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Assessment of Potential Effects of Climate Change on Heavy Lake-Effect Snowstorms Near Lake Erie

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ABSTRACT. *The potential effects of future climate change on the frequency of heavy lake-effect snowstorms in the Lake Erie snowbelt were assessed using recent transient simulations from two General Circulation Models (GCMs): the second-generation Hadley Centre (HadCM2) and the first generation Canadian Climate Centre (CGCM1) coupled ocean-atmosphere models. An analysis of historical heavy lake-effect snowstorms identified six weather conditions to be closely related to heavy lake-effect snowstorm occurrence: surface wind speed > 6 m/s, surface wind direction of south southwest to west northwest, surface air temperature in the range of –10°C to 0°C, lake surface to air temperature difference > 7°C, lower tropospheric stability ($T_{lake-850}$ >15°C), and a highly amplified middle tropospheric wave train. These criteria were applied to daily grid point data from the GCMs for two periods, the late 20th Century and the late 21st Century, to determine the relative frequency with which heavy lake-effect conditions were predicted. Surface conditions favorable for heavy lake-effect snow decreased in frequency by 50% and 90% for the HadCM2 and CGCM1, respectively, by the late 21st Century. This reduction was due almost entirely to a decrease in the number of occurrences of surface air temperature in the range of –10 to 0°C, which in turn was the result of an increase in average winter air temperatures. Other surface conditions favorable for lake-effect snow occurred at about the same frequency in the late 21st Century as in the late 20th Century, suggesting that lake-effect rain events may replace lake-effect snow events. Changes in the middle tropospheric wave train were also noted in both models. However, there were sizable biases in the simulation of the present-day climate, raising questions about the validity of the future projections.*

INDEX WORDS: *Climate change, snow, lake-effect, Lake Erie.*

INTRODUCTION

Lake-effect snowstorms are a common winter season phenomenon in the North American Great Lakes region. These storms result from the rapid modification of cold air masses passing over the relatively warm waters of the Great Lakes. Heat and moisture fluxes from the lake surfaces give rise to precipitation where none would have occurred without the presence of the Great Lakes or intensification of precipitation from larger-scale processes (Niziol 1987, Niziol *et al.* 1995). This phenomenon causes a considerable enhancement of snowfall in lake shore regions. For example, Detroit, Michigan, on the western (upwind) shore of Lake Erie receives an average of 107 cm/yr, while Buffalo, New York, located on the eastern (downwind) shores of Lake Erie, receives an average of 234 cm/yr. Another example is the case of Lake Ontario where Toronto, on the northwestern (upwind) shore receives about 137 cm/yr, while Syracuse, New York, located to the southeast (downwind) of Lake Ontario, receives 277 cm/yr and is the snowiest metropolitan area in the United States. Lake-effect snows can occur as long as the lakes remain largely ice-free. For Lakes Superior, Michigan, Huron, and Ontario, large ice-free areas remain throughout most winters. However, Lake Erie will usually freeze over in January or February.

The enhanced snowfall has a number of positive and negative impacts on human activities. On the negative side, this enhanced snowfall creates transportation problems and results in additional costs for governments to keep roads clear. A major transportation artery, Interstate 90, passes along the

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southern shore of Lake Erie and is vulnerable to lake-effect snow storms. Increased property damage, injuries, and deaths due to accidents and physical over-exertion accompany such events. Major airports at Cleveland and Buffalo are also vulnerable to disruptions. There may be short-term lost economic opportunities when a lake-effect storm occurs, such as reduced retail sales. There are also long-term infrastructure costs; for example, roofs of buildings must be designed to support heavier loads of snow (Schmidlin *et al.* 1992) than for locations away from the snowbelt, at greater cost. On the positive side, there is a large private snow removal business sector that benefits from the snowfall. Sales of winter-related products may increase. Also, the substantial and regular snowfall provides favorable conditions for an important winter recreational industry in some parts of the Great Lakes. For example, there are eight ski resorts near the south shore of Lake Erie whose mean annual snowfall is significantly enhanced by the lake effect. Also, many of the Midwest's premier ski resorts are located in the snow belts of the other Great Lakes.

Changes in the magnitude and frequency of heavy lake-effect snow storms would have a number of consequences. If such snow storms were to decrease in magnitude and/or frequency, then transportation problems would lessen, property damage and human injuries and deaths might decline, economic disruptions would lessen, and the cost of building construction could decrease; however, the winter recreation and the snow removal industries would likely be hurt. If such storms were to increase in magnitude and/or frequency, then the cost to keep roads clear and to construct buildings would increase, economic disruptions would be more frequent, and property damage and human injuries and deaths could increase; however, the winter recreation and snow removal industries would likely benefit.

Significant societal impacts have occurred when lake-effect snowfall amounts have been extreme. Abnormally heavy snow amounts during individual storms have been very disruptive. For example, a single severe lake-effect snowstorm that occurred in November 1996 is estimated to have resulted in eight deaths, hundreds of human injuries, widespread power outages, damage to numerous buildings, and over $30 million in economic losses (Schmidlin and Kosarik 1999; S.A. Changnon, Illinois State Water Survey, Champaign, Illinois, personal communication). These large impacts occurred almost exclusively in the Lake Erie snowbelt, illustrating that these events can be very disruptive locally. Although there have been no systematic impacts studies of entire winter seasons and over the entire basin, the losses from this single event illustrate the potential for aggregate large losses.

Recent research shows that past changes in lake-effect snowfall on decadal time frames were related to climatic shifts. For example, Braham and Dungey (1984) found that the contribution of lake-effect snow to total snowfall on the lee shore of Lake Michigan increased from the 1930s into the 1970s. This was coincident with a decrease in mean winter temperature and they concluded that this was the most likely cause of the observed increase in lake-effect snow. This finding suggests that future climate change will affect lake-effect snowfall. Cohen and Allsopp (1988), using a general circulation model (GCM) simulation for a doubling of CO_2, estimated 60 to 90% decreases in total snowfall on the northern shores of Erie and Ontario. However no work has been done specifically relating the future projections of global climate models to possible changes in heavy lake-effect snow events on the southern shoreline of Lake Erie and the U.S. shorelines of the other Great Lakes.

The purpose of this paper is to outline a method for assessing the potential effects of future climate change on the frequency of heavy lake-effect snowstorms near Lake Erie and then to apply the method to two GCM simulations of climatic conditions in the 21st Century. This study was performed as part of the United States National Assessment of the Consequences of Climate Variability and Change. This study did not examine possible changes of the much more frequent light to moderate lake-effect snow events. Since they are frequent, society has largely adapted to them. Although the heavy events are rather infrequent, they can have large societal impacts, as illustrated by the aforementioned November 1996 event.

METHODS/ANALYSIS

The investigation of lake-effect snowstorm occurrence using GCM simulations of future climate is constrained by the temporal and spatial scales of the phenomenon and the resolution of GCM output. First, heavy lake-effect snow is generally confined to a very narrow region on the lee shores of the lakes, rarely extending more than about 80 km inland. The spatial resolution of available multi-decadal GCM simulations (~150 to 200 km) is too coarse to resolve this phenomenon. Therefore, it was necessary to use downscaling methods to infer the potential impact of climate change on the frequency of heavy lake-effect snows. Furthermore, these events are of short duration (ranging from a few hours to a few days) and require a special set of meteorological conditions described later.

Conceptually, it is not clear whether warmer conditions would result in an increase or decrease in heavy lake-effect snowstorms in the Lake Erie snowbelt. One hypothesis is that warmer conditions would increase the ice-free period on Lake Erie, thus increasing the opportunities for snowstorms. An analysis of historical data shows that the number of heavy lake-effect snow days is negatively correlated with winter temperatures at both Buffalo, NY, and Erie, PA, contrary to this hypothesis. However, this historical relationship may not necessarily hold in a future climate. Leathers and Ellis (1996) found that snowfall trends in snowbelts of Lakes Erie and Ontario were related to the trends in the frequency of individual weather events. Thus, it was considered necessary to examine individual weather events in GCM simulations, rather than rely on historically-based statistical relationships. For that reason, daily (rather than monthly) GCM output were used in this study.

Climatological Analysis of Historical Heavy Lake-effect Events

A number of past studies have examined local and large-scale factors contributing to the development of heavy lake-effect snow storms. Early studies identified the importance of the intensity of surface heat and moisture fluxes (determined by wind speed, air-lake temperature differences, and atmospheric moisture content), distance of the air passing over the lake, and atmospheric stability as being important to lake-effect storms (Wiggin 1950, Rothrock 1969). These investigations also usually included criteria for wind direction, which helped determine fetch and the specific locations where lake-effect snows are most intense (Niziol 1987, Niziol *et al.* 1995). These types of studies, and improved weather modeling efforts, have led to important advances in short-term forecasts of lake-effect storms.

In order to assess lake-effect storm occurrence in GCM simulations, it was necessary to determine which meteorological factors, available from GCM output, are related to the frequency with which these storms occur. An historical climatological snowfall analysis for the period 1950–1996 was used as the basis for this assessment. This analysis utilized daily (TD-3200 data set) data obtained from the National Climatic Data Center (NCDC) for five sites. Two of these (Erie, PA, and Westfield, NY) are located in the lake-effect snowbelt region on the southern shore of Lake Erie. The other three (Flint, MI, Columbus, OH, and Pittsburgh, PA) are located outside of the lake-effect snowbelt (Fig. 1). Westfield is situated about 50 km to the northeast of Erie, at a distance from the lake similar to Erie. Hourly meteorological data (TD-3280 data set) were obtained from NCDC for Erie. All of these stations were chosen for their lengthy periods of record, a necessity for this analysis.

An objective approach was used to identify lake-effect snow days. A heavy lake-effect snow day was defined as having an average daily snowfall at Erie and Westfield of greater than 20 cm and at least double the average of the three sites outside the lake-effect snowbelt. The 23 heavy lake-effect snow days found using this approach were further classified into two categories: 20 to 35 cm (denoted hereafter as *heavy*) and greater than 35 cm (denoted hereafter as *severe*). It must be recognized that this analysis was limited only to the heavy events occurring at these two representative stations. There are many more lighter lake-effect snow events than

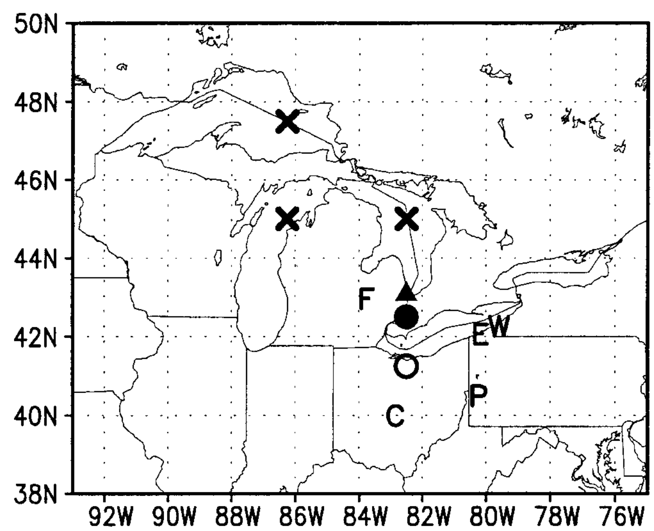

FIG. 1. Location of grid box centers for HadCM2 model water cells (X), HadCM2 wind speed data (○), HadCM2 temperature data and wind direction estimates (●), and CGCM1 model grid point (▲). Also shown are the locations of Erie, PA (E), Westfield (W), Columbus, Ohio (C), Pittsburgh, PA (P), and Flint, Michigan (F).

heavy events. Furthermore, lake-effect snow during a single episode can be highly variable in space; there are days in the historical record when heavy lake-effect snow occurred at some location in the snow belt, but not enough snow fell at the two analyzed stations to qualify (see discussion below).

Assessment of lower tropospheric stability was based in part on radiosonde data collected at Buffalo, NY, which was limited to the period 1960 to 1989. In addition, the stability analysis required information on lake surface temperature. A long-term data set of daily lake surface temperatures for Lake Erie does not exist for the winter months. Climatologically-averaged lake surface temperatures instead were used. These data were based on satellite and aircraft remotely-sensed measurements from the National Oceanic and Atmospheric Administration and Environment Canada for the period 1966 to 1992, with the daily means most heavily weighted toward temperatures observed during 1990 to 1992 (Schneider *et al.* 1993).

The months of November, December, and January were chosen for study because the majority of lake-effect events over Lake Erie (as estimated by visible satellite images) generally occur during these 3 months (Kristovich and Steve 1995). Each day of the historical record was classified into one of four categories: severe lake-effect snow days, heavy lake-effect snow days, all other snow days, and no snow days.

Of the 23 heavy or severe lake-effect days that were identified, nine occurred in November, ten in December, and four in January. Lake Erie is often covered with ice in January and February (Assel *et al*. 1983), which likely accounts in part for the paucity of events during that time period. Of these 23 days, there were nine severe lake-effect snow days and these tended to occur early in the lake-effect season. Six of the nine severe lake-effect days occurred in November. The frequency distribution of daily median surface meteorological conditions at Erie, PA, for the four categories is shown in Figure 2. All of the nine severe lake-effect snow events had median surface air temperatures between –10°C to 0°C (Fig. 2a). Eight of the heavy lake-effect snow events were also in this range, but six were colder (–25°C to –10°C). The temperature distribution for the other snow days is shifted toward higher temperatures, and for the no-snow days even further toward higher temperatures with the median value greater that 0°C.

The 1°C resolution data used to construct Figure 2b reveals that most heavy and severe lake-effect days had median lake-air temperature differences greater than 7°C. By contrast, the distribution of temperature differences for other snow days included a number of days with much smaller positive differences and some days when the lake was colder than the air.

For median daily wind direction (Fig. 2c), nearly all the heavy and severe lake-effect snow events occurred with wind directions from the west to southwest, oriented along the long axis of Lake Erie (which is aligned from the west southwest toward the east northeast). Heavy snow at Erie and Westfield, but not at the other three sites, occurred on 2 days when the winds were from the northeast (40 to 60°). These events occurred under synoptic conditions atypical of severe lake-effect events under consideration here, and thus were placed in the other snow category. The distribution of wind direction for both the other snow days and no-snow days is much broader. Since Lake Erie is oriented west-southwest to east-northeast, it may seem unusual that the favorable wind direction range extends to the south-southwest, which would seem to put the Lake Erie snowbelt on the upwind side. This is due to the choice of station used for the analysis and the modification of wind flow in the vicinity of the lake. The Erie, PA, National Weather Service office is located near the shoreline. During lake-effect snow events, the rising motion of air over the lake often causes the wind at the surface to have a component toward the lake. Thus, the wind direction near the shoreline often tends to have a more southerly (toward-lake) orientation than the large-scale wind direction.

The median daily wind speed (Fig. 2d) tended to be higher for heavy and severe snow days compared to other snow days and no-snow days. All of the severe and 85% of the heavy lake-effect snow events occurred with mean wind speeds greater than 6 m/s. Higher wind speeds would be conducive for enhanced fluxes of heat and moisture from the lake surface during cold-air outbreaks and stronger surface convergence at the downwind lakeshore.

Based on these results, the surface conditions favorable for heavy and severe lake-effect snows southeast of Lake Erie can be summarized as follows: (1) air temperature range of –10°C to 0°C; (2) water-air temperature difference range of greater than 7°C; (3) wind direction from 210° to 280°; and (4) wind speeds greater than 6 m/s. Event occurrence might be expected when the above conditions exist concurrently. These conditions are only

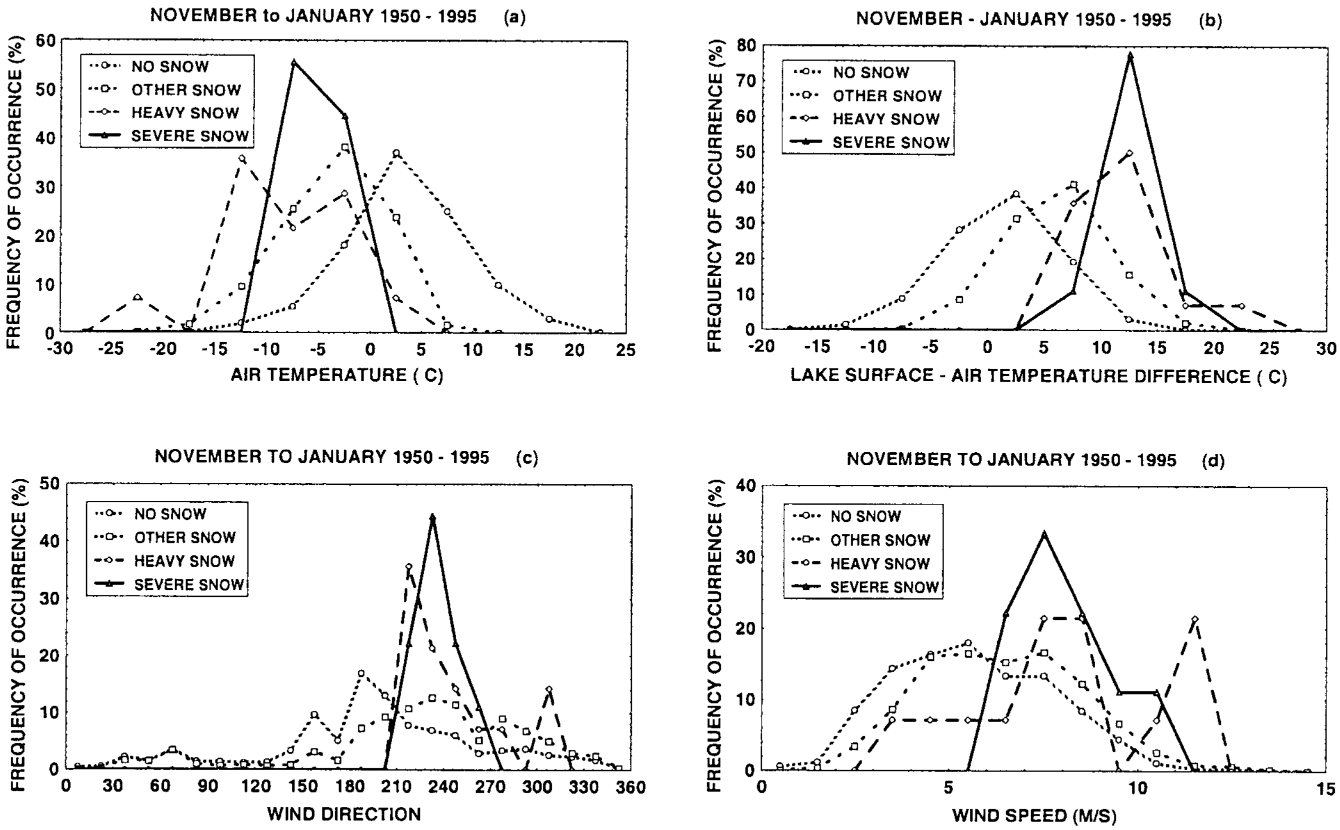

FIG. 2. Frequency of occurrence (%) of median daily (a) surface air temperature, (b) climatological Lake Erie surface -median air temperatures, (c) wind direction, and (d) wind speed, observed from November to January, 1950 to 1995. Each point represents the frequency over (a) and (b) 5°C, (c) 15°, and (d) 1 m/s intervals. Lines connecting these points are included for convenience. Lines labeled "NO SNOW" are days with no reported snow, "OTHER SNOW" are days classified as those with snow from synoptic systems or lake-effect snows with < 20 cm snow totals, "HEAVY SNOW" are lake-effect snow days with snowfalls between 20 and 35 cm, and "SEVERE SNOW" are lake-effect snow days with snowfall totals over 35 cm.

slightly different than the favorable conditions found by other investigators (Wiggin 1950, Rothrock 1969, Niziol 1987).

To determine how frequently these conditions occur, the percentage of days that met each specified atmospheric condition (listed in the previous paragraph) for at least 70% of the hours of each day was determined for the four categories (Table 1). For each category the percentage of days meeting each atmospheric criterion is higher for the heavy and severe lake-effect snow categories compared to other snow days and no-snow days. Table 1 also gives the frequency of days meeting *all* atmospheric criteria for over 50% of the hours. The lower percentage of hours used for this analysis (50% instead of 70%) is necessary to increase the number of samples. Only a few (about 22%) of the heavy lake-effect snow days (20 to 35 cm) met all four atmospheric criteria. By contrast, most of the severe snow days (about 78%) met all four atmospheric criteria.

An exploration of the applicability of the atmospheric criteria for estimation of lake-effect snow intensity must recognize how often the events appear to be favored, but do not occur. There were 78 (many more than the number of observed heavy lake-effect events) days when most of the hours met all criteria and thus a heavy lake-effect snow (> 20 cm) was expected. On 59 of these days (76%), less than 10 cm of snow was observed. On 19 of the 78 days when heavy lake-effect snows were expected, lake-effect snows of greater than 10 cm were observed, although 9 of these days averaged less than 20 cm of snow. The low frequency of heavy events

TABLE 1. Percent frequency of days meeting the specified criteria for > 70% of hours each day (> 17 hours); and for > 50% of hours for the combined criteria. November to January 1950 to 1996 at Erie, OH.

Atmospheric Criteria	Percent of Days Meeting Criteria			
	Non-Snow Days	Other Snow Days	LE Storm: 20–35 cm	LE Storm: 35 cm
Air Temperature	18.4	55.9	42.9	100.0
Water-Air Temp	23.2	62.7	100.0	100.0
Wind Direction	9.6	22.0	50.0	88.9
Wind Speed	27.7	43.6	78.6	77.8
All (> 50%)	0.3	5.6	21.6	77.8
Number of days	~2,700	~1,450	14	9

Note: Atmospheric criteria used were air temperatures –10°C to 0°C, water-air temperature and differences greater than 7°C, surface wind direction between 210° and 280°C, and speeds greater than 6 m/s.

when conditions were considered favorable was examined further by looking at spatial snowfall distributions for these 78 cases using all available snowfall observations, not just those from stations with very lengthy periods of record. An examination of these revealed that there was very high spatial variability of lake-effect snow and this was the cause of the observed low frequency. The stringent definition of heavy lake-effect snow was relaxed to include local peaks in snowfall (more than 20 cm) within 1 to 2 days at a minimum of one site, but usually more sites, anywhere along the southeastern coast of Lake Erie, or in the hills of western New York and northwestern Pennsylvania and extreme northeastern Ohio within 80 km of the Lake Erie coast. These locations are where Scott and Huff (1996) and Niziol *et al.* (1995) found a climatic peak in wintertime lake-effect precipitation. In 82% of the 78 favorable days, at least 1 station in the lake-effect snow belt region reported more than 20 cm of snow. In an additional 16%, at least one station reported more than 10 cm of snow. In all cases, snowfall outside the lake-effect region was much less. Thus, the meteorological conditions derived from the Erie and Westfield records appear to represent necessary and sufficient conditions for the occurrence of heavy lake-effect snow at some location in the Lake Erie snow belt.

The 12 UTC rawinsonde data at Buffalo, New York, were used to determine the importance of the atmospheric thermodynamic profiles on Lake Erie lake-effect events. Sounding data were available for these analyses for 19 of the 23 lake-effect days, and 7 of 9 severe lake-effect days. Critical temperature differences between the lake surface and 850 hPa of > 13°C, or 10°C if accompanied by synoptic forcing, were used by Niziol *et al.* (1995) as indicators of the relative instability of the air with respect to the lake. Figure 3 shows the distribution of the difference between the climatological lake surface temperature and the temperatures at 850 hPa. Nearly all of the heavy and severe lake-effect snows occurred with large temperature differences, generally in excess of 15°C at 850 hPa and 25°C at

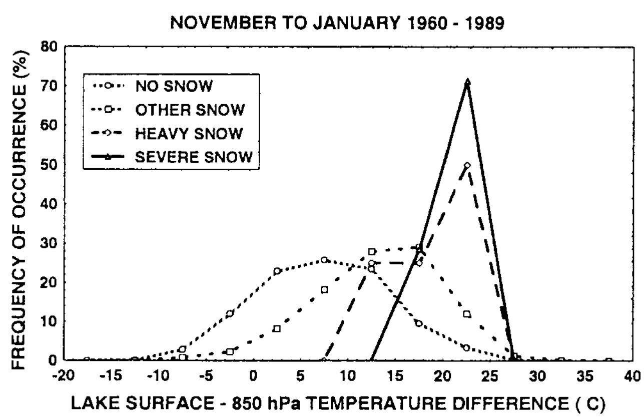

FIG. 3. Frequency diagrams of differences in climatological lake surface temperatures and 850 hPa temperature observed from November to January, 1960 to 1989. Each point represents the frequency over a 5°C interval. Lines connecting these points are included for convenience. The 850 hPa temperatures were taken from NWS Rawinsonde observations at 12 UTC at Buffalo, NY. Line labels are the same as in Figure 2.

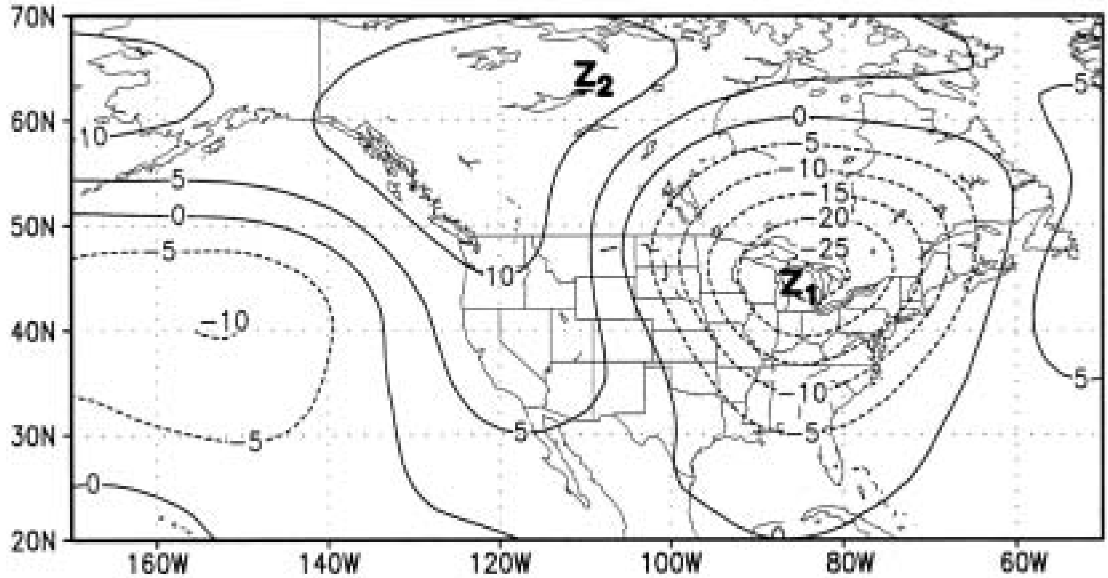

FIG. 4. Mean 500 hPa anomalies (dm) for 18 heavy lake-effect snowstorms during 1955 to 1996.

700 hPa (not shown). In contrast, the distributions for other snow days and no-snow days are much broader and shifted toward smaller lapse rates.

Lake effect snows are generally associated with a ridge over western North America and a trough over eastern North America during a highly amplified synoptic scale wave pattern, resulting in cold air advection over the Great Lakes. In order to assess middle tropospheric circulation patterns that are responsible for cold air advection over the lakes, a composite 500 hPa height map was computed for the observed heavy lake-effect events from the National Meteorological Center octagonal grid point data set. This was limited to the 20 events occurring after 1955 when twice per day 500 hPa fields first became available. The height anomaly map was constructed as the average for these 20 days. This analysis (Fig. 4) shows a trough over the Great Lakes and a ridge over northwestern Canada. Based on this map, a circulation index was defined as follows

$$\text{LES} = z_2\,(110°\text{W}, 65°\text{N}) - z_1\,(86°\text{W}, 45°\text{N}) \qquad (1)$$

where LES = the lake-effect snow circulation index, and z_1 and z_2 = the 500 hPa pressure level height (m) at the locations in parentheses (shown in Fig. 4). This index was used for analysis of both the past and future climate simulation periods from the GCM, for the purpose of examining the large-scale forcing of the local conditions that cause these events.

GCM Simulations

The climate simulations used for this study were generated by the Hadley Centre with their second-generation coupled ocean/atmosphere GCM (HadCM2, Jones *et al.* 1997) and by the Canadian Climate Centre with their first-generation coupled ocean/atmosphere GCM (CGCM1; Flato *et al.* 2000). The HadCM2 (CGCM1) has a spatial resolution of 2.5° (3.7°) latitude by 3.75° (3.7°) longitude. The atmospheric component has 19 (10) vertical levels while the ocean component has 20 (29). The simulations used for the current analysis are transient climate change experiments in which the model was run from the mid 19^{th} Century to 2100 with gradually increasing greenhouse gas and sulfate concentrations. The model physics include the direct reflection and absorption of radiation by sulfate aerosols but not their indirect effects on cloud processes. For the historical period to the present, the historical equivalent greenhouse gas and sulfate concentrations were used. For the period from the present to 2100, a 1% compound increase was assumed. The CGCM1 simulation is considerably more sensitive to enhanced greenhouse forcing than the HadCM2 simulation. The mean annual temperature increase from the late 20^{th} Century to the late

21st Century for the Lake Erie region is 2.4°C for HadCM2 and 5.2°C for CGM1 for this experiment. Ensembles of four simulations for HadCM2 and three simulations for CGCM1 were run. Because of the volume of output involved, the lake-effect analysis was done on only one of these simulations for each model. Daily grid point data were made available by the Hadley Centre for two periods, 1960 to 1989 and 2070 to 2099, for the following variables: mean sea level pressure, 850 hPa height, 500 hPa height, 10 m wind speed, 1.5 m maximum temperature, and 1.5 m minimum temperature. The Canadian Climate Centre provided daily grid point data for 1975 to 1994, 2080 to 2086, and 2094 to 2099 for mean sea level pressure, 850 hPa height, 500 hPa height, 10 m wind speed, and 1.5 m mean temperature.

The periods of the simulations (1960 to 1989) for HadCM2 and 1975 to 1994 for CGCM1 are nominally different than the observational period (1950 to 1996). However, the model "years" are tied to historical years only by the temporally-increasing greenhouse and sulfate forcing used in the model and there is no requirement to have an exact match in the periods. The prime requirement is to have a sufficiently long model simulation to perform a climatological comparison. Twenty years is adequate for this purpose.

There is a crude representation of the Great Lakes in the HadCM2. Specifically, three grid points (Fig. 1) are assigned a surface type of water. The analysis of HadCM2 weather conditions was performed using output for the grid point (42.5°N, 82.5°W) immediately south of the easternmost water grid point, equivalent to the relative location of the Lake Erie snowbelt with respect to the lake (Fig. 1). The Great Lakes have been shown to have an effect on synoptic scale circulation patterns. For example, cyclones can intensify as they pass over the lakes (Angel and Isard 1997, Sousounis and Fritsch 1994). The atmosphere-lake feedback is qualitatively represented in the HadCM2 simulation, but the level of accuracy is not known. If there are biases, this could represent a source of error in the results. There is no representation of the Great Lakes in CGCM1. Thus, uncertainties due to possible feedback effects are greater in this simulation than in HadCM2.

Since one of the variables related to lake-effect snowstorms is the difference in temperature between the lake surface and the air, it was necessary to obtain lake surface temperatures for the simulation. Although lake surface temperature is calculated in the HadCM2 using a simplified lake model and a simplified geographical description of the lakes (Fig. 1), a more realistic estimate was available. As part of an on-going assessment of the effects of climate change on Great Lakes hydrology (Lofgren *et al.* 2002), the NOAA Great Lakes Environmental Research Laboratory (GLERL) used their state-of-the-art Great Lakes hydrology model (Croley *et al.* 1998) driven by the same HadCM2 and CGCM1 simulations for their study. Among many variables, this model calculates lake surface temperature. Monthly values of Lake Erie surface temperature were obtained from GLERL for the late 20th and late 21st Centuries. In the GLERL model simulation, Lake Erie mean monthly surface temperatures are above freezing for both the HadCM2 and CGCM1 forcing throughout the winter, suggesting that Erie would generally remain ice-free throughout the winter during the late 21st Century period. Use of the GLERL simulation lake surface temperatures ensures that the lake-air temperature differences calculated for the HadCM2 and CGCM1 simulations are internally consistent for both model simulation periods.

Surface wind direction data were not made available for either model. For CGCM1, surface geostrophic winds were provided. For HadCM2, this variable was estimated from the mean sea level pressure (P_s) field. Values of P_s at the four grid points nearest to the grid point at (42°N, 82.5°W) were used to calculate the geostrophic wind direction. Since the historical observational analysis utilized wind data at a height of 10 m where frictional influences are large, the surface wind direction was assumed to be 30° counterclockwise from the geostrophic wind direction to account for the influence of surface friction in the atmospheric boundary layer. Alternatively, estimates could have been made of the observed geostrophic wind direction, rather than use the actual wind direction, from the observed pressure field data and compared with the wind direction estimated from the model pressure field data; this would have avoided the need to make a correction for surface friction influences. However, this would have required acquisition of reanalysis surface pressure data for a 45-year period, a substantial additional level of effort. Since subsequent analyses found inconsequential changes in the frequency of occurrence between the two model simulation periods, a more sophisticated technique would not have changed the conclusions of this study. Surface wind speed data from the models were directly used. However, for vector variables the HadCM2 model uses a grid that is offset from the grid for scalar variables. Since the scalar, surface pressure, was used to estimate wind direction, the grid point for wind direction is different than the grid point location for wind speed (40.75°N, 82.5°W) (Fig. 1).

Pressure level temperatures were not made available. To estimate lower tropospheric stability a layer mean temperature was calculated from pressure level heights assuming hydrostatic balance using the equation (Holton 1979)

$$\bar{T}_{850-500} = g(z_{500} - z_{850})/[R \ln (850/500)] \qquad (2)$$

where $\bar{T}_{850-500}$ = layer mean temperature between 850 hPa and 500 hPa, g = acceleration of gravity, z_{500} and z_{850} = heights of the 500 hPa and 850 hPa pressure levels, and R = gas constant for dry air. As noted previously, the 23 heavy lake-effect events occurred generally when

$$T_{lake} - T_{700} > 25°C \qquad (3)$$

where T_{700} and T_{lake} are the temperature at 700 hPa and the lake surface respectively. For $\bar{T}_{850-500}$, the adopted criteria were

$$\bar{T}_{lake} - \bar{T}_{850-500} > 25°C \qquad (4)$$

as favorable for heavy lake-effect snow. It is important to note that the Buffalo radiosonde temperature profiles will often reflect modification of the boundary layer by Lake Erie and the other upwind lakes. This poses a potential problem in this study because of uncertainties about the lake modification processes in the HadCM2. To minimize this concern, the lower atmospheric stability was calculated for the grid cell immediately to the south of the southernmost water cell in the model. Thus, with northerly and northwesterly flow, the temperature profile at this grid cell will be affected by the surface fluxes at the water grid cells. Of course, biases may still exist because the geography of the model land/water surface is a crude representation of the actual geography and the model physics are a simplification of the complex surface-atmosphere interactions. However, this is an inherent limitation of any comparable analysis. The absence of any water grid points in the CGCM1 increases the uncertainty in this element since there will be no modification of the lower troposphere in this model.

RESULTS

A thorough analysis of the HadCM2 results are presented first. These are then contrasted with the results from the CGCM1 simulation.

HadCM2 results

Intercomparisons between the 20th Century HadCM2 simulation period and the observed historical climatic record for variables important to lake-effect snow storm development identified in Section 2 were conducted to assess the accuracy of HadCM2 projections. Figure 5 shows the frequency distributions during November to January for the four surface weather variables: surface air temperature, lake-air temperature difference, surface wind direction, and surface wind speed, respectively. The frequency distributions for three different data sets are shown on each panel: observational data for the period 1950 to 1996 ("CLIM"), the 1960 to 1989 HadCM2 simulation period, and the 2070 to 2099 HadCM2 simulation period. The historical observational data set was for the Erie, PA, National Weather Service airport office (Fig. 1), which was compared with the HadCM2 grid at (42.5°N, 82.5°W). This station was chosen because of its location on the southern side of Lake Erie, in a similar relative (with respect to the lake) position as the grid point used for model simulation analysis. Both the model grid point and the Erie station will experience lake-modified air masses. An alternate approach would have been to use an average of several stations encompassing the area of the grid cell. However, the fields to be examined are quite spatially coherent on climatic time scales and this alternate approach would not likely lead to a significantly different result.

The observational data and 20th Century simulation period distributions for air temperature (Fig. 5a) are quite similar. The total frequency occurring within the lake-effect range favorable for heavy lake effect snow (–10 to 0°C) is nearly identical. The frequency distributions of the difference between lake and air temperature (Fig. 5b) are also quite similar for the observational data and the 20th Century simulation, although the frequency of temperature differences greater than 7°C is slightly higher for the HadCM2 simulation. The distributions of wind direction are somewhat different (Fig. 5c). In particular, the observational data show a higher percentage of southerly wind flow and a lower percentage of westerly flow than the 20th Century CM2 simulation. However, the total fre-

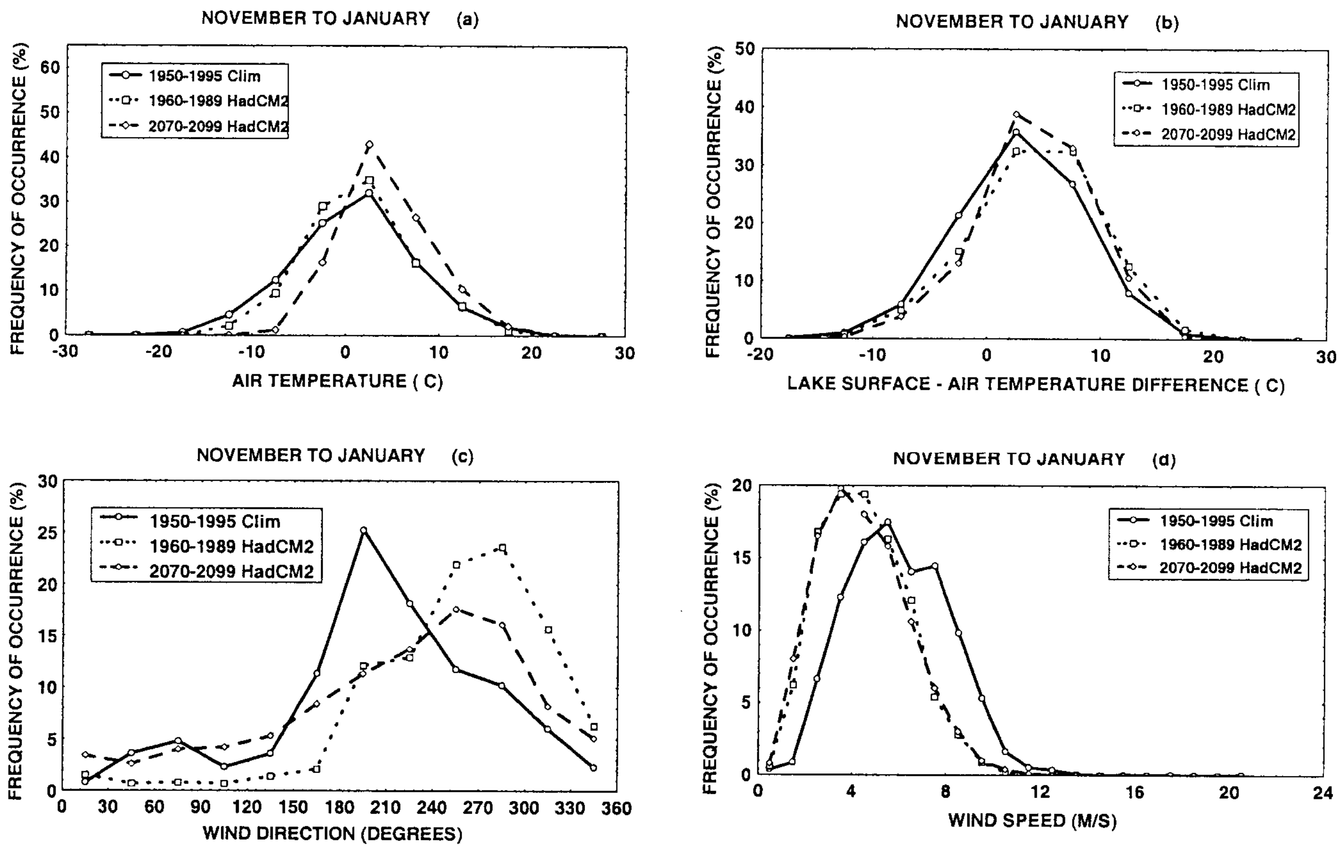

FIG. 5. Frequency of occurrence (%) of daily (a) air temperature (C°), (b) Lake Erie surface-air temperature difference (°C)m (c) wind direction, and (d) wind speed (m/s) for the period of November through January for the observational data from the Erie National Weather Service airport office (solid), the HadCM2 20th Century simulation (dotted), and the HadCM2 21st Century simulation (dashed).

quency in the range of 210° to 280° is nearly identical in the two data sets. For wind speed (Fig. 5d), the 20th Century HadCM2 simulation data are generally shifted toward lower wind speeds compared to the observational data. As a result, the frequency of wind speeds exceeding 6 m/s is significantly higher in the observational data. The wind differences may or may not reflect problems in the HadCM2 simulation. The surface wind is sensitive to the exposure (in the observational data) and the assumed roughness length (in the HadCM2 simulation). These factors could easily result in differences in the wind speed and direction distributions, even if the HadCM2 simulation of the surface pressure field is accurate. To test this, the wind climatologies were examined at six regional locations (Columbus, OH, Dayton, OH, Pittsburgh, PA, Cleveland, OH, Toledo, OH, and Detroit, MI) and compared with the Erie climatology. On average, these six locations have peak frequencies at lower wind speeds and more westerly wind directions than are observed at Erie and are in closer agreement with the model climatology. Thus, the differences in wind climatologies between Erie and HadCM2 may be as much due to local influences on the Erie wind climatology as to possible biases in the HadCM2 simulation of the current climate and in the method used to estimate wind direction.

The simultaneous occurrence of the four surface conditions favorable for heavy lake-effect snows (as identified in Section 2) was examined. In the observational data, this situation occurred approximately 17 times per decade. In the 20th Century HadCM2 simulation period, this occurred approximately 15 times per decade, very similar to the observational record.

The 500 hPa circulation patterns were analyzed by computing the values of the LES index and comparing the distributions. Figure 6 shows the distributions for the observational data, the 20th Century simula-

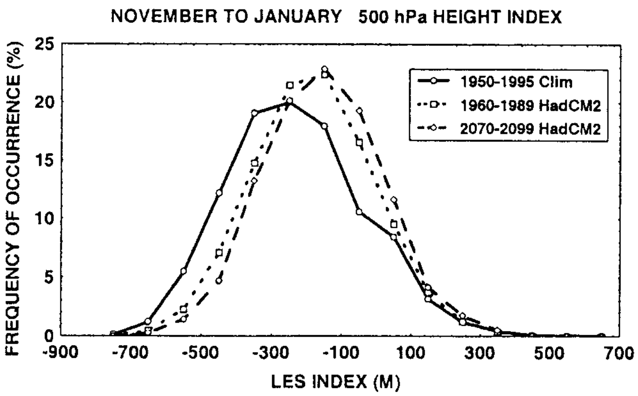

FIG. 6. Frequency of occurrence (%) versus the LES index for the period of November–January for the observational data (solid), the HadCM2 20th Century simulation (dotted), and the HadCM2 21st Century simulation (dashed).

tion, and the 21st Century simulation. There are some differences between the observations and the 20th Century simulation period. The frequency in the HadCM2 simulation is smaller than observations for index values less than –300 m and larger than observations for index values between –200 m and 0. Heavy lake-effect snows occur generally for values of LES greater than 0 m, which correspond to situations with a strong ridge over northwestern Canada and a deep trough over the Great Lakes. In this range, the frequency of occurrence in the 20th Century simulation period is quite similar to that of the observations. However, there is an increase of 20% in the frequency of LES > 0 m from the 20th Century simulation to the 21st Century simulation period.

This increased frequency in favorable large-scale circulation patterns in the 21st Century suggests the possibility of an increase in heavy lake-effect snow events. However, an examination of the local-scale conditions that cause these events shows that this change in large-scale forcing does not increase the frequency of favorable local conditions. The comparison between the 20th Century and the 21st Century simulation periods reveal very little change in the distributions of wind direction (Fig. 5c), wind speed (Fig. 5d), and lake surface to air temperature difference (Fig. 5b) between the 20th and 21st Century periods. For air temperature (Fig. 5a), there is a shift in the distribution toward higher temperatures. This causes a substantial decrease (55%) in the frequency of temperatures in the range favorable for heavy lake-effect snow between the 20th and 21st centuries.

For future conditions, the analysis was extended to include February because of the aforementioned result that Erie would remain ice-free. Even with the additional month, these four favorable conditions occurred simultaneously only seven times per decade for the 21st Century simulation period, as compared to 15 times per decade for the 20th Century simulation period. This change is due almost entirely to the change in air temperature frequencies. The simultaneous occurrence of favorable conditions for the other three variables (lake minus air temperature difference, wind direction, and wind speed) was also examined. There was very little difference between the 21st Century and 20th Century simulation periods (23 times per decade for the 20th Century versus 21 times per decade for the 21st Century). Based on these considerations, the decrease in the frequency of conditions favorable for heavy lake-effect snow is the result of higher temperatures in the 21st Century. This suggests that the decrease in heavy lake-effect snow may be replaced by an increase in the number of winter lake-effect rain events, which are now most frequent in the autumn (Miner and Fritsch 1997, Nicosia *et al.* 1999).

A separate analysis of lower tropospheric stability (lake temperature minus 850–500 hPa layer mean temperature) was conducted. Figure 7 shows the distributions for the observational data, the 20th

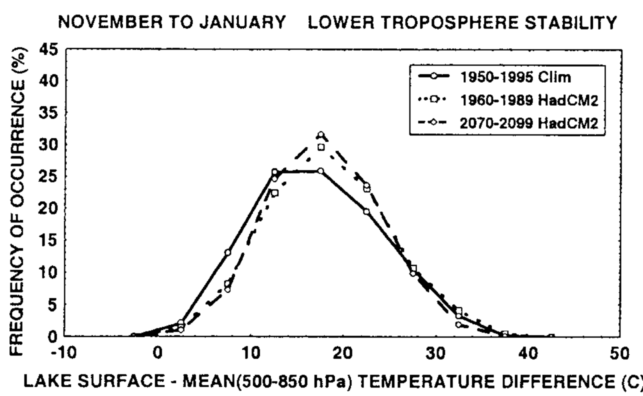

FIG. 7. Frequency of occurrence (%) versus temperature (°C) for the difference between the Lake Erie water surface temperature and the mean layer temperature for the 850-500 hPa layer, for the observational data (solid), the HadCM2 20th Century simulation (dotted), and the HadCM2 21st Century simulation (dashed). The mean layer temperature for the observational data were obtained from radiosonde data for Buffalo, NY.

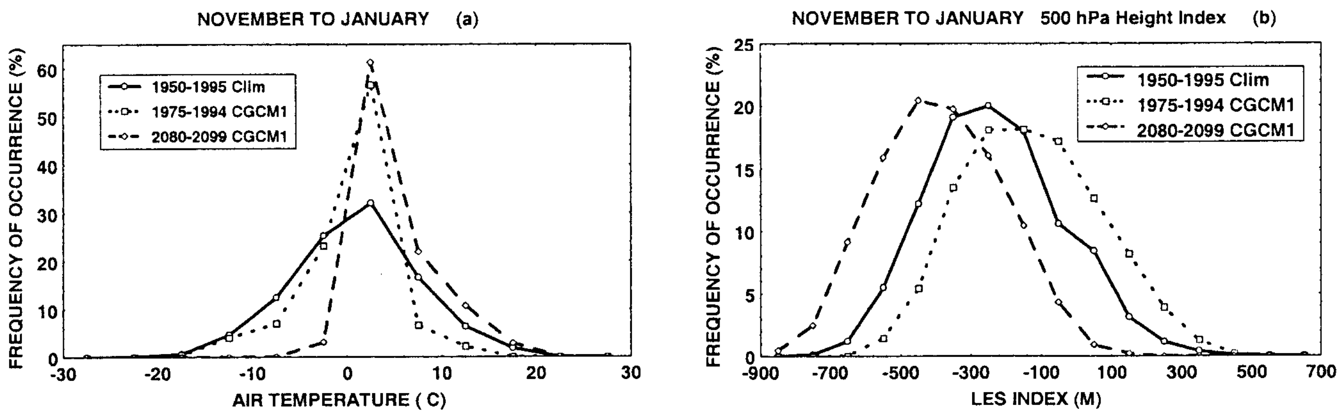

FIG. 8. Frequency of occurrences (%) of daily (a) air temperature (°C) and (b) LES index (m) for the period November through January for the observational data (solid), the CGCM1 20th Century simulation (dotted), and the CGCM1 21st Century simulation (dashed).

Century simulation period, and the 21st Century simulation period. The differences between the observations and the 20th Century simulation are generally small (but larger than the differences between 21st and 20th Century simulation periods; this is discussed later). The frequencies for the 20th Century simulation are slightly higher than observed in the range of 15°C to 25°C and slightly lower than observed in the range of 5°C to 15°C. For the favorable difference range of greater than 25°C, there is very little predicted change in the frequency of occurrence for this range between the 21st Century and 20th Century simulation periods.

As described earlier, there are methodological concerns about the treatment of wind direction and lower atmospheric stability. However, in both cases the differences (Figs. 5c and 7) between the 20th and 21st Century simulation periods are small for the entire range of values. While alternate approaches to the methodology may produce different model distributions of these variables, there would not be changes in the differences between the 20th and 21st Century simulation periods. Thus, the conclusions of this study would not be affected by alternate approaches.

CGCM1 Results

For the CGCM1 simulation, there were small differences (not shown) between the 20th and 21st Century periods for lake-air temperature differences, wind speed, wind direction, and lower tropospheric stability (lake temperature minus 850–500 hPa layer mean temperature), similar to the results for the HadCM2 simulation. However, larger differences were found for air temperature, shown in Figure 8a. The frequency of air temperatures in the favorable range of –10 to 0°C dropped from 30% in the late 20th Century to only 4% in the late 21st Century. As a result, the frequency of the simultaneous occurrence of the four favorable surface conditions dropped from 38 times per decade in the late 20th Century to only three times per decade in the late 21st Century, a lower frequency than found in the HadCM2 simulation. The more drastic reduction in the CGCM1 is due to the greater warming compared to HadCM2.

There were also large differences between the 20th and 21st Century in the LES index, shown in Figure 8b. The frequency for occurrence of LES > 0 m drops from 26% in the 20th Century to only 1% in the 21st Century. This very large decrease reflects a more zonal flow pattern in the CGCM1 by the late 21st Century. This is clearly shown by Sousounis and Grover (2002).

These results indicate that heavy lake-effect snow on Erie would become a very rare occurrence by the end of the 21st Century under the CGCM1 scenario.

SOURCES OF UNCERTAINTY

Both the HadCM2 and CGCM1 simulations show a decreased frequency of opportunities for heavy lake-effect snow in the late 21st Century compared to present-day conditions. This is primarily due to a decrease in the frequency of air temper-

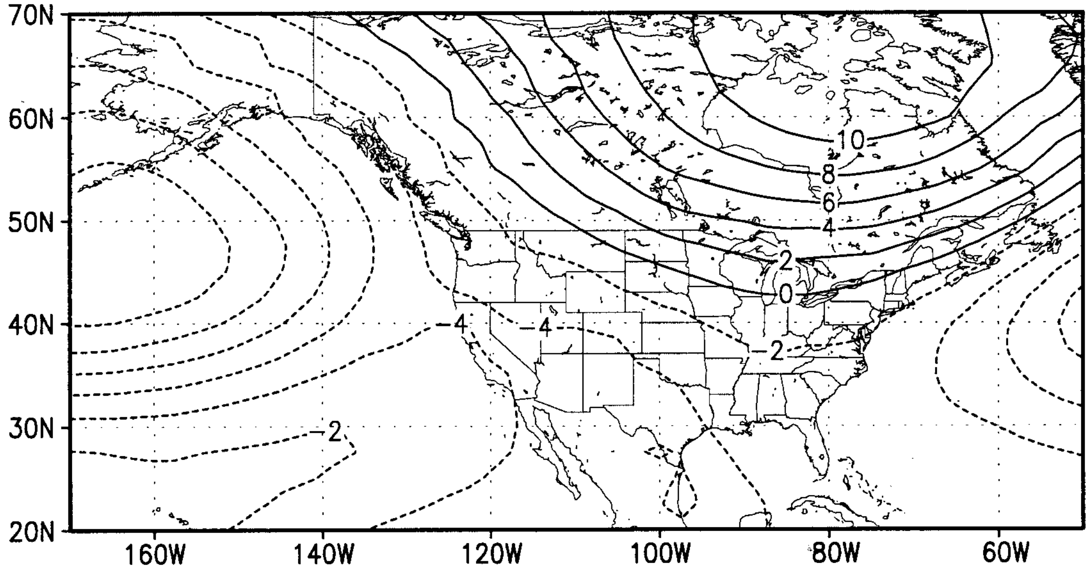

FIG. 9. The difference (dm) in 500 hPa height for the period November through January between the HadCM2 simulation for 1960–1989 and the observations.

atures in the range favorable for heavy lake-effect snow.

The use of these results as a prediction for the future climate must take into account two sources of uncertainty. First, these are results from only two GCM simulations. Although GCM simulations of *global* temperature changes may be associated with a moderate level of confidence, predictions of *regional* temperature changes are less certain. An assessment of the robustness of these results would require an analysis of other independent GCM simulations. A second source of uncertainty results from model biases in simulating current climate conditions. As indicated in Figures 5 and 7, the surface and lower tropospheric weather conditions in the vicinity of Lake Erie are simulated with a varying degree of accuracy in HadCM2. A subjective inspection suggests that the accuracy of the air temperature and lake-to-surface temperature difference distributions is high, but the accuracy for the other variables is lower. This is also the case for the CGCM1 simulation (not shown). Also examined was the ability of the models to simulate larger-scale circulation features, specifically the height of the 500 hPa surface over North America and adjacent oceans. Figure 9 shows the difference between the HadCM2 for 1960 to 1989 and observations. The 500 hPa surface in the model is substantially higher than observations over northeast Canada and lower than observations over the central Pacific. The effect over the Great Lakes is that the intensity of the middle tropospheric westerly flow is somewhat weaker in the GCM simulation than observed.

Figure 10 shows the difference between the 21st Century simulation and the 20th Century HadCM2 simulation. Other than the east-central Pacific, the height of the 500 hPa surface is generally higher in the 21st Century than the 20th Century, an expected outcome because of globally warmer temperatures. The height increases are larger over Canada than over the southeast U.S. because of larger temperature increases in Canada than in the southeast U.S. The distribution of these differences means that the middle tropospheric wind speed over Lake Erie is somewhat less in the 21st Century simulation than in the 20th Century simulation. A possible consequence of this change is that the intensity of extratropical cyclones might decrease in the future. By contrast, Sousounis and Grover (2002) show that the CGCM1 produces mean wind speeds of similar magnitude for the two periods over Lake Erie.

More interestingly, the differences between the 21st and 20th century simulations are generally smaller in magnitude than the differences between the 20th Century simulation and the observational data for HadCM2, although not for CGCM1. This raises a fundamental question about the reliability of assessments of future climate change. Is it possible to trust the accuracy of simulated climate changes that are smaller than model biases? It is

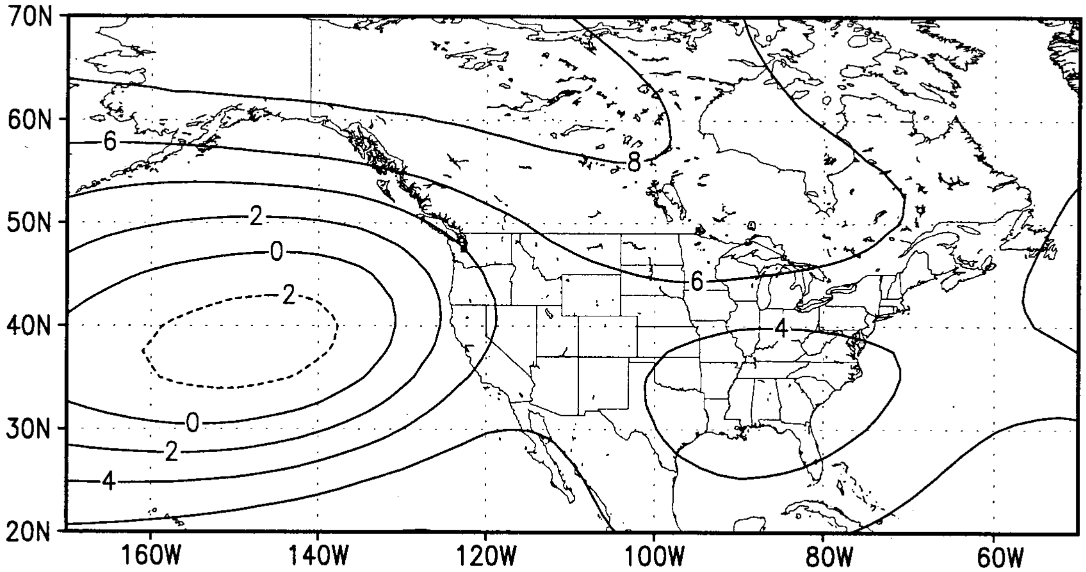

FIG. 10. The difference (dm) in 500 hPa height for November through January between the HadCM2 simulations for the 21st Century and the 20th Century.

common practice to examine the potential effects of climate change by computing differences between GCM simulations with present-day forcing and assumed future forcing. Yet it must be recognized that, since the atmosphere is a highly non-linear system, there is no certainty that model biases will be constant under the scenario of temporally increasing greenhouse gas and sulfate aerosol forcing. This is a potential issue with all assessments that utilize GCM simulation output. Nevertheless, GCM simulations arguably represent the best source of information about future climates. In addition, GCM simulations of the present-day climate will almost certainly improve and this study lays the foundation for future assessments using such improved simulations.

DISCUSSION/CONCLUSIONS

This paper outlines a method for assessing the potential future changes in the frequency of heavy lake-effect snows. A climatological analysis of past heavy lake-effect snowstorms identified the surface weather conditions, lower tropospheric stability conditions, and mid-tropospheric wave patterns usually associated with these events. This analysis provided the criteria for identifying situations in the HadCM2 and CGCM1 simulations that would be favorable for heavy lake-effect snow. These criteria, applied to daily data, were (1) 1.5 m temperature range of –10°C to 0°C, (2) lake surface minus 1.5 m air temperature difference greater than 7°C, (3) 10 m wind direction in range of south southwest through west northwest, (4) 10 m surface wind speed greater than 6 m/s, (5) lake surface minus $\overline{T}_{850-500}$ temperature greater than 25°C, and (6) highly amplified 500 hPa wave pattern with a ridge over western Canada and a trough over the Great Lakes. The application of these criteria required access to GCM simulation output at a daily resolution and is thus a very time and data intensive method to apply to these simulations. In HadCM2 simulation, the frequency of local surface conditions favorable for heavy lake-effect snows decreased by about 50% from the 20th Century to the end of the 21st Century, despite a modest increase in the frequencies of large-scale circulation patterns conducive to such events. In CGCM1, the decrease in favorable conditions was even greater, at 90%.

Use of such results as a prediction of the future must take into account the inherent uncertainties in this analysis. In particular, only two GCM simulations were analyzed. In addition, on a large scale, the differences in atmospheric circulation patterns between the 21st and 20th Centuries are smaller than biases in the model simulation of 20th Century climate conditions for the HadCM2.

Although these uncertainties are significant, it is not unreasonable to speculate that higher temperatures, if they occur, would lead to a decrease in heavy lake-effect snow. As noted previously, Braham and Dungey (1984) found a correlation between average winter temperature and annual lake-effect snowfall amounts near Lake Michigan. Average winter temperatures in the present-day climate are near freezing, and both HadCM2 and CGCM1 projects that average winter temperatures will rise to a few degrees above freezing in the 21st Century. While average temperatures may rise, one possible scenario is that day-to-day variations in temperature could be greater in the future. Since heavy lake-effect snow occurs only on a small number of days, greater temperature variability could maintain (or even increase) the frequency of favorable conditions in spite of rising average temperatures. However, the analysis done in this study investigated the day-to-day variations in weather conditions and found that there is little change in the magnitude of simulated day-to-day temperature variability. The number of occurrences of temperatures favorable for heavy lake-effect snow decreases substantially. All of the other conditions favorable for lake-effect snow occurred at about the same frequency in the late 21st Century as in the late 20th Century, suggesting that lake-effect rain may be more common during November to January. Since there were significant changes between the 20th and 21st Century simulation periods primarily in air temperature, it is unlikely that the assumptions of the use of 850–500 hPa layer mean temperature as a surrogate for 700 hPa level temperature and the estimation of wind direction from the surface pressure field will decrease confidence in these conclusions.

One important question is the timing and nature of this change to less frequent heavy snowstorms. It is possible that as mean winter temperatures gradually rise, the ice-free period will increase faster than the decrease in the frequency of favorable meteorological conditions. If so, the frequency of lake-effect snowstorms could increase temporarily before decreasing by the latter part of the 21st Century. To address this question, it would be necessary to analyze daily GCM simulation output for other 21st Century periods. Such output were not made available.

These results are only directly applicable to the Lake Erie snowbelt because the historical observational data analysis was restricted to this area. Nevertheless, a consideration of the physical forcing provides some basis for making conjectures about the possible impacts on other Great Lakes. It is likely that the temperature and wind speed conditions favorable for heavy lake-effect snow on Lake Erie would also be favorable on the other lakes be-

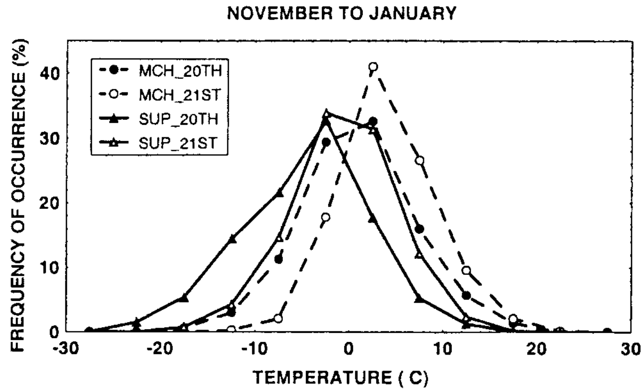

FIG. 11. Frequency of occurrence (%) versus temperature of the HadCM2 20th Century simulation for Lake Michigan grid point (dashed, ●) and Lake Superior grid point (solid, ▲) and 21st Century simulation for Lake Michigan grid point (dashed, ○) and Lake Superior grid point (solid-△).

cause these variables determine the rate of modification of air masses crossing the Great Lakes. However, the distance that air travels over the lakes is also very important and this is dependent on geography; thus, the favorable wind direction range will be specific to each location. An analysis of HadCM2 data for two grid points, one in the vicinity of the southern Lake Michigan snowbelt (42.5°N, 86.25°N) and the other near the Lake Superior lake-effect snowbelt (47.5°N, 90°W), was performed. This analysis indicated that in the HadCM2 simulation, southern Lake Michigan experiences a decrease from 20th Century to 21st Century in the frequency (from 41% to 20%) of favorable (–10°C to 0°C) air temperatures (Fig. 11). This decrease is similar to the changes in the Lake Erie snowbelt. Also there is little change in the frequency of the other favorable conditions. However, for Lake Superior, there is only a small decrease (from 54% to 49%) in the frequency of favorable air temperatures (Fig. 11) despite an overall warming of 3°C because 20th Century temperatures are lower there than in the southern portions of the basin. Based on this analysis, the HadCM2 simulation would suggest little change in the frequency of heavy lake-effect snow in the Lake Superior snowbelt and a substantial decrease in the southern Lake Michigan and Lake Erie snowbelts.

The study was limited to heavy lake-effect snowstorms. It is possible that light-to-moderate lake-effect snowstorms may increase, leading to an increase in total winter snowfall. However, in the historical data record, total snowfall generally decreases as mean winter temperatures increase.

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