

Observed surface wind speed trends from homogenized in situ data and reanalysis datasets

Xiaolan L. Wang, Yang Feng, Victor Isaac, Francis W. Zwiers, Lucie A. Vincent & Megan M. Hartwell

2026

Pacific Climate Impacts Consortium (PCIC)

PCIC Publications

© 2025 His Majesty, the King in Right of Canada, as represented by the Minister of Environment. This is an open access article distributed under the terms of the CC BY-NC-ND license: <https://creativecommons.org/licenses/by-nc-nd/4.0/>

Original citation:

Wang, X. L., Feng, Y., Isaac, V., Zwiers, F. W., Vincent, L. A., & Hartwell, M. M. (2026). Observed surface wind speed trends inferred from homogenized in situ data and reanalysis datasets. *Atmosphere-Ocean*, 64(2), 115–131. <https://doi.org/10.1080/07055900.2025.2570920>

Downloaded from UVicSpace Research & Learning Repository


dspace.library.uvic.ca



University
of Victoria

Libraries

Observed Surface Wind Speed Trends Inferred from Homogenized In Situ Data and Reanalysis Datasets

Xiaolan L. Wang ^{1,*}, Yang Feng¹, Victor Isaac¹, Francis W. Zwiers², Lucie A. Vincent¹, and Megan M. Hartwell¹

¹*Climate Research Division, Environment and Climate Change Canada, Victoria, Canada*

²*Pacific Climate Impacts Consortium, University of Victoria, Victoria, Canada*

[Original manuscript received 5 May 2025; accepted 20 September 2025]

ABSTRACT *This paper describes the development of an updated Canadian homogenized monthly mean wind speed dataset, CanHomW mlyV2, for the period 1953–2023 and characterizes observed changes in surface wind speed across Canada. Hourly data from 154 stations in Canada were first quality controlled and adjusted for any non-standard anemometer heights. Then, monthly mean wind speed series were derived and subject to a semi-automated comprehensive data homogenization procedure to identify and diminish non-climatic changes. The procedure uses a combination of station metadata and multiple statistical tests with and without using reference series. The results of the automated procedure were reviewed manually. All of the 154 data series were identified to have one or more non-climatic changes, which were diminished by quantile matching adjustments. Station relocation and/or joining (i.e. joining of different stations' data records into one data series), and instrument changes/problems were found to be the main causes of non-climatic changes.*

The homogenized dataset shows weakening winds in a large part of southern Canada (spanning from the southern Prairies to Labrador) and strengthening winds in most other regions, particularly in the area that spans south-central British Columbia to the Rocky Mountains. The weakening winds in the southern Prairies are also seen consistently in the three modern reanalysis datasets (ERA5, OCADA, 20CRv3), while the four datasets show inconsistent trends in most of the other regions. The Canadian wind trends show notable seasonality, as do the agreement/disagreement among the four datasets.

RÉSUMÉ [Traduit par la rédaction] *Le présent article décrit l'élaboration d'un ensemble de données homogénéisées mises à jour sur la vitesse moyenne mensuelle du vent au Canada, CanHomW mlyV2, pour la période 1953–2023, et caractérise les changements observés dans la vitesse du vent à la surface à travers le Canada. Les données horaires provenant de 154 stations au Canada ont d'abord fait l'objet d'un contrôle de qualité et d'un ajustement pour tenir compte des hauteurs non standard des anémomètres. Ensuite, des séries de vitesses moyennes mensuelles du vent ont été calculées et soumises à une procédure semi-automatisée d'homogénéisation complète des données afin d'identifier et de réduire les variations non climatiques. La procédure utilise une combinaison de métadonnées de station et de multiples tests statistiques avec et sans utilisation de séries de référence. Les résultats de la procédure automatisée ont été vérifiés manuellement. Les 154 séries de données ont toutes été identifiées comme présentant un ou plusieurs changements non climatiques, qui ont été atténués par des ajustements par appariement quantile. Le déplacement et/ou le regroupement des stations (c'est-à-dire le regroupement des enregistrements de données de différentes stations en une seule série de données) et les changements/problems liés aux instruments se sont avérés être les principales causes des changements non climatiques.*

L'ensemble de données homogénéisées montre un affaiblissement des vents dans une grande partie du sud du Canada (du sud des Prairies au Labrador) et un renforcement des vents dans la plupart des autres régions, notamment dans la zone qui s'étend du centre-sud de la Colombie-Britannique aux Rocheuses. L'affaiblissement des vents dans le sud des Prairies est également observé de manière constante dans les trois ensembles de données de réanalyse modernes (ERA5, OCADA, 20CRv3), tandis que les quatre ensembles de données montrent des tendances incohérentes dans la plupart des autres régions. Les tendances éoliennes canadiennes présentent une saisonnalité notable, tout comme la concordance/discordance entre les quatre ensembles de données.

KEYWORDS surface wind speeds; homogeneity tests; data homogenization; trend analysis; reanalysis data; climate change

*Corresponding author's email: xiaolan.wang@ec.gc.ca

© 2025 His Majesty, the King in Right of Canada, as represented by the Minister of the Environment. Published by Informa UK Limited, trading as Taylor & Francis Group. This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

1 Introduction

Recent studies have shown a decreasing trend in the observed surface wind speeds over land since the mid-twentieth century, which was somewhat reversed in the recent decade or so. For example, decreasing trends in surface wind speed were observed in Canada (Wan et al., 2010), the United States (Klink, 1999; Pryor et al., 2009), Europe (Dumitrescu et al., 2015; Earl et al., 2013; Brázdil et al., 2017), Western Asia (Dadaser-Celik & Cengiz, 2014), China (Fu et al., 2011; Guo et al., 2011) and Australia (McVicar et al., 2008). Such a decreasing trend has been referred as global stilling (Kim & Paik, 2015; McVicar et al., 2012; Zeng et al., 2019; Zhang & Wang, 2020). The term wind stilling was introduced for the first time by Roderick et al. (2007) to refer to a slowdown in wind speed in Australia. The causes of terrestrial stilling have been related to an increase in surface roughness due to forest and vegetation growth (Vautard et al., 2010), urbanization (Wu et al., 2016), and instruments issues (Wan et al., 2010). Several studies have also found that the decadal variability of large-scale atmospheric/oceanic circulation modes were important drivers in the wind speed variation during the past three to five decades (Coburn, 2021; Kodama et al., 2021; Zhang et al., 2019; Azorin-Molina et al., 2014; Minola et al., 2016).

Some recent studies have also reported that the wind stilling trend was reversed in the recent decade or so. For example, reversing trends were detected in Saudi Arabia for 2002–2013 (Azorin-Molina et al., 2018), in China for 1970–2005 (Zhang & Wang, 2020), and in South Korea for 2003–2013 (Kim & Paik, 2015), in Sweden for 1979–2008 during the cold season (Minola et al., 2016), and in Spain and Portugal for 1979–2008 during the warm season (Azorin-Molina et al., 2014). Wind data from worldwide stations have indicated that the stilling has reversed around 2010 and that global wind speeds over land have recovered (Zeng et al., 2019). Ships wind observations have also revealed an increasing trend in wind speed over the oceans (Thomas et al., 2008; Young et al., 2011). The reversal of wind stilling over the Tibetan Plateau region in China has been given the cause that wind over high elevations responds more rapidly to warming and atmospheric circulation changes (Lin et al., 2013). The reversal also indicates a need to reassess wind speed trends and variability as more data become available.

Moreover, robust assessment of long-term wind speed trends is crucial for many applications. For example, wind is a practical source of energy generation (Sailor et al., 2008; Palutikof et al., 1987). Wind power has a history in Canada dating back many decades. As of December 2019, wind power generating capacity was 13,413 megawatts, providing about 6% of Canada's electricity, and the Canadian Wind Energy Association has outlined on its website a future strategy for wind energy that would reach a capacity of 55 gigawatts by 2025, meeting 20% of the country's energy needs (Canadian Renewable Energy Association – Wind. Solar. Storage. (renewablesassociation.ca) (<https://renewablesassociation.ca/>)).

Wind energy generation capacity has been installed in northern Ontario (Arriaga et al., 2013) and northern Quebec (Hooshangi, 2014) amongst many other locations. Further, wind speed analysis is also important for informing airport operation and safety. Wind speeds are also widely used in other applications such as building codes (Canadian Commission On Building And Fire Codes, 2015). For coastal regions, the surface wind speed can affect regional wave conditions and coastal erosion processes and can contribute to surges which may cause flooding along the coastlines (Small et al., 2011; Wang et al., 2021). In situ wind data are also used to calibrate remote surface wind measurement methods (e.g. Stoffelen, 1998).

Unfortunately, in-situ measurements of wind speed are prone to several sources of systematic error. One significant example is the sensitivity of wind speed measurement on sensor placement, where exposure issues can introduce significant bias. For example, an average wind speed difference of up to $15\pm 7\%$ was observed between the well-exposed and obstructed anemometers (Wieringa, 1980). In general, long-term wind speed data series are subject to inhomogeneities resulting from station/anemometer relocations, and changes in anemometer height, instrumentation and observing environment (Pryor et al., 2009; Turner et al., 2019). For Canada, Wan et al. (2010) produced the first set (referred to as version 1 or V1) of homogenized monthly mean surface wind speed series for 117 stations across Canada covering the period 1953–2006. They found that station relocations and changes in the anemometer height are the main causes of inhomogeneities in wind speed time series. Such discontinuities (inhomogeneities) must be detected and diminished through a process called climate data homogenization that allows climate data records to represent the local climate, trend, and variability more realistically. Thus, homogenization of wind speed data time series has become an important component of climate analysis (Azorin-Molina et al., 2014; Azorin-Molina et al., 2018; Minola et al., 2016; Turner et al., 2019; Wan et al., 2010; Zhang & Wang, 2020).

This study aims to assess large scale changes in mean wind speed conditions over Canada using a homogenized wind speed dataset. Thus, its first objective is to produce a homogenized monthly wind speed dataset that covers the period to date. Considering that homogenization methods that work well for data from an observing network of high station density will not be suitable for a network of low station density, this study adopts a semi-automated comprehensive data homogenization procedure that was developed specifically for homogenization of data from Canada's observing networks of low station density to produce version 2 (V2) of a homogenized monthly mean wind speed dataset for Canada. The V2 dataset contains more stations (154 vs. 117) and covers a longer period than the V1 dataset of Wan et al. (2010) and was produced using a new comprehensive homogenization procedure with much more metadata and more reference series. Table 1 compares the techniques and data used in Wan et al. (2010) and in this study. We also

TABLE 1. Method and data differences between this study and Wan et al. (2010).

	Wan et al. (2010)	Present study
Number of stations analysed	117	154
Period analyzed	1953–2006	1953–2023 (17-year longer)
Changepoint detection procedure	Used the functions in the RHtestsV2 software package.	A newly developed semi-automated procedure that includes testing with and without using reference series, accounting for both documented and undocumented changepoints. It is based on the RHtestsV4 package.
References used in changepoint detection	Geostrophic wind speed series from 49 triangles over Canada (Fig. 1).	Four approaches synthesized: (1) the 49 geostrophic wind speed series, (2) four nearest best correlated neighbour stations' data series, (3) 20CRv3 ensemble-mean monthly wind speeds at gridpoints nearest to each station, (4) no reference.
Significance level for changepoint testing	5%	1% (except for points of station joining and/or relocation)
Data homogenization method	Mean adjustments	Quantile matching adjustments (with short segments being mean-adjusted first)
Trend estimation method	Least squares method that accounts for lag-1 autocorrelation (Wang, 2008a)	A variant of Sen's non-parametric slope estimator and Mann-Kendall trend significance test that accounts for lag-1 autocorrelation in the data series (Wang & Swail, 2001)
Reanalysis datasets used	None	Three modern reanalysis datasets were used: ERA5, OCADA, 20CRv3

assess/characterize observed trends in wind speed using the newly homogenized monthly wind speed dataset that covers up to the year 2023 and thus enables assessment of more recent changes in wind speed. Trends from the station dataset are also compared with their counterparts in three modern reanalysis datasets.

The remainder of the paper is organized as follows. Section 2 introduces the source datasets, and Section 3, the data preparation procedures. Section 4 describes the data homogenization procedure, and Section 5, the characteristics of the identified changepoints. Section 6 presents the wind speed trends over Canada, including the effects of non-climatic changes on trend analysis results. Section 7 completes this article with a summary and some discussions.

2 Source datasets

a Source Wind Speed Data

This study utilizes hourly surface wind speed data from the 154 stations shown in Fig. 1. These stations were selected to provide the greatest spatial coverage while assuring that at least 50 years of continuous observations in the period 1953–2023 were present at a location and that the data cover at least up to year 2021 (only two stations end in 2021, and four stations end in July or August 2023). The data were taken from the Environment and Climate Change Canada (ECCC) Digital Archive of Canadian Climatological Data, which contains wind speed values converted to kilometres per hour (km h^{-1}). These data represent the average wind speed in the two-minute interval ending at the hour of observation (Environment Canada, 2015). The data primarily originate from stations operating the Meteorological Service of Canada (MSC) Type 45B, U2A and digital 78D anemometer systems (Environment Canada, 1977, 2015). The 45B (Koren, 1971) is usually connected to a step recorder with a speed indicator lamp and the observer needs to estimate the hourly wind speed using the number of flashes of the lamp. The U2A is equipped with direct dials and/or chart recorders; it produces basically instantaneous values of wind speed and direction. The 78D has a built-in microcomputer to sample and calculate 5-second vector components of wind for averaging to produce the wind speeds that are recorded hourly. More details about these anemometer systems and how wind speed observations are recorded by each system can be found in Section 2 of Wan et al. (2010) and the Manual of Surface Weather Observations (Environment Canada, 1977, 1996, 2015). All three systems use cup-based sensors that rely on cup-wheel measurements and are therefore prone to a host of mechanical issues. For example, ice accretion can hinder cup motion and result in the anemometer readings that are too low or even zero if ice accretion causes the cups to seize completely (Environment Canada, 2015). This highlights the need for careful quality control of such data.

For comparison, this study also used surface wind speed data taken from three recent reanalysis datasets: ERA5, 20CRv3, and OCADA. ERA5 is the fifth-generation atmospheric reanalysis of the global climate produced by the European Centre for Medium range Weather Forecasting (ECMWF) (Hersbach et al., 2020). It uses an extensive archive of historical in situ and satellite observations (including wind observations from ships, buoys, radar, radiosondes, and aircrafts) and provides high resolution (~ 31 km) analyses of the full atmospheric state for 1940 to the present (we did not use the data before 1948 due to inhomogeneity concerns). 20CRv3 is the US National Oceanic and Atmospheric Administration (NOAA) Twentieth Century Reanalysis version 3 (Slivinski et al., 2019). OCADA is the Over-Centennial Atmospheric Data Assimilation (OCADA) reanalysis produced by Japanese institutions (Ishii et al., 2024). Both 20CRv3 and OCADA provide century-long reanalyses of

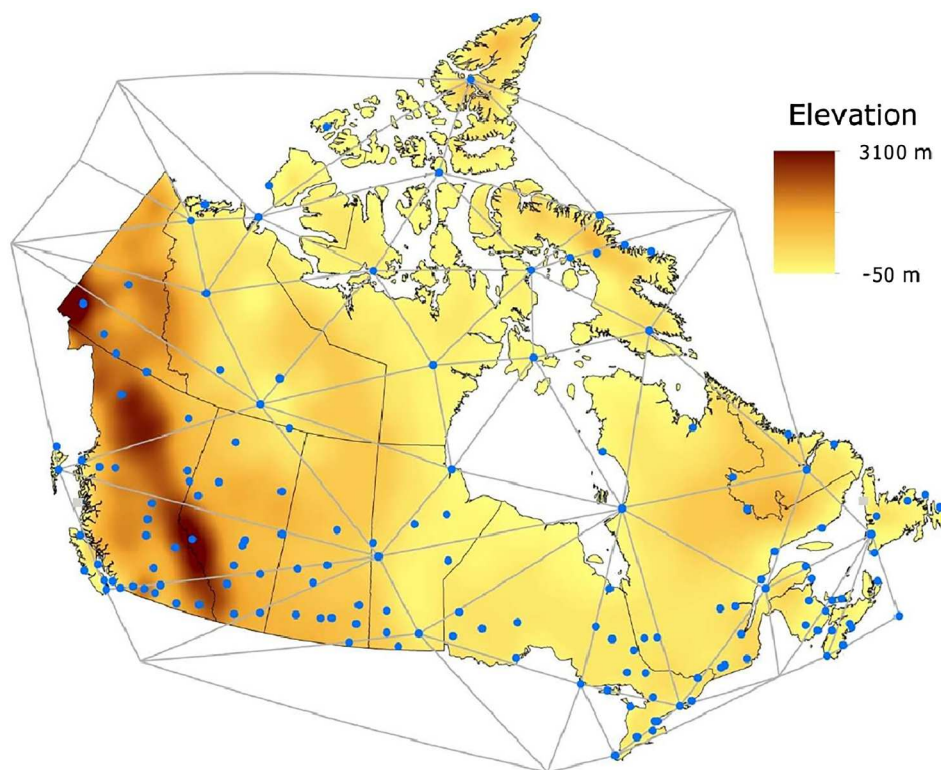


Fig. 1 The 154 stations (blue dots) analyzed in this study and the 49 triangular regions defined for calculating geostrophic wind speeds using previously homogenized sub-daily surface pressure data from the stations at the triangle vertices.

moderate resolution (~ 75 km for 20CRv3, ~ 60 km for OCADA) for the period from 1850 to 2015 (1836–2015 for 20CRv3) by assimilating only atmospheric surface pressure observations and tropical cyclone best track data, with perturbed sea surface temperature and sea ice observations acting as a source of observational uncertainty. The ensemble-mean monthly mean wind speeds of 20CRv3 and of OCADA for the period 1900–2015 were used in this study.

b *Joining of In Situ Hourly Wind Speed Data Series*

Data for a given location are often stored in the ECCC digital archive under a few different station climate identifiers (ClimIDs), since major changes at a station are often marked with a ClimID change. Vincent et al. (2020) discusses this issue in detail, giving examples such as station relocation, automation, and the adoption of new quality control practices as reasons for ClimID changes. To create long-term hourly series for a site, it is therefore often necessary to combine data stored under several ClimIDs. Such combined series are referred to as joined series.

All 154 station data series analyzed in this study are joined series, with some joined series containing more than two station ClimIDs. Since such joins often represent major equipment, procedural, or instrument exposure changes, all times of station joining were recorded as potential documented changepoints for testing their statistical significance during homogenization procedure (see details below).

c *Wind Gust and Surface Roughness Length Data*

Daily extreme gust values taken from the ECCC Digital Archive were also used in quality control (QC) of the station (in situ) wind speed data analyzed in this study. Here, a gust is defined as a measured wind speed that is both 9.26 km h^{-1} (5 knots) higher than the current two-minute average and has a peak of at least 27.78 km h^{-1} (15 knots) (Environment Canada, 2015). Wind gust measurements are also converted to km/h in the archive.

A logarithmic wind profile formulation is used to adjust in situ wind speeds from non-standard anemometer heights (see Section 3a below), which requires surface roughness length data. The values used in this study were the same as in Wan et al. (2010) and originate from a modified geophysical field generator developed by the Canadian Meteorological Centre. The values are based on the vegetation type contained within each 5° latitude by 5° longitude box within a grid and are assumed to remain constant over the time scales utilized in this study, as described in Wan et al. (2010). Note that this approach is only used to make initial adjustments. The adjusted data series are subsequently subject to further homogeneity tests and adjustments (see Section 3a below), which diminish the remaining differences, if any, including those that could arise from the use of constant surface roughness lengths of coarse resolution. The homogeneity adjustments (see Section 4b below) homogenize the whole distribution of data, including inhomogeneities in seasonal cycle arising from seasonal variation of surface roughness

lengths (e.g. due to seasonal changes in vegetation or snow cover).

d Reference and Metadata

This study used the monthly geostrophic wind speed series derived from previously homogenized surface pressure observations (Wan et al., 2007) as reference series for testing the homogeneity of the station wind speed series. Geostrophic wind speeds were computed as in Wan et al. (2010), which followed Wang et al. (2009) (see their Appendix B), but with updated pressure data series from the ECCC Digital Archive for Canadian stations and from the International Surface Pressure Databank (Cram et al., 2015) for stations in the United States and Greenland. Joining of nearby stations was needed and done at a few locations, with all the time-points of station joining being tested to ensure homogeneity. Geostrophic wind components are calculated as

$$u_g = -\frac{b}{\rho f} \text{ and } v_g = \frac{a}{\rho f}$$

where ρ is the density of air ($\rho = 1.25 \text{ kg/m}^3$), f is the Coriolis parameter, constants a and b are determined by solving the following equation with the three instantaneous pressure values (P_1, P_2, P_3) for the same hour at the three stations forming a triangle (Schmith, 1995):

$$\begin{cases} P_1 = aR\lambda_1 \cos\varphi_1 + bR\varphi_1 + c \\ P_2 = aR\lambda_2 \cos\varphi_2 + bR\varphi_2 + c \\ P_3 = aR\lambda_3 \cos\varphi_3 + bR\varphi_3 + c \end{cases}$$

where R is the radius of the earth, and λ_i and φ_i are the longitude and latitude (in arch degrees) of site i (see Appendix B of Wang et al. (2009) for more details). If the three stations forming a triangle do not have observations for the same set of hours (e.g. 06:00, 12:00, 18:00 for two stations, 05:00, 11:00, and 17:00 for the third station), a natural spline was fitted and used to interpolate surface pressure observations to the common hours (06:00, 12:00, 18:00 in the above example).

All the 49 monthly mean geostrophic wind speed series (for the 49 triangles shown in Fig. 1) were subject to a homogeneity testing without using a reference series. Almost all of these series were found to be homogeneous, with only the series for triangles 7 and 21 requiring adjustment due to inhomogeneities that were detected at 1% significance level (both are due to station joining). Before being used as a reference series to test the homogeneity of a surface wind speed series (base series), the geostrophic wind series was adjusted/homogenized and scaled to have the same mean and standard deviation as the base series.

Since the pressure triangles (Fig. 1) are large, geostrophic wind speed series are not always suitable for use as reference, especially for areas of complex topography. Therefore, this study also used up to five other reference series,

including the 20CRv3 ensemble-mean monthly mean wind speed series at the nearest grid-point, as well as up to four significantly correlated data series from neighbouring stations.

Finally, this study made heavy use of a special metadata database, which was built by investigating numerous station inspection reports and other metadata information and provides site-specific details regarding maintenance, equipment failures and upgrades, equipment relocation, site exposure, and other factors that could impact record quality and temporal consistency (Wan & Wang, 2006). Such metadata also proved invaluable in justifying change-points detected through statistical means, while making it possible to account also for documented change-points.

3 Wind speed data preparation

a Adjustment for Non-Standard Anemometer Height

Before using the hourly wind speed data, available station metadata was reviewed to check for documented cases of non-standard anemometer height (AH). For all cases of known non-standard AH, the hourly wind speed data were adjusted to the standard 10 m height using the same procedure as in Wan et al. (2010), which uses a logarithmic wind profile with the surface roughness length data described in Section 2c.

Since AH changes often coincide with other changes to measurement systems, including tower relocations and the installation of new equipment, adjustments using the wind profile above did not necessarily account for all simultaneous non-climatic changes introduced into the data record. To ensure that such changes did not persist in the homogenized data, any time point of AH change was retained as a potential documented change-point and further scrutinized by homogeneity testing and adjustments, which diminish the remaining inhomogeneity (if any) due to the AH change.

b Quality Control and Calculation of Monthly Mean Wind Speed

After completing the AH adjustments, all hourly wind speed data were quality-controlled (QC'd) using the same QC criteria as used in ECCC QC programme checks for hourly data (Environment Canada, 2004), as done in Wan et al. (2010) (see their Table 1). More specifically, hourly wind speed values were set to missing if they are greater than the daily extreme gust value for that day, or greater than 128 km/h, or differ more than 28 km/h from the previous and next hourly values.

Daily mean wind speed values were computed as simple averages of hourly values reported for that day. Such values are meaningless if based on too few measurements, so days for which less than 3 hourly values were present were set to missing. Similarly, monthly mean wind speed was calculated as an average of all daily values for that month. Here, months for which less than 26 daily values were present were set to missing. The same criteria for missing data have also been

used in other wind studies (e.g., Azorin-Molina et al., 2014; Minola et al., 2016; Wan et al., 2010). Seasonal and annual averages are obtained if all corresponding monthly values are not missing. The seasons are defined as winter (December – February or DJF), spring (March – May or MAM), summer (June – August or JJA), and autumn (September – November or SON).

4 Data homogenization method

a Changepoint Detection Procedure

Non-climatic changepoints are discontinuities in a data time series that are caused by non-climatic factors, such as changes in observing techniques/equipment, locations, environment, and so on. These non-climatic changes can affect estimates of the mean or variance or the whole distribution and must be identified and eliminated from the data series so that the data series can better present the true climate and changes therein. To this end, one needs to rely on metadata and statistical tests. Which statistical tests to use depends on whether the causes of discontinuities are known or not. Changepoints of documented/known causes are called documented or type-0 changepoints, for which the regular t- or F-test can be used to determine whether the sudden change in the mean (i.e. mean-shift) is statistically significant. However, for changepoints of unknown causes, which are called undocumented or type-1 changepoints, one needs to use a maximal type of test, such as a maximal t- or F-test (Wang et al., 2007; Wang, 2008a, 2008b), to identify the most probably time of change in a way that appropriately accounts for the multiple testing required to identify type-1 changepoints.

Wind speeds fluctuate considerably over time and across space, particularly at short time scales. The high variability of hourly wind speeds, which are non-Gaussian, non-negative and frequently zero, and very low density of long, hourly records make homogenization of hourly wind speed series infeasible, despite clear user's needs for such high temporal resolution data. Thus, this study has focused on homogenization of monthly wind speed data for assessing large scale changes in wind speeds over Canada. As a byproduct, we also produce a homogenized daily wind speed dataset by diminishing the effects of non-climatic changepoints identified in the corresponding monthly wind speed data series (details in Section 4b below).

We used the RHtestsV4 package (Wang & Feng, 2013) to test for both types of changepoints in tandem, following the procedure of Wang et al. (2023). They developed a semi-automatic comprehensive procedure to detect significant changepoints in monthly precipitation data series by applying multiple homogeneity tests without a reference (noRef) and with reference series (wRef). This procedure used RHtestsV4 functions that are based either on a penalized maximal t-test or F-test for type-1 changepoints and the regular t- or F-test for detecting type-0 changepoints, in which the lag-1 autocorrelation, the long-term mean

annual cycle and the magnitudes of inhomogeneities are estimated in tandem and the homogeneity tests are applied to the de-seasonalized data series (i.e. the long-term mean annual cycle was subtracted) (Wang, 2008a). The Wang et al. (2023) semi-automatic procedure was adopted in this study with two minor modifications: One is that a log-transformation of the data was not necessary because the de-seasonalized wind speed data do not deviate notably from a normal distribution as reported in Wan et al. (2010). Another is that we retained all potential type-0 changepoints of station-joining or relocation until all other significant changepoints were identified, then re-assessed the statistical significance of these type-0 changepoints in the presence of the other significant changepoints. The changepoints associated with station-joining or relocation were retained if they are more likely to be significant than not, considering that these have a reliable cause and could bias the trend estimate for the series to make it inconsistent with its surrounding stations even when the mean-shift it caused is of low statistical significance as noticed in Wang et al. (2023). The homogenization procedure we used in this study is detailed in the Supplementary Material SM1.

For each base series, the homogenization procedure used up to six reference series. These include the adjusted and scaled geostrophic wind speed series for the station (see Section 2 above), the 20CRv3 ensemble-mean monthly wind speed series for the grid point closest to the station, and up to four best significantly-correlated (at 5% level) data series from neighbour stations located within a 200 km radius of the station being homogenized, where correlations are determined based on times series of first differences. The significance level for the identification of inhomogeneities was set to 1% to avoid over-adjustments to the data.

As a final step of the procedure, we manually investigated the changepoints from the automated procedure and the associated trend maps and neighbour station data series to finalize the list of significant changepoints for each base data series. Whenever necessary, we revisited the list of all identified potential changepoints (both type-0 and type-1) to ensure that the automated procedure detailed in the supplementary material SM1 correctly selected the changepoint(s) to retain and that changepoints had not been missed, in which case, additional manual modification was performed. Missing just one changepoint can affect the identification of other changepoints due to the nature of the multi-phase regression approach that is used in changepoint identification. The list of manual modifications to the changepoints identified by the automatic procedure is provided Supplementary Table S1 (see SM2).

As an example, Fig. 2a shows the changepoints found in the data record from the Broughton Island station (Nunavut, Canada). The monthly mean wind speed series were found to have three changepoints, which were associated with anemometer height change (August 1974), station relocation (July 1987), and station joining (June 1996). The homogenized data series is shown on Fig. 2b.

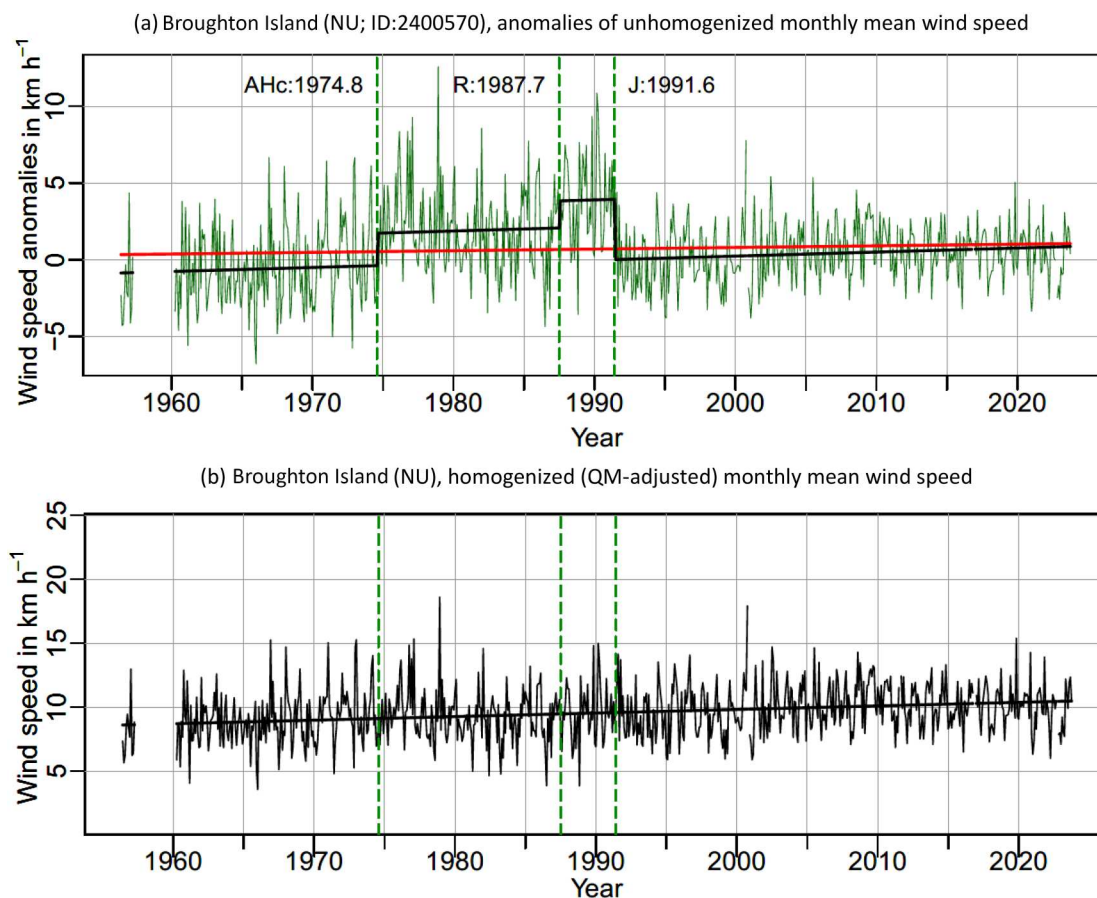


Fig. 2 Example of inhomogeneous observations before and after homogenization. The anomalies are relative to the long-term mean annual cycle. The original data series include non-climatic shifts, such as the change due to joining nearby stations (J; in June 1991) or a relocation of the instrument and/or station (R; in July 1987), and a change in the anemometer height (AHC; in August 1974). The red line is the trend estimated from the original data series without homogenization.

b Adjustments to Eliminate Data Inhomogeneity

Once the list of changepoints identified in each of the 154 data series had been finalized, homogenization of the monthly mean wind speed data series was performed using a slightly modified version of the quantile matching (QM) method in the RHtestsV4 package (Wang & Feng, 2013). The QM method, which is detailed in Wang et al. (2010) and Vincent et al. (2018), adjusts the whole distribution of the data in one segment to match another rather than just the mean. The modification here is to allow segments that are too short for QM adjustments to be feasible to be combined with neighbouring segments by first making mean adjustments after which the remaining changepoints are addressed with the QM method.

Reference series were not used when making the QM adjustments in this study because the station density is too low to find good reference stations for this purpose. Finding reference stations that help improve QM adjustments is challenging even when substantially more stations are available. For example, even with 425 stations over Canada, Wang et al. (2023) reported that QM adjustments to monthly precipitation without a reference are better than those with a

reference for some stations, while they are very similar for the other stations. Thus, we use the QM adjustment method without a reference to homogenize the 154 station wind speed data series, to produce version 2 of the Canadian homogenized monthly wind speed dataset, CanHomW mlyV2.

Although the statistical tests used in this study focus on identifying sudden changes in the mean (mean-shifts), changes in the variance or shape of the distribution that coincide with a change in the mean are also diminished by the QM adjustments that are motivated by the change in the mean. Fig. 3 shows a comparison of homogenization results from using the mean adjustments in the RHtestsV4 package and the QM adjustment method described above. The monthly mean wind speed series from the Armstrong Airport station (ON, Canada. ClimID: 6040325) was found to have eight changepoints (Fig. 3a). The changepoint at the end of December 1977 is due to joining of stations. It is obvious that the two stations are different in variance. Such variance inhomogeneity is diminished in the homogenized data series using QM adjustments (Fig. 3b) but is still present in the homogenized data series using mean adjustments (Fig. 3c).

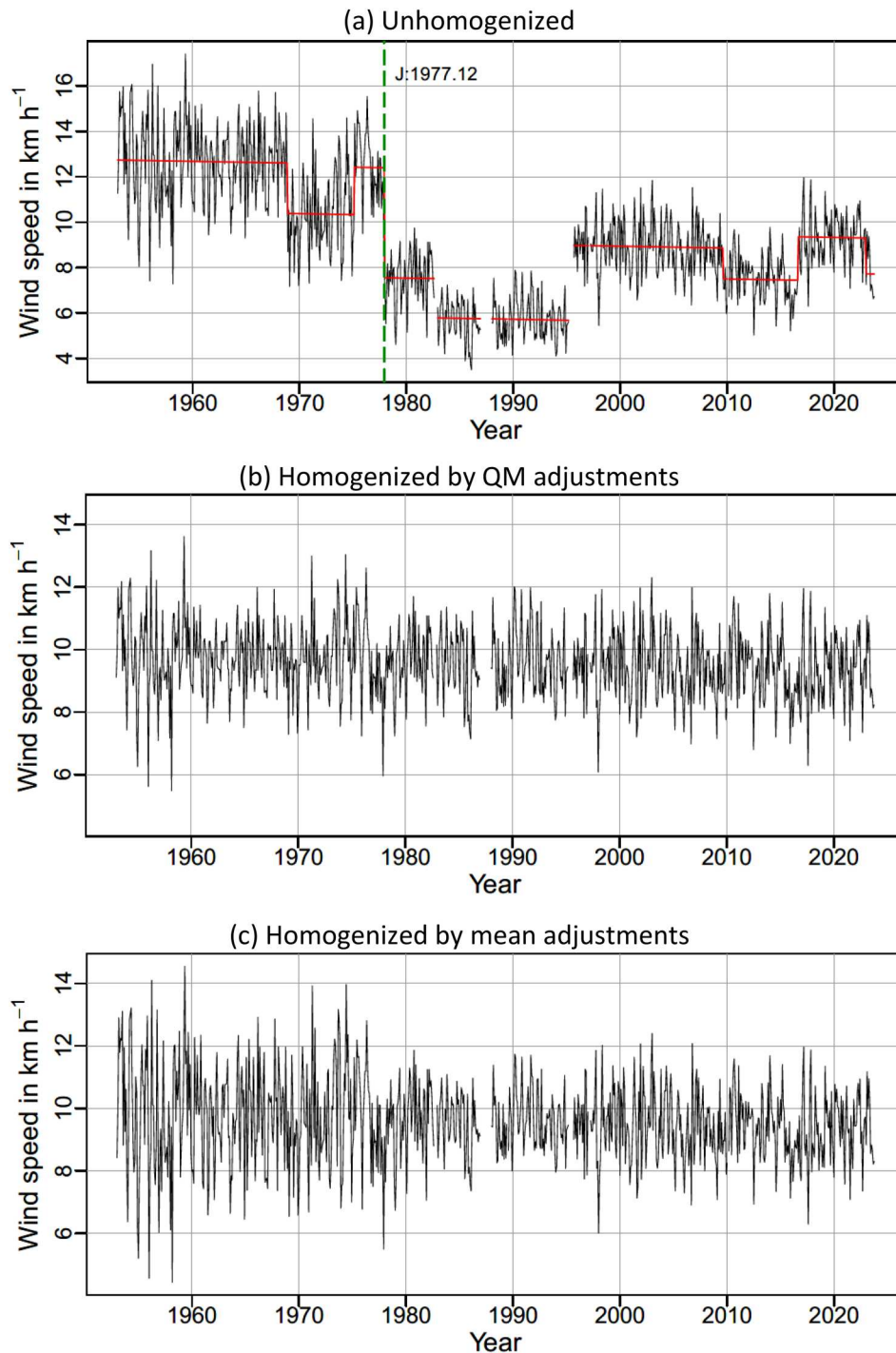


Fig. 3 Unhomogenized and homogenized monthly mean wind speed series for the Armstrong Airport station (ON, Canada. ID: 6040325), with a comparison of homogenization using the quantile matching (QM) adjustments and using only mean adjustments. The red lines are the multi-phase regression fit. Broken red lines mark data gap of at least 5 months; the early-1980s and mid-1990 gaps are associated with sudden changes (type-0). The green line marks the station joining at the end of December 1977. Other changepoints are undocumented (type-1).

5 Changepoint characteristics

The procedure described in Section 4a identified 981 non-climatic changepoints in the 154 wind speed data series, including 391 type-0 and 590 type-1 changepoints; none of the 154 data series was found to be homogeneous at 1% level. Two of

the 154 data series have a single changepoint, and 5, 14, 19, 18, and 96 series have 2, 3, 4, 5, and more than 5 changepoints each, respectively. Among the 391 type-0 changepoints, 31.3% are due to station joining (87 cases) or relocation (35 cases), 23.1% (90 cases) are due to changes in instruments

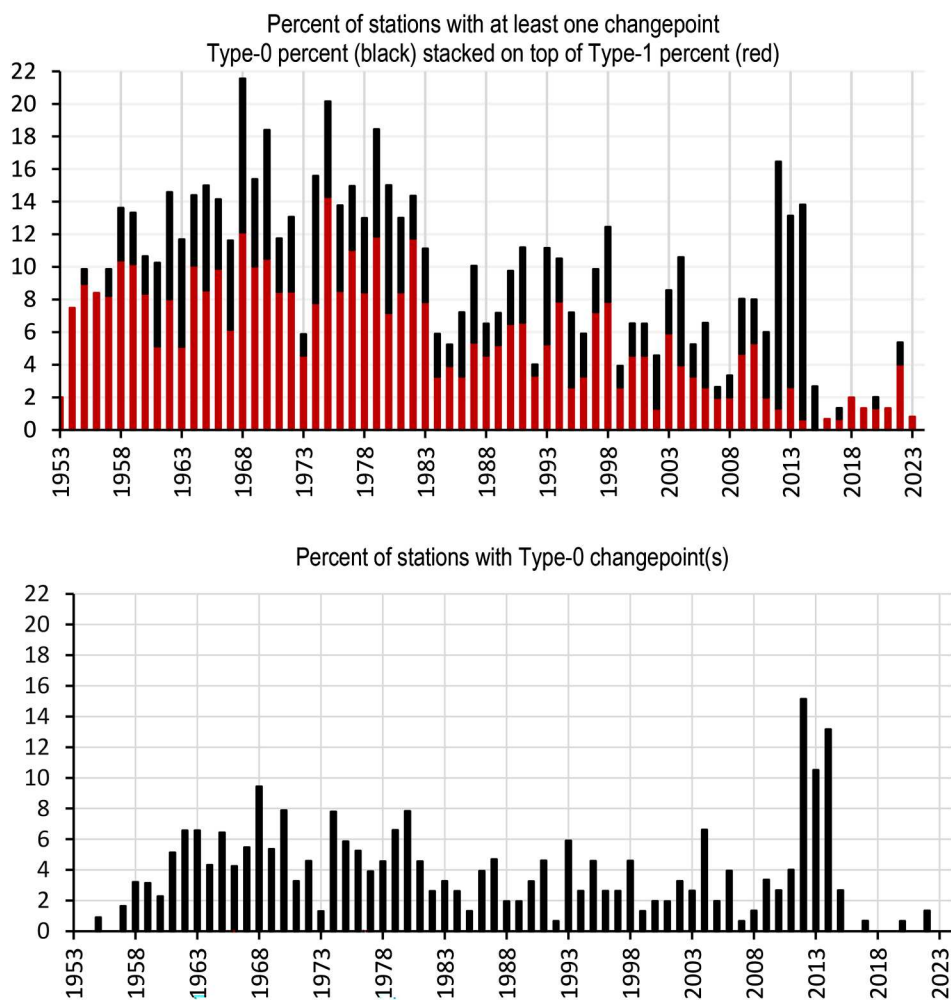


Fig. 4 The annual series of the percent of stations (i.e. data series) with at least one changepoint of the indicated types (type-0 in red, type-1 in black. The cause of the non-climatic change is documented/known for type-0, but undocumented/unknown for type-1).

(e.g. wind speed sensor type), and the remaining 54.4% are due to other causes that are mainly accompanied by data gaps. The high number of type-1 changepoints suggests the incompleteness of metadata.

The annual series of the percentage of stations (i.e. data series) with at least one changepoint (regardless of type) is shown in Fig. 4. The lowest percentage is seen in the period from the recent decade (mostly below 2%), with higher percentages in the pre-1984 period (Fig. 4a). This is also true for the type-1 changepoints, but for type-0 changepoints the percentage is the highest in 2012–2014 (10.5 - 15.1%) due to station joining (56 out of the 59 type-0 changepoints during this period have this cause; Fig. 4b).

6 Wind speed trends

We now examine trends in the homogenized wind speed dataset, termed CanHomW mlyV2, that results from station joining, careful quality control, changepoint identification and QM adjustments to diminish all identified non-climatic changes.

The homogenized station data as well as the ERA5, OCADA, and 20CRv3 data are used to assess historical wind speed trends over Canada. It is important to point out that 20CRv3 was only used to help identify non-climatic changepoints in the station data series and was not used to adjust the station data series to homogenize them. Thus, the homogenized station dataset (CanHomW mlyV2) can be regarded as being independent of all the three reanalysis datasets.

To show the effects of data inhomogeneity on trend estimates, trends over the period of 1953–2023 were also estimated from the unhomogenized station data, which were compared with those estimated from the homogenized station data. Trends are estimated from annual and seasonal mean wind speed series. The magnitudes and statistical significance of wind speed trends are estimated with the method of Wang & Swail (2001), a variant of Sen's non-parametric slope estimator and Mann-Kendall trend significance test that accounts for lag-1 autocorrelation in the data series.

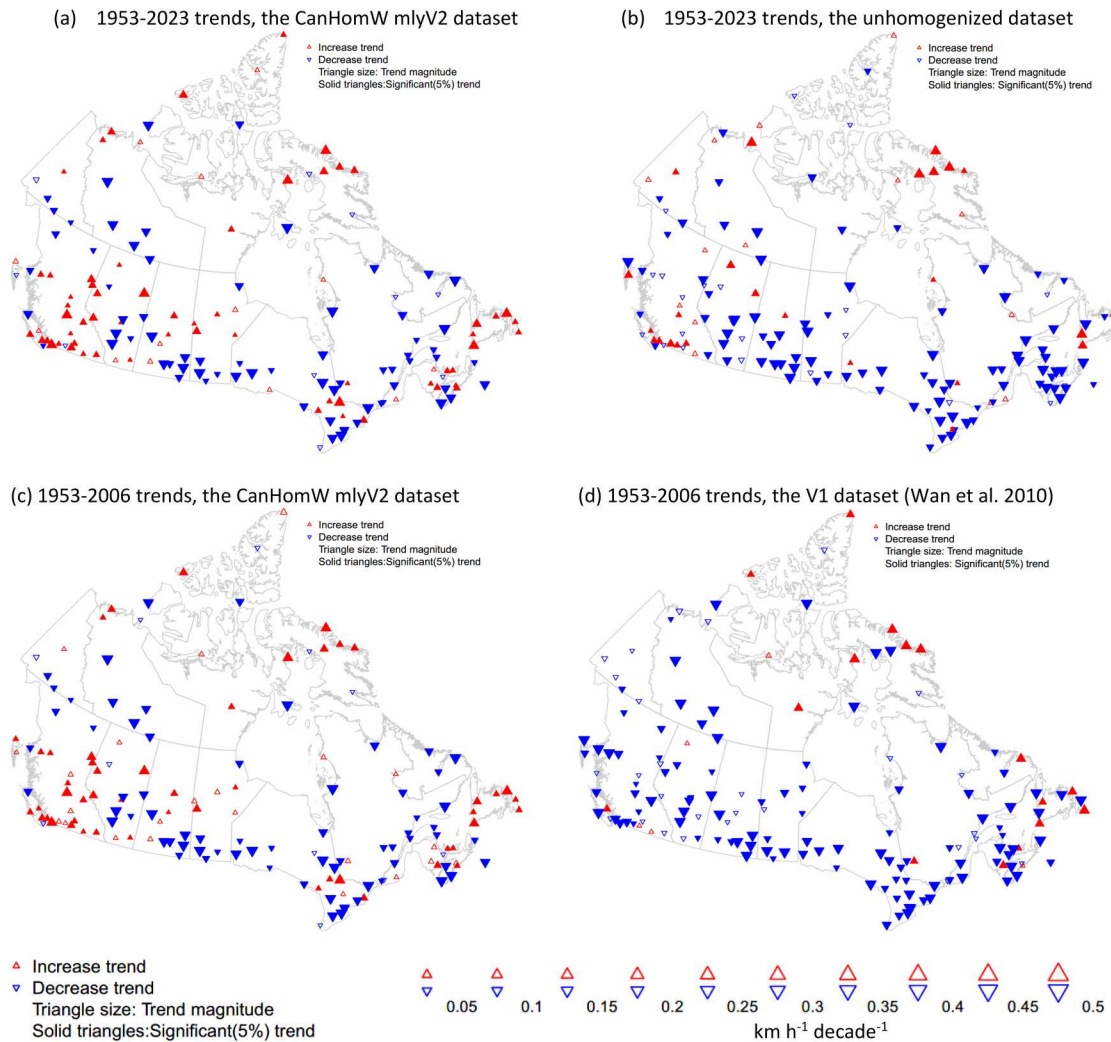


Fig. 5 Trends in monthly mean wind speed over the indicated periods, as estimated from the homogenized dataset, CanHomW mlyV2, and unhomogenized dataset, and the version 1 of homogenized dataset (the V1 dataset) produced by Wan et al. (2010).

As shown in Fig. 5a-b, the homogenized data show better spatial consistency of trends than the unhomogenized data, especially in southwestern and southeastern Canada. On the leeward side of the Rocky Mountains area (along the border of Alberta and British Columbia), the homogenized data show upward trends while the unhomogenized data show downward trends. The homogenized data show smaller decreases than the unhomogenized data in southern Canada (from the southern Prairies to the Maritimes), and smaller increases in Baffin Island.

We also compared the CanHomW mlyV2 with version 1 of homogenized monthly mean wind speed data (the V1 dataset) produced by Wan et al. (2010) in terms of trends over their common period 1953-2006. These two versions of the homogenized wind speed datasets show notable discrepancies in trends, especially in regions of complex topography (Fig. 5c-d). Particularly, the V2 dataset shows strengthening winds in the Rocky Mountains, Newfoundland (not including

Labrador), and Baffin Island, while the V1 dataset shows weakening winds in these regions.

There are several reasons to have substantially higher confidence in the V2 dataset. First, the trends in the V2 dataset are broadly consistent with those estimated from the ERA5 dataset in the regions mentioned above (Fig. 6a and also over the period 1953-2006, not shown). Further, as compared in Table 1, this study uses a much-improved data homogenization method with multiple tests, multiple reference data series, much more metadata, and 17-year longer data series than those used in Wan et al. (2010). Particularly, Wan et al. (2010) did not use any reference data other than the geostrophic wind series. However, the triangles used to calculate the geostrophic winds (Fig. 1) are too large to represent the wind conditions at the individual stations in regions with complex terrain, and thus up to five additional reference series were also used the development of CanHomW mlyV2. Given the higher level of confidence, we used CanHomW

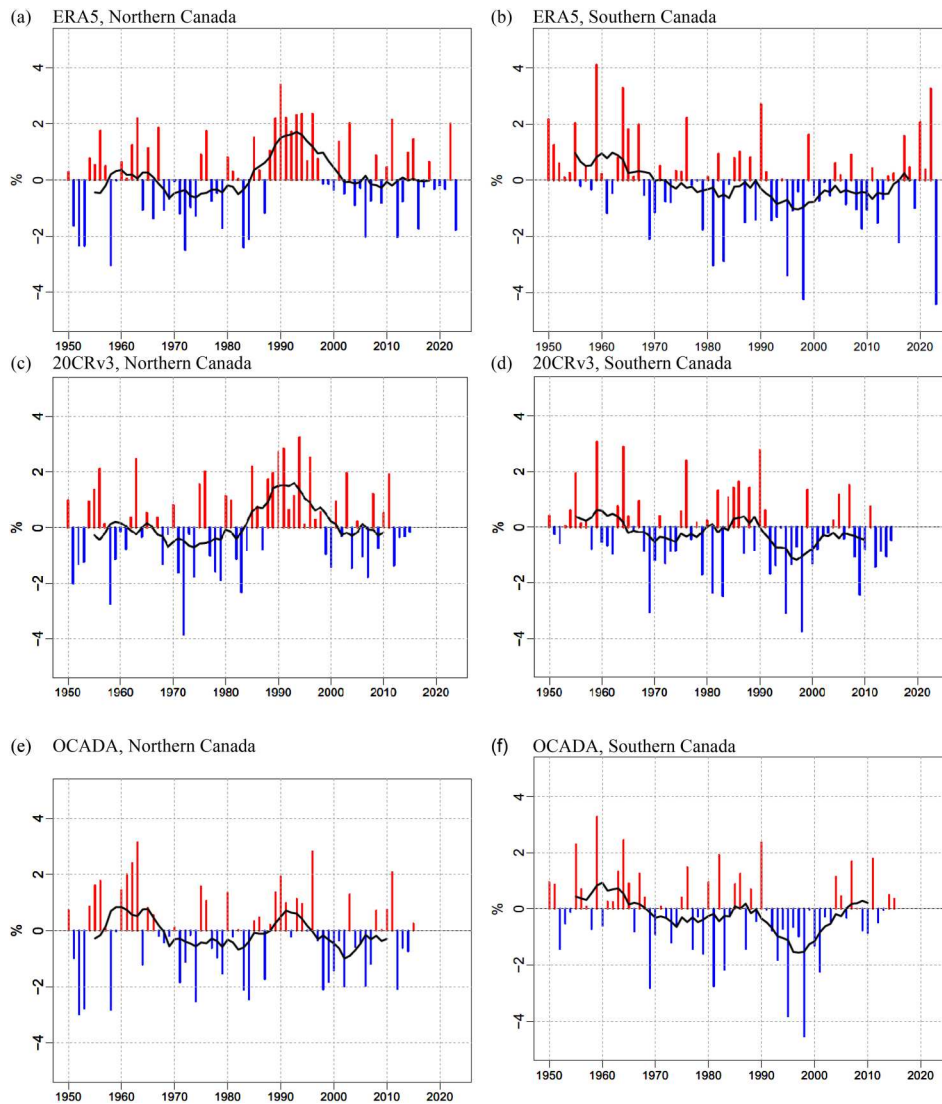


Fig. 7 Regional means of annual mean wind speeds for northern and southern Canada expressed relative to the climatological mean for the period 1961–1990, as derived from the indicated reanalysis datasets. The black lines are 11-year running means.

ERA5 is generally more consistent with the station data, with both showing increases in southern-central BC and the high Arctic, while 20CRv3 and OCADA show mostly insignificant decreases in these regions (Figs. 6b-d). Along the southern Hudson Bay shore, ERA5 and the station data consistently show decreases while 20CRv3 shows statistically insignificant small increases. However, in the region from northern BC to central Northwest Territories, ERA5 shows positive trends while the station data, 20CRv3, and OCADA show negative trends.

Fig. 7 compares the regional mean series of annual mean wind speeds for northern and southern Canada (divided at 60°N latitude) expressed relative to the climatological mean value for the period of 1961–1990 as derived from the three reanalysis datasets. There is a broad consistency in these regional mean wind speed series among the reanalysis datasets, although the trend patterns are not consistent throughout the country.

There is notable inter-decadal variability in the regional mean wind speeds, with the most prominent feature being the large positive anomalies around the 1990s in northern Canada that are matched with negative anomalies in southern Canada.

b Trends in Seasonal Mean Wind Speeds

As shown in Fig. 8, wind speed trends exhibit notable seasonal variations in both the homogenized station data and the ERA5 data, although weakening winds are seen in all seasons in the southern Prairies. Statistically significant trends are most extensive in summer, with significant wind speed decreases at most stations/areas in eastern-central Canada and significant increases along the west coast and in the eastern high Arctic.

The overall agreement on seasonal trends between the homogenized station data and ERA5 is quite satisfying (Fig. 8).

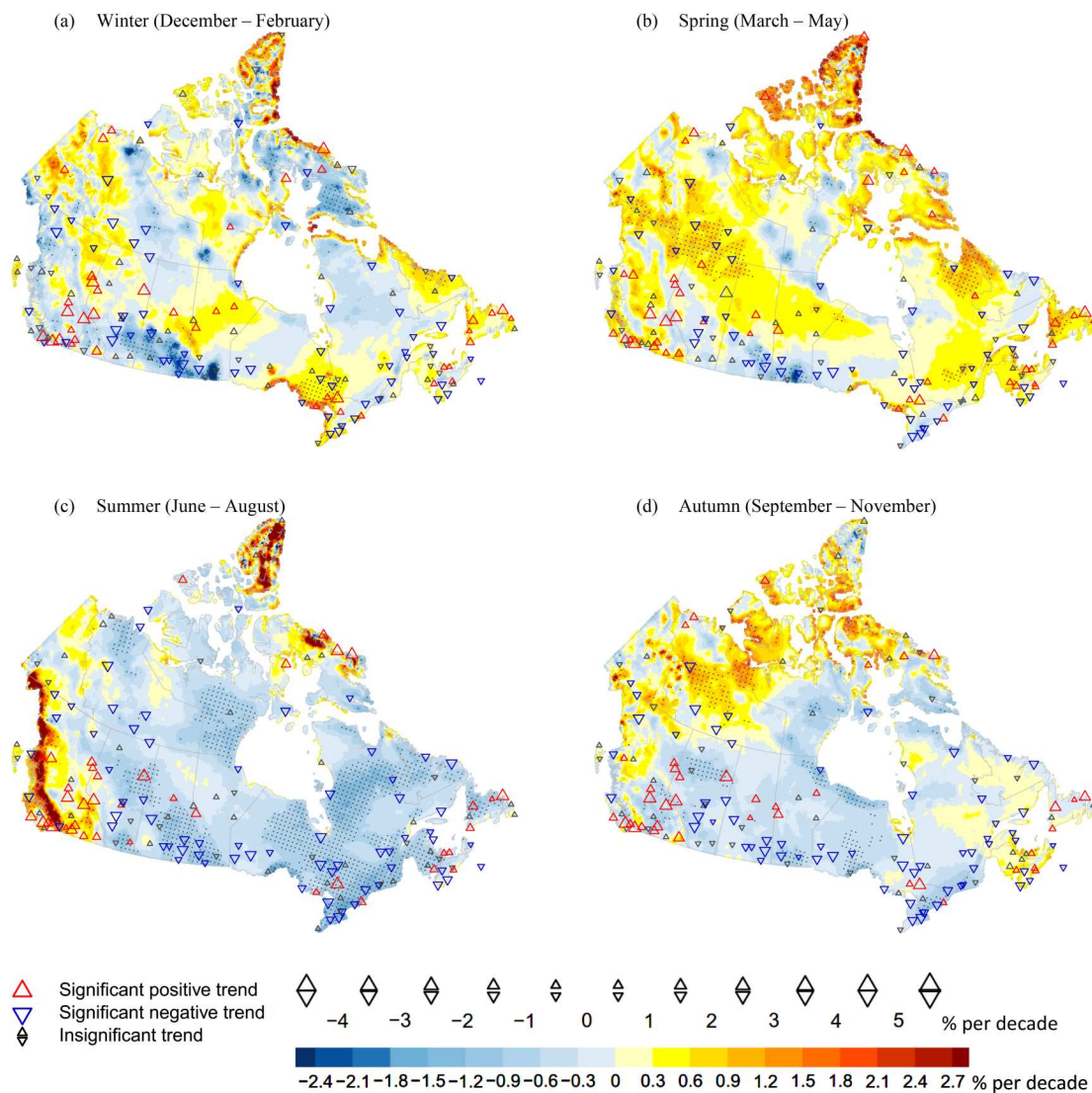


Fig. 8 Observed trends in seasonal mean surface wind speeds for the period 1953–2023 for the four seasons. The linear trends are estimated using homogenized station data CanHomW mlyV2 (triangles) and ERA5 Reanalysis data (colour shadings of grid boxes) and expressed in percentage of the baseline (1961–1990) mean. Areas with statistically significant (at 5% level) trends in reanalysis data are dotted, and stations with significant trends are shown in red or blue triangles.

The best agreement in terms of trends between the two datasets is seen in summer, in which wind speeds increased in the region from the west coast to central Rocky Mountains and on

the Baffin Bay coast but decreased in most of the other regions. In spring, the two datasets disagree with each other in the direction of change in central western Canada (from

TABLE 2. Linear trends in annual and seasonal mean wind speeds between 1953 and 2023 for the indicated regions of Canada, as estimated from the ERA5 reanalysis data over the Canadian land area. The trends are expressed in percentage of the baseline (1961–1990) mean per decade. Southern Canada includes British Columbia, the Prairie provinces, Ontario, Quebec, and Atlantic Canada.

REGION	Annual	Winter	Spring	Summer	Autumn
Canada	-0.06 (-0.2, 0.1)	-0.02 (-0.39, 0.34)	0.26 (-0.07, 0.57)	-0.38 (-0.64, -0.17)	-0.08 (-0.32, 0.14)
Northern Canada	-0.01 (-0.2, 0.21)	-0.01 (-0.54, 0.52)	0.35 (-0.08, 0.74)	-0.23 (-0.54, 0.08)	0.11 (-0.27, 0.45)
Southern Canada	-0.11 (-0.29, 0.05)	-0.03 (-0.41, 0.28)	0.16 (-0.19, 0.52)	-0.5 (-0.87, -0.15)	-0.25 (-0.53, 0.03)
British Columbia	0.11 (-0.21, 0.42)	-0.01 (-0.79, 0.71)	0.34 (-0.31, 1)	0.44 (-0.15, 1.07)	-0.07 (-0.58, 0.53)
Prairies	-0.3 (-0.59, 0.03)	-0.24 (-0.77, 0.34)	0.07 (-0.45, 0.56)	-0.44 (-0.88, 0.02)	-0.38 (-0.75, -0.04)
Ontario	-0.24 (-0.47, -0.01)	0.17 (-0.28, 0.59)	0.04 (-0.43, 0.5)	-0.69 (-1.11, -0.25)	-0.37 (-0.81, 0)
Quebec	-0.07 (-0.29, 0.12)	-0.13 (-0.64, 0.43)	0.27 (-0.21, 0.7)	-0.78 (-1.21, -0.33)	-0.1 (-0.52, 0.29)
Atlantic Canada	0.07 (-0.18, 0.34)	0.32 (-0.14, 0.8)	0.34 (-0.14, 0.86)	-0.65 (-1.05, -0.16)	0.07 (-0.53, 0.6)

northern BC to southern Northwest Territories) while they agree on significant increases in northeastern Quebec, northern Labrador and Newfoundland. The disagreement in central western Canada is also visible in autumn but to a lesser extent. The station data show significant wind strengthening in southern BC and the Rocky Mountains in all seasons, while ERA5 shows mostly negative trends in those regions in winter and autumn.

According to ERA5, wind speed averaged over Canada decreased significantly (at the 5% level) only in summer, with no statistically significant changes in the annual mean and other seasonal mean wind speeds (Table 2). Among the five regions in southern Canada, a statistically significant decrease in the regional mean wind speed series is seen only in Ontario for the annual means and summer means with no statistically significant changes in the other regions or seasons. Trends in OCADA and 20CRv3 are not presented in Table 2 or Fig. 8 because these reanalysis datasets do not have data after 2015.

7 Summary and discussion

After quality control and adjustments of hourly wind speed data for any non-standard anemometer heights, in this study, we first adopted a semi-automated comprehensive data homogenization procedure to produce version 2 of the Canadian homogenized monthly mean wind speed dataset, CanHomW mlyV2. This dataset includes 154 homogenized monthly mean wind speed series spanning the period 1953-2023. The homogenization procedure uses a combination of station metadata and multiple statistical tests with and without using reference series. The results of the automated procedure were reviewed manually using metadata and visual inspection of the multiphase regression fits with expert judgement. All 154 data series were identified to have one or more non-climatic changes, which were diminished by applying quantile matching adjustments. Station joining and/or relocation, and instrument changes/problems were found to be the main causes of non-climatic changes.

The homogenized dataset was used to characterize observed changes in surface wind speed across Canada and compared the wind trends with those in three reanalysis datasets (ERA5, OCADA, and 20CRv3). The homogenized dataset shows weakening winds in a large part of southern Canada (from the southern Prairies to south-central Quebec-Labrador), matched with strengthening winds in most other regions, particularly in the region from south-central BC to the Rocky Mountains and some stations in the Atlantic provinces and the high Arctic. The weakening winds in the southern Prairies are also seen consistently in the reanalysis datasets, while the four datasets show inconsistent wind speed trends in other regions, especially in the area spanning the west coast to the Rocky Mountains (Fig. 6b-d).

The wind trends show notable seasonality. Statistically significant trends are most extensive in summer, with significant

wind speed decreases at most stations/areas in eastern-central Canada and significant increases along the west coast and the eastern high Arctic. The agreement or disagreement between ERA5 and the station data also shows seasonality (Fig. 8). The best agreement in terms of trends between the two datasets is seen in summer. In spring, the two datasets disagree with each other in the direction of change in central western Canada, while they agree on significant increases in northeastern Quebec, northern Labrador and Newfoundland. The disagreement in central western Canada is also visible in Autumn but to a lesser extent. The station data show significant wind strengthening in southern BC and the Rocky Mountains in all seasons, while ERA5 shows mostly negative trends in those areas in winter and autumn.

It is important to bear in mind the differences in the characteristics of the two datasets when interpreting trends. Regardless of trend direction, the station data tend to show stronger wind trends than the reanalysis counterparts. This may be partially due to a difference in the scales represented by these two types of wind data. An hourly value in station data represents the speed of the vector wind averaged over the two-minute interval ending at the hour of observation at the station location (a point) (Environment Canada, 2015). On the other hand, an hourly value in reanalysis data represents the “instantaneous” speed of the model grid box area mean vector wind at the top of each hour for grid boxes of considerable size ($\sim 960 \text{ km}^2$ for ERA5, $\sim 3600 \text{ km}^2$ for OCADA, and $\sim 5600 \text{ km}^2$ for 20CRv3). Those instantaneous values are the values that are generated by the reanalysis models for the time step that occurs at the top of each hour (e.g. in the case of ERA5, see <https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation>). Time steps are 12-minutes in length in the case of ERA5 (see <https://confluence.ecmwf.int/display/FCST/Detailed+information+of+implementation+of+IFS+cycle+41r>), indicating that the u- and v-components of the surface wind change once every 12 min in that model. Spatial averaging of the vector near surface wind across such large areas would inevitably lead to reduced average speeds compared to speeds at individual point locations. Thus, we should generally have higher confidence in trend magnitudes estimated from the homogenized station data than from the reanalysis counterparts.

It is also important to bear in mind that both datasets have challenges in representing the wind speed field in areas of complex terrain, albeit likely for different reasons. For example, ERA5’s surface elevation and terrain characteristics, which both influence near surface wind speed and direction, remain very smooth compared to reality despite its relatively high 31-km resolution (and even more so in 20CRv3 and OCADA). On the other hand, station observations can be strongly influenced by local terrain characteristics and observing stations tend to be located at lower elevations in regions with complex terrain. Thus, wind observations are not representative of wind fields throughout such regions, although the homogenized station data is representative of the wind conditions at the station location.

Nevertheless, while the observations have some challenges in areas of complex terrain, they represent wind speeds and their changes at the scales at which they are observed and experienced rather than being representative of larger scales above a land surface that is smoother than the true surface. Overall, despite observational challenges, we have substantially higher confidence in the wind trend patterns that are found in the very carefully processed direct observations of the wind that are contained in the homogenized CanHomW mlyV2 dataset than those found in the reanalyses.

Acknowledgements

The authors are grateful to Xungang Yin, NOAA Affiliate, for assisting in the collection of ISPD pressure data, and to Rodney Chan for downloading all the reanalysis data used in this study. We thank Hui Wan and Vincent Cheng for

their internal review of a much earlier version of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Funding for this project was provided by Environment and Climate Change Canada.

Supplemental data

Supplemental data for this article can be accessed online at <https://doi.org/10.1080/07055900.2025.2570920>.

ORCID

Xiaolan L. Wang  <http://orcid.org/0000-0002-5656-5903>

References

- Arriaga, M., Canizares, C. A., & Kazerani, M. (2013). Renewable energy alternatives for remote communities in northern Ontario, Canada. *IEEE Transactions on Sustainable Energy*, 4(3), 661–670. <https://doi.org/10.1109/TSTE.2012.2234154>
- Azorin-Molina, C., Vicente-Serrano, S. M., McVicar, T. R., Jerez, S., Sanchez-Lorenzo, A., López-Moreno, J.-I., Revuelto, J., Trigo, R. M., Lopez-Bustins, J. A., & Espírito-Santo, F. (2014). Homogenization and assessment of observed near-surface wind speed trends over Spain and Portugal, 1961–2011*. *Journal of Climate*, 27(10), 3692–3712. <https://doi.org/10.1175/JCLI-D-13-00652.1>
- Azorin-Molina, C., Rehman, S., Guijarro, J. A., McVicar, T. R., Minola, L., Chen, D., & Vicente-Serrano, S. M. (2018). Recent trends in wind speed across Saudi Arabia, 1978–2013: A break in the stilling. *International Journal of Climatology*, 38(S1), e966–e984. <https://doi.org/10.1002/joc.5423>
- Brázdil, R., Valík, A., Zahradníček, P., Řezníčková, L., Tolasz, R., & Možný, M. (2017). Wind-stilling in the light of wind speed measurements: The Czech experience. *Climate Research*, 74(2), 131–143. <https://doi.org/10.3354/cr01492>
- Canadian Commission On Building And Fire Codes. (2015). *National building code of Canada: 2015* (p. v. 1, 714 p.; v. 2, 698 p.). National Research Council of Canada.
- Coburn, J. (2021). Climatological teleconnections with wind energy in a mid-continental region. *Journal of Applied Meteorology and Climatology*, 60(3), 305–322. <https://doi.org/10.1175/JAMC-D-20-0203.1>
- Cram, T. A., Compo, G. P., Yin, X., Allan, R. J., McColl, C., Vose, R. S., Whitaker, J. S., Matsui, N., Ashcroft, L., Auchmann, R., Bessemoulin, P., Brandsma, T., Brohan, P., Brunet, M., Comeaux, J., Crouthamel, R., Gleason, B. E., Groisman, P. Y., Hersbach, H., ... Worley, S. J. (2015). The international surface pressure databank version 2. *Geoscience Data Journal*, 2(1), 31–46. <https://doi.org/10.1002/gdj3.25>
- Dadaser-Celik, F., & Cengiz, E. (2014). Wind speed trends over Turkey from 1975 to 2006. *International Journal of Climatology*, 34(6), 1913–1927. <https://doi.org/10.1002/joc.3810>
- Dumitrescu, A., Bojariu, R., Birsan, M.-V., Marin, L., & Manea, A. (2015). Recent climatic changes in Romania from observational data (1961–2013). *Theoretical and Applied Climatology*, 122(1), 111–119. <https://doi.org/10.1007/s00704-014-1290-0>
- Earl, N., Dorling, S., Hewston, R., & Von Glasow, R. (2013). 1980–2010 variability in U.K. Surface wind climate. *Journal of Climate*, 26(4), 1172–1191. <https://doi.org/10.1175/JCLI-D-12-00026.1>
- Environment Canada. (1977). *Manual of surface weather observations. 7th ed.* Environment Canada. (1996). *Wind. Amendment 14. Manual of Surface Weather Observations, 7th ed.*
- Environment Canada. (2004). *The National Archives System QC program checks for hourly SA's.* Environment Canada. http://nadm.ontario.int.ec.gc.ca/Intranet/nadm/nas/quality_control/hourlies_e.html
- Environment Canada. (2015). *Manual of surface weather observations. 7th edition. Amendment 19.* Environment Canada.
- Fu, G., Yu, J., Zhang, Y., Hu, S., Ouyang, R., & Liu, W. (2011). Temporal variation of wind speed in China for 1961–2007. *Theoretical and Applied Climatology*, 104(3), 313–324. <https://doi.org/10.1007/s00704-010-0348-x>
- Guo, H., Xu, M., & Hu, Q. (2011). Changes in near-surface wind speed in China: 1969–2005. *International Journal of Climatology*, 31(3), 349–358. <https://doi.org/10.1002/joc.2091>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., ... Thépaut, J. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hooshangi, H. (2014). Feasibility study of wind-diesel hybrid power system for remote communities in north of Quebec. *Journal of Advances in Clean Energy*, 1(1), 84–95.
- Ishii, M., Kamahori, H., Kubota, H., Zaiki, M., Mizuta, R., Kawase, H., Nosaka, M., Yoshimura, H., Oshima, N., Shindo, E., Koyama, H., Mori, M., Hirahara, S., Imada, Y., Yoshida, K., Nozawa, T., Takemi, T., Maki, T., & Nishimura, A. (2024). Global historical reanalysis with a 60-km AGCM and surface pressure observations: OCADA. *Journal of the Meteorological Society of Japan. Ser. II*, 102(2), 209–240. <https://doi.org/10.2151/jmsj.2024-010>
- Kim, J., & Paik, K. (2015). Recent recovery of surface wind speed after decadal decrease: A focus on South Korea. *Climate Dynamics*, 45(5–6), 1699–1712. <https://doi.org/10.1007/s00382-015-2546-9>
- Klink, K. (1999). Trends in mean monthly maximum and minimum surface wind speeds in the coterminous United States, 1961 to 1990. *Climate Research*, 13, 193–205. <https://doi.org/10.3354/cr013193>
- Kodama, K., Burls, N. J., & Trenary, L. (2021). The niño-3.4 prediction skill of empirically adjusted wind power. *Journal of Climate*, 34(6), 2001–2015. <https://doi.org/10.1175/JCLI-D-20-0045.1>

- Koren, K. (1971). *Evaluation of the directional bias in the M.S.C. Type 45B wind system. Instrument Research and Development Report No. 8*, Meteorological Branch, Department of Transportation, Canada; SKP Box Number 672672428.
- Lin, C., Yang, K., Qin, J., & Fu, R. (2013). Observed coherent trends of surface and upper-Air wind speed over China since 1960. *Journal of Climate*, 26(9), 2891–2903. <https://doi.org/10.1175/JCLI-D-12-00093.1>
- McVicar, T. R., Roderick, M. L., Donohue, R. J., Li, L. T., Van Niel, T. G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N. M., Mescherskaya, A. V., Kruger, A. C., Rehman, S., & Dinpashoh, Y. (2012). Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology*, 416–417, 182–205. <https://doi.org/10.1016/j.jhydrol.2011.10.024>
- McVicar, T. R., Van Niel, T. G., Li, L. T., Roderick, M. L., Rayner, D. P., Ricciardulli, L., & Donohue, R. J. (2008). Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. *Geophysical Research Letters*, 35(20), 2008GL035627. <https://doi.org/10.1029/2008GL035627>
- Minola, L., Azorin-Molina, C., & Chen, D. (2016). Homogenization and assessment of observed near-surface wind speed trends across Sweden, 1956–2013. *Journal of Climate*, 29(20), 7397–7415. <https://doi.org/10.1175/JCLI-D-15-0636.1>
- Palutikof, J. P., Kelly, P. M., Davies, T. D., & Halliday, J. A. (1987). Impacts of spatial and temporal windspeed variability on wind energy output. *Journal of Climate and Applied Meteorology*, 26(9), 1124–1133. [https://doi.org/10.1175/1520-0450\(1987\)026<1124:IOSATW>2.0.CO;2](https://doi.org/10.1175/1520-0450(1987)026<1124:IOSATW>2.0.CO;2)
- Pryor, S. C., Barthelmie, R. J., Young, D. T., Takle, E. S., Arritt, R. W., Flory, D., Gutowski, W. J., Nunes, A., & Roads, J. (2009). Wind speed trends over the contiguous United States. *Journal of Geophysical Research: Atmospheres*, 114(D14), 2008JD011416. <https://doi.org/10.1029/2008JD011416>
- Roderick, M. L., Rotstayn, L. D., Farquhar, G. D., & Hobbins, M. T. (2007). On the attribution of changing pan evaporation. *Geophysical Research Letters*, 34(17), 2007GL031166. <https://doi.org/10.1029/2007GL031166>
- Sailor, D. J., Smith, M., & Hart, M. (2008). Climate change implications for wind power resources in the northwest United States. *Renewable Energy*, 33(11), 2393–2406. <https://doi.org/10.1016/j.renene.2008.01.007>
- Schmith, T. (1995). *Occurrence of severe winds in Denmark during the past 100 years*. Proceedings of the sixth international meeting on statistical climatology (pp. 83–86).
- Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., ... Wyszy ski, P. (2019). Towards a more reliable historical reanalysis: Improvements for version 3 of the twentieth century reanalysis system. *Quarterly Journal of the Royal Meteorological Society*, 145(724), 2876–2908. <https://doi.org/10.1002/qj.3598>
- Small, D., Atallah, E., & Gyakum, J. (2011). Wind regimes along the Beaufort Sea coast favorable for strong wind events at tuktoyaktuk. *Journal of Applied Meteorology and Climatology*, 50(6), 1291–1306. <https://doi.org/10.1175/2010JAMC2606.1>
- Stoffelen, A. (1998). Toward the true near-surface wind speed: Error modeling and calibration using triple collocation. *Journal of Geophysical Research: Oceans*, 103(C4), 7755–7766. <https://doi.org/10.1029/97JC03180>
- Thomas, B. R., Kent, E. C., Swail, V. R., & Berry, D. I. (2008). Trends in ship wind speeds adjusted for observation method and height. *International Journal of Climatology*, 28(6), 747–763. <https://doi.org/10.1002/joc.1570>
- Turner, R., Safaei Pirooz, A. A., Flay, R. G. J., Moore, S., & Revell, M. (2019). Use of high-resolution numerical models and statistical approaches to understand New Zealand historical wind speed and gust climatologies. *Journal of Applied Meteorology and Climatology*, 58(6), 1195–1218. <https://doi.org/10.1175/JAMC-D-18-0347.1>
- Vautard, R., Cattiaux, J., Yiou, P., Thépaut, J.-N., & Ciais, P. (2010). Northern hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geoscience*, 3(11), 756–761. <https://doi.org/10.1038/ngeo979>
- Vincent, L. A., Hartwell, M. M., & Wang, X. L. (2020). A third generation of homogenized temperature for trend analysis and monitoring changes in Canada's climate. *Atmosphere-Ocean*, 58(3), 173–191. <https://doi.org/10.1080/07055900.2020.1765728>
- Vincent, L. A., Milewska, E. J., Wang, X. L., & Hartwell, M. M. (2018). Uncertainty in homogenized daily temperatures and derived indices of extremes illustrated using parallel observations in Canada. *International Journal of Climatology*, 38(2), 692–707. <https://doi.org/10.1002/joc.5203>
- Wan, H., & Wang, X. L. (2006). Canadian special metadata database for climate data homogenization. *Environment Canada Internal Rep.*, 29.
- Wan, H., Wang, X. L., & Swail, V. R. (2007). A quality assurance system for Canadian hourly pressure data. *Journal of Applied Meteorology and Climatology*, 46(11), 1804–1817. <https://doi.org/10.1175/2007JAMC1484.1>
- Wan, H., Wang, X. L., & Swail, V. R. (2010). Homogenization and trend analysis of Canadian near-surface wind speeds. *Journal of Climate*, 23(5), 1209–1225. <https://doi.org/10.1175/2009JCLI3200.1>
- Wang, X. L. (2008a). Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F test. *Journal of Applied Meteorology and Climatology*, 47(9), 2423–2444. <https://doi.org/10.1175/2008JAMC1741.1>
- Wang, X. L. (2008b). Penalized maximal F test for detecting undocumented mean shift without trend change. *Journal of Atmospheric and Oceanic Technology*, 25(3), 368–384. <https://doi.org/10.1175/2007JTECHA982.1>
- Wang, X. L., Casas-Prat, M., Feng, Y., Crosby, A., & Swail, V. R. (2021). Historical changes in the davis strait baffin Bay surface winds and waves, 1979–2016. *Journal of Climate*, 34(22), 1–44. <https://doi.org/10.1175/JCLI-D-21-0054.1>
- Wang, X. L., Chen, H., Wu, Y., Feng, Y., & Pu, Q. (2010). New techniques for the detection and adjustment of shifts in daily precipitation data series. *Journal of Applied Meteorology and Climatology*, 49(12), 2416–2436. <https://doi.org/10.1175/2010JAMC2376.1>
- Wang, X. L., & Feng, Y. (2013). *RHtestsV4 user manual*. 28 pp. Environment Canada. <https://github.com/ECCC-CDAS>
- Wang, X. L., Feng, Y., Cheng, V. Y. S., & Xu, H. (2023). Observed precipitation trends inferred from Canada's homogenized monthly precipitation dataset. *Journal of Climate*, 36(22), 7957–7971. <https://doi.org/10.1175/JCLI-D-23-0193.1>
- Wang, X. L., & Swail, V. R. (2001). Changes of extreme wave heights in northern hemisphere oceans and related atmospheric circulation regimes. *Journal of Climate*, 14(10), 2204–2221. [https://doi.org/10.1175/1520-0442\(2001\)014<2204:COEWHI>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<2204:COEWHI>2.0.CO;2)
- Wang, X. L., Wen, Q. H., & Wu, Y. (2007). Penalized maximal t test for detecting undocumented mean change in climate data series. *Journal of Applied Meteorology and Climatology*, 46(6), 916–931. <https://doi.org/10.1175/JAMC2504.1>
- Wang, X. L., Zwiers, F. W., Swail, V. R., & Feng, Y. (2009). Trends and variability of storminess in the northeast Atlantic region, 1874–2007. *Climate Dynamics*, 33(7–8), 1179–1195. <https://doi.org/10.1007/s00382-008-0504-5>
- Wieringa, J. (1980). Representativeness of wind observations at airports. *Bulletin of the American Meteorological Society*, 61(9), 962–971. [https://doi.org/10.1175/1520-0477\(1980\)061<0962:ROWOAA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1980)061<0962:ROWOAA>2.0.CO;2)
- Wu, J., Zha, J., & Zhao, D. (2016). Estimating the impact of the changes in land use and cover on the surface wind speed over the east China plain during the period 1980–2011. *Climate Dynamics*, 46(3–4), 847–863. <https://doi.org/10.1007/s00382-015-2616-z>
- Young, I. R., Zieger, S., & Babanin, A. V. (2011). Global trends in wind speed and wave height. *Science*, 332(6028), 451–455. <https://doi.org/10.1126/science.1197219>
- Zeng, Z., Ziegler, A. D., Searchinger, T., Yang, L., Chen, A., Ju, K., Piao, S., Li, L. Z. X., Ciais, P., Chen, D., Liu, J., Azorin-Molina, C.,

Observed Surface Wind Speed Trends Inferred from Homogenized in Situ Data and Reanalysis Datasets / 131

- Chappell, A., Medvigy, D., & Wood, E. F. (2019). A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change*, 9(12), 979–985. <https://doi.org/10.1038/s41558-019-0622-6>
- Zhang, R., Zhang, S., Luo, J., Han, Y., & Zhang, J. (2019). Analysis of near-surface wind speed change in China during 1958–2015. *Theoretical and Applied Climatology*, 137(3), 2785–2801. <https://doi.org/10.1007/s00704-019-02769-0>
- Zhang, Z., & Wang, K. (2020). Stilling and recovery of the surface wind speed based on observation, reanalysis, and geostrophic wind theory over China from 1960 to 2017. *Journal of Climate*, 33(10), 3989–4008. <https://doi.org/10.1175/JCLI-D-19-0281.1>
-