Surface Water Vapor Pressure and Temperature Trends in North America during 1948–2010

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ABSTRACT

Over one-quarter billion hourly values of temperature and relative humidity observed at 309 stations located across North America during 1948–2010 were studied. The water vapor pressure was determined and seasonal averages were computed. Data were first examined for inhomogeneities using a statistical test to determine whether the data were fit better to a straight line or a straight line plus an abrupt step, which may arise from changes in instruments and/or procedure. Trends were then found for data not having discontinuities. Statistically significant warming trends affecting the Midwestern United States, Canadian prairies, and the western Arctic are evident in winter and to a lesser extent in spring while statistically significant increases in water vapor pressure occur primarily in summer for some stations in the eastern half of the United States. The temperature (water vapor pressure) trends averaged over all stations were 0.30 (0.07), 0.24 (0.06), 0.13 (0.11), 0.11 (0.07) °C decade^{-1} (hPa decade^{-1}) in the winter, spring, summer, and autumn seasons, respectively. The averages of these seasonal trends are 0.20°C decade^{-1} and 0.07 hPa decade^{-1}, which correspond to a specific humidity increase of 0.04 g kg^{-1} decade^{-1} and a relative humidity reduction of 0.5% decade^{-1}.

1. Introduction

A preponderance of evidence has accumulated over the last two decades showing that the global average temperature is increasing primarily as a result of increased greenhouse gas emissions (Solomon et al. 2007). The Clausius–Clapeyron equation shows that saturation vapor pressure increases exponentially with temperature. Hence, one expects atmospheric water vapor pressure to increase assuming relative humidity remains unchanged (Sherwood and Meyer 2006). This is important as water vapor is itself a greenhouse gas (Held and Soden 2000). It has been suggested that increased water vapor pressure may increase precipitation (Wentz et al. 2007) and affect storm intensity (Trenberth et al. 2005; Allen and Sodden 2008).

Two recent studies found a significant global increase in surface specific humidity that they attributed mainly to human influence. Willett et al. (2007, 2010) examined a homogenized gridded dataset of surface humidity for the period 1973–2003 that was principally derived from land and marine measurements of dewpoint temperature. The specific humidity q in units of 1-g water vapor per 1 kg of air is related to the water vapor pressure e in units of hPa using

$$q = \frac{0.622\,e}{1013} \times 1000, \qquad (1)$$

where 0.622 is the molecular weight ratio of water vapor to air, 1013 hPa is the atmospheric pressure at sea level and 1000 converts 1-kg water vapor to grams (Glickman 2000). Hence, the observed global mean surface specific humidity increase of 0.07 g kg^{-1} decade^{-1} corresponds to an increase in water vapor pressure of 0.11 hPa decade^{-1}. The increases in specific humidity were strongly correlated with temperature increases. Santer et al. (2007) examined data taken using a microwave satellite imager and found the total atmospheric moisture content over oceans has increased by 0.41 kg m^{-2} decade^{-1} during 1988–2006. Multiplying this by the acceleration due to gravity 9.8 m s^{-2} gives a corresponding water vapor pressure increase of 0.04 hPa decade^{-1}. Both studies compared the observations to predictions of various global climate models. Agreement was obtained when human-generated greenhouse gases were taken into account. A recent study (Simmons

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et al. 2010) examined monthly anomalies in surface air temperature and humidity and found a decrease in surface relative humidity during the 10 years prior to 2008 over low-latitude and midlatitude land areas while specific humidity was found to vary similarly over land and sea.

Increases in specific humidity have also been reported in studies that examined station data. These records exist for a much longer time than data collected using satellites. The advantage of plotting station trends on a map as opposed to using a gridded dataset is that one sees where on the earth there are few stations or even none at all. This facilitates judging the uncertainty of regional variation of climate change. Dai (2006) examined surface data taken at over 15 000 weather stations and ships to calculate specific and relative humidity from 1975 to 2004. Relative humidity increases of 0.5% to 2% decade^{-1} were found over the central and eastern United States, India, and western China. These increases were associated with an increase in temperature and specific humidity. Indeed, specific humidity increased by as much as 6% decade^{-1} over parts of Eurasia. The strong correlation between increasing specific humidity and temperature was found everywhere except for desert regions. Somewhat smaller increases in specific humidity were found by Wang and Gaffen (2001) who examined data collected once every 6 h at 196 stations in China for the period 1951–94. Winter and summer trends averaged over all stations for specific humidity were similar. However, winter had greater trends in some regions but summer had greater trends in other regions.

It is critical to examine data for inhomogeneities. These can occur because of changes in instruments, observation procedure, modification of the station site, and/or automation. Robinson (2000) examined hourly data for 178 stations located in the coterminous United States during 1951–90. The effect of inhomogeneities may have modified the dewpoint temperature trend by as much as 1°C over the 40-yr study. The average annual dewpoint was found to increase by 1°–2°C century^{-1}. A 1°C increase in dewpoint corresponds to a water vapor pressure increase of about 7%. Inhomogeneities were also present in a study that examined relative humidity trends in Canada. The replacement of the psychrometer by the dewcel resulted in a decrease of greater than 10% in winter relative humidity at many northern Canadian stations (Vincent 2005; Vincent et al. 2007).

This study examined hourly data at 309 stations located in Canada and the continental United States. These two countries have operated the world's largest networks of observation stations that were subject to periodic inspection to ensure proper maintenance and calibration of instruments. The stations include a number located in the Arctic where climate change effects should be most evident (Solomon et al. 2007; van Wijngaarden 2008). The time period of 1948–2010 includes several decades when satellite observations were not available. Data were first checked for inhomogeneities before trends were computed. The extended time period of this study facilitated testing whether the trends were statistically significant. Finally, the seasonal trends are plotted to show which regions of North America have been most strongly affected by climate change.

2. Data

Hourly records of temperature and relative humidity were retrieved for stations in the United States for the period 1948–2005 from the University Corporation for Atmospheric Research (http://dss.ucar.edu/datasets/ds470.0/). Data for the period 2005–10 were purchased from Speedwell Weather Corporation (www.speedwellweather.com). Checks were made that the data for the same U.S. station in 2005 agreed for the two datasets. Data for Canadian stations during 1953–2009 were downloaded from the National Climate Data and Information Archive of the Meteorological Service of Canada (Environment Canada 2009). Most American and Canadian stations were located at airports.

Data were measured using a variety of instruments (Robinson 2000). In the 1950s, relative humidity was found using a psychrometer to measure the difference between the wet and dry bulb thermometers. Tables of these temperatures, which were updated at various times, were used to determine the relative humidity (Environment Canada 1977). During the 1960s, the dewcel, which used a lithium chloride absorption sensor, was introduced in the United States. In Canada, this transition occurred in the early 1970s (van Wijngaarden and Vincent 2005). In the 1980s, the dewcel was replaced at American stations by an instrument that determined the humidity using a chilled mirror to detect dew and a thermistor to measure temperature. Automation systems were introduced in both Canada and the United States throughout the 1990s.

There is some evidence of discrepancies between the various instruments affecting temperature by as much as 0.7°C (Jones and Young 1995). The effect of the aforementioned changes on humidity is complex as well as uncertain (Robinson 2000). One study suggested that changes in site location are more significant (Elliott 1995). However, another study (Gaffen and Ross 1999) did not find that site moves led to systematic discontinuities in humidity. Unfortunately, the many changes to instruments and measurement procedure affecting each

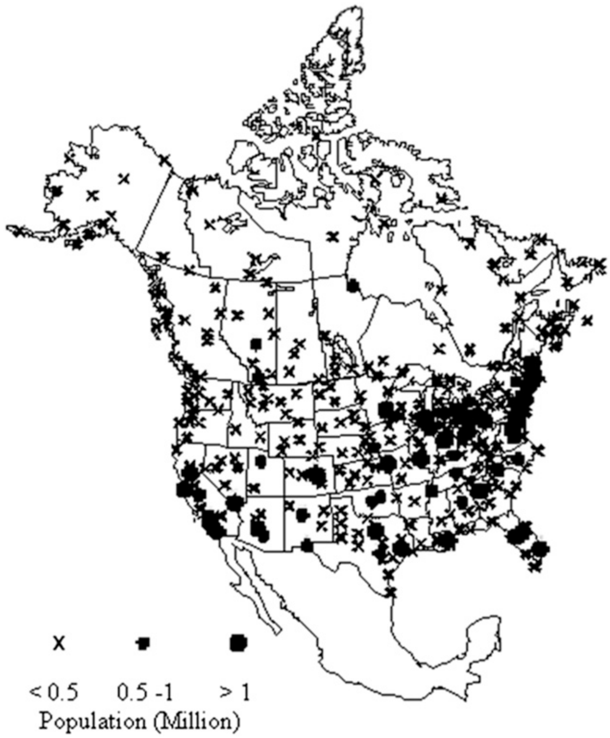

FIG. 1. Stations examined in this study.

station have not been well documented. Indeed, a recent study (Brown and DeGaetano 2009) tested for inhomogeneities in data collected at 10 stations during 1951–2006 by checking how similar the dewpoint temperature and minimum temperatures were when fog was observed. A large number of undocumented inhomogeneities were found. Therefore, it is essential for any trend analysis to critically examine the data for inhomogeneities.

Figure 1 shows the stations examined in this study. Each of these stations was chosen because at least 50% of all hourly observations of temperature and relative humidity were present. Most of the 235 American stations began operating in 1948. Data exists for 80% of all possible hours when averaged over the stations. In Canada, the digital archive begins in 1953. A number of Arctic stations opened later in the 1950s. The average of hourly data present for the 74 Canadian stations exceeds 95%.

Temperature was measured initially in degrees Fahrenheit and later in centigrade. Both American and Canadian datasets list temperature values in units of 0.1°C while relative humidity is given in units of 1%. The U.S. data prior to 1985 exists in a different format than for the subsequent period. Hence, separate files containing data for the periods before and after 1985 were combined for this analysis.

The archives first stored data in written form. Later, punch cards were used and in the 1960s the U.S. data was moved to magnetic tape. Sometimes, problems were encountered in converting data records to a new format. For example, a preliminary examination of the data found 13 stations that had the identical temperature recorded for every hour for periods of several weeks in 1996. These repeated data were treated as missing values.

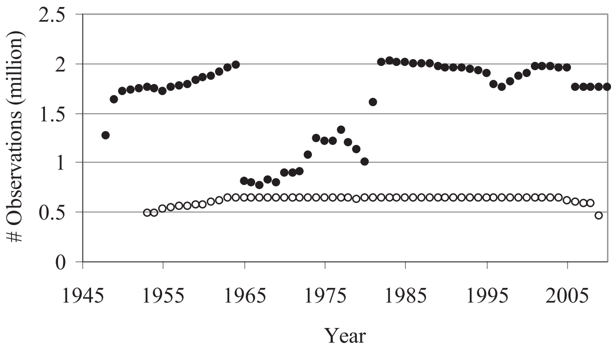

FIG. 2. Relative humidity data examined in this study. Solid points represent data from 235 U.S. stations while empty dots represent data recorded at 74 Canadian stations.

Figure 2 shows the number of hourly relative humidity observations made during 1948–2010. The corresponding graph for temperature observations is nearly indistinguishable. For the period, 1965–80, observations at U.S. stations were made typically once every 3 h. Some stations recorded data only during the day and were closed at night. This is important to consider when estimating trends because relative humidity is generally higher at night when temperatures are lower than during the day.

3. Methodology

The water vapor pressure was computed from the observed relative humidity and temperature as follows. First, the saturation water vapor pressure measured in hPa at a temperature T measured in degrees Celsius is given by (Environment Canada 1977)

$$e_s(T) = 6.112e^{17.62T/(243.12+T)}. \quad (2)$$

This formula is valid for temperatures between −45° and 60°C. Equation (2) yields values that agree to within a few parts in 10^3 with the Goff–Gratch vapor pressure formula (Goff and Gratch 1946; Murray 1967; List 2000). The vapor pressure of water is found by multiplying the saturation vapor pressure by the relative humidity RH or

$$e = \mathrm{RH} \times e_s. \quad (3)$$

The seasonal average of the data was found next. Seasons were defined as follows: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). The seasonal average was only computed if 1) observations existed for at least 30% of all hours and 2) observations existed for at least 25% of all hours in each 4-h period. Averages were also computed for the 4 different 6-h periods of the day: night (0100–0600), morning (0700–1200), afternoon (1300–1800), and evening (1900–2400).

Each seasonal-averaged time series was investigated for possible inhomogeneities (Dai et al. 2011; Wang et al. 2010) using two regression models provided that at least 40 years of seasonally averaged values were present (Vincent et al. 2007). Model 1 was first applied to the seasonal time series of each individual station by fitting the following equation to the data:

$$y_i = a_1 + b_1 t_i + e_i. \quad (4)$$

Here, y_i is the seasonal temperature or water vapor pressure for year t_i and e_i is the residual. The estimate of the slope is given by b_1. The statistical significance of the trends was assessed using the t test at the 5% level. Model 2 was applied to the seasonal time series to describe a potential step. It is given as

$$y_i = a_2 + b_2 t_i + c_2 I + e_i. \quad (5)$$

The estimate of the slope before and after the step is given by b_2. Here, c_2 is the step magnitude. The variable I takes the value 0 (1) before (after) the step year t_s.

Models 1 and 2 were compared using the following F statistic to determine which is a better fit to the data:

$$\mathrm{F} = (\mathrm{SSE}_1 - \mathrm{SSE}_2)/[\mathrm{SSE}_2/(n-3)]. \quad (6)$$

SSE_1 and SSE_2 are the sums of squared errors for models 1 and 2, respectively, and n is the number of data points. It was concluded that model 2 better fit the data if the F statistic exceeded the 95th percentile of the F distribution with 1 and $n - 3$ degrees of freedom, and model 1 was accepted otherwise (Neter et al. 1985; Wang 2003, 2008; Wang et al. 2010).

It should be noted that the program used the same criteria for step detection regardless of when the step occurred. In principle, steps occurring midway in the time series are more readily detectable than ones that exist near the beginning or end of the time series. For this reason, the program only tested for the existence of a step that occurred during the period beginning 5 years after the start of the data and 5 years before the end of the time series. For example, a station having data for the period 1948–2010 was only searched for steps occurring after 1953 and before 2006. The results did not find steps to be congregated near either of those dates as is discussed in the next section.

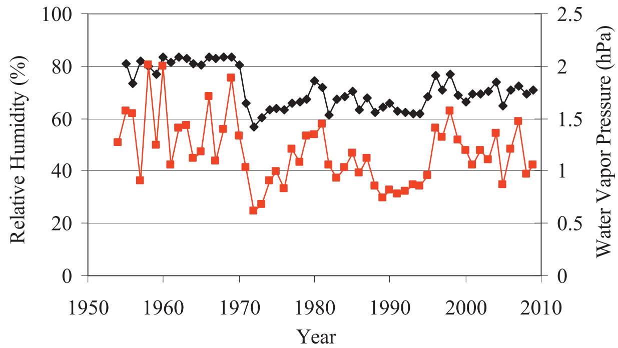

FIG. 3. Discontinuity of winter data for Schefferville, Quebec. Black dots denote relative humidity while red dots represent the water vapor pressure.

The residuals of each time series fitted to Model 1 were also investigated for autocorrelation effects (Wang 2008) by computing its correlogram. Nearly all time series that were found to have large inhomogeneities exhibited statistically significant autocorrelation coefficients using the Durbin Watson test at the 5% level. Correspondingly, time series where inhomogeneities were not found did not exhibit autocorrelation.

4. Results

a. Inhomogeneities

The largest discontinuity uncovered in any of the time series was found for Schefferville, Quebec, and is shown in Fig. 3. The F value was 10 times larger than the threshold value for acceptance of Model 2. The downward step in 1971 coincides with the replacement of the psychrometer by the dewcel. The discontinuity in 1996 is believed to correspond to the automation of the station. The water vapor pressure closely tracks the relative humidity. In principle, a discontinuity can be corrected by comparing to data observed at nearby stations that are presumably free of inhomogeneities. In the case of Canada, nearly 75% of all stations replaced their psychrometers by dewcels in the period 1969–73. Furthermore, the nearest station may be over 500 km away and experience a very different climate. This study took the conservative approach of not considering trends for times series where an inhomogeneity was detected.

The distribution of steps is illustrated in Fig. 4. Several of the points plotted in Fig. 4 occur predominantly in a single year. For example, 36 (22) of the 53 (38) negative temperature (water vapor pressure) inhomogeneities in the 1950s U.S. data occurred in 1958. Of the 36 stations, 32 were located in the southern states, which may be

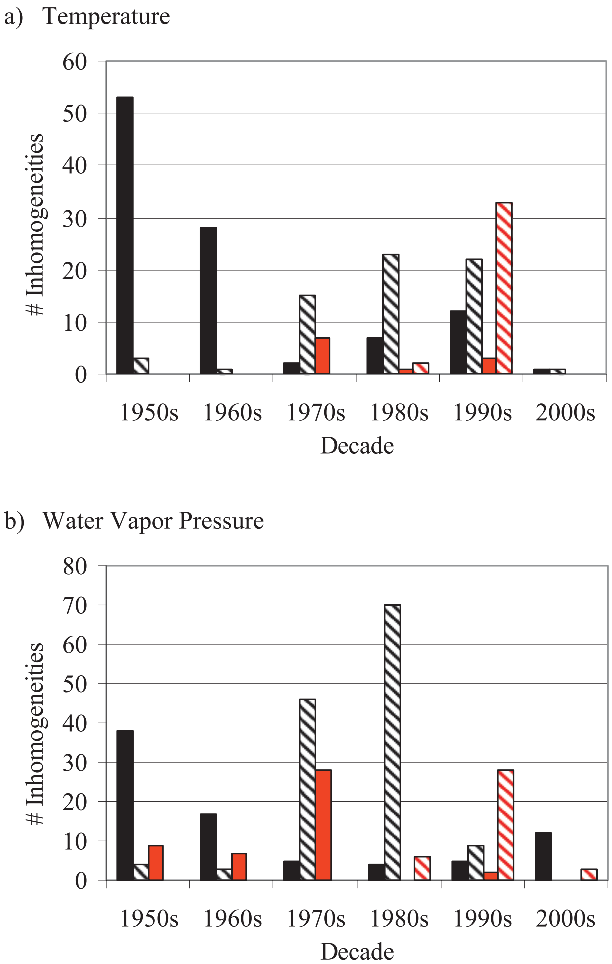

FIG. 4. Temporal distribution of inhomogeneities in (a) temperature and (b) water vapor pressure. Solid (cross hatched) bars refer to a negative (positive) step. Black (red) represents U.S. (Canadian) data.

indicative of a change of instruments at stations in this region. Positive and negative steps, for both temperature and water vapor pressure, do not occur with equal frequency during 1948–2010. For the American stations, negative steps occurred predominantly in the 1950s and 1960s while positive steps were primarily found in the later decades. In Canada, decreasing steps occurred with greater frequency in the 1970s while positive steps were found most often in the 1990s. It is critical to consider these inhomogeneities when computing trends, as the trends would be substantially larger if the inhomogeneities were ignored. Winter trends would especially be affected, as Table 1 shows the largest number of inhomogeneities for both temperature and water vapor pressure occurred in that season. This is reasonable as cold temperatures increase the likelihood of instrument malfunction (Elliott 1995; Makkonen 2005; van Wijngaarden and Vincent 2005).

TABLE 1. Trend and inhomogeneity detection of temperature and water vapor pressure. The numbers in parentheses are the percent of stations for which the trend is statistically significant.

Season	No. of stations with decreasing trend	No. of stations with increasing trend	No. stations with inhomogeneity
Temperature			
Winter	18 (0)	204 (43)	87
Spring	5 (0)	280 (62)	24
Summer	44 (0)	224 (47)	41
Autumn	48 (2)	198 (32)	63
Water vapor pressure			
Season	No. stations with decreasing trend	No. of stations with increasing trend	No. of stations with inhomogeneity
Winter	47 (9)	169 (25)	93
Spring	51 (2)	205 (26)	53
Summer	41 (12)	188 (45)	80
Autumn	48 (2)	191 (17)	70

b. Trends

Figure 5 shows seasonally averaged temperature and water vapor pressure values for two stations during 1948–2010. No inhomogeneities were found for any of the data at either station. At Anchorage, Alaska, statistically significant increases of temperature occurred in winter, spring, and fall of 0.63°C, 0.27°C, and 0.31°C decade^{-1}, respectively. Statistically significant increases of water vapor pressure were also found in winter, spring, summer, and autumn of 0.15, 0.10, 0.16 and 0.15 hPa decade^{-1}, respectively. For Wilmington, Delaware, the only statistically significant change was +0.11°C decade^{-1} for the summer temperature.

The results of fitting models 1 and 2 are given in Table 1. About two thirds of stations experienced increasing trends of temperature and water vapor pressure in all seasons. The difference in the numbers of increasing versus decreasing trends is more dramatic when considering those that are statistically significant.

Table 2 lists the seasonally averaged trends for the time series not experiencing inhomogeneities. These results change very little if station data are discarded for all seasons if an inhomogeneity occurs in any single season. In that case, the average temperature (water vapor pressure) trends are 0.29 (0.04), 0.25 (0.06), 0.12 (0.10), 0.09 (0.06)°C decade^{-1} (hPa decade^{-1}) in the winter, spring, summer, and autumn seasons, respectively. The temperature trends in winter and spring were much larger than in summer and autumn. The water vapor

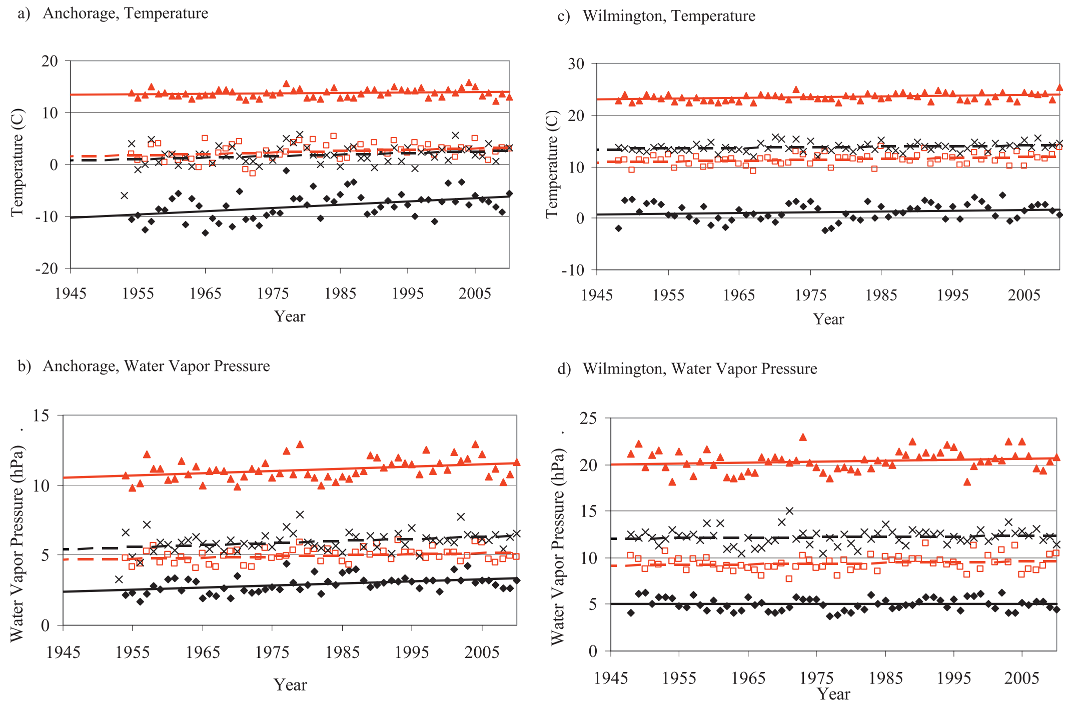

FIG. 5. Season-averaged temperature and water vapor pressure data for Anchorage, Alaska, and Wilmington, Delaware. Data are represented by solid red triangles (summer), open red squares (spring), black crosses (autumn), and solid black dots (winter). Trend lines are fitted as is discussed in the text.

pressure trend, measured in hPa decade^{-1}, was largest in summer. However, the percentage change in water vapor pressure per decade was positive in all seasons and shows little seasonal variation. Slightly larger temperature trends of 0.22°C and 0.23°C decade^{-1} occurred at night and in the evening as compared to 0.15°C and 0.18°C per decade in the morning and afternoon. In contrast, water vapor trends evaluated for the four 6-h periods of the day differed by less than 0.01 hPa decade^{-1}.

Figure 6 compares the seasonally averaged trends occurring during 1981–2010 to those found during 1948–2010 for the time series not experiencing inhomogeneities. The average temperature trend in the last 3 decades is larger than that found for the period 1948–2010 largely due to greater warming in the fall. The average water vapor pressure trend also increased largely due to increases in summer and fall, although there was a small decrease in spring.

Table 3 examines the possible effect of the urban environment surrounding a station. The average trends for time series not experiencing inhomogeneities were plotted for stations in small towns or rural areas, medium cities (population between 0.5 and 1 million) and large metropolitan areas (populations in excess of 1 million) (U.S. Census Bureau 2000 data). The number of urban stations is comparatively small but the water vapor pressure trends affecting stations located in medium cities and large metropolitan stations are larger in every season than those experienced by rural stations. The trend error bar representing 95% confidence intervals is ±0.01 (0.04) hPa decade^{-1} for the small towns or rural areas (metropolitan stations). Hence, the difference between the winter water vapor trends experienced by the small town–rural versus the metropolitan stations is significant. No such effect is evident for temperature trends.

Figures 7 and 8 show the trends plotted on a map of North America for the period 1948–2010. Data for

TABLE 2. Seasonal dependence of averaged trends during 1948–2010 for stations not experiencing inhomogeneities. The percentage change in water vapor pressure was obtained using the average water vapor pressure values of 5.0, 8.4, 16.3, and 10.1 hPa found in winter, spring, summer, and autumn, respectively.

Season	Temp trend (°C decade^{-1})	Water vapor pressure trend (hPa decade^{-1})	Water vapor pressure trend (% decade^{-1})
Winter	0.30	0.04	0.8
Spring	0.24	0.06	0.7
Summer	0.13	0.11	0.7
Autumn	0.11	0.07	0.7
Average	0.20	0.07	0.7

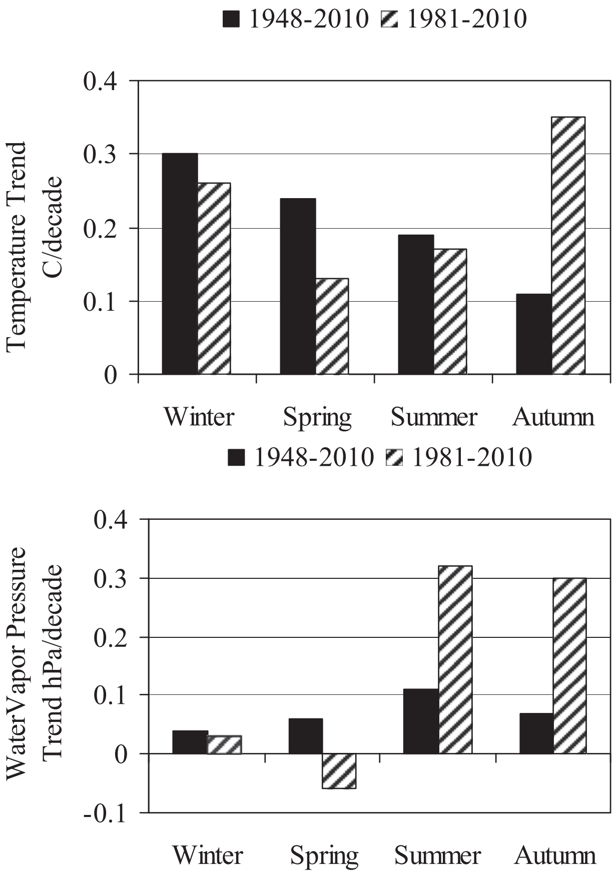

FIG. 6. Seasonal dependence of (top) temperature and (bottom) water vapor pressure trends.

Canadian stations existed for the period 1953–2009. Hence, the trends plotted for Canadian stations were found by multiplying the trends found for the period 1953–2009, by 62/56. In general, the maps are consistent in that a trend found at a particular station was comparable to those observed at surrounding stations. Also, stations experiencing the smallest trends were more likely to be closest to stations not having statistically significant trends. Neither Fig. 7 nor Fig. 8 show evidence of trend discontinuity for stations located adjacent to the boundary between Canada and the United States, either between Alaska and the Yukon or the 49th parallel. Figure 7 clearly shows that temperature increased most in the winter and to a lesser extent in the spring. Stations located in the western Arctic, Canadian prairies, and American Midwest experienced the largest warming. For water vapor pressure, there were fewer stations that exhibit statistically significant trends than was the case with temperature. The largest number of statistically significant increases occurred in summer at stations predominantly located in the eastern half of the United States.

TABLE 3. Dependence of trends during 1948–2010 for stations not experiencing inhomogeneities on urban environment. The number of stations is in parentheses.

	Temperature		
	Temperature trend (°C decade^{-1})		
Season	Small town–rural stations	Medium city stations	Metropolitan stations
Winter	0.29 (193)	0.27 (18)	0.23 (11)
Spring	0.22 (240)	0.21 (26)	0.23 (19)
Summer	0.12 (230)	0.13 (22)	0.09 (16)
Autumn	0.18 (205)	0.13 (25)	0.16 (17)
	Water vapor pressure		
	Water vapor pressure trend (hPa decade^{-1})		
Season	Small town–rural stations	Medium city stations	Metropolitan stations
Winter	0.04 (183)	0.04 (18)	0.09 (15)
Spring	0.06 (213)	0.07 (29)	0.10 (14)
Summer	0.11 (190)	0.13 (23)	0.14 (16)
Autumn	0.07 (202)	0.08 (22)	0.09 (15)

Figures 9 and 10 show plots of the trend dependence with latitude. A strong correlation between increasing temperature and latitude occurred in winter and spring. There was very little if any correlation in either summer or autumn. Figure 10 shows no correlation between water vapor pressure trends and latitude in the winter. Water vapor pressure does appear to have increased slightly at the lower latitudes in the other seasons. It is not clear why this occurred in summer and autumn given that temperature has remained stable at these latitudes. These results differ from previous studies that found a strong correlation between increasing temperature and water vapor pressure (Sherwood and Meyer 2006; Willett et al. 2007; Santer et al. 2007). A possible explanation is that relative humidity is decreasing at upper latitudes in the Arctic even though temperatures are increasing because the region has very little available liquid water available for evaporation or advection in winter. Indeed, studies have found evidence of decreasing relative humidity trends in Canada during winter and spring (Vincent et al. 2007), which could be indicative of changes in atmospheric circulation (van Wijngaarden 2005). This is also consistent with studies that found relative humidity remains constant except in desert areas when temperatures are increasing (Dai 2006).

5. Conclusions

This study found a number of inhomogeneities in the data observed at 309 stations throughout North America of surface temperature and water vapor pressure. Decreasing

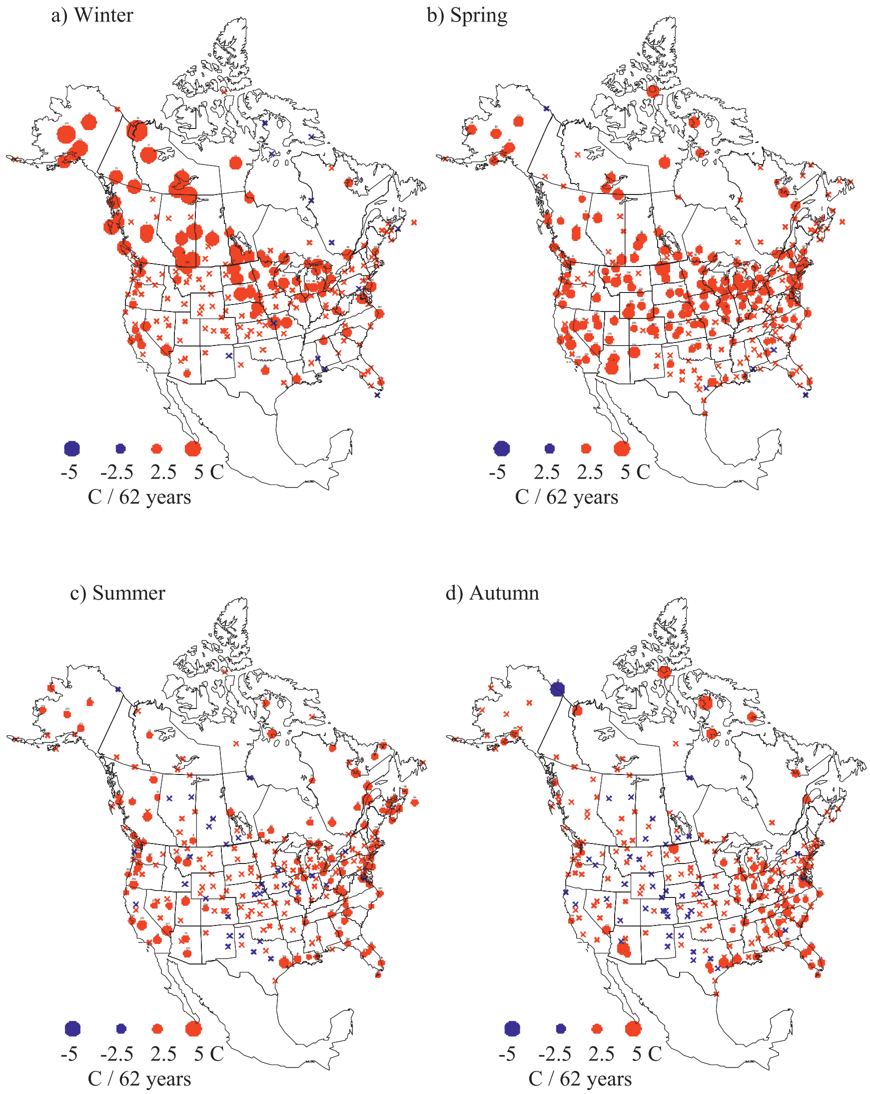

FIG. 7. (a)–(d) Seasonal dependence of temperature trends for 1948–2010 for homogeneous series as described in the text. Crosses denote trends that are not statistically significant.

steps in both temperature and humidity were much more prevalent in the 1950s and 60s while sudden increases occurred primarily in later decades. Trends were computed for time series not exhibiting inhomogeneities.

Large differences in the seasonal and geographic distributions of the temperature and water vapor pressure trends found during 1948–2010 were evident. The largest temperature increases of 0.30° and 0.24°C decade^{-1} occurred in winter and spring and are largest in the western Arctic, Canadian prairies, and American Midwest. Temperature trends were smaller in summer (0.13°C decade^{-1}) and autumn (0.11°C decade^{-1}) and some stations even experienced cooling. Temperature trends were somewhat larger at night than during the day which has been observed by some studies (Wang and Gaffen 2001).

Fewer stations exhibited statistically significant increases in water vapor pressure as compared to temperature. The average trend was largest in summer (0.11 hPa decade^{-1}) as compared to 0.04, 0.06, and 0.07 hPa decade^{-1} during winter, spring, and autumn, respectively. Stations experiencing the largest increasing water vapor pressure trends in summer were located mainly in the eastern half of the United States, which is consistent with that found by Simmons et al. (2010). However, most stations even in summer did not experience increases in water vapor pressure that are statistically significant. The percentage increase in water vapor pressure was approximately the

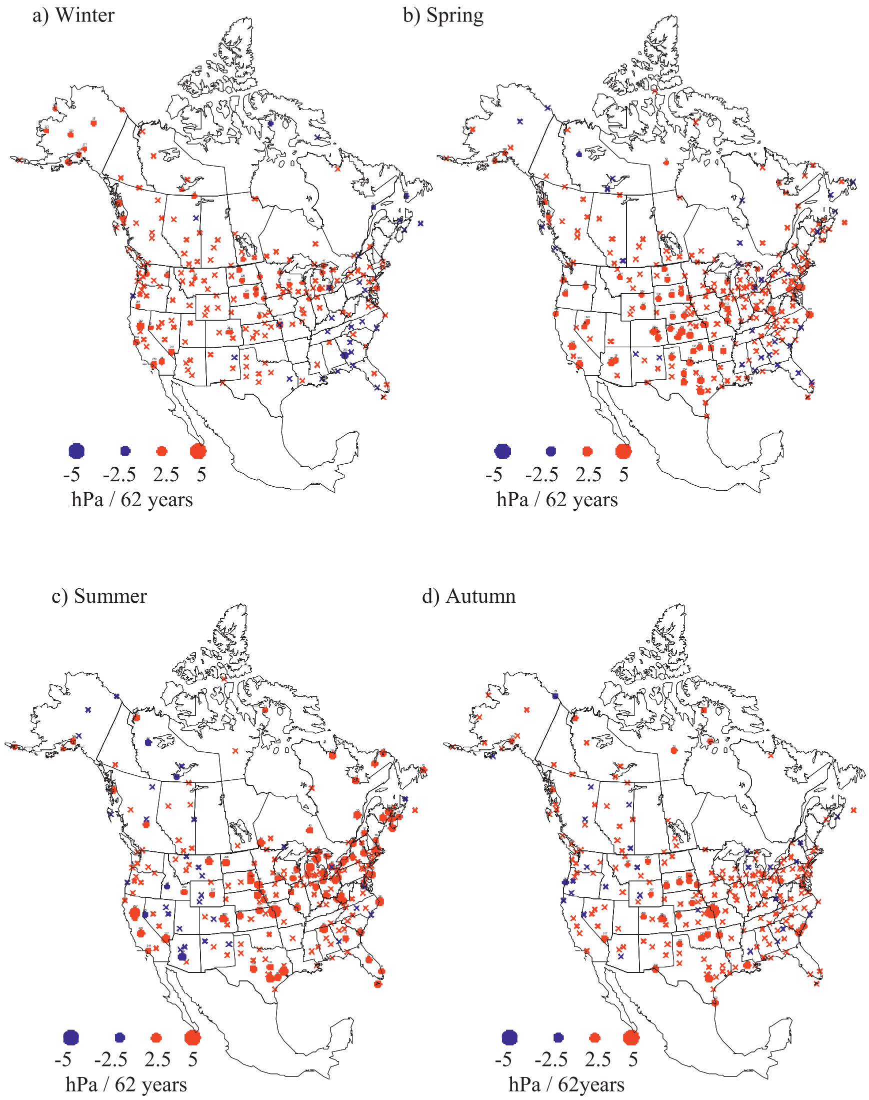

FIG. 8. As in Fig. 7, but for water vapor pressure.

same in all seasons. There are indications that the magnitude of increasing water vapor pressure trends is larger at stations located near large urban metropolitan areas.

Increasing water vapor pressure trends were also found in previous studies that examined specific humidity. The specific humidity trends found by this study using Eq. (1) are 0.02, 0.04, 0.07, and 0.04 g kg^{-1} $decade^{-1}$ during winter, spring, summer, and autumn, respectively. These trends found for the 1948–2010 period are smaller than previous work that only examined data collected in the later decades of the twentieth century (Dai 2006; Willett et al. 2007; Santer et al. 2007). This study also found larger trends for both water vapor pressure and temperature during 1981–2010. The change in relative humidity, found using Eqs. (2) and (3), is given by

$$\frac{\Delta \mathrm{RH}}{\mathrm{RH}} = \frac{\Delta e}{e} - \frac{4283.77\Delta T}{(243.12 - T)^2}. \qquad (7)$$

The trends for ΔRH are −0.9, −0.8, −0.3, and −0.1 in units of percent per decade. during winter, spring, summer, and autumn, respectively. A reduction in relative humidity can occur even though water vapor pressure is increasing if temperature is warming sufficiently. Hence, decreases in relative humidity occur at stations experiencing the largest temperature increases in winter and spring as shown in Fig. 7. The strong correlation between increasing temperature and decreasing relative humidity trends agrees with that found by Vincent et al. (2007).

In conclusion, water vapor pressure and temperature were found to increase at a large majority of 309 stations

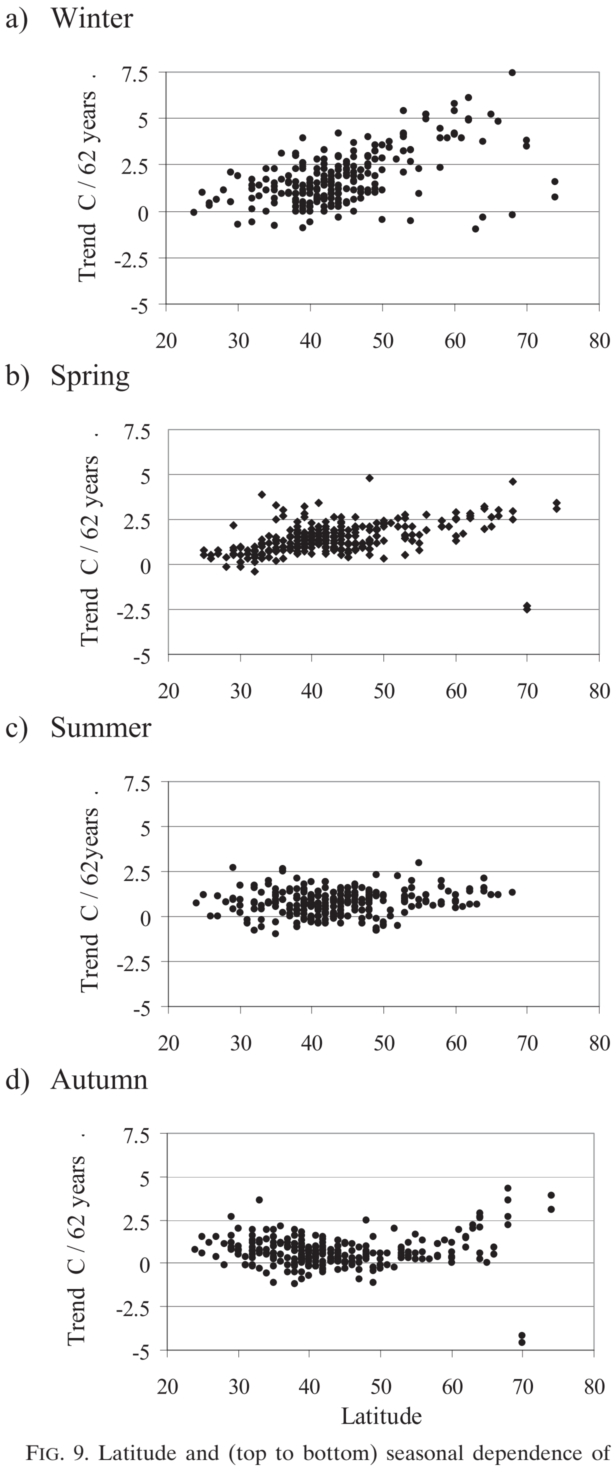

FIG. 9. Latitude and (top to bottom) seasonal dependence of temperature trends for 1948–2010 for homogeneous series as described in the text.

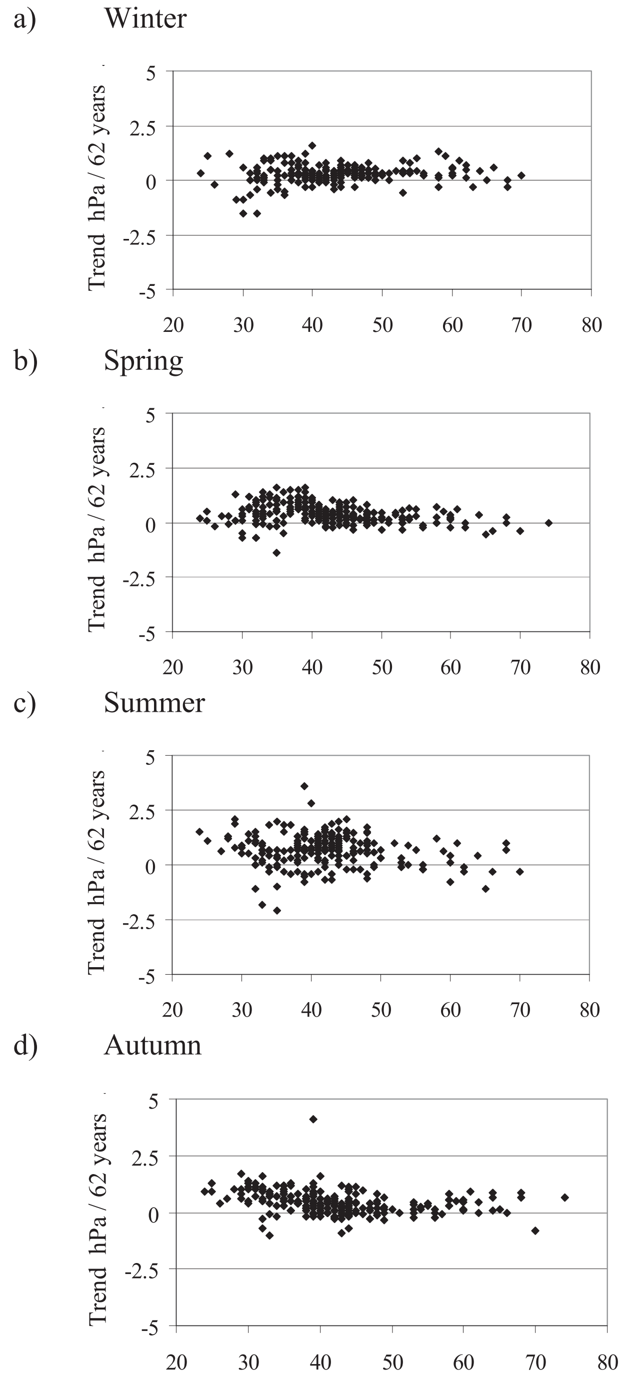

FIG. 10. As in Fig. 9, but for water vapor pressure.

located throughout North America. The average magnitude of the water vapor pressure trends during 1948–2010 is +0.07 hPa decade^{-1} or +0.7% decade^{-1} while the average temperature increase is 0.20°C decade^{-1}. The number of stations exhibiting statistically significant changes in water vapor pressure is fewer than is the case when considering temperature.

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