Summer Nonconvective Severe Wind Frequency over Ontario and Its Correlation with Tropical Pacific Sea Surface Temperature

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(Manuscript received 20 August 2013, in final form 2 December 2013)

ABSTRACT

The summer nonconvective severe surface wind (NCSSW) frequency over Ontario, Canada, in relation to regional climate conditions and tropical Pacific Ocean sea surface temperatures (SSTs) during the period of 1979–2006 is examined using surface wind reports and large-scale analysis data. A statistically robust positive trend in Ontario summer NCSSW frequency is identified using three independent statistical approaches, which include the conventional linear regression that has little disturbance to the original time series, the Mann–Kendall test without a lag-1 autoregressive process, and the Monte Carlo simulation. A composite analysis of the large-scale monthly mean data reveals that the high- (low-) NCSSW occurrence years are linked to stronger (weaker) large-scale horizontal pressure gradients and more (less) intensive vector wind anomalies in the upper troposphere. Unlike the low-event years, anomalous anticyclonic circulations are found at 500 and 250 hPa in the high-event years, which are conducive to downward momentum transport and favorable for severe surface wind development. It is also found that the summer NCSSW occurs more frequently under the conditions of warmer surface air temperature over Ontario. Further analyses indicate that an increase in the summer NCSSW frequency is well correlated with an increase in the previous winter SSTs over the eastern equatorial Pacific, namely, in the Niño-1+2 and Niño-3 areas, through a decrease in sea level pressure over northern Ontario and an increase in surface air temperature over central and southern Ontario.

1. Introduction

Severe surface winds (SSWs) have considerable impact on our society and economy because they often cause property damage, human injuries and casualties, and travel delays (Ashley and Black 2008). Over the Great Lakes region of the United States, for example, cold-season SSW occurrences alone have been responsible for 21%, and 28% of weather-related deaths and property damage (exceeding \$0.5 million) in the fall and winter seasons, respectively (Niziol and Paone 2000). Case studies of SSW occurrences associated with extratropical cyclones have been conducted (e.g., Browning 2004; Clark et al. 2005; Crupi 2004), and some work (e.g., Klink 2002; Lacke et al. 2007; Knox et al. 2011) has been performed to examine the climatology of cold-season SSWs, especially over the Great Lakes region (e.g., Lacke et al. 2007).

As compared to the studies of cold-season SSWs, publications on summer SSWs over the Great Lakes region are less common in the literature. Because the summer SSW occurrence is often a localized and short-lived phenomenon, its detection and prediction are

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DOI: 10.1175/JAMC-D-13-0266.1

FIG. 1. Map of Ontario.

challenging in terms of the location and timing of its occurrence. As the first step toward tackling these problems, we attempt to examine the large-scale environments that are conducive to SSW occurrences. To this end, we need to gain experience through climatological analyses of summer SSW occurrences and then find their associations with large-scale environments.

Observations during the past three decades indicate that there has been an increasing frequency of summer-month (i.e., June–August referred to as JJA hereinafter) SSW occurrences in Ontario, Canada (Cao 2008b). The province of Ontario is located between the Great Lakes and Hudson Bay, with a west–east span of about 1500 km (i.e., from about 96° to 79°W) to the north of 46°N, and its eastern boundary is extended to roughly 74°W to the south of 46°N (Fig. 1). The summer SSW occurrences have substantial societal and environmental impacts over this highly populated area and more than half of the summer SSW occurrences over this region are associated with nonconvective weather systems

(Cao 2008b). This inspires us to examine whether a trend in the summer nonconvective severe surface wind (NCSSW) frequency would exist. Furthermore, it is important to investigate how regional climate settings and external forcings are related to the Ontario summer NCSSW frequency variability.

To consider a surface wind occurrence as an SSW event, we adopt the wind warning criteria currently used by the Ontario Storm Prediction Center (OSPC) of Environment Canada: 1) mean sustained wind speed of 70 km h^{-1} (i.e., 19.4 m s^{-1}) or greater or 2) wind gusts of 90 km h^{-1} (i.e., 25 m s^{-1}) or greater. In OSPC, wind gusts due to thunderstorms are covered by a separate severe thunderstorm warning. Similar threshold criteria have also been used at the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (i.e., 18 and 26 m s^{-1}, respectively; see Lacke et al. 2007).

Summer SSWs in Ontario are usually associated with either mesoscale convective systems or large-scale nonconvective systems. In this study, we attempt to examine the summer SSW occurrences mainly associated with the large-scale pressure systems with little convective influences. Over the past 28 yr (i.e., 1979–2006), about 53% of the summer SSW occurrences in Ontario were nonconvective in nature (Cao 2008b). Ashley and Black (2008) have also found that over the northeast region of the United States, strong nonconvective wind gusts occur in all quadrants of midlatitude cyclones, and the mean annual occurrence of nonconvective peak wind gusts greater than or equal to 22.35 m s^{-1} over the Great Lakes region is about 4.4–6.4. Based on the analyses of 21 yr of wind data in Buffalo, New York, Niziol and Paone (2000) have found that nonconvective wind events occur in the southwest quadrant of a midlatitude cyclone in the wake of cold-frontal passage. In this regard, this work differs from our previous studies on Ontario severe hail (Cao 2008a), summer severe rainfall (Cao and Ma 2009), and tornados (Cao and Cai 2008; 2011) that are mainly convectively driven.

2. Data

The Ontario summer SSW frequency data used for the present study are obtained from OSPC (see Cao 2008a; Cao and Ma 2009; Cao and Cai 2011). Most of the summer NCSSW events, if not all, do not occur at the conventional surface stations. Therefore, these events are not well captured by the current surface observational network because of its coarse resolution. As a result, a severe weather reporting system has been established in Canada, including the routine severe weather sightings by Environment Canada, the trained storm spotter network [i.e., the Canadian Weather Amateur Radio Network (CANWARN)], as well as the other spotters. The reported events are then vetted by a forecaster at OSPC. The reporting data used in this study are similar to NOAA's *Storm Data* (http://www.ncdc.noaa.gov/stormevents/) used in Ashley and Black (2008). As Ashley and Black (2008) pointed out, the storm data have been the primary source of severe weather events for climatologists and meteorologists to examine past severe weather events.

Some localized SSWs associated with mesoscale convective systems (e.g., Weiss et al. 2002) may develop in the environments that are different from nonconvective high-wind occurrences. Hence, we distinguish the two different types of SSW occurrences and only consider NCSSW occurrences with little evidence of convective activity. To isolate the summer NCSSW occurrences from the original datasets, we have performed the scrutiny with (but not limited to) the following procedures. First of all, we exclude events associated with tornadoes, hail, and thunderstorms. In Ontario, wind gusts due to thunderstorms are covered by a severe thunderstorm warning. Second, we exclude the events with descriptions of "convection." Also, we exclude the events with uncertain and/or unknown circumstances as described in the reports. Finally, we check to make sure that the events associated with synoptic systems are nonconvective in nature using atmospheric soundings close to locations where the SSW events occurred and/or soundings obtained from high-resolution reanalysis. As a result, the dataset contains about 860 summer NCSSW occurrences during the period of 1979–2006, a total of 28 yr (Fig. 2).

Note that this dataset is currently only available up to the year 2006. The NCSSW occurrence data are obtained from various reports because most (if not all) NCSSW occurrences, like tornado occurrences (e.g., Brooks at al. 1994; Brooks et al. 2003; Cao and Cai 2008; Cao and Cai 2011), cannot be captured by current (coarse resolution) station observations (e.g., Lacke et al. 2007). Because of this, the NCSSW occurrence data are not station data per se. Therefore, there is no issue related to *station* data homogeneity. Nevertheless, meteorologists may use some observations to verify the NCSSW occurrences afterward.

Surface station observations, if available at close locations (say, about 50 km), are very often not located at the same places as reported severe wind events. If a yes (no) severe wind event is reported at a specific location, and surface observations verify the event with the same sign of yes (no), then both the report and the observation confirm the same event. On the other hand, if the surface observations are against the report, this verification is not

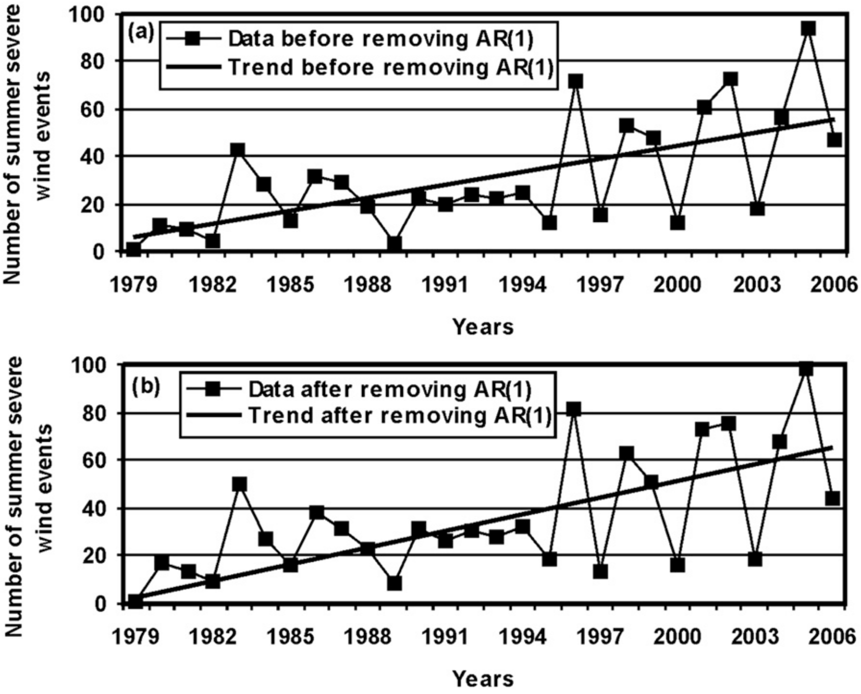

FIG. 2. Time series of summer SSW occurrence number (1979–2006) over Ontario and its trend (a) before and (b) after the removal of the AR(1) process.

consistent with the report and is not certain because of the variability of severe wind over the horizontal distance. Based on our scrutiny criteria, we would exclude this event because it is associated with uncertain and/or unknown circumstances. Because we are interested in binary information (i.e., yes or no) for severe wind events and the total number of the events, the surface station observations provide no additional information in terms of the total number of the severe wind events examined in this study. That is the second reason that we chose to use the reported data.

It is well known that a bias is defined as an average of differences between the estimated (or predicted) and observed values at the same location and the same time. However, at the surface observing-station sites, we do not have (actually we do not need) estimated values, while at the reported (estimated) sites, we do not have ground true values. Therefore, the bias computation cannot be performed if one uses surface station observations.

It should be mentioned that three major improvements in surface wind reporting procedures over Ontario have been made during the past three decades. (i) Since 1979, severe weather sightings have been routinely archived by Environment Canada. This procedure is homogeneous for the time series of Ontario summer NCSSW events examined in this study because it covers the same time period as our data period (i.e., 1979–2006). (ii) Since 1985, Doppler radar has been used to provide additional information for the verification of reported NCSSW events. To date, there are 31 Environment Canada radars that cover the area mainly along the U.S.–Canada border. As shown in Fig. 2, the reported summer NCSSW events in 1985 were less than those occurring in the adjacent years. (iii) In 1987, CANWARN was established, but the reported summer NCSSW events in 1987 were less than those in 1986, and no rapid increases occurred in the years right after 1987 (Fig. 2). Thus, we may state that the improved reporting procedures have no visible effects on the summer NCSSW time series over Ontario, at least during our study period. In addition, based on the work of King (1997), the population bias does not seem to affect the southwestern Ontario tornado reports significantly.

As will be shown in the next section, we have also removed lag-1 autoregressive process [AR(1)] related red noise for trend analyses, because a positive serial correlation of AR(1) in a time series will enhance the probability of detecting a trend of significance.

Individual summer NCSSW occurrences used in this study are quality controlled and then identified using the OSPC Weather Event Verification Decision Tree. The quality control process involves numerous checks and verification steps using different data and is performed by a meteorologist at OSPC. The verifications include the use of various observational data, such as radar

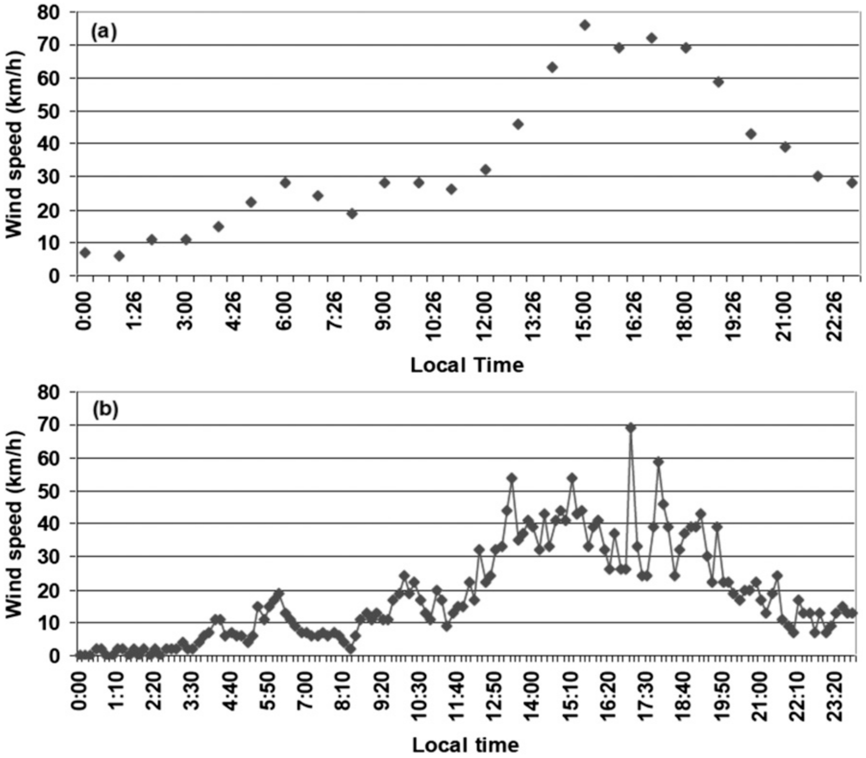

FIG. 3. The observed 10-m wind speed (km h^{-1}) on 18 Aug 2004 at the climate stations (a) Welcome Island (station 6049443) and (b) the Northern Ontario Portable Emergence Weather Station (station 604S001).

observations, surface observations close to locations where NCSSWs occurred, and other non–Environment Canada observations (e.g., Ontario Conservation Authority). As an example, we demonstrate how an NCSSW event that occurred during the afternoon of 18 August 2004 near the city of Thunder Bay (48.4°N and 89.3°W) was recorded in the archive. According to the report, ‘‘winds started picking up 13:30 EDT behind cold front, reaching 70-85 km h^{-1}. Trees and branches were down on power lines causing widespread outages.’’ The detailed description of wind speed is as follows: ‘‘13:39 EDT: wind speed varied from 67 to 85 km h^{-1}; 1432 EDT: wind speed ranged from 65 to 82 km h^{-1}; 1600 EDT: wind speed changed from 61 to 82 km h^{-1}; 1639 EDT: wind speed varied from 46 to 80 km h^{-1}.’’ To verify the report, we checked the surface station observations within a 50-km distance around Thunder Bay that were available on 18 August 2004. For instance, observations at the climate station Welcome Island (48.37°N and 89.12°W), 34.13 km to the southeast of Thunder Bay, showed that from 1426 to 1826 EDT, the wind speeds were about 70 km h^{-1} or greater. Especially, at 1526 and 1726 EDT the wind speeds reached 76 and 72 km h^{-1}, respectively (Fig. 3a). Also, the climate station at the Northern Ontario Portable Emergency Weather Station (48.43°N and 89.22°W), which is 43.07 km to the northeast of Thunder Bay, exhibited a wind speed of about 70 km h^{-1} around 1700 EDT (Fig. 3b). To verify if the SSW event is nonconvective in nature, we have accessed the observed sounding at the closest location, Pickle Lake (51.49°N and 90.20°W). As displayed in Figs. 4a and 4b, this sounding shows stable conditions at 1200 UTC 18 August [CAPE was 7.61 J kg^{-1} while the convective inhibition (CIN) was −18.9 J kg^{-1}] and 0000 UTC 19 August with negligible CAPE of 2.54 J kg^{-1}. Also, we have plotted a potential temperature θ profile [obtained from the North American Regional Reanalysis (NARR)] in Thunder Bay and found that it increases with height or remains unchanged with height at 1200 UTC 18 August (Fig. 4c). Hence, this severe wind event is nonconvective in nature.

3. Trend in summer NCSSW frequency

A nonparametric Mann–Kendall (i.e., MK) statistical test (Mann 1945; Kendall 1975) is employed to detect a possible trend in Ontario summer NCSSW frequency. Following Cao (2008a), we compute the standardized MK statistic Z (see the appendix). If $|Z| > Z_{1-(\alpha/2)}$ is true, a trend in Ontario summer NCSSW frequency is

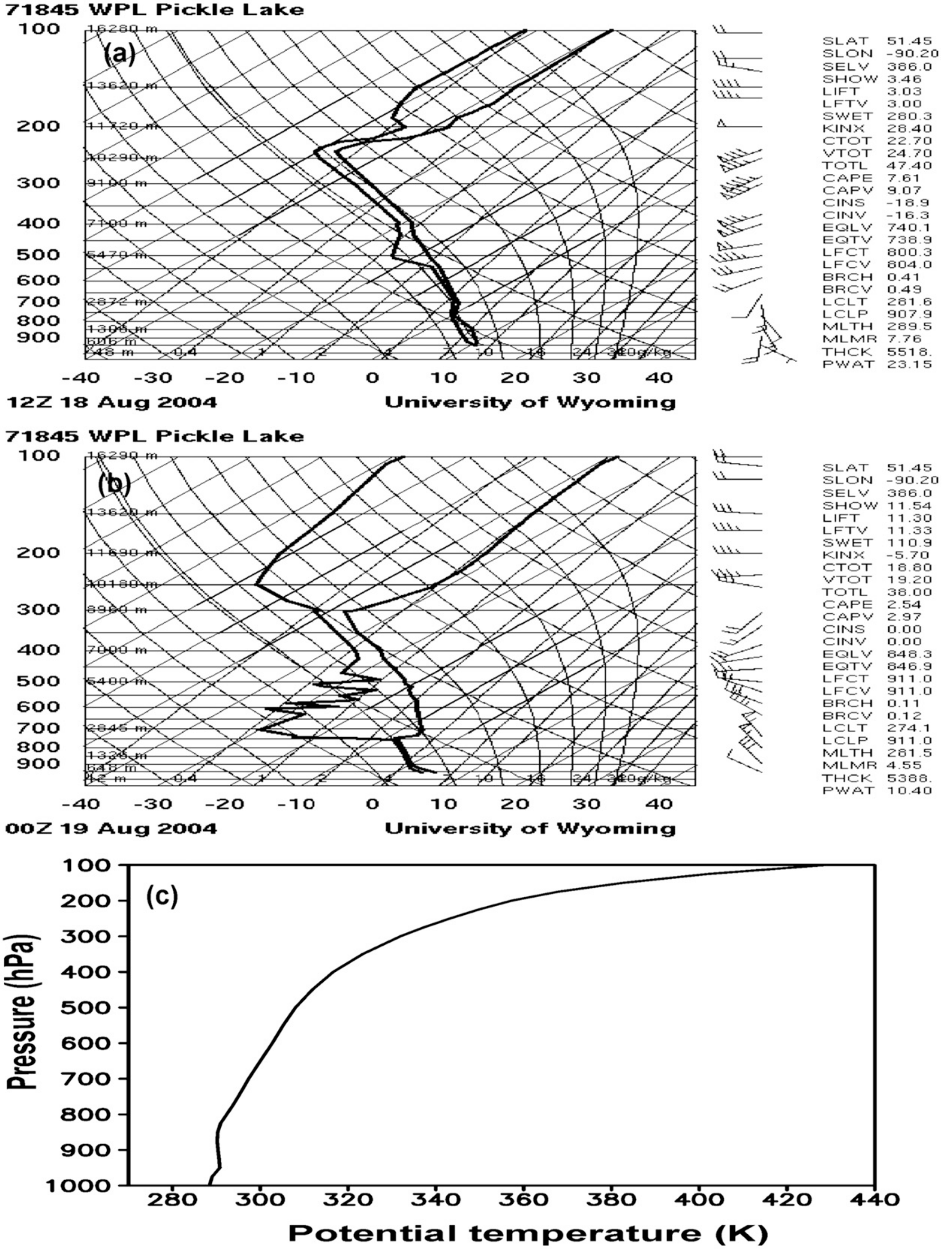

FIG. 4. The observed sounding at Pickle Lake at (a) 1200 UTC 18 Aug 2004 and (b) 0000 UTC 19 Aug 2004, as well as (c) the NARR-based profile of potential temperature (K) at Thunder Bay at 1800 UTC 18 Aug 2004.

TABLE 1. The MK test used to detect the trend in summer SSW frequency in Ontario.

Z statistic	2.94		
$Z_{1-(\alpha/2)}$	2.58	1.96	1.65
α	0.01	0.05	0.10

considered statistically significant at the $\alpha/2$ significance level. It should be mentioned that when the sample number of data is ≥8, the statistic Z is approximately normally distributed (Mann 1945; Kendall 1975).

Our intention in this study is to detect a deterministic trend (i.e., systematic changes over the mean), rather than a stochastic trend introduced by a red noise process that can be represented by an AR(1) process. The existence of a positive serial correlation of AR(1) in a time series (e.g., Pryor and Ledolter 2010) increases the probability of detecting a significant trend by the MK test. Von Storch (1995) suggested removing the AR(1) from a time series through a prewhitening procedure (see the appendix). To decide if the AR(1) process needs to be removed from the original time series, we calculate the autocorrelation coefficient and, then, perform a statistical test to see if it is significant. It is found that the AR(1) process that appeared in the NCSSW time series is statistically significant at the 5% significance level. That is why the AR(1) process should be removed from the time series. Because the previous prewhitening approach removes some portion of the trend (see Yue and Wang 2002), the trend-free prewhitening approach, as used by Cao (2008a), Cao and Ma (2009), and Cao and Cai (2011), is adopted herein prior to the application of the MK test (see the appendix). In this way, the true trend can be maintained, and it would unlikely be contaminated by the impact of autocorrelation.

As given in Table 1, the computed Z statistic is greater than $Z_{1-(\alpha/2)}$ at different statistically significant levels. The positive trend of summer NCSSW frequency over Ontario is at the 1% significance level. Figure 2b shows such a positive trend of summer NCSSW frequency after the AR(1) process is removed. Results indicate that the trend is about 1.9 occurrences per year with the 1% significance level.

In addition, we have performed an independent trend analysis using a conventional linear regression approach. The advantage of this method is in that there is little disturbance to the original time series. It is identified through a t test that this positive trend is at the 1% significance level.

Unlike the previous trend detection procedures (see Cao 2008a; Cao and Ma 2009), a Monte Carlo method (e.g., Chu and Wang 1997; Cao and Cai 2011) is employed to further assess the statistical significance of the detected trend. In this study, the Monte Carlo approach has been used to create synthetic datasets based on the original time series of the Ontario summer NCSSW frequency. We have performed 1000 Monte Carlo simulations. For each simulation, a linear regression slope is computed. After repeating these processes for 1000 times, we have sorted out these slopes into ascending order, and obtained the 990th test statistics (i.e., the absolute value of the slope for a two-tailed test). We found that the slope with the original time series is greater than the 990th test statistics, indicating that the detected trend is again at the 1% significance level.

4. Variability in summer NCSSW frequency

Figure 2a also shows that the Ontario summer NCSSW frequency has considerable variability over the past three decades. The nine high-frequency years are identified as 1983, 1996, 1998, 1999, 2001, 2002, 2004, 2005, and 2006, referred to as high-NCSSW occurrence years, whereas the nine low-frequency years occur during 1979, 1980, 1981, 1982, 1985, 1989, 1995, 1997, and 2000, referred to as low-NCSSW occurrence years.

To gain insight into how the summer NCSSW frequency is related to large-scale climate conditions, we employ the National Centers for Environment Prediction–National Center for Atmospheric Research (NCEP–NCAR) monthly mean reanalysis data (Kalnay et al. 1996) for a simple composite of anomalies for summer (JJA) mean sea level pressure (MSLP), surface air temperature (SAT), the 500–1000-hPa thickness, and upper-level wind vectors during the nine high-NCSSW occurrence years and the nine low-NCSSW occurrence years, respectively. Since the results from composite analyses for the three highest occurrence years (2005, 2002, and 1996) and lowest occurrence years (1979, 1989, and 1982) (with a magnitude > 1.0 standard deviation) are qualitatively the same as those for the nine high-occurrence years and nine low-occurrence years (with a magnitude greater than 0.5 standard deviation), respectively, we only present the results from composite analyses of the 9-yr high and low occurrences in order to have a reasonable sample size.

Prior to composite analyses, we examine how the NCSSW events are distributed in three individual summer month (JJA), similar to the research done by Lacke et al. (2007) for winter months. As shown in Fig. 5, the reported NCSSW events averaged over 28 yr (1979–2006) are about 9.1, 11.8, and 9.6 in June, July, and August, respectively. As a result, these NCSSW events are well distributed over the three summer months, and there is no extreme high or low number of NCSSW

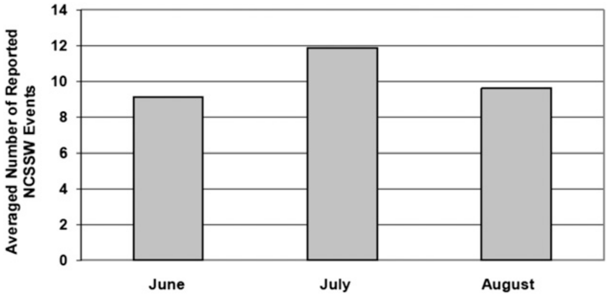

FIG. 5. The average number of reported NCSSW events in June, July, and August.

events in any of these three months. Since these NCSSW events are well distributed in the three summer months (JJA), we are interested in knowing 1) what the mean conditions of these three summer months are and 2) what differences there are in the mean conditions over the three summer months between high-event years and low-event years.

Figure 6 compares the horizontal distribution of MSLP anomalies in the high-NCSSW and low-NCSSW occurrence years over Ontario. To the north of about 46°N, the MSLP anomalies vary from −0.35 to 0.25 hPa, with a closed MSLP anomaly low centered over Lake Superior in the high-NCSSW occurrence years, whereas in the low-NCSSW occurrence years they change from 0.1 to 0.4 hPa. To the south of 46°N, the MSLP anomalies fluctuate from −0.15 to 0.15 hPa in the high-NCSSW occurrence years (Fig. 6a), whereas in the low-NCSSW occurrence years they vary from −0.1 to 0.1 hPa (Fig. 6b). Overall, the MSLP anomaly gradients over Ontario in the high-NCSSW occurrence years are about 1.5–2.0 times of those in the low-NCSSW occurrence years. Since the pressure gradients are proportional to wind speeds as the first approximation, these different large-scale environments may result in different occurrences of summer NCSSWs in the high-NCSSW occurrence years and the low-NCSSW occurrence years, respectively.

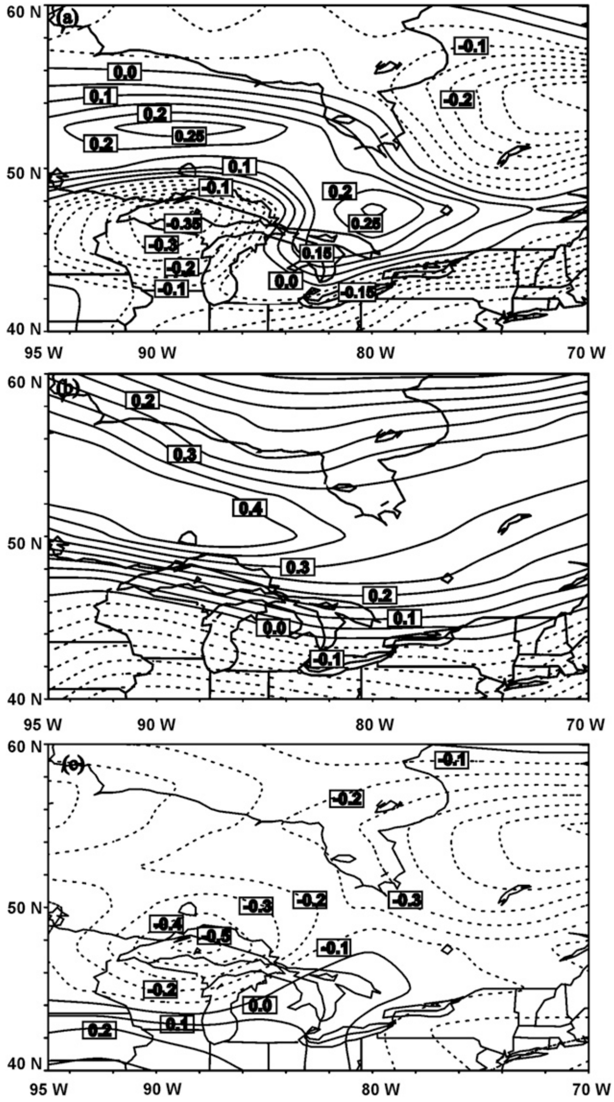

FIG. 6. Composite of the summer (JJA) sea level pressure anomaly (hPa; solid indicates positive, and dashed indicates negative) (a) for the nine high-SSW occurrence years, (b) for the nine low-SSW occurrence years, and (c) for (a) minus (b).

To explore whether the changes in the summer NCSSW frequencies are linked to the large-scale meteorological conditions, we have examined the relationship between the summer NCSSW frequencies and SAT anomalies. As shown in Fig. 7, the SAT anomalies over Ontario vary from 0.2° to 0.8°C in the high-NCSSW occurrence years whereas in the low-NCSSW occurrence years they change from −0.5° to 0°C, indicating that the high- and low-NCSSW occurrence years are indeed linked to the warmer and cooler SATs, respectively. Furthermore, we have examined if more (fewer) NCSSW occurrences have any relationship with the low-tropospheric mean temperatures. According to the thermal wind relation, the 500–1000-hPa thickness field can be used to represent the low-tropospheric (between 500 and 1000 hPa) mean temperatures.

Using the NCEP–NCAR monthly mean reanalysis data, we calculated composite anomalies for summer (JJA) thickness (500–1000 hPa) in the high-NCSSW occurrence years and the low-NCSSW occurrence years, respectively. It is evident from Fig. 8 that the amplitude of the composite anomaly in the nine high-NCSSW occurrence years (from 13 to 17 m) is much greater than that during the low-NCSSW occurrence years (from −1 to −4 m). This result confirms further that the high- and low-NCSSW occurrence years are linked to the warmer and cooler environments over

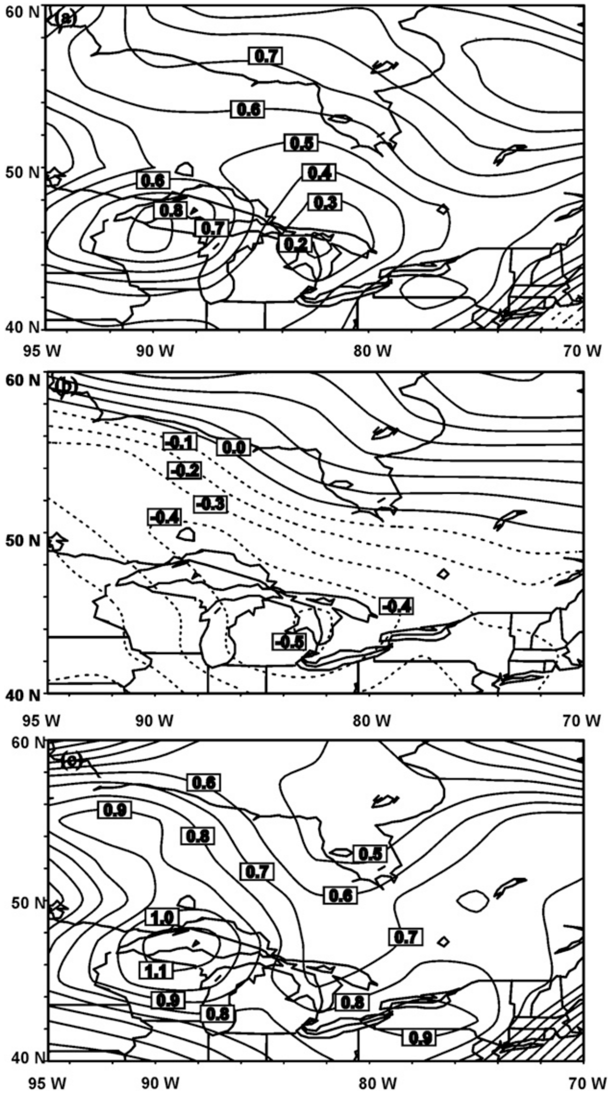

FIG. 7. As in Fig. 6, but for the SAT anomaly (°C).

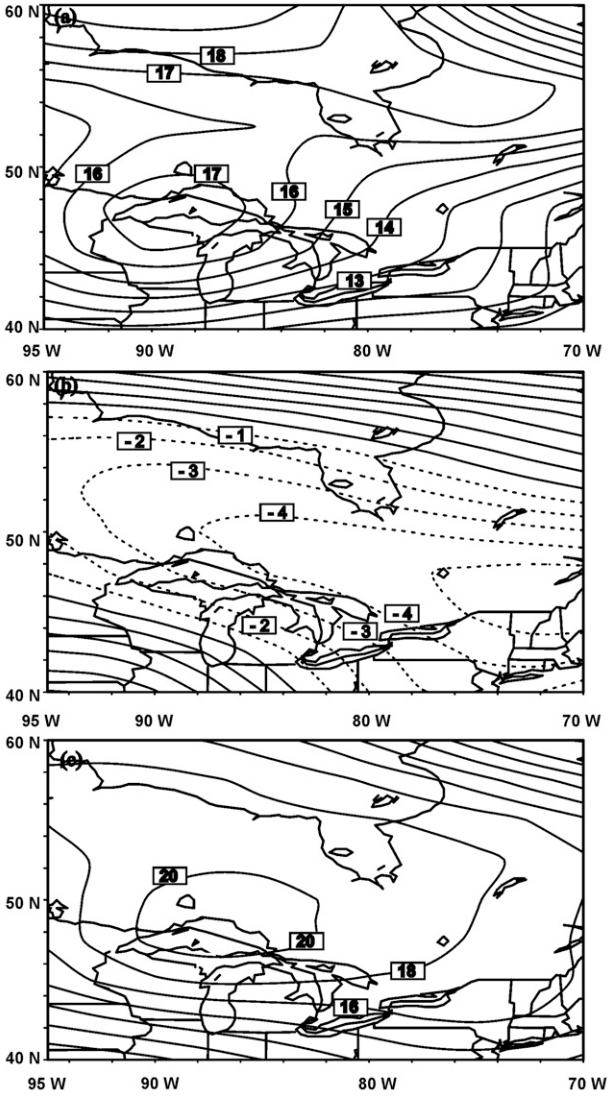

FIG. 8. As in Fig. 6, but for the 500–1000 hPa thickness anomaly (m).

Ontario, respectively. Thus, the low-level warm atmospheric conditions are favorable for more regional occurrences of summer NCSSW.

Furthermore, the higher-level wind may be associated with the surface severe wind development. Figure 9 shows the 500-hPa vector wind anomalies in the high-NCSSW and low-NCSSW occurrence years over Ontario. The magnitudes of the vector wind anomalies in the high-NCSSW occurrence years range from 0.1 to 0.9 m s^{-1} (Fig. 9a) whereas in the low-NCSSW occurrence years they vary from 0.1 to 0.4 m s^{-1} (Fig. 9b). The former is about 2 times that of the latter. In addition, during the high-event years, we have observed anomalous anticyclonic circulations at 500 hPa, which are conductive to downward momentum transport and are favorable for SSW development. In contrast, these phenomena are not observed in the low-event years. Similarly, we have found that the 250-hPa vector wind anomalies over the high-event years (from 0.2 to 1.4 m s^{-1}; Fig. 10a) are stronger in magnitude than those in low-event years (from 0.2 to 0.8 m s^{-1}; Fig. 10b). Also, there exist anomalous anticyclonic circulations at 250 hPa in the high-event years (Fig. 10a), but not in the low-event years (Fig. 10b). These differences between the high- and the low-event years are also true for the individual months of June, July, and August (not shown).

As indicated in Fig. 2a, there also exists substantial interannual variability in Ontario summer NCSSW frequency over the past three decades. Relative to our previous work (Cao 2008a; Cao and Ma 2009), we have further examined whether the interannual variability of

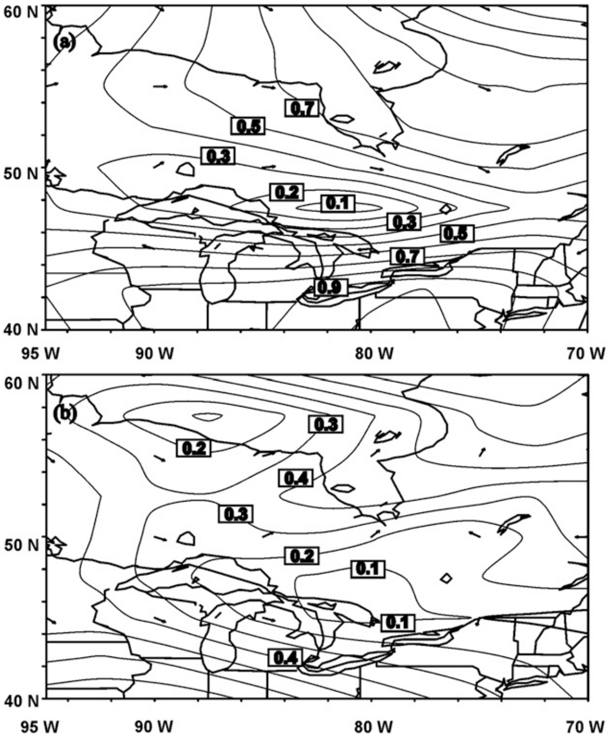

FIG. 9. Composite of summer (JJA) 500-hPa wind vector anomaly (m s^{-1}) for (a) the nine high-SSW occurrence years and (b) the nine low-SSW occurrence years.

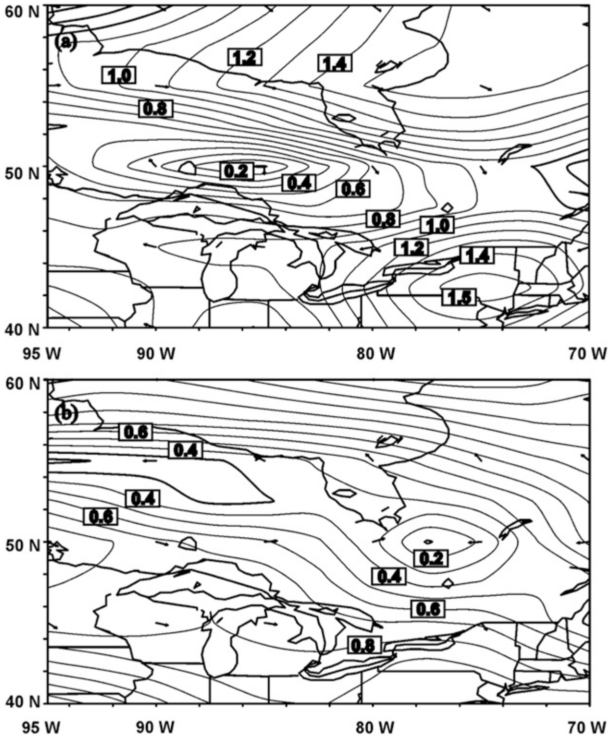

FIG. 10. As in Fig. 9, but for 250 hPa.

the summer NCSSW frequency is linked to external forcings such as tropical Pacific Ocean sea surface temperature (SST). In this work, the summer mean SST over four different areas in the equatorial Pacific is considered: 1) Niño-1+2 (0°–10°S, 90°–80°W), 2) Niño-3 (5°N–5°S, 150°–90°W), 3) Niño-3.4 (5°N–5°S, 170°–120°W), and 4) Niño-4 (5°N–5°S, 160°E–150°W). The area-averaged SSTs over those four areas are often referred to as the Niño-1+2, Niño-3, Niño-3.4, and Niño-4 SST indices, respectively.

To see if there is any relationship between the summer NCSSW frequency and the SSTs, we have first detrended the time series of the summer NCSSW frequency, and then computed the lagged correlation coefficients between the previous winter and current spring SSTs and the detrended summer NCSSW frequency. As shown in Table 2, the previous winter SSTs have systematically stronger correlations with the summer NCSSW frequency than do the current spring SSTs. In particular, the lagged correlations with both the Niño-1+2 and Niño-3 indices in the previous winter and current spring are at the 5% significance level, whereas the lagged correlations with the Niño-4 index do not pass the statistical significant test. Although the lagged correlations with the Niño-3.4 index also pass a statistical significant test at the 5% significance level, these correlations are mainly attributed to the Niño-3 index. Hence, the subsequent analyses will focus mainly on how the Niño-1+2, and Niño-3 indices, especially during the wintertime, are associated with Ontario summer NCSSW frequency.

Figure 11 shows the spatial distributions of correlation coefficients between the summer MSLP and previous winter Niño-1+2 and Niño-3 indices, as well as the summer NCSSW frequency, respectively. In the northern part of the Ontario region, the correlation coefficients between the summer MSLP and previous winter Niño-1+2 index vary from −0.32 to −0.44 (Fig. 11a), exceeding a requirement for a statistical significance level of 5%. It is interesting to note that a zone of higher negative correlation coefficient between the summer MSLP and previous winter Niño-3 index is located along the Hudson Bay (Fig. 11b). These indicate that an increase in the eastern equatorial Pacific SSTs

TABLE 2. Lagged correlation coefficients between SSTs (previous winter and current spring) and Ontario summer SSW frequency during the period 1979–2006.

Index	Niña-1+2	Niña-3	Niña-4	Niña-3.4
Winter	0.51	0.47	0.29	0.41
Spring	0.41	0.43	0.18	0.37

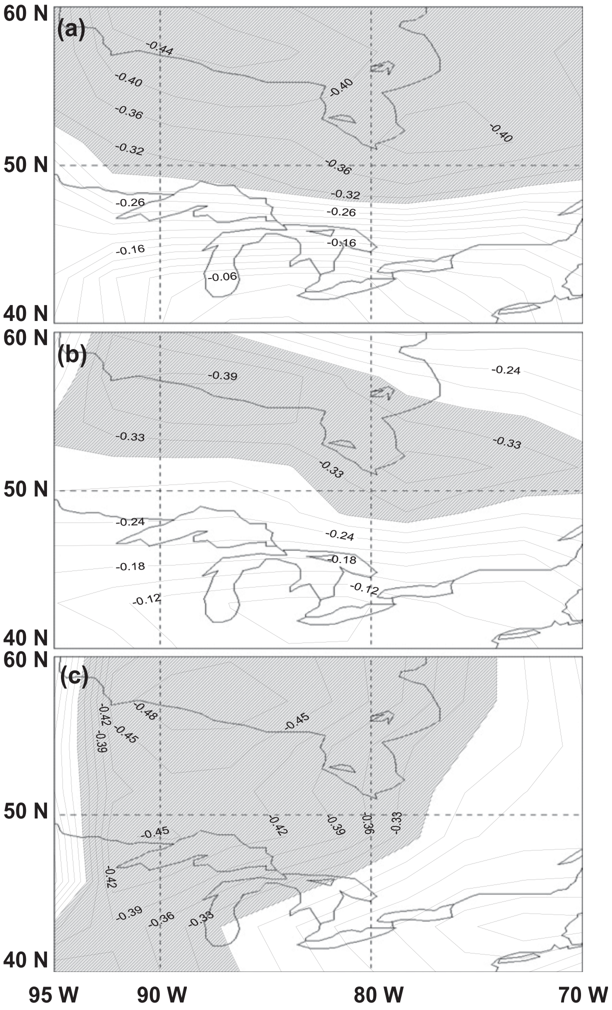

FIG. 11. Spatial distributions of correlation coefficients between the summer sea level pressure (hPa) and (a) the previous winter Niño-1+2 index, (b) the previous winter Niño-3 index, and (c) the summer SSW frequency. Shadings indicate the areas with significance at the 5% level.

during the previous winter is associated with a decrease in the summer MSLP over northern Ontario. Meanwhile, the Ontario summer SSW frequency is negatively correlated with the MSLP field over the northern and central parts of Ontario (Fig. 11c). In short, in northern Ontario, the previous winter Niño-1+2 and Niño-3 SSTs are associated with the summer MSLP decrease, which is in turn associated with the summer NCSSW frequency increase. It is therefore suggested that over northern Ontario, the increase in summer NCSSW frequency responds to the increase in the previous winter Niño-1+2 and Niño-3 SSTs through the decrease in the MSLP.

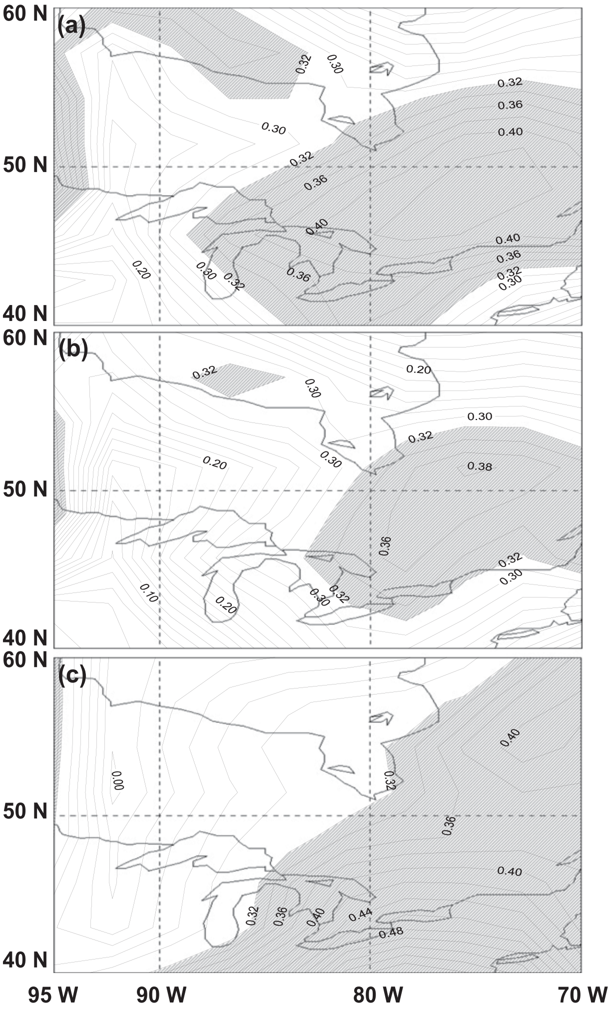

FIG. 12. As in Fig. 11, but for SATs (°C).

In addition to probing the dynamic effects of the previous winter Niño-1+2 and Niño-3 SST indices on the summer NCSSW frequency, the thermodynamic effects of the previous winter Niño-1+2 and Niño-3 indices have also been examined. Figure 12 displays the spatial distributions of correlation coefficients between the summer SATs and the previous winter Niño-1+2 and Niño-3 indices, as well as the summer NCSSW frequency. It is apparent that the areas of statistically significant (at the 5% level) positive correlation coefficients between the summer SATs and previous winter Niño-1+2 and Niño-3 indices are positioned in the middle and southern portions of Ontario (Figs. 12a,b). Correspondingly, the areas of statistically significant (at the 5% level) positive correlation coefficients between the summer SATs and the summer NCSSW frequency are also situated in the middle and southern portions of Ontario (Fig. 12c). In summary, in the areas of central and southern Ontario, the previous winter Niño-1+2 and Niño-3 SST increase is linked to the summer SAT increase, which is further linked to the summer NCSSW frequency increase. This suggests that over central and southern Ontario, the increase in summer NCSSW frequency responds to an increase in the previous winter Niño-1+2 and Niño-3 SSTs through an increase in SATs.

5. Concluding remarks

In this study, the summer NCSSW frequency during the period 1979–2006 over Ontario, Canada, is investigated using surface observations from the OSPC of Environment Canada and large-scale analysis data from NCEP–NCAR. Results show that the summer NCSSW frequency over Ontario exhibits a positive trend over the past three decades. This increased trend is robust, as demonstrated by three independent approaches: 1) the conventional linear regression with no disturbance to the original time series, 2) the MK statistical test without the AR(1) process, and 3) the Monte Carlo simulation.

Composite analyses using the NCEP–NCAR monthly mean fields reveal that the high- and low-NCSSW occurrence years are highly linked to stronger and weaker large-scale horizontal pressure gradients, respectively. It is found that vector wind anomalies at upper levels are larger in magnitude in high-event years than in low-event years. Unlike the low-event years, we have observed anomalous anticyclonic circulations at 500 and 250 hPa in the high-event years, which are conductive to downward momentum transport and favorable for severe surface wind development. Results indicate that under the conditions of warmer SATs, the summer NCSSW occurrences over Ontario tend to occur more frequently than those with colder SAT anomalies. This result appears to have significant implications with respect to the societal and economic impacts of summer NCSSW occurrences over Ontario.

It is found that there is a strong interannual response of Ontario summer NCSSW frequency to the SST changes occurring in the eastern equatorial Pacific (i.e., in Niño-1+2 and Niño-3 areas), through the variations in MSLP over northern Ontario and in SATs over central and southern Ontario. It should be mentioned that the statistical relationship between the SST and the Ontario summer NCSSW events is not yet representative of the cause and effect in physics. The comprehensive physical process for the identified relationship is beyond the scope of this study. This will be an interesting topic for future exploration since the physics behind the linkage will be helpful in improving our understanding of and detecting and forecasting the summer NCSSW events. Moreover, it will be of interest to examine the frequency of summer large-scale systems over Ontario during past decades in relation to the frequency of NCSSW events examined in the present study.

Acknowledgments. We acknowledge Environment Canada/Ontario Storm Prediction Center for providing the observational data on summer severe surface wind frequency. This work was supported in part by NSF Grant ATM0758609 and NOAA Grant NA12NWS4680008.

APPENDIX

Nonparametric Mann–Kendall Test and Trend-Free Prewhitening Approach

A nonparametric MK (Mann 1945; Kendall 1975) statistical test is employed in this study to detect a linear trend. Under the null hypothesis H_o that a sample of data $\{X_i, i = 1, 2, \dots, n\}$ is independent and identically distributed, the MK test statistic S is defined as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i), \tag{A1}$$

where

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \, . \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{A2}$$

Mann (1945) and Kendall (1975) showed that when $n \geq 8$, the statistic S is approximately normally distributed with the mean and the variance as follows:

$$E(S) = 0 \quad \text{and} \tag{A3}$$

$$\sigma_S^2 = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)\right], \tag{A4}$$

where m is the number of tied (i.e., equal values) groups and t_i is the number of data points in the ith tied group. Under the null hypothesis, the standardized MK statistic Z follows the standard normal distribution with mean of 0 and variance of 1:

$$Z = \begin{cases} (S-1)/\sigma_S & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \, . \\ (S+1)/\sigma_S & \text{if} \quad S < 0 \end{cases} \tag{A5}$$

If $|Z| > Z_{1-(\alpha/2)}$, a trend is statistically significant at a level of $1 - (\alpha/2)$.

Given that the existence of positive serial correlation in a time series increases the probability of detection of a significant trend by the MK test, von Storch (1995) suggested removing the AR(1) (a lag-1 autoregressive process) from the time series through a prewhitening procedure. But, this prewhitening also removes a portion of the trend, as demonstrated by Yue and Wang (2002). To detect a trend properly, we use a trend-free prewhitening approach (e.g., Cao 2008a; Cao and Ma 2009; Cao and Cai 2011) prior to applying the MK test so that the true trend is preserved and it is no longer influenced by the effects of autocorrelation. This approach involves the following four procedures:

(a) A nonzero slope β of a trend in a time series $\{X_t, t = 1, 2, \ldots, n\}$ is estimated by a regression method, and the sample data are detrended:

$$X_t' = X_t - T_t = X_t - \beta t. \qquad \text{(A6)}$$

(b) A lag-1 serial correlation coefficient ρ_1 of the detrended series X_t' is calculated and the AR(1) is removed from the X_t':

$$Y_t' = X_t' - \rho_1 X_{t-1}'. \qquad \text{(A7)}$$

(c) The identified trend T_t and the residual Y_t' are blended:

$$Y_t = Y_t' + T_t. \qquad \text{(A8)}$$

(d) The MK test is then applied to the blended series to assess the significance of the trend.

It is noted that the blended series Y_t could preserve the true trend and is no longer influenced by the effects of autocorrelation.

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