Influence of the Laurentian Great Lakes on Regional Climate*

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ABSTRACT

The influence of the Laurentian Great Lakes on climate is assessed by comparing two decade-long simulations, with the lakes either included or excluded, using the Abdus Salam International Centre for Theoretical Physics Regional Climate Model, version 4. The Great Lakes dampen the variability in near-surface air temperature across the surrounding region while reducing the amplitude of the diurnal cycle and annual cycle of air temperature. The impacts of the Great Lakes on the regional surface energy budget include an increase (decrease) in turbulent fluxes during the cold (warm) season and an increase in surface downward shortwave radiation flux during summer due to diminished atmospheric moisture and convective cloud amount. Changes in the hydrologic budget due to the presence of the Great Lakes include increases in evaporation and precipitation during October–March and decreases during May–August, along with springtime reductions in snowmelt-related runoff. Circulation responses consist of a regionwide decrease in sea level pressure in autumn–winter and an increase in summer, with enhanced ascent and descent in the two seasons, respectively. The most pronounced simulated impact of the Great Lakes on synoptic systems traversing the basin is a weakening of cold-season anticyclones.

1. Introduction

The Laurentian Great Lakes represent the largest collection of freshwater lakes in the world, with a total water surface area of 244 000 km^2. The surface area of each Great Lake varies from 19 000 km^2 for Ontario to 82 000 km^2 for Superior, while the average depth ranges from 19 m for Erie to 147 m for Superior. The Great Lakes were formed from meltwater as the Laurentide ice sheet receded at the end of the Last Glacial Maximum, roughly 10 000 years ago.

The Great Lakes influence air masses through differences in moisture, heat, and friction between the lake surfaces and upwind land areas (Changnon and Jones 1972). The lakes are characterized by a large heat capacity, perpetual moisture source to the lower atmosphere through evaporation (unless frozen), and reduced roughness compared to the surrounding land (Bonan 1995; Scott and Huff 1997). The large thermal inertia of the lakes leads to a reduction in the annual temperature range and diurnal temperature range across the basin (Bates et al. 1993; Scott and Huff 1997). The unstable (stable) season in the Great Lakes Basin usually occurs during September–March (April–August), when lake

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surfaces are warmer (cooler) than the overlying air (Eichenlaub 1979; Angel and Isard 1998). The specific timing and duration of the stable and unstable seasons vary by lake, depending on size, depth, and latitude (Angel and Isard 1998).

The Great Lakes' substantial influence on the regional hydrology varies by season. Evaporation from the lakes is a critical source of moisture to the region, particularly during late autumn–early winter, when cold, dry air masses pass over the relatively warm lakes (Bates et al. 1993); by midwinter, extensive lake ice cover reduces turbulent fluxes. During this unstable season of late autumn–early winter, the relative warmth of the lakes and their perpetual moisture source (prior to the development of extensive ice cover) favor enhanced cloud cover and precipitation over and downwind of the lakes (Bates et al. 1993; Scott and Huff 1997). The relatively cool lake surfaces during late spring–early summer support greater atmospheric stability and diminished cloud cover, rainfall, and deep convection (Lyons 1966; Changnon and Jones 1972; Scott and Huff 1997).

The Great Lakes modify synoptic systems that traverse the basin and their associated wind patterns, potentially resulting in downwind influences on the atmosphere (Petterssen and Calabrese 1959; Fritsch et al. 1989). Shoreline convergence zones develop as air flows from the smooth lake surface to the rough land (George 1940). Lemire (1961) found that the low roughness of the lakes causes near-surface wind speeds in winter to be nearly twice as strong over Lake Ontario than over the surrounding land. The Great Lakes Basin is a preferred region of cyclogenesis in winter, since the relatively warm lake surface leads to enhanced low-level convergence (Petterssen and Calabrese 1959; Eichenlaub 1979; Colucci 1976). The lakes tend to strengthen cyclones during winter and anticyclones during summer and weaken cyclones during summer and anticyclones during winter (Cox 1917).

Few studies have employed a climate model to understand the influence of the Laurentian Great Lakes on weather and climate. Sousounis and Fritsch (1994) applied a mesoscale model to assess the effects of lake aggregates on the large-scale environment during a cold surge in late autumn, based on 2-day simulations with and without the inclusion of the Great Lakes. Bates et al. (1993) performed simulations using a regional climate model with and without the Great Lakes for a 10-day period in December 1985, focusing on the lakes' impacts on basinwide precipitation. In these 10-day simulations, lake effects were responsible for 50%–70% of precipitation across the major snowbelts of the Great Lakes Basin. Subsequent studies by Bonan (1995) and Lofgren (1997) focused on climate time scales, using simulations from coarse, global climate models of 5- and 20-yr durations, respectively. Bonan (1995) assessed the importance of including inland water in global climate simulations by running a T42 (2.8° × 2.8°) global climate model with and without inland water subgrid points, in which all lakes were assigned a depth of 50 m. During July, inland water regions were cooler and produced greater latent heat (LH) fluxes and less sensible heat (SH) fluxes than in the absence of the water bodies. The presence of the Great Lakes, in particular, caused greater precipitation in January. In the simulations by Bonan (1995), the lakes imposed surprisingly little influence on radiation fluxes, atmospheric moisture, or the zonal circulation. Lofgren (1997) ran simulations with and without the Great Lakes using an R30 global climate model, with just four grid cells representing the lakes. The presence of the Great Lakes caused simulated evaporation and precipitation to increase during autumn–winter and decrease during late spring–summer. Inclusion of the Great Lakes also led to an intensified, poleward-shifted jet stream in autumn and winter, since the meridional temperature gradient was intensified to the north of the lakes and weakened to the south.

In this paper, we apply a high-resolution regional climate model, the Abdus Salam International Centre for Theoretical Physics Regional Climate Model, version 4 (ICTP RegCM4) (Pal et al. 2007; Elguindi et al. 2011; Giorgi et al. 2012), across much of the eastern United States and southeastern Canada to assess the influence of the Laurentian Great Lakes on the regional climate. The model is interactively coupled to a one-dimensional lake model for simulating lake temperatures and ice cover. We compare two decade-long simulations in which the Great Lakes are either included or replaced by the natural vegetation of the region. Unlike previous studies, our application of 20-km grid spacing permits the model to resolve the individual Great Lakes and their spatial variations in depth.

RegCM has been previously applied and evaluated across the Great Lakes Basin. Bates et al. (1995) validated a 2-yr climate simulation of RegCM2 across the Great Lakes Basin and found primarily small biases in simulated temperature and precipitation compared to observations and reanalysis. Notaro et al. (2013) determined that RegCM4 can reproduce the broad temporal and spatial patterns of lake ice and lake-effect snowfall in the Great Lakes Basin. Given the reasonable simulation of lake ice and lake-effect snowfall, Vavrus et al. (2013) applied RegCM4 in 10 case studies to assess the influence of lake ice on the dynamics of heavy lake-effect snowstorms. Holman et al. (2012) concluded that RegCM4 accurately simulates the seasonal cycle of the temperature difference between the

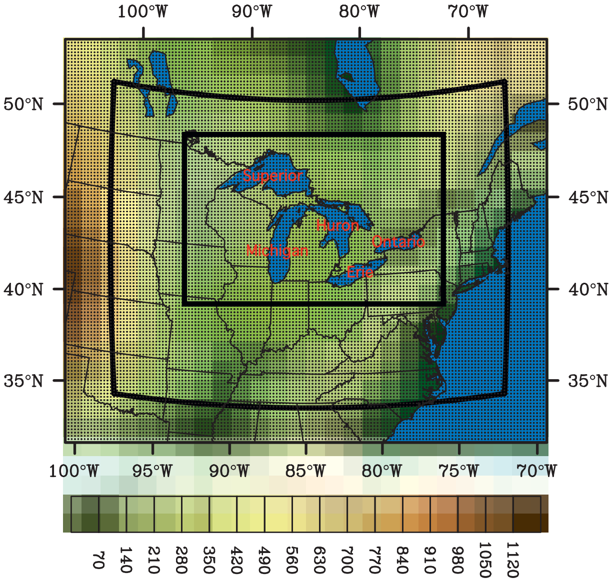


FIG. 1. Simulation domain, with shading for elevation (m) and small dots for the 20-km grid. The inner domain, within the buffer zone, is shown with the outer thick black box, while the Great Lakes Basin (used for area averages) is identified by the inner black box. Modified from Fig. 1 of Notaro et al. (2013).

lake surface and overlying air, compared to buoy and satellite data for Lake Superior, and therefore captures the seasonal influence of the lake on atmospheric stability.

Section 2 describes the data and methods, including details of the regional climate model, experimental design, and methodology for identifying cyclones and anticyclones in the model output. The results are presented in section 3, including a validation of the simulated lake temperatures and an assessment of the simulated influence of the Great Lakes on temperature, surface energy budget, hydrologic budget, atmospheric circulation and moisture, and synoptic systems. Section 4 contains a discussion of model limitations and the conclusions.

2. Data and methods

a. Model description

The influence of the Laurentian Great Lakes on climate is examined using ICTP RegCM4. The dynamical core of RegCM4 is based on the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1994). RegCM4 is a compressible, finite difference model, which is constrained to hydrostatic balance and uses vertical sigma coordinates (18 sigma levels by default). Its radiative transfer scheme is based on the NCAR Community Climate Model version 3 (Kiehl et al. 1996), and its boundary layer physics are based on the nonlocal vertical diffusion scheme of Holtslag et al. (1990). A subgrid explicit moisture (SUBEX) scheme (Pal et al. 2000) determines the resolvable-scale precipitation and nonconvective clouds, while a cumulus convection scheme determines smaller-scale precipitation. The Grell (1993) convective scheme outperformed the Kuo (Anthes 1977) scheme in the Great Lakes Basin (Notaro et al. 2013) and is consequently applied in the current study. According to the Grell convective scheme, clouds are characterized by two steady-state circulations related to an updraft and a downdraft. We apply the cumulus closure scheme of Fritsch and Chappell (1980), which relates convection to the degree of instability. The default land surface model, which computes land–atmosphere exchanges of momentum, water vapor, and energy, is the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1986, 1993) with three soil layers and 20 land cover/vegetation classes.

In the current study, RegCM4 is interactively coupled to the one-dimensional, energy-balance lake model of Hostetler and Bartlein (1990), with a vertical resolution of 1 m. Hostetler et al. (1993) and Bates et al. (1995) previously found that this lake model (coupled to MM4 and RegCM2, respectively) reasonably reproduces the patterns of Great Lakes' temperature and ice cover. The lake model allows for vertical heat transfer within each lake column through eddy diffusion and convective mixing/overturning. The lake ice submodel (Hostetler 1991) is based on parameterizations by Patterson and Hamblin (1988). No advective horizontal heat transfer between neighboring lake points is treated by the lake model. RegCM provides air temperature, vapor pressure, wind speed, snowfall, and surface shortwave and longwave radiation fluxes to the lake model. The lake model computes a vertical lake temperature profile and returns the lake surface temperature and ice cover to RegCM4. Sensible and latent heat fluxes over lake points are computed by BATS parameterizations using the bulk aerodynamic formulas (Dickinson et al. 1993). Lake depths vary spatially based on bathymetry data.

b. Experimental design

The control simulation, LAKE, is a decade-long (1980–89) subset of the simulation by Notaro et al. (2013), which ran from May 1975 to December 2002. The model domain is centered on the Great Lakes, has dimensions of 2520 km × 3000 km, and uses a horizontal grid spacing of 20 km (Fig. 1). The Great Lakes are represented by 648 grid cells, ranging from 61 for Lake

Erie to 220 for Lake Superior. Following Notaro et al. (2013), the vertical extinction coefficients of light in the lake model are modified based on observed estimates, resulting in improved lake temperature profiles and ice cover fractions across the Great Lakes. The initial and lateral boundary conditions (LBCs) are obtained from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (Kalnay et al. 1996) and the Global Sea Ice and Sea Surface Temperature (GISST) dataset from the UK Met Office (Rayner et al. 1996). The atmospheric LBCs from the reanalysis are 6-hourly, on a 2.5° × 2.5° grid. The LBCs are applied to a buffer zone, with a width of 15 grid cells, using a linear relaxation scheme.

In the companion simulation, NOLAKE, for 1980–89, the Great Lakes are replaced by forest/field mosaic. This represents the most common land cover type in the surrounding region according to the BATS classification of 20 vegetation types, which is based on the U.S. Geological Survey (USGS) Global Land Cover Characterization dataset (Loveland et al. 2000). The applied roughness lengths for an inland water body and forest/field mosaic are 0.0004 and 0.3 m, respectively. For a forest/field mosaic, the leaf area index is permitted to range from 0.5 to 6.0 m^2 m^{-2}. A comparison between LAKE and NOLAKE reveals the influence of the Laurentian Great Lakes on regional climate. For the purpose of computing area averages, the Great Lakes Basin is defined as 41°–49.3°N, 75°–93°W (Fig. 1); we later demonstrate that the climate in this region is highly influenced by the presence of the Great Lakes.

c. Method for identifying cyclones and anticyclones

In addition to mean climate characteristics, the influence of the Great Lakes on intense cyclones and anticyclones that traverse the basin is assessed by identifying strong synoptic systems in NOLAKE during 1980–89 and then quantifying the differences in daily mean simulated sea level pressure between LAKE and NOLAKE during these cases. Here, the cold season and warm season are defined as November–March and May–August, respectively. Daily sea level pressure in NOLAKE is averaged across the Great Lakes Basin and used to identify 30 of the strongest cold-season anticyclones ($P \geq 1035$ hPa), cold-season cyclones ($P \leq 1004$ hPa), warm-season anticyclones ($P \geq 1022$ hPa), and warm-season cyclones ($P \leq 1005$ hPa). These specific pressure criteria allow for exactly 30 cases of each synoptic system for both seasons. Results are robust if the pressure criteria or number of cases is modified. By choosing to identify events in the NOLAKE run, we can be certain that the events are synoptically driven and not locally produced solely by the lakes. The list of events is nearly the same if we examined the LAKE simulation instead.

d. Additional datasets

A climatology of simulated monthly lake surface temperatures is validated against the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Surface Environmental Analysis (GLSEA) dataset for 1995–2002, which is generated by the Advanced Very High Resolution Radiometer from NOAA polar-orbiting satellites (Schwab et al. 1992). Hourly observed surface water temperatures for 1980–89, recorded at 0.5-m depth, are obtained from the National Data Buoy Center (NDBC) for eight buoys on the Great Lakes, for computing the diurnal temperature range. Daily sea level pressure and 10-m wind components are obtained from the North American Regional Reanalysis (NARR) (Mesinger et al. 2006) to validate case studies of cyclones and anticyclones in the Great Lakes Basin from RegCM4.

3. Results

a. Validation of simulated lake surface temperatures

The application of RegCM4, coupled to a one-dimensional lake model, to the Great Lakes Basin in the current study is strongly justified by the previous validation analyses of Hostetler et al. (1993), Bates et al. (1995), Holman et al. (2012), Notaro et al. (2013), and Vavrus et al. (2013). Here, we expand the validation to assess the accuracy of simulated Great Lakes' surface water temperatures. Based on the GLSEA data for 1995–2002, the mean lake surface temperatures of the Great Lakes reach a minimum during February–March, when ice cover is most extensive, and a maximum during August, with the highest summertime temperatures for Erie (shallowest lake) and the lowest for Superior (deepest lake) (Fig. 2a). Associated with the spring overturn of the Great Lakes is an observed rapid warming of the lake surface in May–June. All of these observed lake features are well represented in RegCM4 (Fig. 2b). The model exhibits a modest annual warm bias, ranging from +1.1°C on Lake Ontario to +1.8°C on Lake Huron. Simulated lake surface temperatures are generally too warm during spring (April–June) and slightly too cold during summer–autumn (July–December). A comparison between the mean seasonal cycle of lake surface temperatures between RegCM4 and GLSEA yields root-mean-square differences that range from 1.8°C for Lake Erie to 2.8°C for Lake Superior. Averaged across the Great Lakes, the amplitude of the seasonal cycle in lake surface temperatures is underestimated

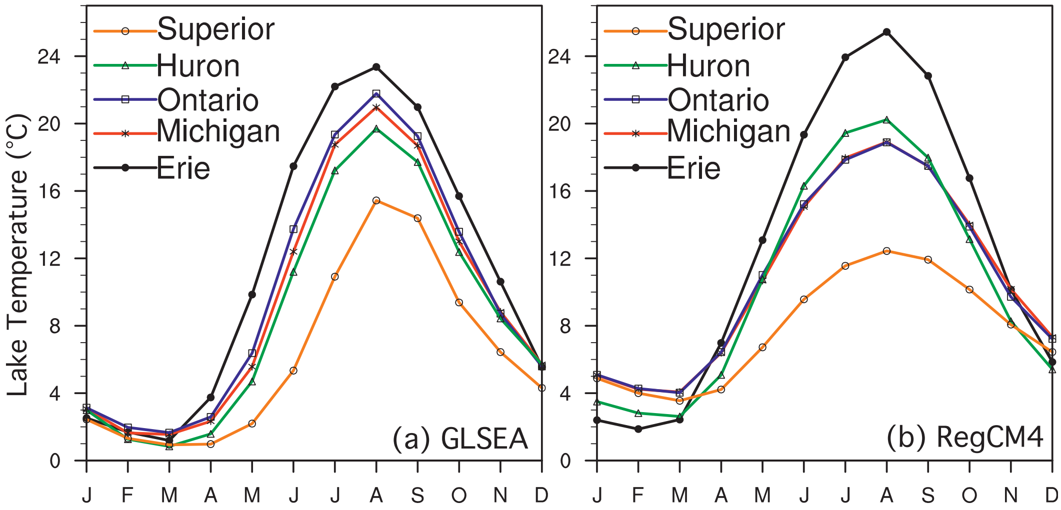


FIG. 2. Climatology of lake surface temperatures (°C), for each of the Great Lakes, during 1995–2002 based on (a) GLSEA and (b) RegCM4 (upper 1 m).

by 20% in RegCM4 (14.4°C) compared to GLSEA (18.0°C), most notably over the deepest lakes, Superior and Michigan. The lack of simulated lake circulation in the Hostetler lake model excludes horizontal heat advection within the lakes and ice movement, resulting in biases in the spatial distribution of both water temperature and ice cover. Problematic overturning dynamics lead to insufficient ice cover formation at deep lake points.

A comparison of lake surface temperatures between the NDBC buoys and RegCM4 indicates that the amplitude of the diurnal cycle of water temperatures peaks during the warm season (not shown). The model underestimates the diurnal temperature range by 20% during the period of primarily open water, April–November (0.42°C for buoys versus 0.33°C for RegCM4). This bias is most pronounced in July, during which the amplitude of the diurnal temperature range is 0.90°C from the buoys and only 0.42°C from the model. The simulated water temperatures are not sensitive enough to atmospheric conditions, with the model underestimating the amplitudes of both the seasonal cycle and diurnal cycle in lake water temperatures.

b. *Influence of Great Lakes: Temperature*

The Great Lakes diminish the variability in air temperature on all time scales, including diurnal, day to day, and seasonal. Averaged over the year, the presence of the lakes results in a 14% reduction (31.4°C in LAKE versus 36.5°C in NOLAKE) in the amplitude of the annual cycle and a 20% reduction (7.2°C in LAKE versus 9.0°C in NOLAKE) in the amplitude of the diurnal cycle of simulated 2-m air temperature in the Great Lakes Basin (Figs. 3a,d). Both surface temperature T_s and 2-m air temperature T_a are substantially increased during October–March and modestly decreased during May–August (Fig. 3a) in LAKE, compared to NOLAKE. The difference between these temperatures, $T_s - T_a$, impacts atmospheric stability, such that $T_s - T_a > 0$ favors unstable conditions and $T_s - T_a < 0$ favors stable conditions (Holman et al. 2012). As evident in Fig. 3a, the lakes produce greater atmospheric instability during late autumn–winter and greater stability during late spring–summer. The response in surface air temperature to the presence of the lakes is roughly 4–5 times greater over the lakes than over the land in the Great Lakes Basin (Figs. 3b,c). The amplitude of the diurnal cycle in 2-m air temperature is diminished year-round across the basin in LAKE, most notably in July by −2.6°C (Fig. 3d); the reduction in amplitude is −66% over the lakes and −3% over the land (Figs. 3e,f). The lakes produce an increase in nighttime air temperatures during October–March (e.g., +4.2°C in January) and a decrease in daytime air temperatures during April–September (e.g., −2.9°C in July), both of which dampen the diurnal cycle; the former is related to enhanced atmospheric moisture and cloud cover and the latter is related to diminished SH fluxes

The Great Lakes tend to dampen the amount of day-to-day fluctuations in air temperature across the basin. The standard deviation of simulated daily 2-m air temperatures in the Great Lakes Basin is reduced annually by 12% (3.55°C in LAKE versus 4.05°C in NOLAKE) in response to the presence of the lakes (Fig. 3g); the reduction in daily variability is −36% over the

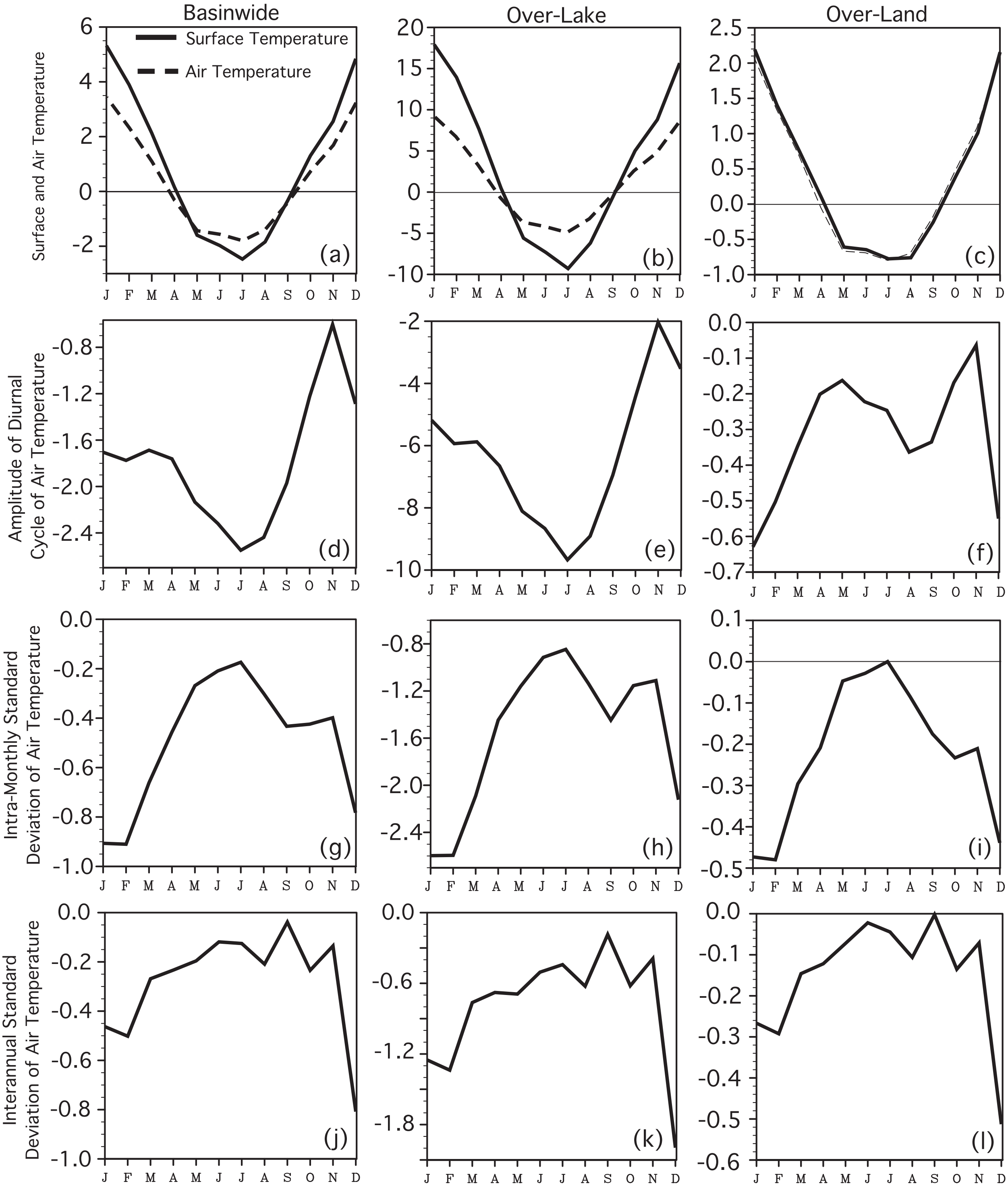


FIG. 3. Monthly mean differences (LAKE − NOLAKE) (°C) across the Great Lakes Basin during 1980–89 in (a)–(c) surface (solid line) and 2-m (dashed line) air temperature, (d)–(f) the amplitude of the diurnal cycle in 2-m air temperature, (g)–(i) the intramonthly standard deviation of 2-m air temperature, and (j)–(l) the interannual standard deviation of 2-m air temperature. Differences are shown (a),(d),(g),(j) basinwide, (b),(e),(h),(k) over lake, and (c),(f),(i),(l) over land.

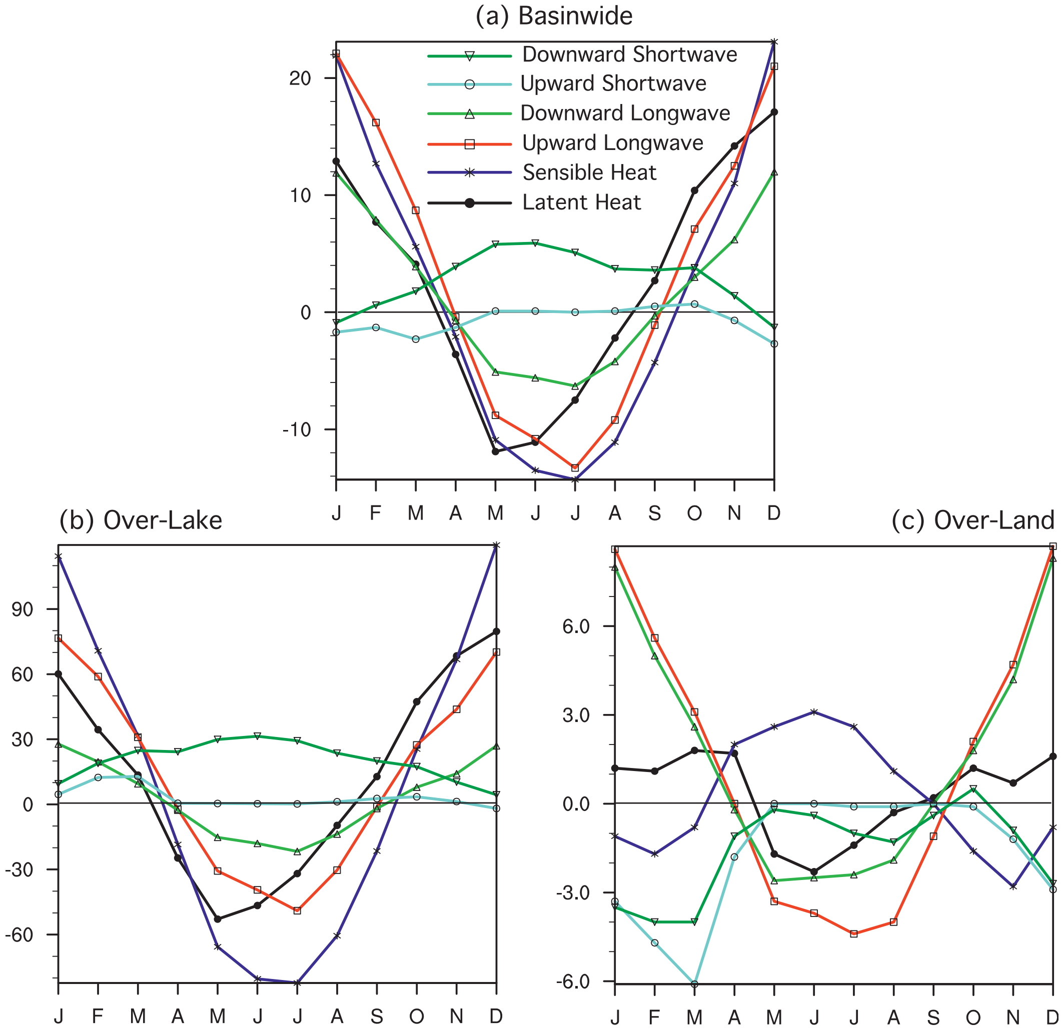


FIG. 4. Monthly mean differences (LAKE − NOLAKE) (W m^{-2}) across the Great Lakes Basin during 1980–89 in downward and upward shortwave radiation flux, downward and upward longwave radiation flux, sensible heat flux, and latent heat flux. Differences are shown (a) basinwide, (b) over lake, and (c) over land.

lakes and −6% over the land (Figs. 3h,i). The largest basinwide reduction in intramonthly standard deviation in air temperature occurs in February, by −0.91°C (−17%), in response to enhanced cloud cover and atmospheric moisture. Likewise, the presence of the Great Lakes results in a year-round reduction in the interannual variability in 2-m air temperature, most notably in December (−21%) (Fig. 3j).

c. *Influence of the Great Lakes: Surface energy budget*

The regional surface energy budget is substantially altered by the Great Lakes (Fig. 4a). The downward surface shortwave radiation flux in the Great Lakes Basin is annually increased by +2.8 W m^{-2} in LAKE compared to NOLAKE, primarily during the warm season when enhanced atmospheric stability reduces cloud cover and atmospheric moisture (precipitable water). The warm-season increase in downward shortwave radiation is limited to over the lakes, where cool lake surfaces stabilize the overlying atmosphere (Figs. 4b,c). A decrease in surface albedo, by replacing forests with lakes, leads to a greater absorption of solar energy into the surface during the warm season (Figs. 4a,b). Simulated upward longwave radiation is increased annually by +3.7 W m^{-2}, largely during the cold season, since the lakes maintain a higher surface temperature than either a forest or the overlying air. In the presence of the lakes, the turbulent fluxes are enhanced during the cold season and diminished during the warm season, with annual increases of +1.8 and +2.7 W m^{-2} for SH and LH fluxes, respectively. The strength of these annual

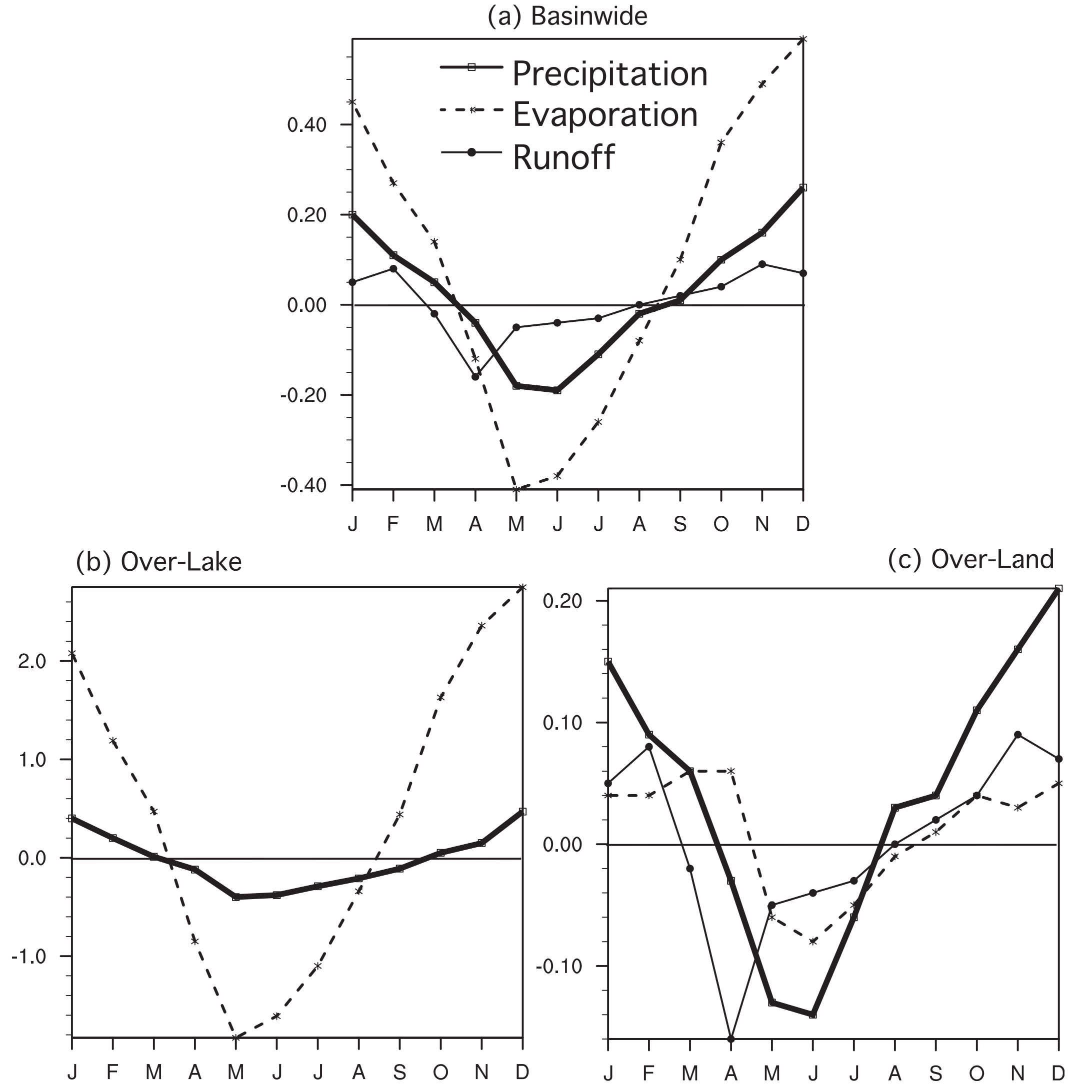


FIG. 5. Monthly mean differences (LAKE − NOLAKE) (mm day^{-1}) across the Great Lakes Basin during 1980–89 in precipitation (thick black), evaporation (dashed), and runoff (thin black). Differences are shown (a) basinwide, (b) over lake, and (c) over land. Unlike precipitation and evaporation, runoff is averaged only over land areas in the Great Lakes Basin for (a).

responses in turbulent fluxes implies that the Great Lakes impose more of a moisture feedback than thermal feedback to the atmosphere. The peak reductions in SH and LH fluxes, in response to the inclusion of the Great Lakes, occur in July (ΔSH = -14.3 W m^{-2}) and May (ΔLH = -11.9 W m^{-2}), respectively, while both fluxes increase the most in December (ΔSH = $+23.1$ W m^{-2}, ΔLH = $+17.1$ W m^{-2}).

d. Influence of the Great Lakes: Hydrologic budget

The presence of the Great Lakes causes an increase in cold-season precipitation and evaporation during September–March and a decrease in both variables during the warm season of April–August, with minimal effect on annual hydrologic terms (Fig. 5a). In LAKE compared to NOLAKE, evaporation and precipitation are increased by $+0.59$ and $+0.26$ mm day^{-1} in December and decreased by -0.41 and -0.18 mm day^{-1} in May, respectively. In general, the response in precipitation is 2.3 times smaller than that of evaporation, suggesting inefficient moisture recycling and greater moisture entering the atmosphere as vapor and clouds during the cold season. Over the lakes, annual evaporation is higher by $+0.43$ mm day^{-1} in LAKE than NOLAKE, yet annual precipitation only changes by -0.02 mm day^{-1} (Fig. 5a). Basinwide changes in total

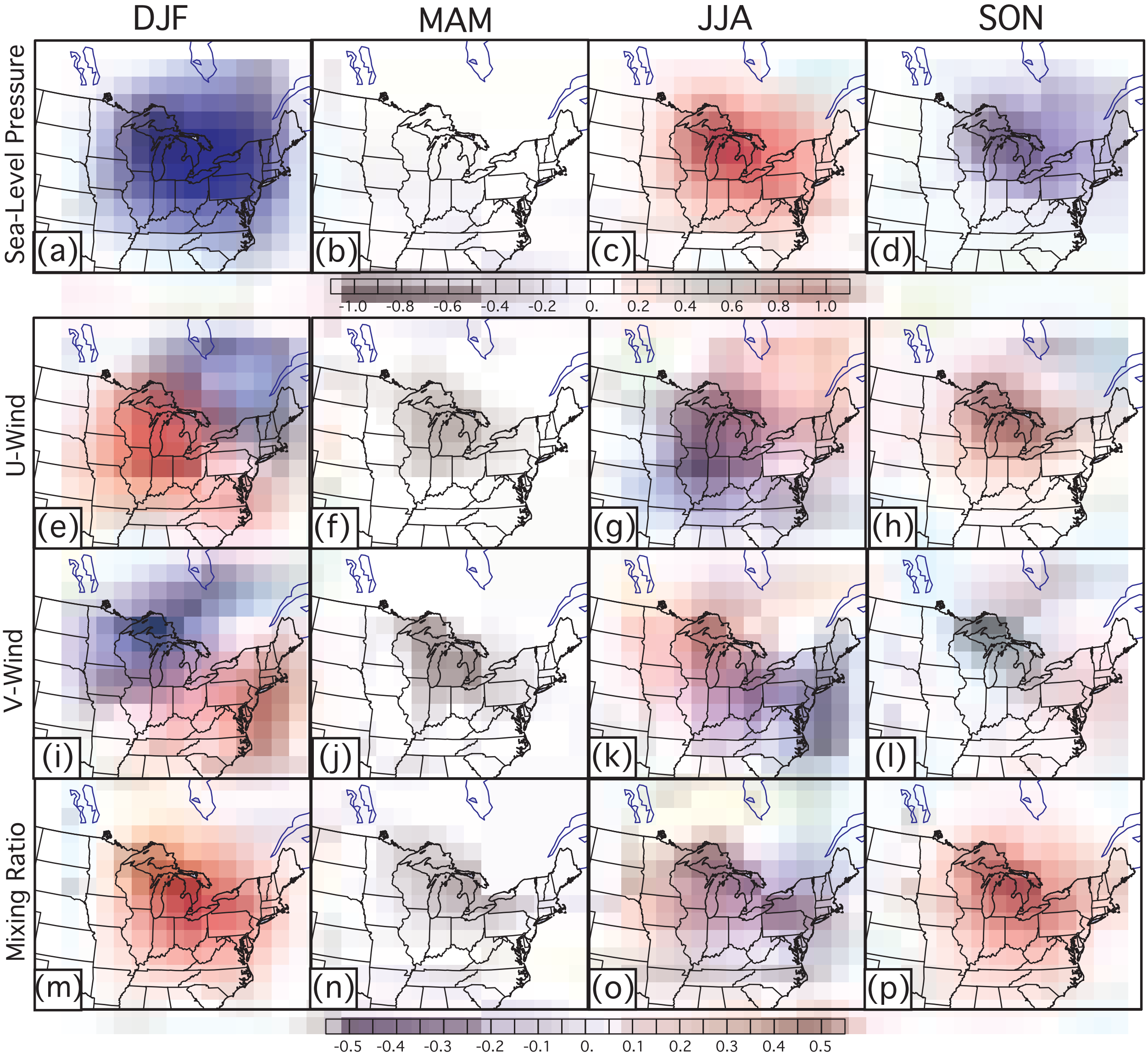


FIG. 6. Seasonal mean differences (LAKE − NOLAKE) during 1980–89 in (a)–(d) sea level pressure (hPa), (e)–(h) 10-m u-wind component (m s^{-1}), (i)–(l) 10-m v-wind component (m s^{-1}), and (m)–(p) 2-m water vapor mixing ratio (g kg^{-1}). The upper and lower color bars apply to (a)–(d) and (e)–(p), respectively.

precipitable water in response to the lakes are generally small, including increases in September–March (+6% in December) and decreases in April–August, with the largest moisture anomalies primarily confined to the planetary boundary layer. The lakes increase the air temperatures during the cold season, which leads to a smaller fraction of falling precipitation occurring as snow (−17% in annual snowfall across the basin). Even though the presence of the Great Lakes leads to a cold-season increase in precipitation (+0.13 mm day^{-1} during November–March) (Fig. 5c), the induced warming causes overland snowfall to decline by −9%. Diminished snowpack results in less springtime snowmelt, thereby reducing runoff during March–April (−0.16 mm day^{-1} in April, averaged over land) in LAKE compared to NOLAKE.

e. Influence of the Great Lakes: Atmospheric circulation and moisture

The seasonal response of the atmospheric circulation and moisture to the presence of the Great Lakes is greatest in winter and summer and minimal in spring, with the autumn response most like that of winter (Fig. 6). The lakes induce lower sea level pressure across the Great Lakes Basin and the Midwest, mid-Atlantic, and northeast United States during winter, peaking at −2.9 hPa (Fig. 6a). Lower pressure during autumn–winter results from the

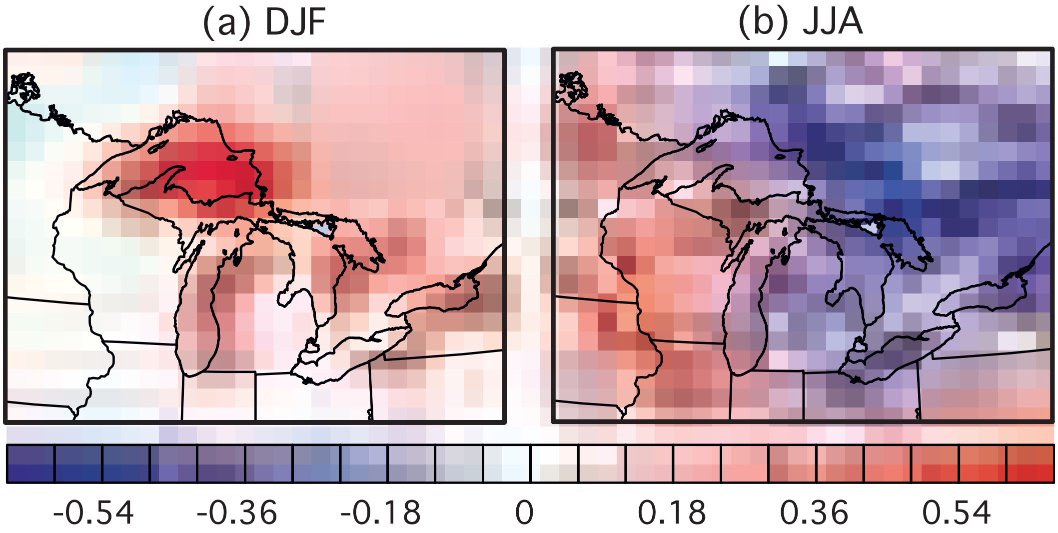


FIG. 7. Mean differences (LAKE − NOLAKE) during 1980–89 for (a) December–February (DJF) and (b) June–August (JJA) in total precipitation (mm day^{-1}).

temperature of the lake surfaces exceeding that of the overlying air (Figs. 6a,d). Relatively cool lake surfaces cause anomalously higher pressure in summer, with differences between LAKE and NOLAKE peaking at +1.5 hPa (Fig. 6c). As a consequence of these sea level pressure anomalies in LAKE, the 10-m wind field is anomalously cyclonic in winter and anticyclonic in summer (Fig. 6i,k). The 2-m water vapor mixing ratio is increased regionwide during autumn-winter, up to 2 g kg^{-1}, due to enhanced evaporation (Figs. 6m,p). The response in mixing ratio to the Great Lakes during summer is dynamically-driven, in response to enhanced higher pressure (Fig. 6o). Anomalous southerly flow in LAKE over Wisconsin, Iowa, and Minnesota brings in warmer, moisture-laden tropical air, while anomalous northerly flow in New York, Pennsylvania, and Ohio brings in cool, dry continental air. In LAKE compared to NOLAKE, wintertime precipitation is increased over and to the northeast of the Great Lakes Basin, while summertime precipitation responds to the change in wind flow, with increases in precipitation to the west of the lakes and decreases over and to the east of the lakes (Fig. 7). The mean annual response of the regional climate to the Great Lakes is dominated by winter, with lower pressure, stronger low-level winds, and increased atmospheric moisture.

Averaged across the Great Lakes Basin, air temperature is increased during October–March and decreased during May–August in the lowest seven sigma levels, comprising the atmospheric boundary layer (Fig. 8a). Because of the inclusion of the Great Lakes in LAKE, enhanced instability and low-level convergence during the cold season support anomalous ascent in the low to midtroposphere, with the opposite response during the warm season (Fig. 8b). Low-level cloud liquid water content is greater in LAKE than NOLAKE across the basin during the cold season due to greater evaporation, while deep convection is limited during summer due to enhanced atmospheric stability (weakened lapse rate) and subsidence (Fig. 8c). This is consistent with a deeper boundary layer in winter (+120 m in January) and shallower boundary layer in summer (−220 m in July) across the basin in LAKE compared to NOLAKE.

f. Influence of the Great Lakes: Synoptic systems

The Great Lakes impose the most pronounced impact on synoptic systems during the cold season, particularly anticyclones. From the NOLAKE simulation, we examine daily sea level pressure fields to identify the 30 strongest synoptic weather systems in the Great Lakes Basin from each of the following four categories: cold-season anticyclones, cold-season cyclones, warm-season anticyclones, and warm-season cyclones. Comparison of LAKE to NOLAKE reveals the influence of the lakes on the intensity of these synoptic systems (Fig. 9). The lakes weaken cold-season anticyclones (−1.72 ± 0.77 hPa) and warm-season cyclones (+0.50 ± 0.27 hPa) and strengthen cold-season cyclones (−0.73 ± 0.46 hPa) and warm-season anticyclones (+0.56 ± 0.25 hPa). Of the 120 weather systems analyzed here, only three of them deviated from these responses, implying a highly robust impact.

To further explore the influence of the Great Lakes on synoptic systems, we select four case studies, one from each of the above categories (Fig. 10). These case studies include a cold-season anticyclone on 21 December 1983, a cold-season cyclone on 7 January 1980, a warm-season

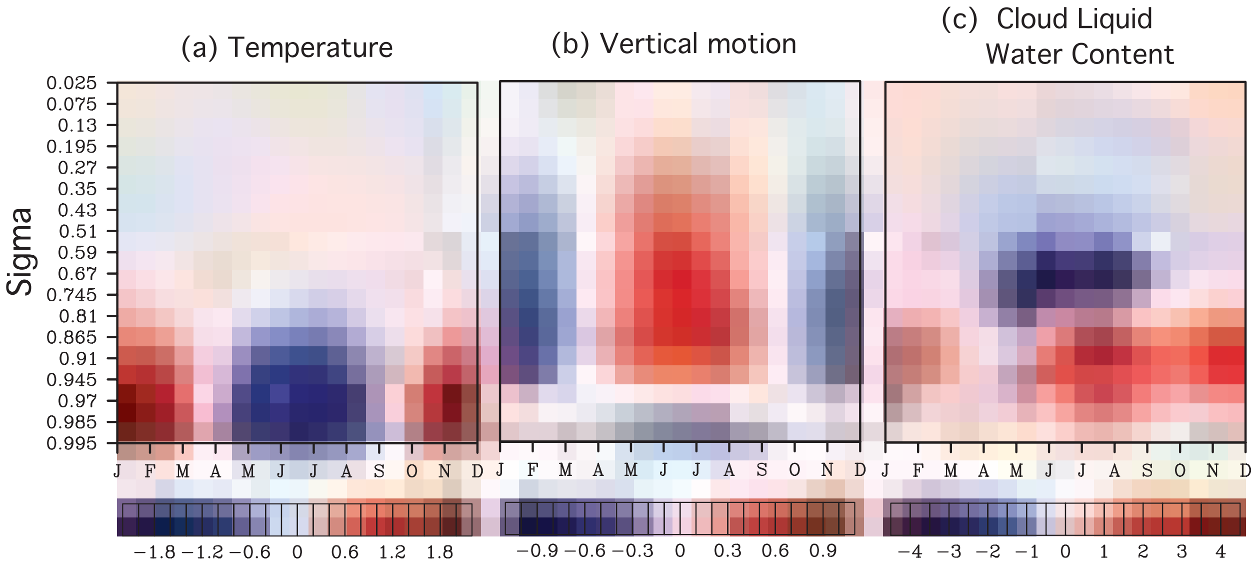


FIG. 8. Vertical profile (using sigma coordinates) of the monthly mean difference (LAKE − NOLAKE) across the Great Lakes Basin during 1980–89 in (a) air temperature (°C), (b) vertical motion (hPa s^{-1}; $\times 10^5$), and (c) cloud liquid water content (g m^{-2}).

anticyclone on 23 July 1989, and a warm-season cyclone on 2 May 1983. In all four case studies, the model accurately simulates the position and intensity of the cyclone or anticyclone in LAKE compared to NARR (Figs. 10 and 11). Averaged across the Great Lakes Basin, the difference in sea level pressure (LAKE − NOLAKE) in these four case studies is −3.59, −1.83, +1.14, and +1.33 hPa, respectively.

On 21 December 1983, NOLAKE simulates a 1046-hPa anticyclone centered over southern Quebec. In LAKE, the relatively warm lake surfaces weaken the western flank of this cold-season anticyclone in excess of −5 hPa, pushing it farther toward the Atlantic Ocean (Fig. 10a). The presence of the lakes causes an enhancement in simulated lake-effect snowfall across north-central Wisconsin and in south-central Ontario, along the northern shores of Lake Superior (not shown). The cold-season cyclone on 7 January 1980 is positioned over the Great Lakes in NOLAKE and is substantially deeper in LAKE by −4 hPa and shifted northwestward (Fig. 10b). While the presence of the lakes increase the simulated snowfall to the north of Lake Superior and Georgian Bay, their relative warmth causes most overlake precipitation to fall as rain, as opposite to in NOLAKE (not shown). In NOLAKE, a 1024-hPa warm-season anticyclone is positioned over the Atlantic on 23 July 1989; this anticyclone is allowed to expand to the northwest across the Great Lakes in LAKE, with an increase in sea level pressure of +2 hPa (Fig. 10c). On 2 May 1983, a 994-hPa warm-season cyclone is centered over Wisconsin in NOLAKE. The lakes deter the advance of the cyclone in LAKE, weakening its north-northeastern flank by +2 hPa (Fig. 10d). As a consequence, the northward progression of the rainbelt into Canada is limited in LAKE (not shown).

4. Conclusions

Two decade-long simulations of RegCM4, with 20-km grid spacing, are performed in which the Great Lakes are either included (LAKE) or excluded (NOLAKE) in order to assess the influence of the lakes on regional climate. Unlike most prior studies (e.g., Bates et al. 1993), the present analysis extends across an entire decade and is not limited to select case studies (e.g., Sousounis and Fritsch 1994), leading a quantitative estimate of the influence of the Great Lakes on regional climate and synoptic systems. By contrasting simulations with and without the lakes, we cleanly isolate the lakes' influence on climate, which cannot be reliably done with observations. Unlike previous modeling studies (e.g., Bonan 1995; Lofgren 1997), we produce high-resolution simulations that accurately represent the individual Great Lakes and their bathymetry.

In RegCM4, the Great Lakes dramatically influence the simulated regional climate. During autumn–winter, the inclusion of the Great Lakes instead of forest/field mosaic leads to increases in both the surface temperature and 2-m air temperature. Since the lakes are warmer than the overlying air in the cold season, atmospheric stability in reduced (Holman et al. 2012). The surface warming in LAKE during the cold season leads to lower sea level pressure than in NOLAKE across the Great Lakes Basin and extending into the northeast, Midwest, and mid-Atlantic states. Fritsch et al. (1989) likewise

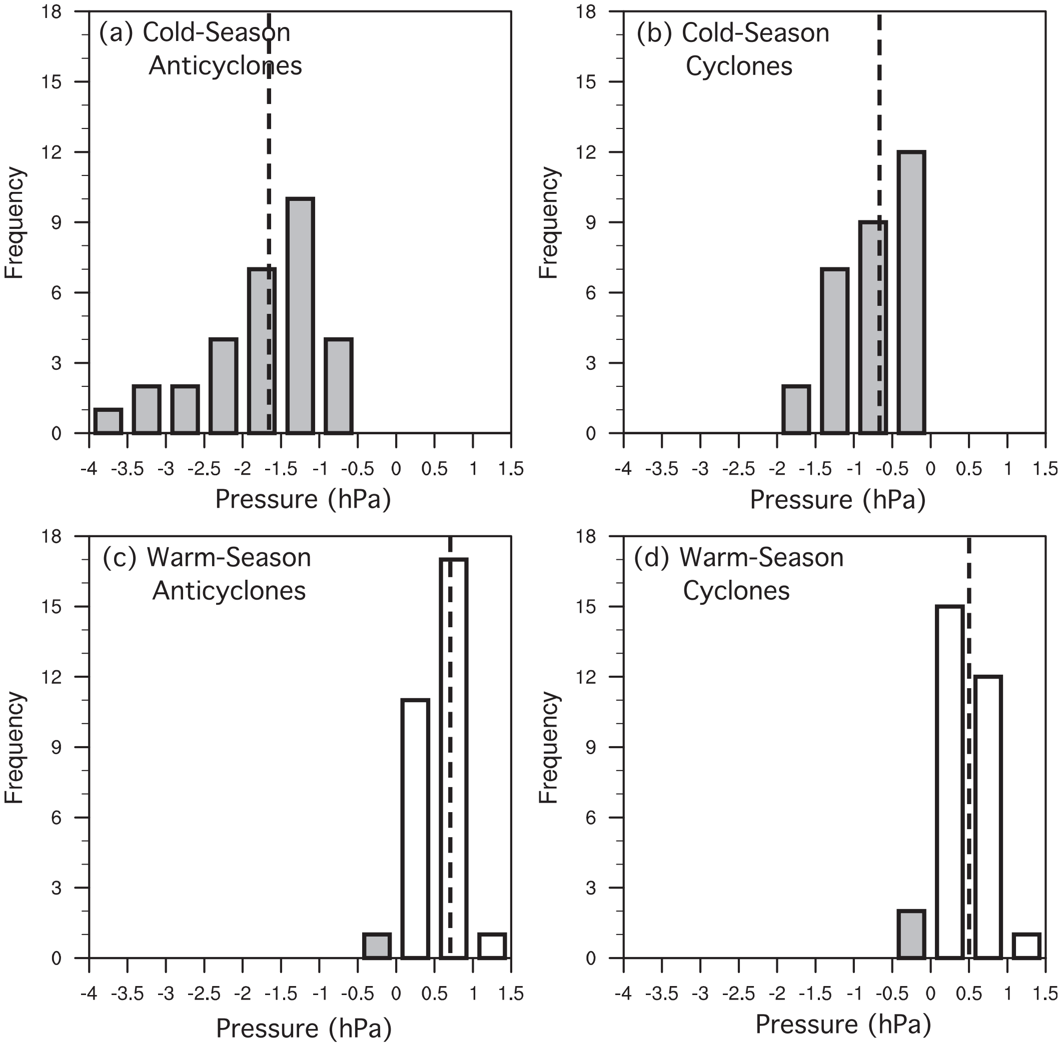
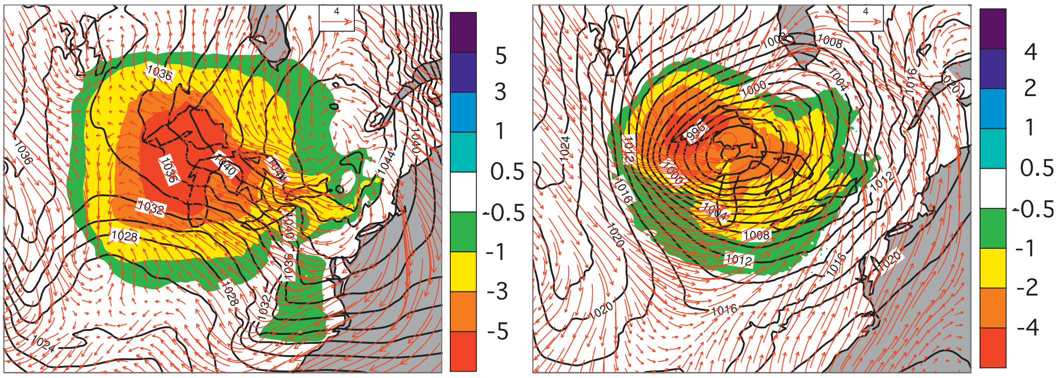


FIG. 9. Histograms of the difference (LAKE − NOLAKE) in the intensity of cold-season (a) anticyclones and (b) cyclones and warm-season (c) anticyclones and (d) cyclones, passing through the Great Lakes Basin during 1980–89. Intensity is assessed based on daily sea level pressure (hPa). The cold and warm seasons are defined as November–March and May–August, respectively. Increases and decreases in sea level pressure are identified by white and gray bars, respectively, while the dashed vertical line indicates the mean change in sea level pressure.

concluded that the Great Lakes impose significant downstream effects on climate, while Petterssen and Calabrese (1959) also showed that the relatively warm lakes during winter tend to generate or enhance cyclonic circulations. Lower pressure enhances low-level convergence and ascending motion in autumn–winter, as a dynamical response to the lakes. The enhanced cyclonic flow and lower roughness of lakes compared to forests favor stronger wind speeds, consistent with the study of Lemire (1961). Turbulent fluxes of SH and LH are more intense in LAKE than NOLAKE during the cold season. In response to enhanced evaporation and rising motion, atmospheric moisture, cloud cover, and precipitation increase across the region, in agreement with studies by Changnon and Jones (1972), Bonan (1995), Lofgren (1997), and Scott and Huff (1997).

The climatic response of the atmosphere to the Great Lakes is generally opposite during late spring–summer than autumn–winter, since the lakes are typically colder than the overlying air during the former seasons. Because of enhanced stability, simulated convective cloud amounts are reduced in LAKE compared to NOLAKE. Lyons (1966) previously suggested that deep convection over large lakes is substantially weakened during summer because of this enhanced atmospheric stability. Eshleman (1921) observed the rarity of cumulus clouds


(a) Cold-Season Anticyclone (21 Dec 1983)
(b) Cold-Season Cyclone (7 January 1980)

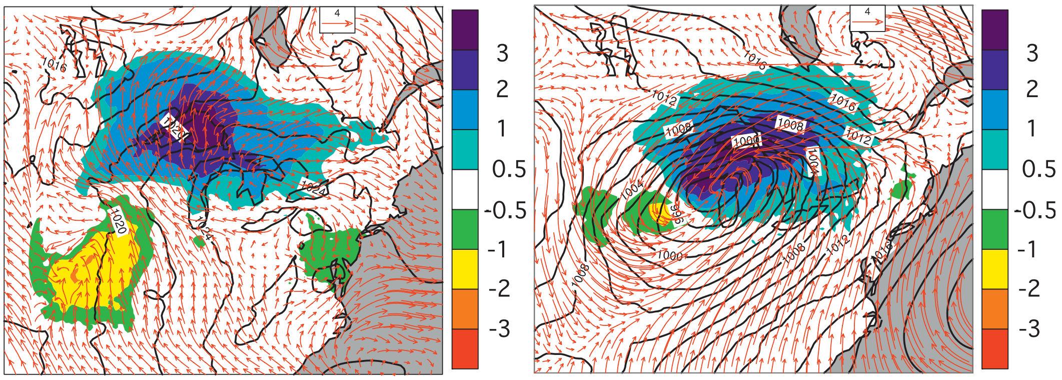

(c) Warm-Season Anticyclone (23 July 1989)
(d) Warm-Season Cyclone (2 May 1983)

FIG. 10. Case studies of (a) a cold-season anticyclone on 21 Dec 1983, (b) a cold-season cyclone on 7 Jan 1980, (c) a warm-season anticyclone on 23 Jul 1989, and (d) a warm-season cyclone on 2 May 1983. Contours and streamlines represent daily-mean sea level pressure (hPa) and 10-m wind (m s^{-1}) from NOLAKE. Shading indicates the difference (LAKE − NOLAKE) in sea level pressure (hPa).

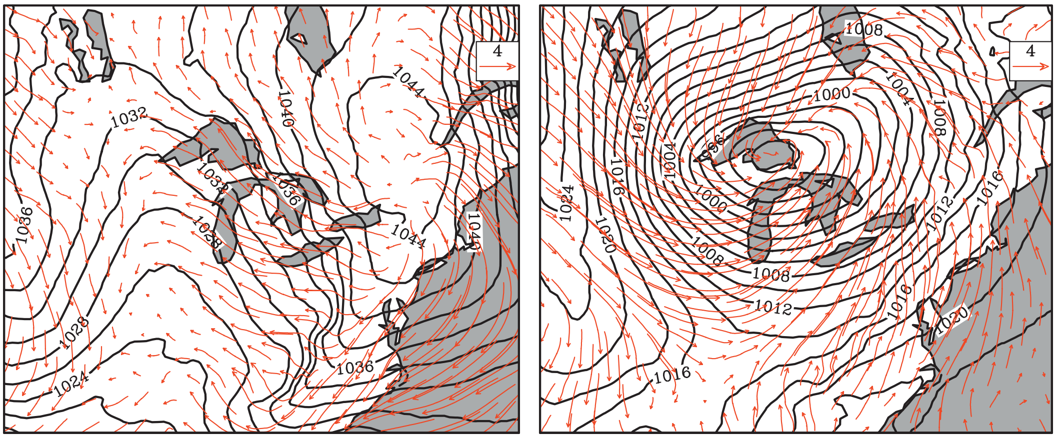
on the east shore of Lake Michigan in summer, consistent with enhanced stability. Diminished atmospheric moisture and cumulus cloud cover in LAKE compared to NOLAKE leads to greater downward shortwave radiation at the surface.

The large thermal inertia of the Great Lakes leads to year-round reductions in the day-to-day variability of 2-m air temperature, the amplitude of the diurnal temperature range, and the amplitude of the annual cycle of air temperature. Bates et al. (1993) also noted that the Great Lakes tend to reduce the amplitude of the diurnal and annual temperature range, but their simulations were limited to 10 days.

A comparison of synoptic systems in LAKE versus NOLAKE indicates that the presence of the Great Lakes favors an intensification of cold-season cyclones and warm-season anticyclones and a weakening of cold-season anticyclones and warm-season cyclones. This finding agrees with the study of Cox (1917), but our study expands the understanding of lake influences on synoptic systems by quantifying and contrasting the sensitivities of different weather systems during different seasons. The most pronounced impact of the Great Lakes is a simulated weakening of cold-season anticyclones, with a mean reduction in sea level pressure across the Great Lakes Basin of −1.72 hPa.

As noted by Notaro et al. (2013), RegCM4 exhibits several biases in the Great Lakes region. The one-dimensional lake model does not consider horizontal heat advection within the lakes or ice movement. Because of problematic overturning dynamics, the deep lake points fail to develop sufficient ice cover, particularly over Lake Superior; this likely results in an exaggerated simulated impact of the lakes on climate during winter. The current study identifies a warm lake surface bias in annual temperature for all of the Great Lakes. Compared with observations, the simulated water temperatures are not as sensitive to atmospheric conditions, as evident by the underestimated amplitude of the seasonal cycle and diurnal temperature range of water temperatures. This exaggerated thermal inertia would somewhat exaggerate the simulated influence of the

(a) Cold-Season Anticyclone (21 Dec 1983) (b) Cold-Season Cyclone (7 January 1980)



(c) Warm-Season Anticyclone (23 July 1989) (d) Warm-Season Cyclone (2 May 1983)

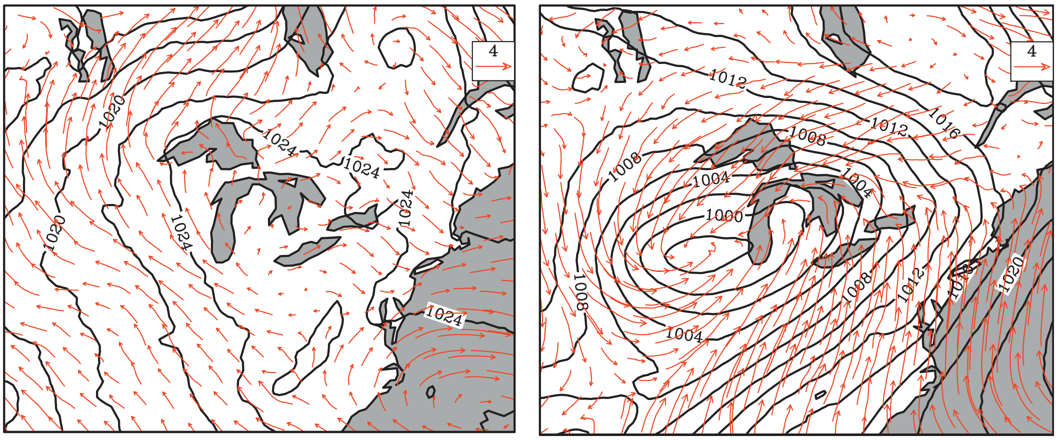


FIG. 11. Daily-mean sea level pressure (hPa) and 10-m wind (m s^{-1}) from NARR for each of the case studies in Fig. 9.

Great Lakes on climate. One key limitation of the study is the inability of a regional model to simulate remote climatic responses to the Great Lakes beyond the domain of eastern United States and southeastern Canada; such considerations would require a global climate model but would suffer from the disadvantages of a coarse grid, inadequate representation of the Great Lakes and their bathymetry, and large climate biases. The domain used in this study is relatively small, particularly in comparison to the North American Regional Climate Change Assessment Program (NARCCAP), which may have allowed the boundary conditions to constrain the large-scale dynamics and prevent a notable change in the wintertime storm track or jet stream in response to the Great Lakes, as seen by Lofgren (1997).

The study has important implications for both paleoclimate and future climate change. The Great Lakes were formed roughly 10 000 years ago, as glaciers retreated, attesting to the dynamic nature of lakes' existence. By comparing simulations with the lakes present and absent, our study reveals the climatic impacts of the formation of these large midcontinental glacial lakes. Furthermore, the study of Austin and Colman (2007), addressing anthropogenic climate change, demonstrated that the rate of summertime warming of the Great Lakes has exceeded that of the regional air. If this trend continues, then the stabilizing effect of the lakes on summertime climate, as found in the present study, may weaken over time. Given the significant influence of the Great Lakes on North American climate, it is critical to include an interactive lake model in any global or regional climate simulations of the continent; future modeling effort should explore the importance of including a three-dimensional lake circulation.

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