On Recent Trends in Atmospheric and Limnological Variables in Lake Ontario

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ABSTRACT

The surface air and water temperatures increased at all seasonal and annual time scales during the last 40 yr in Lake Ontario. The annual mean air and surface water temperatures have increased by 1.43° ±0.39° and 1.26° ±0.32°C, respectively, over 1970–2009. The air temperature increased at a faster rate than the surface water temperature in winter and autumn, whereas in spring and summer the surface water temperature warmed faster than the air temperature. The length of summer stratified season has increased by 12 ± 2 days since the early 1970s due to the increase in water temperature. The decline of surface wind speed over Lake Ontario resulted in a shallower surface mixed layer and enhanced the summer thermal stratification, which increased the summer surface water temperature more rapidly than the air temperature.

1. Introduction

In the last few decades, the global mean air temperatures have increased largely owing to the anthropogenic emissions of greenhouse gases (Hansen et al. 2006; Solomon et al. 2007). Climate change will affect aquatic systems in several ways, including changes to water levels, ice cover, and water temperatures. Climate warming has already affected northern temperate lakes by causing earlier ice breakup and delayed freeze-up and reduced winter ice cover (e.g., Austin and Colman 2008). These effects in turn will lead to earlier spring overturn and a longer warming season, which will further affect the water quality and aquatic ecosystems (e.g., O'Reilly et al. 2003; Winder and Schindler 2004).

The Laurentian Great Lakes have a total surface area of approximately 2 45 000 km^2 and a total water volume of approximately 22 700 km^3. Their thermal state has an important effect on the surrounding ecosystems (e.g., Mortsch and Quinn 1996). However, the thermal response of the Laurentian Great Lakes to climate change is still poorly understood. Because of limitations of long-term and continuous records of measured water temperatures, only limited studies on the variability of thermal properties in the Laurentian Great Lakes under climate change have been conducted. Earlier studies on Lake Huron (e.g., King et al. 1997) showed that the thermal response had increased in parallel with the recent warming trend since the mid-1960s. In another example, McCormick and Fahnenstiel (1999) found a warming trend in the annual mean near-shore water temperatures at five of the seven coastal locations located in the St. Lawrence Great Lakes and a 4–6 h yr^{-1} rate of increase in the maximum potential duration of summer stratification. Austin and Colman (2008) observed that the open water Lake Superior summer temperatures had increased by roughly 3.5°C over the last century and that most of the warming occurred in the last three decades. The thermal response of Lake Superior in summer is significantly in excess of regional surface air temperature change during 1979–2006 (Austin and Colman 2007). This is caused by the decreased winter ice cover documented in many rivers and lakes (e.g., Magnuson et al. 2000), which results in a significant change in albedo and a correspondingly increased heat input in the late winter and spring, leading

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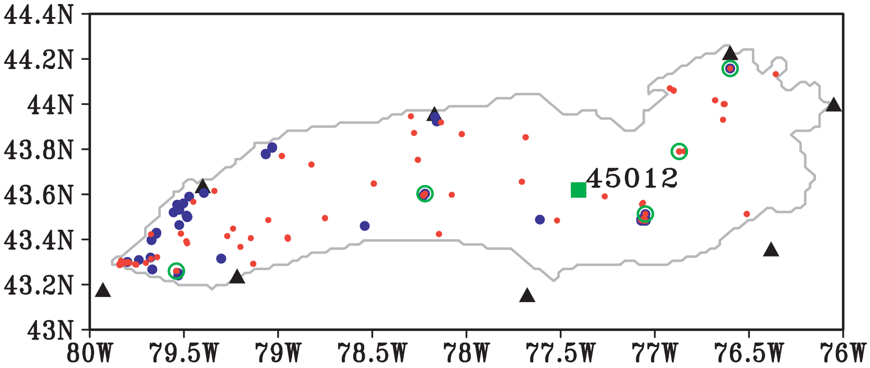

FIG. 1. Locations of limnological and meteorological measurements in Lake Ontario [surveys (red circles); profile observations (blue circles); standard meteorological stations (black triangles); NDBC site 45012 (green square); wind-speed-measured locations (green circles)].

to an earlier onset of summer stratification. However, these studies are limited to surface air and lake parameters during summer or in some cases confined to annual means in the upper Great Lakes. Wang et al. (2012) noted that the ice cover in the Great Lakes has varied significantly since 1973. Although they observed downward trends in all the lakes, the ice cover has reduced more rapidly in Lake Ontario.

Lake Ontario is the 14th largest lake in the world and is located downstream of the other members of the Great Lakes. It is affected by climate change occurring throughout the Great Lakes region. However, few such studies have been carried out for Lake Ontario. This paper is concerned with the recent climatic trends in Lake Ontario, and the major objective of this study is to investigate the thermal response of Lake Ontario to the climate change at different time scales (e.g., seasonal means and annual means) using a 40-yr record of water temperatures and meteorological data. The feedback of the lake–air thermal contrast to the surface atmosphere is also briefly discussed.

2. Data and methods

Systematic meteorological and lake observations in the Great Lakes, particularly in Lake Ontario, are available over the last 40 yr (1970–2009). During this period Environment Canada (EC) and the U.S. Environmental Protection Agency (EPA) conducted lakewide surveillance surveys in Lake Ontario, which include surface water and 2-m air temperatures and water quality measurements (red circles in Fig. 1). The frequency of these data is spatially well spread over the lake; however, it is temporally limited to 3–10 measurements per year. The 40-yr continuous daily 10-m wind speeds and 2-m air temperatures measured at the eight standard meteorological stations (black triangles in Fig. 1) along the south and north lakeshore during 1970–2009 are available online (at http://www.ncdc.noaa.gov/oa/climate/climatedata.html#daily). During intensive field years, such as the International Field Year of the Great Lakes (IFYGL) and the Lake Ontario Nutrient Assessment Study (LONAS), and during several research projects, such as Lake Ontario coastal boundary layer experiments, extensive overlake buoy-based time series measurements of winds and water temperatures were obtained in the lake. In one such experiment, EC also obtained hourly vertical temperature profiles during late spring to early fall from at least one or two moorings in the lake for each year between 1996 and 2009 (blue circles in Fig. 1). All the data are archived in EC's storage and retrieval (STAR) database at the Canada Centre for Inland Waters (CCIW).

Since the scale of the atmospheric weather patterns is typically much larger than Lake Ontario, the mean (>24 h) wind field is observed to be rather uniform over the lake (Simons and Schertzer 1989). The 40-yr (1970–2009) daily lake surface temperatures (measured at the locations marked by red circles in Fig. 1), 2-m air temperatures (measured at the sites marked by red circles and the eight standard weather stations marked by black triangles in Fig. 1), and 10-m wind speeds (the eight standard weather stations marked by black triangles in Fig. 1) averaged spatially using a distance weighing method (Huang et al. 2010) over these stations (Fig. 1) are considered representative of the whole lake conditions during 1970–2009. In addition, we also used National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) daily reanalysis (Saha et al. 2010) winds at the 850-hPa level during 1970–2009 to assess the changes of winds in the free atmosphere over the lake.

To qualify the in situ lake-averaged surface temperatures, we adopted the daily lake-averaged surface temperatures obtained from satellite (available from the National Oceanic and Atmospheric Administration (NOAA)'s CoastWatch site at ftp://coastwatch.glerl.noaa.gov/glsea/avgtemps) during 1992–2009. These values were used to verify the consistency of in situ lake surface temperatures. Since 2002 EC and NOAA have been operating weather buoys from May to November in the open lake. The daily wind speed data measured at National Data Buoy Center (NDBC) buoy 45012 (available at http://www.ndbc.noaa.gov/station_page.php?station=45012) and the other five locations in the open lake (green circles in Fig. 1), which are spatially well spread over the lake, have been used to verify the representation of shore-based wind data. The monthly wind speed over the open lake and the air–lake temperature difference during late spring to early fall range from ~4.5 to ~7 m s^{-1} and from approximately −3 to approximately 4°C, respectively (not shown). At monthly time scales, the lake is nearly under neutral stability during late spring to early fall. Therefore, the monthly winds over the open lake measured at 5 m above the lake level have been adjusted to 10 m using a power-law scaling (Hsu et al. 1994). For further verification of the NCEP–NCAR reanalysis 850-hPa winds, we also used the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) daily winds at 850 hPa from 1970 to 2002 (Uppala et al. 2005). The detailed assessment of the lakewide averaged surface temperature, 10-m wind speed, and the NCEP–NCAR reanalysis 850-hPa winds will be given in section 3.

In this study we adopt the standard least squares regression with linear slope and 1-σ slope uncertainty and a two-tailed t test to examine all trends. The r^2 in the standard least squares regression indicates the square of coefficients between two time series data. The two-tailed t-test p value reflects the significance level of the regression. We also calculated the root-mean-square error (RMSE) (Huang et al. 2010) to assess the accuracy of the data used in this study.

3. Results

The daily in situ lake-averaged surface temperatures show significant seasonal variation, with warmer temperature over 18°C in summer and colder temperature below 6°C in winter (Fig. 2a). The daily lake surface temperatures also show notable interannual variability, with the standard deviation ranging from 2° to 3.5°C in summer. Comparisons of the daily in situ lake-averaged surface temperatures with the data derived from the 18-yr (1992–2009) daily NOAA CoastWatch's satellite data (Fig. 2b) show good agreement (r^2 = 0.97, RMSE = 0.83°C). To establish the reliability of the lake-averaged wind data, we compared daily lake-averaged wind speeds with winds measured on different locations in the open lake (Fig. 1). As shown in Fig. 3a, the lake-averaged wind speeds are in good agreement with those from the open lake (r^2 = 0.87, RMSE = 0.48 m s^{-1}). The frequency distribution of wind speed (Fig. 3b) also shows that the lakewide averaged wind speeds have very high consistency with the data from the different locations in the open lake. The NCEP–NCAR reanalysis winds at 850 hPa are compared with the ERA-40 daily winds at 850 hPa. During 1970–2002, the regionally averaged 850-hPa ERA-40 and NCEP reanalysis wind speeds over Lake Ontario have high correlations over the 99% significance level (r^2 = 0.95 for winter, r^2 = 0.87 for summer) (Figs. 4a,b). These results suggest that the in situ lake-averaged surface temperatures, 10-m wind speeds, and NCEP–NCAR 850-hPa wind speeds are reliable and can be used to study the trends in atmospheric and limnological variables in Lake Ontario.

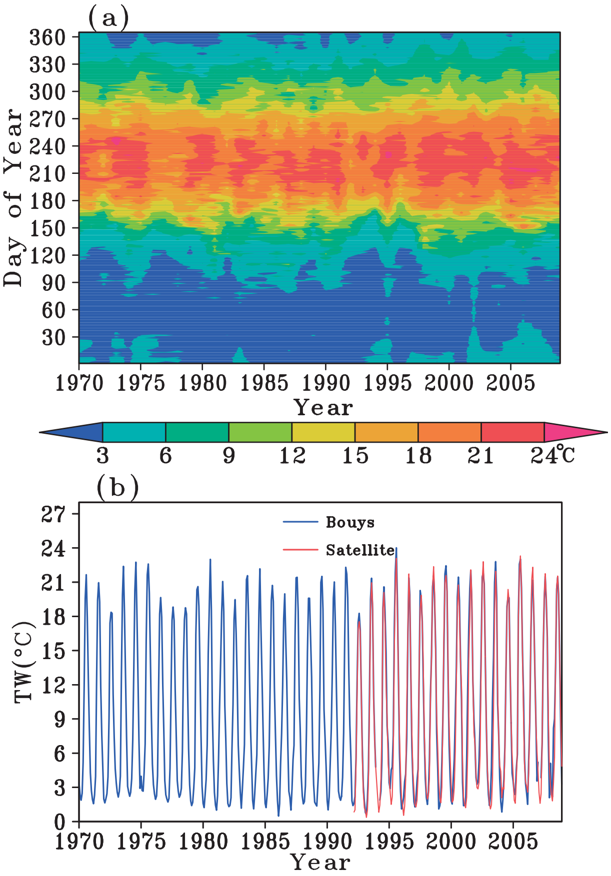

FIG. 2. (a) Daily observed lake-averaged surface water temperature from buoys. (b) Time series of observed monthly lake-averaged surface water temperature from buoys (blue) and satellite (red).

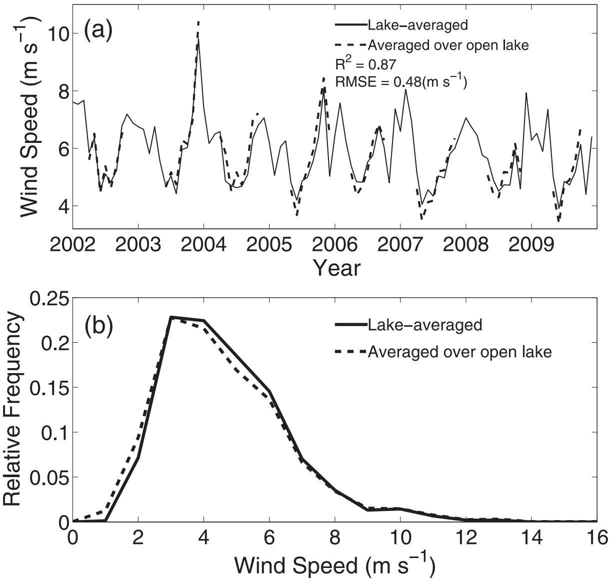

FIG. 3. (a) Time series of the monthly lake-averaged wind speeds and those measured over the open lake during 2002–09. (b) Frequency distributions of monthly wind speeds of lakewide averages (solid line) and those measured over the open lake during 2002–09 (dashed line).

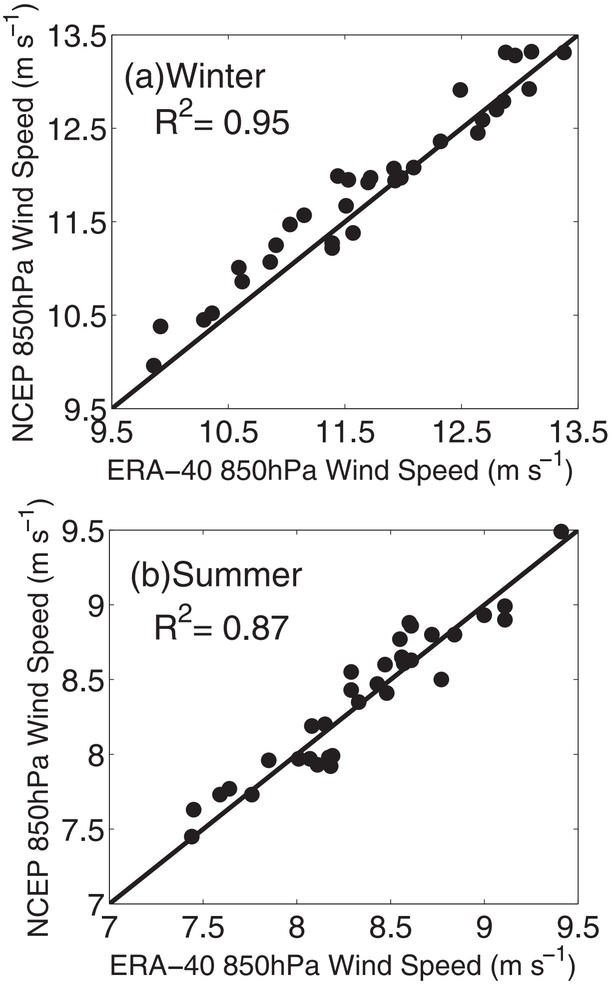

FIG. 4. The regionally averaged 850-hPa wind speed over Lake Ontario for the (a) winter mean and (b) summer mean of the ERA-40 and NCEP reanalysis data over 1970–2002.

To analyze the in situ data at seasonal scales, we defined the four seasons as following: winter (January–March), spring (April–June), summer (July–September), and autumn (October–December). As shown in Figs. 5a–e and Table 1, both the lake-averaged surface water temperature and the 2-m air temperature show warming trends at all seasonal and annual time scales during 1970–2009. The maximal warming rate of 2-m air temperature (0.52 ±0.21°C decade^{-1}, $r^2 = 0.14$, $p = 0.02$) and surface water temperature (0.43 ±0.17°C decade^{-1}, $r^2 = 0.21$, $p = 0.003$) are found in winter and summer, respectively; whereas the minimal rate of warming for air temperature (0.16 ±0.15°C decade^{-1}) and surface water temperature (0.13 ±0.04°C decade^{-1}) are observed in spring and winter, respectively. In winter and autumn, the air temperature warmed notably faster than the surface water temperature. Especially in winter, the warming rate of the 2-m air temperature is about 4 times the surface water temperature warming rate. Although ice cover in Lake Ontario is not significant compared to other members of the Great Lakes, the increased air temperature in winter may have played a minor role in the enhanced downward trend of ice cover in the lake (Assel et al. 2003; Wang et al. 2012). In contrast to winter, the surface water temperatures increased more rapidly than the air temperatures in summer. This is consistent with the observations in Lake Superior (e.g., Austin and Colman 2007), where the positive ice albedo feedback contributed to the faster warming of the surface water temperature than the surface air temperature. Meanwhile, it can be noted that the warming rates of the annual mean lake surface temperature and the air temperature are comparable. As shown in Figs. 5f–j and Table 1, the 10-m wind speed over Lake Ontario significantly decreased on the order ranging from −0.20 to −0.33 m s^{-1} decade^{-1} ($p < 0.001$) at all seasonal and annual time scales over the last four decades. This is consistent with the studies of Wan et al. (2010), who showed a decreasing trend in wind speed over Ontario over 1953–2006. These changes in wind speed will play a role in observed changes in the mixed-layer depth (MLD) (e.g., Pollard et al. 1973).

Figure 6 shows the anomalies of the lake-averaged surface water temperature and 2-m air temperature at seasonal and annual time scales. As shown in Fig. 6a, the decadal averaged anomalies, which are calculated from the individual year averages for 1970s, 1980s, 1990s,

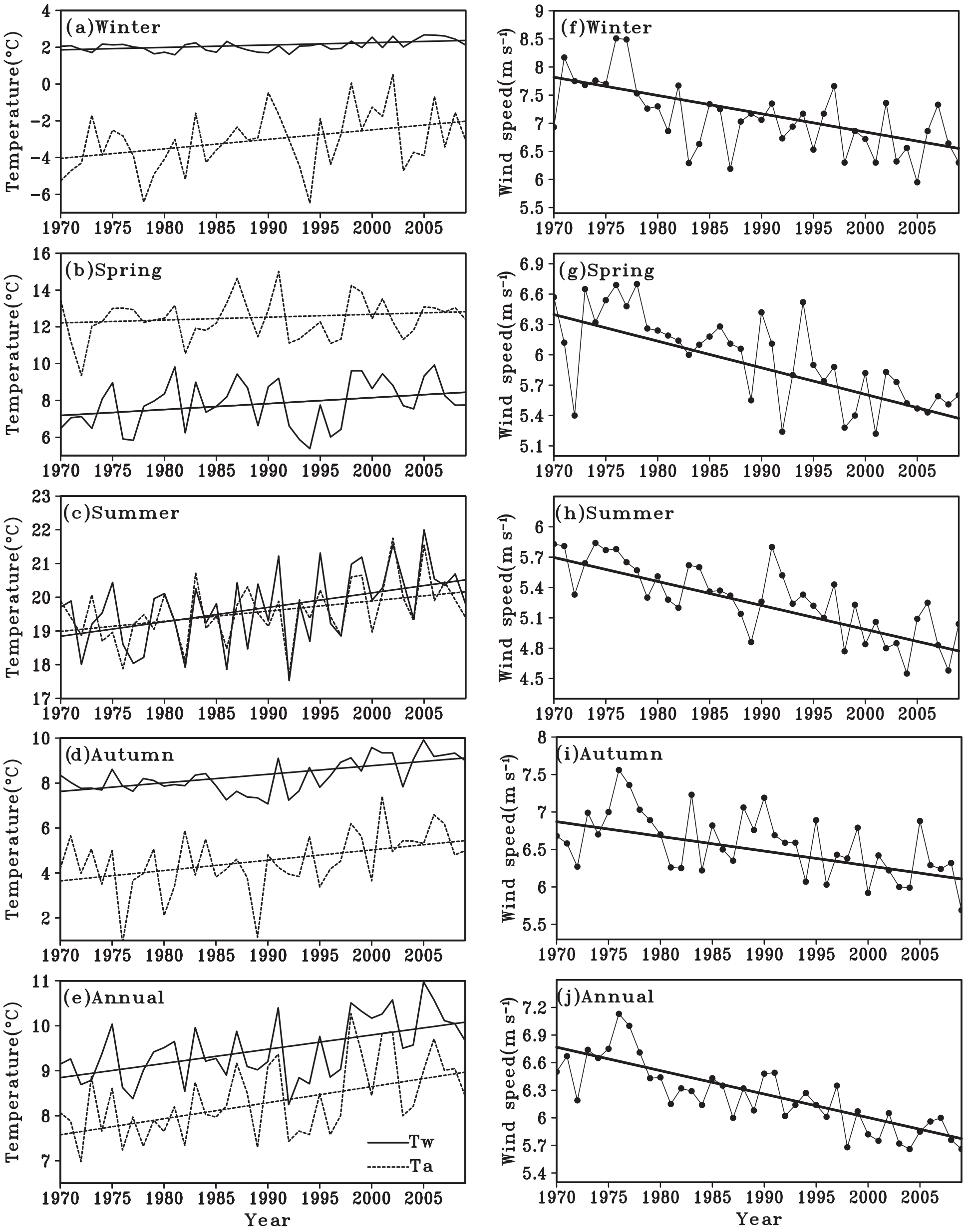

FIG. 5. Seasonal and annual mean lakewide averaged (left) surface water temperature (solid line) and 2-m air temperature (dashed line) and (right) 10-m wind speed and their linear regressions (straight lines).

and 2000s in winter, clearly show that the lake surface temperature anomalies are very close to 0 before the 2000s and after that they have slightly positive values. However, compared with the lake surface temperature, the 2-m air temperature anomalies have a larger magnitude and negative values in the 1970s and attain positive values in the 2000s. This suggests that the 2-m air temperature warmed notably faster than the lake surface water temperature over 1970–2009 (Fig. 5a, Table 1). In summer (Fig. 6c), the lake surface temperatures have slightly larger negative anomalies in the 1970s–1980s. The anomalies turned into positive values in the 1990s and the 2000s compared to the 2-m air temperature, resulting in a larger warming trend in lake surface temperature than in 2-m air temperature during the past four decades. This is consistent with the trends shown in Fig. 5c and Table 1. At the annual time scales (Fig. 6e), the decadal averages show close anomalies between the air and water temperatures during the last four decades except in the 1990s, during which the 2-m air temperature and the lake surface temperature have very small anomalies. The warming rate of the annual mean lake

TABLE 1. Regression results of the lakewide averaged seasonal and annual mean lake surface temperatures (Tw), 2-m air temperatures (Ta), and 10-m wind speed (Ws) over 1970–2009. Values following ± in the linear slope indicate 1-σ slope uncertainty.

		Slope	r^2	Two-tailed *t*-test p value
Winter	Tw (°C decade^{-1})	0.13 ±0.04	0.27	0.00
	Ta (°C decade^{-1})	0.52 ±0.21	0.14	0.02
	Ws (m s^{-1} decade^{-1})	−0.33 ±0.07	0.39	0.00
Spring	Tw (°C decade^{-1})	0.32 ±0.17	0.09	0.07
	Ta (°C decade^{-1})	0.16 ±0.15	0.09	0.31
	Ws (m s^{-1} decade^{-1})	−0.26 ±0.04	0.50	0.00
Summer	Tw (°C decade^{-1})	0.43 ±0.14	0.21	0.00
	Ta (°C decade^{-1})	0.30 ±0.11	0.17	0.01
	Ws (m s^{-1} decade^{-1})	−0.24 ±0.03	0.62	0.00
Autumn	Tw (°C decade^{-1})	0.38 ±0.08	0.36	0.00
	Ta (°C decade^{-1})	0.46 ±0.17	0.17	0.01
	Ws (m s^{-1} decade^{-1})	−0.20 ±0.05	0.29	0.00
Annual	Tw (°C decade^{-1})	0.32 ±0.08	0.29	0.00
	Ta (°C decade^{-1})	0.36 ±0.10	0.26	0.00
	Ws (m s^{-1} decade^{-1})	−0.26 ±0.03	0.66	0.00

surface temperature and air temperature are comparable (shown in Fig. 5e, Table 1). From the regression between the surface water temperature anomaly and the 2-m air temperature anomaly at seasonal and annual time scales, it may be noticed that 2-m air temperature and lake surface water temperature have high correlation over the 99% significance level for summer and annual averages.

The long-term means of the lake surface temperature and the 2-m air temperature show their maxima and minima in summer and winter, respectively (Table 2). However, the long-term mean of 10-m wind speed shows higher values in winter than in summer. The ratio of standard deviation to mean, indicating the variability of a given variable, shows that the lake surface temperature, 2-m air temperature, and 10-m wind speeds have maximum and minimum variability in winter and summer, respectively. This indicates that the atmospheric and limnological variables are more stable in summer than in winter.

The increasing lake surface temperature will have an influence on the start and end dates of summer stratification, and further affect the length of summer stratified season in the lake. Following McCormick and Fahnenstiel (1999), the last occurrence of a 4°C lake surface temperature in spring and the first occurrence of a 4°C in fall were considered to estimate the potential duration of summer thermal stratification. Figures 7a,b show slightly early and significantly late trends for the start and end dates of the summer stratification, respectively. The duration of summer stratification has increased by nearly 12 ±2 days (Fig. 7c) since 1970. This increasing rate is comparable to that of the duration of summer stratification season of Lake Superior, which has extended from 145 to 170 days over the last century (e.g., Austin and Colman 2008).

The relationship between the lake surface temperature and 10-m wind speed is shown in Fig. 8. It is clear that the lake surface temperature and 10-m wind speed have significant negative correlation (over the 95% significance level) at all time scales except winter, indicating that the wind speed has an important impact on the lake surface temperature (e.g., Huang et al. 2010). To assess the response of MLD to the changes in wind speed, only a 14-yr summer mean MLD was derived from the daily MLD averaged over July–September in each year between 1996 and 2009 due to a lack of long-term water temperature profile data, which were calculated from the daily water temperature profile data in each summer. In this study a threshold method is used to define the MLD as the depth where temperature changes by a value of 0.25°C relative to the one at a reference depth of 3 m (e.g., de Boyer Montégut et al. 2004). As shown in Fig. 9a, there is a clear relationship ($r^2 = 0.44$; $p < 0.05$) between the summer mean 10-m wind speed and MLD, signifying that increased (decreased) wind speed can lead to deeper (shallower) MLD. These results suggest that declined wind speeds decreased the MLD by about 1.2 m over the last 14 yr. A numerical study using a three-dimensional model in Lake Ontario shows that a shallow mixed layer is a result of weak wind speed (e.g., Huang et al. 2010). As shown in Fig. 9b, the summer mean water temperatures in the thermocline area have larger variability than those layers above and below the thermocline. This indicates that the variability of temperature in the thermocline region is sensitive to surface wind forcing, which resulted in stronger summer stratification with much warmer shallow surface mixed layers and cooler sharp thermocline in the lake (Fig. 9c), which is consistent with the numerical study of Huang et al. (2010).

4. Discussion

In summer the decline of wind forcing reduces the transport of heat via turbulent mixing to deeper parts of the lake. This leads to a stronger thermal stratification with a warmer surface layer and cooler deep waters. The strengthened thermal stratification and reduced wind-induced mixing will provide favorable conditions for increased warming of the surface-mixed layer compared to warming in the deeper waters due to climate warming. The decreasing trend in surface winds is another positive feedback in the warming of surface water temperatures in addition to the positive ice albedo feedback noted by Austin and Colman (2007) in Lake Superior; Wang et al.

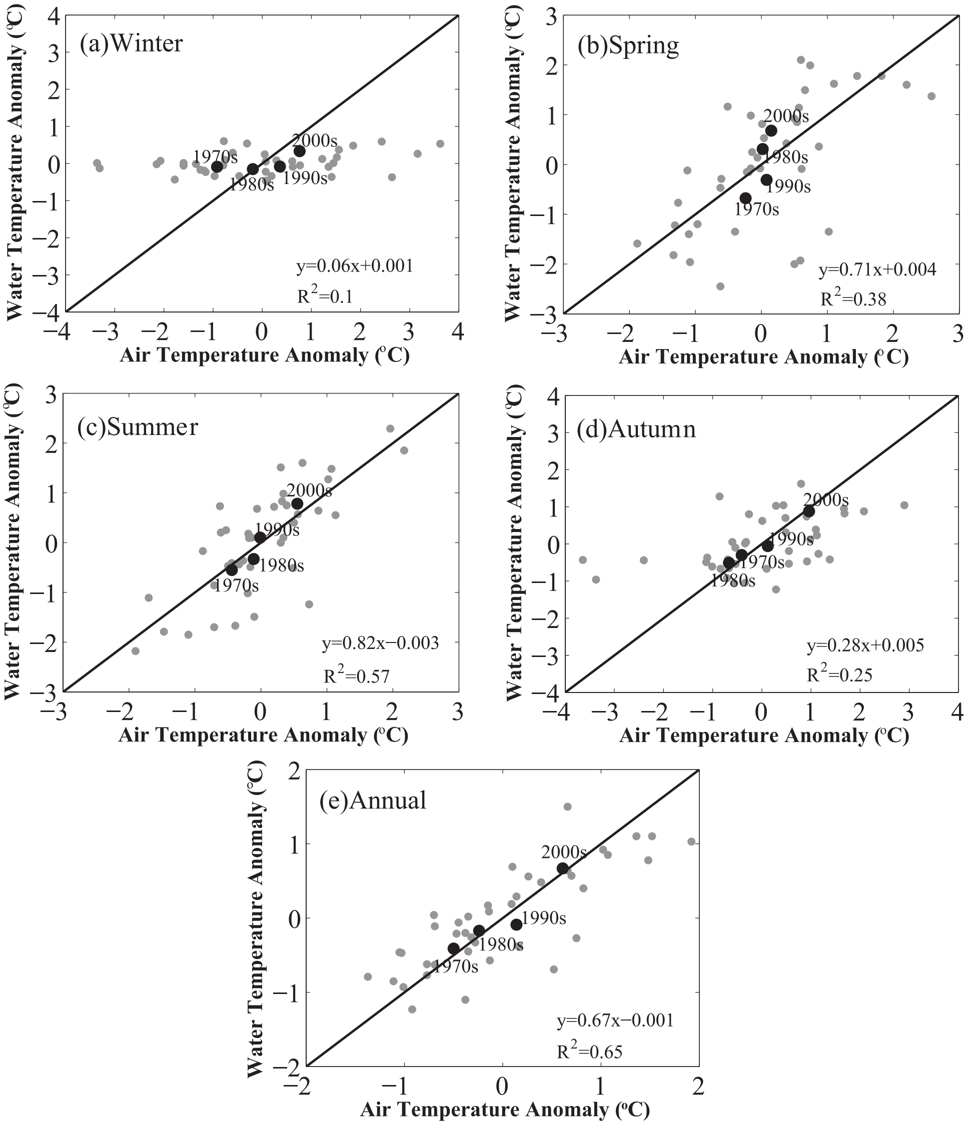

FIG. 6. Seasonal and annual lakewide averaged surface water temperature anomaly as a function of 2-m air temperature anomaly. Gray points are individual years; black points are decadal averages. The regression between surface water temperature anomaly and 2-m air temperature anomaly is shown at the bottom-right corner of each panel.

(2005) also showed that the positive ice albedo feedback plays a large role in ice-covered lake temperatures. As ice cover in Lake Ontario is not as significant in other members of the Great Lakes (Assel et al. 2003; Wang et al. 2012), the decline of wind forcing plays an important role in increasing the summer surface temperature in Lake Ontario.

Desai et al. (2009) observed that the air and water temperatures increased along with wind speed over Lake Superior during summer. However, in Lake Ontario during this period, wind speeds at 10 m decreased by -0.33 and -0.24 m s^{-1} $decade^{-1}$ in winter and summer, respectively. Desai et al. (2009) further concluded that the wind speeds increased because of the stability of the atmosphere declined over the lake and not because of regional and large-scale changes in the atmospheric flow. To verify this, we analyzed NCEP–NCAR reanalysis wind data at the 850-hPa level, representing free troposphere winds over Lake Ontario from 1970 to 2009. Figures 10a,b show that the NCEP–NCAR reanalysis winds decreased by the rates on the order of -0.30 and -0.27 m s^{-1} $decade^{-1}$ in winter and summer, respectively. Although these trends are similar to 10-m winds over the lake, minor differences can be noticed.

TABLE 2. The long-term mean, standard deviation, and ratio of the std dev to the mean of the lakewide averaged seasonal and annual mean lake surface temperatures, 2-m air temperatures, and 10-m wind speed over 1970–2009.

	Tw			Ta			Ws		
	Mean (°C)	Std dev (°C)	Std dev/mean	Mean (°C)	Std dev (°C)	Std dev/mean	Mean (m s^{-1})	Std dev (m s^{-1})	Std dev/mean
Winter	2.07	0.29	0.14	−3.11	1.60	0.51	7.09	0.61	0.09
Spring	6.48	1.26	0.19	12.42	1.09	0.09	5.96	0.43	0.07
Summer	19.11	1.08	0.06	19.58	0.85	0.04	5.29	0.32	0.06
Autumn	8.35	0.73	0.09	4.51	1.30	0.29	6.57	0.42	0.06
Annual	9.15	0.67	0.07	8.35	0.81	0.10	6.23	0.38	0.06

The trend in the lower troposphere is slightly smaller than lake surface winds in summer and vice versa in winter. These discrepancies are mainly because of the effect of the lake on the near-surface winds. Although the effect of declining stability over the lake in summer may have slightly modified the rate of decrease, regional and synoptic-scale weather patterns are the main factors in the trends of lake surface winds. This can be further assessed in winter trends. In winter the lake is negatively stratified with colder surface layer and warmer deeper waters. Decreased winds provide conditions of stronger negative stratification. Although the surface water temperatures increased as a response to the increasing air temperature, they are slower than the regional air temperatures (shown in Fig. 5a, Table 1). This increase in the stability of the atmospheric surface boundary layer would have played a role in decreasing 10-m wind speed at a slightly larger rate compared to the wind speed at 850 hPa.

The differences in the warming rates of air and water surface temperatures caused changes in the lake–air thermal contrast. This has affected the stability of the atmospheric surface boundary layer, which showed some effects on the surface wind speed and other atmospheric variables in the boundary layer. Preliminary studies using global (Lofgren 1997) and regional (Bates et al. 1993) climate models coupled with 1D lake models show that the lake-aggregate effects are evident over the Great Lakes and the surrounding areas. The approach we take here certainly cannot provide more elaborate discussion of dynamical and physical mechanisms. Further investigations are required to understand the complex air–lake interactions over the Great Lakes and the

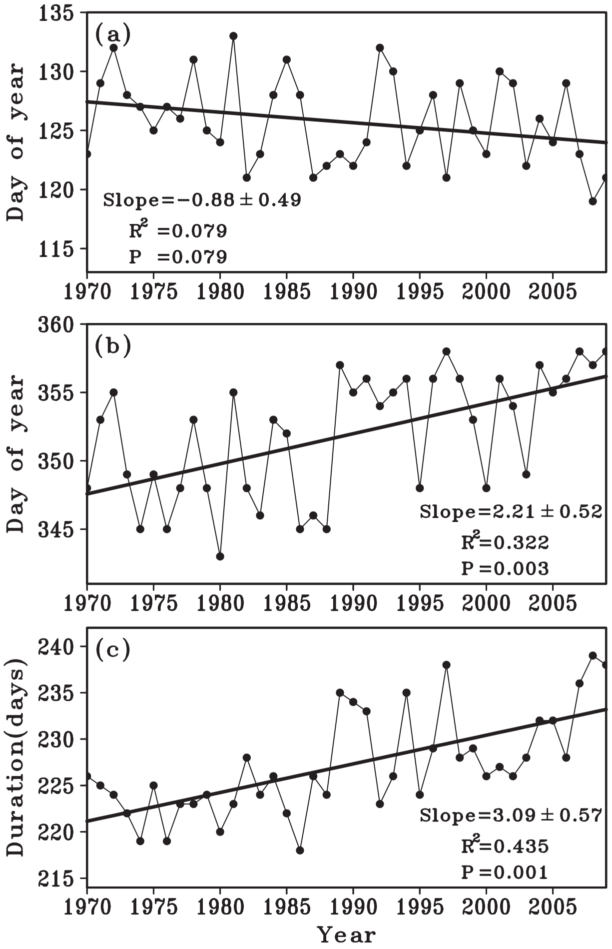

FIG. 7. (a) Start and (b) end dates of summer thermal stratification. (c) Length of summer thermal stratification season in Lake Ontario.

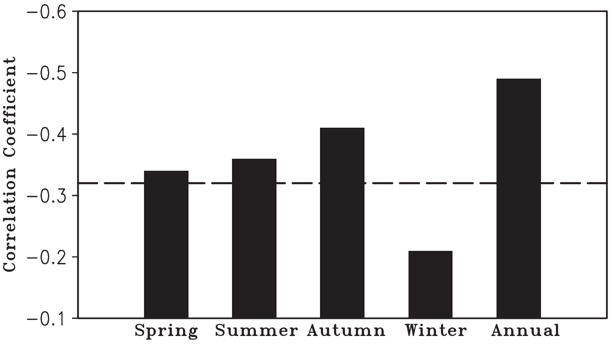

FIG. 8. Correlation coefficients between the lake surface temperature and 10-m wind speed during 1970–2009 on seasonal and annual scales. Dashed line shows the 95% significance level.

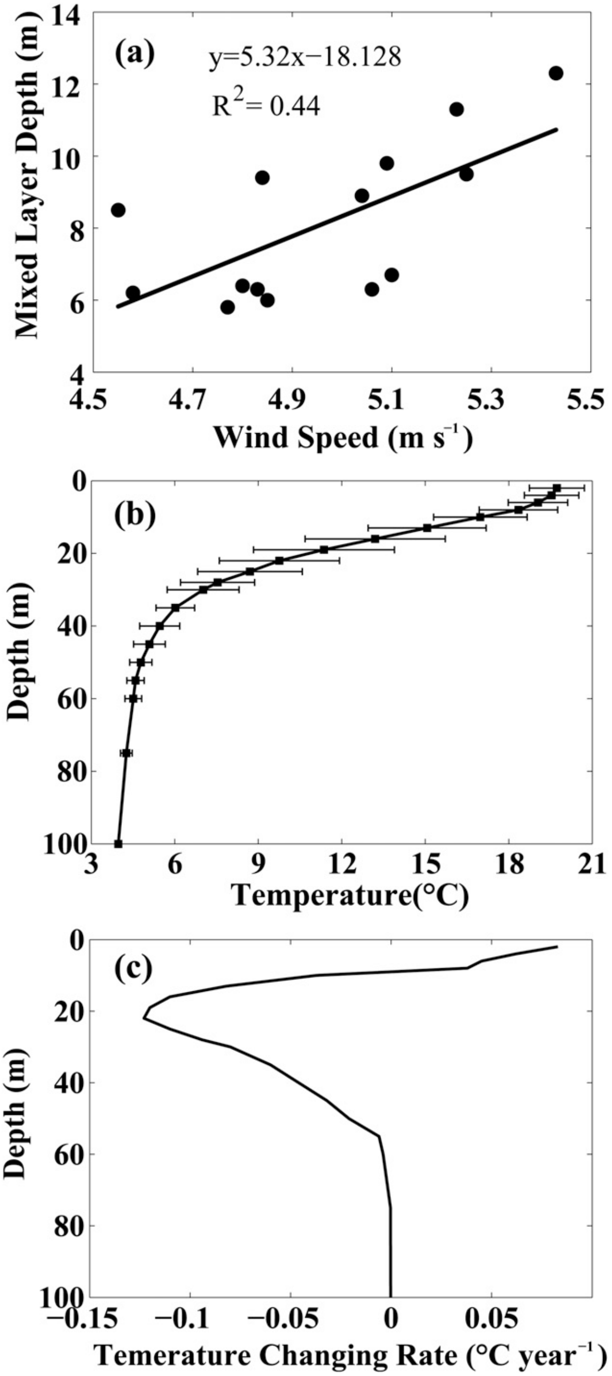

FIG. 9. (a) Relationship between the summer mean 10-m wind speed and MLD over 1996–2009. (b) Vertical profile of summer water temperature averaged over 1996–2009 (solid square dots represent 14-yr mean, while error bars correspond to two standard deviations). (c) Vertical distribution of summer temperature changing rates during 1996–2009.

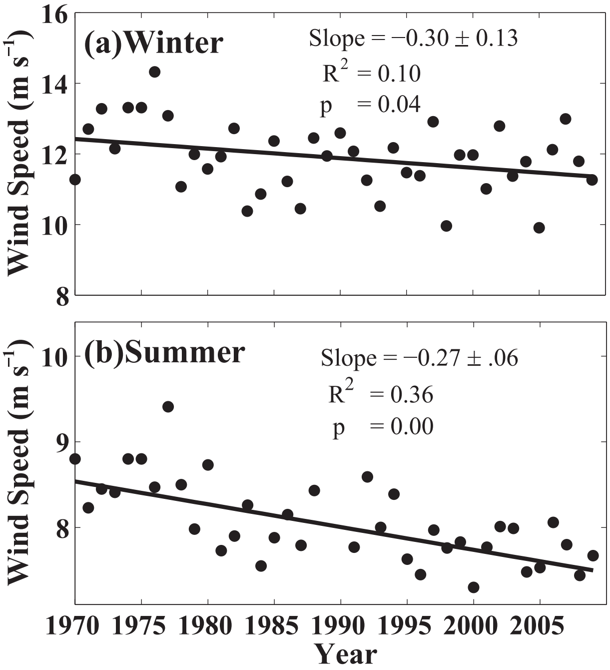

FIG. 10. Regionally averaged (a) winter mean and (b) summer mean of NCEP–NCAR reanalysis wind speed at 850-hPa level over Lake Ontario during 1970–2009 (slope in units of m s^{-1} $decade^{-1}$).

possible causes of differences in warming of the atmosphere and lakes. Such studies should consider a fully coupled regional air–lake modeling system with high resolution over the Great Lakes and the surrounding regions.

5. Conclusions

During the past 40 yr, the annual mean air and surface water temperatures increased by 1.43° ±0.39°C and 1.26° ±0.32°C, respectively, in Lake Ontario. In winter and autumn, the air temperature increased faster than the surface water temperature, with the warming rate of the air temperature in winter about 4 times the rate of warming of the surface water temperature. In contrast, the surface water temperature increased faster than the air temperature in spring and summer. The 10-m wind speed over Lake Ontario has significantly decreased in the order of -0.20 to -0.33 m s^{-1} $decade^{-1}$ at all seasonal and annual time scales since 1970. The warming surface water temperature resulted in early start and late end dates of summer stratification and a correspondingly longer summer stratified season. This study clearly showed that the decline of the wind speed has resulted in a shallower surface mixed layer in summer. The decrease of wind forcing is also mainly responsible for increased thermal stratification with warmer surface layer and cooler deep waters. The linear trend analysis is a simplification of the more complex temporal behavior of the time series. However, the high statistical significance of the trends does indicate that the change in thermal characteristics of Lake Ontario is a result of atmospheric changes at both large and local scales.

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