Surface Temperature and Humidity Trends in Canada for 1953–2005

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ABSTRACT

Annual and seasonal trends in temperature, dewpoint, relative humidity, and specific humidity are presented for the period 1953–2005. The analysis uses hourly observations from 75 climatological stations across Canada. Data were examined for discontinuities due to changes in instruments and observing practice. It was found that the main discontinuity corresponds to the replacement of the psychrometer by the dewcel in the early 1970s, which created an artificial negative step in relative humidity and dewpoint at many locations. After accounting for these discontinuities, the results of trend analysis show evidence of an increase in air moisture content associated with the warming observed in the country. During winter and spring, the significant warming in the western and southern regions is accompanied by an increase in dewpoint and specific humidity and by a decrease in relative humidity; in summer, warming is observed in the southeast and it is associated with significant positive trends in dewpoint and specific humidity. Although there is no strong evidence of a greater nighttime warming in Canada over 1953–2005, the nighttime dewpoint and specific humidity trends are slightly larger than the daytime trends, especially during the spring and summer.

1. Introduction

An important feedback for the warming predicted by climate models due to an increase in greenhouse gas concentration is an increase in atmospheric water vapor (Philipona et al. 2005). As temperatures rise, the atmosphere's capacity to hold water increases. Knowledge about changes in water vapor in the upper troposphere and lower stratosphere is important because it can result in strong alterations in radiative forcing. Changes in the surface air temperature and humidity are also important because they can have serious impacts on the hydrological cycle and the surface energy budget. Therefore, accurate quantifications of recent changes in air moisture become essential to understanding climate variations and to reducing uncertainties about future climate changes due to greenhouse gas emissions.

Previous studies of climate trends in Canada have shown a significant warming in the west and south accompanied by a cooling in the northeast over 1950–98 (Zhang et al. 2000). This pattern was mostly evident in winter and spring. For the country as a whole, the annual mean temperature has increased by about 1°C during the second half of the twentieth century. During the same period, the total precipitation has increased across the country in every season except for significant decreasing trends observed in the west during winter. The increase in precipitation was accompanied by a decrease in the ratio of snowfall to total precipitation, which is mostly evident in the west and south during the spring. These results were based on the homogenized daily temperature (Vincent and Gullett 1999) and the adjusted daily precipitation (Mekis and Hogg 1999), which are datasets adjusted for changes in instruments and observing practices. In this study, trends in tem-

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perature and humidity are closely examined in order to determine if there are any significant changes in the moisture content of the surface layer associated with the warming observed in Canada.

Trends in surface humidity and temperature have been analyzed for other regions of the globe. For the United States, specific humidity and dewpoint have significantly increased during 1961–95 over most of the country in the winter, spring, and summer (Gaffen and Ross 1999). Nighttime humidity trends were usually larger than daytime trends. Relative humidity showed smaller positive trends, especially during the winter and spring. Overall, the trends in humidity were consistent with the positive trends observed in temperature. Similar results were also observed over China for the longer period of 1951–94 (Wang and Gaffen 2001). The data showed some evidence of significant positive trends in both temperature and atmospheric moisture content, and trends were larger at nighttime and during the winter; however, negative trends in relative humidity associated with the warming were also found in China.

Radiosonde observations of water vapor above the surface have been examined for evidence of change. Ross and Elliott (2001) analyzed the surface–500-hPa water vapor trends over the Northern Hemisphere for the period 1973–95. Significant increases in water vapor were identified in North America with negative trends in northeast Canada. Significant increases in water vapor were also found over China and the Pacific Islands. The remainder of Eurasia showed a mixture of positive and negative trends with a contiguous region of decrease over Europe and western Russia.

The objective of this study is to analyze the annual and seasonal trends in surface air temperature, dewpoint, relative humidity, and specific humidity over Canada for the period 1953–2005. The previous studies of the Canadian climate trends were based on daily observations while the current study used hourly values. Because climate observations can contain artificial biases due to changes in instruments and observing procedures, a complete homogeneity assessment was first performed and adjustments were applied when necessary. The data and methodologies are presented in section 2. They are followed by the trend results in section 3. Section 4 contains a discussion and the conclusions of the paper.

2. Data and analysis

a. Description

Dewpoint temperature is a measure of the amount of moisture (water vapor) in the air. It is the temperature to which air must be cooled at constant pressure until the air is saturated with respect to liquid water (Hess 1959). When the dewpoint is high, the moisture content of the air is also high. When the dewpoint is very close to the air temperature, the relative humidity is high. Locations with high relative humidity indicate that the air is almost saturated, and clouds and precipitation are therefore quite possible. The specific humidity is defined as the ratio of the mass of water vapor to the mass of air containing the water vapor (Hess 1959).

Hourly values of temperature, dewpoint, and relative humidity were directly retrieved from the National Climate Data Archive of Environment Canada for the period 1953–2005 (53 yr). Hourly observations first began at airports in the late 1940s and early 1950s but have been archived in digital form only from 1953. Some Arctic stations became operational in the late 1950s. The data were checked for outliers: very few temperature and relative humidity observations were outside the intervals of −55° to 40°C and 0% to 100%, respectively. At most stations, the observations were made every hour, for a total of 24 observations per day; however, they were done only every third hour at some northern stations in the early 1950s. Most stations had less than 1% missing hourly values over 1953–2005 and there was less than 5% missing values for Arctic stations. Figure 1 shows the locations of the 75 stations used in this study.

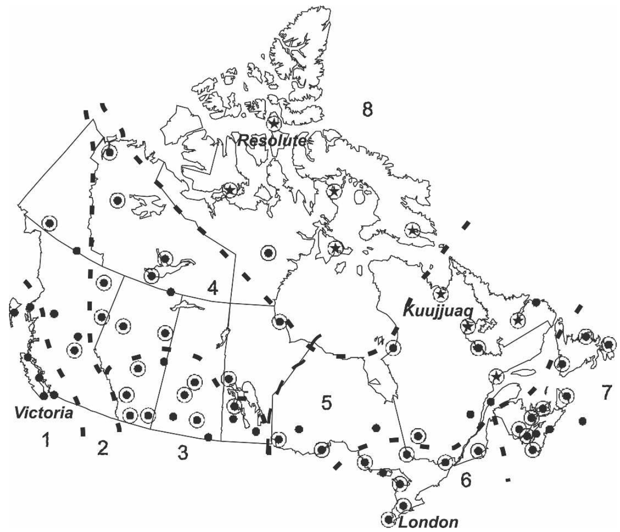

FIG. 1. Locations of the 75 stations. Outer circles indicate that the relative humidity data were adjusted while the stars indicate that the dewpoint data were adjusted. The labeled stations are mentioned in the text. Canada is divided into eight climatological regions: 1, Pacific; 2, cordillera; 3, prairies; 4, western boreal forests; 5, eastern boreal forests; 6, Great Lakes and St. Lawrence; 7, Atlantic; and 8, Arctic.

Different measurements systems have been employed to obtain the humidity values. In the 1950s and 1960s, dewpoint and relative humidity were determined using a psychrometer consisting of wet- and dry-bulb thermometers mounted in a Stevenson screen. In the early 1970s, the psychrometer was replaced by the dewcel at many stations (van Wijngaarden and Vincent 2005). In addition, a change from the imperial to the metric system was applied to the National Climate Data Archive in 1977. Dry- and wet-bulb temperature observations were recorded with a resolution of 0.1°F prior to 1977 while dewpoint temperatures were recorded to the nearest degree Fahrenheit because they were determined from psychrometric tables. In the digital archive, all temperatures have been converted to the Celsius scale. Commencing in 1977, they were measured and recorded with a 0.1°C resolution. Relative humidity has always been recorded with a resolution of 1%.

In this study, the specific humidity was calculated from the dewpoint and station pressure values. The station pressure was also retrieved from the National Climate Data Archive. First, the saturation water vapor pressure e was calculated using the Goff–Gratch formula (Goff and Gratch 1946; Murray 1967; List 2000):

$$\begin{aligned}\log_{10}e = &-7.902\,98\left(\frac{T_s}{T} - 1\right) + 5.028\,08\log_{10}\left(\frac{T_s}{T}\right)\\ &- 1.3816 \times 10^{-7}\{10^{11.344[1-(T/T_s)]} - 1\}\\ &+ 8.1328 \times 10^{-3}\{10^{-3.49149[(T_s/T)-1]} - 1\}\\ &+ \log_{10}e_{\mathrm{ws}}, \end{aligned} \tag{1}$$

where T is the hourly dewpoint (in kelvins), $T_s = 373.16$ K, and $e_{\mathrm{ws}} = 1013.246$ for the vapor pressure in millibars (hPa). Then, the specific humidity q was computed as

$$q = \frac{0.622e}{p - 0.378e}, \tag{2}$$

where p is the hourly station pressure (hPa). The value q was further multiplied by 1000 to obtain the units of grams per kilogram.

Annual and seasonal mean temperature, dewpoint, relative humidity, and specific humidity were computed at each station separately. The daily averages were calculated if at least eight hourly values were present during the day. This rule was used to accommodate the few northern stations that had observations taken only every 3 h in the early 1950s. The monthly values were the averages of the daily values when fewer than 8 days were missing during the month, and annual and seasonal means were computed if all months were present. The seasons were defined as follows: winter (December of the previous year to February), spring (March to May), summer (June to August), and fall (September to November). The annual average was obtained from the 12 months beginning in January and ending in December.

b. Homogeneity

At each station, annual and seasonal time series were examined for discontinuities due to changes in instruments and observing practices. A statistical procedure based on regression models was used to identify steps in each time series. A first model was applied to the data:

$$y_t = a_1 + b_1 t + e_t, \tag{3}$$

where y_t is the annual or seasonal values of the tested station, t represents the time (given in yr), and e_i is the residuals. This model was compared to a second model describing a potential step:

$$y_t = a_2 + b_2 t + c_2 I_t + e_t, \tag{4}$$

where I was equal to 1 for $t \geq p$ and to zero otherwise. Because the year of change (or changepoint p) was unknown, Eq. (4) was applied for $p = 4, \ldots, n - 3$, where n is the total number of years. The value of p providing the minimum residual sum of squares was retained as the most probable year with a potential step (Vincent 1998). The $F_{\max}$ statistic was then used to compare both models and to determine whether the second model substantially improved the fit (Wang 2003). This procedure was used for detecting discontinuities in annual and seasonal series. Their potential causes were retrieved from the station history files when possible.

The homogeneity results showed that very few stations had a significant step detected in the temperature time series over 1953–2005. The changepoint sometimes corresponded to a very cold or very warm year. No changes in instrumentation, observing procedure, or exposure were associated with the identified steps so it was concluded that it was not necessary to adjust the temperature series.

For relative humidity, a significant step was frequently detected near the date of the introduction of the dewcel. A recent study of the discontinuities in surface relative humidity in Canada has shown that the replacement of the psychrometer by the dewcel has often created an artificial negative step in the datasets, mainly for stations experiencing very cold temperature (van Wijngaarden and Vincent 2005). Many dewcels were installed in the early 1970s although some were installed as late as the 1980s. It should be noted that it is very difficult to make accurate wet-bulb measurements at very cold temperatures. It is suspected that the psychrometric measurements at cold temperatures are positively biased with respect to the wet-bulb values determined by the dewcel. A second smaller positive step was detected in the beginning of the 1990s at a few stations. The date corresponded to a change in the observing agency (from the Atmospheric Environment Service to Transport Canada) and to the installation of a remote observing system. The physical cause of this step is not yet well understood and requires further attention.

Only a few stations had significant steps identified in the winter mean dewpoint time series. These steps were also detected near the date of the introduction of the dewcel. The wet- and dry-bulb thermometers were removed when the temperature fell within 2°C of the freezing point of mercury (approximately −39°C). The air temperature was then measured using the alcohol minimum temperature thermometer (Environment Canada 1977). If the wet-bulb measurements are missing at very cold temperatures, the monthly mean dewpoint is biased warm with respect to the true mean. Hence, it is plausible that the introduction of the dewcel may have improved the measurement of dewpoint at very low temperatures but caused a downward step. The stations affected by the dewpoint steps are mostly located in the northeast.

Finally, very few significant steps were detected in the specific humidity time series. The main problems identified in the relative humidity and dewpoint took place in cold temperatures, when the specific humidity values are very low and do not vary much. It was concluded that it was not necessary to adjust specific humidity series.

c. Adjustments

Both relative humidity and dewpoint needed adjustment at several locations. The dewcel installation dates and starting dates for Transport Canada were directly retrieved from the station history files. The annual and seasonal adjustments were obtained using a regression model and the time series of a neighbor (or far neighbor in the north). The following regression model was applied (Vincent et al. 2002):

$$y_t = a_3 + b_3 x_t + c_3 I_t + e_t, \qquad (5)$$

where y_t was the tested station, x_t the neighbor, and $I = 1$ for $t \geq p$ and zero otherwise, with p being the known date of change. The parameter c_3 represents the magnitude of the step (the adjustment) and the t test was used to establish if it was statistically different from zero at the 5% significance level.

It was crucial to select a neighboring station with a dewcel installation date different from the tested site. In addition, periods for computing the adjustments were chosen such that a potential discontinuity of a neighbor would not interfere with the discontinuity of the tested site. Adjustments were obtained for annual and seasonal values separately. Each time series was divided by one or two steps and adjustments were applied to bring each segment into agreement with the most recent part of the series. For the relative humidity, the adjustments were always larger in the winter than the summer. For example, the relative humidity adjustments for data before the introduction of the dewcel for the station at Kuujjuaq, Quebec, were −8.0%, −7.1%, −2.8%, and −3.3% for winter, spring, summer, and fall, respectively (Fig. 2). For dewpoint, the adjustments were significant only during the winter. In total, the relative humidity was adjusted at 52 stations for the introduction of the dewcel (including 8 stations for the change in agency also) and the dewpoint was adjusted at only 9 stations for the dewcel. The stations with adjustments are indicated in Fig. 1.

d. Trend computation

Annual and seasonal trends were analyzed using a nonparametric method based on a Kendall's tau slope estimate (Sen 1968). This method is robust to outliers and does not assume an underlying probability distribution of the data. The slope estimate is the median of the slopes connecting each pair of points in the series. Serial correlation is often present in climatological data and false detection of significant trends can be greater than the specified significance level. Therefore, a procedure was applied to test the trend's significance, taking into account the first lag autocorrelation, when present. This procedure has been used to compute trends in other climatological datasets (e.g., Zhang et al. 2000; Vincent and Mekis 2006). Details on the trends estimation and significance can be found in Wang and Swail (2001). In the current study, the trends were computed at individual stations for the period 1953–2005 only if more than 90% of the values were present. Their statistical significance was assessed at the 5% significance level.

e. National and regional series

It is of interest to produce a single time series to represent the climate variations of a region or a country in order to summarize the changes observed over a geographic area. However, it can be difficult to create such a series for a vast country such as Canada because it contains different climate regimes. In addition, the

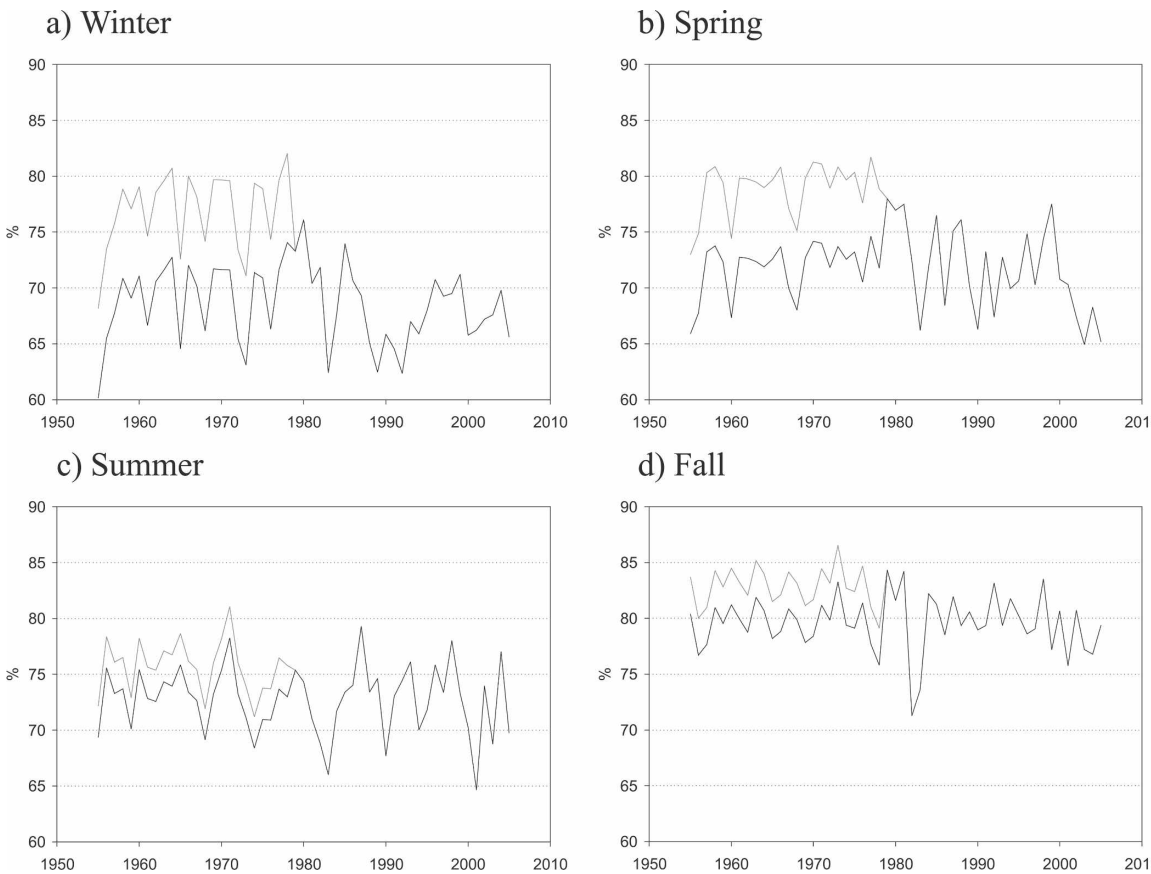

FIG. 2. Original seasonal mean relative humidity (gray) and adjusted values (black) for Kuujjuaq for 1953–2005: (a) winter, (b) spring, (c) summer, and (d) fall.

station density is sparse in the north and the data do not necessarily cover the entire period of analysis. In the current study, the trends in temperature, dewpoint, relative humidity, and specific humidity are calculated for eight different climatic regions and for the country as a whole. Climate and physiographic characteristics were the key components in defining eight climatic regions (based on Hare and Thomas 1974). Departures from the 1971–2000 normals were first calculated at individual stations and then they were averaged over each region or the nation. Because there are more stations with missing values in the early years, the regional and national series were computed for the 1955–2005 period. The eight climatic regions are shown in Fig. 1.

f. Nighttime versus daytime

Seasonal trends in nighttime and daytime temperature, dewpoint, relative humidity, and specific humidity were compared over the eight climatic regions. The nighttime value was the average of the six hourly observations from 0200 to 0700 local standard time (LST) while the daytime value was the average from 1400 to 1900 LST. These intervals correspond to when the daily minimum and maximum temperatures frequently occur. As mentioned previously, the monthly averages were calculated when fewer than 8 days were missing during the month and the seasonal values were computed if all months were present. The seasonal nighttime and daytime relative humidity and dewpoint series were adjusted separately using the procedure described in section 2c. Overall, it was found that the adjustments for the nighttime and daytime series were similar to those computed for the full day and adjustments were applied for the same stations.

3. Variations and trends

Temperature and relative humidity in Canada have strong diurnal variations. For example, on the west and east coasts, the summer daily temperature can change from about 10°C at night to 20°C in the afternoon while the relative humidity can vary from 90% at night to

TABLE 1. Seasonal averages over 1971–2000 for three stations.

Station	Season	Temp (°C)	Dewpoint (°C)	Relative humidity (%)	Specific humidity (g kg^{-1})
Victoria	Winter	4.3	1.9	85.1	4.6
	Spring	9.1	4.6	75.4	5.5
	Summer	15.8	10.5	72.8	8.0
	Fall	10.0	6.8	82.3	6.4
Resolute	Winter	−31.6	−35.8	65.1	0.2
	Spring	−21.6	−24.9	71.6	0.8
	Summer	1.9	-0.2	86.6	3.9
	Fall	−14.2	−16.8	80.7	1.4
London	Winter	−4.5	−7.3	81.2	2.6
	Spring	6.5	1.2	71.7	4.9
	Summer	19.5	14.3	74.2	10.9
	Fall	9.3	5.7	79.7	6.5

70% in the afternoon. The variations are more pronounced in the continental interior where, for example, the summer daily temperature varies from 10°C at night to 25°C in the afternoon while the relative humidity can vary from 80% at night to 40% in the afternoon. In the north, the diurnal variations are much smaller and the summer daily temperature and relative humidity can change from 0° to 5°C and from 85% to 80%, from night to afternoon, respectively. These variations are less pronounced during winter. There is little evidence of diurnal patterns in the dewpoint and specific humidity.

Considerable seasonal variations were observed in these four climate elements (Table 1). For Victoria, British Columbia, on the west coast, the seasonal mean temperature varies from 4.3°C in the winter to 15.8°C in the summer. The temperature range is greater in the interior and north. For example, it varies from −4.5° to 19.5°C for London, Ontario, and from −31.6° to 1.9°C for Resolute, Nunavut. The dewpoint and specific humidity also follow a seasonal pattern: for example, the dewpoint at London varies from −7.3° to 14.3°C and its specific humidity ranges from 2.6 to 10.9 g kg^{-1} from winter to summer, respectively. In contrast, the relative humidity is often lower during the summer than the winter, for example, 72.8% and 85.1% for summer and winter, respectively, in Victoria. However, the maximum relative humidity occurs in the summer for the Arctic stations, when snow and ice melt and open water is readily available for local evaporation.

a. Trends at individual stations

Trends in seasonal mean temperature are presented in Fig. 3. Overall, there is a significant warming in Canada, which is largest in winter and spring. During the winter, the warming is mainly observed in the west and south, and many stations show a temperature increase of 2.5°–4.0°C over 1953–2005, whereas some stations in the northeast have decreasing trends but these are not statistically significant. A lesser but significant warming is observed in western and southern Canada during the spring with many stations indicating significant warming of 1.5°–2.5°C over the 53 yr. During the summer, the temperature has generally increased across the country and some stations show a significant increase of 0.5°–1.5°C, mainly in the east and extreme west. However, some nonsignificant negative trends are also observed in the southern Canadian prairies. Finally, the temperature has increased slightly during the fall with a few stations showing significant increases in the northeast.

Some increase in the surface dewpoint is associated with the warming observed in Canada (Fig. 4). During the winter, nonsignificant positive trends in dewpoint correspond to the strong warming observed in the west and south. In contrast, where temperatures are cooling in the northeast, a decrease in dewpoint is observed with some stations showing significant trends of −1.5° to −2.5°C over 1953–2005. In the spring, there is a mixture of positive and negative trends and overall there are no significant changes in the dewpoint. During the summer, several stations in the southeast show a significant increase in the dewpoint of 0.5°–1.5°C over the past 53 yr, which also corresponds to the surface warming. There is no evidence of changes in the dewpoint during the fall with the exception of a few stations in the northeast with positive trends.

Figure 5 shows the trends in the seasonal mean relative humidity. In general, there are no strong corresponding patterns between the temperature and relative humidity trends. During the winter and spring, it seems that there is a decrease in relative humidity associated with the warming observed in the west and south. Some stations show a significant decrease of 2%–4% over the past 53 yr. In the summer, nonsignificant positive trends correspond to the warming in the southeast, and in the fall, some stations in the northeast show significant positive trends of 3%–5% associated with the observed warming.

The trends identified in specific humidity (Fig. 6) are similar to those observed in dewpoint. During the winter, increases in specific humidity correspond to the strong warming observed in the west and south with some stations showing a significant increase of 0.3–0.4 g kg^{-1} for 1953–2005. A decrease in specific humidity corresponds to the cooling observed in the northeast where several stations indicate a significant decrease of

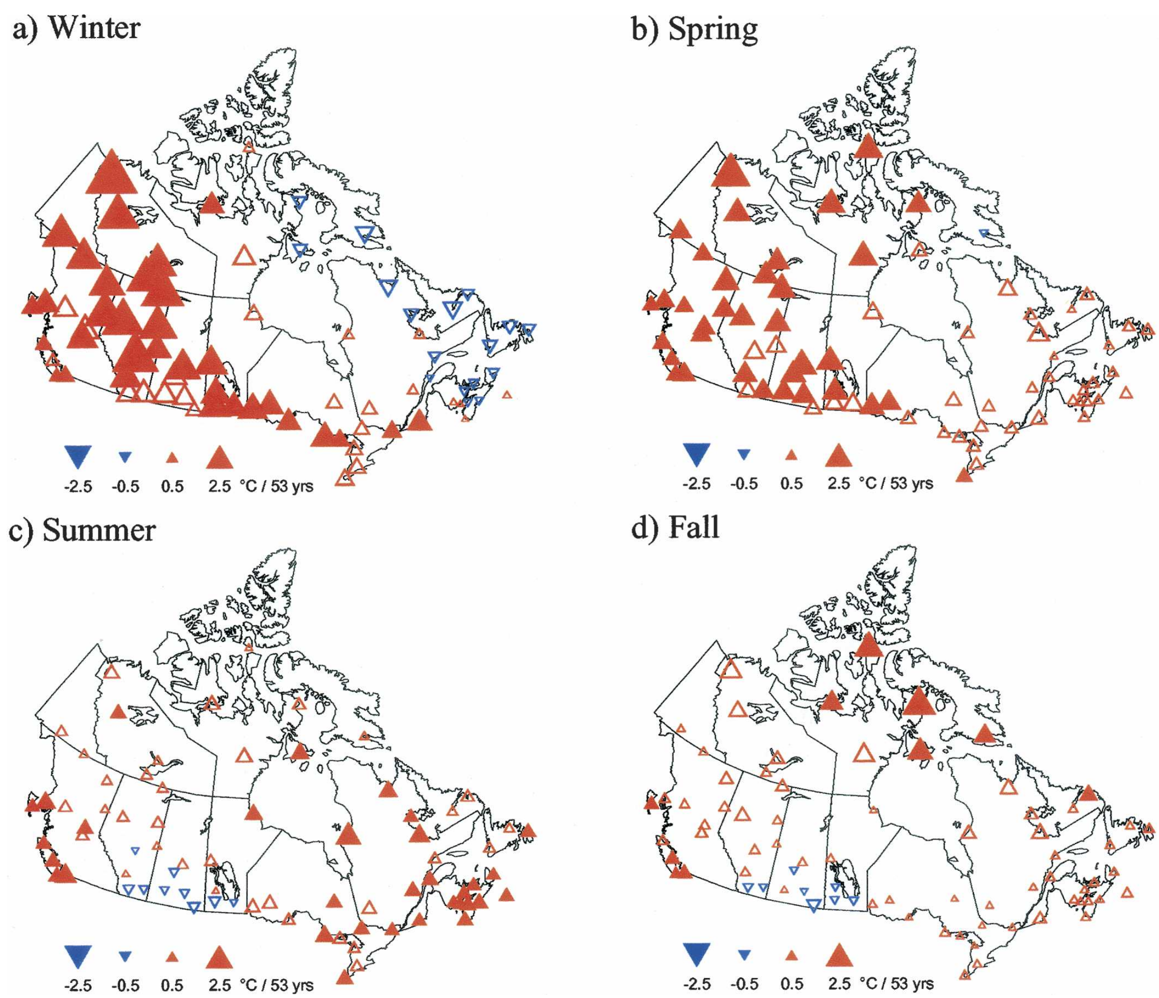

FIG. 3. Trends in seasonal mean temperature (°C) for 1953–2005: (a) winter, (b) spring, (c) summer, and (d) fall. Upward- and downward-pointing triangles indicate positive and negative trends, respectively. Filled triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend.

0.3–0.4 g kg^{-1} over the 53 yr. The spring shows several stations with increasing trends in specific humidity although most of the trends are not statistically significant. The most important change in specific humidity is observed during the summer where many stations in the southeast indicate a significant increase in air moisture content of about 0.5–0.7 g kg^{-1} over the 53 yr. Significant positive trends were also observed in the dewpoint in this area but to a lesser extent. Finally, there are no strong patterns in the fall with the exception of a few stations in the northeast showing significant positive trends.

b. National trends

The anomaly time series for the whole nation were examined for the period 1955–2005 (Fig. 7). The data clearly indicate that temperatures have warmed in the whole country since 1955, with the coolest and warmest years being 1972 and 1998, respectively. The dewpoint time series shows a similar temporal pattern although it seems that the dewpoint is a little high during the period prior to 1971 compared to the temperature. The dewpoint was adjusted at only nine stations and mostly in the winter. The impact of the adjustments on the dewpoint is not as evident on the national time series as opposed to the relative humidity. Examining the original and adjusted relative humidity, it becomes obvious that it was crucial to adjust the data prior to 1971 due to the introduction of the dewcel. Several stations were also adjusted over the 1972–92 interval for the change in observing agency. The temporal variations presented by the specific humidity are similar to those observed in

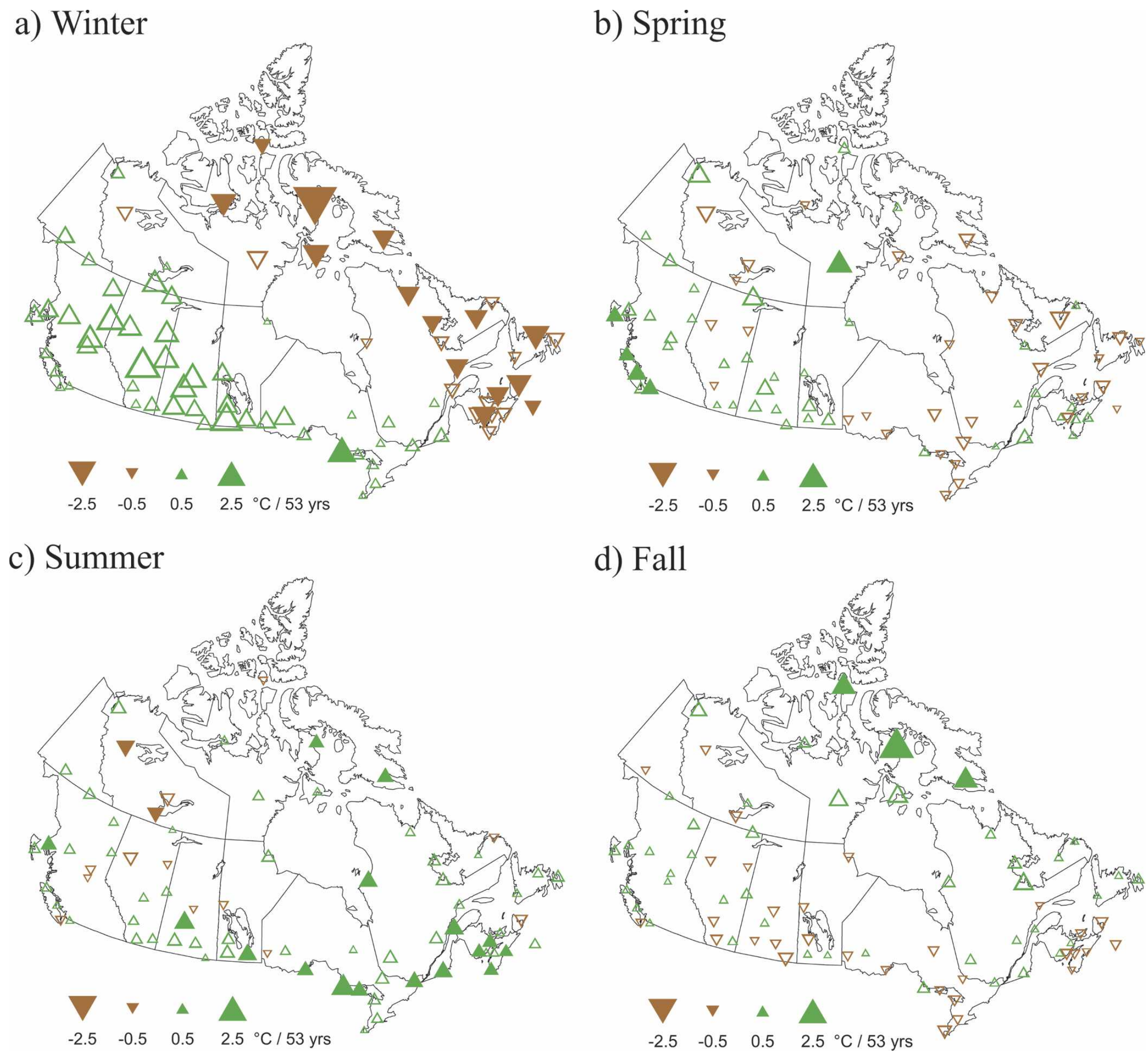

Fig. 4. Same as Fig. 3, but for dewpoint.

the dewpoint. The coolest and warmest years correspond to the years with the least and greatest amounts of air moisture content, respectively.

Overall, the annual mean temperature in Canada has increased by 1.2°C over 1955–2005 (Table 2). The warming corresponds to a nonsignificant increase in dewpoint of 0.4°C, to a nonsignificant decrease in relative humidity of 0.6%, and to a significant increase in specific humidity of 0.2 g kg^{-1} over the same period. The seasonal trends for the nation indicate that the warming is greater in the winter with an increase of 1.6°C over the 51 yr. The warming is less in the spring and much smaller during the summer and fall showing increases of 1.4°, 0.7°, and 0.8°C, respectively, over the 51 yr. Corresponding to this, the national trends show no significant changes in air moisture content for the country as a whole with the exception of a significant increase in the dewpoint and specific humidity of 0.5°C and 0.3 g kg^{-1}, respectively, in the summer. The relative humidity has decreased in every season with the greatest and significant decrease of 1.8% during the spring.

c. Regional trends

The 1955–2005 seasonal time series were closely examined for every region (Fig. 8). During the winter, the temperature has significantly increased in the four western regions: the Pacific, cordillera, prairies, and western boreal forests (Fig. 1). It is important to notice that a strong warming of 4.0°C is observed in the western boreal forests over the 51 yr. Corresponding to the winter warming in western Canada is a nonsignificant

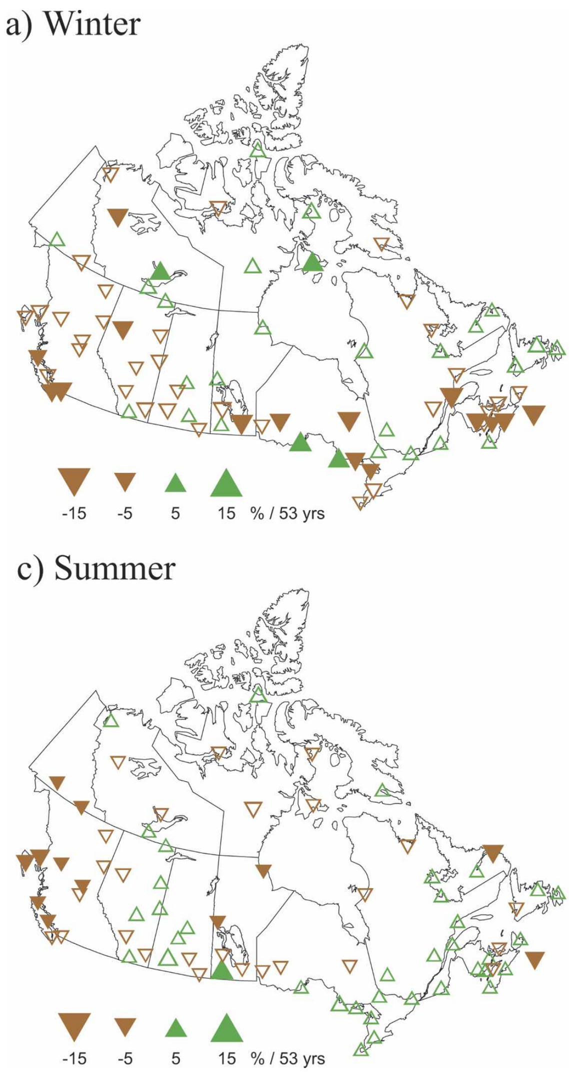

FIG. 5. Same as Fig. 3, but for relative humidity.

increase in dewpoint for the four regions, a decrease in relative humidity (significant in the Pacific and prairies), and an increase in specific humidity (significant in the western boreal forests). Therefore, it appears that the strong winter warming observed in the west has increased the capacity of the air to hold more moisture to a greater extent than any measurable increase in atmospheric moisture, resulting in a decrease in relative humidity. Likewise, there is a significant warming in the Great Lakes and St. Lawrence region associated with an increase in air moisture and decrease in relative humidity. Conversely, the winter temperature has cooled in the Atlantic and northeastern Arctic region, which has been accompanied by a decrease in air moisture content over these areas (statistically significant in the Arctic region).

During the spring, the temperature has increased in the four western regions but to a lesser extent than in winter. The warming is associated with an increase in dewpoint and specific humidity (except for the western boreal forests), and a strong decrease in relative humidity. A smaller and nonsignificant warming continues toward the east and north but its relation with the air moisture content becomes less evident. In the summer, the warming is definitively smaller in every region but not necessarily nonsignificant. It corresponds to a small increase in air moisture that is particularly evident in the Great Lakes and St. Lawrence region. A small summer cooling trend is also observed in the prairies where there is an increase in relative humidity. During the fall (not shown), there are no significant regional trends with the exception of a small significant warming in the Pacific and Arctic related, respectively, to a decrease and an increase in relative humidity.

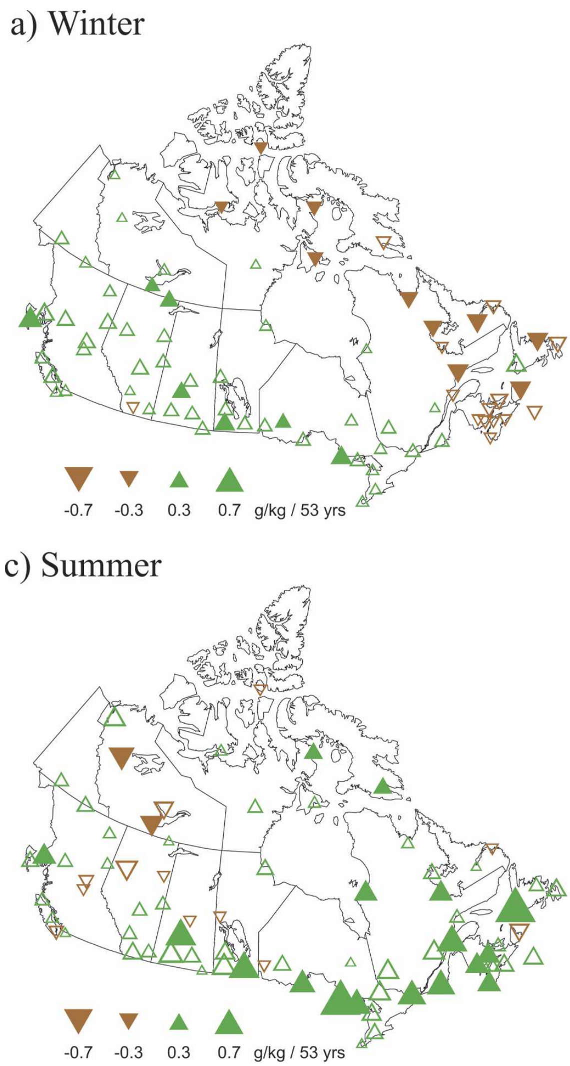

Fig. 6. Same as Fig. 3, but for specific humidity.

d. Nighttime versus daytime trends

Overall, there is no strong evidence that the warming observed in Canada is more pronounced in the nighttime than in the daytime temperature over the period 1955–2005. For example, the winter trends are slightly higher in the nighttime in only three regions: the cordillera, the eastern boreal forests, and the Great Lakes and St. Lawrence (Fig. 9). The same thing is observed in the other seasons (not shown) where the nighttime trends are greater than the daytime trends in only a few regions. This finding is in agreement with the results of Vincent and Mekis (2006) and Zhang et al. (2000), which suggest that no consistent changes were found in the diurnal temperature range in Canada over the second half of the century. For the dewpoint and specific humidity, the trends in Canada are slightly larger during the nighttime than daytime, particularly during the spring and summer (not shown). For relative humidity, significant negative trends are frequently detected when there is a strong warming in Canada and it appears that the daytime negative relative humidity trends have been of greater magnitude than the negative nighttime trends in most regions and every season.

4. Discussion and conclusions

It is essential to carefully examine the climate time series for discontinuities due to nonclimatic changes before analyzing the trends. In this study, the relative humidity was adjusted at 52 stations for the significant negative step due to the replacement of the psychrometer by the dewcel, which occurred mostly in the 1970s.

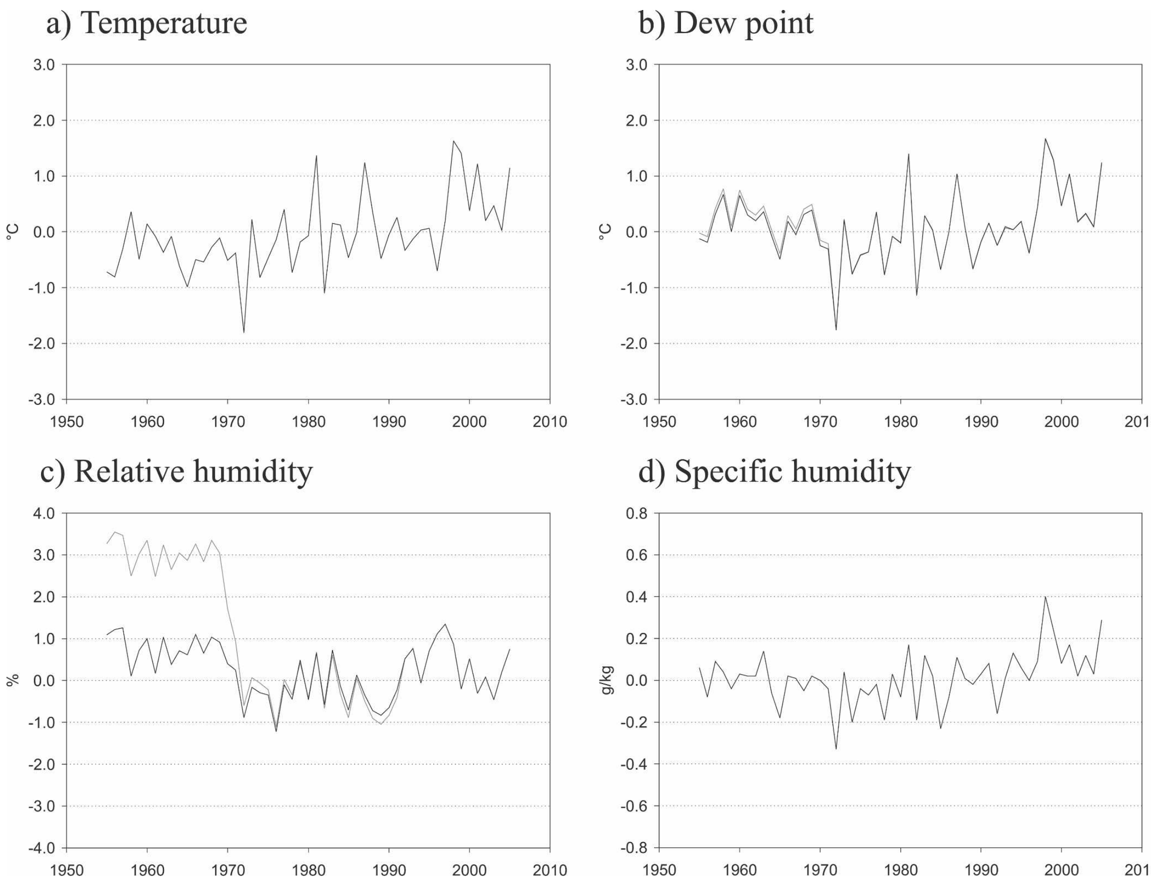

FIG. 7. National series for annual mean (a) temperature, (b) dewpoint (gray) and adjusted values (black), (c) relative humidity (gray) and adjusted values (black), and (d) specific humidity over 1955–2005.

Of these stations, eight were also adjusted for a positive step in the beginning in the 1990s due to the change in observing agency. Furthermore, the dewpoint time series was adjusted at nine stations for the introduction of the dewcel. For relative humidity, the unadjusted values would have indicated significant negative trends varying from −5% to −15% over 53 yr at most locations across the country during the winter and spring. With the adjustments, the annual national trend was reduced from −3.8% to −0.6% over the 51 yr. The adjustments for the dewpoint do not have as much impact on the annual national trends, but the unadjusted values would have indicated a significant decrease of −4.0° to −6.0°C over 1953–2005 for the stations in the northeast.

TABLE 2. Seasonal and annual national trends for 1955–2005. The numbers in boldface indicate the trends statistically significant at the 5% level.

Season	Temp (°C)	Dewpoint (°C)	Relative humidity (%)	Specific humidity (g kg^{-1})
Winter	**1.6**	0.4	−1.0	0.1
Spring	**1.4**	0.2	**−1.8**	0.1
Summer	**0.7**	**0.5**	−0.1	**0.3**
Fall	0.8	0.4	−0.1	0.1
Annual	**1.2**	0.4	−0.6	**0.2**

The statistical procedure based on regression models can provide only a rough estimate of the stations that need adjustment and of the magnitude of the adjustments. If more years are included in the homogeneity assessment or if different neighbors are used for the computation of the steps, the results could be slightly different. It is also possible that a small number of stations remain with undetected and unadjusted steps due to high noise and low signal. To obtain accurate adjustments, it is necessary to compare concurrent hourly observations from the dry-bulb–wet-bulb thermometers with the dewcel measurements over a period of time; however, such studies have not been done yet. In spite of this, it is asserted that the seasonal and annual trends presented in this study are closer to the real climate trends.

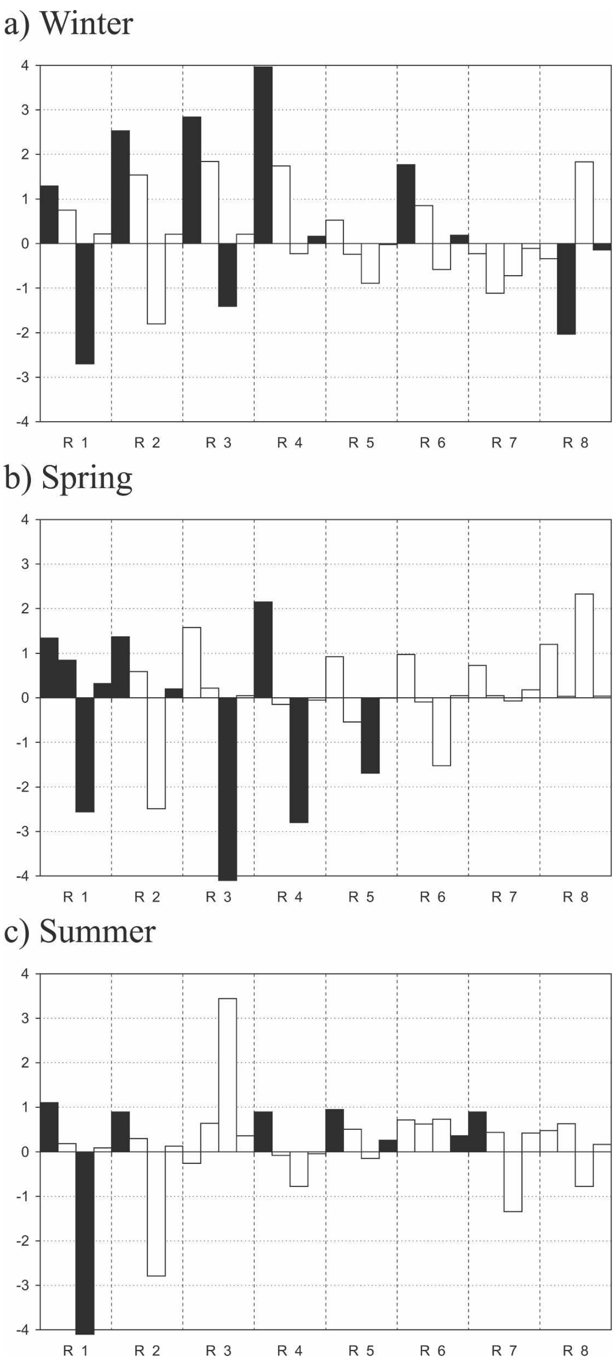

FIG. 8. Regional trends for (a) winter, (b) spring, and (c) summer over 1955–2005. For each region, the trends are given for temperature (°C), dewpoint (°C), relative humidity (%), and specific humidity (g kg^{-1}), respectively. Filled bars correspond to trends significant at the 5% level.

A significant warming was observed in the United States over 1961–95 during the winter, spring, and summer whereas the fall showed less significant warming in most regions (Gaffen and Ross 1999). The strongest temperature trends were detected in Alaska during the winter, which is consistent with the strong warming observed in the Canadian northwest. The comparison of nighttime and daytime trends in the United States has shown some tendency for a greater nighttime warming in winter and fall, whereas the results were mixed for spring and summer (Gaffen and Ross 1999). In Canada, there was no strong evidence for a greater nighttime increase over 1955–2005 with only a few regions having higher nighttime trends for some seasons. However, over the past century, the nighttime warming was more pronounced than the daytime warming (Vincent and Mekis 2006). The nighttime temperature was much cooler prior the 1940s and became warmer in the 1940s and 1950s. The cause of the sudden increase is uncertain but it could be due to the change in cloudiness (Henderson-Sellers 1989; Karl et al. 1993). A recent study of the maximum and minimum temperature trends for the globe has shown that land diurnal temperature ranges have stopped reducing over the past 20 yr (Vose et al. 2005).

The significant warming observed in Canada is frequently accompanied by a significant increase in air moisture content. During the winter, the warming in the west and south is associated with an increase in dewpoint and specific humidity. There is a small increase in air moisture content corresponding to the warming in the spring. The summer warming in the southeast is accompanied by a significant increase in dewpoint and specific humidity. It appears that the nighttime atmospheric moisture trends are slightly larger than the daytime trends, particularly in the spring and summer. These findings are in general agreement with the reported trends over the United States and China, which indicate that the dewpoint and specific humidity trends are associated with the upward temperature trends (Gaffen and Ross 1999; Wang and Gaffen 2001). However, the results also show that the warming in Canada is accompanied by a decrease in relative humidity in the winter and spring. Relative humidity trends in the United States do not show strong spatial consistency but suggest an increase in the same two seasons. In China, decreasing relative humidity trends often accompanied the warming observed over the country.

The trends in specific humidity over Canada are fairly consistent with the trends observed in the tropospheric column water vapor over the same area (Ross and Elliott 1996; Ross and Elliott 2001). For 1973–95, the annual trends of the surface–500-hPa precipitable water have generally increased over the country except for the northeast. Summer was the season with the most significant increase in precipitable water but some de-

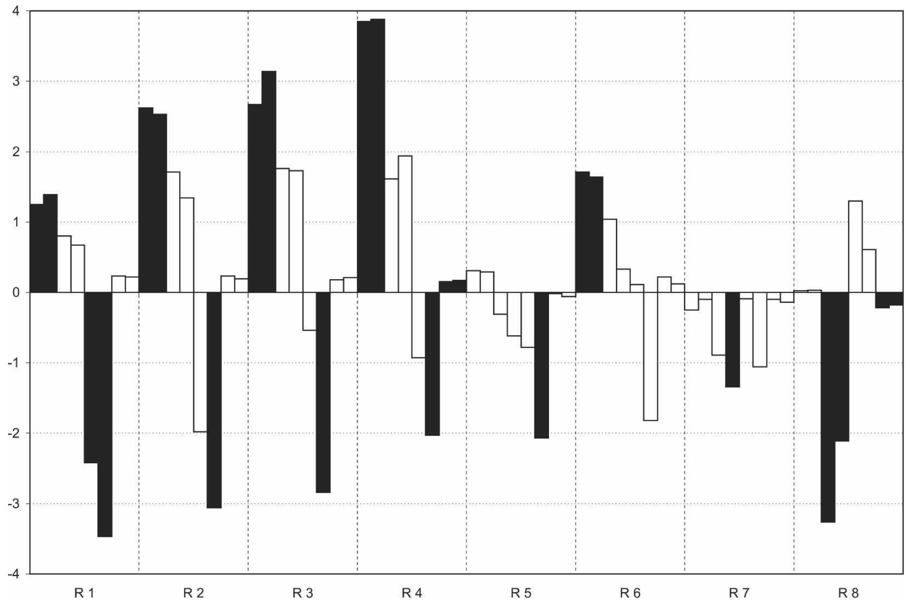

FIG. 9. Diurnal regional trends for winter over 1955–2005. For each region, the trends are given for nighttime and daytime temperature (°C), nighttime and daytime dewpoint (°C), nighttime and daytime relative humidity (%), and nighttime and daytime specific humidity (g kg^{-1}), respectively. Filled bars correspond to trends significant at the 5% level.

crease in precipitable water was observed over northern and eastern Canada during the winter and spring. An increase in the annual mean dewpoint was observed at the 700-hPa level while relative humidity trends were generally negative at the northernmost latitudes. The tropospheric humidity trends are also consistent with the trends observed in cloudiness over Canada for 1953–2002 (Milewska 2004). The results have shown that the number of hours when more than half of the sky dome was covered by clouds has significantly increased during the past 50 yr at numerous stations along the Canada–U.S. border and a few stations in western Canada.

In conclusion, the warming observed in Canada is generally accompanied by an increase in the moisture content of the surface layer during 1953–2005. Dewpoint and specific humidity trends are mainly positive in the west and south during the winter and spring, and significantly so in the southeast during the summer. Even if there is no evidence for a greater nighttime warming, the nighttime humidity has increased slightly more than the daytime humidity, particularly in the spring and summer. For Canada as a whole, the annual mean temperature has increased by 1.2°C over the past 53 yr, while the dewpoint and specific humidity have increased by 0.4°C and by 0.2 g kg^{-1} over the same period, respectively. The warming is also accompanied by a decrease in relative humidity, which is observed mostly in the winter and spring.

This study contributes toward a more accurate quantification of the recent trends in surface atmospheric moisture in Canada and helps to resolve some of the uncertainties associated with climate change. Future work will include the analysis of radiosonde temperature and humidity records over the country for a better assessment of the trends occurring in the troposphere.

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