1. Introduction

Wind is an atmospheric response to air pressure gradient, with increasing wind speed proportional to the magnitude of the gradient. It can be sustained over an extended period of time or can occur as gusts which are sudden and rapid increase in the wind speed over a short period of time. A sustained high wind is usually caused by a strong pressure gradient associated with an intense synoptic cyclonic system, and is usually more common in the winter season. A gust is a sudden occurrence of strong wind over a short period of time caused by a combination of dynamical and thermodynamical forces usually associated with mesoscale storms such as thunderstorms and squall lines, and is more common in the summer season in Ontario. Spatially, wind damages from mesoscale storms are relatively confined to a small area. On the other hand, because of its size, a synoptic cyclonic storm can cause extensive damages over a wide region with winds sometimes reaching greater than those experienced in a hurricane. Intense synoptic storms are more common in the winter season.

In Ontario, extreme wind events have caused significant damage to infrastructure, and have posed significant monetary and socio-economic costs to the society. Extreme wind events have also known to pose a direct threat to human health and safety through wind-driven debris and structural failure. Forecasting extreme winds and reconstructing extreme wind events for post-analysis, therefore, remains an important challenge. Identifying regions in Ontario with high probability of strong wind occurrences serves an important contributing factor in alleviating and reducing direct impacts of wind hazards to people and society.

Damages and injuries (as well as deaths) from intense wind storms associated with large-scale storm systems (including hurricanes and hurricane remnants), tornadoes, straight line winds and severe thunderstorms (including squall lines). For example, a series of storms hit Vancouver area during the period December 2006 to January 2007. During the peak of the
storm on December 15, 2006, trees in Stanley Park were snapped and/or uprooted (Figure 1), over 250,000 customers were left without power. The storm caused property losses amounting to more than $100 million. The cost of restoring Stanley Park resulted in an estimated expenditure of about $9 million (Joan Klaassen, Environment Canada, personal communication).

Another example demonstrating the vulnerability of social and economic infrastructure to wind storms occurred on July 17, 2006 over southern Ontario. There were actually two fatalities that resulted from the storm. The time sequence of the storm is shown in Figure 2.
Figure 2. Time sequence of the storm advancement on July 17, 2006, from morning (top), afternoon (middle) and evening (bottom). (Source: Environment Canada)

Associated with the storm were microbursts and straight line winds. Two tornadoes (F0 and F1) were confirmed touch downs. State of emergency was declared in several communities near North Bay, Ontario. The storm caused nearly 170,000 Hydro One customers to be without electricity for up to 5 days. The storm event was assessed to be the worst in damage to the provincial power grid since Ice Storm'98 (Joan Klaassen, Environment Canada, personal communication).

The July 17 storm was followed by another storm on August 2 that swept through south, central and eastern Ontario. The storm spun 17 tornadoes in one day that included two F2 category tornadoes. Fortunately there were no recorded injuries (Joan Klaassen, personal communication). There were extensive damages and destructions to buildings, homes and electrical grid. More than 150,000 Hydro One customers were left without power, some for more than one week. Then on September 24, another severe wind storm hit areas east of Georgian Bay, Ontario, causing some 90,000 Hydro One customers to lose power.
There is certainly a perception that severe wind events are increasing in recent years, perhaps due to climate change. A shifting climate can affect natural and human systems due to changes in mean and/or extremes. If climate change causes an increase in the frequency and/or intensity of wind-related hazards at various geographical locations, then the number of wind-related disasters can be expected to increase. There is compelling evidence in our observed climate data and from the climate model outputs that point to a warming climate associated with increasing concentration of CO₂ in the atmosphere (Intergovernmental Panel on Climate Change – WG1, 2007). Basic physics indicates that as the atmosphere warms, resulting in an increased warming of the sea surface temperature, evaporation of water from the ocean surface will increase, adding more moisture to the atmosphere. The resulting intensification of the hydrological cycle will likely result in an increase in the intensity of the mid-latitude synoptic storm systems, causing an increase in the IDF (intensity, duration, frequency) characteristics of the wind over Ontario in the future.

In this report, we present geographical distributions of climatological and extreme winds over Ontario using the NCEP-NARR (National Centers for Environmental Prediction-North American Regional Re-Analysis) data obtained from NCAR (National Center for Atmospheric Research), Boulder, Colorado (Mesinger et al., 2006). We initiate the discussion with the presentation of the climatological mean wind field over Ontario, followed by seasonal variations. These diagrams are shown with associated standard deviations used as a metric for gaining insight into the interannual variability. Because of the 3-hourly time resolution of the NARR data, we focus on wind generated by non-convective mechanism, as opposed to extreme winds associated with convective storms that usually last less than an hour. Although damages associated with convective extreme wind events often catch the media, non-convective high winds do cause damages with high societal impact, such as those observed during the December 2006-January 2007 period over the
southwestern shores of British Columbia (see Figure 1). In addition, we present geographical distributions of seasonal trends in wind magnitude over the 31-year period (1980-2010).

The latter part of the report will focus on the climatology of extreme winds over Ontario using the same NARR data as above. Characterisation of extreme winds is broken down into two aspects: (1) frequency of occurrence of winds above specified threshold values, and (2) distribution of winds for specified return periods.

2. North American Regional Re-Analysis (NARR) Data

In this study, we have used the NCEP North American Regional Reanalysis (NARR) surface wind data with a spatial resolution of 32 km in horizontal and 45 layers in the vertical (Mesinger et al., 2006). The output data are archived at a high temporal resolution of every 3 hours. The reanalysis data are generated from the NCEP Eta Model and its Data Assimilation System (EDAS). The dataset contains a large number of meteorological and hydrological variables. The study covers a 31-year period from 1980 to 2010. The NARR data domain is shown in Figure 3.
The NARR dataset constitutes a long-term, meteorologically consistent data generated by the NCEP mesoscale operational forecast mode called Eta model (Black, 1988) complemented by the Eta Data Assimilation System. With a more sophisticated land surface model (Luo et al., 2007), along with a more advance data assimilation procedure, the NARR data offer a more realistic representation of the meteorological condition at any one time than the NCEP-NCAR Global Analysis data (Mesinger et al., 2006). In particular, the EDAS process involves the assimilation of observed surface wind into the calculation that improves significantly the wind at 10-m height. It has been found that the comparison of the NARR 10-m wind with the observed wind at more than 400 surface meteorological stations in the United States showed a significant correlation in the summer and winter (Mesinger et al., 2006).

3. Methodology
The climatological mean and interannual variability of the NARR wind speed data in the study domain (mostly over Ontario) are calculated using the standard descriptive statistics for (a) 31-year (1980-2010) mean wind and its corresponding standard deviation, and (b) seasonal mean winds (winter – average of December of year t plus January and February of year t+1; spring – average of March, April, May; summer – average of June, July, August; fall – average of September, October, November) and their corresponding standard deviations. The equations for a scalar quantity like wind $v_i$ are

\[ V = \frac{1}{N} \sum_{i=1}^{N} v_i \quad \text{and} \quad \sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (v_i - V)^2 \]

for a set of N wind speed values (over a specified time domain – overall record mean, seasonal or monthly) and the corresponding variance, respectively.

For extreme winds, we have used two methods of characterisation. One is based on the frequency of occurrences of winds above certain specified threshold. Another one calculates wind strength associated with specified return periods using Gumble distribution of extreme value statistics.

4. Results and Discussion (Mean and Variability)

With the NARR winds archived at 3-hour intervals, we focus on non-convective high wind distributions over Ontario. Many of the non-convective high wind cases are associated with extratropical cyclones in mid-latitudes and are associated with large surface pressure gradients. There are several mechanisms by which non-convective high winds are generated over a relatively long time duration (long relative to extreme winds associated with convective storms such as thunderstorms and tornadoes which usually last less than an hour). These are (a) isallobaric condition that causes strong winds by a rapid change in the pressure gradient (Glickman, 2000), (b) tropopause folds that are associated with
bringing down high winds in the upper troposphere/lower stratosphere with large
momentum to the planetary boundary layer where momentum gets transferred to the
surface wind through shear instability (Schultz and Meisner, 2009), (c) string jet that occurs
in the dry area in the southern part of the occluded low centre. It is located to the northeast
of the southern tip of the occluded front associated with the cold conveyor belt (Clark et al.,
2005; Brown, 2004), and (d) topography that forces winds to extreme values by differences
in elevation and surface roughness, resulting in wind convergence (Hultquist et al., 2006).
As we will show below, most of the non-convective high winds are observed during the
winter season.

4.1. 31-Year Mean and Interannual Variability

Figure 4 shows (a) the 31-year (1980-2010) climatology of winds derived from the NARR
data and (b) the corresponding interannual variability. Strongest winds are observed over
Lake Superior, Lake Michigan and Lake Huron. This is consistent with results from many
investigations, such as those by Lacke et al. (2007). Hudson Bay is also identifiable with
winds in the range of 5.0-5.5 m/s. It is interesting to note that Lake Erie and Lake Ontario
are not visibly highlighted, in contrast to the other three Great Lakes.

![Figure 4. (Left) The 1980-2010 (31 years) wind climatology and (Right) its corresponding
standard deviation (metric for interannual variability). Wind speed scale in m/s is given in
the vertical colour bar to the right.](image-url)
The spatial distribution of the standard deviation (Figure 4b) again highlights the locations of the main water bodies, with winds over James Bay showing the largest interannual variability in Ontario with values greater than 0.35 m/s. Lakes Superior, Michigan and Huron stand out, particularly Lake Superior with an interannual variability with a range of 0.35 to 0.40 m/s. Over land, much of northwestern Ontario shows only a weak variability of 0.10 to 0.15 m/s. Regions around the Great Lakes and much of southern Ontario shows a slightly larger variability of 0.15 to 0.20 m/s.

4.2. Seasonal Mean and Interannual Variability

Figure 5 shows the distribution of seasonal mean wind and associated interannual variability. Winter is defined as December, January, February (DJF), spring as March, April, May (MAM), summer as June, July, August (JJA), and fall as September, October, November (SON).

(a)

Winter Seasonal Mean Wind Speeds for Months December, January and February over years 1980 to 2010
(b) Standard Deviation of Winter Seasonal Mean Wind Speeds for Months December, January and February over years 1980 to 2010

(c) Spring Seasonal Mean Wind Speeds for Months March, April and May over years 1980 to 2010
Standard Deviation of Summer Seasonal Mean Wind Speeds for Months June, July and August over years 1980 to 2010

(g)

Fall Seasonal Mean Wind Speeds for Months September, October and November over years 1980 to 2010
Figure 5. Winter (a) mean and (b) variability, spring (c) mean and (d) variability, summer (e) mean and (f) variability, and fall (g) mean and (h) variability. Wind speed scale in m/s is given in the vertical colour bar to the right.

Much of Ontario experiences a climatological wind regime in the range of 4-5 m/s through all the four seasons. A slight decrease is noted in the summer over southern Ontario (Figure 5e). A more dramatic seasonal change in the wind speed is noted over the various water bodies. Hudson Bay/James Bay area shows a wind regime of around 4-5 m/s in the winter, decreasing to 3-4 m/s in the spring. The wind speed starts to increase again in the summer, reaching maximum values of 7-8 m/s in the fall. This is consistent with the observation that extratropical cyclones passing over open waters could intensify due to heat transfer (Angel and Isard, 1997). During the fall season, water temperature reaches its annual maximum. With advection of cold air over warm water associated with an extratropical cyclone, thermodynamic forcing is most intense during this time of year. The Great Lakes region also shows a similar seasonal variation in the wind speed intensity, but unlike the Hudson Bay/James Bay region, one sees a slightly elevated wind regime during
the winter over some areas where the lakes do not freeze over, providing the greatest contrast between the atmospheric and water temperature.

The greatest interannual variability is observed over the water regions and during the colder winter and fall seasons. Of particular note is the large variability observed over James Bay and along the southwestern areas of Hudson Bay during the fall season. This may be associated with the year-to-year variation in the ice formation.

5. Climatological trend in wind magnitude

Figure 6 shows the geographical distributions of 31-year linear trends in seasonal mean winds. Statistical significance of a trend is determined by the Pearson statistical test.
Figure 6. Trends in seasonal mean wind are displayed on the left (units are in m/s/yr), with corresponding level of statistical correspondence expressed in Pearson p values. Winter (DJF: December, January, February), spring (MAM: March, April, May), summer (JJA: June, July, August), fall (SON: September, October, November).

Figure 6 shows noticeable seasonal variations in the trends, with significant increases in the wind strength over large bodies of water. The area over James Bay displaying highly significant increases in windspeed of up to 13 km/hr over the past 31 years includes the Ontario communities of Lake River, Atawapiskat, Kashechewan, Fort Albany, Moosonee and Moose Factory. The area also includes the protected regions of Polar Bear Provincial Park, Akimiski Island Bird Sanctuary, Moose River Migratory Bird Sanctuary, Hannah Bay Bird Sanctuary and Tidewater Provincial Park.

An area of highly significant increases in windspeed of up to 9 km/hr over the past 31 years also envelopes the entire Great Lakes during the winter season. During the spring, most of Lake Superior and northern Lake Huron and Georgian Bay have experienced statistically significant increases in wind strength; a zone that includes the port city of Thunder Bay and...
Sault St. Marie. In the summer, highly significant trends persist over northern Lake Huron and portions of eastern Georgian Bay; a zone that includes Round Lake and O’Donnel Pt. Provincial Nature Reserves, Killbear, Massasauga and Awenda Provincial Parks, Georgian Bay Islands National Park, the community of Parry Sound and the entrance to the Trent Canal system. The fall season appears to be a transition season as most of the trends in increasing windspeed weaken and disappear in the Great Lakes, only to strengthen again each winter.

Most of the terrestrial portion of Ontario removed from the Great Lakes and James Bay region has not experienced significant change in windspeed over the last 31 years. The exception is a triangular zone of highly significant decreases in windspeed at the eastern end of Lake Ontario coinciding with the major population centre of Kingston. In this zone, the summertime windspeeds have decreased modestly by as much as 2.2 km/hr. Calmer winds now experienced during this season may have implications for reduced dissipation of heat, gases, aerosols or insects present within urban areas.

Most of the large and highly significant increases in windspeed observed over the last 31 years are associated with water bodies. Depending on the season, this will likely have repercussions for commercial and recreational marine transport. In smaller communities of the northern Ontario, fishing represents a traditional component of the diet. Shoreline erosion is another potential impact particularly given the abundance of communities and protected areas represented by provincial parks and wildlife reserves situated along those shorelines. This may hold particular relevance for exposed habitats like Long Point and Rondeau on Lake Erie during the winter season when ice development is delayed or ice coverage is reduced. The winter season increases in wind strength could have significant impact on visibility due to increased frequency in blowing snow, as well as potential implications for snow clearing. The strengthening wind patterns also raise concerns of
potential water quality issues, as expected increases in the epilimnion surface mixed layer depths in the Great Lakes, particularly during the spring and summer seasons, could impact on nutrient availability and contribute to the development of noxious algal blooms, with consequential disturbances in the food web.

Although it is difficult to provide a set of definitive causes for the changes in the wind strength shown in Figure 6, we speculate that these changes are associated with changes in water conditions, since the observed secular increases over the last 31 years appear to have taken place over large bodies of water (such as the Great Lakes and James Bay). It is physically plausible that these increases in windspeeds are related to similar changes observed in water temperature owing to the disappearance of ice (see Figure 7 below).

Figure 7. Historical total accumulated ice coverage between May 14 and November 15 for the period 1981-2010 for the western portion of Hudson and James Bays (left) and the corresponding eastern portion (right). (Source: http://ice-glaces.ec.gc.ca/ Canadian Ice Service, Environment Canada)

6. Extreme Winds over Ontario
In this study, we have categorised the extreme wind occurrences over Ontario by employing two methods: (1) frequency of occurrences of winds above specified threshold for each season, and (2) windspeed associated with specified return periods.

6.1. Frequency of Windspeeds Above Specified Threshold

Using the 3-hourly wind observation from the NARR dataset, we have calculated (in terms of percentage) the frequency of wind above specified threshold values. These values are: 5, 10, and 15 m/s. The results are plotted in Figures 8, 9, and 10 for 5, 10, and 15 m/s threshold values, respectively, for each season.

Figure 8. Frequency (in percentage) of occurrences of wind greater than 5 m/s over the period 1980-2010. Colour scales not uniform from season to season.

Consistent with the seasonal mean wind distributions shown in Figure 5, winds above 5 m/s are observed mainly over bodies of water. In the winter, nearly 75% of the wind observed over the Great Lakes region is above 5 m/s, particularly over Lake Superior, Lake Michigan
and Lake Huron. Only about 20-30% of the time is the winter winds above 5 m/s over James Bay and the southern part of Hudson Bay. The percentage of occurrence decreases in the spring and summer, but rises dramatically in the fall. The pattern in the fall is slightly different from the one observed in the winter, with about 70-80% occurring in James Bay and Hudson Bay. This is likely due to the influence of seasonal variation in the sea ice.

Figure 9. Frequency (in percentage) of occurrences of wind greater than 10 m/s over the period 1980-2010. Colour scales are different from season to season.

While the patterns in Figure 9 are similar to those shown in Figure 8, the percentage occurrences have decreased. About 15 to 30% of winds experienced over the Great Lakes are above 10 m/s in the winter, the frequency drops to less than 10% in the spring and summer. While James Bay and southern Hudson Bay do not generally experience winds over 10 m/s during winter to summer, the winds over the region increases noticeably in the fall, with about 20-30% of the winds observed to be over 10 m/s.
Figure 10. Frequency (in percentage) of occurrences of wind greater than 15 m/s over the period 1980-2010. Colour scales are different from season to season.

The percentage of time a region is impacted by winds greater than 15 m/s is significantly reduced from those shown in Figures 8 and 9. As before, the frequency of occurrence is greatest over James Bay and southern Hudson Bay during the summer and fall (2-3%), while over the Great Lakes there are areas experiencing 1-2% in the winter time.

6.2. Return Periods

Applying the Gumble distribution to the NARR 3-hourly wind data, we have calculated the distribution of wind values for each specified return period. In this study, we have examined the wind values for return periods of 10, 20, 30 and 50 years. The results are shown in Figure 11.
For a 10-year return period, James Bay/southern Hudson Bay region experiences winds of about 8-10 m/s. For the Great Lakes region (mostly Lake Superior, Lake Michigan and Lake Huron), there are significant areas with slightly greater than 10 m/s. For Lake Erie and Lake Ontario, the 10-year return period winds are generally less than 8.5 m/s. For a 20-year return period, the magnitude of the wind increases, with the Great Lakes (Lake Superior, Lake Michigan and Lake Huron) experiencing winds over 12 m/s in some areas. For a 30-year return period, that value rises to over 13 m/s, increasing further to over 14 m/s for a 50-year return period.

With heightened interest in wind energy as part of the overall “green energy” initiative, any strategy that places wind turbines over water, such as Lake Ontario, needs to seriously take into account the real possibility of increasing windspeed and shortening return periods of
extreme winds under climate change. Our analysis of the observed NARR wind dataset from 1980 to 2010 indicates that this is already happening.

7. Conclusions

In this report, we have presented geographical distributions of climatological and extreme winds over Ontario derived from the NCEP-NARR dataset containing dynamically consistent meteorological and hydrological variables at a spatial resolution of 32 km in the horizontal and 45 layers in the vertical. The data are archived every 3 hours. In regards to the surface wind, the NARR data have been shown to be in relatively good agreement with more than 400 surface meteorological stations in the United States. Because of the temporal resolution of the data, the results in the report refer mainly to the non-convective winds associated with extratropical cyclones in the mid-latitude regions.

We have presented 31-year (1980-2010) mean wind climatology over Ontario. Interannual variability has been expressed by its corresponding standard deviation. We then resolved the overall mean wind climatology to seasonal variation and associated standard deviations. We have shown that the strongest winds occur over bodies of water, i.e., Hudson Bay/James Bay and Great Lakes (in particular, Lake Superior, Lake Michigan and Lake Huron). Seasonally, high winds are typically observed in the late fall (November) to the winter season. In addition to the year-to-year variation in the passage of extratropical cyclones over Ontario, the complex interaction between the atmosphere and the large bodies of water contributes to the large interannual variability in surface wind over Hudson Bay/James Bay region, as well as over the Great Lakes region.

The same complex interaction enhances regional changes in trends and extreme wind that are being induced by altered atmospheric circulation on a larger hemispheric scale. Winds,
particularly in the winter season, have increased over the last 31 years over large bodies of water such as the Great Lakes and James Bay and their corresponding coastal zones. Furthermore, these regions have experienced high percentage of winds exceeding 15-20 m/s. Return periods of 30 to 50 years characterised by high winds are also located over the same bodies of water and the surrounding regions. Since we are already experiencing climate warming in mid to high latitudes with some major impacts (see Figure 7 for impact on sea ice), the results from our observational data analysis indicate that we will see increasing windspeed in Ontario, particularly in regions over and around large bodies of water. This will likely have major impacts on ecosystems around water bodies, such as contribution of increased windspeed to increases in noxious algae blooms in Great Lakes. The increasing wind speed and extreme wind occurrences will also impact policies and strategies associated with structural standards and codes of wind turbines and their geographical placements. Blowing snow in the winter season along the coastal regions of large bodies of water which include Highway 401 that hugs the northern shores of Lake Ontario, will increasingly become a major issue, in terms of both economic and safety policies, as climate continues to warm over Ontario. A large urban centre like Toronto will need to start planning for extreme wind-related issues.
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