Analysis of Snow Cover Variability and Change in Québec, 1948-2005

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EXTENDED ABSTRACT

The spatial and temporal characteristics of annual maximum snow water equivalent (SWEmax) and fall and spring snow cover duration (SCD) were analyzed over Québec and adjacent area for snow seasons 1948/49-2004/05 using reconstructed daily snow depth and SWE on a 50-km grid from a simplified snowpack model driven with 6-hourly National Centers for Environmental Prediction (NCEP) reanalyzed air temperature and observed daily precipitation derived from the CANGRID dataset. Rotated principal component analysis of annual snow cover series from the reconstruction revealed that fall and spring SCD varied coherently over much of northern Québec, and over a wide region extending from northern-Ontario across James Bay into western Québec. In contrast, SWEmax was observed to exhibit strong regional variability with six of the seven identified coherent regions explaining <10% of the total variance. Snow cover variability in Québec was found to be significantly correlated with most of the major atmospheric circulation patterns affecting the climate of eastern North America but the influence was characterized by strong multidecadal-scale variability. The strongest and most consistent relationship was observed between the Pacific Decadal Oscillation (PDO) and fall SCD variability over western Québec. Evidence was found for a shift in circulation over the study region around 1980 associated with an abrupt increase in sea level pressure and decreases in winter precipitation, snow depth and SWE over much of southern Québec, as well as changes in the atmospheric patterns with significant links to snow cover variability. El Niño-Southern Oscillation (ENSO) was found to have a limited impact on Québec snow cover with the main influence associated with earlier snow melt over most of central Québec in El-Niño years. The sign of ENSO correlations with SWEmax was observed to switch in the late 1970s which coincides with a well-documented shift in atmospheric circulation over the north Pacific in 1976. Trend analysis of the reconstructed snow cover over 1948-2004 provided evidence of a clear north-south gradient in SWEmax and spring SCD with significant local decreases over southern Québec and significant local increases over north-central Québec. The increase in SWEmax over northern Québec is consistent with proxy data (lake levels, tree growth forms, permafrost temperatures), with hemispheric-wide trends of increasing precipitation over higher latitudes, and with the transient response of global climate model simulations. The full paper was submitted to Hydrological Processes for publication in the ESC 2008 Special Issue.

Keywords: snow cover; SWE; atmospheric circulation/teleconnection patterns; Québec; interannual variability; trends

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INTRODUCTION

Snow accumulation over Québec and adjacent Labrador is significant at a continental scale representing the second largest maxima after the western cordillera with annual maximum snow accumulation averaging 200-300 mm of water equivalent (Brown et al., 2003). Variations in snow cover amount and duration have important economic and ecological consequences in this region. For example it is estimated that 1 mm of SWE in the headwaters of the Caniapiscau-La Grande hydro corridor is equivalent to $1M CDN in hydro-electric power production (R. Roy, personal communication, 2006). Reductions in the amount and continuity of winter snowpack over southern Québec in recent years have contributed to significant root damage to yellow birch (Zhu et al., 2002) and perennial crops such as millet, alfalfa and hay as well as to the rapid expansion of white-tail deer into southern Québec. Results from recent GCM simulations (Räisänen, 2007) suggest a contrasting response of winter snow accumulation over this region in response to climate warming with increases of up to 15% over northern Quebec and reductions of up to 30% over southern Québec. However, Frei et al. (2005) showed that atmospheric global climate models tend to underestimate SWE over the northeastern U.S. and Canada with large differences between models suggesting climate models have some difficulty simulating winter climate over this region of North America (NA).

A number of studies have demonstrated significant links between atmospheric circulation variability in the North Atlantic, as expressed in the North Atlantic Oscillation (NAO) and related indices, and climate, cyclone frequency and stream flow in the Québec-Labrador region (e.g. D'Arrigo et al., 1993; Rasmussen et al., 1999; Sheridan, 2003; Sveinsson, 2003; Anctil and Coulibaly, 2004; Déry and Wood, 2004; Wang et al., 2006, Qian et al., 2008). A number of studies have also documented significant linkages between El Niño (ENSO) and climate over many regions of Canada (Shabbar and Khandekar, 1996; Shabbar et al., 1997), with the hydrological response of river basins in Québec (Rasmussen et al., 1999) and with snow cover over NA (Karl et al., 1993; Brown, 1998). Déry et al. (2005) showed a statistically significant link between Eurasian snow cover and annual maximum SWE for the Churchill Falls river basin through a teleconnection mechanism proposed by Gong et al. (2003). However, to the best of this author's knowledge there has been no systematic investigation of the role of atmospheric circulation on the onset, melt and accumulation of snow over the Québec-Labrador region.

One of the main obstacles to a systematic study of snow cover variability over Québec is the lack of continuous data. To overcome this problem, this study has undertaken a reconstruction of daily snow depth and SWE on a 50-km grid over Québec over the winter seasons 1948/49-2004/05. These data are used to (1) characterize the spatial and temporal variability and trends in snow cover over Québec from 1948-2005; and (2) determine to what extent atmospheric circulation patterns influence the observed spatial and temporal variability. The results from work contribute to improved understanding of spatial and temporal variability in snow cover over Québec, to seasonal prediction of snow cover, and to validation of climate model snow cover simulations.

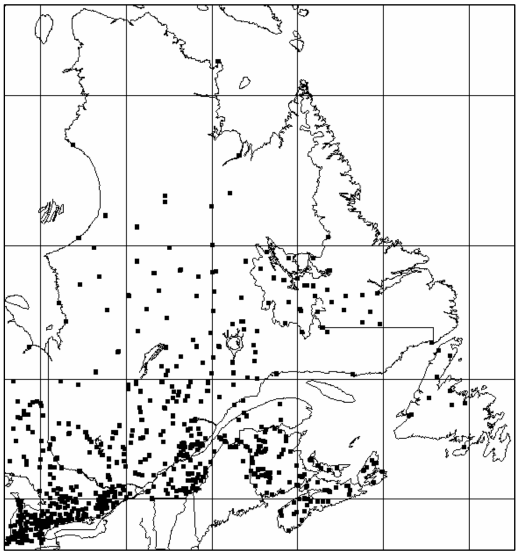

Figure 1: Location map of the study area showing the spatial distribution of snow courses used in evaluating the snow cover reconstruction.

STUDY REGION AND DATA SETS

The overall study region is centred on the province of Québec and adjacent regions and extends from 43-65ºN and 55-82ºW (Fig. 1). This region is characterized by strong spatial gradients in snow cover duration with snow cover duration ranging from four months (December to April) over southern Québec to eight months (October-June) over northern Québec, and mean annual maximum SWE (SWEmax) values ranging from less than 100 mm in the south and north to more than 300 mm over higher elevations of the zone of maximum accumulation which extends over a broad band along the north shore of the St. Lawrence River out to the Labrador Coast . This region of higher SWE is related to topography and to the fact that this area coincides with several of the preferred tracks for winter storms (Zishka and Smith, 1980). A description of the main data sets used in this study is provided below. Note that in this study a snow year was defined from August to July with the year assigned from the start year of the season i.e. 2004 refers to the 2004/05 snow year from August 2004 to July 2005.

Reconstructed SWE, 1948-49 to 2004-05

The main data set used in this study was reconstructed daily snow depth and SWE on a 50-km grid over the study area using the Brown et al. (2003) temperature index model driven with 6-hourly temperature data from the National Centers for Environmental Prediction (NCEP) Reanalysis (Kalnay et al., 1996) with daily precipitation amounts estimated from the product of daily precipitation intensities from NCEP (i.e. NCEP daily total precipitation divided by NCEP monthly total precipitation) and monthly precipitation totals from the CANGRID (Milewska et al., 2005) dataset. CANGRID provides monthly total precipitation on a 50-km grid over Canada corrected for inhomogeneities and systematic errors (e.g. gauge undercatch) and adjusted for topographic and physiographic influences. NCEP temperatures were interpolated to the CANGRID 50-km grid for running the snow model. Details of the reconstruction and validation process are provided in Brown (2008).

Atmospheric circulation indices, 1950-

The investigation of links between major modes of NH atmospheric circulation and snow cover variability in the study region was carried out using the standardized monthly NH teleconnection indices maintained at the NOAA Climate Prediction Center (CPC) (www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml).The indices are computed from a rotated principal component analysis of monthly mean standardized 500-hPa height anomalies in the NCEP Reanalysis over the region north of 20°N from 1950, and include the major atmospheric circulation patterns that influence the climate of NA e.g. NAO, the Pacific-North American pattern (PNA), and the Eastern Pacific-North Pacific Pattern (EP/NP). The Arctic Oscillation (AO) series was also included in the study; AO resembles the NAO but has a stronger correlation with air temperature and precipitation over northern Québec in the winter and spring. The AO series was obtained from NOAA CPC and is the first EOF (empirical orthogonal function) from a rotated principal component analysis of monthly mean 1000-hPa height anomalies north of 20°N.

The monthly atmospheric indices were supplemented with sea surface temperature-related anomaly series from the Pacific and the North Atlantic that are linked to climate variability over the North American sector. These included: (1) North Atlantic tropical sea surface temperatures (SSTs) (5-20°N, 30-60°W), (2) the Atlantic Multidecadal Oscillation (AMO) which represents an index of monthly SST averaged over the north Atlantic and which has been shown to be significantly correlated with temperature and precipitation in Europe and NA (e.g. Enfield et al., 2001); (3) the Southern Oscillation Index as a measure of Pacific tropical SST variability and El Niño-La Niña (ENSO) activity, and (4) the Pacific Decadal Oscillation (PDO) which reflects sea surface temperature variability over the north Pacific (Mantua et al., 1997). The PDO series was obtained from U. Washington (http://jisao.washington.edu/pdo/PDO.latest) and is defined as the leading EOF of monthly SST anomalies in the North Pacific Ocean poleward of 20°N. The SOI was obtained from NOAA CPC as the standardized difference between the standardized sea level pressure (SLP) at Tahiti and the standardized SLP at Darwin. SOI is highly correlated with the Nino 3.4 SST series (r= -0.89) so it captures the variability associated with tropical Pacific SSTs. The detrended unsmoothed monthly AMO series computed by NOAA (http://www.cdc.noaa.gov/Timeseries/AMO/) based on the Kaplan SST dataset (Kaplan et al., 1998) were used in this study.

METHODS

Snow cover variables

Three key properties of snow cover variability were selected for analysis in this study: snow cover duration in the first (SCD1 - Aug.-Jan.) and second (SCD2 - Feb.-Jul.) halves of the snow year, and annual maximum SWE (SWEmax). A depth threshold of 2 cm was used to compute the number of days with snow cover. SCD1 and SCD2 are highly correlated to the start and end dates of continuous snow cover but are less ambiguous to calculate in regions like southern Québec where winter snow cover can be ephemeral in character during the early winter period.

Trend analysis

Trend analysis of annual snow cover statistics was carried out by applying the method developed by Zhang et al. (2000) based on the non-parametric Kendall's rank correlation (Sen, 1968) and taking serial correlation into account. The Kendall estimate is used instead of least squares as it is less sensitive to non-normally distributed variables and is less affected by extreme values or outliers in the series. A Monte Carlo method was used to estimate the confidence interval for the estimate slope. Throughout this paper the 5% level is used to define statistically significant trends.

Principal component (PC) analysis

Spatial and temporal variability in the gridded snow cover dataset was assessed using rotated (varimax) principal component analysis. Rotated PCs explaining 5% or more of the variance were retained for analysis as previous experience has shown that these correspond to clear regional patterns (Brown and Braaten, 1998). In this study PC numbers were assigned prior to rotating but since rotation can change the relative importance of a component, the identified PCs do not necessarily follow a sequence where the explained variance is inversely proportional to PC number.

Correlation analysis

The correlation analysis of snow cover and atmospheric circulation patterns was carried out in two steps. In the first step the time series of the identified major PCs of SCD1, SCD2 and SWEmax were correlated with monthly or seasonally-averaged atmospheric circulation patterns over the 1950-2004 period. Correlations were carried out on a monthly basis using the Pearson product moment method for SCD1 and SCD2 for the periods corresponding to snow cover onset over Québec (August to December) and snow cover disappearance (February-June). For SWEmax, correlations were carried out with 4-monthly averaged atmospheric indices over the entire snow season as the processes affecting SWEmax are cumulative such as the timing of snow cover onset, the amount of winter precipitation, the frequency and intensity of winter thaw events and the timing and intensity of winter thaw. Statistically significant (0.05 level) correlations were determined from Student's t-test. All series were detrended prior to computing correlations.

The second part of the correlation analysis involved the spatial correlation of the atmospheric indices with snow cover series at each of the 1182 grid points in the study domain for a moving 21-year window to identify changes in the temporal and spatial structure of the atmosphere-snow cover correlations. This approach was taken because of well-documented multi-decadal variability in the relative influence of the various modes of circulation as well as abrupt changes or regime shifts such as the 1988-1989 shift in the Arctic Oscillation (Watanabe and Nitta, 1999), and the 1976-1977 shift in the Aleutian low (Trenberth, 1990) and PNA (Leathers and Palecki, 1992). The field significant of the spatial correlations was determined by constructing the probability distribution of the number of locally significant grid points for 21-year periods of data from a bootstrapping approach. The results indicated that 275 locally significant grid point correlations were require for statistically significant spatial correlations for SCD1 and SCD2 and 185 for SWEmax. This corresponds to approximately 25% and 16% of the total grid area respectively.

Only atmospheric circulation patterns with significant spatial correlations for 10 or more 21-year windows were included in the discussion to avoid patterns with only transitory influences on snow cover.

SUMMARY OF MAJOR FINDINGS

The results of this study have generated a number of new insights into snow cover variability and change over Québec and the role of atmospheric circulation patterns in explaining the observed variability. First, the principal component analysis (Figs. 2-4) revealed that SWEmax exhibited relatively strong regional variability over the study region with six of the seven identified regions explaining only ~5-10% of the total variance. The strong regional character of SWEmax interannual variability is consistent with the large number of processes influencing regional-scale snow accumulation (e.g. position of winter storm tracks, frequency and intensity of winter thaw events, topography, snow-vegetation interactions, cloud cover anomalies etc.). This study showed that this regional variability was also contributed to by decadal-scale variability in the atmospheric circulation patterns influencing temperature and precipitation over eastern NA (Figs. 5-6). The relative strength and the regions of influence of important patterns such as NAO and PNA were observed to vary at multi-decadal time scales; this has implications for seasonal forecasting of snow cover with multiple regression type methods such as canonical correlation analysis (e.g. Shabbar and Barnston, 1996).

So why do we see such strong variability in the influence of circulation patterns on SWEmax? Firstly, a number of the important patterns linked to North Atlantic climate variability such as NAO, AO, EA and SCA have steep gradients in their zones of influence over the study region which is an indication of strong spatial and temporal variability. Second, SWEmax depends more closely on precipitation than temperature (the date of snow cover onset and SWEmax are uncorrelated over most of the study region except northern Québec) and the precipitation signals in the circulation patterns tend to be more localized than temperature.

This study also provided evidence of a major shift in atmospheric circulation over eastern Canada around 1980 which was associated with abrupt changes in winter sea level pressure, precipitation, and snow cover over much of southern and central Québec. The change follows a shift in the Aleutian Low in 1976 (Trenberth, 1990) and was associated with shifts in the relative importance of a number of the atmospheric circulations patterns for SWEmax over the study area. For example the SCA and PNA patterns were significantly correlated with SWEmax prior to 1980 but were replaced by NAO and EP/NP after 1980, and SOI correlations with SWEmax were observed to change sign around this time. This study also found evidence of cyclical variations in the influence of North Atlantic SSTs on climate and SWEmax over Québec with the AMO index exhibiting the strongest correlations with temperature, precipitation and SWEmax over Québec during periods when North Atlantic SSTs were cooling (1958-1978s) and warming (1984-2004). These results underscore the importance of decadal scale variability in atmospheric and oceanic circulation in both the North Pacific and the North Atlantic on the snow cover climate of Québec.

Spring and fall snow cover duration exhibited considerably less spatial variability than SWEmax with large regions of coherent interannual variability over north-central Québec and western Québec. The greater spatial coherence is due to the closer link between snow cover duration and air temperature and the larger spatial coherence of temperature anomalies over the study region. Regionally-averaged SCD anomalies over the entire study area were significantly correlated with regionally-averaged seasonal air temperature anomalies from the CRUtem3v data set (Brohan et al., 2006) in the fall (Sept-Oct) and spring (April-May) with correlations of -0.77 and -0.53 respectively. No significant correlations were observed between regionally-averaged air temperature and SWEmax. The most important atmospheric circulation patterns explaining interannual variations in SCD were the PDO and EP/NP over western Québec, and AMO and NAO over northern Québec. The PDO link to fall SCD variability over western Québec was the strongest and most consistent relationship observed in this study which further highlights the importance of North Pacific oceanic variability in the snow climate of Québec. In contrast, tropical Pacific SST variability (ENSO) was only found to play a limited role.

Lastly, trend analysis of snow cover variables over the 1948-2004 period (see lower panels in Figs. 2-4) provided evidence of a clear north-south gradient in SWEmax and spring SCD with significant local decreases over southern Québec and significant local increases over north-central Québec. The increase in SWEmax over north-central Québec is consistent with proxy data on lake levels (Bégin, 2000), tree growth forms (Lavoie and Payette, 1992) and permafrost temperatures (Payette et al., 2004). It is also consistent with the transient response of climate model simulations (e.g. Plummer et al., 2006; Räisänen, 2007), and with increasing precipitation over Northern Hemisphere high latitudes (north of ~55°N) in response to climate warming (Zhang et al.., 2007, Min et al., 2008). What will be of particular interest to water resource planners in Québec are the future evolution of these two zones (e.g. Will the current zero-change line migrate northward? Will the increases in available water in the north compensate for the reductions in the south?), and the future evolution of the interannual variability which has major impacts on operations and energy pricing and which this study has shown varies significantly on multi-decadal scales involving the North Pacific and North Atlantic ocean circulation. These questions will be investigated in a planned follow-on study which will assess the evolution of the snow climate over Québec in a warming world.

REFERENCES

Anctil, F. and P. Coulibaly, 2004: Wavelet analysis of the interannual variability in southern Québec streamflow. *J. Climate*, **17**, 163-173.

Bégin, Y., 2000: Reconstruction of subarctic lake levels over past centuries using tree rings. *J. Cold Regions Engineering*, **14**, 192-212.

Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophysical Research*, **111**, D12106, doi:10.1029/2005JD006548.

Brown, R.D., 1998: El Niño and North American snow cover. *Proc. 55th Eastern Snow Conference*, Jackson, NH, June 4-6 1998, 165-172.

Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. *Atmosphere-Ocean*, **36**, 37-45.

Brown, R.D., B. Brasnett and D. Robinson, 2003: Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. *Atmosphere-Ocean*, **41**, 1-14.

Brown, R.D., 2008: Analysis of snow cover variability and change in Quebec, 1948-2005. *Hydrol.Proc.* (submitted June 2008)

D'Arrigo, Rosanne D.; Cook, Edward R.; Jacoby, Gordon C.; Briffa, Keith R., 1993: NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews*, **12**, 431-440.

Dery, S.J. and E.F. Wood, 2004: Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophys. Res. Letters*, **31**, L18205, doi:10.1029/2004/GL020729.

Dery, S.J., J. Sheffield and E.F. Wood, 2005: Connectivity between Eurasian snow cover extent and Canadian snow water equivalent and river discharge. *J. Geophys. Res.*, **110**, D23106, doi:10.1029/2005JD006173.

Enfield, D.B., A.M. Mestas-Nunez, and P.J. Trimble, 2001: The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S. *Geophys. Res. Lett.*, **28**, 2077-2080.

Frei, A., R. Brown, J.A. Miller, and D.A. Robinson, 2005: Snow mass over North America: observations and results from the second phase of the Atmospheric Model Intercomparison Project (AMIP-2). *J. Hydromet.*, **6**, 681-695.

Gong, G., D. Entekhabi and J. Cohen, 2003: Relative impacts of Siberian and North American snow anomalies on the winter Arctic Oscillation. *Geophys. Res. Lett.*, **30**, doi:10.1029/2003GL017749.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR Reanalysis Project. *Bul. Amer. Met. Soc.*, **77**, 437-471.

Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856-1991. *J. Geophys. Res.*, **103**, 18,567-18,589, 1998

Karl, T.R., P.Y. Groisman, R.W. Knight and R.R. Heim Jr., 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate*, **6**, 1327-1344.

Lavoie, C. and S. Payette, 1992: Black spruce growth as a record of a changing winter environment at treeline, Québec, Canada. *Arctic and Alpine Research*, **25**, 40-49.

Leathers, D. J. and M. A. Palecki, 1992: The Pacific/North American teleconnection pattern and United States Climate. Part II: temporal characteristics and index specification. *J. Climate,* **5,** 707-716.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific decadal climate oscillation with impacts on salmon. *Bull. Amer. Meteorol. Soc.*, **78**, 1069-1079.

Milewska, E, Hopkinson, RF, Niitsoo A. 2005. Evaluation of Geo-Referenced Grids of 1961 – 1990 Canadian Temperature and Precipitation Normals. *Atmosphere-Ocean* **43**, 49-75.

Min, S-K, X. Zhang, and F. Zwiers, 2008: Human-induced Arctic moistening. *Science*, **320**, 518-520.

Payette, S., A. Delwaide, M. Caccianiga and M. Beauchemin, 2004: Accelerated thawing of subarctic peatland permafrost over the last 50 years. *Geophys. Res. Letters*, **31**, 18208.

Plummer, D.A., D. Caya, A. Frigon, H. Cote, M. Giguere, D. Paquin, S. Biner, R. Harvey, and R. de Elia, 2006: Climate and climate change over North America as simulated by the Canadian RCM. *J. Climate*, **19**, 3112-3132.

Qian, M., R. Laprise, C. Jones and D. Caya, 2008" The Influences of NAO and the Hudson Bay sea-ice on the climate of Eastern Canada. *Climate Dynamics*, doi:10.1007/s00382-007-0343-9.

Räisänen, J, 2007: Warmer climate: less or more snow? *Clim. Dyn.*, **30**, 307-319, doi:10.1007/s00382-007-0289-y

Rasmussen, P.F., V. Fortin, M. Slivitzky and B. Bobée, 1999: Impact des oscillations climatiques a basse fréquence sur les apports des rivières québécoises: étude statistique exploratoire. Research Report R-541, Institut national de recherché scientifique, INRS-Eau, Sainte-Foy, Québec, July, 1999, 60 pp. (confidential)

Sen, P.K., 1968: Estimates of the regression coefficient based on Kendall's Tau. *J. Am. Stat. Assoc.*, **63**, 1379–1089.

Shabbar, A. and A.G. Barnston, 1996: Skill of season climate forecasts in Canada using canonical correlation analysis. *Mon. Wea. Rev.*, **124**, 2370-2385.

Shabbar, A. and Khandekar, M. 1996. The impact of El Niño-Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean 34:401-416.

Shabbar, A., Bonsal, B. and Khandekar, M. 1997. Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate, 10: 3016-3027.

Sheridan, S.C., 2003: North American weather-type frequency and teleconnection indices. *Intl. J. Climatol.*, **23**, 27-45.

Sveinsson, O.G.B., 2003: Relationships between measures of atmospheric circulation and climate indices with streamflows in the Québec-Labrador region, Canada. Report submitted to Hydro-Québec by the International Research Institute for Climate Prediction, Columbia University, January 2003, 81 pp. (confidential)

Trenberth, K.E., 1990: Recent observed interdecadal climate changes. *Proc. Symp. on Global Change Systems - Special Sessions on Climate Variations and Hydrology*, American Meteorological Society, 91-95.

Wang, X.L., H. Wan, and V.R. Swail, 2006: Observed changes in cyclone activity in Canada and their relationships to major circulation regimes. *J. Climate*, **19**, 896-915.

Watanabe, M., and T. Nitta, 1999: Decadal changes in the atmospheric circulation and associated surface climate variations in the Northern Hemisphere winter. *J. Climate*, **12**, 494–510, 1999.

Zhang, X., L.A. Vincent, W.D. Hogg and A. Niitsoo, 2000: Temperature and Precipitation Trends in Canada during the 20th Century. *Atmosphere–Ocean*, **38**, 395–429.

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, T. Nozawa., 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, doi:10.1038/nature06025.

Zhu, X.B., R.M. Cox, C.P.A. Bourque and P.A. Arp, 2002: Thaw effects on cold-hardiness parameters in yellow birch. *Canadian Journal of Botany*, **80**, 390–398.

Zishka, K. and P. Smith, 1980: The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950-1977. *Mon. Wea. Rev.*, **108**, 387-401.

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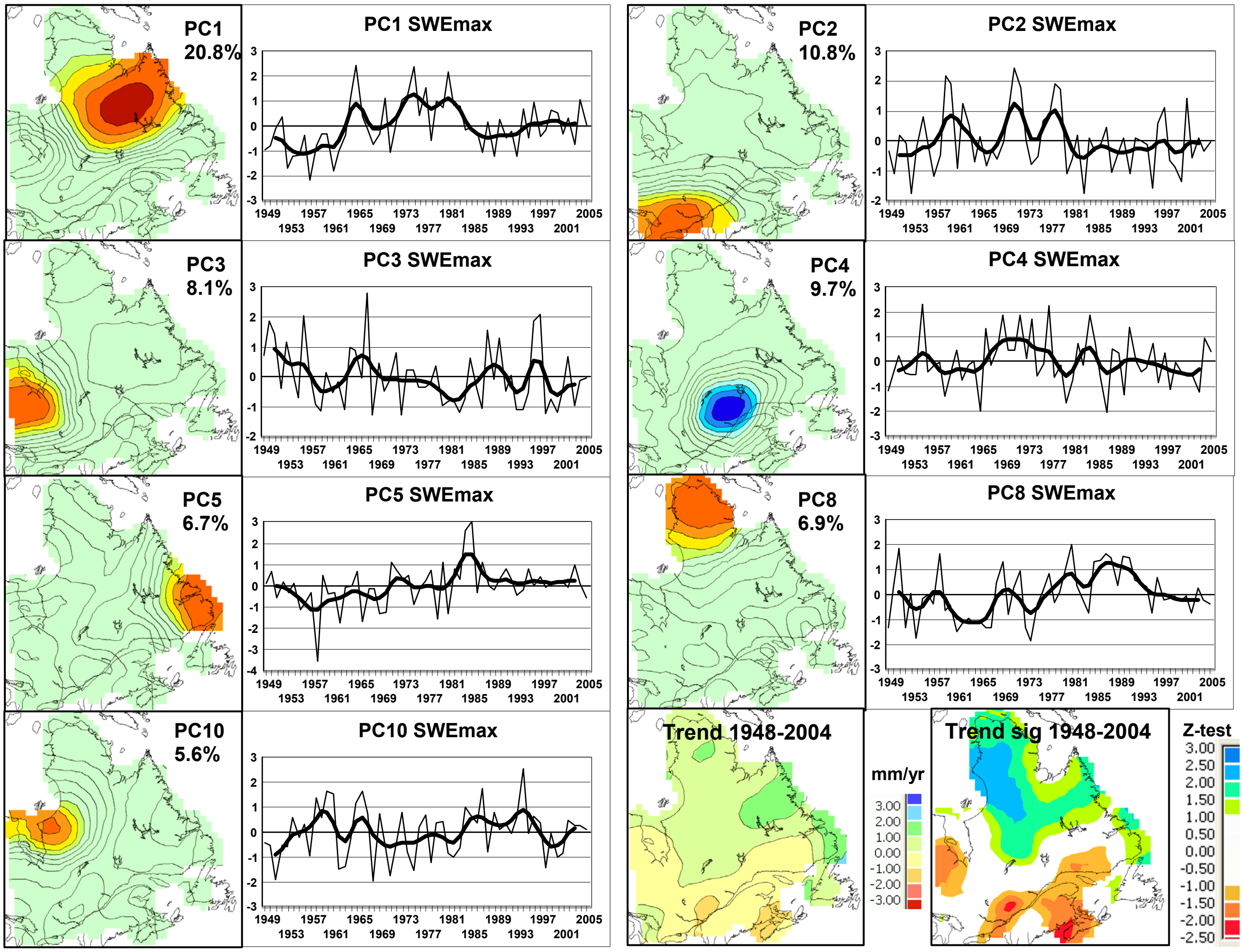


Figure 2. Loading patterns and series for rotated principal components explaining 5% or more of the interannual variability in annual maximum SWE over the 1948/49 to 2004/05 snow seasons. The loading patterns are contoured at a 0.1 interval and are shaded above/below ± 0.5. The linear trend (mm.y^{-1}) and trend significance at each gridpoint are shown in the bottom right panels. The heavy solid line in the PC series is the result of passing a 9-term binomial filter.

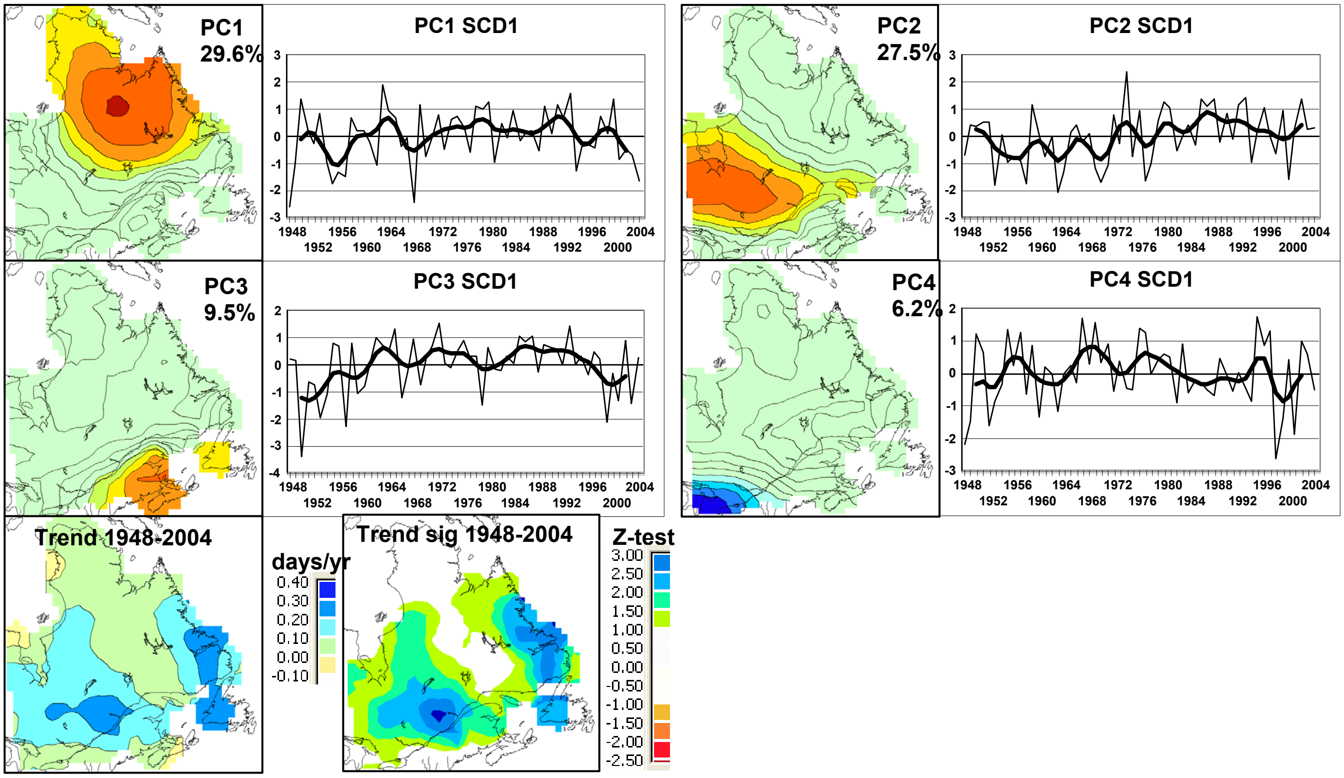


Figure 3. As in Figure 2 for fall snow cover duration. The linear trend (days.y^{-1}) and trend significance at each gridpoint are shown in the bottom left panels.

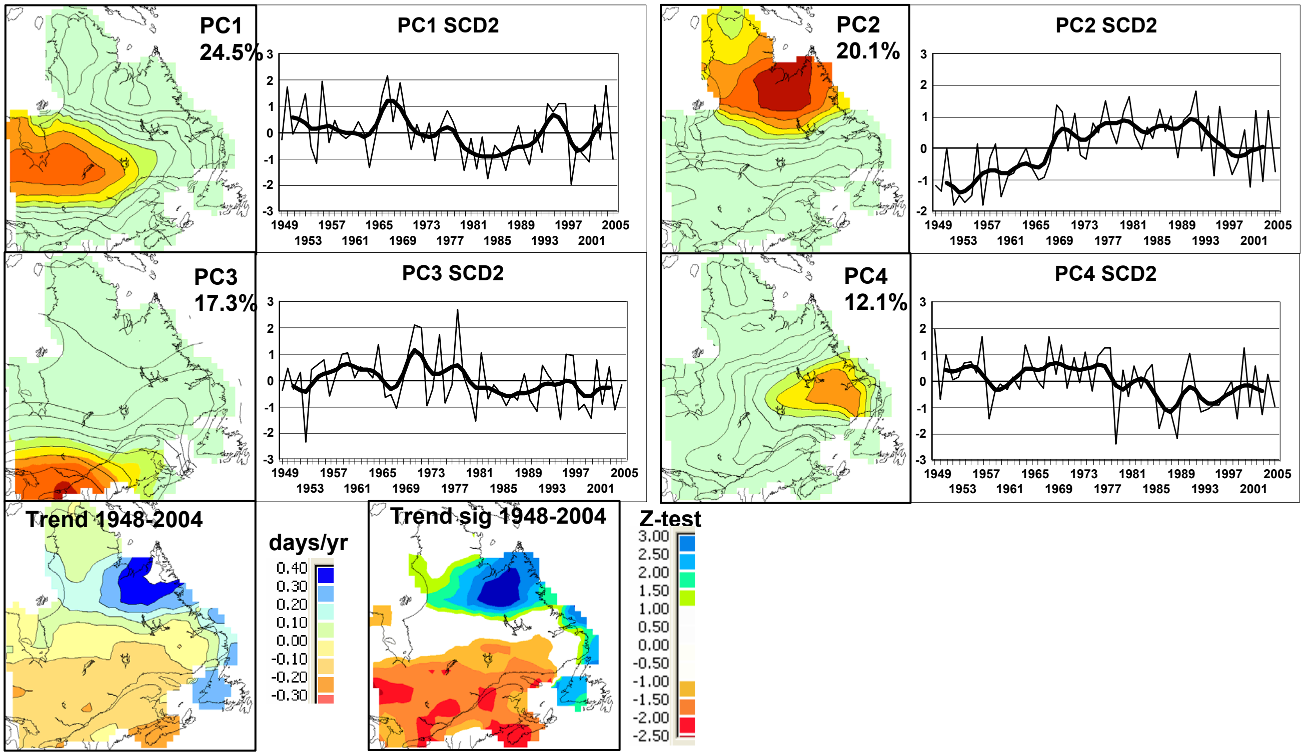
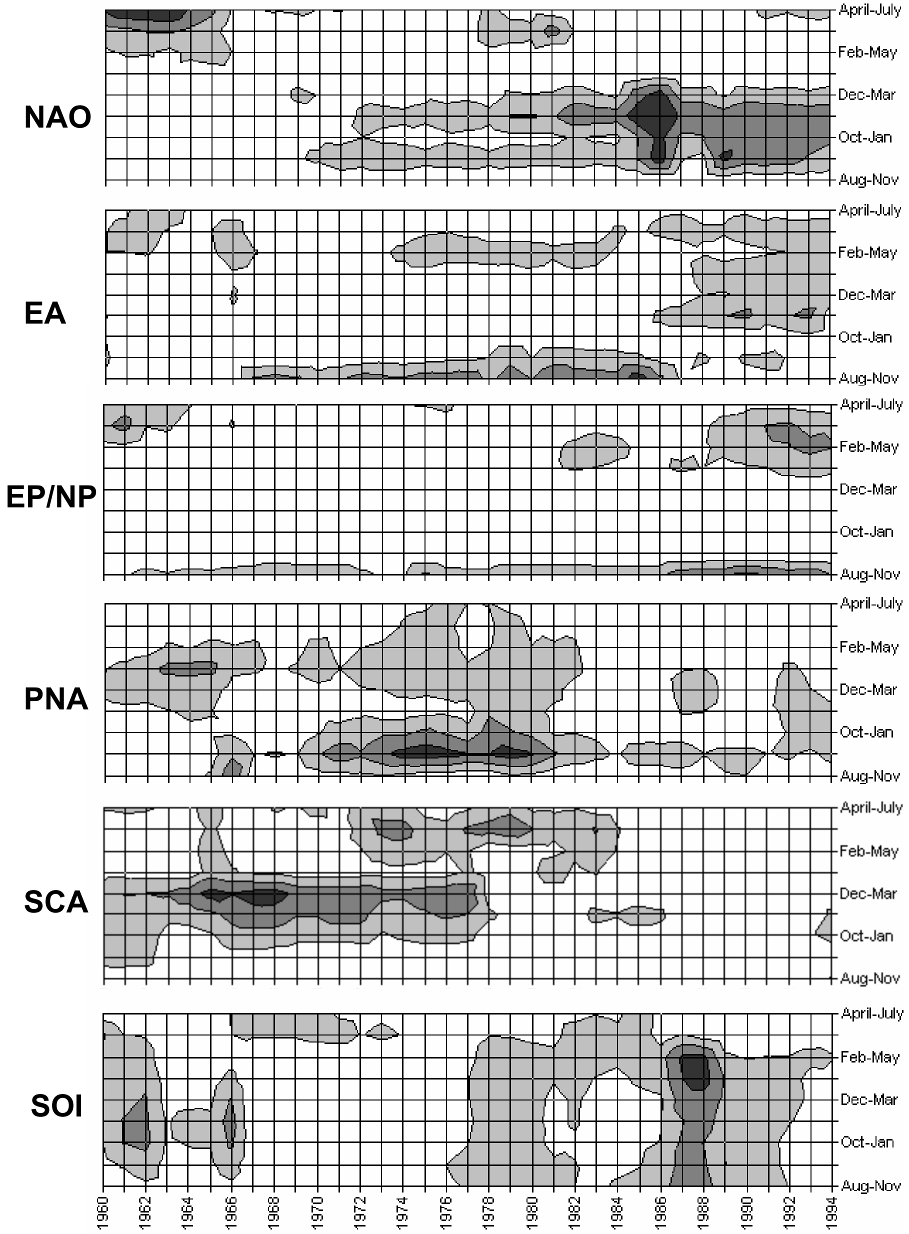


Figure 4. As in Figure 6 for spring snow cover duration.

SWEmax



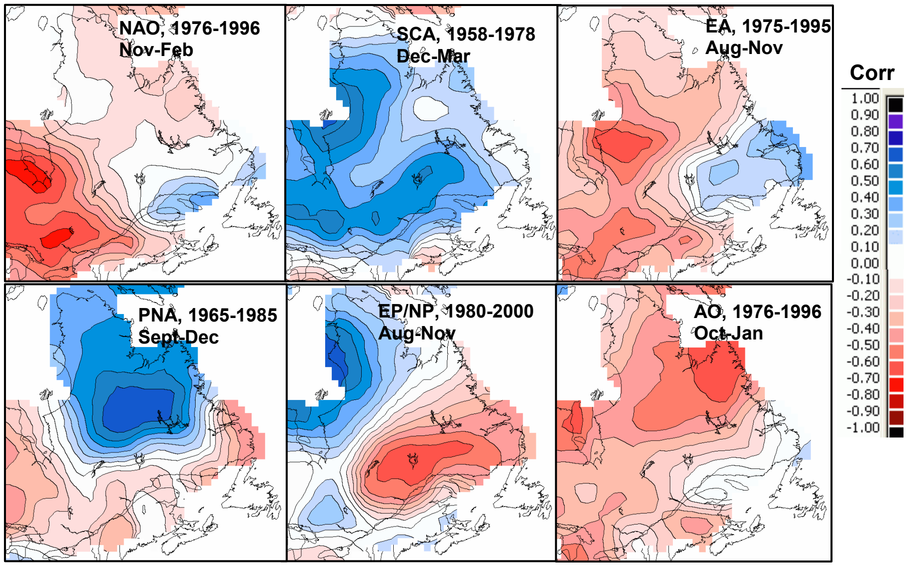


Figure 5. Left: Contour plots of the number of gridpoints exhibiting statistically significant correlations based on 21-year moving window correlations of SWEmax and 4-monthly averaged values of atmospheric circulation indices. Correlations are plotted against year 11 of each 21-year block. Values exceeding 180 are approximately statistically significant based on a bootstrapping analysis. Above: SWEmax correlations patterns for modes of NH atmospheric circulation exhibiting statistically significant spatial correlations over 10 or more 21-year windows. The correlation patterns correspond to the 21-year period and season exhibiting the largest number of gridpoints with locally significant correlations. AO did not meet the 10 window criterion but is included for comparison with the NAO results.

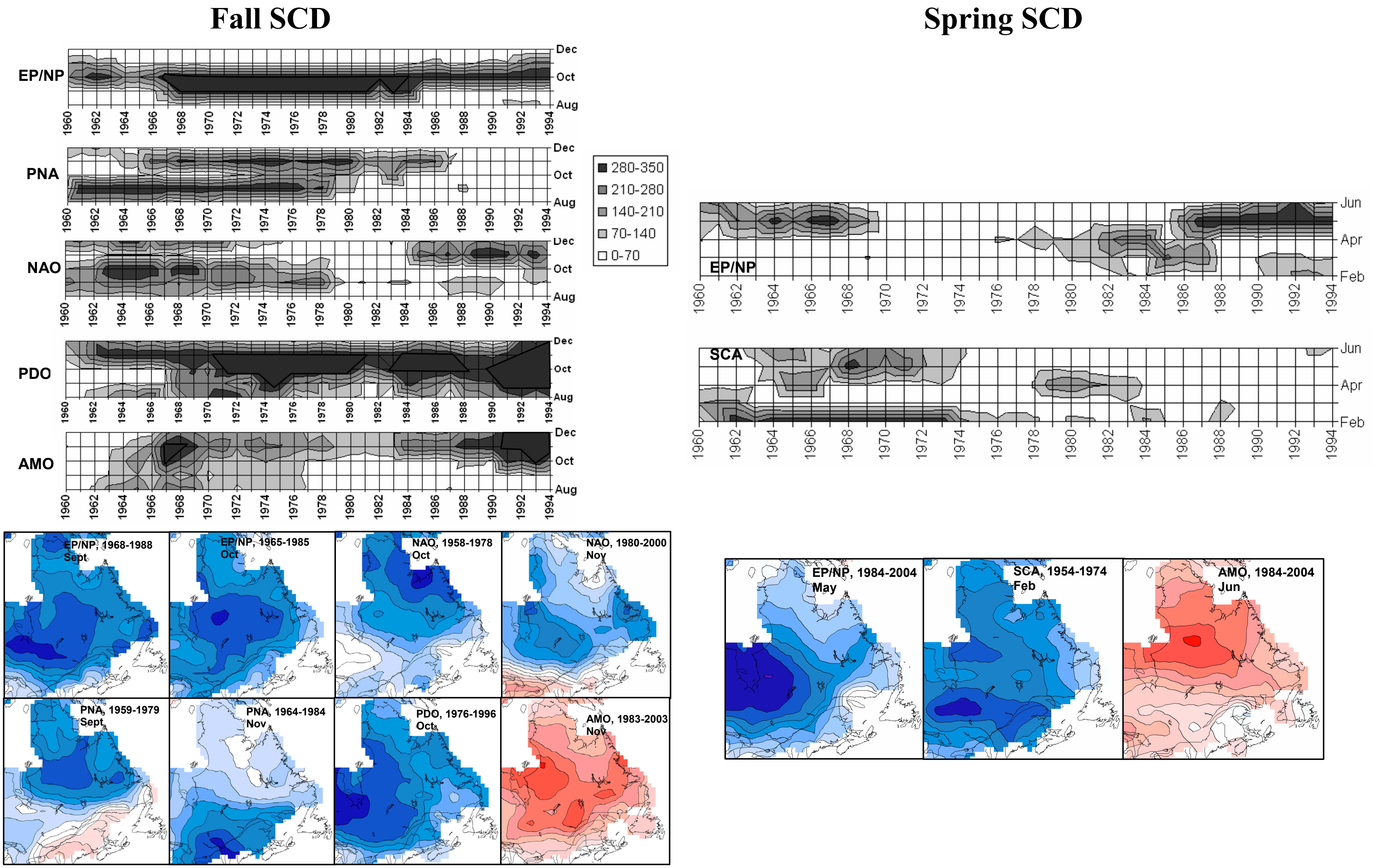


Figure 6. Same as Figure 5 for fall (left) and spring (right) snow cover duration versus monthly values of atmospheric circulation indices during each season. The upper panels show the temporal and seasonal variability in the number of grid points with locally significant correlation (values exceeding 280 are significant based on a bootstrapping analysis). The lower panels show the spatial correlation patterns for the 21-year period with the largest number of grid points with locally significant correlations. The AMO spring results did not meet the 10 window criterion but are included for comparison with the EP/NP results.