (GCMs) to local scales, and permit researchers to detect adverse climate change effects arising from global warming, and upon precipitation regimes at local scales (Lapp et al., 2002.). In addition, it may be possible to differentiate existing precipitation variability from fluctuations that may be induced by global warming (Kidson, 1995). As forecasting methods for ENSO are improved within GCMs, and as downscaling methods develop, improved seasonal precipitation forecasts will be available for BC. It may also be possible to downscale further to a daily precipitation record using the variance inflation methods of Von Storch (1999), and precipitation event probabilities (Wilby 1995). Finally, classification and downscaling techniques based upon neural networks should be considered as methods to better include within-type variability in future downscaling efforts.

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