Examination of Archival Data for Inhomogeneities and Determination of Climate Change in North America

William A. van Wijngaarden

Physics Department, York University, 4700 Keele St., Toronto, ON, Canada, M3J 1P3

Received: December ??, 2013/Accepted: December ??, 2013/Published: January ??, 2014.

Abstract: Numerous articles have examined archival weather observations and attributed climate changes on time scales ranging from centuries to decades and in one case even days to human activity. This article gives examples showing how climate variability and sudden changes in instruments affect trend determination. In particular, surface temperature and water vapor pressure trends in North America during 1948-2010 are discussed. Over ¼ billion hourly observations taken at 309 stations, were first carefully examined for inhomogeneities. Positive and negative steps, for both temperature and water vapor pressure were found to not be evenly distributed in time. Inclusion of such data in a trend analysis would overstate decadal changes in temperature and water vapor. Time series free of such discontinuities show a statistically significant warming has primarily affected the western Arctic, Canadian prairies and the Midwestern U.S. during winter. Increases in water vapor pressure are most pronounced in summer in the eastern U.S. The decadal water vapor pressure trends are somewhat smaller than found in other studies that examined data for far shorter time periods. The claim of a change in the diurnal temperature range (DTR) during the 3 day flight ban following Sept. 11, 2011, is not substantiated. The observed change in the DTR was likely caused by a reduction in cloudiness during the flight ban.

Key words: Climate change, inhomogeneities, temperature, humidity trends, diurnal temperature range.

1. Introduction

It is recognized that the Earth's climate has changed throughout the millennia. Ten thousand years ago, North America was covered by glaciers. Recorded history contains evidence of a very different climate. For example, the Viking settlement of Greenland a thousand years ago was made possible by a warmer climate in the North Atlantic region. In recent years, concern has mounted that climate is changing on faster time scales because of human activities [1]. This is due primarily to the increasing use of fossil fuels that began with the industrial revolution. Carbon dioxide emitted by heating millions of buildings and operating hundreds of millions of motor vehicles, has increased CO_2 from a level of about 280 ppm in 1750 to 385 ppm in 2008 [2]. Its emission has accelerated over the last 50 years and is presently increasing at the rate of 2 ppm per year. Carbon dioxide, along with other gases such as methane, is believed to contribute significantly to the 1 ^{o}C observed increase in global temperature over the past century [1]. This so called anthropogenic climate change may also be caused by other human activities such as changing land use. Concern about climate change has been highlighted by the Intergovernmental Panel on Climate Change. Their 4th 2007 Assessment Report forecast the Earth's average temperature will increase by several ^{o}C in the 21st

Corresponding author: William van Wijngaarden, Professor, main research fields: climate studies, environmental monitoring and laser spectroscopy. E-mail: wlaser@yorku.ca.

century unless steps are taken to curtail the emission of greenhouse gases [1].

A number of studies have found significant changes of temperature [3] and humidity [4] on decadal time scales and attributed much of these changes to human influence [5-7]. There even was a claim published in Nature [8] and featured on the respected PBS scientific series NOVA [9] that the diurnal temperature range (DTR) defined as the difference between the daily maximum and minimum temperatures, changed by over 1 ^{o}C in the hours following the grounding of commercial airplanes over North America after Sept. 11, 2001. The change in DTR was attributed to a lack of aircraft contrails which act like clouds reflecting sunlight during the day and radiation from the Earth's surface at night. Some policy makers, notably former U.S. Vice president A. Gore, have cited these studies to emphasize the need for immediate action [10].

A warmer atmosphere is expected to significantly affect the Earth's climate. The Clausius-Clapeyron equation shows that saturation vapor pressure increases exponentially with temperature. Increasing water vapor pressure may increase precipitation [11,12] and affect storm intensity [13-15]. Increases in water vapor are also likely to be larger in the Arctic than in the equatorial regions due to melting ice. Water vapor is a greenhouse gas and global climate models predict the greatest warming will occur near the Earth's poles [16].

Several recent studies found a global increase in surface absolute humidity that they attributed to human influence. One group found the global mean water vapor pressure increased by 0.11 hPa per decade [5]. The increases were strongly correlated with temperature increases. Another group examined data taken using a microwave satellite imager and found the total atmospheric moisture content over oceans increased by 0.04 hPa per decade during 1988-2006 [6]. A third group examined data taken at over 15,000 weather stations and ships during 1975-2004. Relative humidity increases of 0.5 to 2% per decade were found over the central and eastern U.S., India and western China that were associated with an increase in temperature and absolute humidity [7]. The latter increased by as much as 6% per decade over parts of Eurasia.

This paper presents some examples showing how abrupt change likely caused by changes in instruments or climate variability can affect trends. We show how step discontinuities can be found when determining temperature and water vapor trends. Finally, the issue of possible change in the diurnal temperature range following Sept. 11, 2001 is examined.

2. Data Description

Hourly records of temperature and relative humidity as well as daily amounts of precipitation are available from Environment Canada beginning for most airport stations in 1953 [17] and from the University Corporation for Atmospheric Research (UCAR) in the U.S. for the period 1948-2005 [18]. American data for 2006-2010 can be purchased [19]. The fraction of hours for which data were present averaged 95% for the 74 Canadian stations and 80% for the 235 American stations. For each station, seasonal and annual averages were computed for every year. Seasons were defined as: winter (December-February), spring (March-May), summer (June-August) and autumn (September-November). The seasonal average was only computed if observations existed for ≥30% of all hours and ≥25% of all hours in each 4 hour period.

Fig. 1 shows a plot of the winter relative humidity at Schefferville, Quebec. The 20% drop in 1971 coincided with the replacement of the psychrometer with the dewcel. The psychrometer consists of two thermometers, one of which is covered by a wet "sock". Evaporating water lowers the temperature of this thermometer. The relative humidity is found from the temperature difference between the wet and dry thermometers. At very cold temperatures, the wet "sock" quickly freezes reducing the temperature difference resulting in a relative humidity that is too high. The dewcel measures the change in resistance of lithium chloride when it absorbs moisture. Nearly 75% of Canadian stations installed dewcels during 1969-1973 and their observed winter relative humidity exhibits a downward step similar to that shown in Fig. 1 [20].

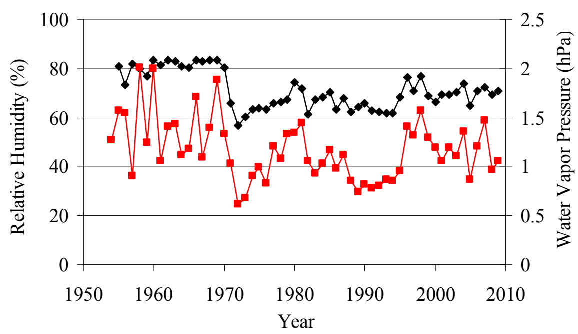

Fig. 1 Discontinuity of winter data for Schefferville, Quebec. Black dots denote Relative Humidity while red dots represent Water Vapor Pressure.

Inhomogeneities can be corrected by comparing observations to those found at neighboring stations [4]. However, in Canada the closest stations may be over 500 kilometers distant and experience a very different climate. Correcting data to accurately determine trends is especially difficult for large inhomogeneities. It is harder to detect changes occurring over many years due to urban sprawl which can increase temperature more at night than during the day [21]. Detecting inhomogeneities is also more difficult for observations that have large year to year variation. Fig. 2 shows the winter precipitation at Medicine Hat, Alberta. There is a large decreasing trend during 1953-2005 which disappears if one considers the entire 20th century.

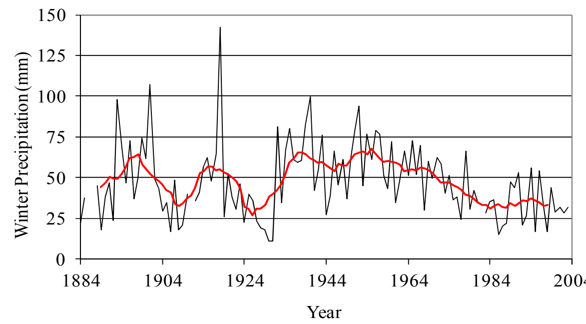

Fig. 2 Winter Precipitation at Medicine Hat, Alberta. The red line is the 5 year running average. This is computed using daily observations of precipitation that are available for a longer period of time than hourly measurements.

3. Temperature and Water Vapor Trend Detection in North America

Temperature and water vapor trends were determined by analyzing over 1/4 billion hourly observations taken during 1948-2010 [22]. The water vapor pressure p_w was computed from the relative humidity RH and temperature T measured in ^{o}C using

$$p_w = RH * p_{sat} \quad (1)$$

where the saturation water vapor pressure measured in hPa is given by [23]

$$p_{sat}(T) = 6.112\, e^{17.62\, T / (243.12+T)} \quad (2)$$

The trend of each seasonally averaged time series such as shown in Fig. 3 was calculated if data existed for at least 40 years. The data was tested for inhomogeneities using two regression models. The first model fit the data to a straight line

$$y_i = a_1 + b_1\, t_i + e_i \quad (3)$$

where y_i is the seasonal temperature or water vapor pressure for year t_i. A t-test compared the mean of the residuals e_i when the data was fit to a line. The statistical significance of the trend, given by the slope b_1 was found at the 5% level meaning the probability of falsely concluding there was a statistically significant difference between the means is less than 1 in 20. Next, data was fitted to a straight line plus a step of magnitude c_2.

$$y_i = a_2 + b_2 t_i + c_2 I + e_i \qquad (4)$$

I equals zero (one), before (after) the step year t_s. A F-test, which compares the standard deviations of two populations, determined whether the data was better fitted by (3) or (4).

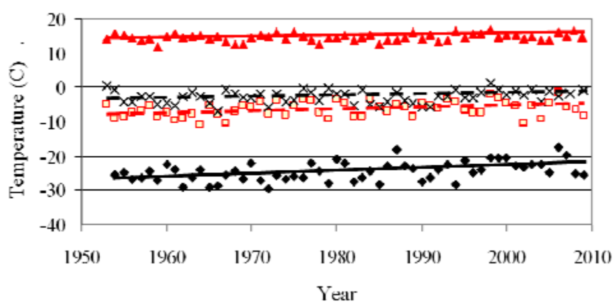

Fig. 3 Seasonal Temperatures for Yellowknife, North West Territories. Data is represented by solid red triangles (summer), open red squares (spring), black crosses (autumn) and solid black dots (winter). In winter and spring, there is a statistically significant warming of 0.7 and 0.4 °C per decade while the trends for summer and fall are not significant.

Inhomogeneities were not evenly distributed throughout the year. The percentage of stations exhibiting temperature (water vapor) steps was: 28% (30%) in winter, 8% (17%) in spring, 13% (26%) in summer and 20% (23%) in autumn. The highest number occurs during winter which is reasonable as cold temperatures increase the likelihood of instrument malfunction [24,25]. Positive and negative steps, for both temperature and water vapor pressure were also not evenly distributed in time. 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, negative steps occurred with greatest frequency in the 1970s while positive steps were found most often in the 1990s.

Figs. 4 and 5 display trends for data not experiencing sudden inhomogeneities. The trends for Canadian stations found during 1953-2009 were prorated to take into account the slightly different time intervals. Temperature increased most in the winter and to a lesser extent during spring. Stations located in the western Arctic, Canadian prairies and American Midwest experienced the largest warming. For water vapor pressure, fewer stations 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 U.S. The decadal temperature (water vapor pressure) trends averaged over all stations are 0.30 (0.04), 0.24 (0.06), 0.13 (0.11) and 0.11 (0.07) °C (hPa) in the winter, spring, summer and autumn, respectively. The percentage change of water vapor pressure found by dividing the trends by the seasonal average pressure, was nearly constant for all seasons at +0.7% per decade.

Higher trends were found for the 1981-2010 period. The average annual temperature decadal trend increased to 0.23 °C from 0.20 °C for 1948-2010 while the water vapor pressure trend nearly doubled to 0.15 hPa per decade. There are indications that water vapor trends affecting metropolitan areas having populations of over 1 million, were about 50% larger than those affecting rural or small town stations.

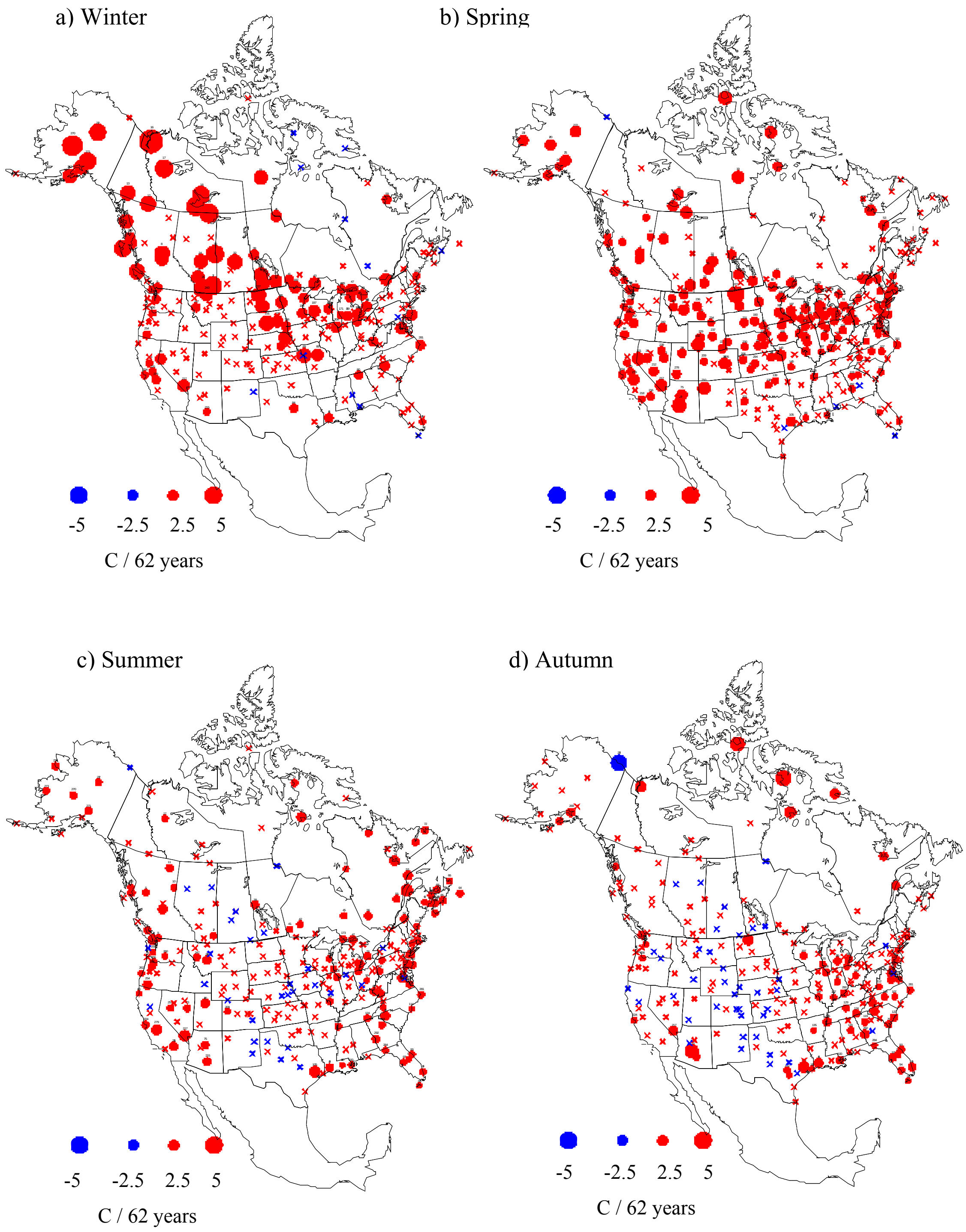

Fig. 4 Seasonal Dependence of Temperature Trends for 1948-2010. Crosses denote trends that are not statistically significant.

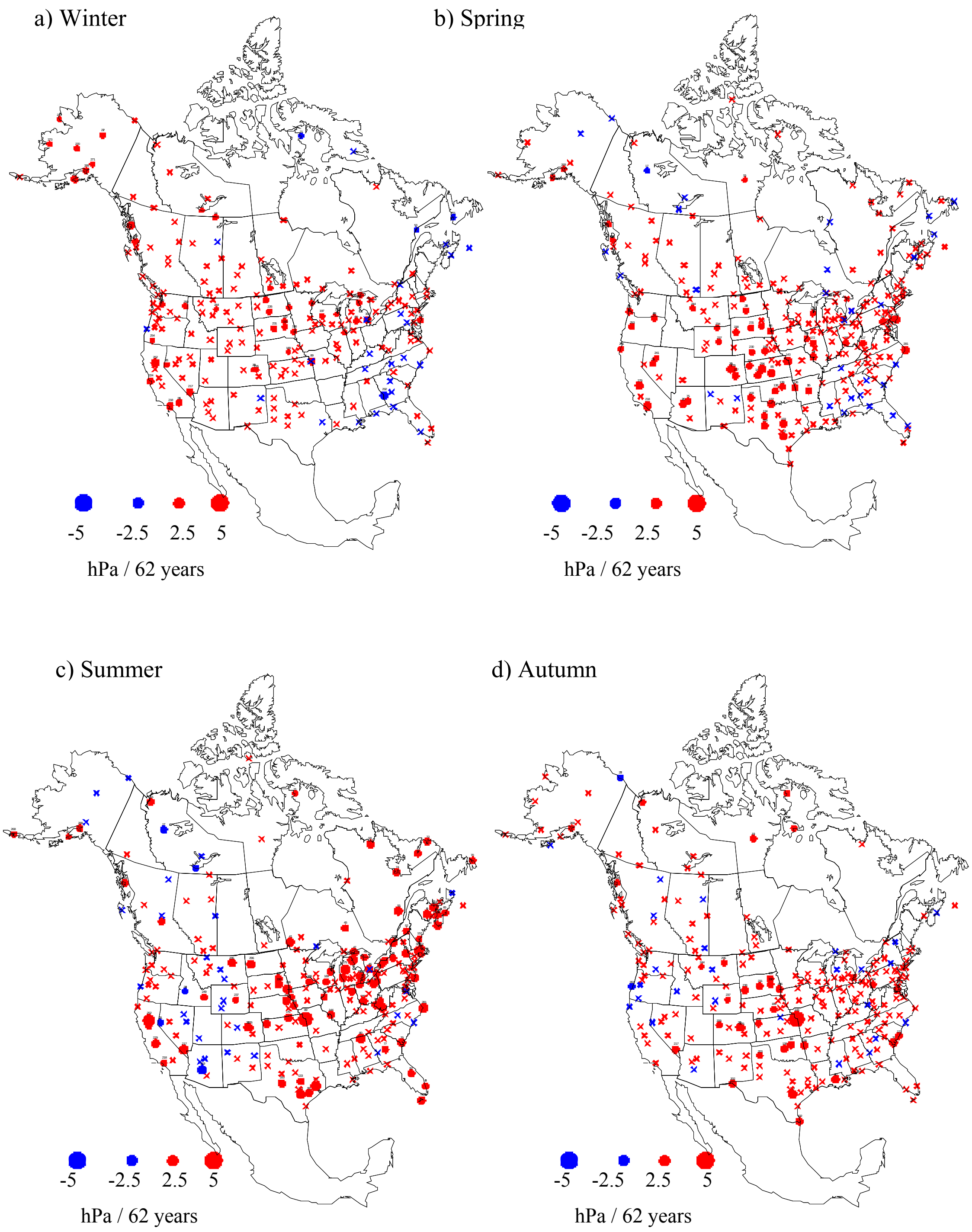

Fig. 5 Seasonal Dependence of Water Vapor pressure Trends for 1948-2010. Crosses denote trends that are not statistically significant.

4. Diurnal Temperature Range after Sept. 11, 2001

Commercial flights were suspended over North America for 3 days immediately after the tragic events of Sept. 11, 2001. One study compared the DTR over the coterminous U.S. (continental U.S. minus Alaska) during Sept. 8-17 for 2001 to the average occurring during 1971-2000 [8]. The DTR increased by 1.1 ^{o}C during Sept. 11-14, 2001 as compared to the value for the previous 30 year period. The corresponding changes in the DTR during Sept. 8-11 and Sept. 14-17 were -0.2 and -0.8 ^{o}C, respectively.

The DTR was computed from the daily maximum and minimum temperatures found using the hourly observations [26]. The values were averaged over all stations located in the coterminous U.S. to produce Fig. 6. The data for 2001 are scattered close to the average observed during 1975-2005 [27]. Neither this figure nor similar plots of average daily temperature, maximum/minimum temperature or relative humidity show any indication of anomalies during September 2001. The largest departures of the 2001 data from the averaged values occur in months other than September.

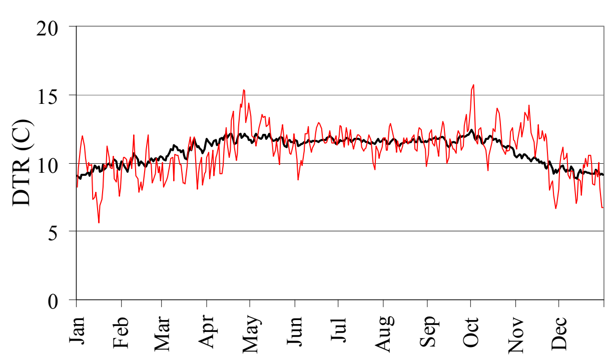

Fig. 6 The Diurnal Temperature Range averaged over stations located in the coterminous U.S. The black curve represents data averaged for 1975-2005 while the red curve is data for 2001.

Fig. 7 shows the change in DTR for Sept. 8-17, 2001 relative to the average DTR observed during 1975-2005. The DTR increased during each of the 4 days from Sept. 8-11 and then decreased until Sept. 14, where after it increased. This does not correlate well with the flight ban. Fig. 7 also displays the 3 day averaged values. The changes in DTR averaged during Sept. 8-10, 11-13, 14-16 were -0.3, 0.6 and -0.5 ^{o}C respectively, which are comparable to those found by Travis et al [8].

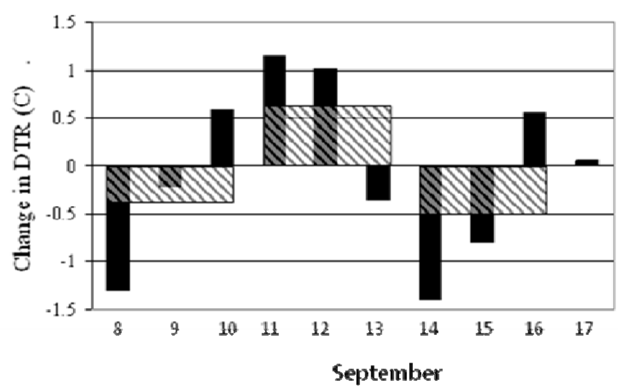

Fig. 7 Change in Diurnal Temperature Range averaged over stations located in the coterminous U.S. during Sept. 8-17, 2001 compared to the value during 1975-2005. The cross hatched bars denote the 3 day average values.

Fig. 6 shows the 2001 data fluctuates about those averaged over 1975-2005 with a time constant of several days which is comparable to the time for a weather system to move across North America. Maps have been plotted showing the change in DTR during Sept. 8-17 [26]. For each station, the Sept. 2001 DTR was computed and the average DTR on the same day that occurred during 1975-2005 was subtracted. The maps indicate North America had predominantly clear skies during the flight ban which agrees with other work that found a reduction of cloudiness was responsible for the observed change in the DTR [28] [29].

5. Conclusions

The Earth's climate has undergone major changes on time scales of a century that are well supported by archival observations. It is important to check data for inhomogeneities that can significantly affect trends. Statistical tests can detect sudden changes arising from the introduction of new instruments which is especially useful when such changes are poorly documented. Examination of hourly temperature and water vapor pressure data show over a quarter of stations in winter and a lesser but nonnegligible number in the other seasons, are so affected. Positive and negative steps are not evenly distributed throughout the 1948-2010 observation period.

Statistically significant warming has most notably affected the Western Arctic, Canadian prairies and the American Midwest during winter. Changes in surface water vapor pressure are less dramatic. This does not correspond to the expectation that warmer temperatures are automatically associated with increased water vapor pressure. The trends found for 1948-2010 are smaller than those reported by studies that only considered one or two decades of data [5-7]. This work also found larger trends for 1981-2010. It is not clear whether this acceleration of warming will continue or is partly due to natural climate variability. This underscores the difficulty in extrapolating trends based on only one or two decades of data. The lack of substantiation of the claim that the DTR changed due to the flight ban after Sept. 11, 2001, shows some caution is warranted when claiming that dramatic climate change has occurred on very short time scales and concluding it is due primarily to anthropogenic effects.

The possibility that human activity is making the Earth's climate less habitable is serious. Most researchers expect substantial climate change will occur in the 21st century even if greenhouse emissions are sharply curtailed. Scientists and engineers with their training in instrument design and measurement as well as data analysis, bring unique skills to this inherently interdisciplinary problem. It would be appropriate to facilitate the access of researchers to archival climate records which are not always conveniently available. These data, which precede satellite measurements by decades, are invaluable to test global climate models. This is necessary to improve quantitative estimates of the anthropogenic contribution to climate change. A better understanding of seasonal and geographic variation of climate change might also help mankind to adapt. This is critical as government leaders need accurate scientific advice to make sound policy decisions.

Acknowledgments

The author wishes to thank Environment Canada and UCAR for access to the observations and the Natural Science and Engineering Research Council of Canada for financial support.

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