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# Lake Effects on Climatic Conditions in the Great Lakes Basin

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Robert W. Scott and Floyd A. Huff
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Illinois State Water Survey
Atmospheric Sciences Division
Champaign, Illinois

A Division of the Illinois Department of Natural Resources

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## ABSTRACT

Average spatial distributions of general climate conditions over the Great Lakes basin were investigated to derive seasonal estimates of lake-induced changes for six weather conditions: precipitation, mean maximum and mean minimum temperatures, cloud cover, vapor pressure, and wind speed. The objective of the research was to provide information on the climatic effects of the entire Great Lakes on the long-term weather features and existing feedback mechanisms within the basin. Lake effects were estimated by comparing analyses of each weather condition using: (1) all basin data, and (2) data excluding stations within an 80-kilometer (km) zone around the lakes. In general, results confirm theory and analyses from previous research but point to inadequacies in data collection procedures and the spatial resolution necessary for a more precise analysis.

Lake-induced modifications maximize over and just downwind (generally to the east and southeast) of all lakeshores and are proportional to lake size. Upwind regions are minimally affected. Climate departures east of Lakes Ontario and Erie are also influenced by the increase in elevation leading towards the Adirondack Mountains and Allegheny Plateau, thereby complicating detection of effects due solely to the lakes.

Lake effects are most noticeable in precipitation and temperature patterns and vary considerably by season. Influences on precipitation are highest during late autumn and winter when lake waters are typically much wanner than the air flowing over the lakes. Effects are most pronounced near Lake Superior where up to 100 percent more precipitation falls in winter than that expected without the presence of the lake. Concurrently, Lakes Huron and Michigan increase precipitation by 60 and 40 percent, respectively. During the summer, all lakes cause a decrease in precipitation, ranging from 10 to 20 percent, due to the stabilizing force the relatively cool water surfaces impose on the lower atmosphere, thereby serving as a deterrent to convective rainfall production.

Mean minimum temperatures in the region are wanner due to the lakes during all seasons and over all lakes. Increases are highest in winter, reaching 8°C over Lake Superior, and 4°C near Lakes Huron and Michigan. Lake effects on mean maximum temperatures result in substantial cooling during spring and summer. General decreases of-3°C to -4°C are found in both seasons over Superior, Michigan, and Huron, the three largest lakes, maximizing at a -6°C departure in summer due to Lake Superior.

Lake effects on cloud cover and vapor pressure parallel the influences indicated in precipitation and temperature, respectively. However, these conditions are observed with less resolution due to a sharp reduction in the number and optimum spacing of available observation sites. Effects on cloud cover are highest during winter, reaching a 25 percent increase downwind of Lakes Superior and Michigan. Conversely, cooler lake waters in summer reduce cloudiness by roughly 10 percent over Lakes Michigan and Huron. Average vapor pressure is 10 to 15 percent higher across the central part of the basin during autumn and winter. Likewise, the lakes decrease vapor pressure in summer by roughly 5 to 10 percent, concomitant with lake-induced cooling. Finally, seasonal wind speed data were considered inadequate to determine climatic lake influences due to current station spacing and data quality.

## INTRODUCTION

It is well known that the Great Lakes exert a considerable influence on the climate of then-region. Much of this influence is due to differences in the heat capacities between the water and land surfaces of the area, and to the large source of moisture the lakes provide to the lower atmosphere. In addition, changes in terrain height adjacent to the lakes further alter climate conditions. Theory suggests three major effects of the lakes: 1) to moderate maximum and minimum temperatures of the region in all seasons (with perhaps little net effect on mean temperatures), 2) to increase cloud cover and precipitation over and just downwind of the lakes during winter due to the relatively large heat and moisture source present, and 3) to decrease summertime convective clouds and rainfall over the lakes because of the greater atmospheric stability imparted at the surface by the relatively cooler summertime water temperatures.

Past research has confirmed these theories for portions of several lakes or entire individual lakes. However, seasonal climate effects over the entire Great Lakes basin are still somewhat poorly defined. This is due largely to a continued lack of quality long-term climatic data surrounding the lakes, which is obtained from stations spaced sufficiently to resolve and define adequately the boundaries and extents of lake effects superimposed on synoptic weather conditions. Substantial climate research has been performed on portions of the Great Lakes, specifically for Lakes Michigan and Ontario. Indeed, recent work has been completed on short-range mesoscale forecasting and monitoring of wintertime conditions over Lake Ontario (Reinking et al., 1993). Effects of the remaining lakes and of the entire basin on local climate have received much less attention.

Climate studies over the Great Lakes basin are not new. Day (1926) investigated precipitation totals in the drainage area of the Great Lakes and found higher annual precipitation just east of all lakes, especially Lakes Michigan and Huron. In an explanation of these findings, he described a seasonal distribution of precipitation dominated by more frequent snowfall events just east of the lakes in winter. However, he further suggested relatively higher summertime thunderstorm activity on western lakeshores. Horton and Grunsky (1927) investigated precipitation within the basins of the four westernmost lakes and found larger totals over land areas than over-lake values, regardless of the lake or season being considered. The one exception was Lake Superior, which showed higher lake precipitation in winter.

In contrast, Blust and DeCooke (1960) compared precipitation over Lake Michigan, using island stations, with nearby shore sites, and found higher precipitation totals over land in summer and over lake waters in winter. Other work echoing these findings includes Hunt (1959) and Wilson (1977) in studies conducted around Lake Ontario, and Changnon (1968) and Bolsenga (1977) in additional research on Lake Michigan. The wintertime increases, for the most part, were attributed to lake-effect snow events created by the transfer of substantial amounts of heat and moisture to cold, dry polar air masses moving over the lakes. Indeed, Danard and McMillan (1974) have estimated through numerical studies that approximately 52 percent of the moisture evaporated from the lakes results in increased precipitation over and downwind of the lakes in the form of enhanced snowfall. Preferred regions for heavy accumulation have been well documented (Petterssen and Calabrese, 1959; Changnon, 1968; Strommen, 1968; Eichenlaub, 1970; Wilson, 1977; and Braham and Dungey, 1984, among others).

Similarly, Changnon (1966), Lyons (1966), and Wilson (1977) documented Day's (1926) presumption of enhanced thunderstorm activity over land during warm months due to convergence generated locally by the lake breeze phenomenon. On the other hand, deep convection over the lakes has been shown to dissipate substantially in summer due to the massive stability imparted to the lower atmosphere by the cooler lake surfaces (Lyons, 1966).

Lake effects on temperature have been studied as well, with many researchers documenting large seasonal variances similar to those of precipitation. For example, Kopec (1967) used isonomal analyses to study temperature departures from latitudinal normals and found conditions along the northern shores of Lake Superior to be about 7°C warmer in January and 3°C cooler in July than areas at the same latitude but further from the lake. Other seasons and lakes showed similar, but smaller differences. Danard and Rao (1972) also found a +7°C temperature modification in the near surface atmosphere. Similarly, Dare (1981) showed a large negative departure of heating degree- day accumulations near Lake Michigan shores in early winter. The departure lessened as winter progressed due to the natural trend towards an equalization of land/lake temperature differences and, in some years, the freezing of lake waters.

Temperatures within the basin vary due to uneven heating of air over land surfaces compared to air over water. Phillips (1972), calculated factors controlling temperature modification over Lake Ontario and explained 86 percent of the variance by: 1) surface temperature of the upwind air mass (a land site), 2) surface water temperature, and 3) length of time that air was in contact with me lake. Phillips determined that temperature modification occurred quite rapidly as air moved out over the lake, with more than half of the change occurring within the first ten minutes of air/lake contact and within about 3 kilometers (km) of the windward coastline. This suggests the development of a rather tight horizontal temperature gradient on the windward side of the lakes in winter due to much colder land surfaces adjacent to these borders. Wylie and Young (1979) provided boundary-layer observations over Lake Michigan that concur with these results: they reported on surface-based temperature inversions in wintertime which rose to maximum heights after only 50 km of travel from the windward shoreline. Braham, and Dungey (1995) documented frequent occurrences of lake-effect snow near the windward shore of Lake Michigan, also indicating rapid modification.

Although changes in precipitation and temperature patterns attributed to lake effects are the climate elements best documented, other weather parameters also experience measurable influences. Danard and McMillan (1974) estimated that 48 percent of moisture evaporated from the Great Lakes remains in the atmosphere as increased water vapor and clouds downwind of the lakes. Changes in atmospheric pressure were suggested by Petterssen and Calabrese (1959), Eichenlaub (1970), and Colucci (1976), citing the Great Lakes as a preferred region for wintertime cyclogenesis. The lag in the cool down of lake waters compared to land surfaces after each summer season results in warming of near surface air over lakes, and thus lower surface pressures as continental polar air masses move over the lakes during late fall and early winter. The above research, plus the modeling efforts of Hjelmfelt (1988), cite the southern parts of Lakes Michigan and Huron as preferred locations for cyclone development due to their shapes. Shorelines of these lakes provide for a converging land breeze into the lakes, enhancing vertical motion and the formation of lower pressure. Quantifying the change, Danard and Rao's (1972) numerical model suggests as much as 70 meter (m) drop in the

1000 millibar (mb) height within individual storms due to the lake's presence. In a similar procedure for summer, Strong (1972) documented the formation of anticyclonic conditions over the lakes due to cooler lake waters.

Wind speed and direction and cloud cover have been reported as other climate elements largely affected by the lakes. Lyons (1966), Weber (1978), and Comer and McKendry (1993) are just a few of the many researchers relating occurrences of summertime lake breezes resulting in cloud generation and convective precipitation inland from lake boundaries. These works document the transfer of surface moisture from the environment over the lake to the land, increasing shoreline humidity and cloud formation while also decreasing rainfall opportunities over and immediately adjacent to the lake. Scott and Grosh (1979) and Kristovich and Steve (1995) used satellite imagery to document cloud frequencies near the lakes in summer and winter, respectively. Similarly, Passarelli and Braham (1981) described a link between land breezes and parallel shoreline snow bands in winter. More recently, Sousounis and Fritsch (1994) provide a case study and numerical evidence that the lakes not only alter the speed and direction of the surface wind fields, but also alter the structures and paths of weather systems moving through the region.

Interests in the impacts of the Great Lakes extend far beyond their initial meteorological influences. Lake hydrologjsts and lake managers are interested in long-term weather features of the region and existing feedback mechanisms within the basin. What is not available for hydrologic research is detailed information on the average spatial patterns of lake effects by all Great Lakes basin lakes on seasonal precipitation, temperatures, winds, clouds, and vapor pressure. Therefore, the primary objective of this research was to estimate with as much detail as possible the magnitude of lake-effects imposed by each of the Great Lakes on the above climate variables.

It was our intent to remove substantial lake influences from the climate data. Climate conditions likely are dominated to a much greater extent by the large-scale synoptic weather patterns moving across the region. However, the magnitude of aggregate lake effects may not be addressed adequately by this work, and may remain in some analyses at a noticeable level. Although reference is made to "lake effect" or "no lake effect," analyses may not always encompass the total of these larger scale lake influences. The effects of the Great Lakes on climate are substantial. Procedures and analyses in the following sections will quantify these effects seasonally for all lakes and for much of the entire basin.

# DATA AND METHOD OF ANALYSIS

The climate of the Great Lakes basin was analyzed to determine lake effects on six weather conditions: precipitation, mean maximum temperature, mean minimum temperature, cloud cover, wind speed, and water vapor pressure. Although each parameter is recorded within standard meteorological observations, all data were not obtained from a single source. Temperature and precipitation data were extracted from the archives of daily data from the National Climate Data Center (NCDC) or Canada's Atmospheric Environment Service. Cloud cover, vapor pressure, and wind speed data in the United States were averaged from hourly surface airways observations at selected first-order stations obtained from NCDC (1986) and arranged by Petersen (1991). Data for Canada were taken from averages listed in several data publications (Canada Department of Transportation, 1968; Environment Canada, 1982,1984).

Data for each condition were averaged by season for the period 1951 -1980, the last 30-year interval for which all data elements were available (the only exception being cloud cover data for Canada for 1941 - 1960). A large number of stations reported observations that were relatively complete, on the order of 90 percent or greater. Only those sites with a data availability of this magnitude were included in the temperature and precipitation analyses. Some of the U.S. hourly data and some of the Canadian published data were of a lesser temporal quality. No attempt was made to adjust for missing values.

Past Water Survey research based on the Lake Michigan basin provided climatological techniques for defining the extent of lake-effects on monthly, seasonal, and annual precipitation, temperatures, and other weather conditions (Changnon, 1968). Inspection of these results and those of other studies revealed significant lake influences within various distances from the lakeshores. Gatz and Changnon (1976) considered lake-induced visibility restrictions due to enhanced condensation on hygroscopic nuclei to be confined to within 10 kilometers (km) of the lake. Scott and Grosh (1979) found a tendency for pre-existing afternoon cloud cover in summer (cloudy or clear) to be adverted over the land/lake boundaries for distances up to 40 km. Braham and Dungey (1984) used a 40-km wide band to estimate the effects of Lake Michigan on winter snowfall. Lyons (1966) described the effects of a lake breeze on a squall line 80 km inland from Lake Michigan. Strommen and Harman (1978) tracked lake-effect snows 65 km inland from the Michigan shore.

From these studies and other considerations based on long-term climatic data and air mass and storm characteristics, an 80-km wide band around the lakes was selected as the basic study region. This area should encompass most lake-effects on climate detectable within the conditions studied and data sets available. Although specific events such as long-lasting lake breezes often travel much further inland, these events do not occur with sufficient frequency to appear in the climatic record. In addition, the use of a wider zone to the east of the Great Lakes would encounter topographical influences, confounding results designed to measure effects due solely to the lakes. Coincidentally, the 80-km limit very nearly encompasses the entire basin.

Surrounding this band, a relatively large region was used to provide a measure of the spatial pattern characteristics well beyond the lake-effect region. This "buffer" zone around the basin extended for approximately 300 km, beyond the lake-effect areas except for only about 100 km in Pennsylvania and New York where the effects of topography on climatic elements become important and complicate the analysis.

All data were averaged by season (winter: December, January, and February, etc.), and a computer plotting routine was developed to map and display the data. Two maps were generated for each element. The first included data from all sites and thereby established a spatial distribution pattern for each element over the Great Lakes basin and the surrounding areas by season. A second map was constructed by eliminating all stations within the 80-km lake-effect band, which resulted in a pattern across the basin derived from the unaffected buffer region only: "no lake effect." A difference chart was generated by comparing the two maps and using graphical subtraction. The resulting analysis was attributed to the "lake effect" within the basin.

Adequate documentation of the variability of the above parameters across the Great Lakes basin due solely to lake effects is complex because much of the basin is devoid of observational data: water covers approximately 35 percent of the region. Unfortunately, quality, high-resolution, long-term climate data does not exist for much of the land area, especially in sparsely populated regions north of Lake Huron and surrounding a considerable part of Lake Superior. Therefore, isopleths over water and sparsely sited land areas were subject to interpretation error.

In some cases, patterns over the lakes in areas devoid of data were drawn with the assistance of patterns elsewhere that had more shoreline observation sites. For example, if a well-defined pattern over and around Lake Michigan appeared to fit with the few shoreline data sites around Lake Superior, the pattern over Superior was drawn accordingly. This assumes that the two lakes exert similar influence on the particular parameter being drawn. In addition, prior research has provided some useful guidance in pattern estimation. As stated earlier, Phillips (1972), Wylie and Young (1979), and Braham and Dungey (1995) reported research showing rapid modification of surface airflows over Lakes Ontario and Michigan. Thus, taking into consideration the prevailing seasonal wind, analyses in the current research were drawn to reflect a relatively rapid change in weather conditions on the windward side of the lakes.

Analytical difficulties are not limited to poor data coverage. A substantial change in topography around the basin has equally large effects. Air approaching the Great Lakes from the west is usually continental polar. It moves off the vast, relatively flat croplands of the North American prairies, bringing defining characteristics that are relatively homogeneous and typically cool and dry. Thus, the influence on the atmosphere induced by the Great Lakes is likely the first major change experienced by the air mass in quite some time or distance.

East of the Great Lakes the terrain rises abruptly into the rolling hills of the Appalachian Mountains, quickly terminating the investigation of lake-only influences. Petterssen and Calabrese (1959), Wilson (1977), and Strommen and Harman (1978) have documented strong terrain effects in the climate data, especially east of Lake Ontario. Estoque and Gross (1981) used numerical simulations to document the effects of terrain variations on geopotential height and found a vertical change of 100 meters (m) over a horizontal distance of 10 kilometers (km), a situation similar to what actually exists around Lake Ontario. They speculated that these effects on regional wind fields are large enough to redirect the wind flows. Hjelmfelt (1988) has produced numerical results showing the importance of topography east of Lake Michigan during wintertime snowstorms. Thus, isopleth construction of weather conditions in areas adjacent to the basin (essential for an accurate depiction of no lake effect), was made more difficult as the hilly terrain creates its own effect on air masses.

Furthermore, there are complications with the data. During the analysis of wintertime precipitation, it became apparent that along the common border between Canada and the United States, precipitation totals at Canadian sites were higher by 25 to 40 percent than totals at U.S. sites. Other seasons displayed no such trend, however. Barring unknown local effects, it is suggested that this apparent discrepancy results from the method of quantifying snow as melted precipitation, a different process in the two countries (Bailey and Grainger, 1977). From personal communications with State Climatologists and Cooperative Observer Supervisors in the Midwest, it appears that most NWS Cooperative Observers measure precipitation during snow events by melting the amount of snow collected in the standard 8-inch raingage. According to officials at the Atmospheric Environmental Service, the method used by most Canadian Cooperative Observers take sample depths of new snow on the ground and divide by 10 (that is, observers use a 10-to-l ratio of snowfall to liquid precipitation). Observations made at the few first-order stations of the United States vary from use of Alter shielded or unshielded (either standard 8-inch or weighing bucket) gages to making a surface depth measurement adjusted by a moisture content factor based on temperature. Most Canadian observers at primary stations melt the snowfall catch of a Nipher shielded gage.

In general, the quality of snowfall measurements is poor. Quantitative problems are associated with the occurrence of snow concurrent with moderate to strong surface winds that tend to direct snow around and/or over many types of gages. Even in open areas, strong winds force snow to accumulate more in ground depressions or behind exposed taller objects, leaving smaller than accurate sample across the general terrain. Numerous previous researchers have documented the difficulties of measuring wintertime solid precipitation, most recently Groisman and Legates (1994). Larson (1971a) presented a summary of articles, all indicating that in general gage catch is reduced considerably with increasing wind speeds. For example, Larson (1971b) found that at wind speeds of 5.5 ms, an unshielded gage would catch between one-third to one-half of the actual snowfall while shielded gages would catch from two-thirds to three-fourths of the actual amount. Warnick (1956) found unshielded gage deficiencies as high as 80 percent with high wind speeds. Groisman and Legates (1994) extended the problem to wind-driven rainfall as well. Thus, as Bolsenga (1977) summarized, these deficiencies substantially obscure small lake versus land differences in precipitation.

These and other studies relate gage deficiencies to "ground truth." As stated above, it is well established that unshielded gages largely underestimate melted precipitation totals. Likewise, a straight 10-to-l ratio depth measurement is arguably too moist of an estimate during periods of moderately dry snowfall (a likely frequent occurrence in Canadian winters), resulting in an overestimate of actual precipitation. Thus, comparison of wintertime precipitation totals across the

U.S. - Canadian border was complicated. Because the current research considered only the changes in climatic parameters induced by the Great Lakes, the wintertime precipitation charts were analyzed separately across the United States and Canada, and only the lake-effect changes were combined. In general, isopleths drawn approximately matched amounts on the U.S. side with values 25 percent higher in Canada.

## ANALYSIS

### *Precipitation*

The following series of precipitation maps contains isohyets for every 25 millimeters (mm; approximately 1 inch). In the charts constructed with all available data, dashed lines over the lakes indicate that the analyses in these areas represent only a best approximation of the actual condition.

**Winter.** Figure la shows the total precipitation pattern for winter (which includes lake-induced effects) for the Great Lakes basin and the surrounding region. Dots indicate precipitation site locations. As stated earlier, data across Canada and the United States were analyzed separately for this season only; isohyet values in parentheses are for Canada.

A general trend of precipitation increase exists from northwest to southeast across the entire area. However, the influence of the lakes appears quite evident as large centers of precipitation over and adjacent to all lakes. The largest centers are found over central and eastern sections of Lake Superior and along the eastern shores and adjacent inland areas of Lakes Huron, Erie, and Ontario. A less pronounced maximum center is indicated along the eastern shore of Lake Michigan.

The pattern over Lake Michigan is similar to that developed by Gatz and Changnon (1976), in a report based on 1931-1965 data over Lake Michigan and adjacent land areas. All major maxima and minima features are present in both studies, but some differences in magnitude exist. Gatz and Changnon placed a center of maximum precipitation in northern Michigan, well west of the location of a similar feature in the current study, with a magnitude about 10 percent higher. Both studies show similar patterns inland from the eastern Lake Michigan shore, but the current study reports slightly greater precipitation amounts. These differences are within natural variability caused by the different temporal domains of the two studies.

The analysis over Lake Michigan in the two studies differed. Gatz and Changnon placed isohyets in a tighter gradient in the eastern part of the lake, while isolines in the current study are spread further west. This reflects the results from Phillips (1972), Wylie and Young (1979), and Braham and Dungey (1995), who revealed a rapid modification in air masses moving over the lake.

There is also good broad pattern agreement with Wilson's (1977) one-year study over Lake Ontario. Although specific differences occur due to differences in site locations between the studies, both show: 1) increases in precipitation over western parts of the area due to Lake Erie and over eastern Lake Ontario due to the lake itself, and 2) the enhanced influence from the rise in elevation east of the lake. Both studies indicate precipitation decreases to the south and northwest of Lake Ontario. Differences in magnitude are not comparable since Wilson's study was for just one winter season that also included November and March.

Figure lb shows the estimated spatial pattern when data for stations in the potential lake-effect areas are eliminated within the 80-km buffer zone around the lakes. The relatively smooth increase in precipitation from the northwest to southeast shows none of the local high centers seen in figure la. Westward shifts of the 75-mm and 100-mm isopleths over Wisconsin and the Upper Peninsula of Michigan may suggest a continued lake effect outside the 80-km band around the lakes. The region of maximum precipitation in southwestern Quebec is likely terrain-induced, as are patterns just east of the basin in New York and Pennsylvania. A large portion of the lake effects appear to have been removed, however.

Figure lc shows differences between the location and magnitude of lake effects for the patterns presented in figures la and lb. A large center of precipitation is located in the eastern portion of Lake Superior, and it extends over land areas east of the lake. The increase, which reaches 125 mm, corresponds to a percentage increase slightly greater than 100 percent of the no lake-effect value in figure lb. Similar increases, but smaller in areal coverage, exist over and east of Lake Huron, maximizing at 90 percent wetter just east of the southern part of the lake, but with a more general increase of 60 percent. Increased precipitation also is observed east of Lakes Ontario and Erie but is quickly influenced topographically and becomes difficult to separate by cause. A general 25 percent increase due to lake effects appears likely in these areas, maximizing at near 40 percent on the extreme eastern ends of both lakes. Wilson (1977) found precipitation increases of approximately 25 percent associated with Lake Ontario, rising to more than 50 percent in regions of higher terrain just to the east.

A 50-mm increase found along the eastern shore of lower Michigan represents an increase of approximately 35 percent. Using data around Lake Michigan from 1901-1965, Changnon (1968) calculated a somewhat smaller increase of about 10 to 30 percent for this area, but he found a much higher increase (50 percent) in extreme northwestern Michigan where the current study indicates only about a 20 percent increase. Strommen and Harman (1978) found substantially greater snowfall in winter over northwestern Michigan that they attributed to a combination of lake effect and the 200-m rise in topography from the Lake Michigan shoreline to the hillier terrain toward the east.

The large local maximum over Lake Superior is likely related to a high frequency of arctic and polar fronts in winter, combined with a large deep lake and a surface area oriented west-east. Thus, a substantial portion of the lake surface seldom freezes, allowing for a long fetch of airflow over open water and, thus, a continuous strong influence of relatively warm, moist surface conditions. It is likely that this effect is also largely responsible for the maximum found just to the southeast of Lake Huron, whereas the narrow east-west width of Lake Michigan decreases the time available for moisture transfer, and therefore, resulting in a reduced climatic effect to its east.

**Spring.** Figure 2a shows total precipitation across the basin for spring (March, April, and May). In general, precipitation increases from north to south across the region; average seasonal values range from less than 125 mm in northwestern Minnesota to more than 275 mm across central portions of Illinois and Ohio. No exceptionally large high or low precipitation centers are evident, except for a local maximum over central New York, probably due to lake effect, in part, but with a substantial orographic influence as well. Small regions of precipitation maxima are scattered around the basin, the most prominent being along the eastern shore of Lake Superior. Rainfall minima are present over Lake Michigan and portions of Lakes Huron and Ontario, however, reflecting conditions typical of summer. As springtime land temperatures progressively warm at a rate faster than the lakes, temperatures over the water become cooler than those over the land, and a seasonal change in the lakes' influence on precipitation occurs. This initiates a trend towards temperature retardation over the lake.

These patterns also bear similarities to those of Gatz and Changnon (1976). Both studies indicate that Lake Michigan and northern Lake Huron cause a decrease in precipitation over the lake waters with minimum centers in northern parts of the lakes. The current study shows 5 to 10 percent greater precipitation in these areas. As before, the pattern differences between the two studies are small and result from natural variability and because different stations were used.

Figure 2b shows the estimated pattern for no lake effect. Pattern construction was complicated by the large variability of data on the southeast side of the basin, where orographic effects mix strongly with lake effects. In addition, there is a substantial change in the gradient of precipitation over the basin from west to east. The gradient is very ordered, running from northwest to southeast in the buffer region to the west. However, the gradient is poorly defined in the east. Thus, in placing the isopleths, great importance was given to the area outside the buffer area in central Michigan.

Figure 2c shows the resulting lake-effect map for spring. The 50-mm high just east of Lake Superior represents a 30 percent increase. Other small localized areas of increase exist over extreme northwestern Indiana and north central Lake Erie (and adjacent land areas), representing about a 10 percent change. A broad band of precipitation decrease of about 10 to 15 percent exists over most of Lake Michigan and parts of southern Lake Ontario. Changes over Lake Huron are less than 5 percent, being slightly negative in the central part of the lake and slightly positive on the northern and southern ends. Changnon (1968) found a small precipitation maximum just southeast of Lake Michigan similar in magnitude to the current study, but stretching further north along the Michigan shore. Likewise, his analysis showed a decrease in precipitation over most of the remainder of the lake.

<u>Summer.</u> Long-term summer precipitation patterns (figure 3a) show a general trend of higher precipitation in all directions away from the basin. Distinct minima of precipitation are seen over all lakes except Lake Erie, by far the shallowest of the Great Lakes. This lake warms faster; thus the air temperature above Lake Erie quickly approximates air over adjacent land. This reduces the negative effect a cooler lake surface would have on convective precipitation. Lake Superior again shows the largest area of lower rainfall; however, Lakes Huron and Ontario receive the lowest actual precipitation. The orientation of isolines around the southern end of Lake Michigan is perhaps indicative of high incidence of lake breezes and associated convective precipitation.

The Lake Michigan patterns parallel those of Gatz and Changnon (1976) quite well, although rainfall amounts in the current study are about 10 percent higher. Away from the lake, Gatz and Changnon observed higher precipitation over Wisconsin and less rainfall over eastern Lake Superior, values that generated a larger precipitation gradient over Michigan's Upper Peninsula than observed in the present study. Nevertheless, both studies suggest convergence of lake breezes between Lakes Superior and Michigan. Wilson (1977) also found lower precipitation over Lake Ontario to the western side of the lake rather than the eastern side in this study. The difference is likely due to his short (May-September) one-year study period. Wilson and the current report both show higher precipitation southeast and northwest of the lake.

The summer no-lake-effect map (figure 3b) suggests that some lake effect remains. The rainfall patterns outside the basin were quite variable but generally show higher rainfall towards the southwest, southeast, and northeast. It is possible that the cooling effect of the lakes and concomitant large- scale subsidence extends beyond the 80-km boundary. However, with no aggregate lake-effect analysis attempted, a no lake-effect pattern was hard to determine with great confidence.

The resulting lake-effect pattern (figure 3c) indicates less rainfall across all lakes during the summer. Maximum departures exceed 50 mm (about 20 percent) over north central Lake Huron, eastern Lake Ontario, and south central Lake Superior. Elsewhere, decreases total 25 mm, or about 10 percent, the only exception being essentially no change in rainfall over Lake Erie. An increase in rainfall is found well inland from the southeastern shores of Lake Erie (again likely enhanced topographically) and over far southern Ontario; the cause is unknown but perhaps due to interpretation error in the construction of figure 3b.

This general summertime lake-effect pattern has similar attributes to those described in Changnon (1968) and Lyons (1966), showing decreases in rainfall over Lake Michigan. In addition, results here agree with Augustine et al. (1994), who used a satellite-based rainfall estimation technique to find mean summer decreases on precipitation of 18, 14, and 32 percent over Lakes Michigan, Superior, and Huron, respectively. Changnon (1968), however, shows a 20 percent increase in rainfall over northern Michigan from the no lake effect that is not detected here. This results from part of that area being in the buffer zone of the current study, and therefore by definition, not being affected by te lake (the small maximum center in figure 3b). Changnon's 10 percent increase in rainfall over Michigan's Upper Peninsula due to converging lake breezes from Lakes Superior and Michigan was more substantial than was observed here.

**Autumn.** Figure 4a presents basin-wide precipitation for autumn (September-November), and the pattern reveals a trend back toward the wintertime pattern. Centers of maximum precipitation are found on the eastern sides of all lakes, most noticeably near Lakes Superior, Huron, and Erie. The larger maximum east of Lake Ontario is again likely due to topographic effects. A smaller, elongated maximum exists along the eastern side of Lake Michigan, consistent with maxima for the other lakes. A precipitation minimum appears over western Lake Ontario, with a trend for similar conditions on the western sides of the remaining lakes. This suggests that the zone of rapid lake modification seen in figure la and work cited earlier has not developed sufficiently in this season to be observed in the climatic data. Comparison of these results and those of Gatz and Changnon (1976) shows similarities in pattern orientation and magnitude in western Michigan. However, Gatz and Changnon show a region of minimum rainfall along the eastern border of Wisconsin 10 percent smaller in magnitude than obtained in the present study. Again, these differences are likely due to sampling vagaries between the two different periods of data. Determination of a no lake-effect pattern was difficult for autumn since there is a strong east-west gradient to the west of the lakes and a strong north-south gradient to the south just north of the Ohio valley (not shown). Thus, the resulting analysis (figure 4b) yields a fluctuating pattern across the central part of the study region. A larger extended area of analysis may have been useful for precipitation in both summer and autumn.

The lake-effect map (figure 4c) indicates that nearly all precipitation maxima shown in figure 4a are lake induced. The largest effect, just east of Lake Superior, is in excess of 100 mm, more than 50 percent greater than the value expected without the presence of the lakes. Increases of 15 to 25 percent exist east of Lakes Huron, Michigan, and Erie. A region of greater precipitation is observed over eastern Lake Ontario, totaling about 10 percent; oddly, a region of decreased precipitation is found over the western side of the lake. Changnon(1968) shows similar patterns of rainfall increases east of Lake Michigan, but indicates a much larger increase in northwestern lower Michigan (more than 40 percent), and decrease of 10 percent just west of Lake Michigan. These differences (as in summer) are likely due to natural variability, in part, but may also be related to the difficulty in obtaining a reliable no lake-effect seasonal pattern.

**Temperature**

Differences between the heat capacities of water and land cause substantial lake effects to occur in the mean seasonal temperatures of the region. In general, the Great Lakes produce a substantial moderation in temperatures by warming conditions during the cooler seasons and cooling the region in summer. Seasonal analyses conducted in this study indicate that the greatest influence from the lakes occurs on mean minimum temperatures in winter and on mean maximum temperatures in summer.

**Winter.** Figure 5a shows wintertime mean minimum temperatures along with site locations of all temperature analyses that follow. Data indicate a substantial increase in values from north to south across the region. Averages range from as low as -25 °C (north of Lake Superior) to -7°C (central Indiana). Superimposed on this pattern are warmer values over and southeast of each lake. Except for Lake Erie, tight gradients in temperature are drawn on the north shores of all lakes, based on findings of Phillips (1972) and others. Strongest gradients are observed over Lake Superior. Minimum temperatures are warmed in the mean by 6°C over a distance of about 40 km from the northwestern shore, with a total warming of 8°C across the lake. Similarly, warming of 4°C to 5°C exists along the northern shore of Lakes Huron and Ontario. Conditions over Lake Michigan display a latitudinal component due to the north-south orientation of the lake with a 3°C to 4°C west-to-east increase. The effect over Lake Erie is more minimal than that observed around the other lakes. The lake's smaller volume permits more rapid temperature modification, and its location just southeast of Lake Huron suggests that the air upstream has been greatly modified and are no longer as cold as the conditions upstream of the three larger lakes.

To the east of the Great Lakes, the rapid increase in elevation creates a strong influence on temperatures as occurred with precipitation. This increased the difficulty in the placement of no lake-effect isopleths in that region. Temperature patterns outside the 80-km band to the west of the lakes appear to be quite zonal, but they become rather variable just to the east. As these patterns are extended across the lake (figure 5b), the zonal nature of their orientation is maintained across most of the basin. The analysis over Lake Erie is viewed with less confidence than that over the remainder of the basin.

The resulting lake-effect pattern shows positive departures in mean minimum temperature for winter associated with each lake (figure 5c). Warming in excess of 8°C exists over south central Lake Superior, with a 6°C increase over all but the extreme western part of the lake. Likewise, northern Lake Michigan and central Lake Huron create a 4°C maximum increase while most of the balance of these lakes, plus Lake Ontario, cause a +2°C departure. The smaller and more southerly Lake Erie presents a +1°C change.

A small, 2°C negative mean minimum temperature departure is seen over southern Ontario, but the cause is unknown. This negative departure also appears in the isonomal analysis for January (Kopec, 1967). The region may be sufficiently away from adjacent lakes to be outside the region of lake influence. The center of the region is approximately 85 km from any lakeshore, and technically outside the 80-km buffer region selected for the study. However, considering the relatively small size of the area and the few weather stations it encompasses, the entire peninsula was defined as totally within the region of lake influence. Temperature departures observed here suggest this may have been an incorrect definition and that, at least for temperature, the 80-km boundary is potentially too large Nevertheless, some of the precipitation analyses suggested that the zone may be too small. Thus, to eliminate analytical bias and for consistency in the analysis, the 80-km buffer zone was retained.

Wintertime mean maximum temperatures likewise increase from north to south across the domain (figure 6a) but with considerably less range than was observed nocturnally. Temperatures north of Lake Superior average about -10°C, while those over central Illinois and Indiana are near 3°C. Diurnal heating raises temperatures in the far northern part of the region by an average of 15 °C but in the far south by an average of only 10°C. Bulges of warmer conditions are again quite visible over all lakes, but not nearly to the extent seen in figure 5a. The pattern across the domain as a whole is again quite zonal, especially in Canada, and with less variability over mountainous regions here than in the minimum temperature field.

This same observation is reflected in the no lake-effect analysis (figure 6b). Comparison of figures 6a and 6b confirms that maximum winter temperatures are also warmed by the lakes (figure 6c). These temperature departures are considerably smaller than those observed in rninimum temperature data; however, it is interesting to note that even during daylight hours, lake waters in winter exceed temperatures over the land. A 2°C increase occurs over parts of extreme western and southeastern Lake Superior and northern Lake Michigan, with a 1°C increase over most larger lakes and south central Lake Ontario. Lake Erie temperatures show essentially no change, while a small 1 °C negative departure is again present between Lakes Ontario and Huron.

Analyses in this research were performed on the components of daily temperature (mean minimum and mean maximum temperatures), but not on mean temperature directly. Comparison of figures 5c and 6c, however, suggests that maximum departures of mean temperature in winter approach +5°C over southern Lake Superior and exceed +3°C over nearly all of the lake. Mean positive departures of 2°C to 3°C exist over the northern portions of Lakes Huron and Michigan. Lake Ontario causes warming from 1°C to 2°C, while Lake Erie indicates just a slight positive temperature change. These seasonal data (December-February) are in reasonable agreement with Kopec (1967), who showed warming in January mean temperatures of 7°C over Lake Superior; 2°C to 3°C over Lakes Michigan, Huron, and Ontario; and 1°C to 2°C over eastern Lake Erie. Likewise, Gatz and Changnon (1976) revealed a +3°C lake-effect warming over northern Lake Michigan for January.

**Spring** Patterns of mean minimum temperatures in spring (March - May) parallel the wintertime findings; that is, the lakes continue to be warmer than land temperatures at night (figure 7a). Average minimum temperatures range from -8°C to 4°C across the domain. Strong temperature gradients observed over the northern shores of most lakes during winter are reduced in magnitude by about one-half in this season. An overall zonal pattern in the analysis continues to be apparent as a dominant feature; however, a cold pool seems to exist north of Lake Superior. The analysis could have benefitted from a larger domain of sites well away from the lakes to better define this pattern.

Mean temperatures outside the buffer zone define the nearly zonal no lake-effect pattern across the basin (figure 7b). Patterns east of the basin again make the analysis difficult to obtain with confidence. Comparison of these two maps yields the lake-effect analysis (figure 7c), which continues to show warmer conditions over the lakes than would be expected without their presence, but less departure than observed during winter. Lake Superior with its large heat capacity again provides the greatest warming, in excess of 3°C in the south, while most other lakes are only about 1°C warmer. Unexpected cooling of-2°C over the western part of Michigan's Upper Peninsula helps provide a tight temperature gradient with south central Lake Superior.

Springtime mean maximum temperatures (figure 8a) display a pattern different from that observed thus far. As the spring season progresses, the land with its lower heat capacity warms rapidly compared to adjacent water surfaces. This creates a lake-induced temperature variance opposite in sign from the winter daytime mean temperature. Largest gradients develop around Lakes Michigan and Huron, and along the southern shores of the remaining lakes. All waters are relatively cold still from the just ended winter months. Lesser gradients appear around northern lakeshores where the adjacent land areas have been slower to warm.

Analysis of the region surrounding the basin again shows the zonal pattern observed in most temperature analyses (figure 8b), facilitating construction of the no lake-effect pattern. However, mountainous regions east of the basin continue to have a noticeable effect. The resulting lake-effect analysis shows daytime maximum departures more than 4°C cooler over southern Lake Michigan, and in excess of 3°C over east-central Lake Huron and southwestern Lake Superior (figure 8c). All remaining lake areas and some adjacent land regions conditions cool at least 1°C.

Comparing figures 7c and 8c, lake cooling appears to dominate the springtime mean temperatures over Lakes Michigan, Huron, Erie, and western Superior, while those over Lake Ontario appears to create Utile temperature departure and those over eastern Lake Superior generates slight warming. Greatest cooling, -1°C to -2°C, is found over southern Lake Michigan. Gatz and Changnon (1976) showed a comparable temperature variation with cooling in the April mean temperature across central Lake Michigan of nearly 2°C. However, looking at April data alone, Kopec (1967) found water and land area temperatures across the Great Lakes to be essentially similar, i.e., no lake effect.

**Summer**: Mean minimum temperatures in summer (figure 9a) display the same pattern found for nocturnal conditions during winter and spring. That is, the effect of the Great Lakes on nighttime temperatures in summer is to continue to warm the overlying air. Although the temperature range across the map is only about 10°C, temperature gradients are observed along most lakeshores comparable to those in winter, about 3°C. Data over Lake Superior stand out as the primary exception: essentially no shoreline temperature differences exist, except in one small region of warming (3°C) in the south central lake area.

Cooler temperatures over rising terrain just east of the Great Lakes basin again reduce confidence in the placement of isotherms on the no lake-effect map (figure 9b). Elsewhere these values are fairly well-defined. Comparison of figures 9a and 9b confirms that mean minimum temperatures in summer are higher over the lakes (figure 9c). Greatest warming (in excess of 3°C) occurs over northern Lake Huron and on the western sides of Lakes Ontario and Erie. Temperatures at least 2°C warmer exist over the balance of these lakes, and in small areas in eastern Lake Michigan and extreme south central Lake Superior (although most of Superior shows essentially no change). Overall, these data indicate that in summer the diurnal warming of the smaller lakes and "protected" regions in northern Lake Huron and southern Lake Superior (east of the Keweenaw Peninsula) raises temperatures over the lake to values warmer than the nocturnal cooling of the land. Thus, this creates warmer mean minimum temperatures near the lakes. For the rest of Lake Superior, it is apparent that due to its large size (hence, slower warming) and more northerly location (less insolation) temperature over the lake more closely approximate nocturnal land temperatures.

Diurnal hearing increases summertime mean maximum temperatures over land to values well above those observed near lakeshores (figure 10a). Substantial cooling is indicated over all of the Great Lakes, but not outside the 80-km buffer region. As may be expected, coolest air over the lake and strongest gradients are found over the northern portions of the larger lakes where 3°C to 4°C gradients are common. The increase in temperatures from far north to far south across the study area is again small, only about 9°C. However, the coolest temperatures of the entire region are actually over the waters of northern Lake Superior.

The zonal nature of temperatures in the west was extended across the basin with little deviation and combined with the terrain-influenced surface analysis to the east (figure 10b). Comparison with figure 10a quantifies the overall cooling due to the lakes. The greatest departures in maximum mean temperatures occur over north central Lake Superior (-6°C). However, temperature decreases of at least -3°C are present over nearly all surface areas of Lakes Superior, Huron, and Michigan. Lakes Erie and Ontario show small changes (-2°C) due to their smaller water mass.

Combining figures 9c and 10c indicates that a -2°C to -3°C seasonal lake effect exists in mean temperature during summer over most of Lake Superior. Likewise, Lake Michigan appears to decrease mean temperature by about 1°C. However, over Lakes Huron, Ontario, and Erie, the positive departures in minimum temperature are nearly canceled by negative changes in maximum temperatures, yielding essentially no overall lake influence. Results compare well with prior studies. Kopec (1967) found departures in July mean temperatures of-4°C to -5°C over Lake Superior, and only small lake effects elsewhere (about -1°C). Similarly, Gatz and Changnon (1976) analyzed a general -1°C departure in July mean temperatures over most of Lake Michigan, -2°C over the extreme southern portion of the lake. Data for neither June nor August were included in either Kopec (1967) or Gatz and Changnon (1976).

**Autumn.** Autumn mean minimum temperatures show relatively warm conditions over all lakes (figure 11a) and, as with all other seasonal minimum temperatures, reveal lake-induced cooling, a trademark for this condition. The range of temperatures across the study area is small (about 8°C); the exceptionally cold arctic air masses of winter have yet to invade the region. Warmest temperatures occur over Lakes Michigan, Erie, and Ontario. Lakeshore gradients of 3°C to 4°C are present in many areas. Values over Lake Erie once again tend to more closely match those in adjacent land areas, and thus, show no gradients.

The general increase of temperatures from north to south easily define isotherms for the no-lake-effect map (figure 1 lb). Once again, the pattern is quite zonal and becomes complicated only in the hilly regions of Pennsylvania and New York. Comparison of this partem with that on figure 1 la reveals strong warming due to the lakes over the central portions of most lakes (figure 1 lc). This is created by the rapidly seasonal cooling of land surfaces adjacent to water areas. Departures in excess of+3°C are common over all lakes. Small regions of negative departure are limited to land areas in central lower Michigan and in far southern Ontario, again suggesting that the width of the 80-km buffer zone may need reconsideration.

Autumn mean maximum temperatures show patterns across the Great Lakes that appear to be rather zonal, implying virtually no-lake-effect (figure 12a). Although the range of temperatures across the study area is about 12°C, approximately the same for this condition in winter, diurnal warming during autumn across the study area nearly equals lake water surface temperatures. The no-lake-effect map (figure 12b) shows this fact quite well, and this map appears very similar to figure 12a. Comparison of both maps (figure 12c) reveals only a small region of warming (1°C) over western Lake Huron and south central Lake Ontario, with all other lake regions showing no detectable change due to lake effects. Again, a small area of cooler temperatures (-3°C) exists over southern Ontario.

Mean temperatures for autumn (based on the average of figures lie and 12c) exhibit a 1°C to 2°C warming over all lakes. Kopec (1967) also found trends of lake warming in the October mean temperature, with warmest regions (3°C to 4°C) in eastern Lake Superior and northern Lake Michigan. In all other regions, he showed 1°C to 2°C increases. Gatz and Changnon (1976) suggested wanning of +2°C to +3°C in northern Michigan for October.

### *Cloud Cover*

Cloud cover measurements were taken from hourly data at selected stations across the United States and Canada. However, far fewer sites were available than for the precipitation and temperature analyses, resulting in a much reduced spatial resolution for the cloud cover analyses. Nevertheless, patterns of mean cloud cover were observed in some seasons. Since station spacing in over-land areas was separated now by distances similar to those across the lakes, use of dashed isolines over the lake on the "all data" maps was discontinued.

Average wintertime cloud cover, presented in tenths of the sky covered, is shown in figure 13 a. Station locations for this and all remaining conditions are superimposed. Lake influences apparently increased regional cloud cover across each lake from west to east or north to south, depending upon lake orientation. Isonephs are drawn close to the prevailing upwind lake shores in conjunction with earlier research that suggested a rather rapid modification of air moving over the lakes. Although in many areas, cloud data in support of these patterns was sparse, reliability was substantiated by applying the locations of isohyets in the precipitation analysis (figure 1a).

Cloud cover in excess of 7.5 tenths exists over all lakes and across much of the entire basin. Maximum coverage occurs along the eastern coastlines of Lakes Michigan and Huron where wintertime values exceed 8 tenths. This is a sharp increase in cloud cover compared with the 6.5 tenths observed in eastern Wisconsin. Although precipitation totals in central Michigan are comparable to amounts observed along the Wisconsin shore (figure 1a), the lack of climate stations with cloud observations prevents the determination of similar cloud cover levels between the two areas. However, lake-effect cloud cover should not revert to pre-lake conditions as quickly as precipitation since residual clouds remain after precipitation ends. Thus, cloud cover across Michigan was kept relatively high. The few existing sites in eastern sections of the state support this analysis.

Placement of isonephs in the no lake-effect analysis shows a general but slowly changing trend of increasing cloudiness from northwest to southeast across the domain (figure 13b). Maximum values occur just to the southeast of Lakes Erie and Ontario where the increase may suggest terrain enhancement of cloud cover in that area. The balance of the study area shows little lake-induced cloud cover. The resulting lake-effect map (figure 13c) indicates an increase in clouds over much of the central part of the basin by about one tenth (about 15 percent). The effect maximizes over extreme southeastern Lake Superior and northwestern lower Michigan (1.5 tenths, nearly 25 percent). Smaller lake effects of only 0.5 tenths increased cloud cover (~ 7 percent) exist over Lake Ontario and eastern Lake Erie.

These results are comparable to those reported in a study of the percentage of possible sunshine during winter across Lake Michigan (Changnon and Jones, 1972). They found a reduction of sunshine from west to east across the lake of 25 to 30 percent. Kristovich and Steve (1995) obtained similar results in a five-year study of daytime cloud generation over the lakes during cold months (October to March). Using visible satellite imagery, cloud formation in the region was termed lake induced: 30 percent of the time over Lake Superior and 16 percent of the time over Lake Erie. Unlike the present study, both of these studies excluded nighttime hours.

The analysis of cloudiness in spring (figure 14) revealed values across the region ranging from 5.8 to 6.8 tenths. However, no discernible partem of cloud cover was observed. Although more data sites would be beneficial, the current data suggest that any lake effect on cloud cover in this season is quite small.

Summertime cloud cover (figure 15a) shows a broad pattern of increasing cloudiness across the study area from 4.7 tenths coverage in Missouri to 6.7 tenths near James Bay, a range comparable to that found during winter. Cloudiness appears lower over the basin due to the increased stability imparted by the relatively cooler lake waters. The apparent reductions were most evident over northeastern Lake Huron and in extreme southeastern Lake Michigan. Overall, however, the pattern suggests that lake-induced reductions in summertime cloudiness are smaller than in winter, and the no-lake-effect map (figure 15b) is similar to figure 15a. Departures shown in figure 15c total 0.7 tenths over northern Lake Huron (about a 12 percent decrease) and about 9 percent less over southern Lake Michigan. Other researchers indicated a more substantial, albeit still limited, lake effect during summer. Scott and Grosh (1979) used hourly infrared satellite data to quantify substantial cloud reductions over Lake Michigan, but indicated similar conditions over adjacent land areas only when data were stratified by wind direction. Without stratification, cloudiness over the land areas on both west and east sides of the lake was essentially identical. Likewise, observations of lake breeze cloud reduction made by Lyons (1966) and others are substantial. However, these data basically measure a diurnal condition of the atmosphere and the cloud cover data identifying these events of average to negligible proportions in the climate record when coverage for all hours is included. These summertime cloud features are in opposition to lake-effect snow conditions in winter, which have no large diurnal tie and influence cloudiness 24 hours a day.

Mean cloud cover in autumn (figure 16a) ranges from less than 5.0 tenths in the southwest to more than 7.5 in the northeast. The pattern exhibits a general region of greater cloudiness over southern Canada and the central lakes' region; a maximum axis occurs along the eastern shores of Lake Michigan. A second region of greater cloudiness exists just southeast of Lakes Erie and Ontario, but with less cloudiness just to the north. The no lake effect isoneph pattern (figure 16b) removes the two regions of high cloudiness, leaving the balance of the study area with the same analysis. When compared to figure 16a, an 11 percent increase in cloud cover is found over north central Michigan along with a 5 percent increase southeast of Lakes Erie and Ontario. As in other seasons, these patterns are in general agreement with autumnal precipitation patterns in their respective regions.

***Vapor Pressure***

Strong latitudinal and seasonal differences are observed in average vapor pressure across the area. Wintertime values range from 1.5 mb near James Bay to 4.5 mb over southern Indiana and Ohio (figure 17a). In summer, higher temperatures and increased evapotransporation yield average vapor content amounts, ranging from 12.0 mb to 20.0 mb over the same region (figure 19a). These large-scale variations are, of course, directly related to the wide range in annual temperatures combined with the various and different source regions for air masses that influence the area. Nevertheless, lake influences are detectable.

Average vapor pressure in winter shows a zonal pattern across the region with a trend toward higher values over each of the Great Lakes (figure 17a). Data to determine vapor pressure trends downwind of Lakes Erie and Ontario were not available across Pennsylvania and New York. A northward bulge in the isopleths exists across the central part of the basin and defines the region of lake effects. In comparison with the no lake effect map (figure 17b), a large area of increase in vapor pressure (8 percent) is defined for the central portion of the basin, with largest departures (nearly 17 percent or 0.5 mb) over west central lower Michigan and central Lake Huron (figure 17c). A 14 percent increase is estimated over Lake Ontario. These observations are consistent with measurements of warmer lake-induced temperatures over the same areas (figures 5c and 6c). The strong warming over Lake Superior is not reflected in a concomitant rise in vapor pressure, perhaps due to a lack of sufficient data in the region. Additional sites may re-orient the analysis to a pattern more aligned with lakeshore boundaries shown prominently in the temperature analysis.

As expected, mean vapor pressure for spring increases across the area, due to seasonal warming (figure 18a). Increases are greater in the south and result in a larger vapor pressure gradient across the region than was observed in winter. Overall, the pattern across the basin remains quite zonal with just a slight indication of lower vapor pressure over Lake Superior. A largely temperature-driven, slower rise in values over such a large water body compared with land is not surprising, and the lag in vapor pressure increases over lake waters is expected. Therefore, the no-lake-effect map in figure 18b quite closely resembles figure 18a and results in a lake-effect map with very low magnitudes (figure 18c). Largest departures, just to the south of Lake Superior, are negative, but barely exceed 0.25 mb (about 4 percent). This is consistent with the slight cooling observed in this area in the springtime mean temperature analysis. The balance of the Great Lakes show lake influences on vapor pressure to be quite minimal or nonexistent.

Summertime patterns reveal the largest latitudinal change in vapor pressure for any season (figure 19a). Across the domain, values range from 12 mb in the northeast to more than 20 mb in the southwest. Tightest gradients occur just south of Lake Superior where the cooler water temperatures exert a negative effect on vapor pressure. A bulge of higher vapor pressure is observed, unexpectedly, over eastern Lake Huron. Elsewhere, the pattern across the study area is nearly zonal. The no-lake-effect map (figure 19b) presents a much more uniform set of isolines than was observed with the basin data included. The gentle dip in isolines over the basin suggests that the effects of the lakes may extend far from the basin. However, an analysis with a much larger domain than that used here may also reveal significant aggregate effects in control of the observed pattern instead of the implied local influences.

The resulting lake-effect map shows lower vapor pressure overlying all lakes except northern Lake Huron (figure 19c), with the maximum departure over southern Lake Superior and much of Michigan's Upper Peninsula. In these regions, vapor pressure is lower by more than 1 mb or about 8 percent. Decreases associated with the other lakes are about half as great. The higher vapor pressure over northern Lake Huron is small. These results parallel similar changes in mean temperatures (figures 9c and 10c), which also show large decreases over southern Lake Superior and northern Lake Michigan. The lack of a large decrease in vapor pressure over northern Lake Superior to match cooler temperatures may again be due to a lack of regional data.

Vapor pressure patterns across the Great Lakes basin in autumn (figure 20a) reflect cooler temperatures and indicate a trend back toward the conditions observed in winter. Values across the domain of the study area continue to be relatively high, ranging from 7.0 to 10.5 mb. Higher vapor pressures exist along the eastern side of Lakes Michigan and Huron with just a slight positive bulge over Lake Superior. Analysis of the buffer region outside the basin provides the expected zonal pattern over the area when lake effects are ignored (figure 20b), thereby quantitatively revealing the extent of the positive departures described in the all-data map. Lake-induced increases in vapor pressure exceed 0.5 mb over all of Lake Huron and central Lake Michigan (figure 20c). Values maximize over east central Lake Huron at 1.0 mb, a 12 percent increase. Elsewhere, lake effects are minimal. Again, results are consistent with the patterns observed in mean temperatures (figures 11e and 12c).

### *Wind Speed*

Of all the parameters evaluated in this study, surface wind speed presents the least amount of evidence for measurable lake effects on the climate of the Great Lakes basin. This is due, in part, to poor data quality. For example, wind speed data are accumulated differently than minimum temperature. In any given season, mean minimum temperature is an average of 92 daily values, a single value being the lowest temperature reading for each day. The average of wind speed, however, uses considerably more data by averaging hourly observations over a three-month period, 24 times as much. Clearly, if mean temperatures were obtained in the same manner as wind speed, little of the extremes presented earlier in the component analyses of minimum and maximum temperatures would have been detected.

Moreover, the density of long-term climate stations with wind data available to this investigation is insufficient to develop a quality isotach analysis, especially around the lakeshores. In addition, of all climate elements, wind speed is the most difficult to collect. The data have a strong sensitivity to site exposure; that is, nearby objects greatly influence the accuracy and representativeness of measurements. Furthermore, as a site's exposure changes over the years with construction of new buildings, growth or removal of adjacent flora, etc., wind flow past a station will be influenced. Even seasonal agriculture and the leaf cycle of deciduous trees have measurable effects on local winds (Hollinger et al., 1994). Due to the nature of the measurement, non-meteorological influences are typically much larger on wind than on other elements.

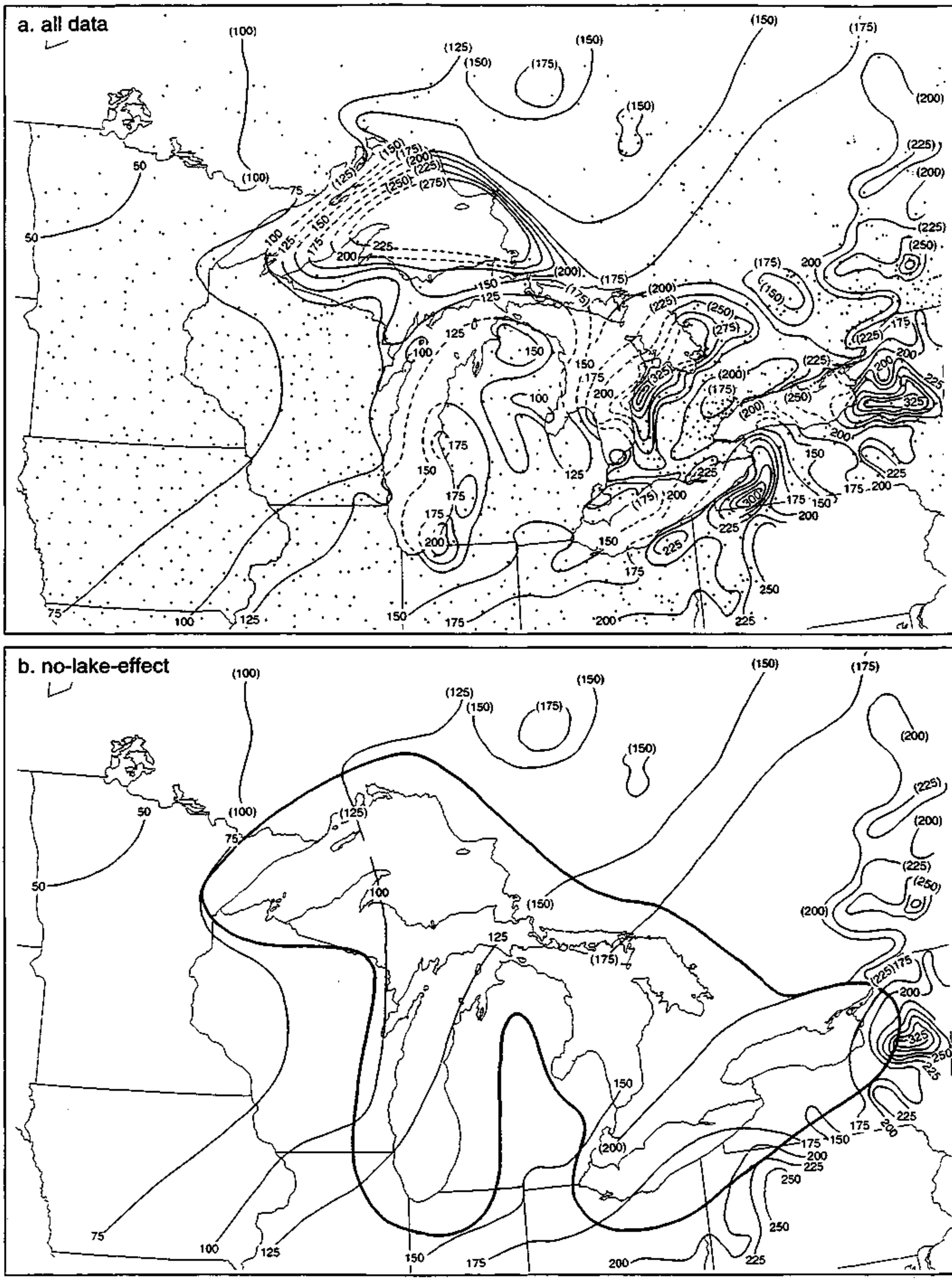
Wind speed analyses shown in figures 21a-d raise questions about proper exposure at several sites in this research. On each map major characteristics are present in the same areas and aligned with the same orientation. For example, wind speeds at Sudbury, Ontario, are always about 1.7 $ms^{-1}$ higher than at North Bay, Ontario, 100 km to the east. Similarly, centers of relatively high or low wind speeds consistently occur each season over areas well away from lake influences. These observations suggest that individual wind speed values are controlled by the siting of the instrumentation to the extent that small perturbations in the local climate cannot be measured.

If one assumes that exposure histories at most sites are reasonably constant and that instrumentation is maintained well (a reasonable assumptions but without verification here), the strongest lake effects on wind speeds are likely to occur during a lake breeze or land breeze phenomenon, a local thermal circulation created by land/lake surface temperature differences that alter the stability of the surface air mass by generating pressure-density solenoids. However, these are only occasional diurnal variations. In a two-year study, Comer and McKendry (1993) found lake breeze occurrence around Lake Ontario on just 30 percent of summer days. When these data are averaged hourly and seasonally, wind speed variations that were very prominent in the hourly observations become much less pronounced and often lost.

Reduction of surface friction in air moving from land to water surfaces also raises wind speeds over the lakes. Highest observed effects are expected near the predominant leeward shore. Hjelmfelt and Braham (1983) provide observational and numerical simulation indicating that the magnitude of wintertime wind speeds over the lakes could be at least twice those found over land. They also found a substantial frequency of the land breeze phenomena. However, these short-term phenomena were largely erased in averaged data.

In consideration of all of the above discussion, the following observations are made from figures 21-24. Relatively high wind speeds occur over Lakes Erie and Ontario, eastern Lake Huron, and to a lesser degree along the eastern Lake Michigan shoreline. In general, these higher wind speeds appear to extend away from the lakes further to the east than to the west. In fact, a strong gradient in wind speeds is revealed on the north (windward) shores of Lakes Erie and Ontario, and appear to be more developed in autumn and winter than in spring and summer. These results are all in general agreement with Hjelmfelt and Braham (1983).

Other judgments on the data are masked by the curious permanent location of maximum and minimum wind speed centers. Thus, a climatic lake-effect analysis of wind speed is not considered credible from these data. It is certainly not suggested that wind speeds are less affected by the lakes. Sousounis and Fritsch (1994) concluded that the locations of heavy snow events around the Great Lakes vary considerably due to the combined effects of the mesoscale system generating the snow bands, the synoptic-scale dynamics, and the lakes themselves within each event—all of which determine the local wind regime. Earlier citations by Lyons (1966) and others on lake breeze research can be used as verification of strong lake-influenced winds. However, from a climate perspective, wind speeds at sites around the lakes appear to average out in a manner similar to mean temperature and leave the primary control of wind speed observations within synoptic features.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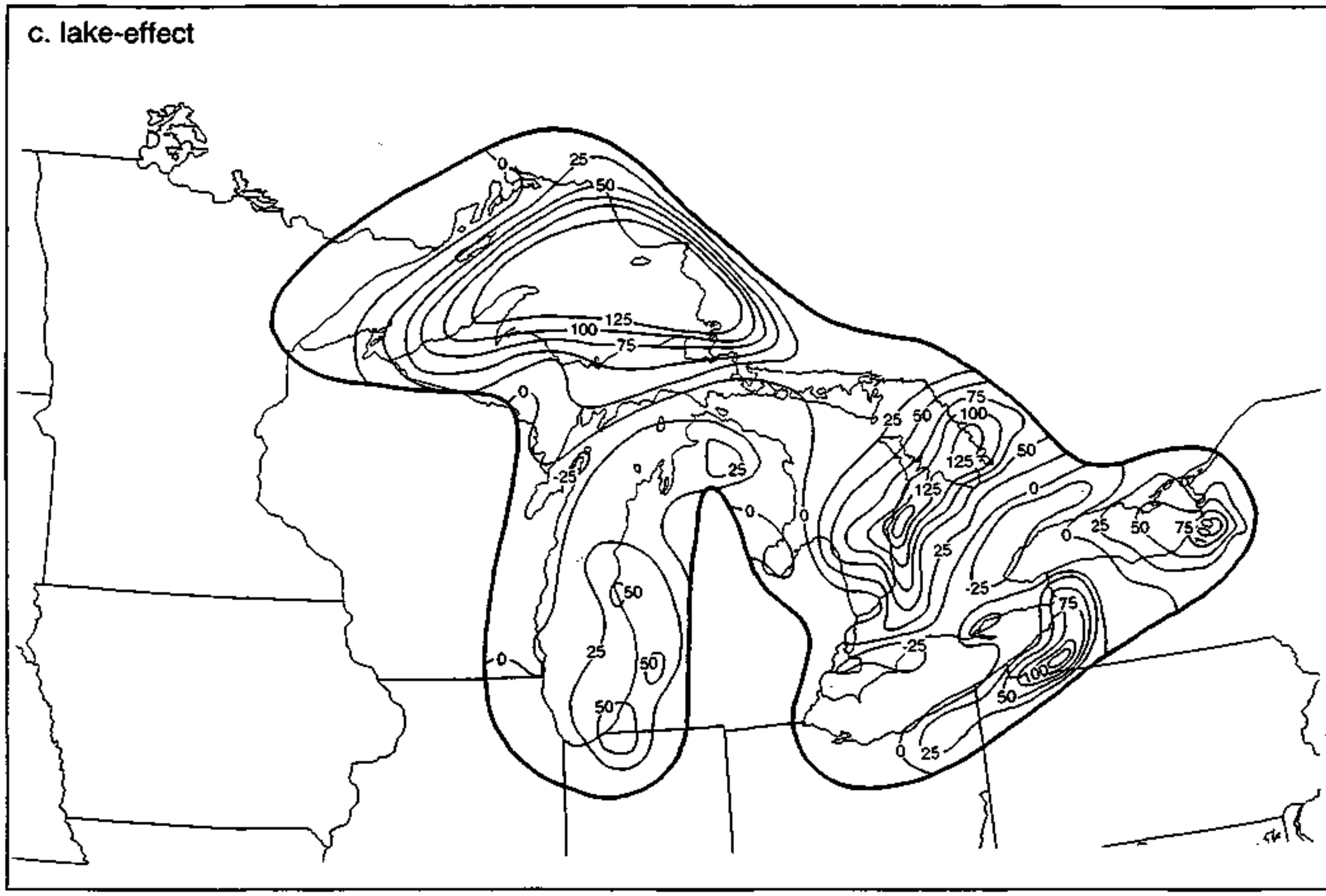
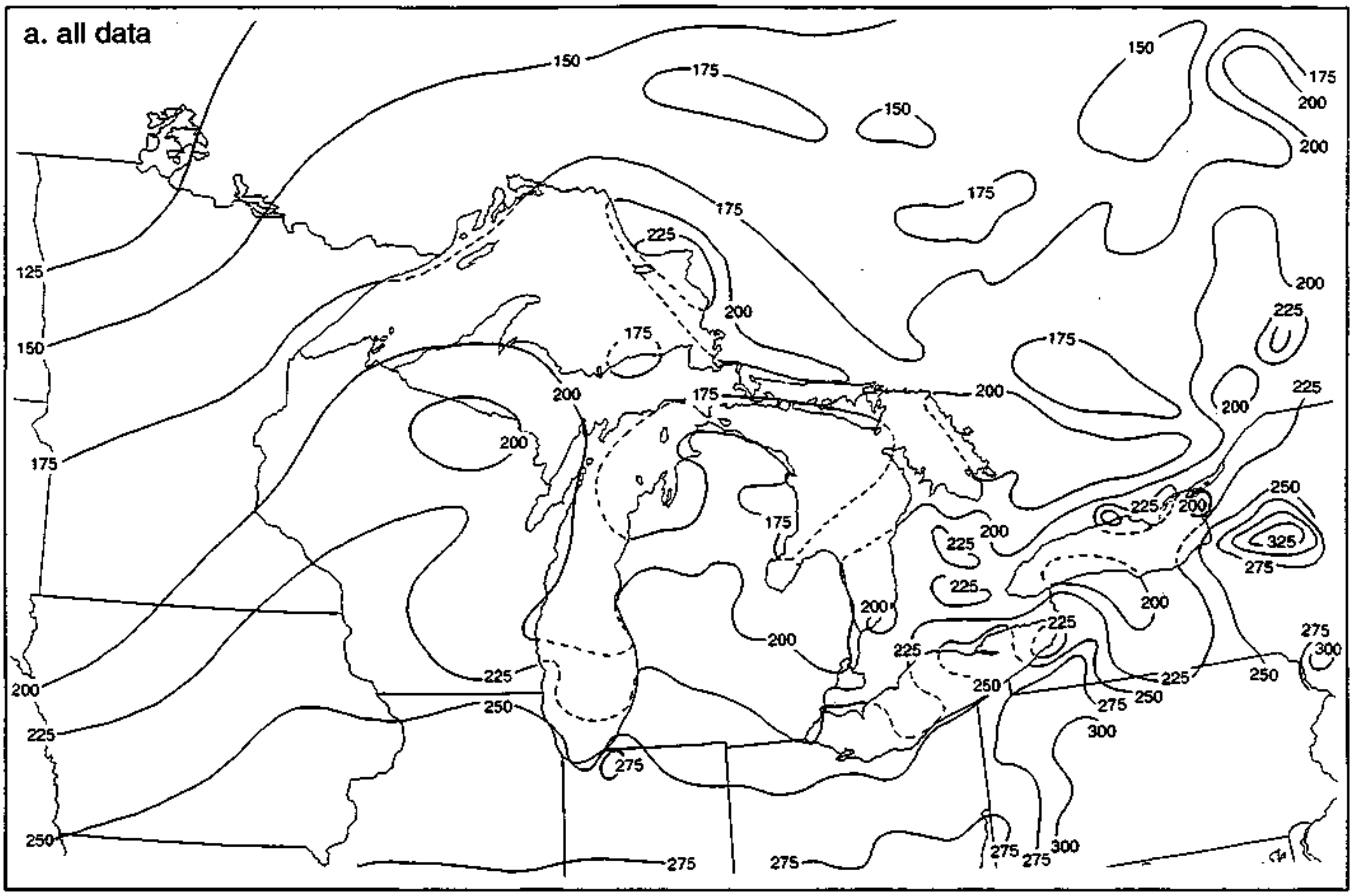



Figure 1. Average precipitation (millimeters) over the Great Lakes basin for winter: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. Dots (a) represent precipitation site locations for figures 1-4. The heavy line (b and c) represents the 80-km lake-effect boundary. Isoline values in parentheses (a and b) are for Canada.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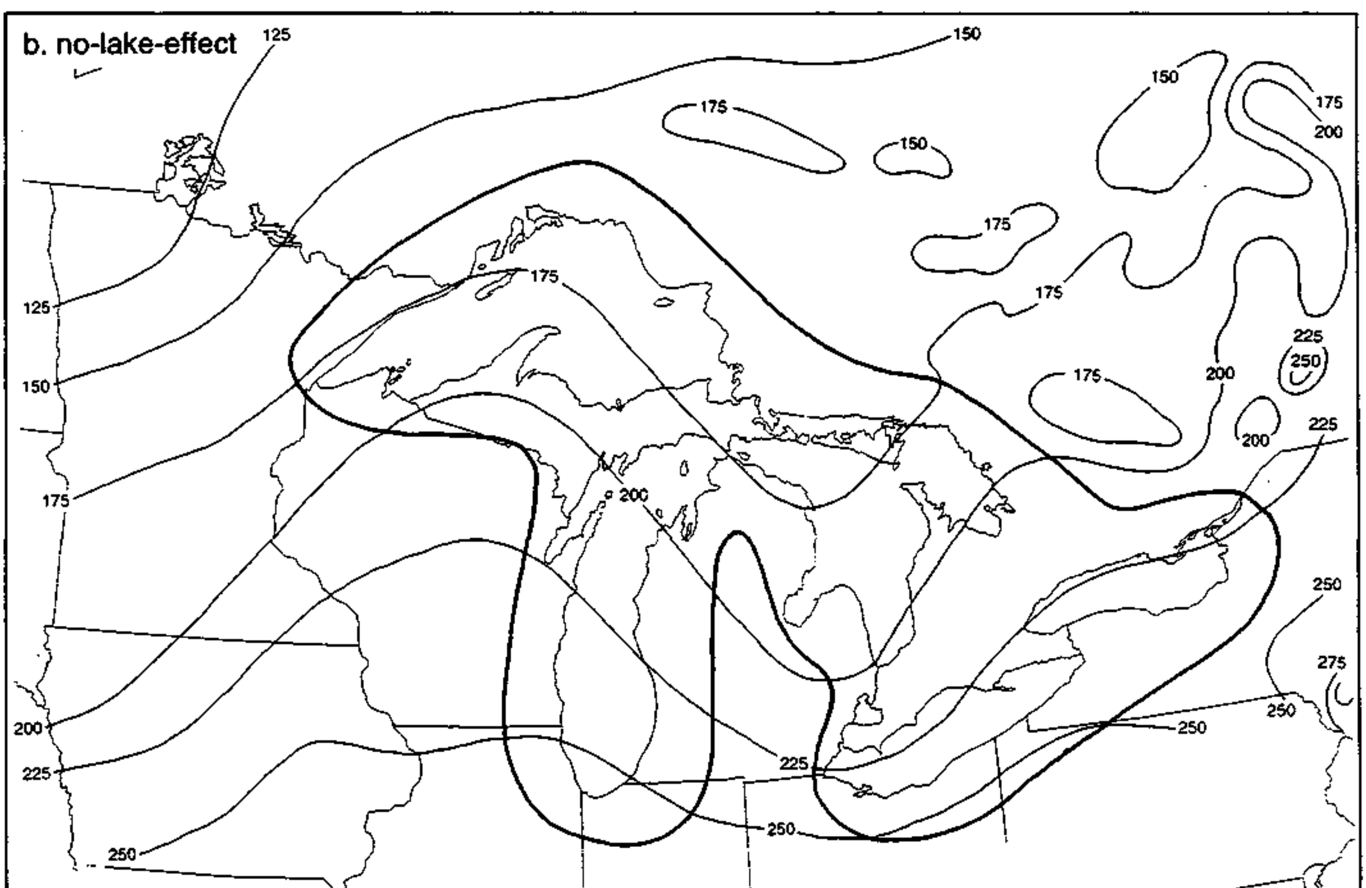
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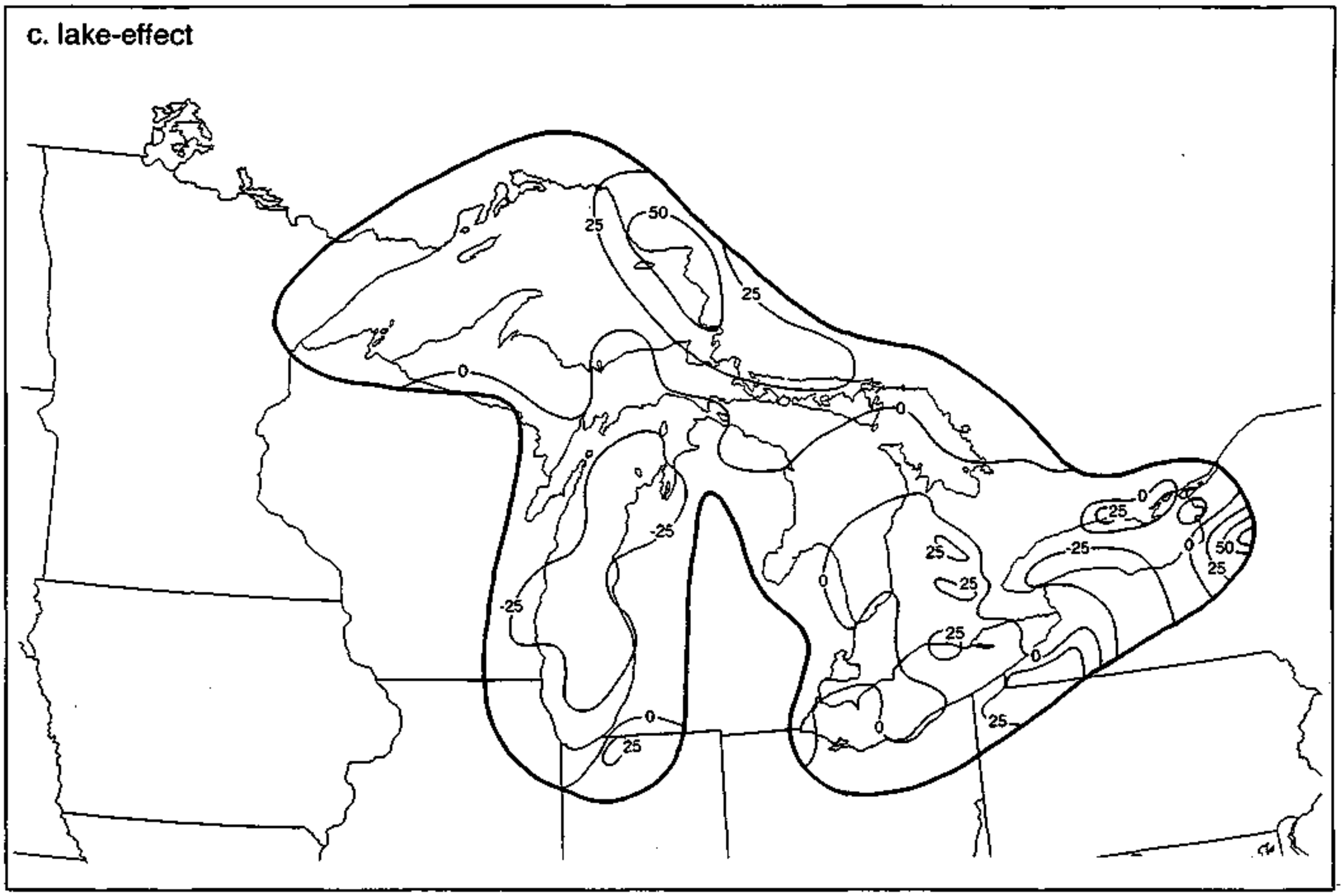
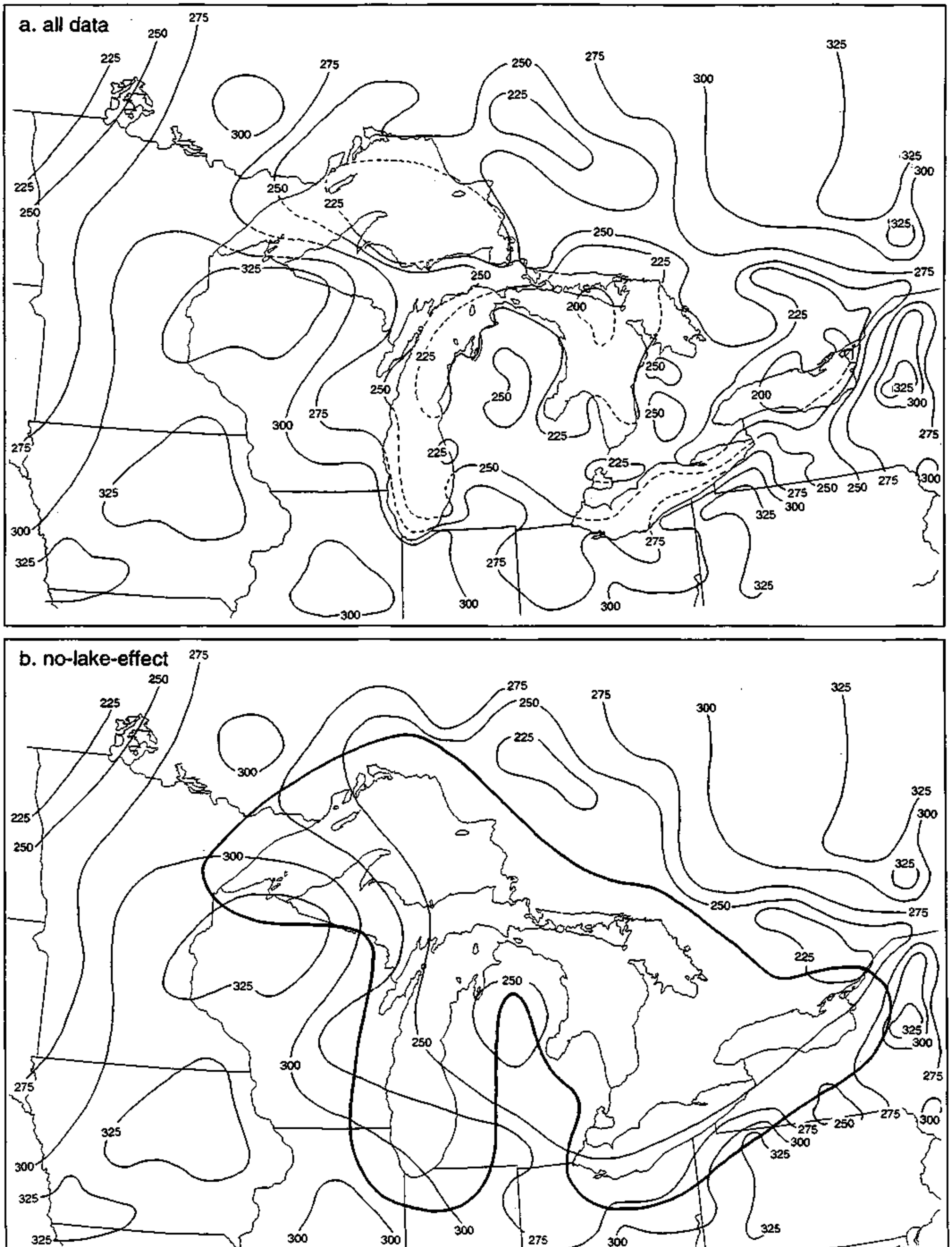



Figure 2. Average precipitation (millimeters) over the Great Lakes basin for spring: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the lake-effect boundary.


a. all data
b. no-lake-effect

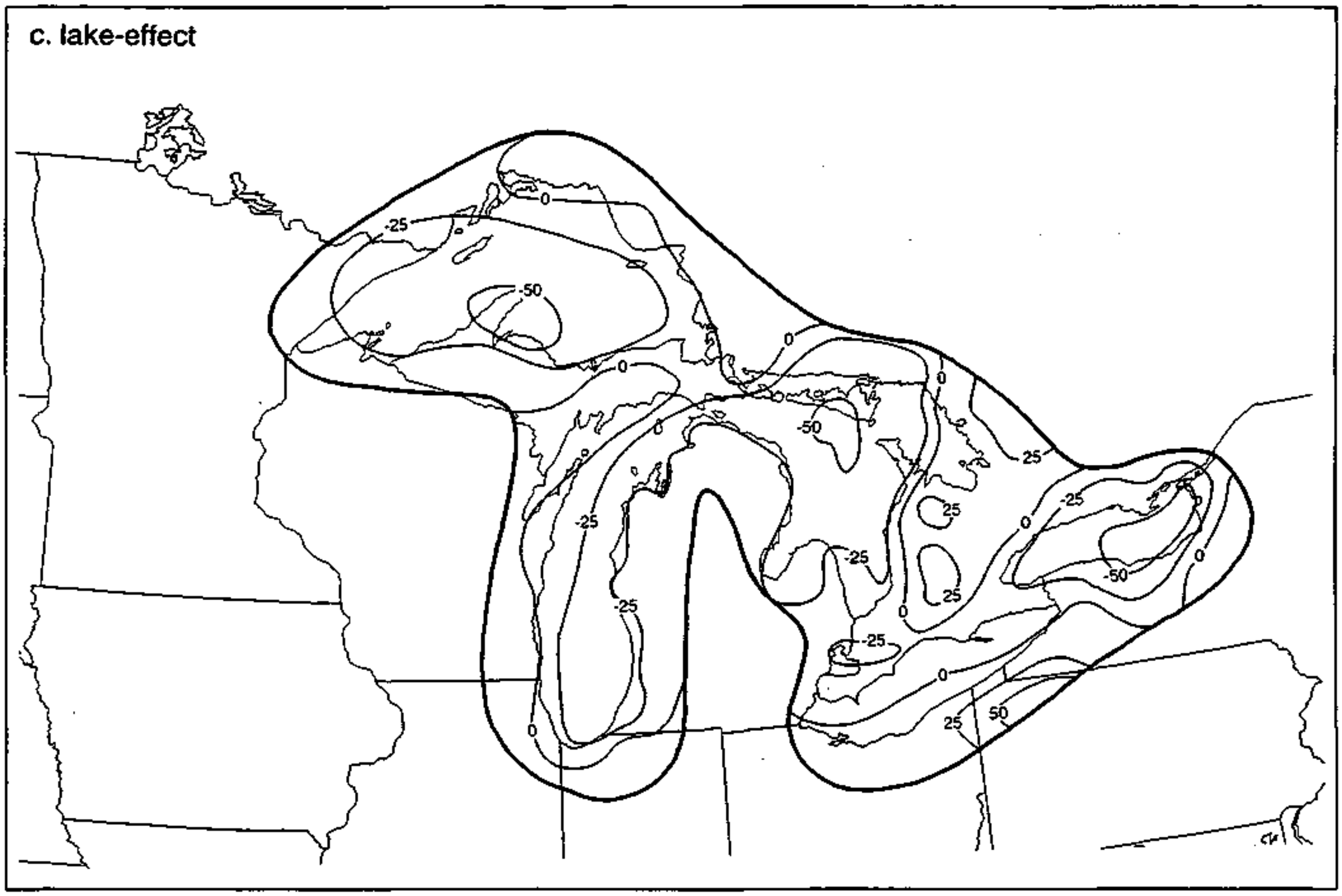
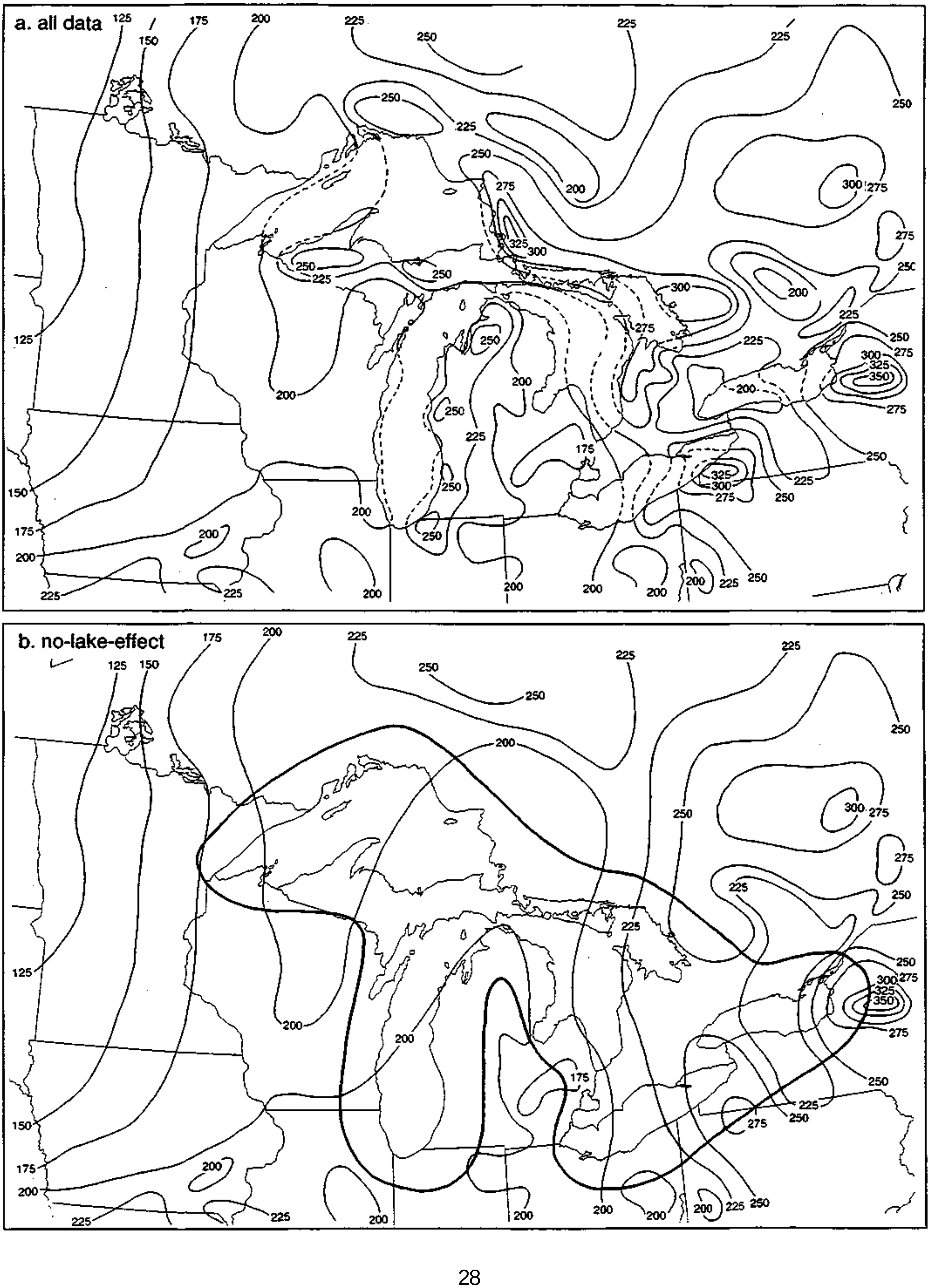



Figure 3. Average precipitation (millimeters) over the Great Lakes basin for summer: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the lake-effect boundary.


a. all data
b. no-lake-effect

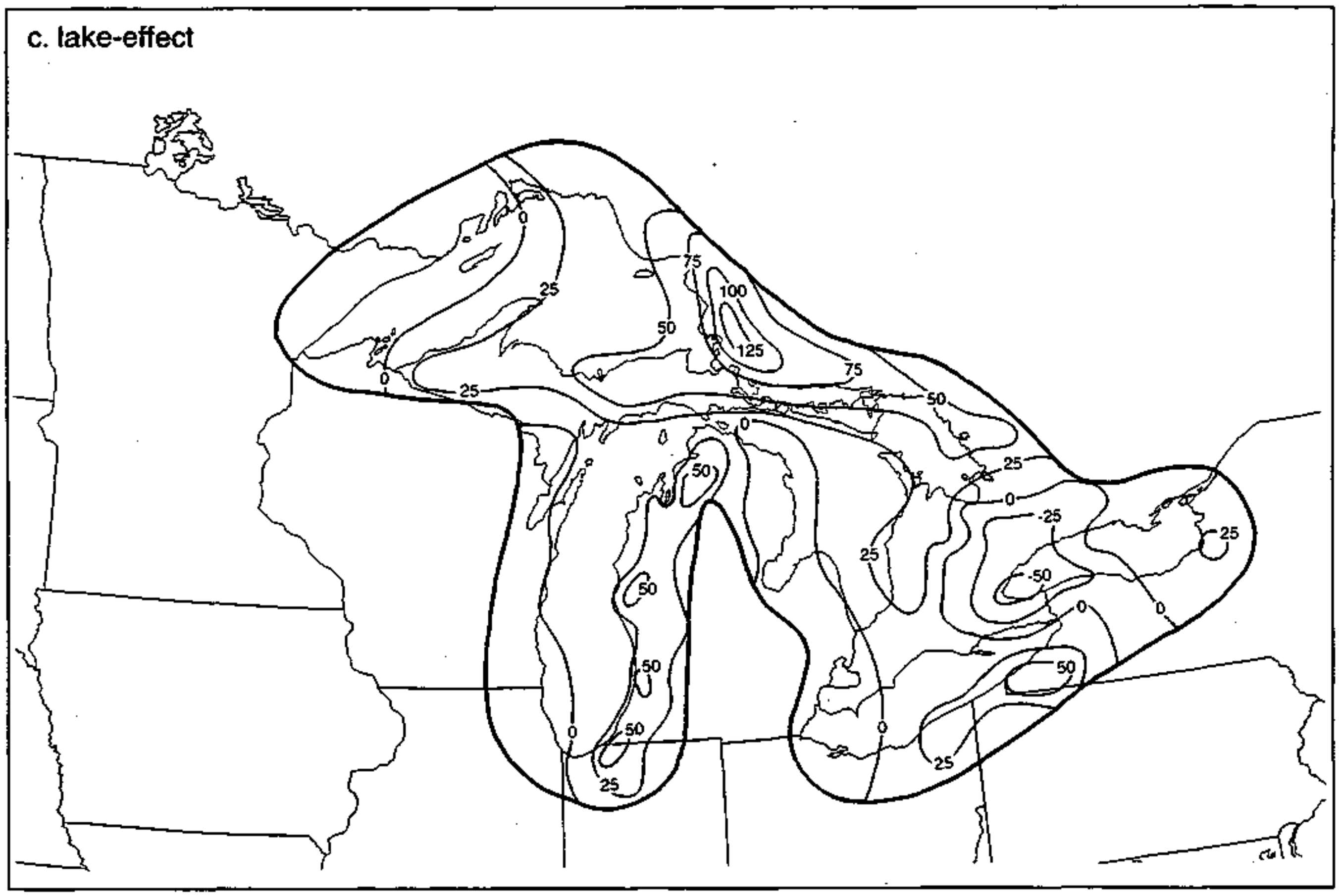
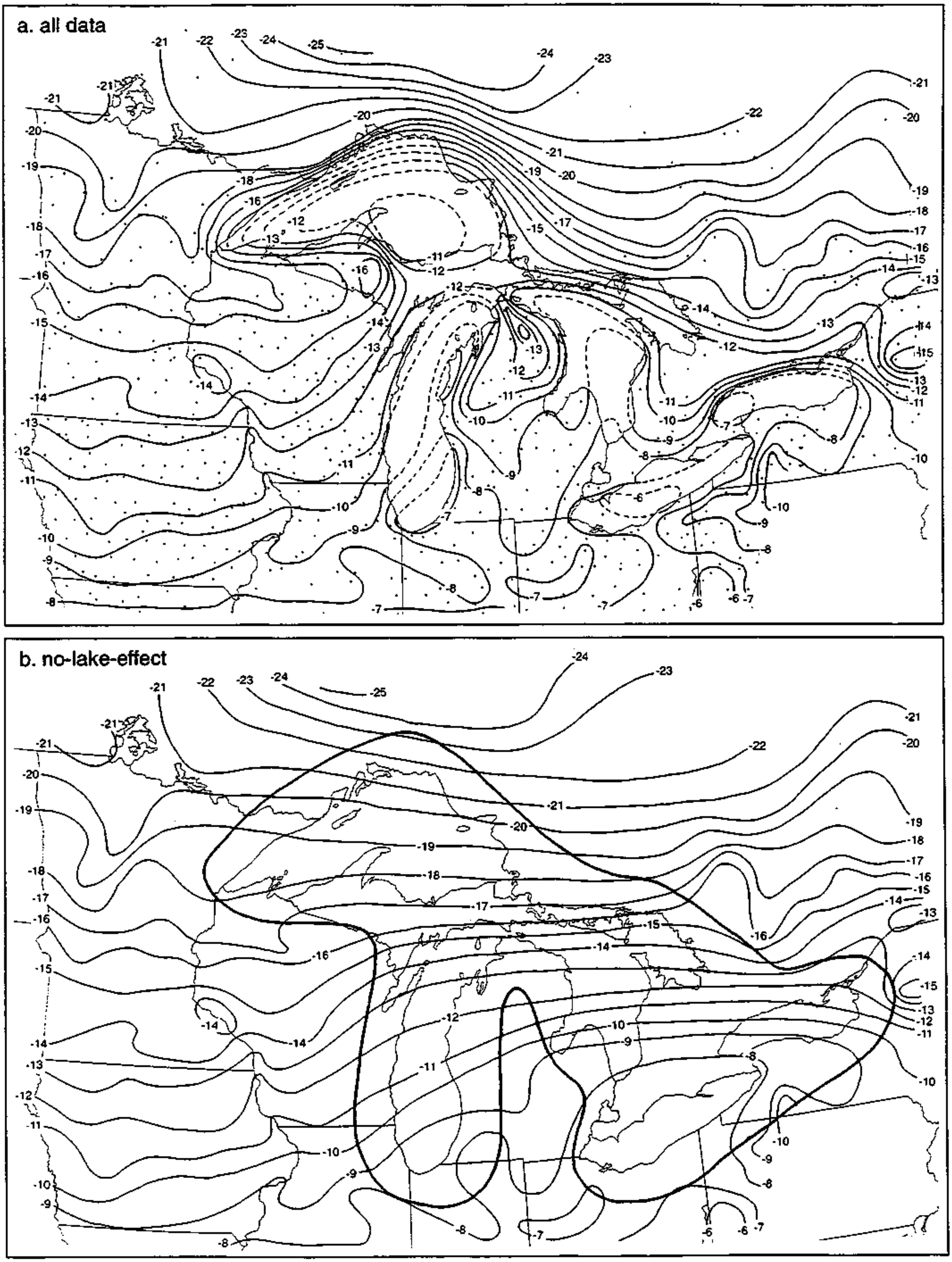



Figure 4. Average precipitation (millimeters) over the Great Lakes basin for autumn: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the lake-effect boundary.


a. all data
b. no-lake-effect

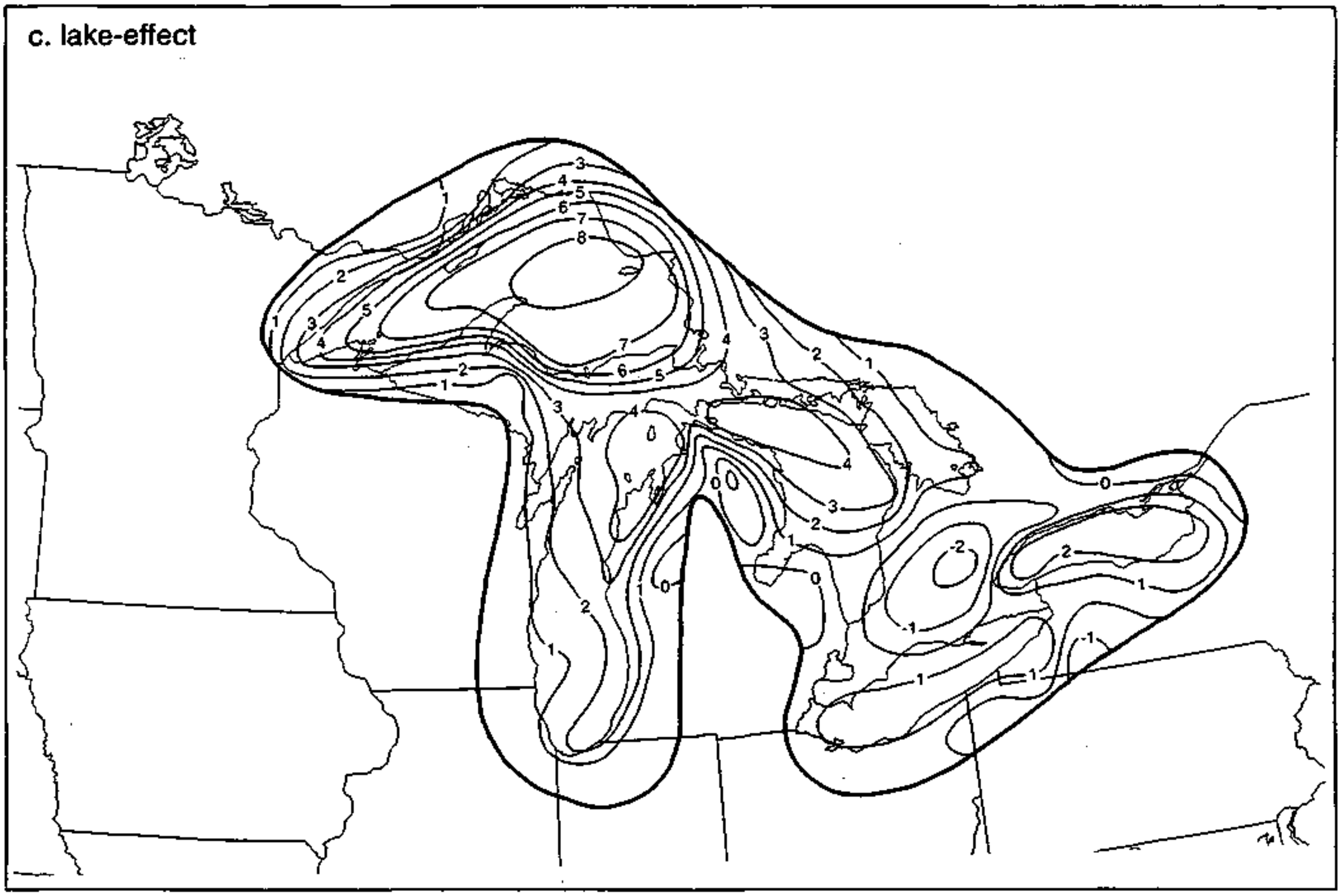
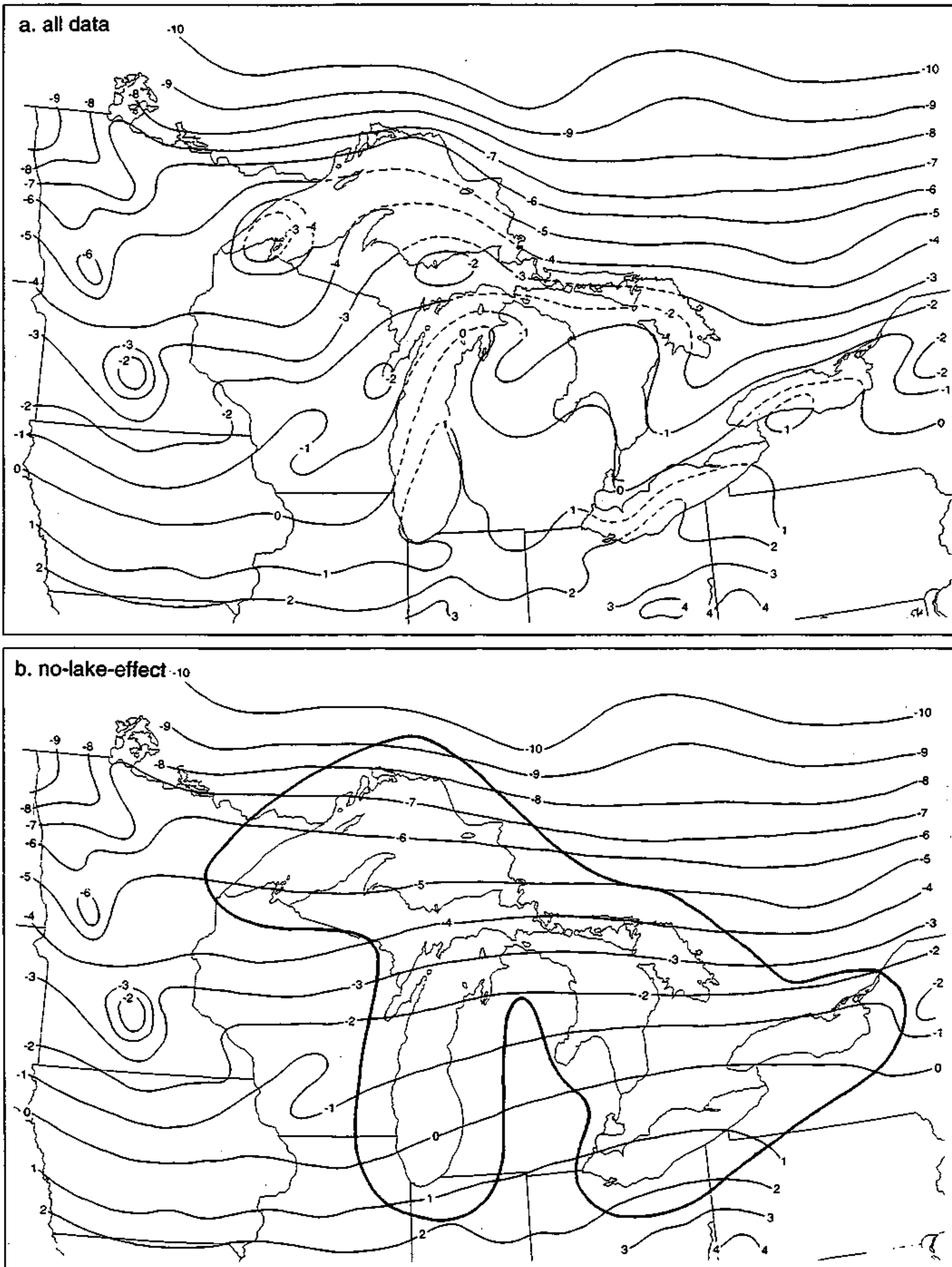



Figure 5. Average minimum temperature (°C) over the Great Lakes basin for winter: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. Dots (a) represent temperature site locations for figures 5-12. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

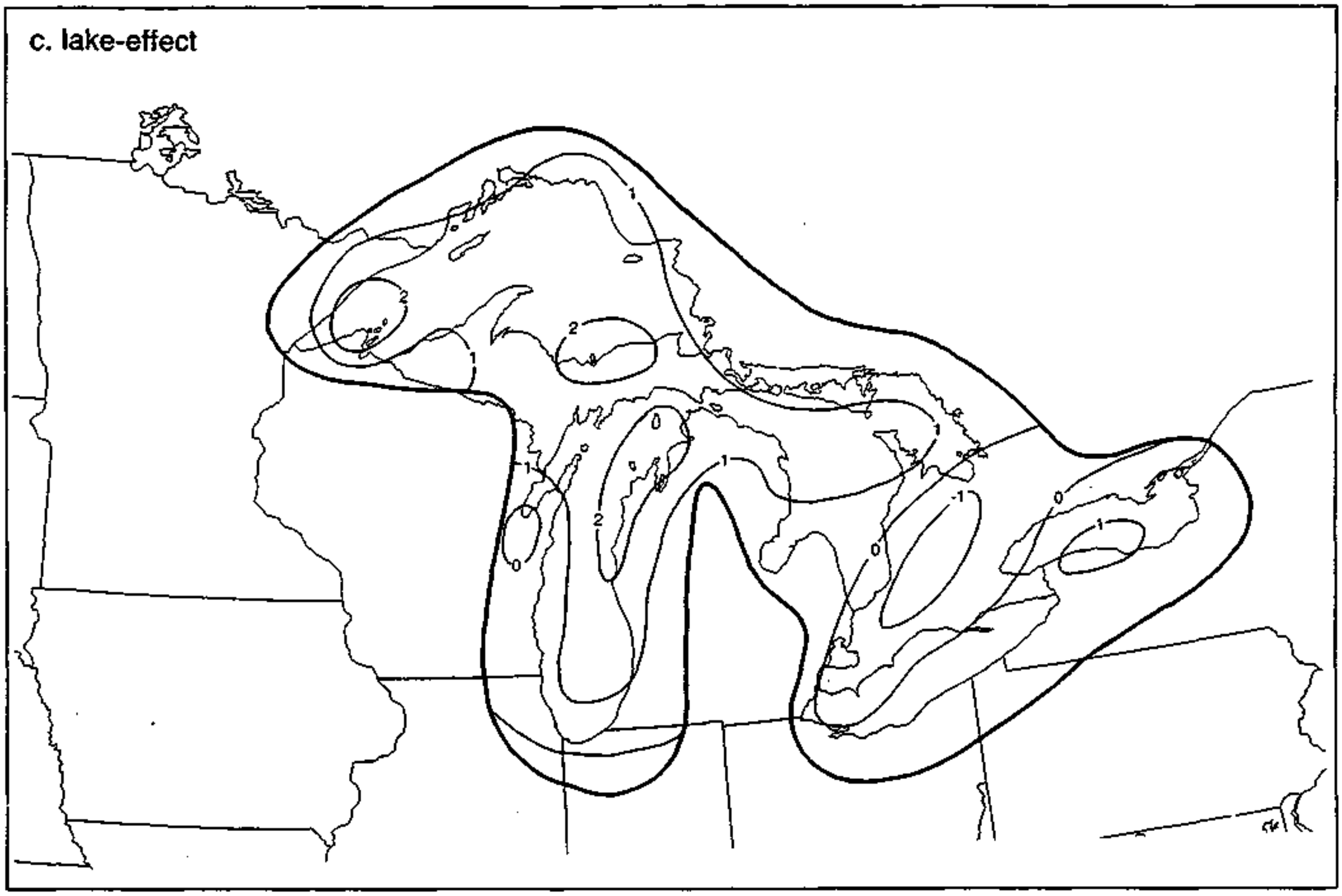
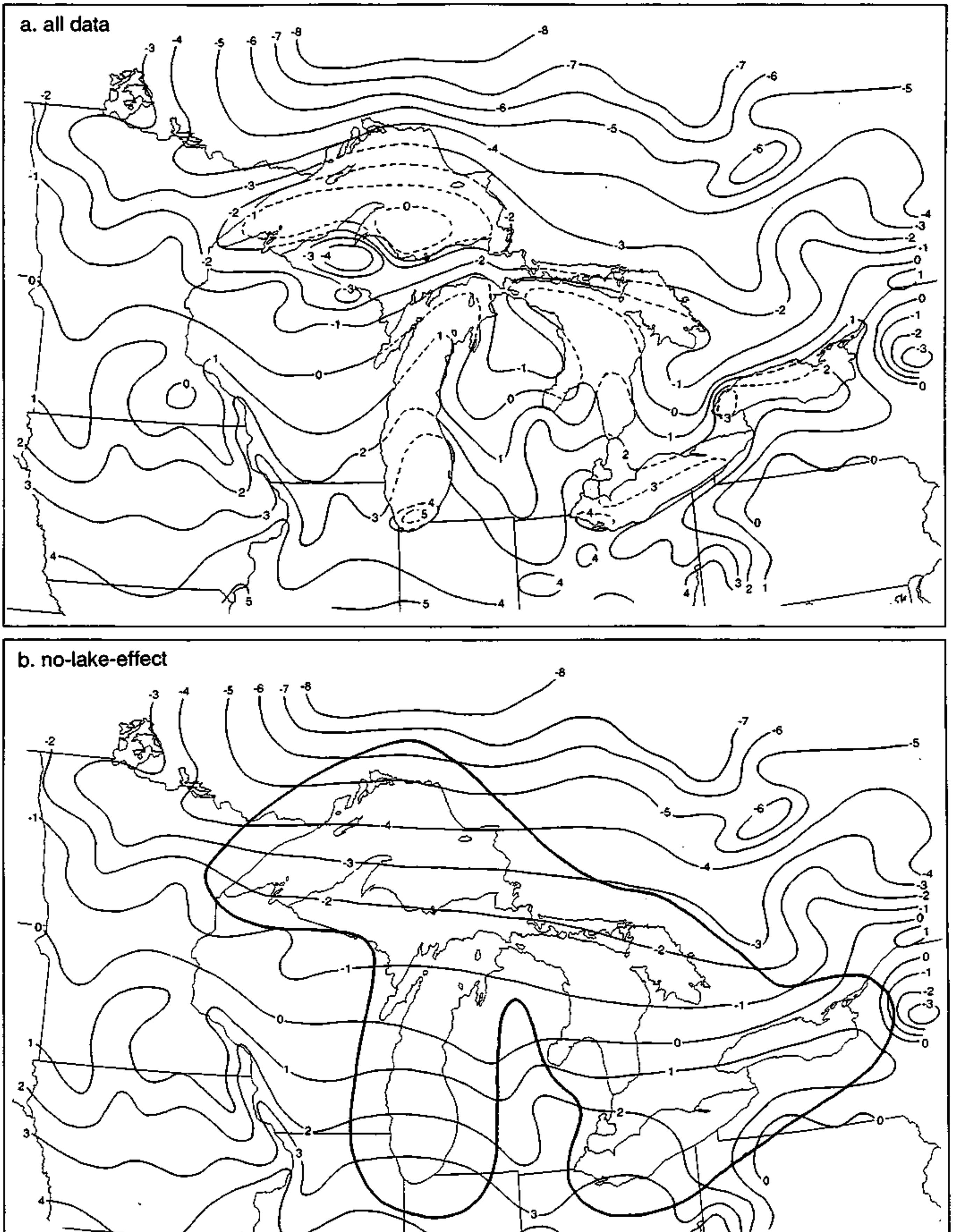



Figure 6. Average maximum temperature (°C) over the Great Lakes basin for winter: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

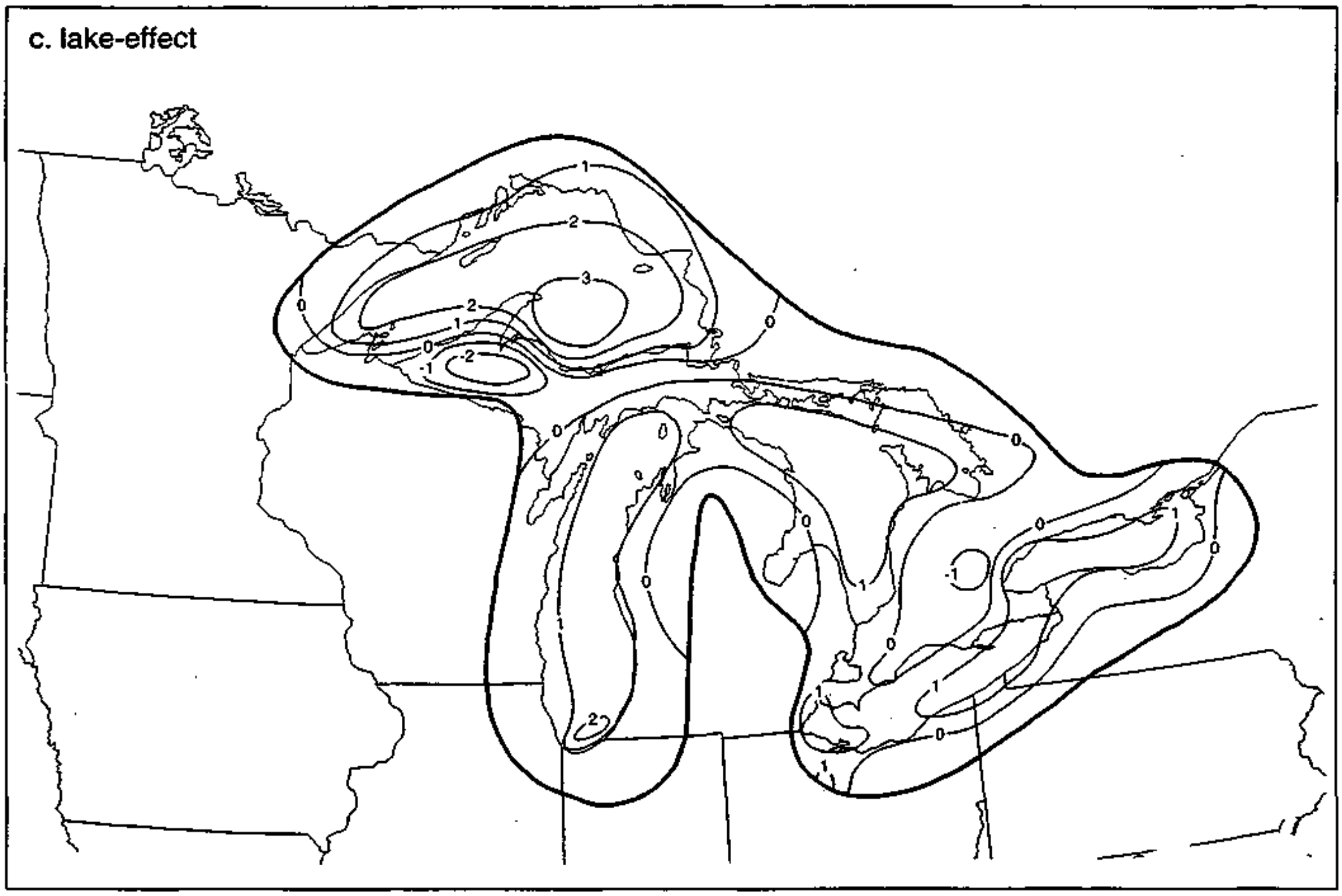
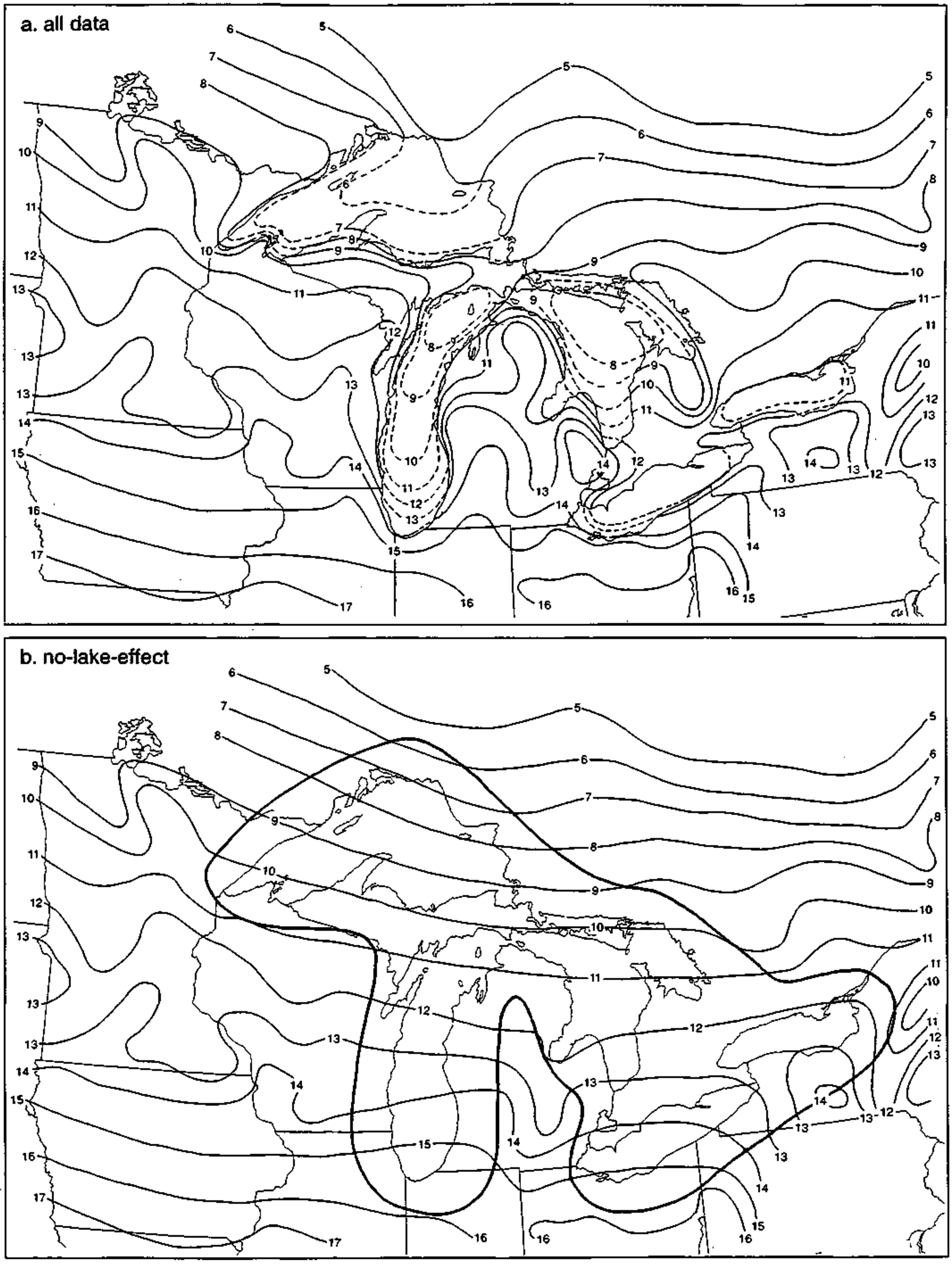



Figure 7. Average minimum temperature (°C) over the Great Lakes basin for spring: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

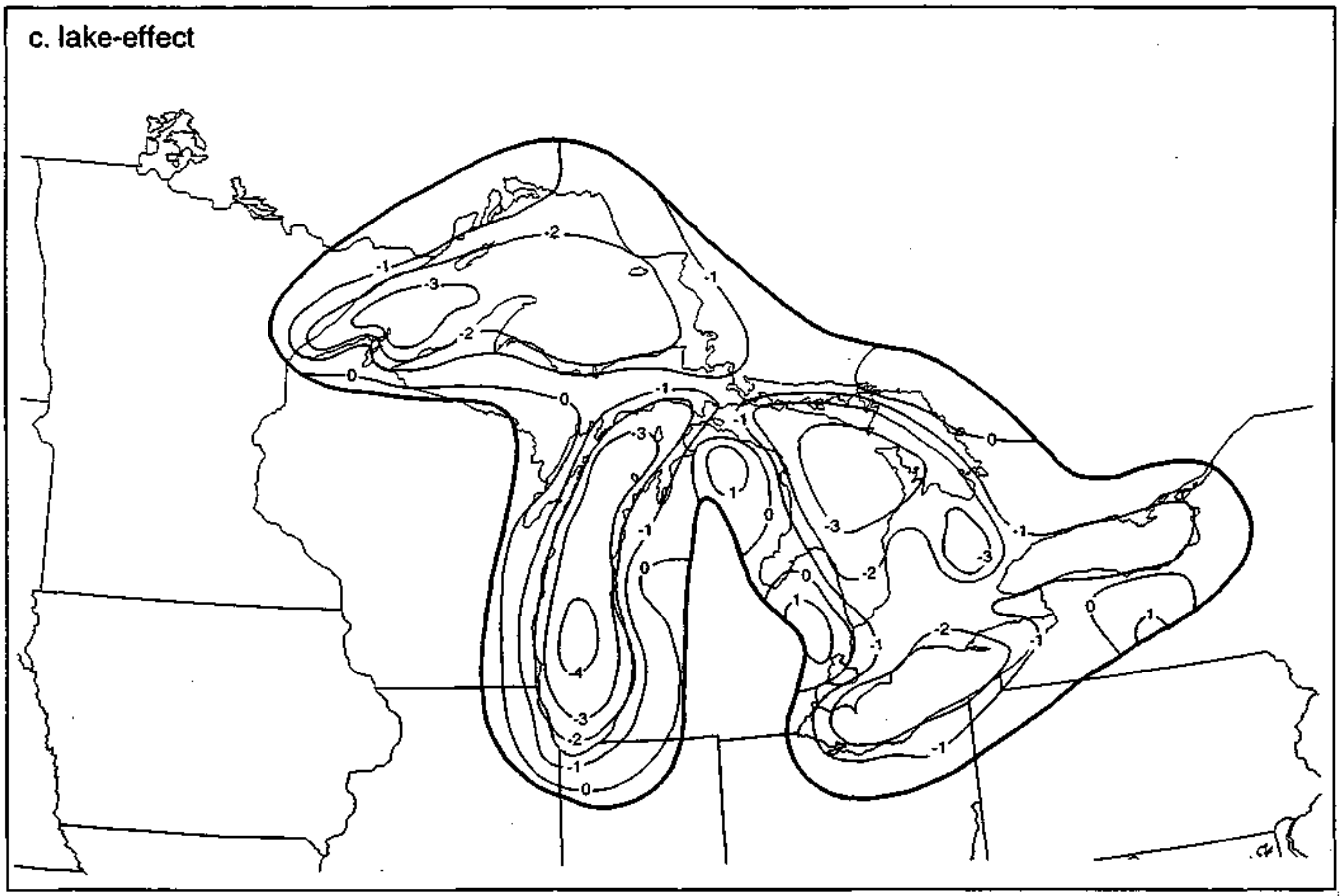
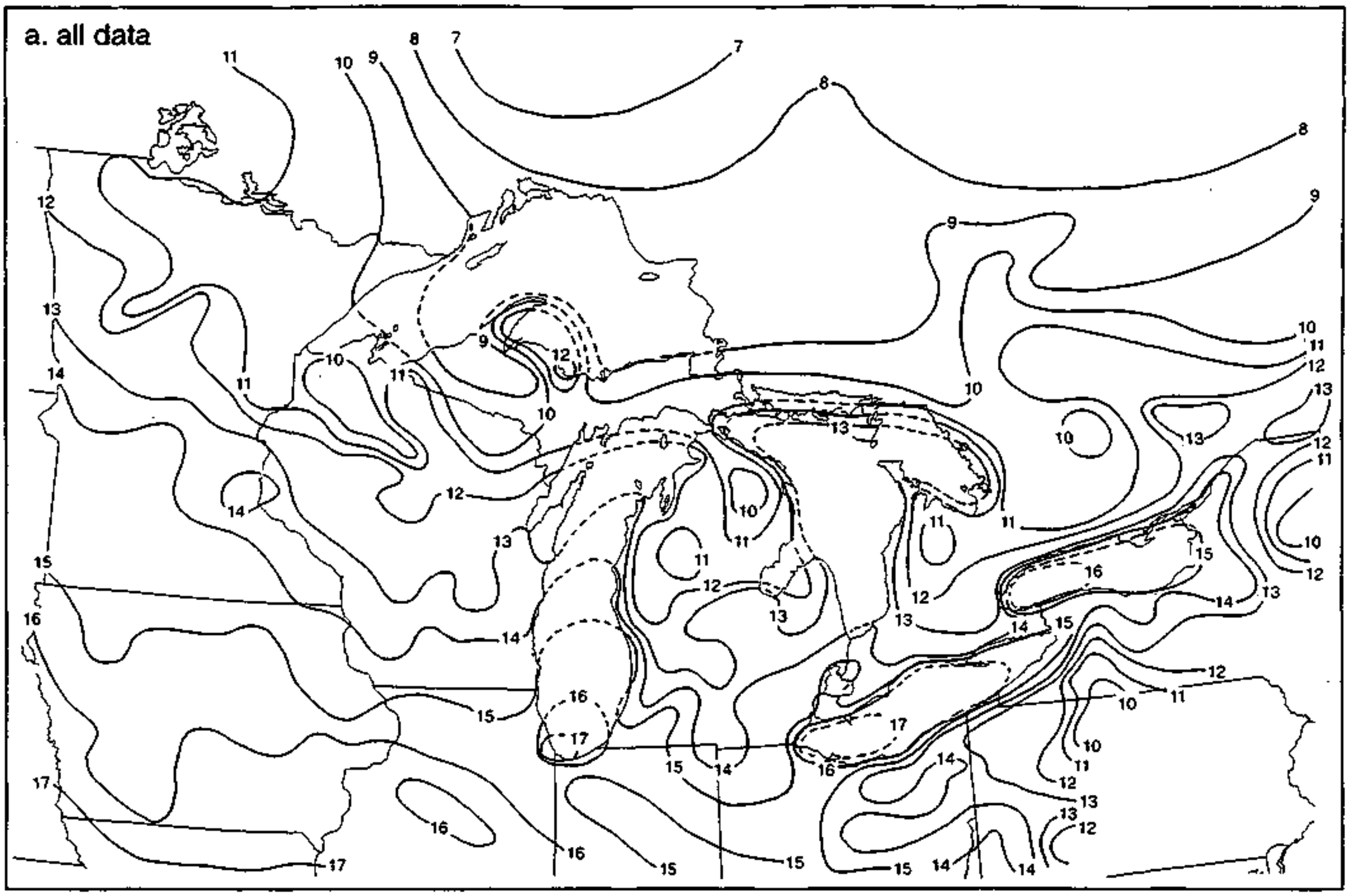



Figure 8. Average maximum temperature (°C) over the Great Lakes basin for spring: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.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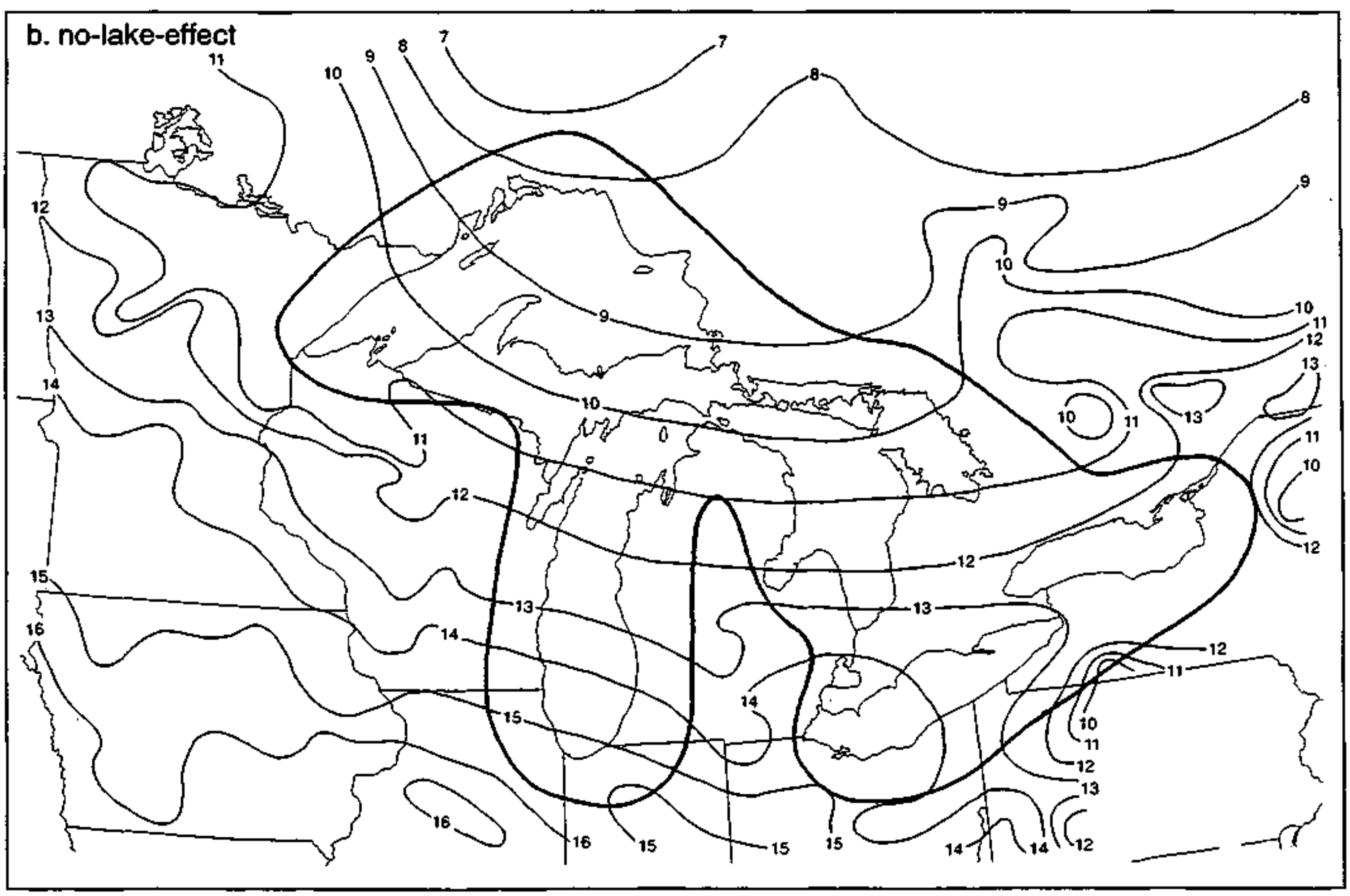

b. no-lake-effect

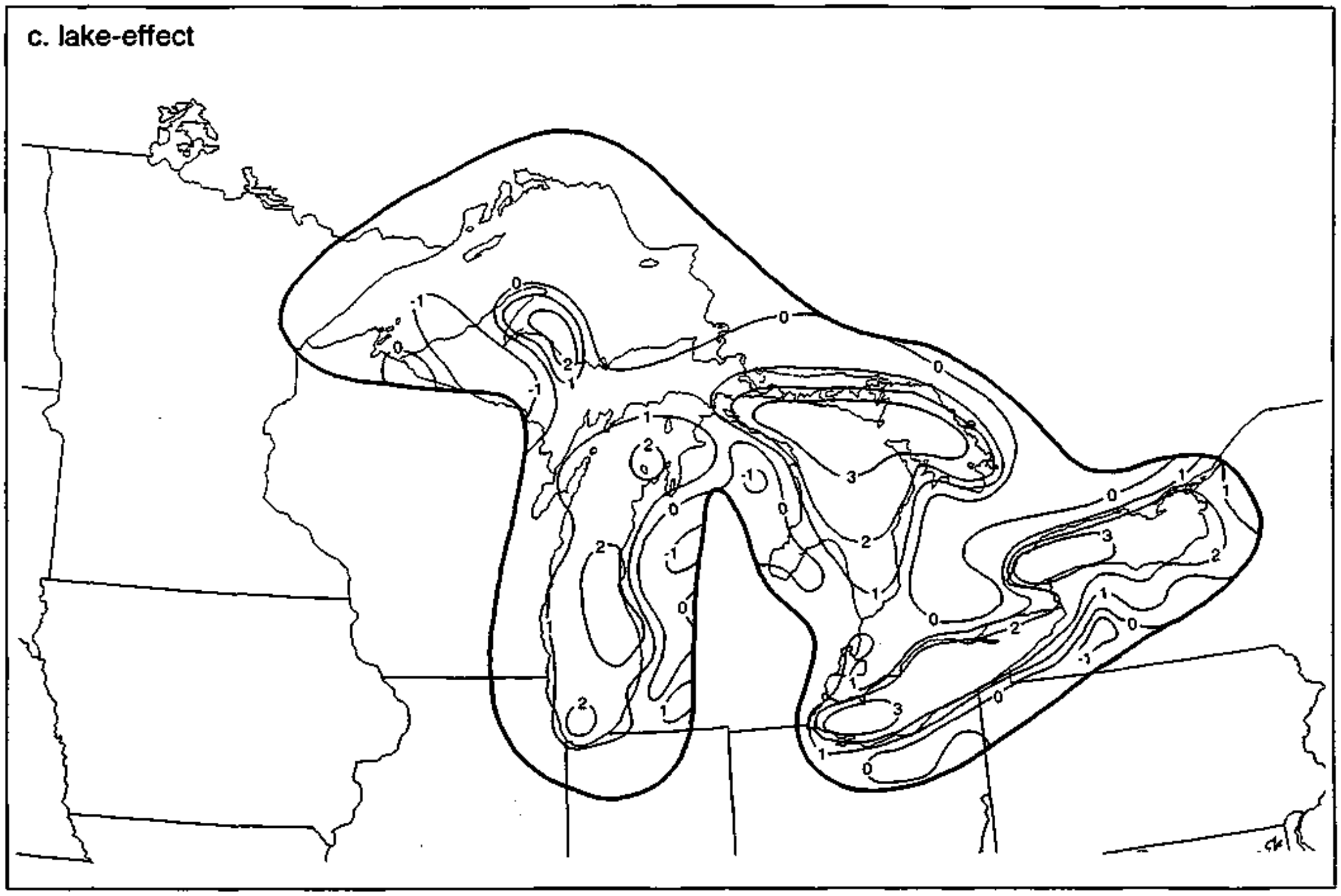
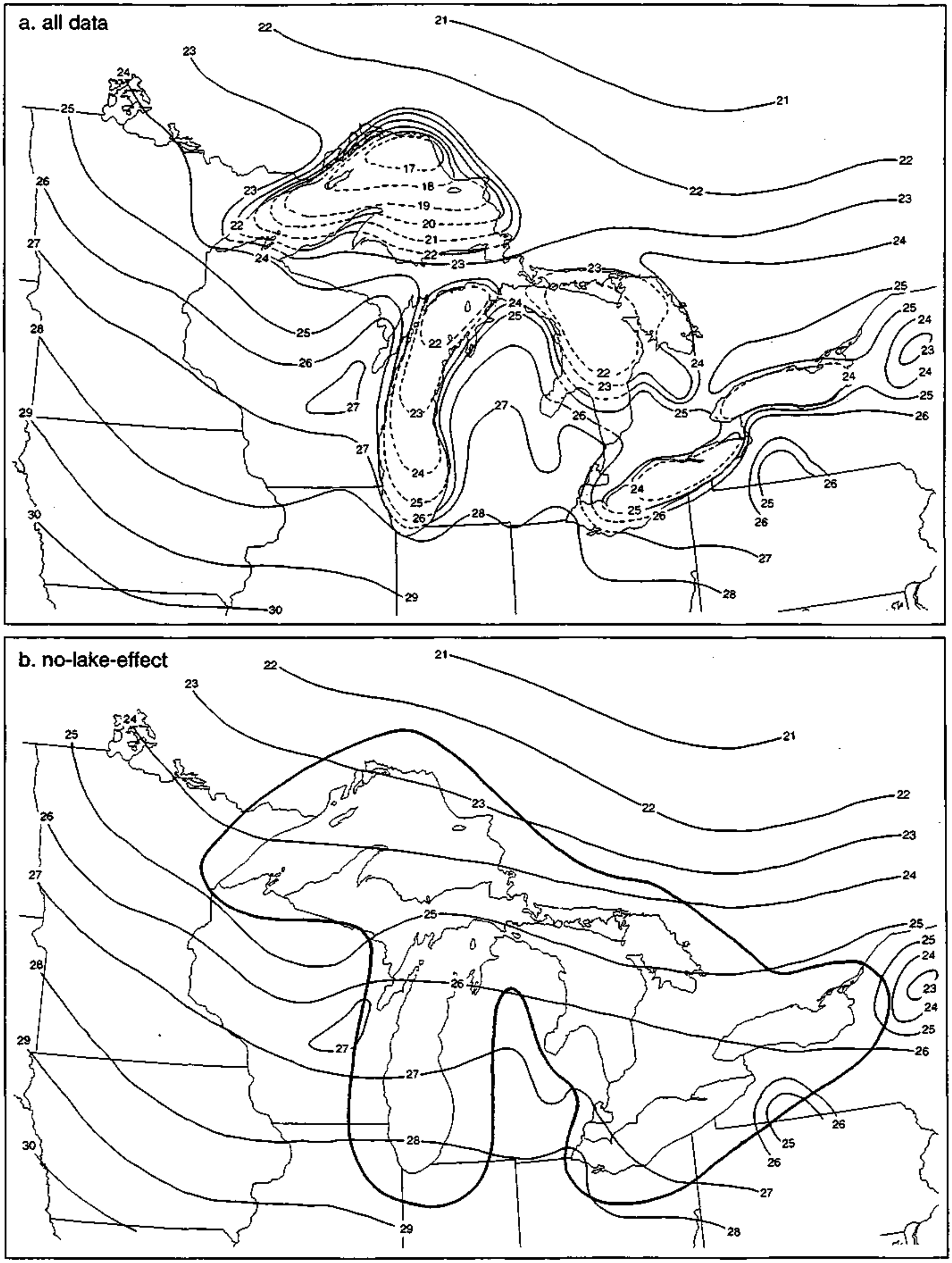



Figure 9. Average minimum temperature (°C) over the Great Lakes basin for summer: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

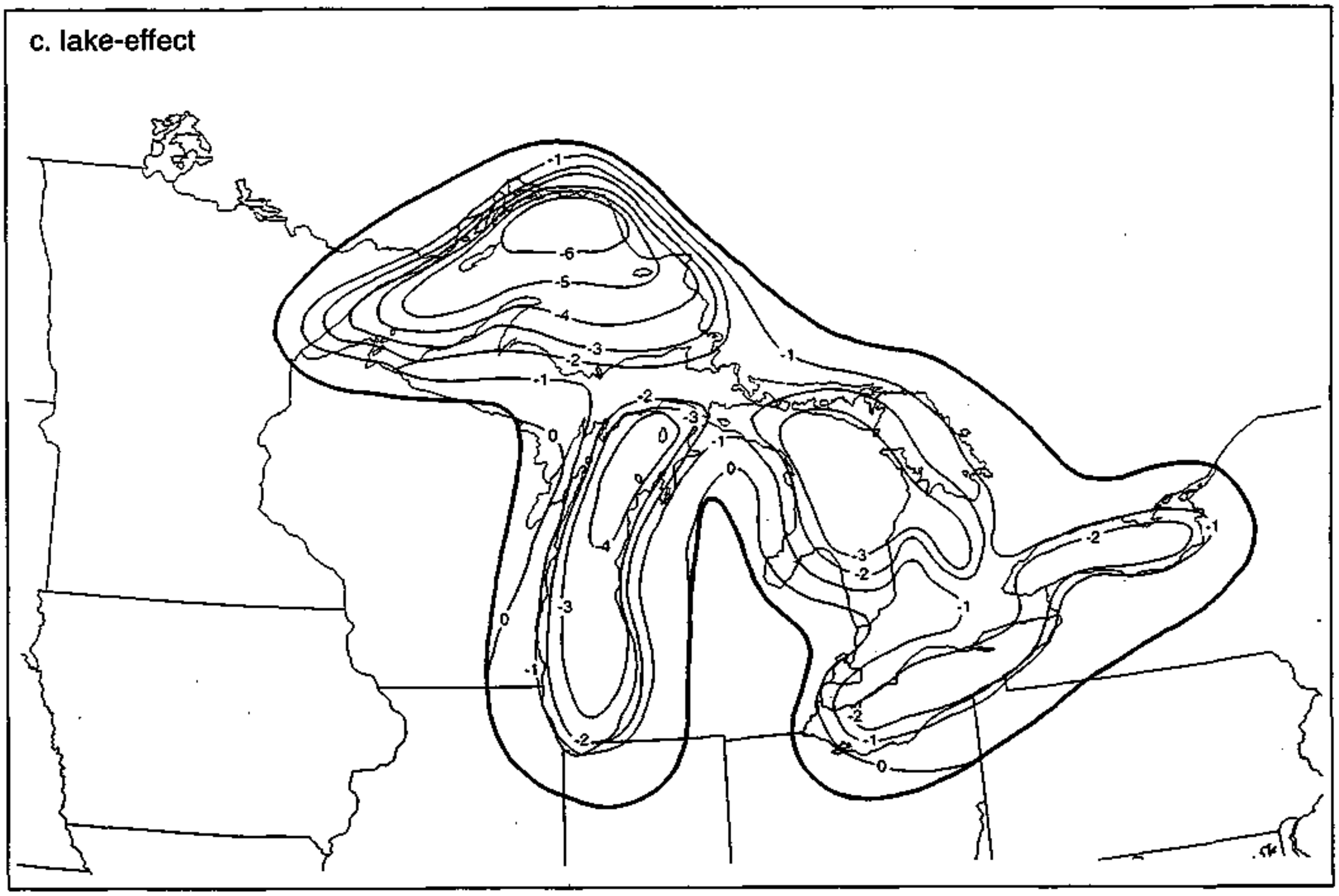
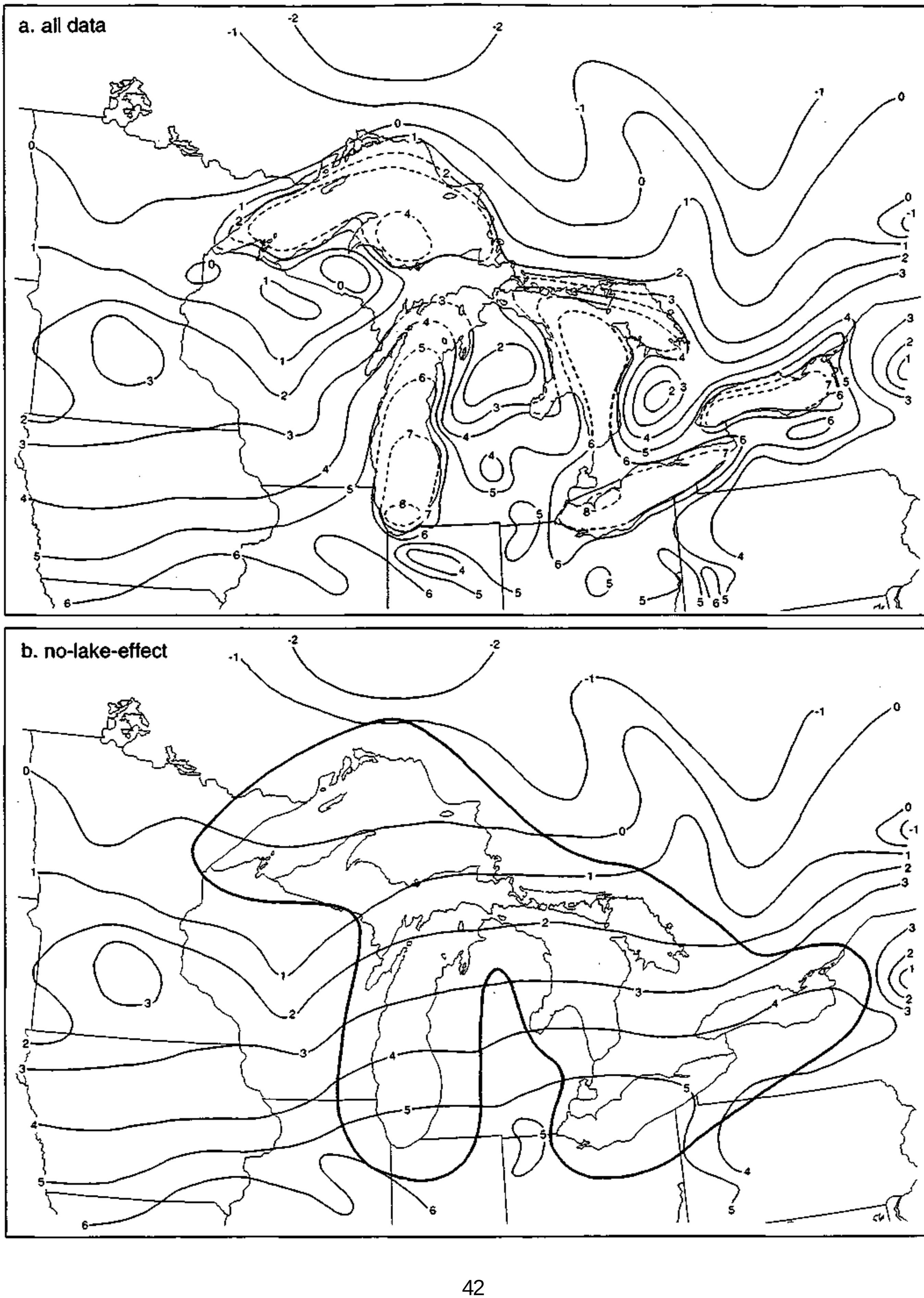



Figure 10. Average maximum temperature (°C) over the Great Lakes basin for summer: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

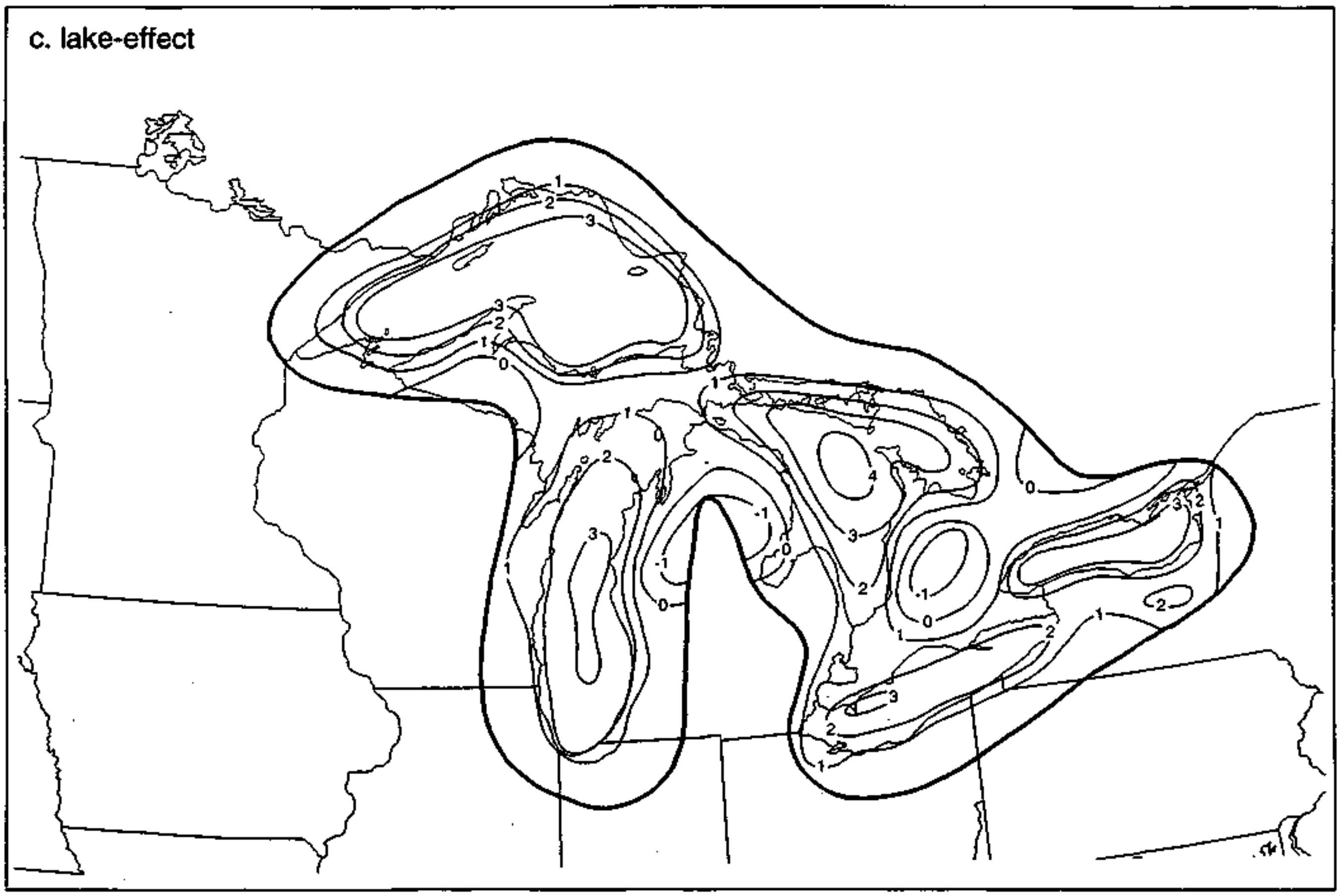
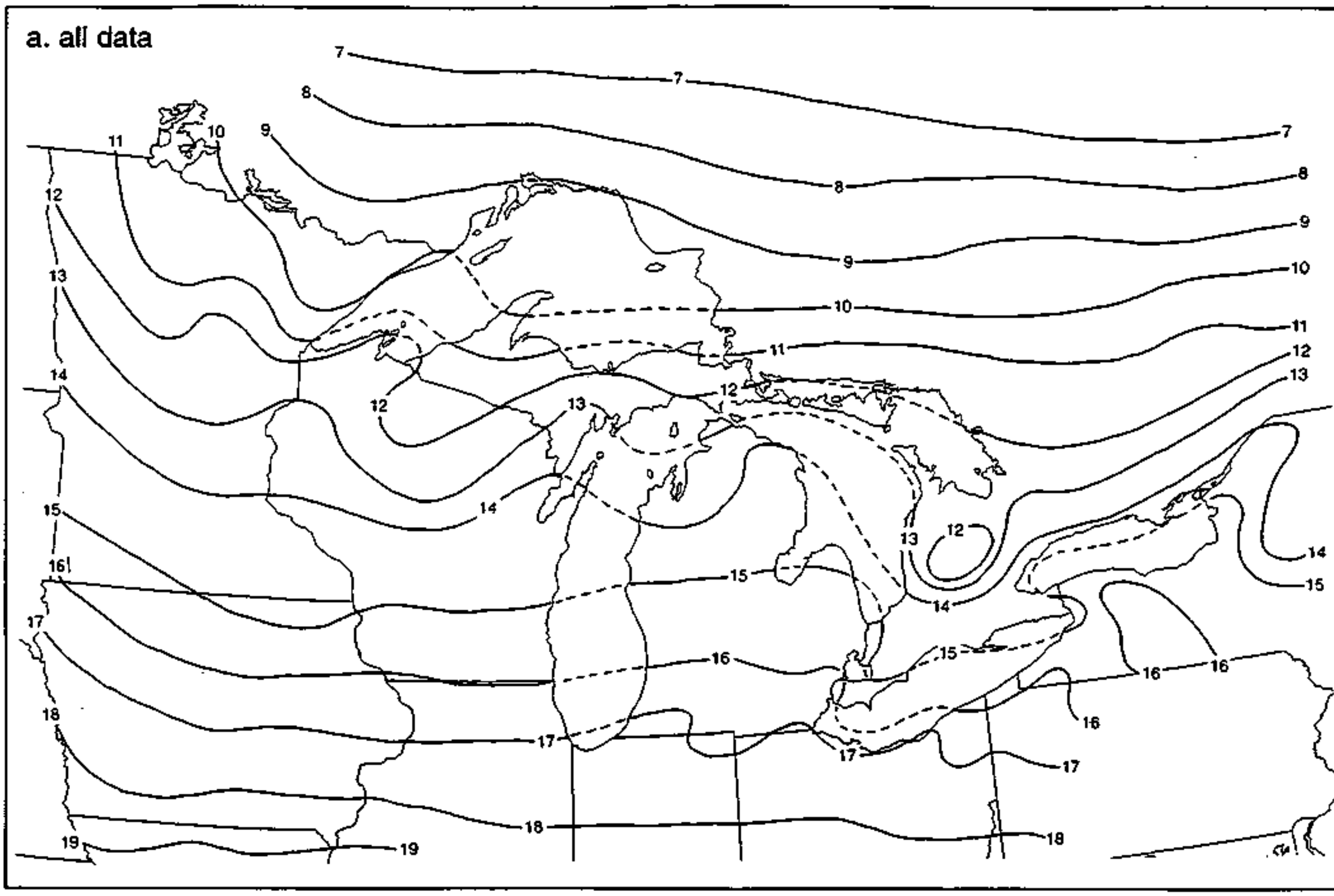
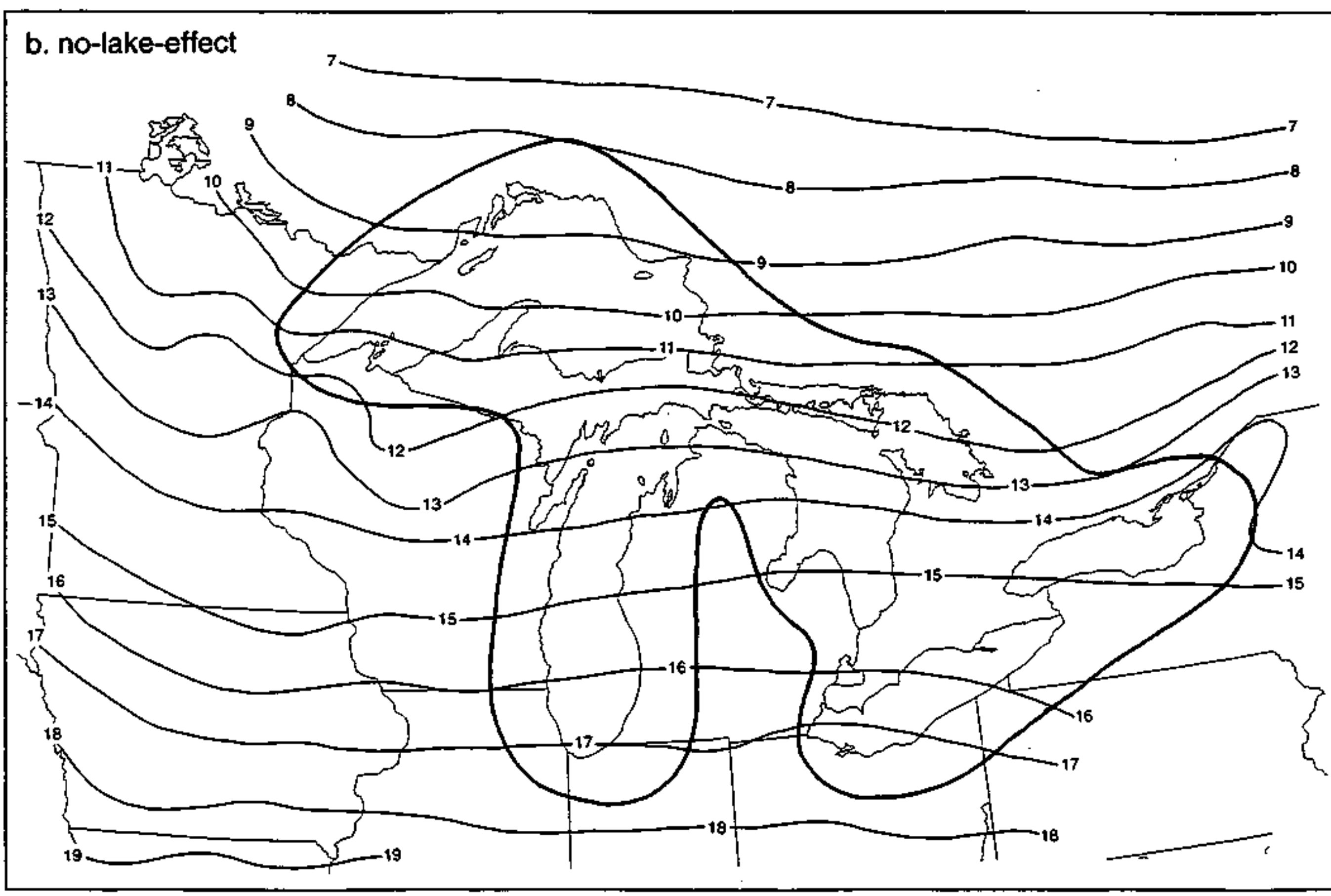



Figure 11. Average minimum temperature (°C) over the Great Lakes basin for autumn: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake effect boundary.


a. all data
7
8
9
10
11
12
13
14
15
16
17
18
19


b. no-lake-effect
7
8
9
10
11
12
13
14
15
16
17
18
19

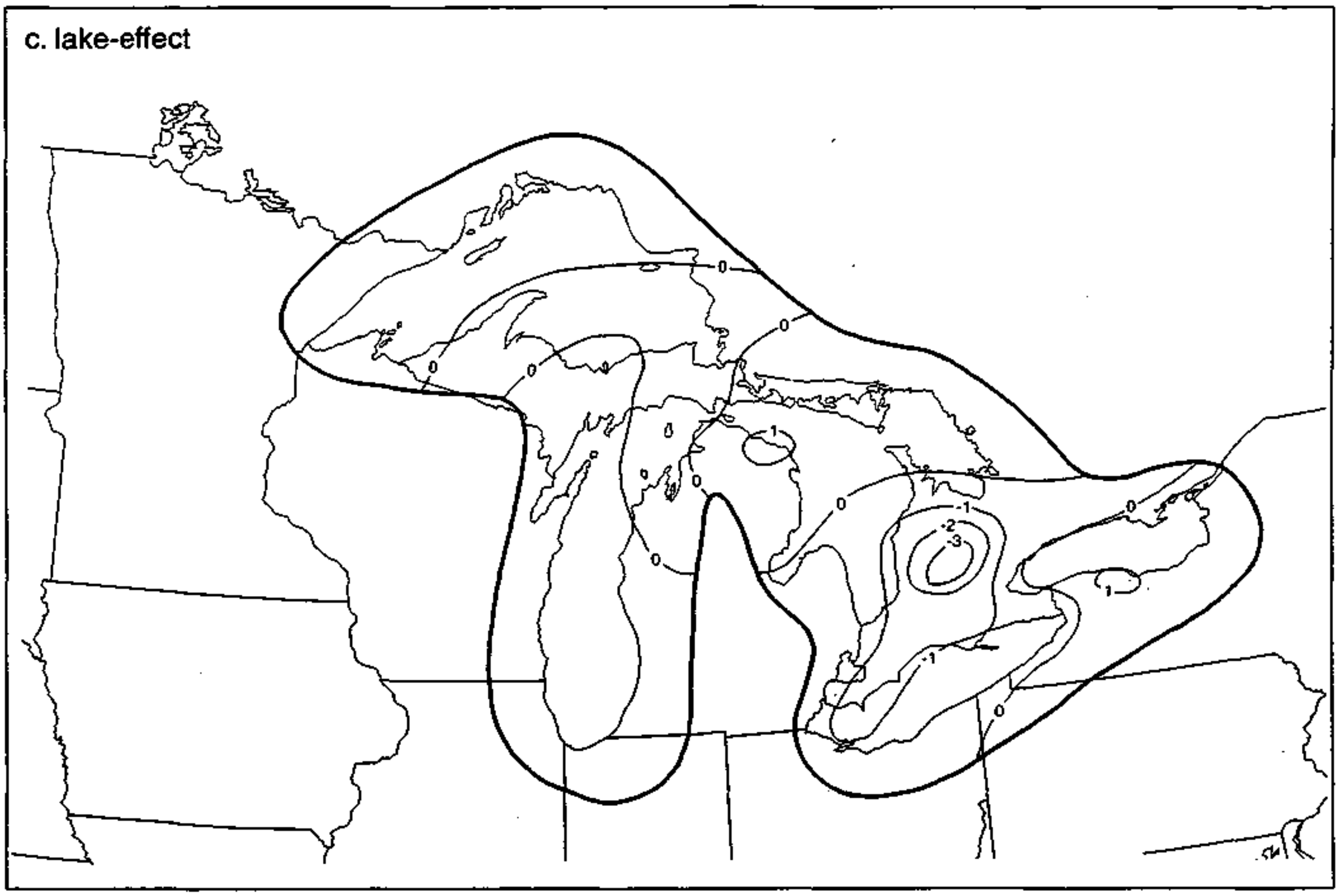
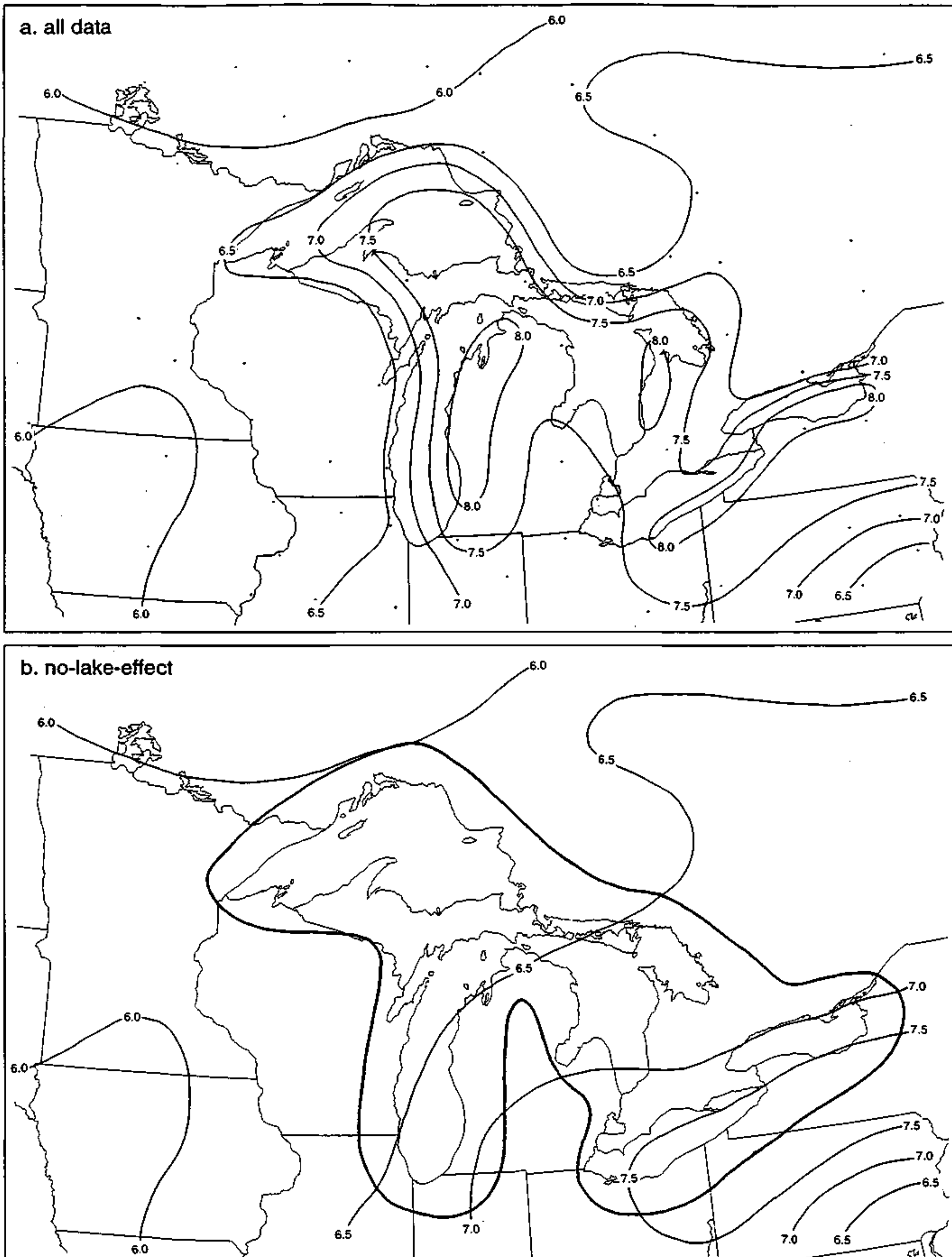



Figure 12. Average maximum temperature (°C) over the Great Lakes basin for autumn: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
b. no-lake-effect

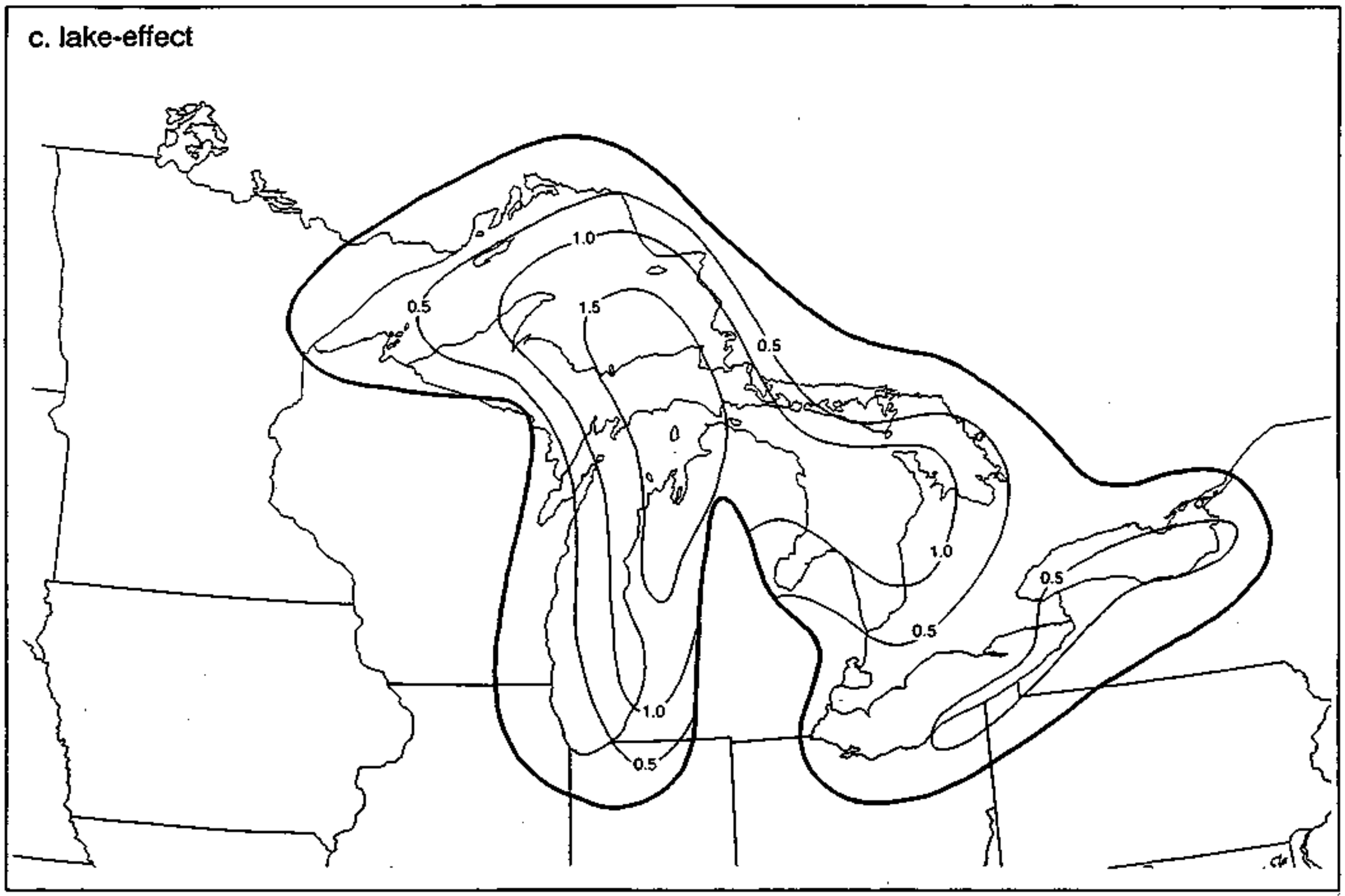



Figure 13. Average cloud cover (tenths) over the Great Lakes basin for winter: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. Dots (a) represent site locations for hourly data in figures 13-24.

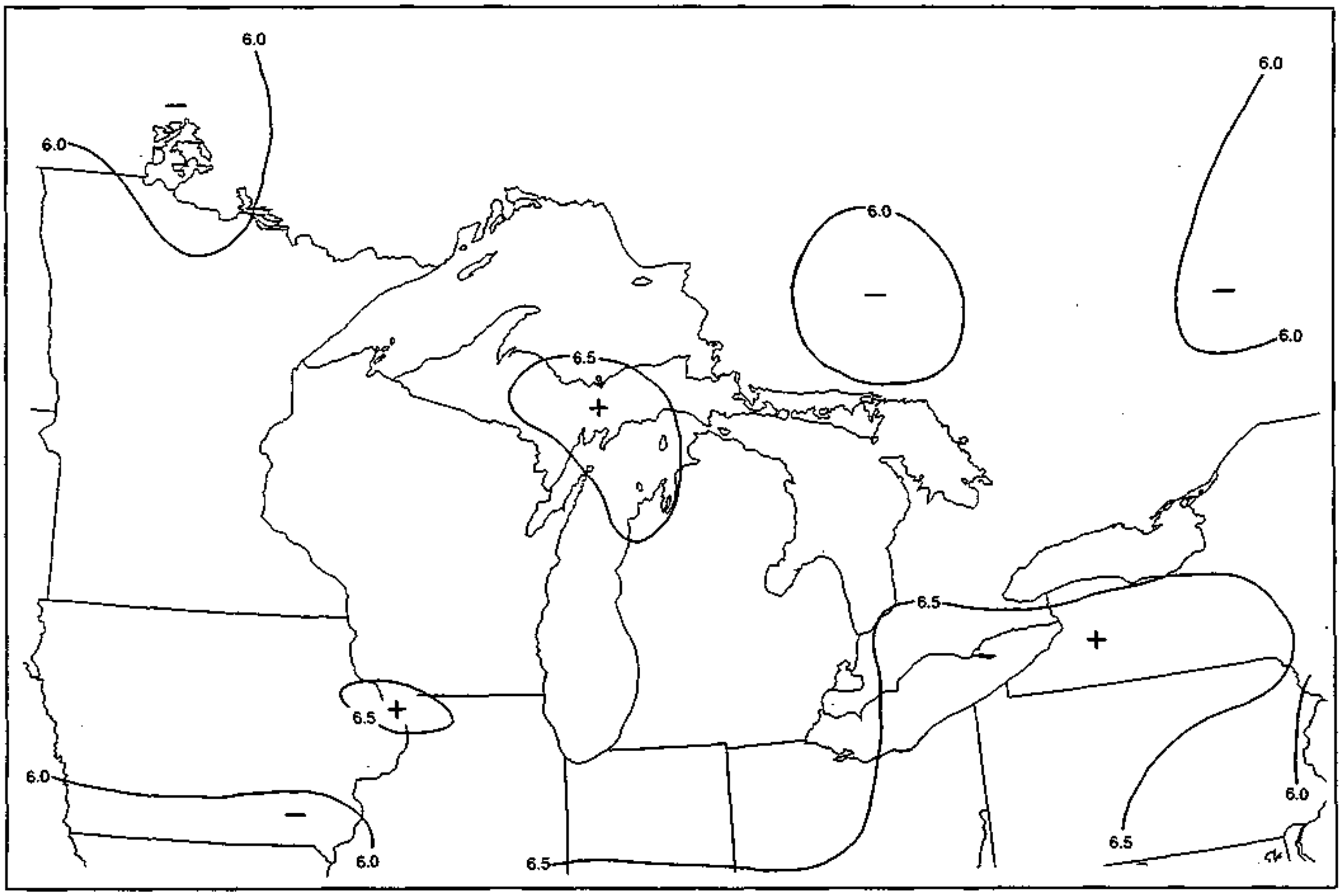
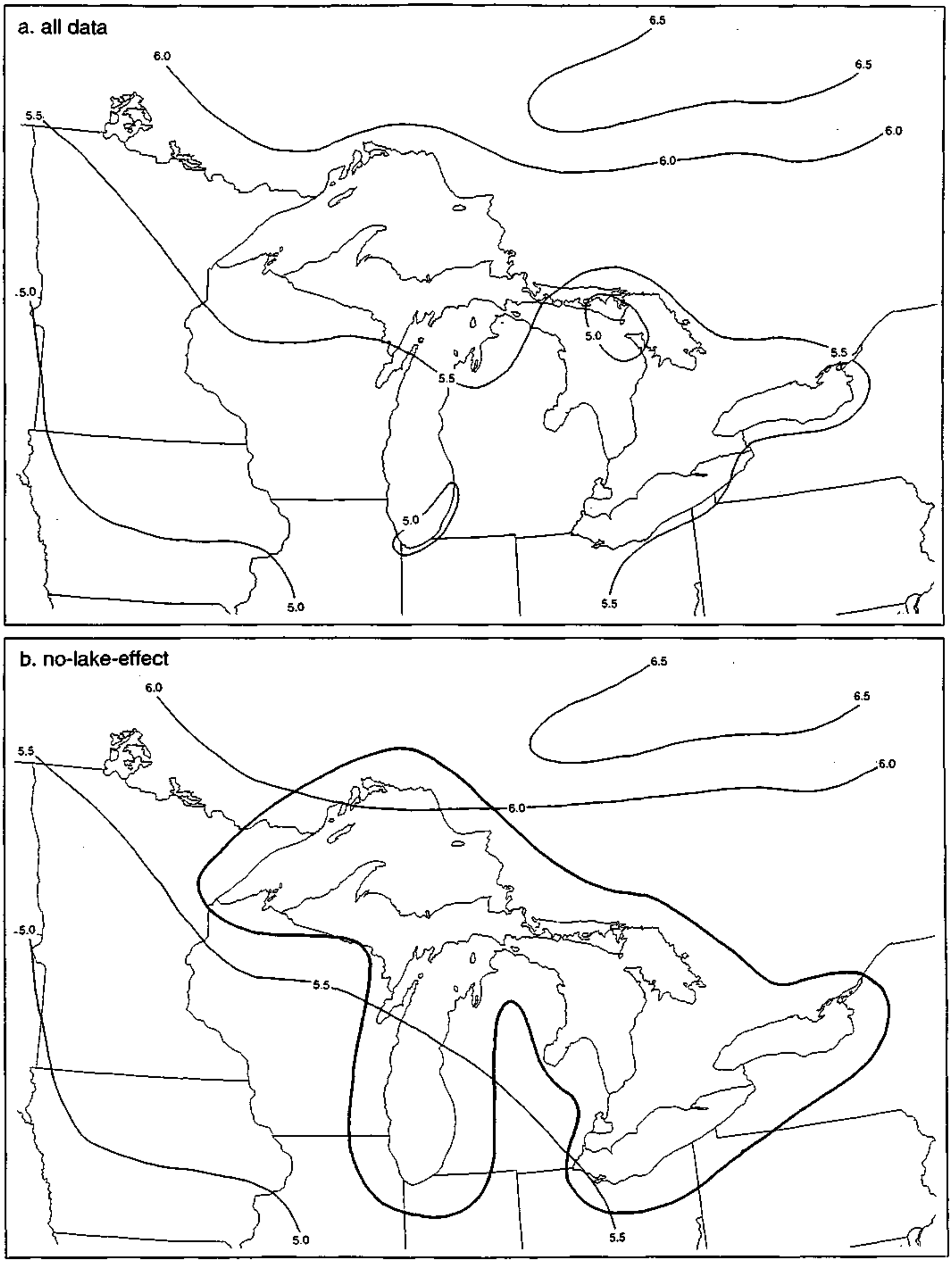



Figure 14. Average cloud cover (tenths) over the Great Lakes basin for spring: all data only.



a. all data
6.5
6.5
6.0
6.0
6.0
5.5
5.0
5.5
5.0
5.5
5.0
5.0
5.5
b. no-lake-effect
6.5
6.5
6.0
6.0
6.0
5.5
5.0
5.5
5.0
5.5

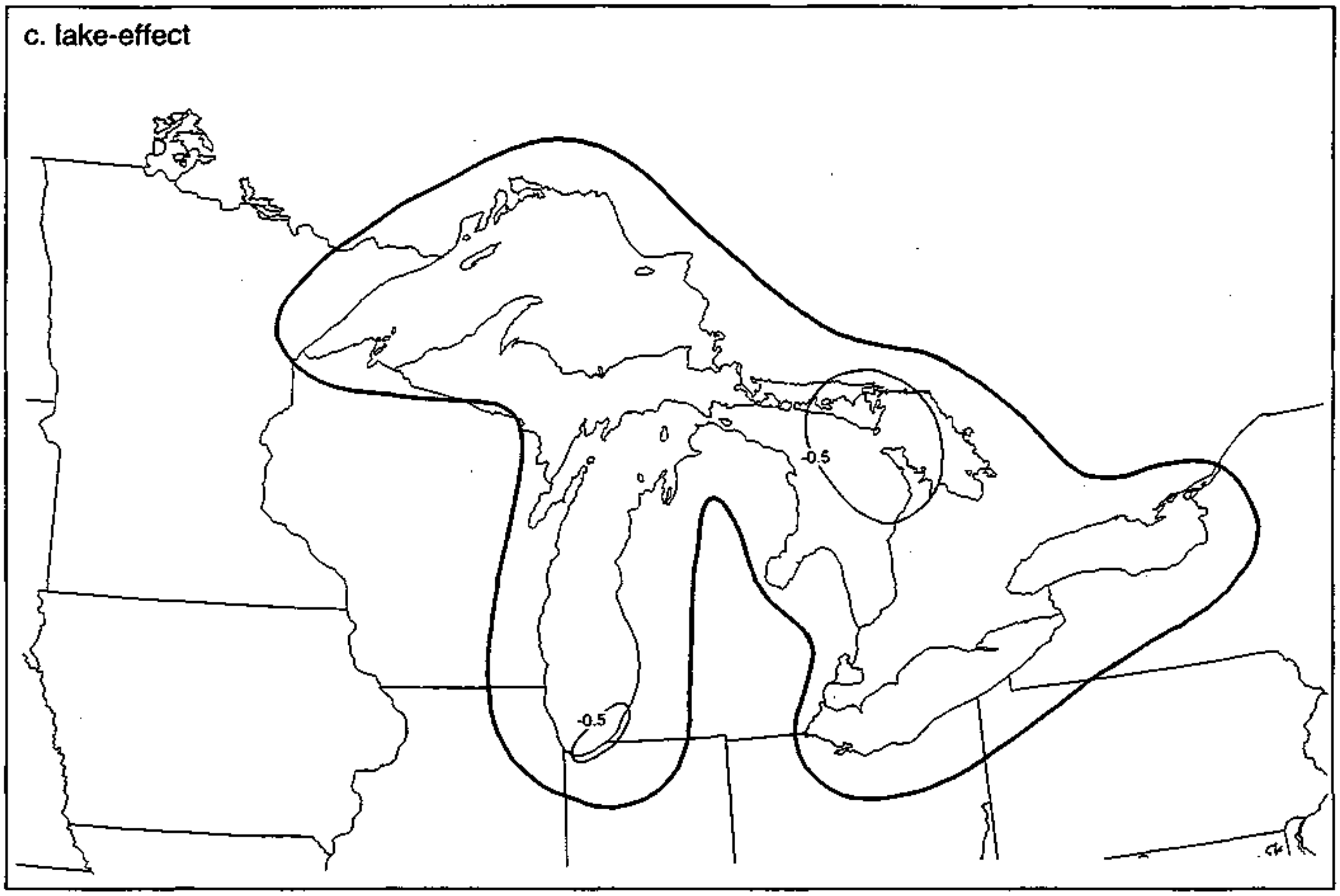
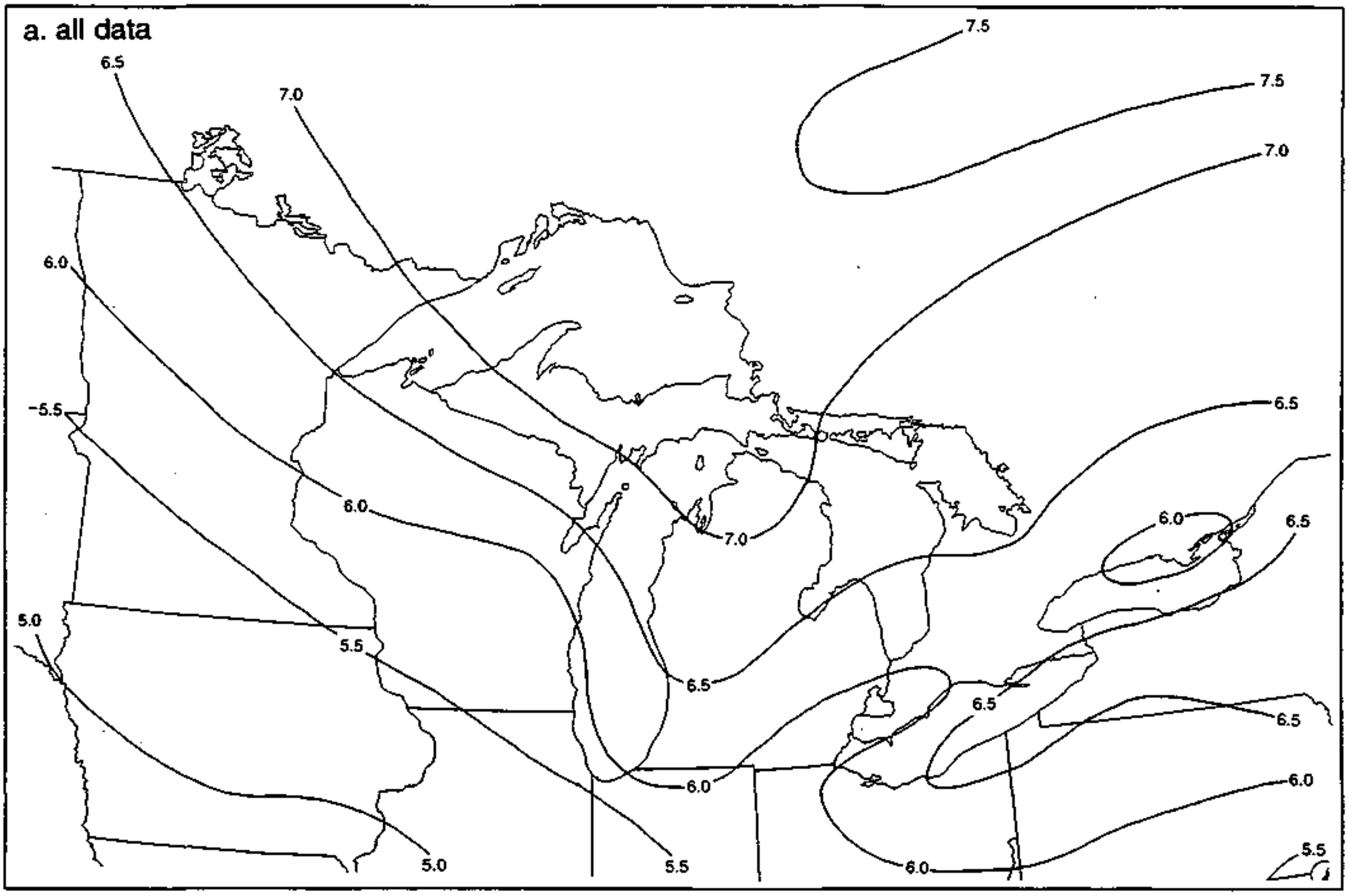



Figure 15. Average cloud cover (tenths) over the Great Lakes basin for summer: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
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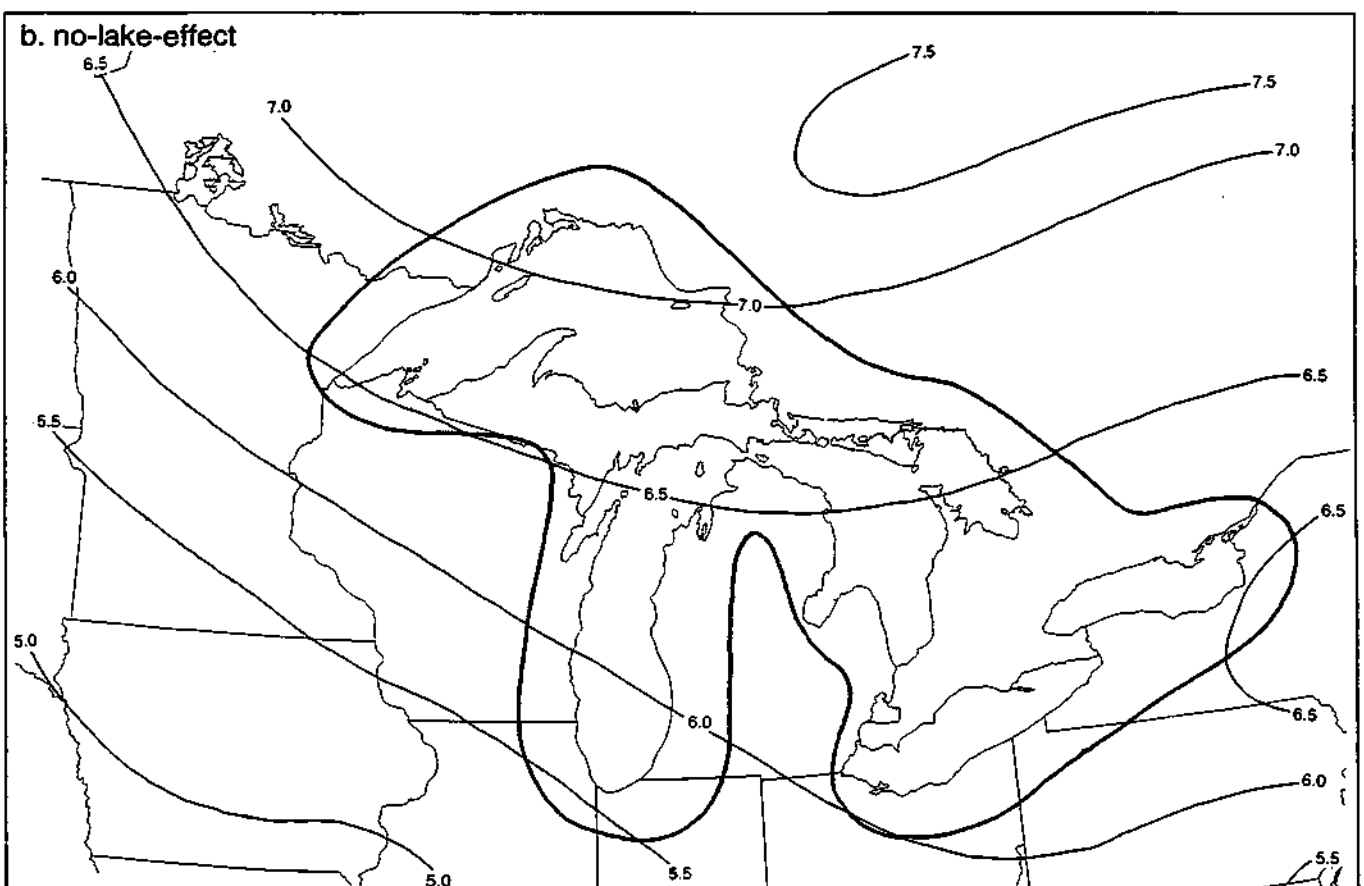
7.5
7.0
6.5
7.0
6.0
-5.5
6.0
7.0
6.5
6.0
6.5
5.0
5.5
6.5
6.5
6.5
6.0
6.0
5.0
5.5
6.0
5.5


b. no-lake-effect
7.5
7.5
6.5
7.0
7.0
6.0
7.0
6.5
5.5
6.5
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5.0
5.5
5.5

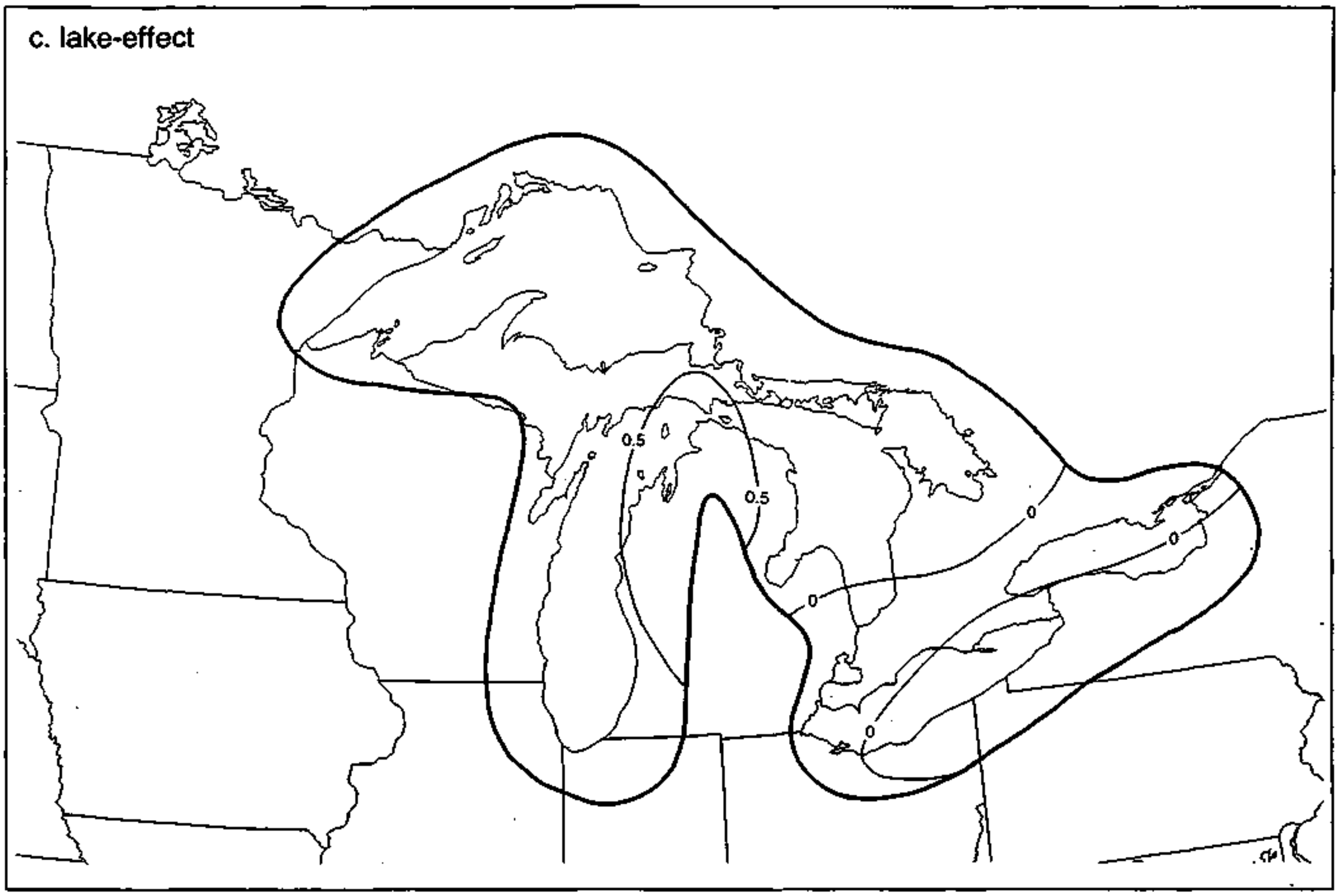
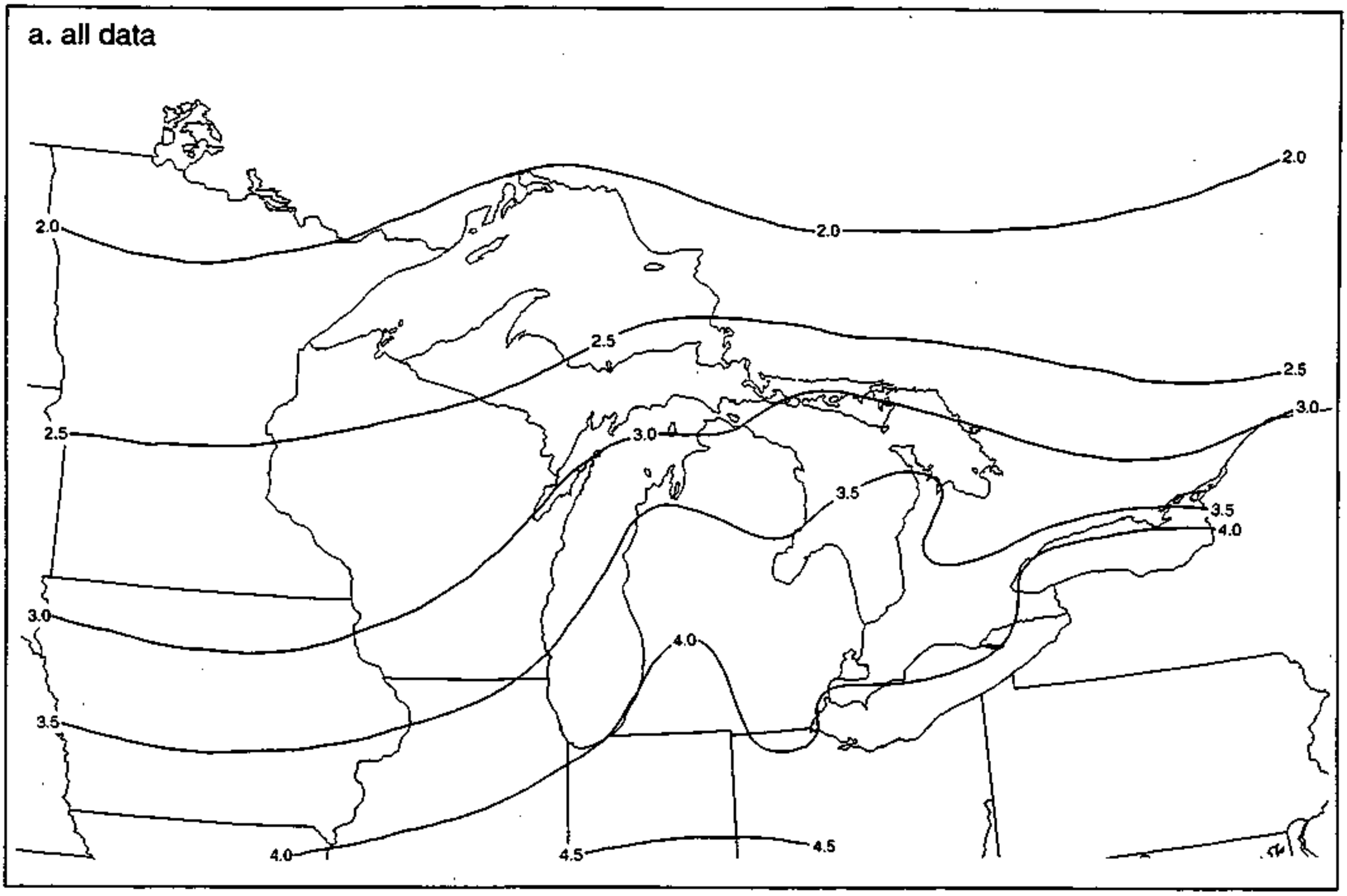



Figure 16. Average cloud cover (tenths) over the Great Lakes basin for autumn: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.



a. all data
2.0
2.0
2.0
2.5
2.5
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3.0
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3.0
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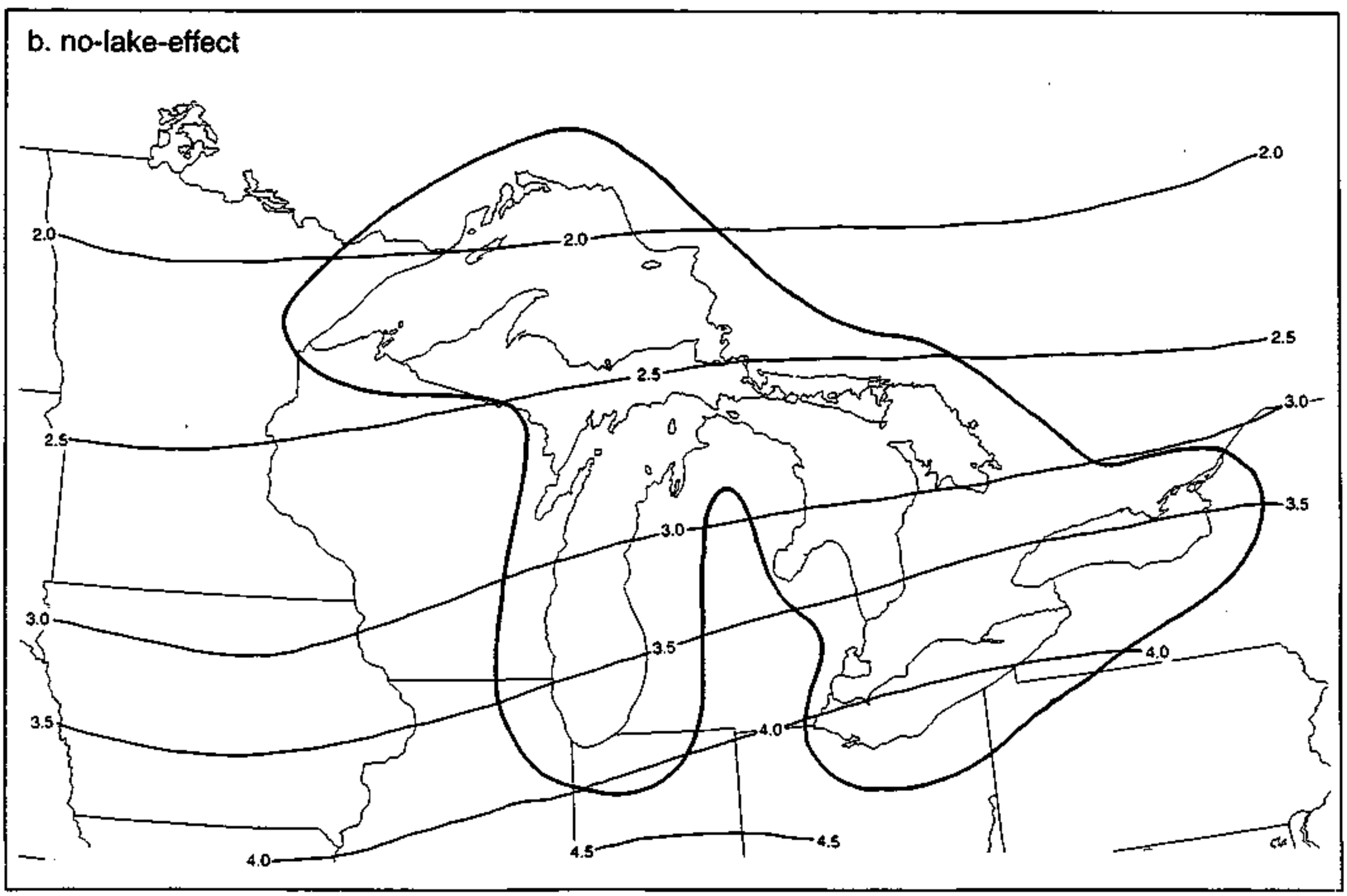
4.0
4.5
4.5

b. no-lake-effect
2.0
2.0
2.0
2.5
2.5
2.5
3.0
3.0
3.0
3.5
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4.0
4.5
4.5

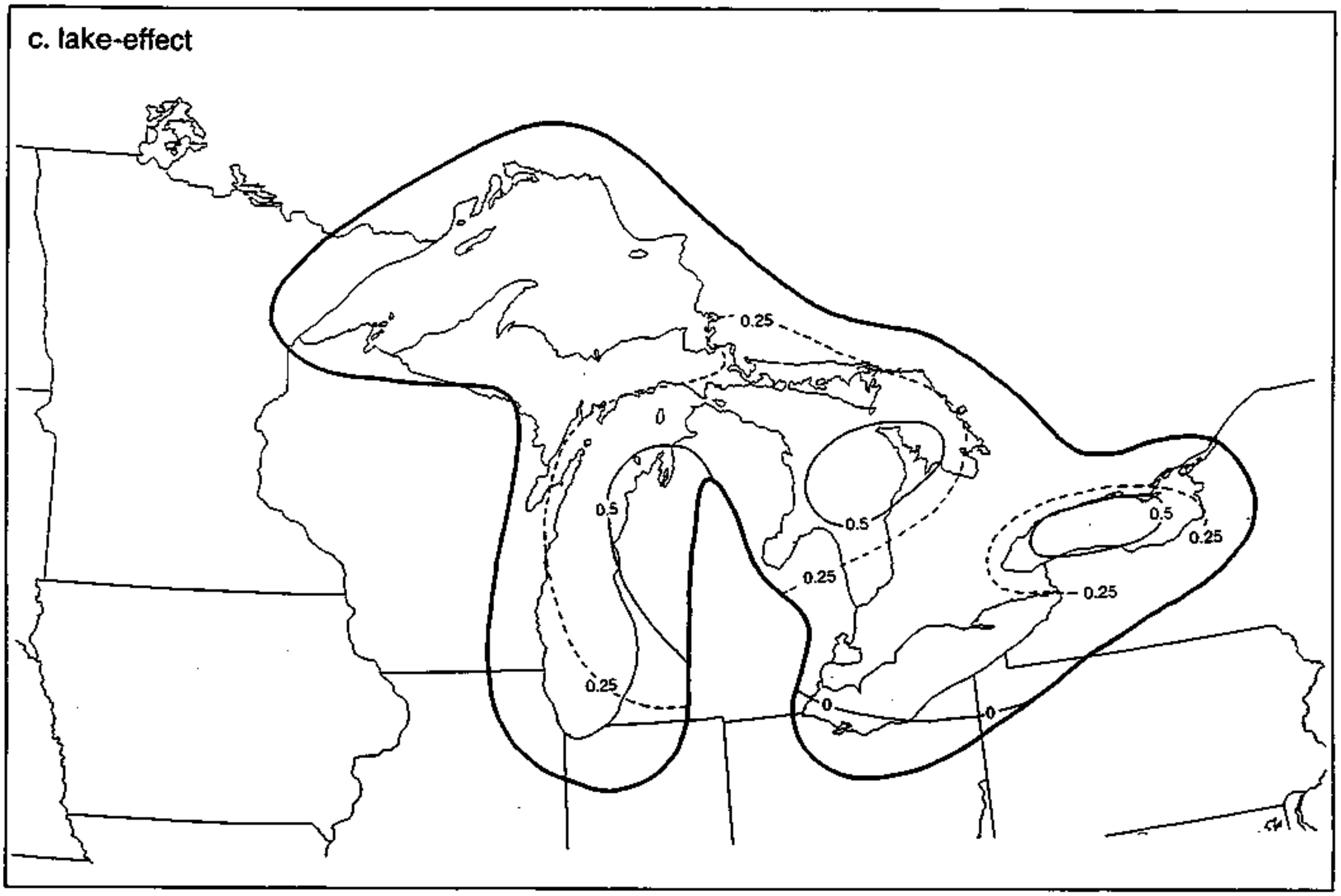
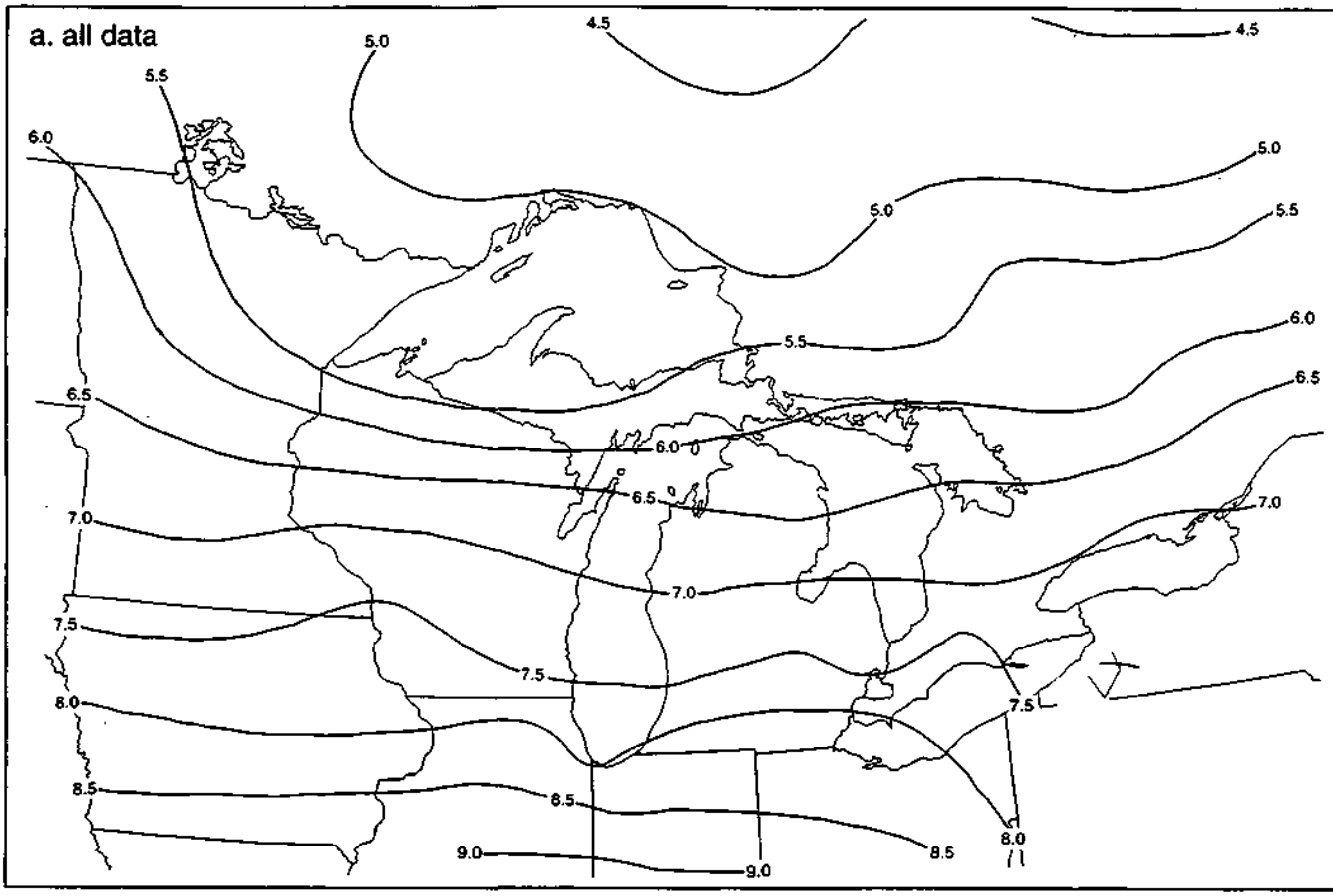



Figure 17. Average vapor pressure (millibar) over the Great Lakes basin for winter: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.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6.5
7.0
7.5
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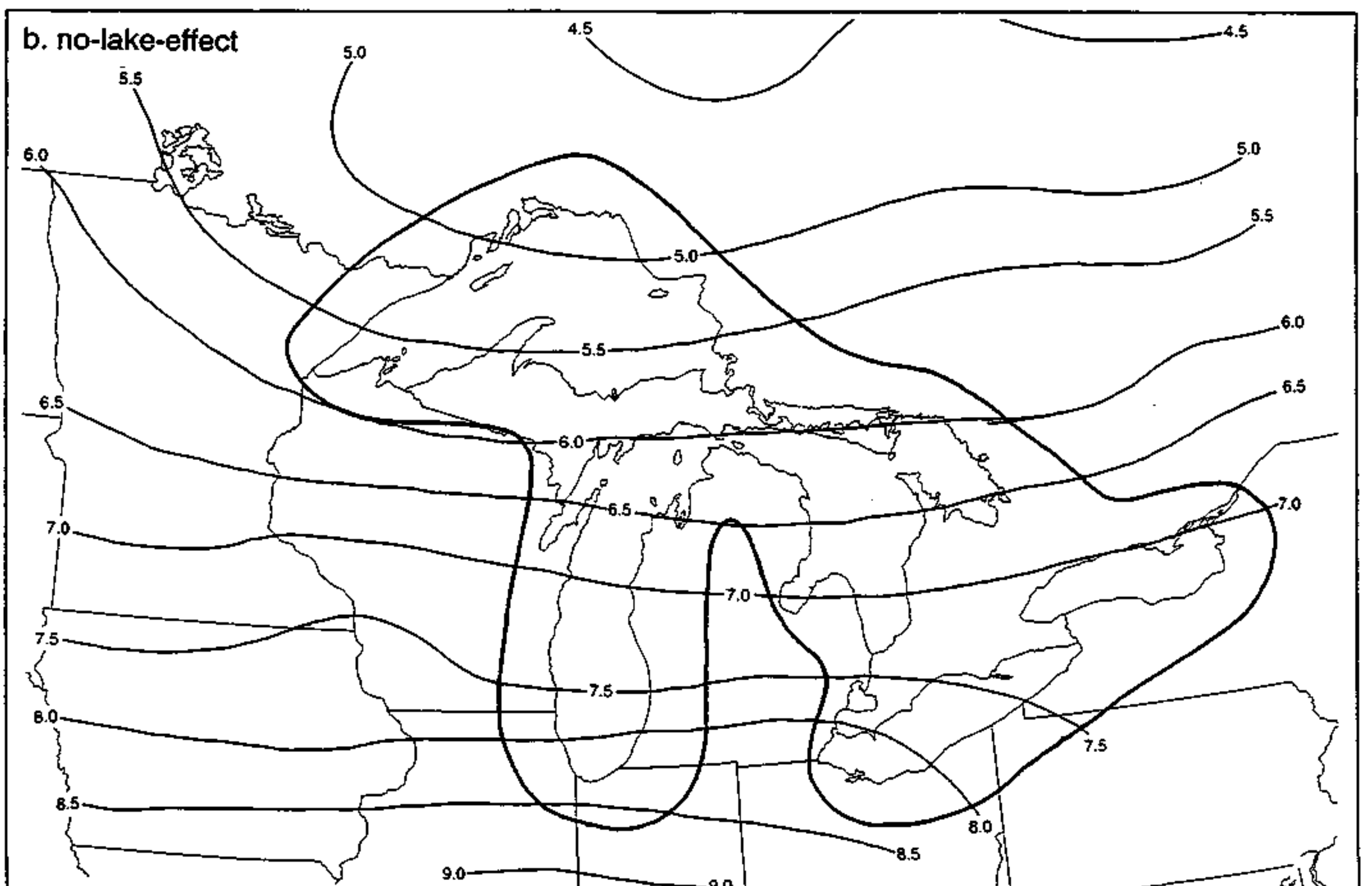
8.5
9.0


b. no-lake-effect
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5.5
6.0
6.5
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9.0

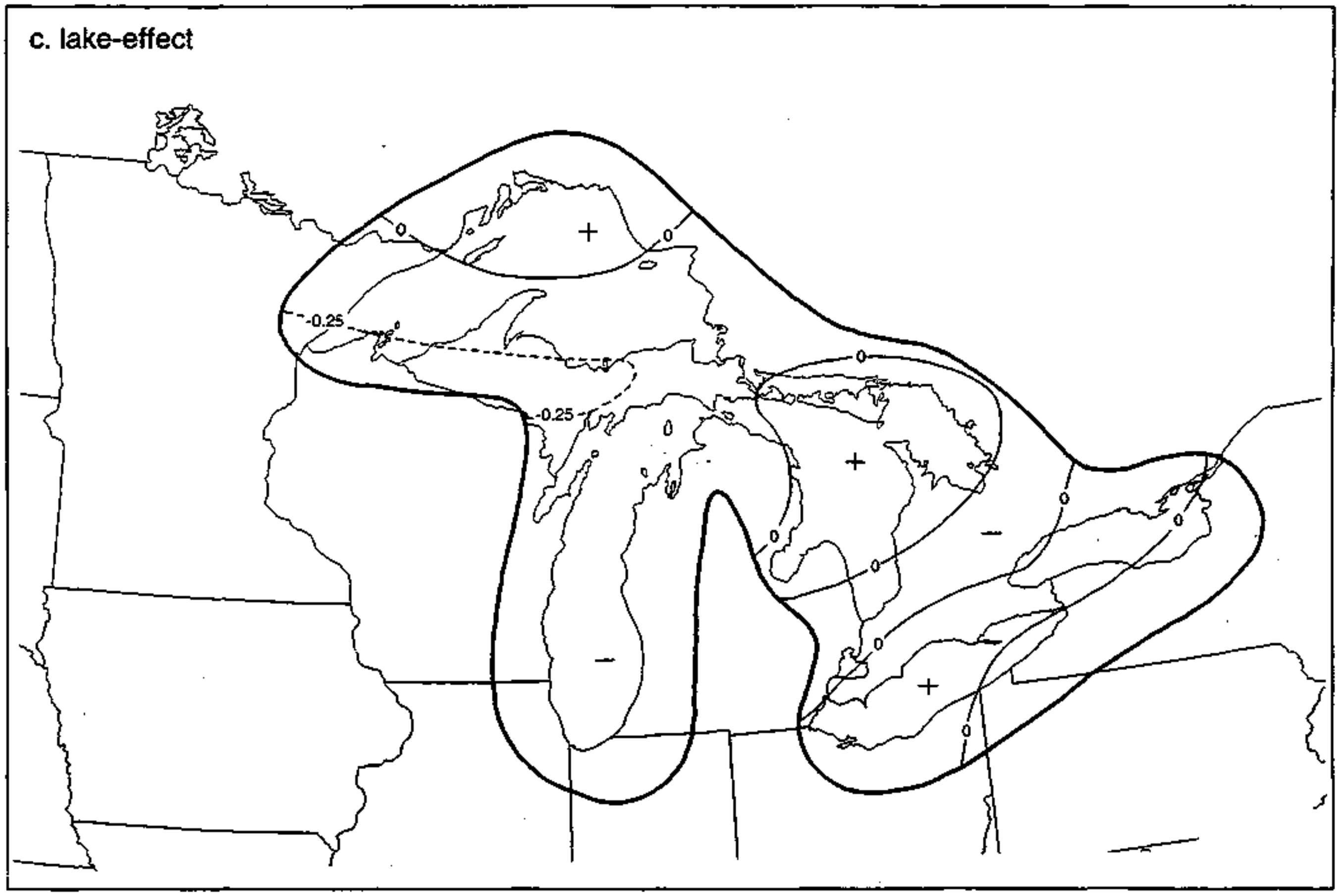
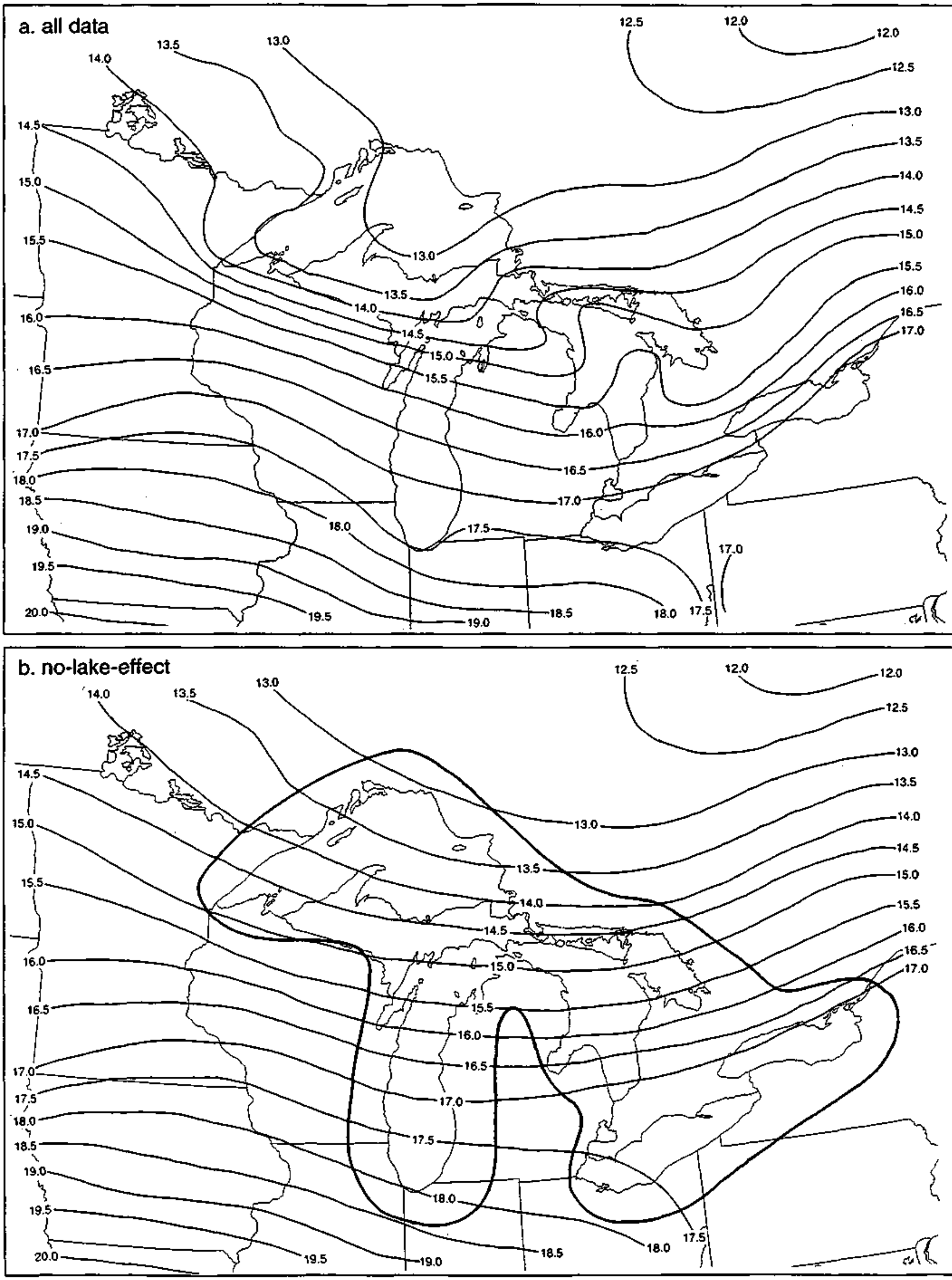



Figure 18. Average vapor pressure (millibar) over the Great Lakes basin for spring: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.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15.0
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16.0
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
b. no-lake-effect
12.0
12.5
13.0
13.5
14.0
14.5
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18.0
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20.0

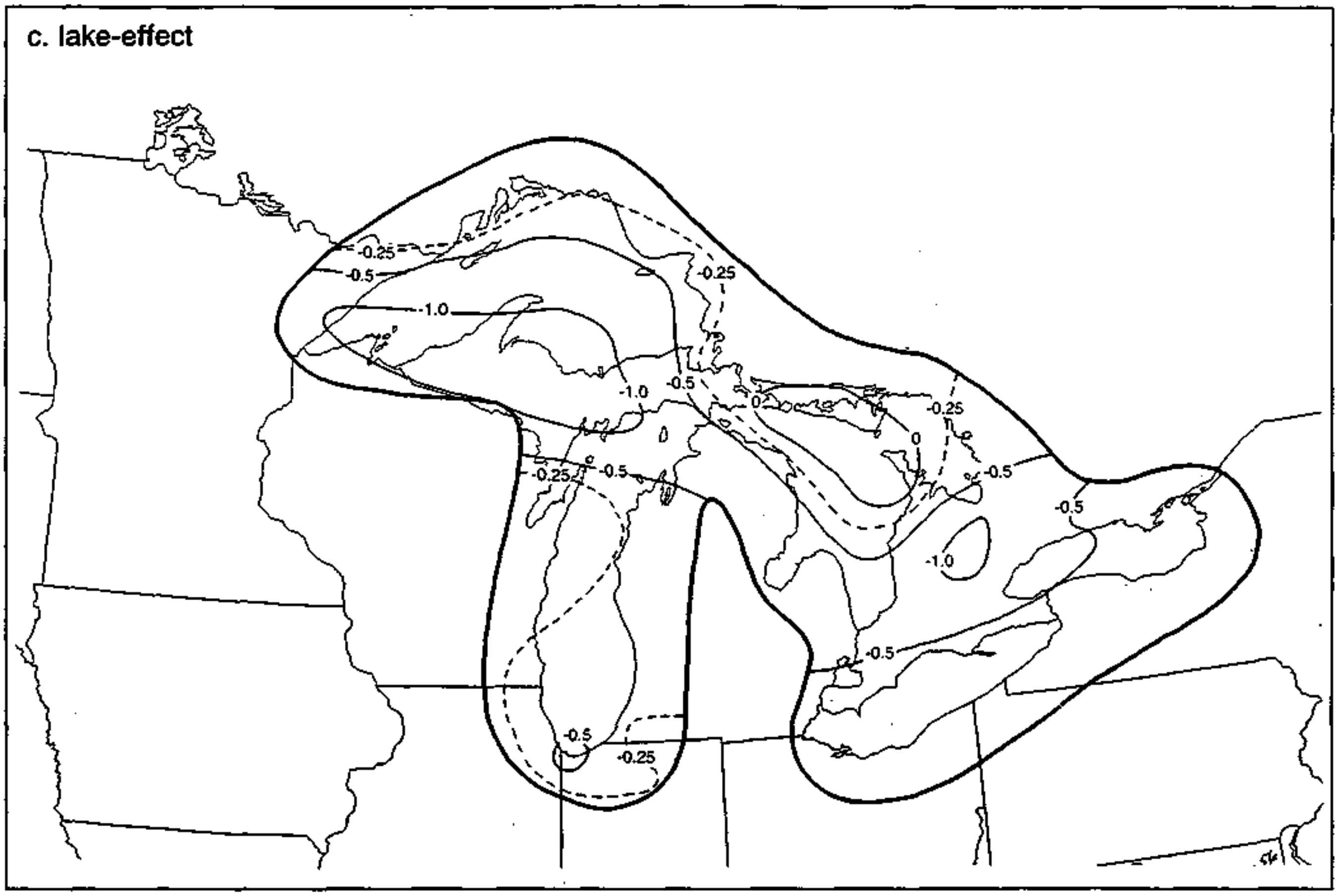
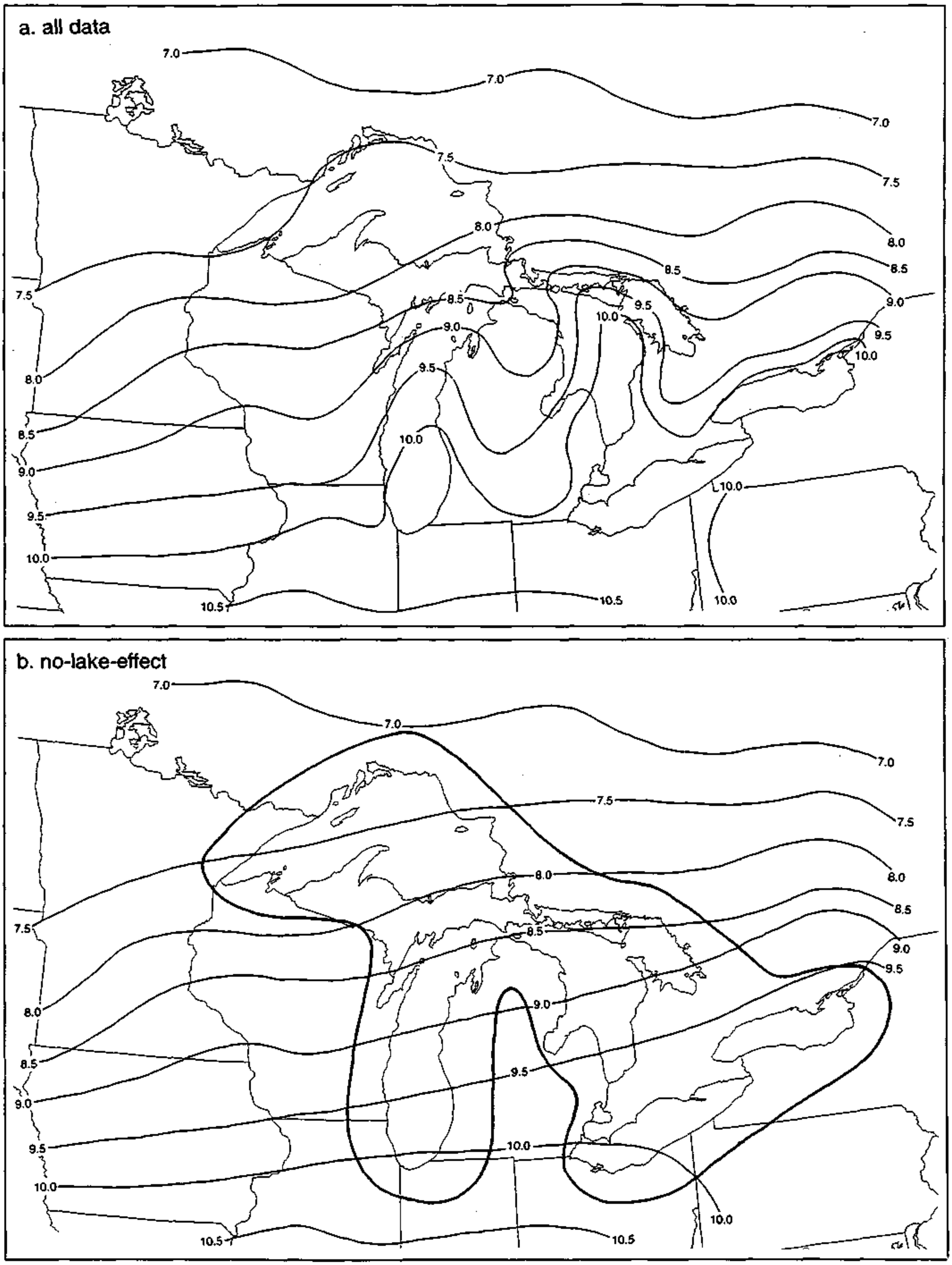



Figure 19. Average vapor pressure (millibar) over the Great Lakes basin for summer: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.


a. all data
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7.0
7.0
7.5
7.5
8.0
8.0
8.5
8.5
9.0
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10.0
10.0
7.5
8.0
8.5
9.0
9.5
10.0
10.0
10.0
10.5
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10.0
b. no-lake-effect
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7.0
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8.0
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10.5

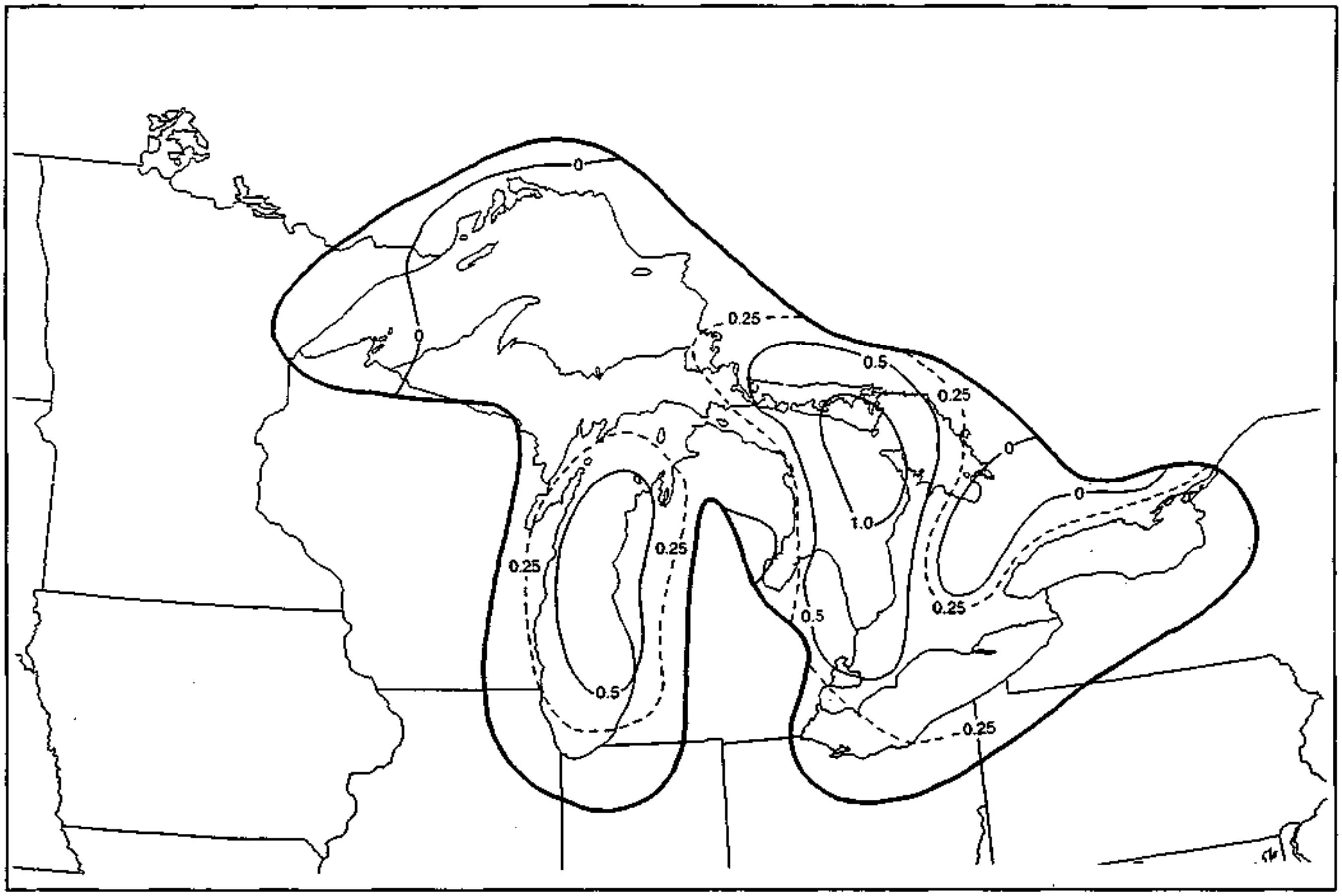


Figure 20. Average vapor pressure (mb) over the Great Lakes basin for autumn: a) using all data, b) using only data outside the 80-kilometer (km) lake-effect boundary (no lake effect), and c) showing the lake effect. The heavy line (b and c) represents the 80-km lake-effect boundary.

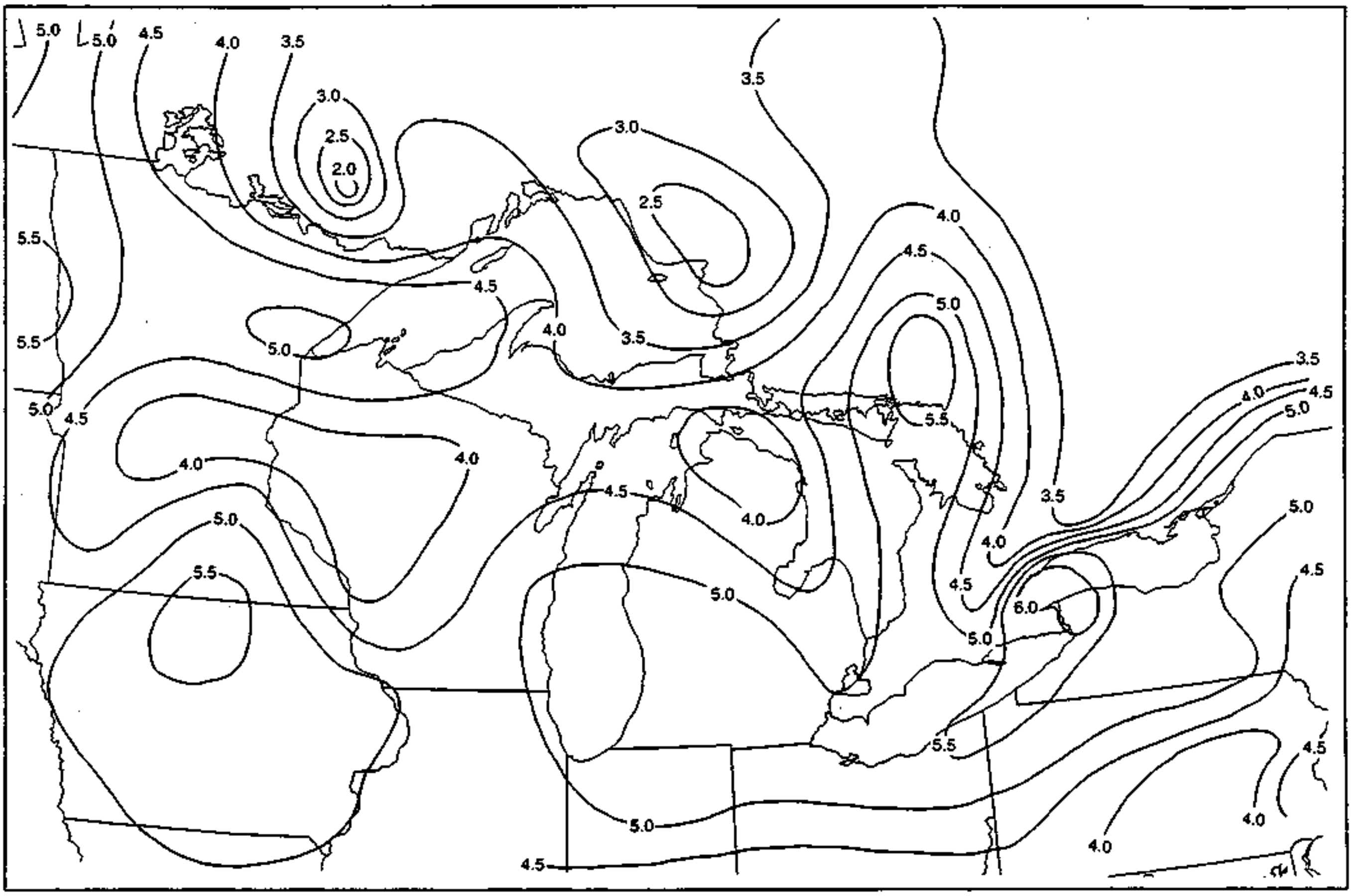


Figure 21. Average wind speed ($ms^{1}$) over the Great Lakes basin for winter: all data only.

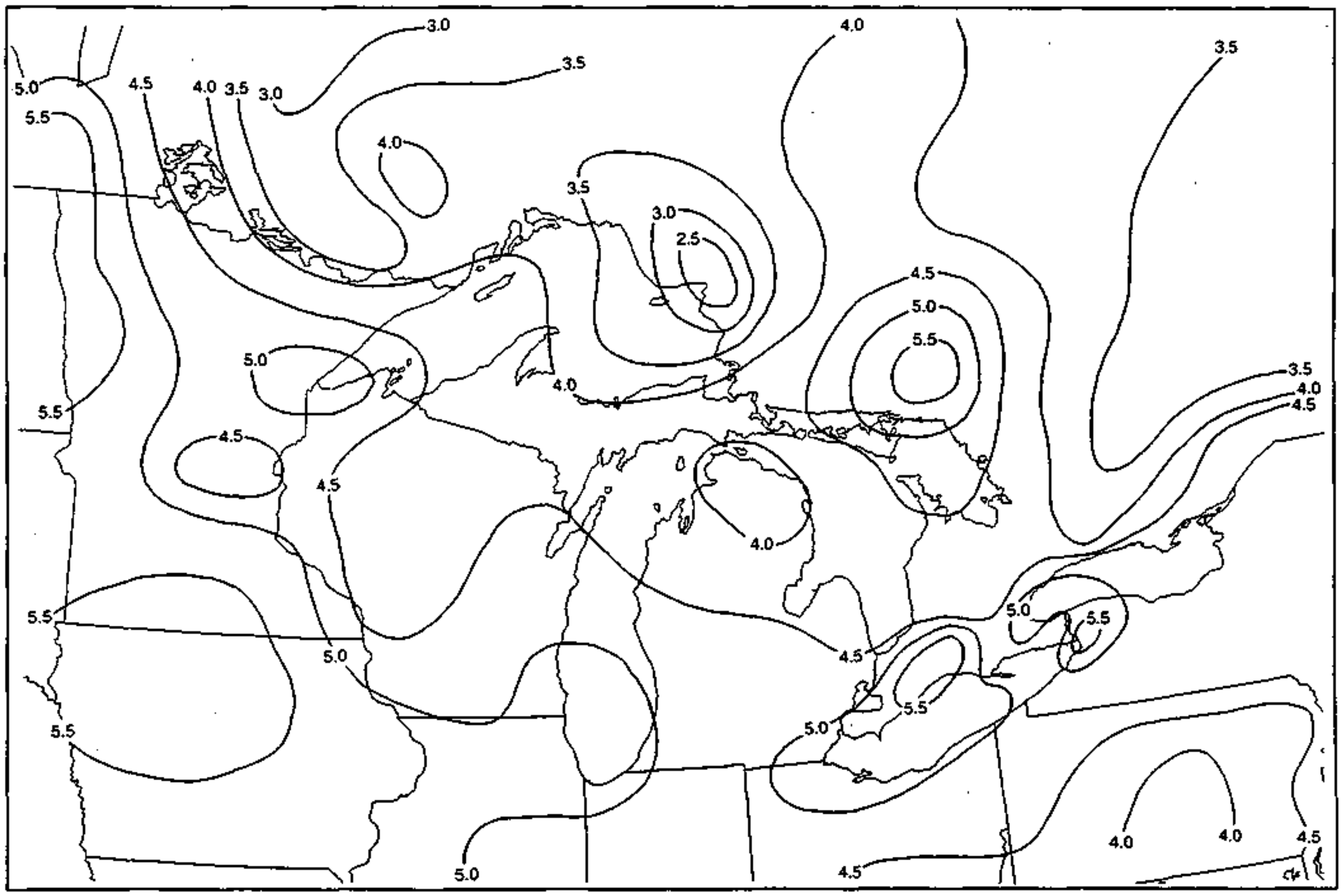


Figure 22. Average wind speed (ms$^{1}$) over the Great Lakes basin for spring: all data only.

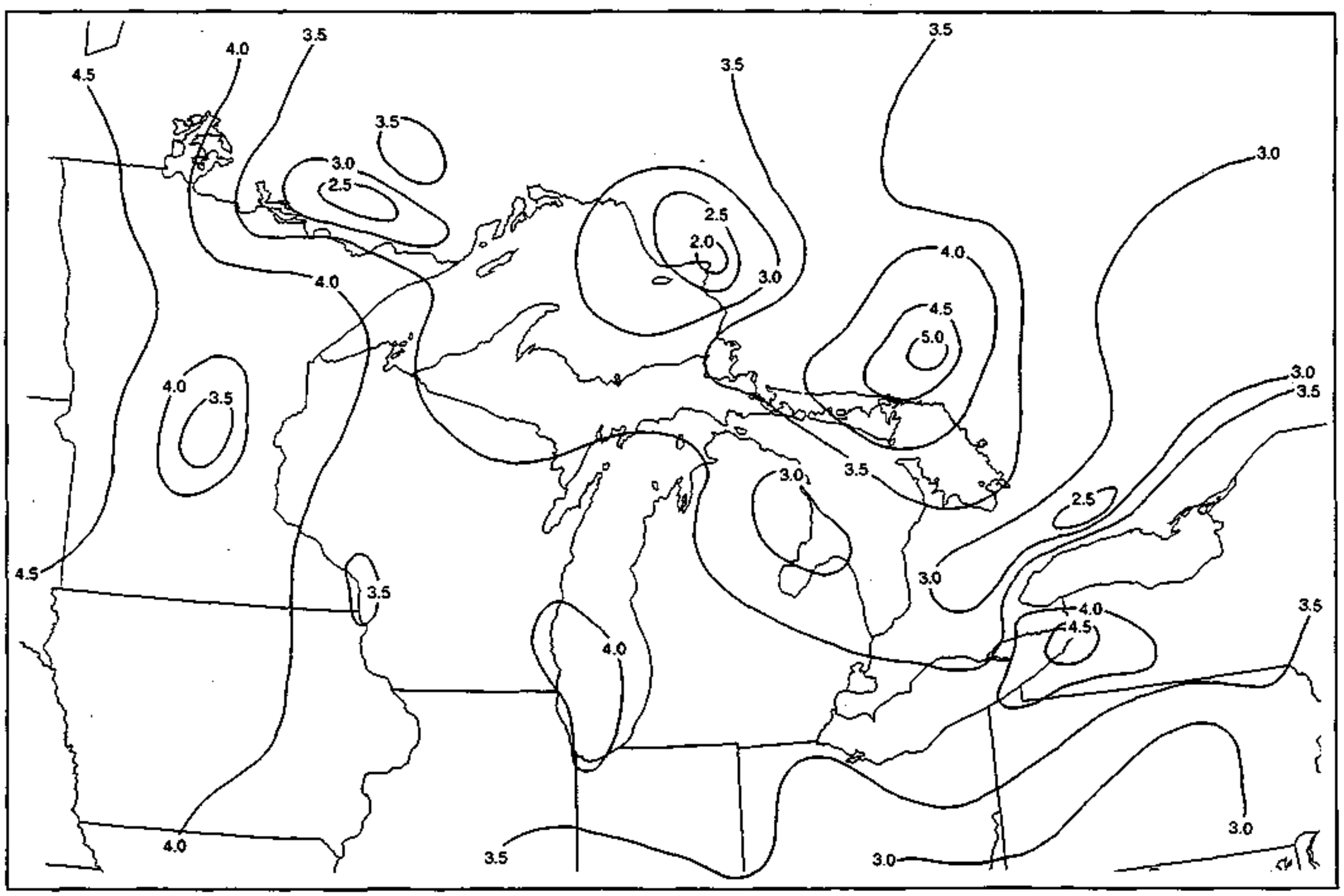


Figure 23. Average wind speed (ms[1]) over the Great Lakes basin for summer: all data only.

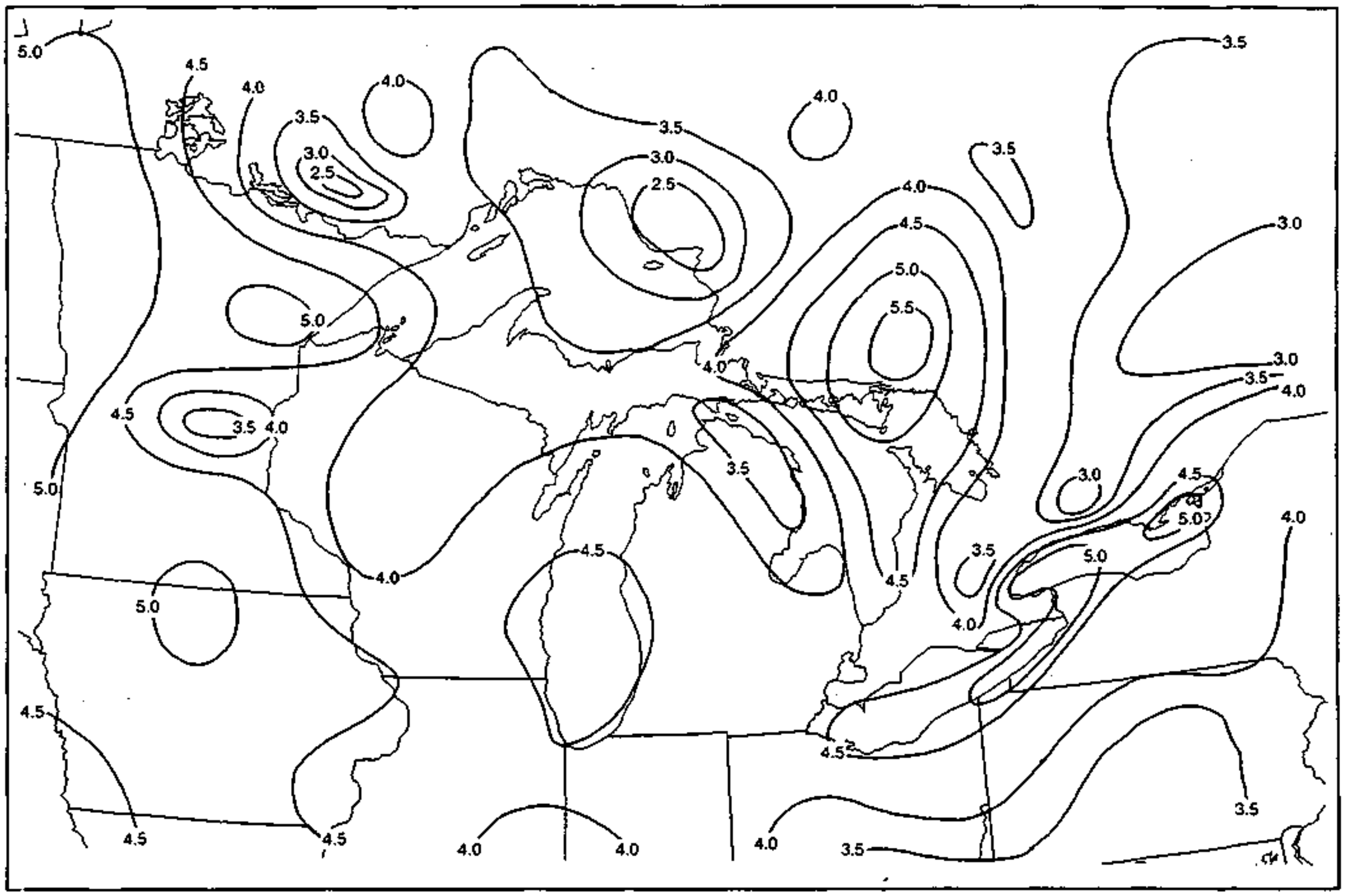


Figure 24. Average wind speed ($ms^{1}$) over the Great Lake basin for autumn: all data only.

## SUMMARY AND CONCLUSIONS

Average spatial distributions of seasonal climate conditions over the Great Lakes basin were investigated to derive estimates of lake-induced changes for six weather conditions: precipitation, mean maximum and mean minimum temperatures, cloud cover, vapor pressure, and wind speed. Lake influences were estimated by first analyzing each condition using all data within the basin, and then performing a second analysis that eliminated data within an 80-km buffer zone around the lakes, a zone assumed to encompass all lake-induced effects. Quantitative measures of lake effects were obtained by a comparison of these two analyses.

The intent of the research was to remove substantial lake effects from the climatic record, leaving primarily the synoptically based influences. Aggregate lake effects likely were not resolved adequately by this research as was observed in some analyses. However, the use of an 80-km band around the Great Lakes to encompass all local lake effects appeared to be sufficient. Discrimination between lake effects and topographical influences on climate conditions, especially large just east of the basin, was not undertaken.

In general, results confirm theory and analyses from previous research. Observed differences between this study and those in the past are likely due to natural temporal and spatial variability of the different investigations. Due to the strong subjective nature of the various analyses, it would be difficult to suggest any one study as presenting a more accurate analysis. This is also the first analysis to specify seasonal influences by all lakes on these conditions for the entire basin.

The influence of the lakes were most noticeable on precipitation and temperature, but were observed in several other climate conditions. As expected, there are considerable variations in the effects between seasons. Table 1 summarizes over-lake precipitation, expressed as percent of change attributed to lake effects. The presence of the lakes results in greater precipitation primarily during winter and autumn when lakewaters are typically much warmer than the air flowing over the lakes, a condition providing moisture to enhance clouds and precipitation. In all seasons, effects are greatest over Lake Superior due to its large size and east-west orientation (parallel to prevailing westerly winds). These factors maximize the time for air to reside over the lake, leaving ample opportunity for modification. In winter, precipitation near Superior's eastern shore is more than double what is expected without the presence of the lake. The effects of Lakes Michigan and Huron during this season are also substantial. The rapid increase in elevation of the Appalachian Mountains has a great influence on precipitation departures east of Lakes Ontario and Erie, masking the effects due solely to the lakes.

Influences of the other lakes and during the remaining seasons are generally much less but still considerable. Springtime lake effects on precipitation vary across the basin from a continued large increase over the more northerly Lake Superior, to decreases in rainfall over Lakes Michigan and Ontario where the warm season pattern has been initiated. This standard progresses to all lakes during summer when the lakes act as a cooling and stabilizing force on the lower atmosphere, and thereby decrease connective rainfall. In general, analyses during all seasons indicate the greatest modification occurs over and just downwind (to the east and southeast) of all lakeshores while upwind regions are only minimally affected.

**Table 1. Approximate Seasonal Change in Precipitation (in percent) of the No Lake Effect Amount for the Great Lakes by Season.**

| *Lake* | *Winter* | *Spring* | *Summer* | *Autumn* |
|---|---|---|---|---|
| Superior | 105 | 30 | -20 | 50 |
| Michigan | 35 | -15 | -10 | 25 |
| Huron | 60 | 0 | -20 | 15 |
| Ontario | 30 | -15 | -20 | -5 |
| Erie | 25 | 10 | 0 | 15 |

Lake-induced changes in temperature vary considerably between both seasonal and diurnal values. Table 2 represents maximum seasonal departures found over any portion of each lake. Lake effects on mean minimum temperatures result in warmer conditions during all seasons and over all lakes. Conversely, the influence of the lakes on mean maximum temperatures results in cooling during spring and summer, additional warming in winter, and essentially no effect in autumn. Not unexpectedly, due to its large mass and specific heat capacity, the greatest absolute changes occur over Lake Superior in both mean minimum temperature during winter and mean maximum temperature during summer. Similarly, effects generated by Lake Erie exhibit the least lake influence due to the lake's smaller size and depth and, therefore, a tendency to more quickly parallel changes in air temperature over land. For the basin as a whole, smallest effects occur in spring (mean niinimum temperatures) and in autumn (mean maximum temperatures), both transitional periods.

Seasonal values of cloud cover, vapor pressure, and wind speed were computed from hourly data and were derived from a much reduced station density than that used in assessing precipitation and temperature. Nevertheless, Table 3 summarizes measurable lake influences. Cloud cover levels parallel the precipitation and temperature results. Cloudiness is heavily influenced by the lakes during winter due to the vast moisture and heat source the lakes present to the cold, dry continental polar air masses that move them, substantially increasing average cloud cover. Once again as expected, maximum effects occur over the larger lakes. Conversely, summertime cloudiness is reduced by the lakes due to increased stability imparted to the lower atmosphere from relatively

**Table 2. Maximum Temperature Departure (°C) Attributed to Lake Effect for the Great Lakes by Season.**

| | *Mean minimum temperature* | | | | *Mean maximum temperature* | | | |
|---|---|---|---|---|---|---|---|---|
| *Lake* | *Winter* | *Spring* | *Summer* | *Autumn* | *Winter* | *Spring* | *Summer* | *Autumn* |
| Superior | 8 | 3 | 0 | 3 | 2 | -3 | -6 | 0 |
| Michigan | 4 | 1 | 2 | 3 | 2 | -4 | -4 | 0 |
| Huron | 4 | 1 | 3 | 4 | 1 | -3 | -3 | 1 |
| Ontario | 2 | 1 | 3 | 3 | 1 | -1 | -2 | 1 |
| Erie | 1 | 1 | 3 | 2 | 0 | -2 | -2 | 0 |

**Table 3. Maximum Departures in Cloud Cover and Vapor Pressure (percent) Attributed to Lake-Effects for the Great Lakes by Season.**

| | *Cloud cover* | | | | *Vapor pressure* | | | |
|---|---|---|---|---|---|---|---|---|
| *Lake* | *Winter* | *Spring* | *Summer* | *Autumn* | *Winter* | *Spring* | *Summer* | *Autumn* |
| Superior | 2 5 | 0 | 0 | 0 | 0 | 4 | -8 | 3 |
| Michigan | 25 | 0 | -9 | 11 | 15 | 0 | -6 | 6 |
| Huron | 15 | 0 | -12 | 0 | 17 | 0 | 0 | 12 |
| Ontario | 7 | 0 | 0 | 5 | 14 | 0 | -4 | 3 |
| Erie | 7 | 0 | 0 | 5 | 0 | 0 | -2 | 3 |

cooler lake waters. Influences on cloud cover in summer are not as evident as those during winter since the summertime cloud reductions generally occur much closer to the lakeshore than in winter. The current data network is likely insufficient to totally resolve the actual condition of this smaller spatial event. In addition, summertime cloudiness is strongly related to diurnal heating, whereas the conditions controlling increases in wintertime cloud cover are also active nocturnally. Thus, averaging of hourly data in the analysis reduces the lake influence on clouds in summer.

Average vapor pressure values show strong lake influences (higher values) across the central part of the basin during winter and autumn when temperature differences over lakes and over land are high, providing a strong concomitant effect on vapor pressure. Although actual vapor pressure is higher in summer than in winter, moisture sources from evaporation and transpiration over the land in warm seasons are comparable to lake evaporation, keeping the differences across their boundaries small. This is not the situation in winter when very dry continental polar air masses lie adjacent to the strongly modified air over the lakes. Summertime decreases are highest near Lakes Superior and Michigan. Both of these large lakes have a long lag time for seasonal warming, thus holding down vapor pressure. As with cloud cover, lake influences on vapor pressure are minimal during spring when lake effects make the transition between positive and negative influences.

Seasonal wind speed patterns were considered insufficient to determine lake influences. The data suggest that site exposure at many sites renders the data incomparable for such analyses. Indeed, the lack of good quality, long-term climate data within a high station density network across the entire basin is a limiting factor for an improved future analysis in all climate parameters. Many lake influences are much more localized than is resolvable by the data set used in this research. This is especially true in the documentation of cloud cover, vapor pressure, and wind speed, but also in determination of precipitation and temperature variations in sub-basins around the lakes.

One suggested future study would be a cloud climate investigation using infrared satellite imagery over the region as the period-of-record for these data increases towards an acceptable climate norm. Improved sensors within current and future satellite imagery and NEXRAD radar facilities, combined with enhanced surface measurements, should assist in quantifying conditions in areas lacking data. Perhaps, by limiting data to a time period shorter than 30 years, a substantial increase in the number of sites may be possible while still preserving the integrity and extent of lake influences. Development of an alternative technique to incorporate greater resolution of aggregate lake effects would also be beneficial.

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