10.5 ATMOSPHERIC AND OCEANIC VARIABILITY ASSOCIATED WITH GROWING SEASON DROUGHTS AND PLUVIALS ON THE CANADIAN PRAIRIES

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1. INTRODUCTION

Droughts are caused by disruptions to an expected precipitation pattern and can be intensified by unusually high temperatures. At synoptic scales, the major factor in the onset and perpetuation of drought involves anomalous circulation patterns in the mid troposphere. Over the agricultural region of the Canadian Prairies, growing season (May to August) extended dry periods have been associated with a persistent mid-tropospheric circulation pattern that includes a large-amplitude ridge centred over the area. The ridging creates 'blocking conditions' that displace cyclonic tracks and associated moisture advection (from both the Pacific and Gulf of Mexico) away from the area (e.g., Dey, 1982; Liu et al., 2004). Conversely, pluvial conditions are associated with a collapse of the mid-tropospheric ridge and thus a higher frequency of zonal flow over the Prairie region. The upper level jet stream is often displaced southward in a west-east alignment along the Canada-United States border causing surface level cyclones to be steered over the Prairies. The wet conditions are aided by the advection of moist air into the Prairies from the southern United States and the Gulf of Mexico.

Although some research has been carried out regarding specific aspects of the synoptic to large-scale atmospheric conditions associated with droughts and to a lesser extent, pluvials on the Canadian Prairies, there has been no comprehensive analysis that has examined several inter-connected processes at various scales (i.e., knowledge required for a better understanding into the physical mechanisms responsible for the initiation of and perpetuation of these extremes). The main focus of this paper is to analyze the inter-relationships among large to synoptic scale atmospheric circulation patterns, and moisture transport during extreme drought and pluvial periods on the Canadian Prairies for the period 1950 to 2007. The analysis will focus on the agricultural growing season of May to August when the majority (up to two-thirds) of annual precipitation is received (Dey, 1982) and impacts from extreme precipitation events are the greatest, particularly for agriculture. As alluded to previously, the balance between precipitation and evaporation resulting from changes in the atmospheric circulation is most likely teleconnected to surface boundary conditions with long-term SST variability being the most important. A secondary objective of this study is therefore to understand both the dynamical and statistical relationships between slowly varying global SSTs and warm-season moisture availability over the Prairies via linkages with the large to synoptic-scale atmospheric circulation.

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2. DATA AND METHODOLOGY

Although no universally accepted definition for drought exists, numerous indices are used to quantify their severity. Meteorological approaches range from indices that only consider precipitation (e.g., the Standardized Precipitation Index or SPI; McKee et al., 1993), to more complex methods that incorporate a water balance approach using precipitation and temperature as input variables to derive potential evapotranspiration, antecedent soil moisture, and runoff (e.g., the Palmer Drought Severity Index or PDSI; Palmer, 1965). The Palmer Z-index (a derivative of the PDSI calculation) reflects the departure of temperature and precipitation from average conditions regardless of what has occurred in prior or subsequent months (Heim Jr., 2002). Since it is more responsive to shorter-term moisture anomalies, the Z-index also has some desirable characteristics that may make it preferable to the PDSI for agricultural applications. The SPI, PDSI, and Z-index are all used to monitor and assess drought conditions over various regions of North America and have the advantage of only requiring monthly temperature and or precipitation as input variables. For this study, all three aforementioned indices were calculated, however, only those for the Z-index are presented. Note that the identification of extreme dry and wet periods on the Prairies was almost identical for all three indices and each one displayed similar temporal variations throughout the study period. The choice to use the Z-index stems from its incorporation of temperature and precipitation in its calculation (that both have an effect on drought) and the absence of any lag effects (thus making it more applicable to relate to contemporaneous atmospheric conditions).

Atmospheric circulation data are from the NCEP-NCAR reanalysis (Kalnay et al., 1996). They included lower tropospheric (1000 to 500 hPa) geopotential heights, horizontal (u,v) and vertical (w) wind components, and specific humidity (q). Moisture transport at the 850 hPa level was calculated as $qu\vec{i}+qv\vec{j}$. Monthly anomalies for all of the above fields are relative to the 1961-90 base period.

Monthly global SST values on a 2^{o} latitude-longitude grid (1950 to 2007) are obtained from the Extended Reconstruction Sea Surface Temperatures Version 3 (ERSST3) data set described in Smith et al. (2008). As with the atmospheric variables, monthly SST anomalies are also determined relative to the 1961-90 normal.

For each of the 35 stations in Fig. 1, monthly May through August Z-indices are averaged to determine a growing season value for every year from 1950 to 2007. Interannual variability is then decomposed into its low frequency component by empirical orthogonal function (EOF) analysis thus allowing identification of preferred spatial modes in Z-index patterns over the Prairie region. Atmospheric circulation, low level moisture, and cyclone frequency are then composited on the leading mode of variability for extreme dry (standardized amplitude below -1.0) and extreme wet seasons (standardized amplitude in excess of 1.0).

The spatial statistical technique singular value decomposition (SVD) (Bretherton et al., 1992) is used to extract coupled modes of variability between global SSTs and the Z-index. The SVD method relates two fields by decomposing their covariance matrix into singular values and two sets of paired orthogonal vectors, one for each field. The covariance between the expansion coefficients of the leading pattern in each field is maximized. The relationship between the two fields is discerned by the spatial patterns of the heterogeneous correlation, which is defined as the serial correlation between the expansion coefficients of one field and the grid point anomaly values of the other field. In this study, the correlation patterns reveal teleconnections between winter SST anomalies and the following growing season moisture conditions over the Canadian Prairies.

3. RESULTS

3.1 *Canadian Prairie Droughts and Pluvials*

Fig. 2 shows average growing season Z-index values over the Prairie region for the period 1950 to 2007. The series displays considerable interannual and in some cases, multi-year variability with extreme drought seasons (i.e., negative Z-indices) occurring in 1958, 1961, 1967, the late 1980s, and 2001. These

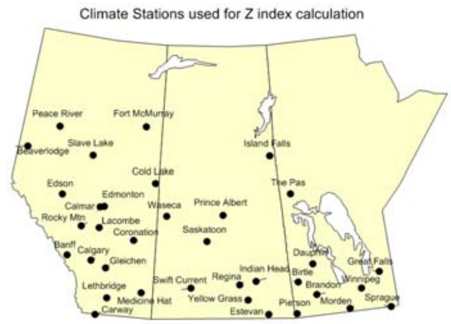

Fig. 1. Climate stations used for Z-index.

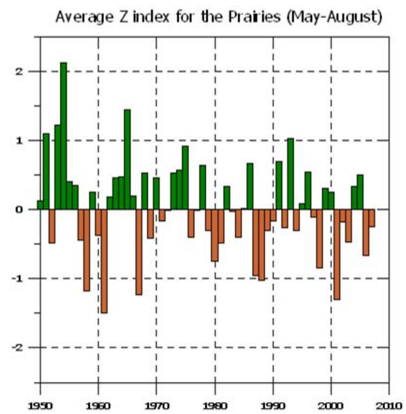

Fig. 2. Average growing season Z-index 1950-2007

correspond closely to other studies that have identified historical Canadian Prairie droughts. For the most part, the early 1950s, early to mid 1960s, early 1970s, and individual years within the 1990s were associated with wetter than normal conditions. The first EOF mode from the interannual variability in the Z-index field and its associated time series are provided in Fig. 3. This leading mode explains over 35% of the total variance in the growing season Z-indices and is comprised of same-sign loadings throughout the Prairie region. Highest values are found over southern Saskatchewan and southern Alberta and decrease in an easterly and northerly direction. The time series of this mode (Fig. 3b) is almost identical to that of the original Z-index series in Fig. 2, with the correlation between the two series being 0.98. For the composite analysis, drought seasons were identified as those years with a standardized PC1 value below -1.0, and pluvials as those with a standardized value above +1.0. This results in seven drought (1958, 1961, 1967, 1980, 1987, 1988, and 2001) and seven pluvial (1951, 1953, 1954, 1965, 1975, 1991, and 1993) seasons.

3.2 *Atmospheric Circulation*

Moisture transport and other atmospheric controls of extreme droughts and pluvials on the Canadian Prairies are better understood by examining the role of large-scale atmospheric circulation patterns.

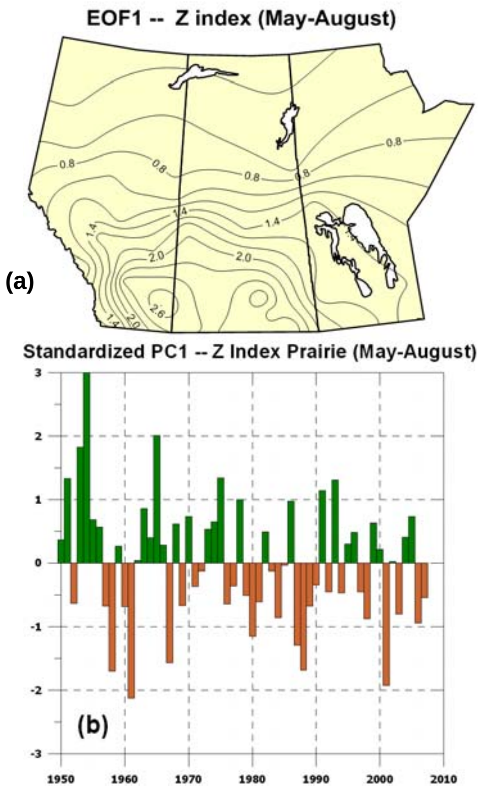

Fig. 3. (a) The first EOF of Z-index and (b) the associated PC1 from 1950 to 2007.

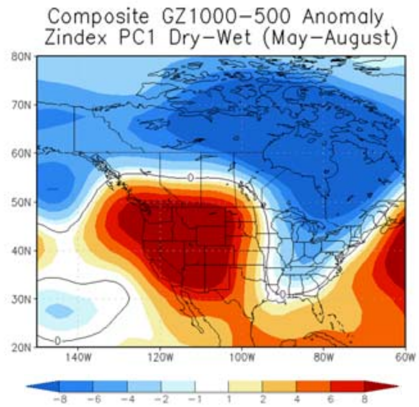

Fig. 4. Average 500-1000 hPa height anomaly in dam for drought minus pluvial years.

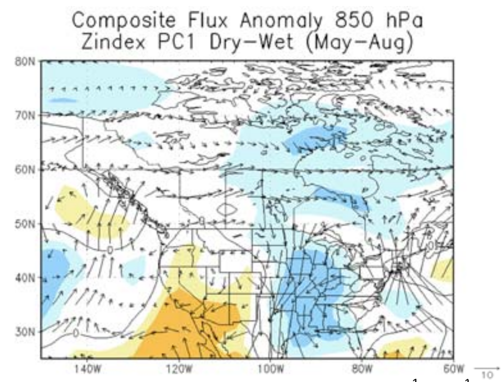

Fig. 5. Moisture flux anomaly at 850 hPa (g kg^{-1} m s^{-1}) denoted by vector and column precipitable water (kg m^{-2}) denoted by shading for drought minus pluvial years. Reference vector is 10 g kg^{-1} m s^{-1}.

Since the transfer of moisture mainly occurs at lower tropospheric levels (Brimelow and Reuter, 2005), geopotential height anomalies averaged from 1000 to 500 hPa are analysed in this study. Although the structure of atmospheric circulation at a constant geopotential height provides information on moisture transport at that level, the overall regional moisture transport is to a large extent governed by the dynamics of the averaged atmospheric circulation in the lower troposphere. Fig. 4 displays composite 1000 to 500 hPa circulation anomalies over North America associated with the identified drought minus pluvial growing seasons on the Prairies. The circulation feature over the northwestern United States controls the moisture availability for the Canadian Prairies during May to August period.

3.3 *Moisture Flux and Precipitable Water*

During the warm season, convection is the main atmospheric process by which moisture is transported from the Gulf of Mexico northward into continental interior regions (Dirmeyer and Brubaker, 1999). The composite 850 hPa spatial structure of anomalous moisture transport (arrows) and precipitable water content (shading) through the depth of the atmosphere for drought minus pluvial seasons is shown in Fig. 5. Note that the difference between dry and wet seasons (dry minus wet) shows moisture mainly directed away from the Prairie region.

3.4 *Coupled SST and Z index Patterns*

The dimensionality of Prairie Z-index values and previous winter (December-March) global SSTs was initially reduced by EOF analysis. The 10 leading EOF modes (that capture over 70% of the total variance in their respective datasets) were then chosen as input into the SVD procedure described previously. Most of the variance is concentrated in the first two EOFs that explain 47% of the total variability for growing season Z-indices and 40% for winter SSTs.

Fig. 6a shows the heterogeneous correlation pattern in the first SVD expansion associated with winter SST anomalies and the following growing season Z-index for the period 1950 to 2007. The

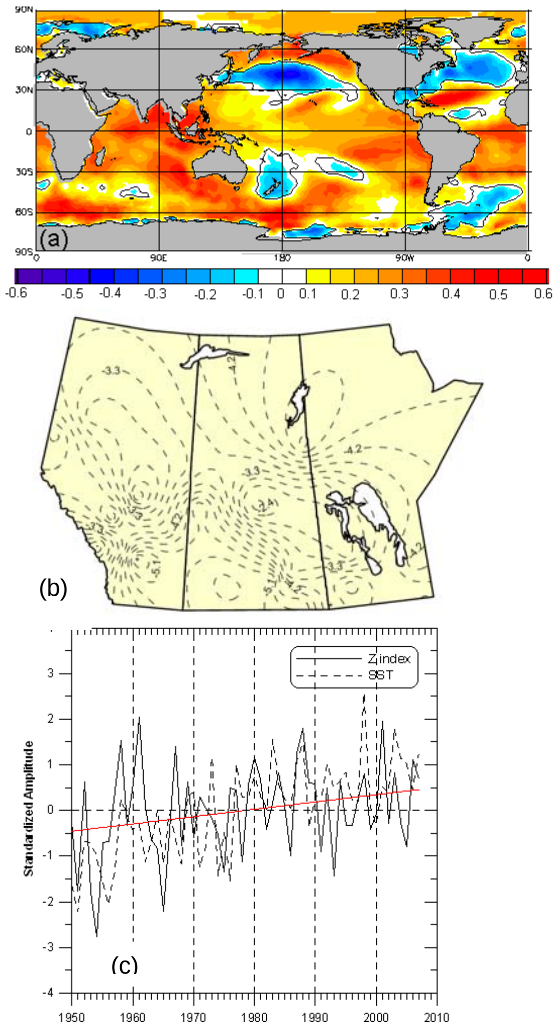

Fig. 6. Heterogeneous correlation pattern in the first SVD expansion of SST anomaly, (b) same as (a) but for Z index. (c) First SVD standardized amplitude of SST and Z index.

primary characteristic of this pattern involves the pronounced warming of the southern oceans as indicated by the positive loadings, mainly south of the equator and the cooling in the central North Pacific and the North Atlantic. The accompanying Z-index SVD pattern (Fig. 6b) shows a moisture deficit throughout the Canadian Prairies. The strongest negative values are in southern Saskatchewan and southern Alberta. The time series associated with the leading SVD mode (Fig. 6c) displays considerable interannual variability, however, the salient feature is a strong positive trend in the time component of both fields. This suggests that a winter warming of the southern oceans is associated with following summer dryness over the Canadian Prairies.

The heterogeneous correlation pattern for the second SVD mode (Fig. 7) reveals characteristics of the Interannual ENSO mode and ENSO-like decadal variability in the North Pacific as identified by Zhang et al. (1997) and Deser and Blackmon (1995). In particular, Fig. 7a displays correlation between the time series of the second SVD mode of the Z-index and the grid point values of SST anomaly. The pattern shows a structure in the tropical Pacific SSTs mimicking the positive phase of ENSO (i.e., El Niño) with positive loadings stretching from the west coast of South America to central tropical Pacific Ocean. The mid-latitude SST fluctuations in the central North Pacific resemble the coupled ocean-atmosphere mode known as the Pacific Decadal Oscillation (PDO; Mantua et al., 1997). Correlation between the time series of the second SVD mode of the SST and the Z-index (Fig. 7b) shows that positive loadings in the tropical eastern Pacific (resembling the El Nino phase) and negative loadings in the North Pacific (resembling the positive phase of the PDO) leads to negative growing season Z-index values in the south-central and northwestern Prairies. The extremes in the associated time series identify strong to moderate warm (positive) and cold (negative) years of the ENSO phenomenon (Fig. 7c). While investigating covariance between global winter SSTs and following summer dry conditions, Shabbar and Skinner (2004) also identified the SST warming trend and ENSO as the most prominent source of variability affecting summer moisture patterns in Canada. In addition, a strong relationship between seasonal Canadian temperature and precipitation, key factors in the formation of drought, and the ENSO cycle has been established both during the cold season (Shabbar et al. 1997) and the subsequent growing season.

In SVD, the strength of the relationship between the two fields can be measured by the squared covariance fraction (SCF) while the temporal variations of the mode are reflected by the correlation coefficient (r). The SCF is concentrated in the first two modes (over 80%) and the r value remains near 0.5 for both of these modes. Examination of the first two modes indicates that they are well separated from the rest, in terms of explained variance, squared covariability, and correlation. Furthermore, as shown previously, they can be physically interpreted. The higher order modes identified in the SVD procedure are not statistically significant. A third statistic, normalized covariance fraction (NCF**),** is the ratio of the squared singular value of the mode to the greatest possible total squared covariance of the matrix. It measures the absolute importance of the SVD mode in the relationship between the two fields. In this study, over 15% of NCF is concentrated in the first two modes.

The robustness of this investigation's findings is also established by the Monte Carlo technique. Test results on 1000 Monte Carlo SVD expansions, with randomly shuffled time series, show that r and NCF statistics for both modes of the Z index and SST anomalies are statistically significant at the 5% level.

The above findings suggest a connection between the large-scale teleconnections forced by winter diabatic heating in the central and eastern

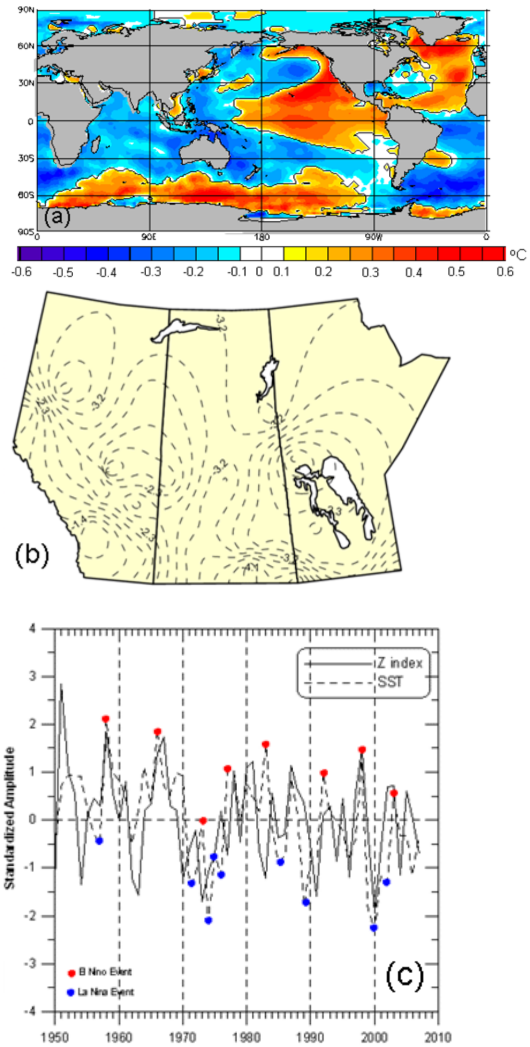

Fig. 7. . Heterogeneous correlation pattern in the second SVD expansion of SST anomaly, (b) same as (a) but for Z index. (c) First SVD standardized amplitude of SST and Z index.

tropical Pacific during warm ENSO events and the following growing season synoptic-scale circulation anomalies over parts of the North American sector.

4. SUMMARY AND CONCLUSIONS

This study focuses on the inter-relationships among large to synoptic/ regional-scale atmospheric circulation features that aid in the better understanding of moisture transport, convergence of moisture associated with extreme dry and to a lesser extent, wet growing seasons over the Canadian Prairies. It also attempts to relate the larger-scale circulation features with the previous winter's SST patterns, with focus on those over the Pacific Ocean. Individual drought and pluvial growing seasons (May to August) during the period 1950 to 2007 were identified using the Palmer Z-Index. Composite analysis keyed to drought periods revealed anomalous lower to mid-tropospheric ridging to the west and south of the Prairie Provinces (Fig. 4) that helped divert moisture away from the study region. A number of studies (e.g., Liu et al., 1999) have suggested that the primary source of moisture for summer precipitation in the Prairies originates from the Gulf of Mexico.

Although changes in the balance between precipitation and evaporation could result from changes in the atmospheric circulation and regional feedback processes, the persistence of drought and pluvials on the Canadian Prairies is likely connected to slow varying global SSTs. Coupled modes of variability between winter SSTs and following summer Z-index show that the leading mode of covariability relates to the warming trend in global SSTs, particularly in the southern oceans (Fig. 6).

The associated Z-index pattern shows a deficit of moisture throughout the Prairies. The striking feature of the time series of this mode is a strong positive trend throughout the study period. The warming of the southern oceans, notably over the western tropical Pacific and the Indian Oceans has been partly attributed to the build up of greenhouse gases in the atmosphere (Levitus et al., 2000). The results of this analysis suggest that if the warming trend in the southern oceans continues, this would imply more drought-like conditions for the Canadian Prairies during the growing season. Further studies are needed to understand the role of human-induced climate change, possibly leading to warmer oceans, and a higher frequency of droughts in the Canadian Prairies.

The second covariability mode has its origin in the equatorial interannual ENSO and ENSO-like interdecadal variability in the North Pacific, and its time component identifies the warm and cold phase of ENSO (Fig. 7). The Z-index coupled pattern shows that the warm phase of ENSO leads to negative (i.e., drier) growing season values, especially in the south central and northwestern Prairies. Results from composite analysis show that there are some resemblances between mid-tropospheric height anomalies that characterize the drought seasons and those associated with the warm-phase ENSO events over the off-shore and coastal regions of western North America and eastern Canada (not shown). This suggests that some aspects of the warm ENSO-related mid-tropospheric teleconnections established during winter could persist into summer. These results, along with the six-month lag relationship between the Z-index and large-scale SSTs provide a basis for developing long-range forecasting schemes for the occurrence of drought in Canada.

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