Homogenization and Trend Analysis of Canadian Near-Surface Wind Speeds

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ABSTRACT

Near-surface wind speeds recorded at 117 stations in Canada for the period from 1953 to 2006 were analyzed in this study. First, metadata and a logarithmic wind profile were used to adjust hourly wind speeds measured at nonstandard anemometer heights to the standard 10-m level. Monthly mean near-surface wind speed series were then derived and subjected to a statistical homogeneity test, with homogeneous monthly mean geostrophic wind (geowind) speed series being used as reference series. Homogenized monthly mean near-surface wind speed series were obtained by adjusting all significant mean shifts, using the results of the statistical test and modeling along with all available metadata, and were used to assess the long-term trends.

This study shows that station relocation and anemometer height change are the main causes for discontinuities in the near-surface wind speed series, followed by instrumentation problems or changes, and observing environment changes. It also shows that the effects of artificial mean shifts on the results of trend analysis are remarkable, and that the homogenized near-surface wind speed series show good spatial consistency of trends, which are in agreement with long-term trends estimated from independent datasets, such as surface winds in the United States and cyclone activity indices and ocean wave heights in the region. These indicate success in the homogenization of the wind data. During the period analyzed, the homogenized near-surface wind speed series show significant decreases throughout western Canada and most parts of southern Canada (except the Maritimes) in all seasons, with significant increases in the central Canadian Arctic in all seasons and in the Maritimes in spring and autumn.

1. Introduction

Wind is a central element of the global climate system that both describes climate change and variability and influences key aspects of the terrestrial environment. It reflects atmospheric circulation, transferring heat and moisture between the earth's surface and the atmosphere and from one place to another. Wind speed is largely a function of the atmospheric pressure gradient, which in turn is related to air temperature. Changes in winds imply associated changes in atmospheric circulation, which are an integral part of climate variability and change. Near-surface wind (simply referred to as wind or surface wind hereafter) is a dominant factor affecting pan evaporation (Rayner 2007), and, more importantly, its effect on evaporation rates alters the hydrological balance of lakes and reservoirs. Moreover, winds could be closely related to extremes of climate. For example, intense cyclones are accompanied by potentially destructive extreme gusts, while heat waves may be associated with low wind speeds. Wind data can be used to validate model simulations (e.g., Roads et al. 1995) and to quantify local aspects of the changing climate (e.g., Klink 2002). They are also widely used in various applications (e.g., building codes, estimation of evapotranspiration, and wind erosion) and by the insurance industry [reinsurance/insurance companies are especially interested in the frequency, or return period, of very rare extreme wind events because these are associated with a large loss potential (e.g., SwissRe 2000)]. For coastal regions, the surface wind affects regional wave conditions and costal erosion processes, and contributes to surges, which may cause flooding along coastlines. In addition, the surface wind is a practical source of energy generation (e.g., Palutikof et al. 1987; Rohatgi and Nelson 1994; Sailor et al. 2008).

In the climate literature, several studies have analyzed surface winds for various purposes. For example, Klink

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(1999a,b, 2002), Pirazzoli and Tomasin (2003), Tuller (2004), and McVicar et al. (2008) have characterized surface wind climatology, variability, and long-term trends; while Smits et al. (2005) and Yan et al. (2002) have examined surface wind extremes, which could be directly linked to intense storms and even natural disasters. There are also several studies of surface winds for purposes of wind energy generation or other human activity (e.g., Yim et al. 2007; Sanz-Andres and Cuerva 2006; Pryor et al. 2005; Rohatgi and Nelson 1994; Palutikof et al. 1987). However, Canadian surface wind observations have not been analyzed systematically [Tuller (2004) analyzed only four stations on the west coast], although recent studies have revealed observed long-term trends in air temperatures, precipitation, and cyclone activity in Canada (Zhang et al. 2000; Stone et al. 2000; Bonsal et al. 2001; Wang et al. 2006a). Thus, it is of great interest to see if Canadian surface wind speeds have experienced significant changes in the historical record of digital data, and whether these changes are consistent with the reported trends in other climate variables during the same period. These questions motivate the current study.

Unfortunately, wind observations are very sensitive to changes in anemometer height (AH) and in the location and exposure of the observing site. Changes in these factors could cause large discontinuities in the wind data series; however, they are often inevitable, especially over a long period of record (see examples in section 3 below). Thus, corrections and homogenization of wind data are imperative for climate studies and other applications, especially for the assessment of observed wind speed trends. For similar reasons, Klink (1999a) adjusted wind speed data for 216 stations in the United States to diminish the effects of anemometer height changes, prior to her attempt to characterize U.S. wind speed climatology and interannual variability. Thomas et al. (2005) used regression models to homogenize wind speed observations from ships and buoys. In this study, we first homogenized series of wind speeds recorded at 117 long-term stations across Canada, using available metadata information and a newly developed statistical homogeneity test. Then, we used the homogenized data series to characterize wind speed climatology, variability, and long-term trends.

The remainder of this paper is structured as follows. The wind data used in this study are described in section 2. Wind data problems and the procedures for correction and homogenization of wind speed data are detailed in section 3. An assessment of Canadian wind speed climatology, interannual variability, and long-term trends is presented in section 4. This paper is completed with a summary and some discussion in section 5.

2. Data

The Environment Canada (EC) digital archive is the source of the wind data analyzed in this study. It contains hourly wind observations in Canada for the period from 1953 to date (some pre-1953 wind observations in Canada exist, but in paper form rather than digitally). In this study, we focus on stations with at least 45 yr of continuous observations of wind speed in the period from 1953 to 2006 (54 yr). There are 117 such long-term stations in Canada. As shown in Fig. 1, these stations are reasonably well distributed over Canada (with a much higher station density in the south).

Several types of anemometers have been in use in Canada. Type 45B and U2A anemometers are usually used at manned stations and are connected to a recorder to provide a continuous record of the wind speed. The digital 78D anemometer system is used in recent years at both automatic and manned stations; it provides 5-s wind messages to the display unit for further averaging. The Rosemount pressure anemometer, which is designed with a heater to operate in extreme icing conditions, is also used at one of the stations analyzed. Regardless of the anemometer type, an hourly wind speed recorded in the EC archive (either on paper or digitally) refers to a 2-min-average wind speed ending at the time of its observation, and it is recorded to the nearest nautical mile per hour (i.e., kt) since 1996; prior to 1996, a 1-min average was used and these values were reported to the nearest statute mile per hour (Environment Canada 1996). However, the way in which the 2- or 1-min averages were obtained does depend on the anemometer type, according to the latest version of the Manual of Surface Weather Observations (MANOBS; Environment Canada 1977). For the 45B, which is usually connected to a step recorder (which has a speed indicator lamp that lights for each 1/120 miles of wind; the number of flashes in every 15 s is counted), the observer needs to estimate the hourly wind speed using the number of flashes of the speed indicator lamp in the last 15 s of the hour of observation, supplemented by visual observation of the effects of the wind. For U2A, which produces more or less instantaneous values of wind speed and direction, the midpoint of the position on the dial or chart over which the indicator or recorder pen moved for the major part of the time is taken as the mean value. The 78D system has a built-in microcomputer to sample and calculate 5-s vector components of wind; every 5 s it transmits a wind message to its display unit, which provides further averaging for periods of 2 and 10 min. Despite the change of wind speed unit in 1996, all of the wind speed data in the EC digital archive have been converted to the same kilometer per hour (km h^{-1}) unit.

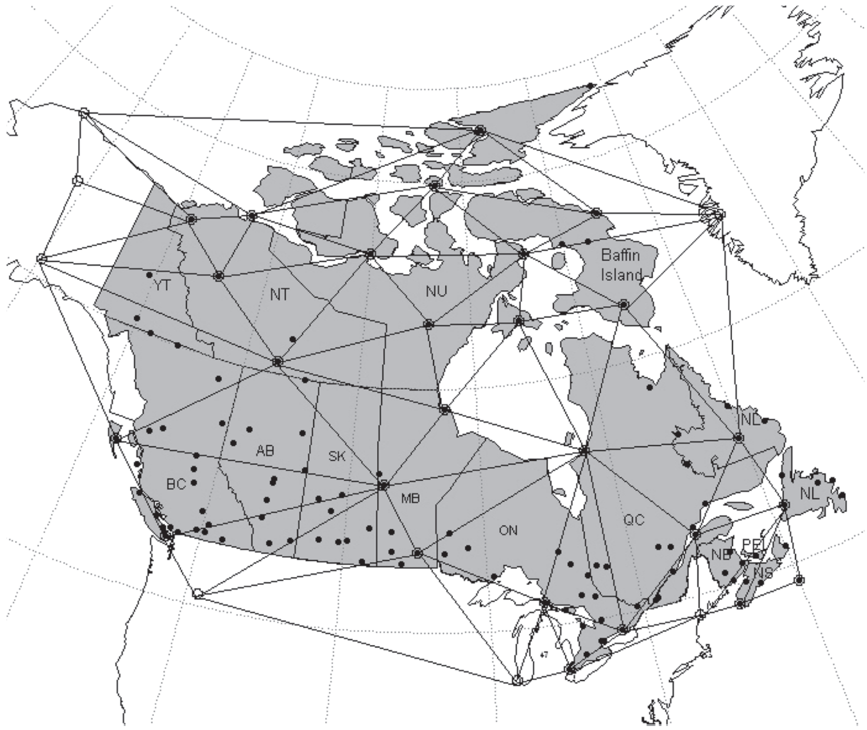

FIG. 1. Locations of the 117 stations (solid dots) of long-term wind speed series analyzed in this study, and the 49 pressure triangles used to calculate geowind speed series for use as reference series in the homogeneity test on monthly mean surface wind speed series. Stations whose surface pressure data are used to calculate geowind speeds in this study are represented (open circles).

This is also the unit of wind speed in this study, unless specified otherwise.

First, we used the quality control criteria (Table 1) taken from the EC hourly data quality control document (Environment Canada 2004) to screen out suspicious values in hourly wind speed data. Note that daily extreme gust wind speeds, which are the 24-h maximum value of gust recorded in a 10-min period, were also used to help identify suspicious hourly wind speed values (Table 1), although they are not analyzed for trends and variability in this study. As a result, about 0.02% of the hourly wind speed data were identified as outliers. These suspicious, most likely erroneous, values were excluded from our analysis (they were set to missing). Monthly mean wind speeds were calculated only for months with at least 26 days of observations, after excluding days with fewer than three observations. Also, the hourly wind speeds were first adjusted for nonstandard anemometer heights, whenever and wherever applicable, before they were used to derive monthly mean wind speeds. Such adjustment is the first step in the wind speed homogenization process, as described in the next section.

3. Homogenization of wind speed series

Our wind speed homogenization process consists of two major steps: First, we adjusted hourly wind speeds for all known anemometer height changes using metadata information and a logarithmic wind profile. Then, we derived monthly mean wind speeds and used a statistical method to test and homogenize the monthly mean wind speed series for each of the 117 stations. The homogenization process is detailed in the two subsections below.

a. Adjusting for the effects of nonstandard anemometer heights

According to the manual of wind-measuring equipment for type 45B and U2A (Department of Transport

TABLE 1. Quality control criteria for identifying suspicious values in hourly wind speeds w_t. A suspicious value is identified if any of the three criteria is met.

1) $w_t >$ daily extreme gust
2) $w_t > 128$ km h^{-1}
3) if $\lvert w_t - w_{t-1}\rvert > 28$ km h^{-1} and $\lvert w_t - w_{t+1}\rvert > 28$ km h^{-1}

1966, 1969, respectively), the standard height of a wind speed detector should be 10 m. However, the instruments could be mounted on the roof of a building or at nonstandard heights when an unobstructed exposure could not be secured. In particular, in order to get good exposure, it was quite common in the 1950s and 1960s to mount anemometers on the roofs of buildings in Canada, resulting in nonstandard anemometer heights (usually more than 10 m). Most anemometers were moved to standard 10-m (33 ft) wind towers in the 1970s. Such AH changes often caused notable discontinuities in wind data series. In such cases, wind data need to be adjusted to the standard 10-m level to attain homogeneity. A wind profile can be used to make such an adjustment if the exact AH is known (which is the case here).

Let $U(h)$ denote the observed hourly wind speed (m s^{-1}) at a height of h (m), and $U(10)$, the estimated hourly wind speed (m s^{-1}) at the 10-m level. There are two commonly used forms of wind profiles, that is, the logarithmic wind profile,

$$U(10) = \frac{\left[\ln\left(\frac{10}{Z_0}\right)\right]}{\left[\ln\left(\frac{h}{Z_0}\right)\right]} \times U(h), \tag{1}$$

and the wind power law,

$$U(10) = \left(\frac{10}{h}\right)^{\lambda} \times U(h). \tag{2}$$

The Z_0 in (1) is the roughness length (m), and the power-law exponent λ in (2) is set to 1/7 in this study, which would yield reasonable estimates of total wind power according to Peterson and Hennessey (1978). In this study, the Z_0 values were calculated from a modified geophysical field generator that has been developed by the Canadian Meteorological Centre (CMC) for use in the numerical weather prediction system. The generator considers Z_0 as a function of land vegetation type; it accounts for the percentage of 26 vegetation types in each 5° latitude × 5° longitude grid box (each value represents the average roughness in the grid box). This is the best roughness length dataset available for our use, although the spatial resolution is limited. However, our results indicate that the roughness length dataset is good enough for our application here, because the resulting adjustments can effectively diminish the artificial shifts resulting from AH changes. We use the roughness length of the grid box in which the station is located. The Z_0 values used in this study are in the range from 0 to ~2 m. Although station development could change the roughness over time, the changes should be small because most stations with hourly observations are located at airports,

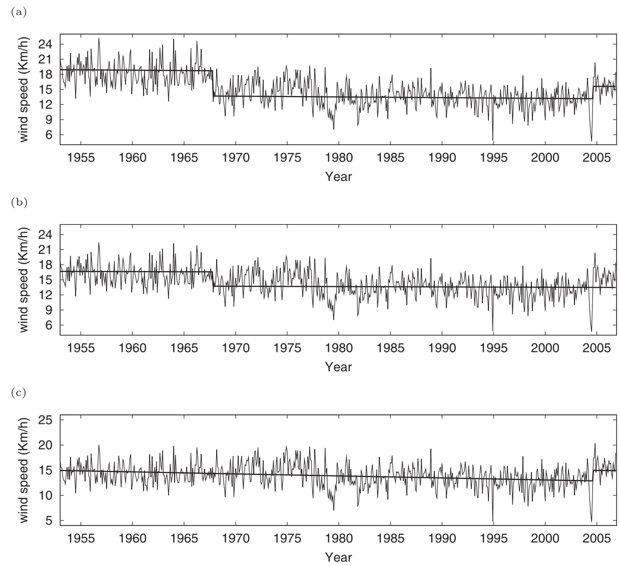

FIG. 2. Time series of monthly mean wind speeds for Fort St. John Airport (BC, Canada) derived from (a) the original hourly data, (b) the hourly data that have been adjusted for nonstandard anemometer heights using the wind power law, or (c) using the logarithmic wind profile. The trend lines and mean shifts are estimates from the multiphase regression fits (Wang 2008).

as Klink (1999b) has noted. Thus, it is assumed in this study that the Z_0 value does not change over time.

Following Peterson and Hennessey (1978), Klink (1999a,b) used the power law with $\lambda = 1/7$ to adjust wind speeds from nonstandard levels to the standard 10-m level. However, results of our comparison study indicate that the logarithmic wind profile is a more reliable estimator than the power law, because it accounts for the roughness of the surface. For example, using the statistical homogeneity test PMTred [i.e., the penalized maximal *t* (PMT) test (Wang et al. 2007) that can account for the first-order autocorrelation in the respective series (see Wang 2008)], with a geostrophic wind speed series as the reference series (more details given later), for Fort St. John Airport we identified from the series of raw monthly mean wind speeds two significant (at 5% level) changepoints, in November 1967 and September 2004, respectively (Fig. 2a). The related metadata confirm that the first changepoint was caused by the AH change on 11 November 1967 (from 22.9 to 10 m, when it was relocated from the roof of the control tower to the standard wind tower), and that the second changepoint was caused by a replacement of the U2A speed sensor (because of low readings) on 23 September 2004. We will adjust for the second changepoint later because it is not associated with an AH change. To compare the two forms of wind profiles, we first adjusted the hourly wind data measured at the 22.9-m level to the 10-m level using the two forms of wind profiles, obtaining two AH-adjusted wind speed series, respectively. Then, we repeated the PMTred test on each of the two adjusted series, using the same geostrophic wind reference series. As shown in Fig. 2b, the adjustments based on the wind power law fail to diminish the effects of AH change in November 1967; it also alters the characteristics of the wind speed series, making the second changepoint undetectable. On the contrary, as shown in Fig. 2c, the adjustments based on the logarithmic wind profile successfully diminish the discontinuity resulting from the AH change without changing the characteristics of the series (i.e., keeping the second changepoint detectable). Clearly, the logarithmic wind profile is better than the wind power law in accounting for the effects of AH change; thus, it is used in this study to adjust hourly wind speeds measured at a nonstandard level to the standard level.

Figure 3 shows the relationship between AH and wind speed for several surface roughness lengths ranging from 0.03 to 2.0 m, as represented by the logarithmic wind profile (1). Clearly, for a given surface roughness length Z_0, wind speed increases with the anemometer height h; while, for a given AH change, the change in wind speed increases with an increase in the Z_0 (Fig. 3). For example, when $Z_0 = 0.03$ m [which is typical for stations located in an open, flat terrain with few obstacles nearby, such as most airport stations (see Wieringa 1980)], the wind speed at the 20-m (5 m) level is about 12% higher (lower) than that at the 10-m level (Fig. 3). However, when $Z_0 = 1.0$ m [which is typical for a site with regular large obstacle coverage (see Wieringa 1980)], the wind speed at the 20-m (5 m) level is about 30% higher (lower) than that at the 10-m level (Fig. 3). The effects of surface roughness on wind speed change due to AH changes are well accounted for in the logarithmic wind profile (1), but not in the wind power law (2). This is why the logarithmic wind profile works better for adjusting wind speed data for AH changes.

Our analysis revealed that 114 out of the 117 stations experienced one or several (up to six) occurrences of AH change in the period analyzed. The anemometer heights range from about 5.2 (17 ft) to 31.7 m (104 ft). Such frequent AH changes caused biases in the wind speed data. We removed such biases from the hourly wind speed data using the logarithmic wind profile, along with the exact anemometer heights documented in the special metadata database (Wan and Wang 2006). This metadata database summarizes information related to all of the changes in the observation history that could cause nonclimatic changes in climate data series, from systematically investigating voluminous station inspection reports and other metadata sources (e.g., different versions of MANOBS).

b. *Detecting and adjusting for other systematic errors*

In addition to the AH change, changes in the location and exposure of the observing site or in anemometer

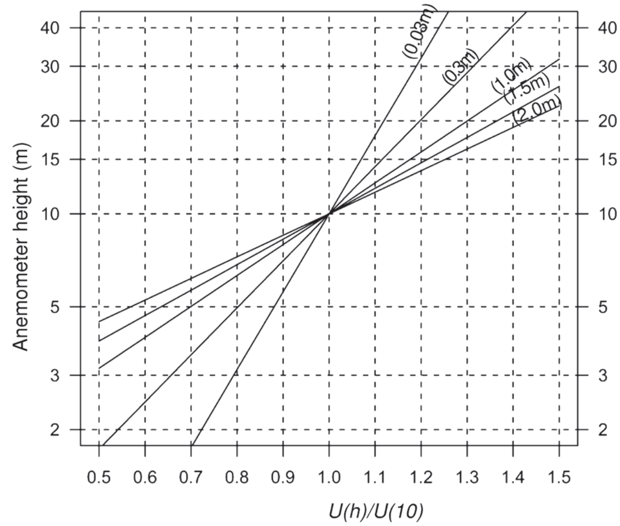

FIG. 3. Nomogram for determining ratios of wind speed at a nonstandard anemometer height (h) over that at the std 10-m height for five different values of surface roughness length Z_0 (Z_0 values are shown in parentheses).

type, or malfunctioning of the instrument, etc., could also cause discontinuities in the wind speed series. Some of these changes are documented in the metadata (such as most AH changes), while others are not, because metadata are often incomplete or unavailable. It is a common practice in climatology to use a statistical method to detect sudden changes (i.e., shifts) in climate data series and to estimate the magnitude of the detected or known shift for use in homogenizing the data series, and to use available metadata to check the veracity of statistically identified shifts (e.g., Wang 2008; DeGaetano 2006; Wang et al. 2006a,b; Peterson et al. 1998; Vincent 1998). In this study, we used the PMTred algorithm (Wang 2008) in a data homogenization software package called RHtestV2 (Wang and Feng 2007) to test the homogeneity of monthly mean wind speed series that were derived from AH-adjusted hourly wind speeds, and to homogenize the monthly series whenever necessary.

The PMTred algorithm (Wang 2008) is for detection and adjustment of mean shifts in time series of zero trend and identically Gaussian-distributed independent or first-order autoregressive [AR(1)] errors. It shall be used with a reference series that is homogeneous and of the same climate signal (including any long-term trend and periodic components) as the base series, so that the underlying assumption (i.e., zero trend and identically Gaussian distributed errors) is largely valid for the time series being tested (i.e., the base-minus-reference series). However, such a reference series is not always available and/or its homogeneity cannot be assumed. Fortunately, Wang (2008) also developed the PMFred algorithm, which is used for the detection and adjustment of mean shifts in time series of a constant trend and identically Gaussian-distributed independent or AR(1) errors. It can be used without a reference series. The PMFred uses iterative procedures to estimate the linear trend, annual cycle, first-order autocorrelation, and mean shifts of the time series in tandem (this procedure is also used in the PMTred functions of the RHtestV2 package to obtain the multiphase regression fit to the base series, including trend estimates; more in section 4b).

As explained above, the PMTred needs to be used with good reference series to diminish the trend and periodic components that may exist in the data series. The most common way to build a good reference series is to use data series from nearby stations; however, this is not appropriate for wind speed data, as shown in Wang (2008). We used monthly mean series of geostrophic wind (geowind hereafter) speed as reference series in this study, because geowind speeds calculated from a pressure triangle can be regarded as a first-order proxy of real wind speeds, and hence storminess over the triangle region (e.g., Schmidt and von Storch 1993; Schmith 1995; Alexandersson et al. 1998, 2000; Wang et al. 2008). Using the method detailed in Wang et al. (2008, their appendix B), we derived geowind series from previously homogenized instantaneous hourly sea level pressure (SLP) data recorded at 26 Canadian stations (Wan et al. 2007) and 7 U.S. stations, which form 49 pressure triangles over Canada (see Fig. 1). Most of the stations that are analyzed are located in one of these triangle regions; the geowind series from the triangle that covers the base station (the station being tested) is used as the reference series (this is usually the geowind series that has the highest correlation with the base series). For stations that are either not in any of the 49 triangles or are right on a boundary between triangles (e.g., those used to build the pressure triangles), we used the geowind series that has the highest correlation with the base series, with the correlation being calculated using the first-order difference series (see Alexandersson and Moberg 1997; Peterson et al. 1998). As shown in the wind example of Wang (2008), these geowind series are much better reference series than the area-averaged wind series that were derived from preliminarily homogenized wind speed series from nearby stations.

Note that a geowind series represents the average wind conditions over the triangle region, while a station wind series represents the wind conditions at a single site. Thus, a geowind speed series often has a more regular and distinct seasonal cycle than does the corresponding station wind speed series; a strong seasonality would remain in the base-minus-reference series if the base and reference series are not deseasonalized in advance. To diminish seasonality from the series being tested, the PMTred algorithm deseasonalizes both the base and reference series (by removing their respective sample annual cycle) before calculating their difference series. The data being tested are the differences between the deseasonalized base series and the deseasonalized reference series (i.e., the difference series).

In this study, we used the data homogenization procedure as described in Wang (2008) and Wang and Feng (2007). First, we used the FindU.wRef function (Wang and Feng 2007) of the PMTred algorithm to identify all type-1 changepoints [i.e., those that are statistically significant even without metadata support (see Wang 2008)]. Then, we added in all potential type-0 changepoints (i.e., those associated with changes documented in the special metadata database), if they were not already identified statistically as significant type-1 changepoints, to determine their statistical significance. The statistical tests were conducted at the 5% level of significance. All of the available metadata were used to verify the veracity of changepoints identified statistically. For obtaining the final estimates of parameters, we replaced the estimated time of shift with the known actual time of shift if there is a small difference (a few months) between them. In the mean time, both the difference and base series are plotted along with their regression fits, and they are visually inspected to help determine whether or not to take a statistically significant changepoint as a real changepoint that will be adjusted. All mean shifts that are determined to be significant were adjusted to obtain homogenized monthly mean wind speed series.

Figure 4 shows an example of applying PMTred to the Charlottetown Airport monthly mean wind speed series. Adjustments for a nonstandard AH were first performed on the hourly wind speed series for the period from 9 October 1958 to 5 August 1970 (adjusting the red curve in Fig. 4a to the black one; the AH changed from 47 to 33 ft; i.e., a 4.3-m change). Then, the PMTred was applied to the difference series shown in Fig. 4b (which was derived after the AH adjustments). As a result, October 1984 was identified as a highly significant changepoint ($PT_{max} = 9.4528 > 3.8226$, the upper bound of the corresponding 95-th percentile of PT_{max}), which is also easily visible in Fig. 4b. According to the related metadata, a new U2A wind system was installed in the new instrument area on 19 September 1984. That is, the estimated time of change (October 1984) in the monthly mean series is only 1 month later than the actual time of change. In this case, we replaced the estimated time of change with the actual time of change in the list of changepoints to estimate the final adjustment for this shift. We adjusted the series to the most recent segment by adding $\Delta_d = -3.0341$ km h^{-1} to all data before October 1984 (Δ_d is

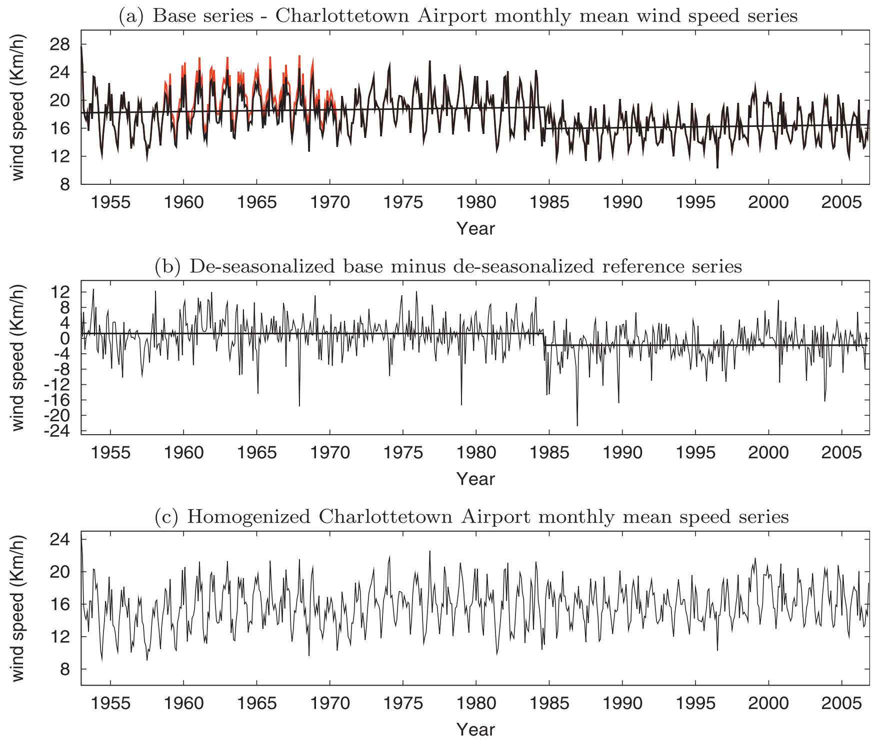

FIG. 4. The Charlottetown Airport (PEI, Canada) wind speed series and the associated base − reference series. (a)–(b) The estimated mean response along with the estimated mean shift (solid lines) are shown, as are (a) the wind speeds before the anemometer height adjustments (red lines).

the shift size estimated from the difference series shown in Fig. 4b). The resulting homogenized monthly mean series is shown in Fig. 4c. The estimated liner trend is 0.0246 km h^{-1} yr^{-1} for the homogenized series, but it is −0.0768 km h^{-1} yr^{-1} for the series before adjusting for the artificial shift in September 1984. That is, the artificial shift would bias the positive trend to a negative one if it were ignored (more examples shown later in section 4).

c. *Main causes for discontinuities in wind speed series*

As mentioned in section 3a, AH change is a very common and influential cause for discontinuities in Canadian wind speed series. Unfortunately, for some stations, the AH adjustments cannot completely diminish the associated systematic bias; the changepoint at the time of an AH change could still be identified to be significant in the AH-adjusted wind speed series. This could result from incomplete/erroneous metadata information or from complications resulting from other concurrent change(s). For example, as shown in Fig. 5a, the small AH change (from 10.7 to 10 m) at the Hay River Airport in December 1970 caused only small biases in the monthly mean wind speed series (see the red curve in Fig. 5a); December 1970 was still identified to be a significant changepoint after the AH adjustments. According to metadata, this station was relocated 488 m (1600 ft) west-southwest of its previous site on 8 December 1970, which was accompanied with a change in station elevation (from 163.7 to 169.5 m), and also a change in anemometer type (from 45B to U2A). The observing surrounding change is speculated to be the main cause for the discontinuity in December 1970; the AH adjustments are relatively trivial in this case. Because an adjustment for the artificial shift caused by the relocation and changes in anemometer type and station elevation needs to be estimated statistically, and the statistical estimate of the compound shift size can also account for the shift resulting from AH change, we applied the PMTred algorithm to the raw wind speed series in this case, accounting for the compound shift using the shift size estimated from the difference series in the PMTred algorithm while discarding the AH adjustment (it would be redundant to adjust the same shift twice). Note that this is relatively rare, because physically based AH adjustments can often diminish the associated bias completely if the AH change was not accompanied by other causes for a shift.

The type of anemometer used in Canada also changed during the study period; and such an anemometer type change was frequently accompanied with relocation and

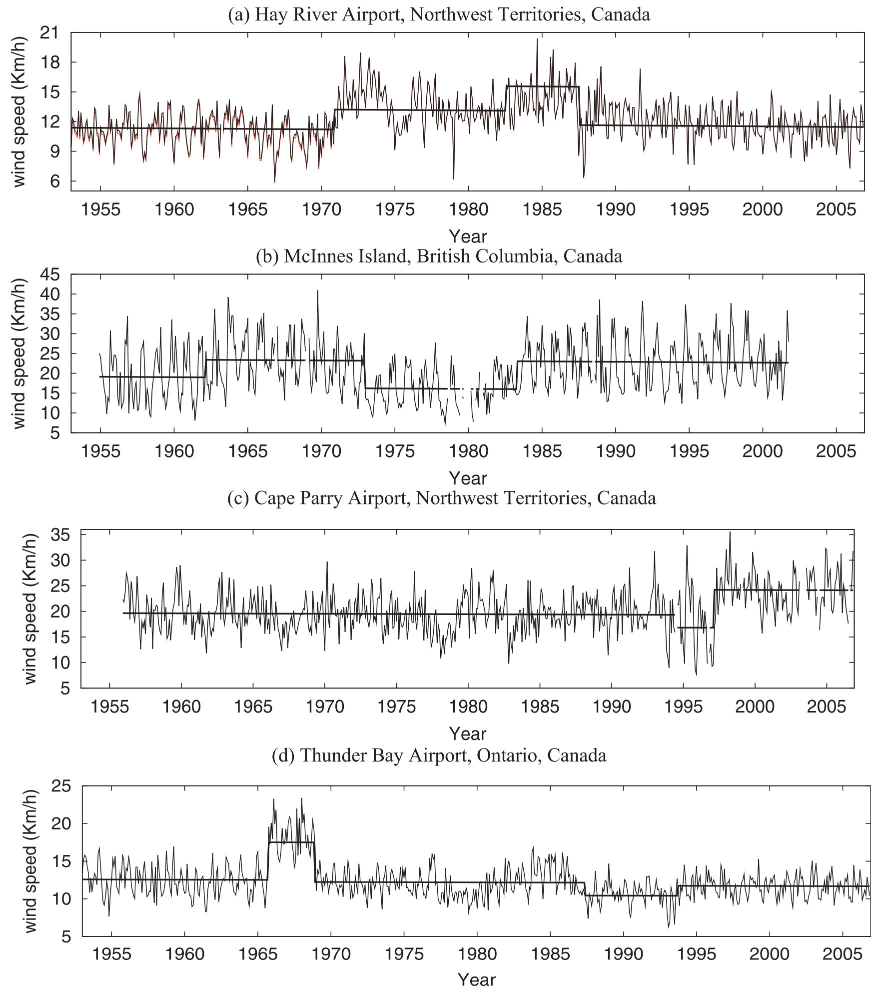

FIG. 5. Monthly mean wind speed series at selected locations. The estimated mean response along with the estimated mean shift(s) is shown (solid line).

an AH change. In Canada, it is very common that an anemometer was moved from a rooftop to a standard 10-m mast at the time when the anemometer type was changed from 45B to U2A. We noticed that anemometer or station relocation always caused a significant discontinuity in the associated wind speed series, even without an accompanying AH change. For example, the anemometer at McInnes Island (British Columbia) was relocated twice, in February 1973 and November 1982; the first relocation was accompanied by an AH change (from 30 to 33 ft, or from 9.1 to 10 m), but the second relocation was not. Nevertheless, both relocations caused a significant mean shift, as shown in Fig. 5b (the other shift, in June 1963, was due to some other undocumented change that was accompanied by an installation of a new anemometer of the same type and at the same height). This is because wind observations are sensitive to the observing environment (including anemometer exposure), which often changes with an anemometer or station relocation. Anemometer type changes alone could also cause significant shifts in wind speed series, especially when the Rosemount pressure anemometer was involved. For example, there were two anemometer type changes at Cape Parry Airport: 1) from U2A to 78D in July 1994, when the station was automated; and 2) from 78D to the Rosemount model in May 1997. Both changes caused a significant shift in the wind speed series, along with a change in the variance, as shown in Fig. 5c (note that changes in variance are very rare in the dataset and are not dealt with in this study. Although a change in variance could have an effect on the estimated significance of trend, it should have little effect on the estimated value of the linear trend, unlike a mean shift that could greatly bias the estimated value of trend). The change from 78D to a Rosemount anemometer in May 1997 caused a much larger shift than the change

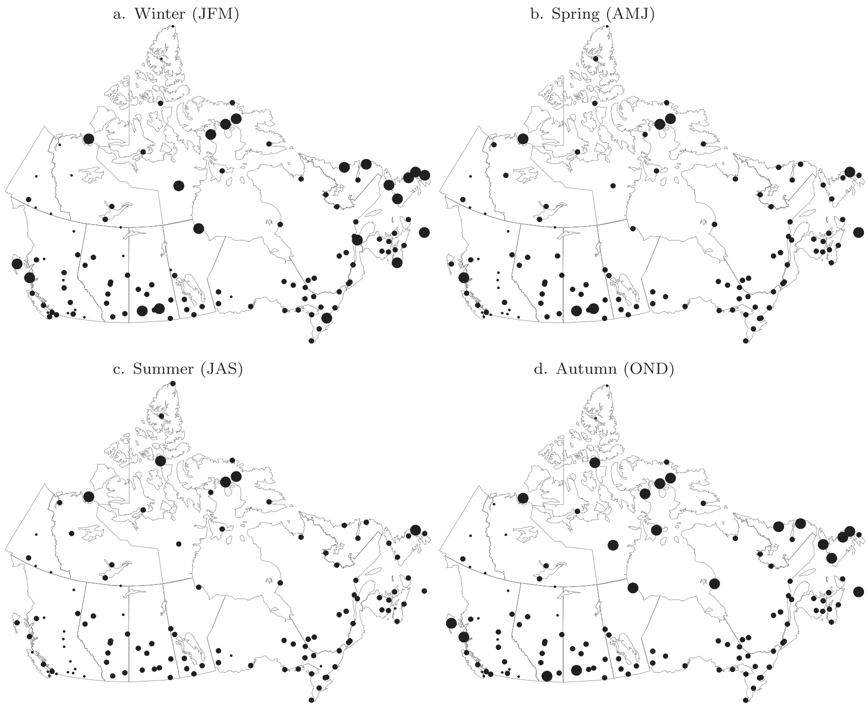

FIG. 6. Long-term means of wind speeds in each season. Indicated are wind speeds of <10 (small dots), 10 to ~20 (medium dots), and >20 (large dots) km h^{-1}.

from U2A to 78D in July 1994; the former can be detected even without metadata support (it is a significant type-1 changepoint), but the latter would not be detected if it was not documented because it is only a significant type-0 changepoint (Wang 2008). Similarly, for wind speeds at Thunder Bay International Airport, a significant shift was found to be associated with an anemometer type change from U2A to 78D in October 1993 (Fig. 5d). This is statistically significant even without metadata support. The other three significant changepoints in this series are in October 1965, December 1968, and June 1987, respectively. Except for the changepoint in June 1987, which is due to anemometer relocation (to 80 m northeast of the previous site), the other two changepoints in the earlier period were found to have no reliable metadata support. However, they are highly significant type-1 changepoints (PT_{max} = 11.124 > 3.425 and PT_{max} = 11.729 > 3.450, respectively), and thus were also adjusted.

Analyzing all occurrences of anemometer type change from 45B to U2A at the 117 stations, we noticed that an anemometer type change from 45B to U2A alone (this situation is very rare) generally does not introduce a discontinuity of any statistical significance (type 1 or type 0) to the monthly mean wind speed series. On the contrary, an anemometer type change from U2A to 78D often caused a significant shift in the monthly mean wind speed time series. As shown in Fig. 5c, and mentioned earlier in this section, a change to a Rosemount pressure anemometer could also cause a highly significant large discontinuity in the monthly mean wind speed series.

We also noticed that hourly wind observations in Canada experienced a system-wide change in wind speed unit (from miles h^{-1} to kt) and in the observing interval (from 1-min mean to 2-min mean) in 1996. DeGaetano (1998) also reported the same changes in hourly wind observations in the United States. However, we found that the unit and observing interval changes did not cause significant mean shifts in the monthly mean wind speed series analyzed in this study.

4. Wind speed climatology, interannual variability, and trends

a. Wind speed climatology and interannual variability

Figure 6 shows the pattern of the long-term mean (over the period analyzed) wind speeds in each of the four seasons of year, separately. The general feature is that it is windier in the Arctic, the west coast of British Columbia, and on the east coast than in the inland part of southern Canada (Fig. 6c). Also, southern Canada is less windy in summer than in other seasons (especially winter; Figs. 6a,c). The least windy area in Canada is seen in the interior of BC in western Canada. The wind speed climatology appears to be homogeneous across

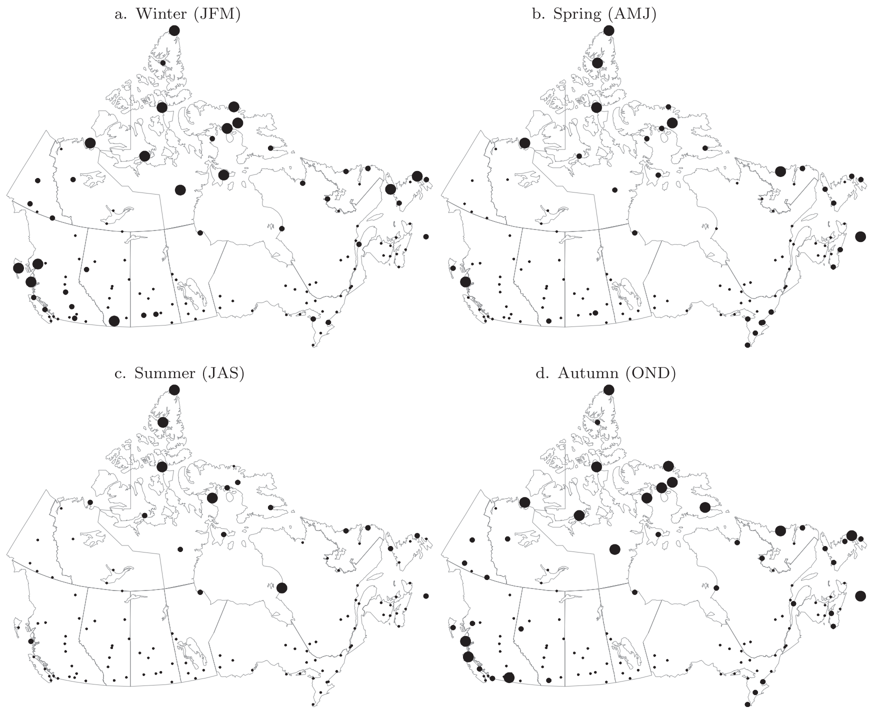

FIG. 7. Interannual variances of wind speed in each season. Indicated are variances of <5 (small dots), 5 to ~10 (medium dots), and >10 (large dots) $km^2\ h^{-1}$.

the Canada–U.S. border, when compared with results shown in Klink (1999a).

The interannual variability of the seasonal mean wind speed is shown in Fig. 7 for each season, separately. The most striking feature is that the Canadian Arctic has much larger variability than most areas in southern Canada, in all seasons. Larger variability is also seen at a few locations in the west and east coasts in the cold seasons (winter and autumn). Slightly larger variability is also seen in southern Ontario in the transition seasons than in summer.

b. Wind speed trends

In this study, linear trend estimates were obtained using the PMFred algorithm (Wang 2008). Because the lag-1 autocorrelation, linear trend, and seasonal cycle (if applicable) were estimated in tandem (see section 3b), the trend estimates shown in this study are robust to the first-order autocorrelation of the respective series. The p value of the linear trend is determined by the t-test statistic of the slope parameter (von Storch and Zwiers 1999). A one-sided t test is used in the RHtestV2 package. Thus, the p value is the probability for an estimated positive trend to be greater than zero, or for an estimated negative trend to be smaller than zero. We also give the 95% confidence interval of the trend estimate, which is a result of a two-sided t test. The probability for the estimated trend to be within the interval is 95%.

We estimated linear trends for the raw, the AH-adjusted, and the homogenized monthly mean series of wind speeds, separately, to show the effects of data discontinuities on trend estimates (Figs. 8a–c). We also estimated linear trends for the monthly mean series of geowind speeds that were used as reference series in the homogenization of wind speed series (Fig. 8d). As shown in Fig. 8c, the pattern of trends estimated for the homogenized monthly mean wind speed series is characterized by significant decreases throughout western Canada and most parts of southern Canada (except the Maritimes), with increases in the central Canadian Arctic and the Atlantic region of Canada. It shows good spatial consistency and is in good agreement with the geowind trends that were derived from homogenized surface pressure data series (Fig. 8d). However, the trends estimated from the raw wind speed series are very different from the trends estimated from either the homogenized wind or geowind speed series, especially in the Arctic, the Maritimes, and the western mountainous regions of Canada (Figs. 8a,c; in these areas the raw and homogenized wind trends are often of the opposite signs). The inconsistency indicates that artificial shifts in the raw wind speed series largely bias the linear trend estimates, as would be expected. Note that the AH-adjusted wind series also show a trend pattern of little spatial consistency (Fig. 8b), which indicates that the removal of biases

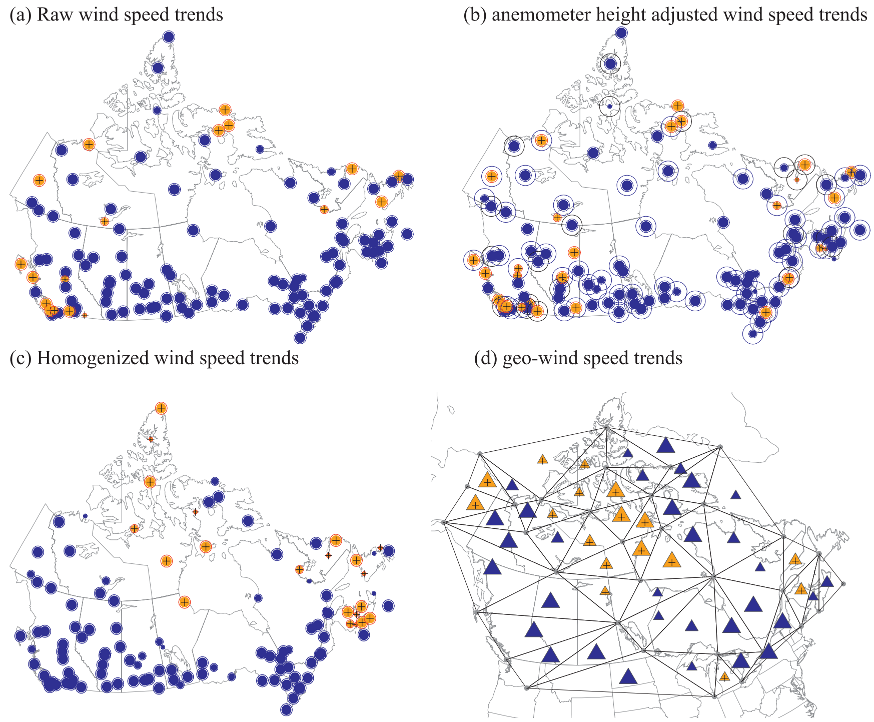

FIG. 8. Linear trends estimated for monthly mean series of (a) raw wind speeds, (b) anemometer height–adjusted wind speeds (the circle indicate station with anemometer height adjustment), (c) homogenized wind speeds, and (d) geowind speeds (the color triangle is plotted at the centroid of the respective pressure triangle). Orange symbols (i.e., dots or triangles) superimposed by a plus sign indicate upward trends, and blue symbols indicate downward trends. Indicated are trends of $p \geq 0.95$ (small dots), $0.80 \leq p < 0.95$ (medium dots), and $p < 0.80$ (large dots).

resulting from AH changes alone did not make the wind speed series homogeneous. To obtain a reliable trend estimate, the data series must be homogenized; all significant data discontinuities therein must be eliminated prior to the trend estimate. All significant shifts shall be accounted for simultaneously in a statistical model, in order to obtain good estimates of the shift sizes and trend. Otherwise, the estimates could be biased by the unaccounted shifts in the series.

Based on the trend pattern shown in Fig. 8c, we derived regional mean series of monthly mean wind speeds in the following eight regions across Canada: (i) the central Canadian Arctic, including Nunavut (NU), except for Baffin Island, and including northernmost Manitoba (the station Churchill; also see Fig. 1 for locations of the provinces and Table 2 for the station list); (ii) Yukon (YT) and Northwest Territories (NT); (iii) British Columbia (BC); (iv) the prairies, including Alberta (AB), Saskatchewan (SK), and Manitoba (MB; except for the northernmost MB station, Churchill); (v) Ontario (ON); (vi) Quebec (QC) and Baffin Island; (vii) the Maritimes, including New Brunswick (NB); Nova Scotia (NS), and Prince Edward Island (PEI); and (viii) Newfoundland and Labrador (NL). Let $\{W_{it}\}$ denote the monthly mean wind speed series at station i, and $\overline{W}_i$ and S_i denote its sample mean and standard deviation over the period of 1970–99, respectively. For a region of m stations, the regional mean series $\{\overline{W}_t\}$ was derived as follows:

$$\overline{W}_t = \overline{W} + \overline{S}\frac{1}{m}\sum_{i}^{m}\overline{W}_t^{\text{std}}, \tag{3}$$

where

$$\overline{W} = \frac{1}{m}\sum_{i}^{m}\overline{W}_i; \quad \overline{S} = \frac{1}{m}\sum_{i=1}^{m}S_i; \quad \overline{W}_t^{\text{std}} = \frac{1}{m}\sum_{i}^{m}W_{it}^{\text{std}};$$

$$W_{it}^{\text{std}} = \frac{W_{it} - \overline{W}_i}{S_i}.$$

Note that this involves a standardization of the monthly wind speed series at each station, separately, before taking the regional average (the superscript "std" is used above to denote a standardized quantity). The standardization here is necessary; without it, a data gap in a station in the region could result in discontinuities in the regional

TABLE 2. The eight regions and the stations in each of these regions (the letter A stands for Airport).

Central Canadian Arctic	Hall Beach A (NU), Cambridge Bay A (NU), Baker Lake A (NU), Alert (NU), Resolute Cars (NU), Coral Harbour A (NU), Eureka (NU), and Churchill A (MB)
Yukon–Northwest Territories	Norman Wells A (NT), Inuvik A (NT), Yellowknife A (NT), Cape Parry A (NT), Hay River A (NT), Fort Smith A (NT), Watson Lake A (YT), Mayo A (YT), Teslin A (YT), and Whitehorse A (YT)
British Columbia	Port Hardy A (BC), Mcinnes Island (BC), Kamloops A (BC), Victoria Int'l A (BC), Princeton A (BC), Quesnel A (BC), Terrace A (BC), Smithers A (BC), Nanaimo A (BC), Abbotsford A (BC), Fort Nelson A (BC), Williams Lake A (BC), Comox A (BC), Prince George A (BC), Kelowna A (BC), Penticton A (BC), Fort St John A (BC), Castlegar A (BC), Sandspit A (BC), and Vancouver International A (BC)
Prairies	Grande Prairie A (AB), Peace River A (AB), Medicine Hat A (AB), Red Deer A (AB), Edmonton City Centre A (AB), Lethbridge A (AB), Edmonton International A (AB), Calgary International A (AB), Fort Mcmurray A (AB), Cold Lake A (AB), Dauphin A (MB), Brandon A (MB), Winnipeg Richardson International A (MB), The Pas A (MB), Flin Flon A (MB), Pilot Mound (AUT) (MB), Estevan A (SK), Regina A (SK), Moose Jaw A (SK), North Battleford A (SK), Yorkton A (SK), Saskatoon Diefenbaker International A (SK), Prince Albert A (SK), and Swift Current A (SK)
Ontario	Muskoka A (ON), Kapuskasing A (ON), London International Airport (ON), Earlton A (ON), North Bay A (ON), Sioux Lookout A (ON), Kenora A (ON), Gore Bay A (ON), Sudbury A (ON), Toronto Lester B. Pearson International A (ON), Timmins Victor Power A (ON), Toronto Island A (ON), Thunder Bay A (ON), Sault Ste Marie A (ON), Red lake A (ON), Wiarton A (ON), Trenton A (ON), Ottawa Macdonald-Cartier International A (ON), and Windsor A (ON)
Quebec and Baffin Island	Clyde A (NU), Longstaff Bluff (NU), Dewar Lakes (NU), Iqaluit A (NU), Val-D'or A (QC), Sept-Iles A (QC), Bagotville A (QC), Montreal A (QC), Schefferville A (QC), Kuujjuaq A (QC), Baie-Comeau A (QC), Rouyn A (QC), Quebec International A (QC), Montreal International A (QC), Roberval A (QC), Kuujjuarapik A (QC), and Mont-Joli A (QC)
The Maritimes	Moncton A (NB), Sable Island (NS), Fredericton A (NB), Yarmouth A (NS), Greenwood A (NS), Shearwater A (NS), Saint John A (NB), Charlottetown A (PEI), Sydney A (NS), and Miramichi A (NB)
Newfoundland and Labrador	St John's A (NF), Hopedale (AUT) (NF), Bonavista (NF), Goose A (NF), Wabush Lake A (NF), Daniels Harbour (NF), Gander International A (NF), Cartwright (NF), and Stephenville A (NF)

mean series, because fewer sample means are available for estimating the regional mean during the data gap period, which could result in a large bias (especially when the station with the data gap has a wind speed climatology that is notably different from that of other stations in the region). The regional mean series of standardized monthly mean wind speeds were scaled back using the regional mean and standard deviation, $\overline{W}$ and $\overline{S}$, so that the resulting regional mean series, shown in Figs. 9a–h (along with their linear trend estimates), can better represent the regional wind speed climatology and variability. Consistent with Fig. 8c, a statistically significant upward trend was estimated for the central Canadian Arctic (Fig. 9a) and an insignificant upward trend was estimated for the Maritimes (Fig. 9g), with downward trends being estimated for all of the other regions. Except for the Newfoundland and Labrador region, where the downward trend is only marginally significant ($p = 0.9277$; Fig. 9h), all of the other downward trends are highly significant (of higher than 99.99% confidence, i.e., $p > 0.9999$; Figs. 9b–f).

Further, in order to determine if there is a seasonality of trends in wind speeds, we also derived seasonal mean wind speed series from the corresponding homogenized monthly mean series for each of the four seasons of the year and carried out the trend analysis on each of these seasonal series. The results are shown in Fig. 10. The largest seasonality of trend is seen in the Maritimes (NS, NB, and PEI in Fig. 1) and northwestern Canada (YT and NT in Fig. 1), with most stations in the Maritimes showing significant increases in spring and autumn but no notable trends in winter, and with most stations in northwestern Canada (YT and NT) showing strong decreases in summer but no notable trends in winter. On the contrary, wind speed in most parts of southern Canada (except the Maritimes) shows a decreasing trend in all seasons, with little seasonality (Fig. 10). Note that the trends in summer wind speeds vary significantly (i.e., change sign) from station to a nearby station in the Maritimes (Fig. 10c). We speculate that this arises from the dominant small-scale features of summer weather regimes, after we double checked and confirmed the homogeneity of these series. Overall, more stations in the Maritimes have a negative wind speed trend in summer than in the

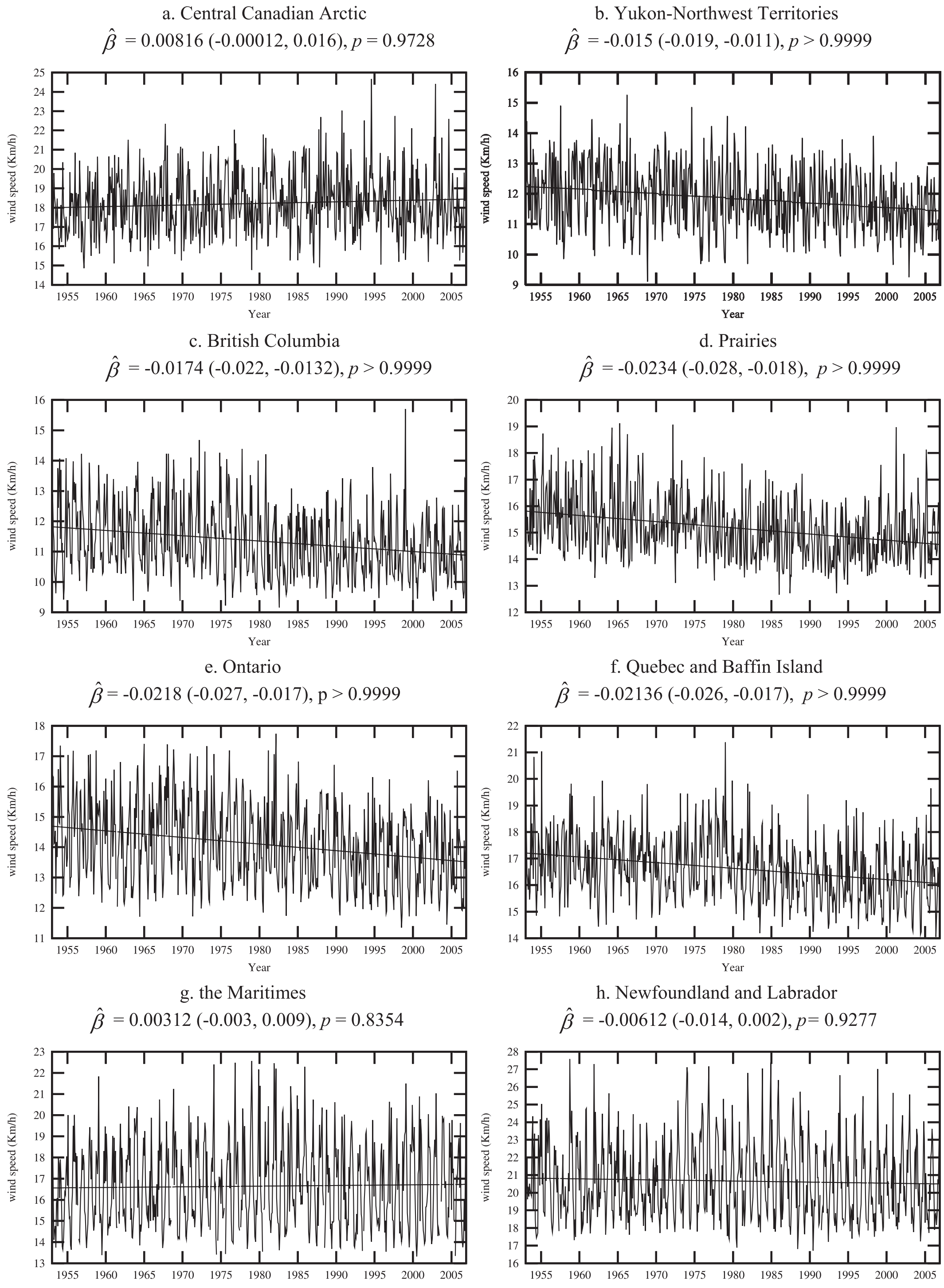

FIG. 9. Regional mean series of monthly mean wind speeds and the corresponding linear trend estimate $\hat{\beta}$ (km h^{-1} yr^{-1}) and its 95% confidence interval (in parentheses) and p value (given on top of each panel).

other seasons, while the trend is dominantly positive in spring and autumn (Fig. 10).

Similar seasonality of trends can also be inferred from the regional mean series of seasonal mean wind speeds, as shown in Table 3. The seasonality of the trend is also strongest in the Maritimes, where the wind speed trend is positive in spring and autumn but negative in other seasons, although the trend is statistically significant

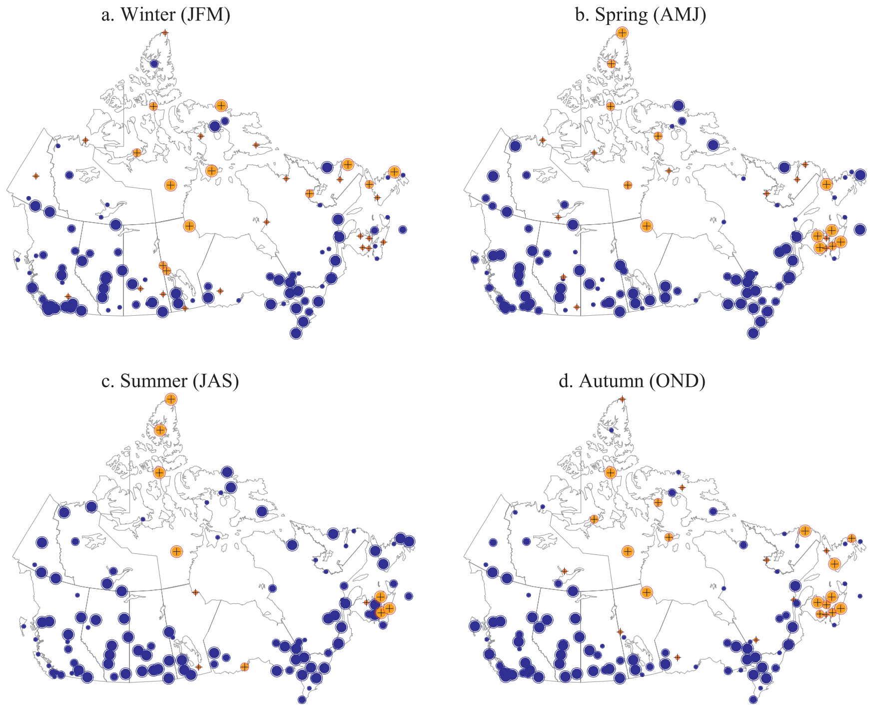

FIG. 10. Same as in Fig. 8, but for linear trends in seasonal mean wind speeds in the indicated seasons.

only in summer (Table 3). The decline in summer wind speeds is highly significant and seen in all regions except the central Canadian Arctic (Table 3). Wind speeds were found to have increased in the central Canadian Arctic in all seasons, although the increases were found to be statistically significant only in autumn and spring (Table 3). Trends estimated from the annual mean series (Table 3) are consistent with the trends estimated from the corresponding consecutive monthly mean series shown in Fig. 9. A statistically significant upward trend is seen in the central Canadian Arctic, but downward trends are seen in all other regions. The downward annual trend is highly significant almost everywhere except the Maritimes.

TABLE 3. Linear trend estimates $\hat{\beta}$ (km h^{-1} yr^{-1}), their p values, and 95% confidence interval (in parentheses below) for regional mean series of seasonal mean wind speeds. Trends of $p \geq 0.95$ are in bold.

Region	Winter		Spring		Summer		Autumn		Annual	
	$\hat{\beta}$	p	$\hat{\beta}$	p	$\hat{\beta}$	p	$\hat{\beta}$	p	$\hat{\beta}$	p
Central Canadian Arctic	0.00765	0.8683	**0.00958**	0.9727	0.00029	0.5136	**0.0160**	0.9896	**0.0102**	0.9880
	(−0.0059, 0.0212)		(−0.0002, 0.019)		(−0.017, 0.017)		(0.0025, 0.029)		(0.0014, 0.019)	
Yukon–Northwest Territories	**−0.0122**	0.9783	**−0.01775**	0.9999	**−0.02298**	1.0000	**−0.0171**	0.9994	**−0.0185**	1.0000
	(−0.024, −0.0004)		(−0.0267, −0.009)		(−0.032, −0.014)		(−0.027, −0.007)		(−0.0248, −0.012)	
British Columbia	**−0.02390**	1.0000	**−0.01653**	1.0000	**−0.01228**	1.0000	**−0.0260**	1.0000	**−0.0181**	1.0000
	(−0.033, −0.015)		(−0.024, −0.009)		(−0.018, −0.006)		(−0.035, −0.017)		(−0.0226, −0.014)	
Prairies	**−0.02084**	0.9999	**−0.02266**	0.9996	**−0.02253**	1.0000	**−0.0301**	1.0000	**−0.0257**	1.0000
	(−0.032, −0.01)		(−0.035, −0.01)		(−0.036, −0.018)		(−0.041, −0.019)		(−0.032, −0.019)	
Ontario	**−0.02318**	1.0000	**−0.0242**	1.0000	**−0.02178**	1.0000	**−0.0223**	1.0000	**−0.0208**	1.0000
	(−0.033, −0.013)		(−0.031, −0.017)		(−0.028, −0.016)		(−0.032, −0.012)		(−0.027, −0.015)	
Quebec and Baffin Island	**−0.01898**	0.9992	**−0.02210**	1.0000	**−0.03553**	1.0000	**−0.0169**	0.9994	**−0.0214**	1.0000
	(−0.03, −0.007)		(−0.032, −0.012)		(−0.045, −0.026)		(−0.027, −0.007)		(−0.029, −0.014)	
The Maritimes	−0.0075	0.8668	0.00232	0.712	**−0.00926**	0.996	0.00522	0.8106	−0.0030	0.8631
	(−0.021, 0.006)		(−0.006, 0.01)		(−0.016, −0.002)		(−0.007, 0.017)		(−0.008, 0.0025)	
Newfoundland and Labrador	−0.00305	0.6512	**−0.01415**	0.9979	**−0.02748**	1.0000	−0.0084	0.8606	**−0.0094**	0.9578
	(−0.019, 0.013)		(−0.024, −0.005)		(−0.037, −0.018)		(−0.02, 0.007)		(−0.02, 0.001)	

The decline of wind speeds in southern Canada is consistent with the findings of previous studies. For example, Tuller (2004) reported a weakening in the wind at three west coast stations in Canada. Klink (1999b) also noted decreases in mean monthly minimum wind speeds at northwestern U.S. stations over the period of 1961–90. Declines in wind speeds have also been reported in a range of midlatitude regions, including Australia, China, Europe, and North America (McVicar et al. 2008).

The estimated wind speed trends are also consistent with the reported trends in cyclone activity over Canada. In an analysis of 3-hourly pressure tendencies derived from surface observations for the period of 1953–2002, Wang et al. (2006a) reported that winter cyclone activity has become significantly more frequent and stronger in the lower Canadian Arctic, but less frequent and weaker in southern Canada. Wang et al. (2006b) also showed a northward shift of winter storm track over Canada, using two global reanalysis datasets. The consistency arises from the fact that cyclone activities are often associated with windy conditions, although not all windy conditions are associated with cyclone activity.

An increasing trend in frequencies of tropical cyclones entering Canadian waters and landfalling in the Atlantic provinces beginning in 1995 has also been reported (Environment Canada 2005), corresponding to the increase in tropical cyclone frequency elsewhere in the western Atlantic. In the tropics, tropical cyclones generally affect smaller areas and a change in frequency might not be expected to impact regional monthly means. However, in about half of the cases, when tropical cyclones move into the middle latitudes, they transition into extratropical systems (Hart and Evans 2001), which do increase winds over a greater spatial extent. Tropical cyclone frequency peaks in September. Thus, increases in wind speeds in the Maritimes in summer [July–September (JAS)] and autumn [October–December (OND)] could have resulted from increases in tropical (and transitioning or post-tropical) cyclone frequency. This is also consistent with the reported increases in ocean wave heights south of NS in autumn (Wang and Swail 2002).

The significant and persistent upward trends in wind chill temperatures (toward less cold) over Alaska and northwestern Canada during the period of 1953–93 (Keimig and Bradley 2002) are also consistent with the downward trends in wind speeds in northwestern Canada. Wind chill temperature can be defined as "the temperature that would, with no wind, produce a heat loss from human skin equivalent to the loss produced by the ambient air temperature and ambient wind" (Keimig and Bradley 2002). Wind chill temperatures increase (less cold) as wind speeds decrease, which makes sense physically. Although we know little about the relationship between wind speeds and air temperatures, their trend patterns share some sort of similarity. The reported strong warming for the period of 1950–98 in southwestern Canada (Zhang et al. 2000) is associated with decreasing wind speeds, while the cooling in northeastern Canada (NU and NL) in winter (Zhang et al. 2000) corresponds to increasing wind speeds.

5. Summary and discussion

We have homogenized monthly wind speed series for 117 stations in Canada for the period from 1953 to 2006. First, we used metadata and a logarithmic wind profile to adjust hourly wind speeds measured at nonstandard anemometer heights to the standard level. Then, we derived monthly mean wind speed series from the AH-adjusted hourly wind speeds and tested the homogeneity of these monthly series, using homogeneous monthly mean geowind speed series as reference series. Artificial mean shifts in monthly wind series were then adjusted using the results of statistical tests/modeling along with available metadata.

The results of homogeneity analysis show that relocation and AH changes are the main causes for discontinuities in the wind data series, followed by instrumentation problems or changes, and observing environment changes. In the period analyzed, 97% of the stations analyzed in this study experienced from one to six occurrences of AH change. The results of the homogeneity test suggest that, even after all necessary AH adjustments, only 32 of the 117 series can be considered homogeneous at the 5% level of significance.

We have shown that the effects of artificial mean shifts on the results of trend analysis are notable. We argue that the homogenized wind speed trends are more realistic and reliable, because the homogenized series show good spatial consistency of trends, which are in agreement with trends that were estimated from independent datasets, such as the wind speed trends across the border in the United States and wind chill temperature trends in North America (Klink 1999b; Keimig and Bradley 2002). These indicate success in the wind speed homogenization. Regarding the estimated linear trends over the period analyzed, the homogenized wind speed series show significant decreases throughout western Canada and most parts of southern Canada (except the Maritimes) in all seasons, with significant increases in the central Canadian Arctic in all seasons and in the Maritimes in spring and autumn.

Again, a geowind series represents the average wind conditions over the triangle region, while a station wind series represents the wind conditions at a single site.

Although the two variables should share the same long-term trend, they may be very different in terms of their absolute values (e.g., the difference in annual cycle mentioned in section 3b). High-quality surface wind speed data for specific sites are needed and used in many applications, such as building codes and wind farm planning, etc. They cannot be replaced by geowind speed data.

Changes in wind speeds are influenced by changes in a variety of factors, such as cyclone activity, pressure gradient, and air temperature, etc., which are associated with major atmospheric circulation regimes. For example, cyclone activity in Canada was found to be closely related to the North Atlantic Oscillation (NAO), especially in winter and autumn (Wang et al. 2006a). In winter [January–March (JFM)], the simultaneous NAO–cyclone frequency relationship is significantly negative in southeastern Canada (the Great Lakes area, Quebec, e Maritimes, and the NL region) but positive in northwestern-central Canada. Autumn (OND) cyclone activity in southeastern Canada is also negatively correlated with the simultaneous NAO index (Wang et al. 2006a). A study on the relationships between Canadian wind speeds and major circulation regimes [including the Arctic Oscillation (AO), NAO, Pacific decadal oscillation (PDO), and ENSO] is presently underway.

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