Hodographs of Slowly Rotating Winds in Midlatitudes

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ABSTRACT
Trend analysis of hourly wind direction angle recorded at nine meteorological stations across southern Canada (in the 43°–53°N belt) identified wind direction rotation periods in the range of 7–9 days. Rotation persists during the “summertime” season from May to mid-October during 1953–2001. Rotation with a 7.5-day period was also established in the 850-hPa geostrophic summertime wind over the Canadian province of Saskatchewan in 2000. Hodographs built from wind vectors corresponding to consecutive days of the 7.5-day period (summertime average vectors of winds binned into separate days of the period) formed nearly elliptical loops centered around the end point of the net westerly transport vector that ranged from 0.5 to 1.3 m s⁻¹ and was either smaller than or of comparable magnitude to the zonal and meridional oscillations of wind. The observed rotations appear quasi periodic rather than purely periodic, because nearly elliptical loops of relatively large amplitude were present at different hodographs constructed at each location for sampling periods of 6.5, 7.0, 7.5, and 8.0 days. For sampling periods outside the 6.5–8.0-day range, the rotational magnitude in a hodograph appears diminished because of partial cancellation of wind vectors in corresponding hodograph bins. Quasi-periodical rotation occurs in the clockwise direction.

1. Introduction
Analysis and evaluation of surface winds are required in air quality applications, which to a large extent deal with pollutants routinely released by industry and employ probabilistic evaluation of atmospheric transport and dispersion based on the long-term average characteristics of wind. These include, but certainly are not limited to, the traditional wind rose. Of particular note is recurrence of airborne pollutants due to periodic circulations in the near-surface atmosphere (Keeler and Kristovich 2012; Wagner et al. 2012) and the role such recurrence plays in large populated centers. For example, consequences of the 7-day recurrence are particularly well documented (Bell et al. 2009; Kim et al. 2010; Georgoulis and Kourtidis 2011; Daniel et al. 2012; Sanchez-Lorenzo et al. 2012). Accurate quantification of low-level winds is also important for wind-power applications. Both of these applications motivate our work on the in situ observations of periodicity and the magnitude of periodic movement.

Examples of low-frequency variability (LFV or periodicity) in the atmosphere immediately beyond the scale of synoptic disturbances (7–30 days) have been reported. Hamilton (1987) observed 5- and 16-day waves. Luo et al. (2000, 2002) reported waves over the Canadian provinces of Saskatchewan and Ontario with 12–24-day periods and Korolevych and Richardson (2012) observed rotation of the direction of surface winds over Canada with the period increasing with latitude and ranging from 7 to 30 days. Atmospheric LFV was also observed in global reanalysis data, particularly in that of ERA-15 and NCEP–DOE (Hodges et al. 2003), ERA-40 (Wallace et al. 1988; Dell’Aquila et al. 2005), and NCEP–NCAR (Madden 2007 and references therein). The period of midatmospheric LFV in the Northern Hemisphere (NH) ranged from 10 to 40 days (Benzi et al. 1986; Benzi and Speranza 1989) and from 2 to 20 days according to Dell’Aquila et al. (2005). The theoretical considerations (Benzi et al. 1986; Kuo and Polvani 2000; Shipton 2009; Sterk et al. 2010) and results of laboratory experiments and numerical simulations (Kuo and Polvani 2000; Shipton 2009) contribute to our understanding of the low-frequency atmospheric oscillations.

Slow continental wind rotation exemplifies LFV and differs from rotation subject to a strong diurnal oscillating
force of combined land–sea breezes and mountain winds observed in regions adjacent to the coast (i.e., Pacific coast of North America, the Mediterranean, and Japan) and in regions influenced by steep large-scale orography (Chambers 1873; Haurwitz 1947; Neumann 1977; Kusuda and Alpert 1983; Alpert et al. 1984; Furberg et al. 2002; Gille et al. 2003; Sakazaki and Fujiwara 2008). Away from the coast and mountains (e.g., Rocky Mountains), the cumulative or “unwrapped” angle of continental surface wind direction (with 360° added at 360°/0° crossings) follows a linear temporal trend; that is, a smooth and periodic clockwise directional change occurs in wind over most of Canada (Korolevych and Richardson 2012). Of particular note are 118 inland Canadian stations (out of 149 in the current study expands the applicability of wind energy and Engineering Dataset (CWEEDS) representing 41–49 years of observations from 1953 to 2001 (Environment Canada 2008). The largest temporal data gap was encountered in the 1961 record for Earlton and amounted to 9% of the annual record. Remaining temporal gaps for Earlton were small and sporadic, but in the 1979–2001 record interval amounted to 32% in each year. The other case of a lower-quality record (total of 24% of missing data per year) was encountered for North Battleford in 1954–55. Apart from that, on average, only 3% of the hourly data (calms included) was missing each year for the analyzed Canadian locations.

Data gaps (sporadic temporal omissions and calms) in the surface wind data shorter than 12 h were filled by interpolation and longer data gaps (outages, etc.) were filled with data taken from a similar period of another year in which there were minimal gaps (Fernandes et al. 2007). The wind data from analyzed CWEEDS stations were checked against 1951–80 wind roses reported in the Canadian weather atlas (Atmospheric Environment Service 1982; Environment Canada 2007).

The set of surface wind data has been complemented by 850-hPa geostrophic winds retrieved from the North American Regional Reanalysis (NARR; Mesinger et al. 2002). This study investigates the previously reported effect of surface WDR. The primary aim of this study is the evaluation of the magnitude of this rotational effect across southern Canada. Analysis of rotation also includes 850-hPa geostrophic winds over a portion of the province of Saskatchewan in the box located between latitude 52° and 56°N and between longitude 108° and 104°W.

Section 2 describes the methodology and data preprocessing (sampling and binning) required for hodograph construction. Section 3 presents the resulting hodographs showing surface wind rotation and its relative magnitude. Section 4 is the discussion, and section 5 provides the conclusions.

2. Methods

a. Datasets and data quality

Multidecadal records of hourly observations of wind at eight locations away from large water bodies were selected within inland southern Canada. One additional location at similar latitude but near a large body of water (Toronto by Lake Ontario) was added for comparison (Table 1). Wind data for Edmonton, North Battleford, Medicine Hat, Saskatoon, Winnipeg, North Bay, Earlton, London, and Toronto were obtained from a publicly available Canadian Weather Energy and Engineering Dataset (CWEEDS) representing 41–49 years of observations from 1953 to 2001 (Environment Canada 2008). The largest temporal data gap was encountered in the 1961 record for Earlton and amounted to 9% of the annual record. Remaining temporal gaps for Earlton were small and sporadic, but in the 1979–2001 record interval amounted to 32% in each year. The other case of a lower-quality record (total of 24% of missing data per year) was encountered for North Battleford in 1954–55. Apart from that, on average, only 3% of the hourly data (calms included) was missing each year for the analyzed Canadian locations.

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The set of surface wind data has been complemented by 850-hPa geostrophic winds retrieved from the North American Regional Reanalysis (NARR; Mesinger et al.
(2006) for May–October of year 2000 within the latitude–longitude box (52°N, 108°W–56°N, 104°W) centered at the province of Saskatchewan and including Saskatoon and North Battleford.

b. Reconstruction of a continuous record of wind direction drift and WDR period

The procedure of unwrapping the wind direction angle is applied to produce a cumulative angle and the continuous evolution of wind direction (see appendix A).

WDR is associated with the persistent trend in wind direction evolution measured either in terms of a cumulative wind direction angle or, alternatively, in accomplished WDR counts (Korolevych and Richardson 2012). The period of WDR is calculated as the slope of a WDR trend line over 5.5 months. The mean and standard deviation values are calculated for WDR periods encountered over 41–49 years in the CWEEDS dataset.

c. Rotary spectral analysis

Components of the rotary spectra of wind (Gonella 1972; Barat and Cot 1992; Emery and Thomson 2001) are calculated for all Canadian locations during all summertime seasons, which last from the beginning of May until mid-October.

d. Construction of surface wind hodograph: Sampling and binning of wind speed record using the WDR period

In this study we limit the subject of our analysis to a 3-day moving average of wind direction and speed allowing cancellation of a large portion of random fluctuations on a diurnal and subdiurnal scale. A 5.5-month-long meteorological record from each available year on record is analyzed for each location.

Sampling and binning of the wind vector for further construction of wind hodographs was based on the WDR period $T$ defined during the May–October summertime season by the wind unwrapping procedure (see appendix A) and followed by trend analysis described in section 2a. Each summertime record was divided into a sequence of periods and further cut into daily (24 h) intervals, which were used as hodograph bins. The averaging within each daily bin was performed over the whole summertime record. For periods containing a fraction of the day (e.g., 7.5 days) the last bin covered just this short fraction (e.g., 12 h as illustrated in appendix B). Hodographs were prepared using the sampled and binned wind data, which did not have the net transport excluded (as opposed to traditional diurnal hodographs). The net transport vector was identified on
each hodograph so as to allow comparison with wind rotation magnitude.

e. Analysis of sensitivity of wind hodograph to the ill-defined length of sampled period

To check the sensitivity of hodograph shape to the length of the sampled period, we constructed hodographs for different test periods chosen with a 0.5-day time step from 4.0 to 20.0 days for wind data for Saskatoon, which is centrally located within the inland (continental) locations away from water bodies. Averaging over the whole duration of the analyzed record was performed within each daily (24 h) bin of rotation period as per section 2c.

f. Analysis of rotation of ambient winds

Persistence of wind rotation aloft has been evaluated using 850-hPa geostrophic winds over Saskatchewan. Geostrophic winds calculated from the horizontal derivatives of geopotential height and interpolated onto a regular $0.5^\circ \times 0.5^\circ$ latitude–longitude grid (Carrera et al. 2009) were further averaged within a latitude–longitude box having lower-left- and upper-right-corner coordinates of $52^\circ$N, $108^\circ$W and $56^\circ$N, $104^\circ$W. The existence of a wind rotation effect and its sensitivity to the ill-defined length of the assumed period was evaluated as described in section 2d using a set of hodographs constructed for test periods ranging from 4.0 to 20.0 days.

3. Results

a. Net rotation of surface wind direction and its persistence on interannual scale

The evolution of the 3-day moving average of unwrapped (cumulative) wind direction angle for Saskatoon during 1953–2001 is shown in Fig. 1. One cycle or full rotation corresponds to a $360^\circ$ gain in unwrapped angle and cycle counts correspond to multiples of $360^\circ$ of the unwrapped wind direction angle. The slope of a trend line defines the rotation rate (or the rotation period). Figure 1b shows that in the summertime the rotation rate is significantly larger than in wintertime. In particular the rotation rate increases from May [day of year (DOY) 122] and persists through mid-October (DOY 288); the last few weeks are not shown in Fig. 1b. This seasonal pattern repeats each year and the corresponding variation is clearly seen in the slope of unwrapped wind direction angle in Fig. 1b. High-rate WDR amounts to about 20 cycles in 5 months, corresponding to a period of 7.5 days cycle$^{-1}$.

Seasonality in the unwrapped wind direction angle evolution is further illustrated in Fig. 2a for Saskatoon for all years between 1953 and 2001 and includes the evolution shown in Fig. 1b for a single year. Figure 2b specifically targets the high WDR season from May to mid-October and indicates the period of WDR of 7.37 days corresponding to the slope of a trend line. The similar WDR period of 7.59 days was established for summertime geostrophic winds at 850 hPa analyzed in 2000 over a small region over central Saskatchewan covering Saskatoon and North Battleford.

WDR trend analysis for summertime of 2000 results in WDR periods from 6.99 to 9.93 days for nine analyzed locations (Table 1). A least squares fit to constant rotation (i.e., to linear trend) is significant at level $\alpha \leq 0.001$ each year at all locations, with dispersion during the summertime of 2000 characterized by the coefficient of determination in the range between $R^2 = 0.981$ for Toronto and $R^2 = 0.993$ for Saskatoon. During 1953–2001 the summertime WDR period stays within the same range (Table 1).

b. Rotary spectra

Rotary spectra of the surface wind at all locations and all summertime seasons appear generally similar. An example of rotary spectra is shown in Fig. 3 for Saskatoon. Peaks on the spectrogram appear broad and not very prominent, which presents difficulties in identifying the WDR frequency solely on the basis of rotary spectra. On the one hand, such spectrogram structure reflects inter- and intra-annual variability of the dominant frequency occurring at about 0.14 cpd for Saskatoon (Fig. 2a), which corresponds to a 7.37-day period. On the other hand, the broad main peak reflects the coexistence of different frequencies in the neighborhood of the dominant frequency, indicating that the wind is quasi periodic.

c. Hodographs of rotation in surface winds in Saskatoon and geostrophic winds in central Saskatchewan: Sensitivity of hodograph shape to predetermined period

Since hodographs are constructed using wind vectors binned into daily time steps of a predefined period, it is relevant to ask how sensitive is a hodograph’s ability to show rotation to the length of a predefined sampling period. Robustness of rotation and sensitivity to the predefined period were established empirically by varying the sampling period within a wide range.

It is expected that for ill-defined sampling periods, wind vectors sampled and accumulated from far-apart moments of time will act as random samples and cancel out. Such a random distribution of wind directions is
traditionally reflected in wind roses, where no systemic directional shift or rotation is observed. However, if the sampling period corresponds to actually existing periodicity, the hodograph loop emerges showing oscillations of significant amplitude that is often larger than the average wind vector.

In the case of Saskatoon, test periods were chosen in the wide range of 4–20 days (some illustrated in Fig. 4). Those within a narrower range, at 7.0, 7.5, and 8.0 days, exhibit nearly elliptical loops (Figs. 4b–d). These results agree with the rotary spectrogram in Fig. 3, which shows that any LFV present has quite broad and rather indistinct peaks. Nevertheless, outside of this approximately 2-day window of periods, no manifestation of rotation remains and the hodograph loop shrinks to an inconsequentially small magnitude (the size of a systemic error) with a quite irregular shape, as exemplified in Figs. 4a and 4e. Sampling of wind into 15- or 16-day periods, that are about twofold longer than the true WDR period of 7.37 days, results in hodographs showing prominent double loops (Figs. 4g and 4h). The double loops resemble the single loop emerging for a period of 7.5 days in Fig. 4c, in both its shape and its magnitude. Double loops persist within a 3-day window centered at a 15-day period as illustrated in Figs. 4f–h, whereas outside of this 3-day broad band (in clear correspondence with hodographs showing a
single loop) double loops shrink to an inconsequentially small magnitude (not illustrated).

The same approach was undertaken with geostrophic winds at 850 hPa over Saskatchewan. The results appear very similar to those for the surface winds for Saskatoon. A large-amplitude elliptical loop emerged at about the WDR period defined by trend line analysis and a double loop emerged at an ~2-times-longer period, accompanied by irregular hodographs of suppressed amplitude for other periods (Fig. 5). However, unlike for the surface winds, the prominent elliptical loop for 850-hPa geostrophic winds emerges only for a single period of 7.5 days, while even for an 8.0-day period the loop magnitude markedly drops and for 7.0 days the loop vanishes (Figs. 5a–c). Therefore, the sensitivity of hodograph shape to a chosen test period for 850 hPa is found to be higher than at the surface.

d. Sensitivity of hodographs to sampling period for Earlton and Toronto

Large-amplitude nearly elliptical loops are encountered for periods in the range of 7–8 days both for Earlton and Toronto (as shown in Figs. 6, 7, 8f,h) indicating quasi periodicity. Outside of this range hodograph shows either vacillations (at 10-day period for Toronto) or less consequential variability reflected in irregularly shaped and smaller magnitude loop (at 6 and 9 days for Earlton). It is necessary to note smaller sensitivity for Toronto located on the shore of Lake Ontario, where

FIG. 2. Box plot for (a) annual evolution of the unwrapped wind direction angle during 1953–2001. Dark shaded area bounds mean ± std dev, and outer lines represent min and max encountered during analyzed 49 yr. (b) As in (a), but for the summertime and adjusted season from May to October; trend line (red dashed line) and rotation period of 7.37 days corresponding to trend line slope are added for reference.

FIG. 3. Rotary wind spectra between known diurnal and seasonal oscillations at Saskatoon. The red line is the clockwise anticyclonic component, and the blue line is the counterclockwise cyclonic component. Two peaks marked by gray and black arrows correspond to 15- and 7.37-day periods, respectively.
diurnal circulation caused by diurnal shoreline effect (Lyons 1972; Keeler and Kristovich 2012) is substantial.

In contrast with Saskatoon, the prominent loops for Toronto at 7.0 and 7.5 days (Figs. 7 and 8h) did not match the trend line WDR period of 9.93 days (Table 1). The longer WDR period of ~10 days in Toronto appears manifested by the different kind of periodicity (i.e., wind vacillations, but not rotation) accompanying the net transport vector (Fig. 7d). For Edmonton the similar significant discrepancy between the period of 7.5 days characterized by the large-amplitude hodograph loop and the WDR period of 9.1 days was observed in 2000.

Fig. 4. Surface wind hodographs constructed for different test periods at Saskatoon (52.17°N, 106.68°W) from May to October 2000. Two arrows (indicating the average transport vector and direction of rotation) are added for reference.
Surface wind evolution from May to October 2000 at all other locations was analyzed using the same 7.5-day period and subsequently constructed hodographs. As shown in Figs. 4 and 8, hodographs in all cases appear in the form of elliptical loops at the 7.5-day period observed at the

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**e. Wind rotation recorded by hodographs of surface winds**

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rest of the locations in 2000 appear only in remote correspondence with the WDR period (Table 1). Because of the quasi-periodic nature of rotation established for Saskatoon, Toronto, and Earlton, all other years were assessed using uniform hodographs constructed for an empirically chosen 7.5-day period (Table 2).

Hodographs allow evaluation of the relative magnitude of rotational oscillations. The magnitude of rotation $A$ generally appeared comparable to the average wind vector $|\mathbf{u}|$ and in numerous cases far exceeded it, as indicated by the maximum amplitude $A_{\text{max}}$ (Table 2). The net transport in Canada ranged from 0.35 m s$^{-1}$ at North Battleford to 1.29 m s$^{-1}$ at Medicine Hat, and its direction appears close to zonal at all locations, which reflects the influence of prevailing westerlies. The summertime rotation amplitude $A$ ranges from 0.83 m s$^{-1}$ at Toronto to 1.31 m s$^{-1}$ at Saskatoon (Table 2). In the prairies $A$ exceeds $|\mathbf{u}|$ as evident from the ratio of magnitudes $R_t = 1.78$ and is comparable to $|\mathbf{u}|$ in Ontario where $R_t = 0.90$. In general the average wind speed with prevailing westerlies (the net transport) matches the magnitude of wind rotational oscillations in all nine cases (Table 2, Figs. 4 and 8).

The change with time of rotation amplitudes and their interannual variability are substantial as indicated by the standard deviation of rotation’s amplitude $A$ (Table 2). No temporal correlation was found for the whole dataset that contains nine locations. Also, the year of occurrence of maximum amplitude of rotation appeared random (Table 2). Nevertheless, analysis of regional groups of stations reveals a weak interstation correlation of rotation amplitudes across the prairies (e.g., between Saskatoon and Winnipeg, $R^2 = 0.58$) during 1984–2001 and across Ontario (e.g., between Toronto and Earlton, $R^2 = 0.42$) during 1953–77, when annual amplitudes appeared synchronized to some extent.

The summertime wind rotation is equally pronounced at all analyzed locations across southern Canada as shown in Fig. 8. These include both inland stations and Toronto located on the shore of Lake Ontario.

4. Discussion

It appears that summertime wind decomposes into net transport, rotation, and fluctuations, which are more or less successfully cancelled out by averaging. Each selected 5.5-month-long summertime wind record has been cut into succession of sampling periods chosen within a range of the WDR period and binned daily. Hodographs built from wind vectors corresponding to consecutive days of the period formed a smooth loop, which shows that, in addition to the previously reported purely directional rotation (Korolevych and Richardson 2012), there is a prominent rotational component in the evolution of the wind vector itself. As noted in the introduction, particularly important are occurrences of an 7-day period of rotation. Since the long-term net atmospheric transport can be represented in finer detail as a wind rose, this result can be interpreted as wind decomposition into the wind rose and slow rotation.
In this study we have analyzed eight inland locations in Canada away from water bodies and have included a location at similar latitude, Toronto, which is exposed to breezes from and toward Lake Ontario. Notwithstanding this significant difference from the rest of locations, similar wind rotation period was observed and similar hodographs resulted for all nine locations, with the sites being separated by 2700 km. The interannual variability of the WDR period is the largest at Toronto (Table 1).

As illustrated for Saskatoon but also carried out for the eight other locations, the surface WDR period was evaluated in detail (i.e., during summertime of all available years) using trend analysis of the unwrapped wind direction angle. Wind rotation was found to be most stable and prominent during the summertime from May through October. Summertime surface winds were also analyzed using rotary spectra, which revealed rather broad peaks indicating the quasi-periodic nature of the wind rotation. Wind hodographs constructed for the year 2000 showed large-amplitude mostly elliptical loops. During the summertime of other years the hodograph period of 7.5 days in many cases appeared significantly different from the trend-analysis-based WDR period.

The large-amplitude loops seen in hodographs corresponding to a range of periods indicate the relative insensitivity of hodograph-based identification of quasi-periodical oscillations (wind rotations) to the length of sampling period. Such insensitivity points to the quasi-periodic nature of wind rotation phenomenon. It is also worth emphasizing that ambient airflow (geostrophic winds at 850 hPa) demonstrates similar quasi periodicity, but within a narrower range of periods. On the one hand, such sharp sensitivity for winds aloft could simply be an artifact of the coarse spatial resolution of the analyzed phenomenon and thus of no real consequence. On the other hand, this feature could be an indication of a stronger monochromatic component aloft, which could point to the driver causing less coherent quasi-periodic variability at the surface.

The summertime wind rotation effect clearly persists aloft at 850 hPa. However, the mechanisms driving rotation and linking processes at the surface with those aloft remain unexplained. Reported studies not only show no clear teleconnection between the LFV in the upper atmosphere (from troposphere up to the stratosphere) and that at the surface, but also a different periodicity (Luo et al. 2002 and references therein). In this respect it should be emphasized that surface wind rotation is found to be most prominent during summertime, which is somewhat in contrast with the emphasis on enhanced wintertime variability more frequently encountered in the literature on atmospheric LFV than for cases of summertime intensification and relevant conditions like those reported by Williams and Avery (1992). A comprehensive analysis of upper-atmospheric LFV across the NH should therefore be done as a follow-up to this study. Such analysis should include the search for mechanisms of teleconnection with the

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**Fig. 7.** Surface wind hodographs constructed for different test periods for Toronto from May to October 2000: (a) 6, (b) 7, (c) 8, and (d) 10 days.
near-surface atmosphere, radar observations at locations other than that in Saskatoon and London in Canada, observations at intermediate heights (in the troposphere), and analysis of observations robustness, particularly in summertime.

All analyzed stations are surrounded by relatively flat terrain, and this may be a factor in the small variability of rotation period observed across this group of locations. The uniformity of the summertime rotation period across southern Canada likely points to a uniform driver operating on a continental scale. However, with regard to the rotation amplitude (Table 2), the influence of local, and to some extent region-specific, factors apparently dominate. During the whole analyzed record from 1953 to 2001 the occurrence of maximum amplitude of rotation $A_{\text{max}}$ did not follow any systematic temporal pattern at different locations, which likely points to the influence of local factors. However, it was noted that some limited interstations correlation of rotation amplitudes did occur across the prairies during 1984–2001 and across Ontario during 1953–77, but these episodes point to regional-scale interactions at most and thus warrant further investigation.

Presented results imply that short-range transport of pollutants from an industrial point source to individual receptors and critical groups in populated areas within the study domain will be quasi periodic, which leads to regulatory and licensing questions associated with periodic plume reoccurrence. With regard to long-range

FIG. 8. Summertime (May–October 2000) hodographs at southern Canada locations.
transport of pollutants we can speculate that in the summertime, large directional shifts within the surface layer of the atmosphere could be commonplace, with the long-range path arching or even spiraling and being up to 3 times as long as transport along a straight line that neglects rotation. However, a similar supposition may not apply to the bulk of the plume that is transported by winds aloft for significantly larger distances. This warrants expansion of analysis presented in this study across a range of atmospheric heights and a wide range of latitudes. The probability of entrainment of Arctic air masses during long-range midlatitudinal transport and other relevant questions may benefit from such studies.

As reported by Korolevych and Richardson (2012), the multidecadal evolution of unwrapped wind appears rather steady with a trend line defining an annual rotation period in between the wintertime and summertime rotation periods. The relevance of analysis, by the annual wind hodograph constructed for any complete yearlong record, was further evaluated at North Bay and Toronto (not shown for brevity). It was found that for annual average hodographs, the summertime and wintertime wind vectors sampled into the annual average period partially cancel out. However, because of their quasi-periodic nature either the relatively large-amplitude wind oscillations remain reflected in annual hodograph (in Toronto), or smoothly nearly elliptical loop shape (in North Bay). Nevertheless, it would seem that scientific relevance of the annual hodograph (as opposed to the summertime hodograph targeted in this study) is limited, because the shape of the annual loop appears either distorted or affected by a secondary loop (in Toronto), or the annual loop amplitude shrinks almost to the detection limit of the three-cup wind anemometer (in North Bay).

5. Conclusions

Results show that at all nine analyzed locations at the surface and at 850 hPa above Saskatchewan, the summertime (May–October) evolution of the averaged wind vector consists of a mean component representing the net atmospheric transport with prevailing westerlies and the wind rotation component. Periodical rotation is confirmed to be a general attribute of this wind vector, in addition to a previous finding in Canada of rotation of wind direction alone. Here, the magnitude of the slow rotation, in terms of its zonal and meridional wind oscillations, is either comparable to the magnitude of the net atmospheric transport by prevailing winds or substantially exceeds it.

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APPENDIX A

Methodology of Wind Direction Angle Unwrapping and Construction of Hodograph

Discontinuous standard wind direction angle \( \alpha \) based on compass bearing was reconstructed to be continuous. Conventionally, the latter is discontinuous at 360°/0° crossings. Individual discontinuity \( |\alpha_N - \alpha_{N-1}| \geq 180° \) for two consecutive angles \( \alpha_{N-1} \) and \( \alpha_N \) in the wind direction record can be removed by counting the missing full rotation in

\[
\alpha'_N = \alpha_N + 360° \times i, \quad \{ i = -1, (\alpha_N - \alpha_{N-1}) \geq 180° \}
\]

A commonly defined wind unwrapping procedure (Gonella 1972; Barat and Cot 1992; Emery and
Thomson 2001) detects discontinuities or jumps between consecutive angles and recalculates the unwrapped angle $\alpha_{uw}$ by adding multiples of $\pm 360^\circ$ corresponding to jumps greater than jump tolerance (e.g., a threshold of $180^\circ$) to the initially recorded angle (compass bearing $\alpha$):

$$\alpha_{uw} = \alpha_N + 360^\circ \times k,$$

where the counter $k$ is incremented by $i$ as defined above for negative jumps between successive angle values (clockwise change in compass bearing $\alpha$ across $360^\circ/0^\circ$) and decremented by $i$ for positive jumps (counter-clockwise change in compass bearing $\alpha$ across $0^\circ/360^\circ$) (Gonella 1972; Barat and Cot 1992; Emery and Thomson 2001).

This seemingly trivial operation does not work well for sparse, rapidly changing phase values (angles in our case), as previously assessed empirically by varying jump tolerance values beyond $180^\circ$ and by corresponding sensitivity analysis in Korolevych and Richardson (2012).

**APPENDIX B**

**Calculation of Hodograph Components**

Hodograph components are calculated by sampling wind vectors into daily bins and averaging within each bin. The process of defining bins for sampling procedure is illustrated in Fig. B1.

![Time from the beginning of analyzed summertime season (DOY, bottom) and corresponding enumerated hodograph daily bins (shown to scale) for different sampling periods T (top three lines).](image-url)

**REFERENCES**


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