Soils Cool as Climate Warms in the Great Lakes Region: 1951–2000

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We modeled soil temperatures at 50-cm depth, using 1951–2000 air temperature and precipitation data from 194 National Weather Service stations in Wisconsin and Michigan. The accuracy and bias of the physical model used in this study were validated by comparing its output data to 22,401 actual soil temperature readings taken from sandy soils at thirty-nine forested sites throughout northern Michigan; the model was shown to have almost no temperature bias. Although mean annual air temperatures across the region show no strong spatial or temporal trends over the fifty-year period, at many sites, especially in Wisconsin, *wintertime* air temperatures have been *increasing* slightly in recent years. Conversely, mean annual *soil temperatures* have been *decreasing* at most sites in the region, some by more than 0.5°C. Likewise, wintertime soil temperatures are also decreasing, especially at sites downwind from the Great Lakes—many of which are in snowbelt locations. Increasing wintertime air temperatures over the past fifty years coincide with (and probably have led to) more variable and thinner snowpacks, lessening their insulating impact and contributing to decreasing wintertime soil temperatures that our model show are occurring in the eastern and northern parts of the region. These findings illustrate the complex response of natural systems to slow atmospheric warming, and draw attention to the potential changes that are occurring in growing season characteristics, phenology, and spring runoff characteristics in the Great Lakes region. *Key Words: climate, global change, Great Lakes region, lake-effect snow, soil temperatures*.

Historical air temperature data series indicate that the climate of the Great Lakes region has been warming over the past few decades, especially in spring and winter (Bolsenga and Norton 1993; Magnuson et al. 1997; Sousounis and Albercook 2000). Proxy climatic data, gleaned from physical and biotic systems that respond slowly but predictably to long-term temperature change, are a second approach to characterizing these types of trends, especially over long time periods (Parmesan and Yohe 2003; Schwartz 2003). These types of data confirm the slow, regional warming trend. For example, increasing winter and spring temperatures have resulted in earlier phenological development of both natural (Schwartz and Reiter 2000) and agronomic (Andresen and Harman 1994) perennial plant species during the past few decades. Similarly, data collected from inland lakes in the Great Lakes region show noticeable declines in ice cover since 1950 (Assel and Robertson 1995). Lastly, various projections from climate general circulation models also suggest that the climate of the region will continue to warm in the future as CO_2 levels increase (Magnuson et al. 1997).

The response of biological and physical systems to increased temperatures is highly complex (Burnett et al. 2003; Schwartz 2003). The focus of many studies has, therefore, been on the potential biological and human responses to these climate variations (Solomon and Bartlein 1992; Peñuelas and Flella 2001). Our focus is the response of the soil system, particularly soil temperatures, to changing air temperature and snowfall patterns for the period 1951–2000, in the Great Lakes region.

Like open water, soil is a buffered system that may respond slowly to changes in atmospheric climate, and it is therefore a potentially excellent proxy indicator of climatic (temperature) change (McCormick and Fahnenstiel 1999). The soil is also a key, complex earth system to study in this regard, as soil temperatures are impacted by a number of variables in addition to air temperature, including vegetative ground cover, snowpack thickness and density, and soil water content (Smith 1986; Isard and Schaetzl 1995, 1998; Wahren, Walker, and Bret-Harte 2005). In turn, soil temperatures have measureable, direct impacts on agronomic and natural ecosystems (Larsen et al. 1988; Johnsson and Lundin 1991; Berry and Radke 1995; Schaetzl and Isard 1996), and on such parameters as CO_2 and N release, plant growth, and ecosystem health (Lükewille and Wright 1997; Schwarz, Fahey, and Dawson 1997; Davidson, Trumbore, and Amundson 2000; Wang,

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Amundson, and Niu 2000; Rodeghiero and Cescatti 2005). For example, recent, widespread declines in snowpack thicknesses in the mountains of the western United States and Europe, presumably due to increasingly warmer winters, have led to colder soil temperatures and reduced amounts of CO_2 loss from soils by wintertime respiration (Monson et al. 2006). Soil temperature data are also important for estimating evaporation rates, mineral weathering rates, freeze-thaw processes, and frost development within soils (Stein, Proulx, and Levesque 1994). Indeed, Gilichinsky et al. (1998) argued that soil, not air, temperatures should be used to gauge trends in global climate change, as the former are more integrative and less volatile.

The purpose of our study is to report on modeled soil temperature patterns for the last half of the twentieth century in the northern Great Lakes region, and to explain these patterns based on our best understanding of their related physical systems.

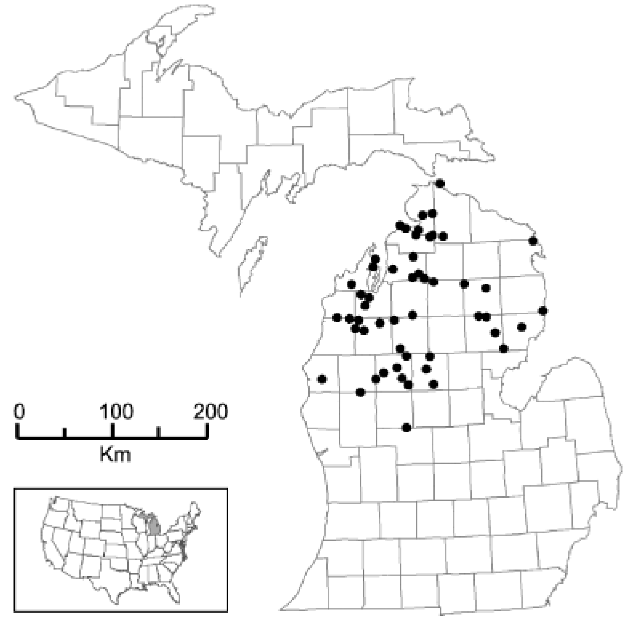

Figure 1. Locations of the thirty-nine sites at which soil temperatures were monitored, data from which were used to validate and test the soil temperature model.

Measurements and Methods

This modeling study begins with air temperature and precipitation data from 194 National Weather Service (NWS) stations in the Great Lakes region, and uses these data as inputs to a physically based computer model that calculates instantaneous soil temperatures at 50-cm depth. In this article we provide only the basic workings and assumptions of the model, and refer the reader to Schaetzl, Knapp, and Isard (2005) for details.

The use of biophysical models to determine soil temperatures at various depths and at various times is now widely accepted in the literature (Bonan 1991; Isard and Schaetzl 1993; Hinzman, Goering, and Kane 1998; Schaetzl, Knapp, and Isard 2005). Our model has a long and successful history, having been developed in the early 1990s and calibrated using soil temperature measurements collected over several years at "soil temperature network" sites throughout northern Michigan (Isard and Schaetzl 1993, 1995; Schaetzl and Isard 1996; Schaetzl, Knapp, and Isard 2005). This network, which has evolved over time, eventually expanded to include thirty-nine sites where soil temperatures at 50-cm depth are recorded (Figure 1). All of these sites are located in well-drained soils, under mature or nearly mature broadleaf or mixed broadleaf-coniferous forest. Outputs from the soil temperature model were compared to 22,401 soil temperature observations, taken at the thirty-nine network sites from 1997 through the end of 2000, to establish its accuracy and bias. These comparisons indicate that the predicted soil temperatures are remarkably accurate and unbiased (Table 1).

Data

We used NWS daily maximum and minimum air temperatures and precipitation data from 194 stations in Wisconsin and Michigan as model inputs (Figure 2). Because there are occasional missing values in the 1951–2000 data for most stations, as obtained from the National Climatic Data Center in Asheville, North Carolina, we developed a "buddy" system for estimating missing temperature and precipitation data (Schaetzl, Knapp, and Isard 2005). Eventually, we developed a complete data temperature and precipitation set (free of missing values) for the 194 NWS stations in the study area (70 in Michigan's lower peninsula, 19 in Michigan's upper peninsula, and 105 in Wisconsin).

Table 1. Error statistics for the soil temperature model

Period of measurement	No. of observations	RMSE[a] (°C)	MBE[a] (°C)
Entire period (annual)	22,401	1.5	0.0
Warm season (May–Oct)	11,142	1.9	– 0.1
Cold season (Nov–Apr)	11,259	1.1	0.0

Note: Model output versus actual soil temperatures (at 50-cm depth) was measured at thirty-nine Michigan locations. After Schaetzl, Knapp, and Isard (2005). RMSE = root mean square error; MBE = mean biased error.
[a]A positive error or bias indicates that the model predicted higher temperatures than actually existed in the field. Negative errors or biases indicate the opposite.

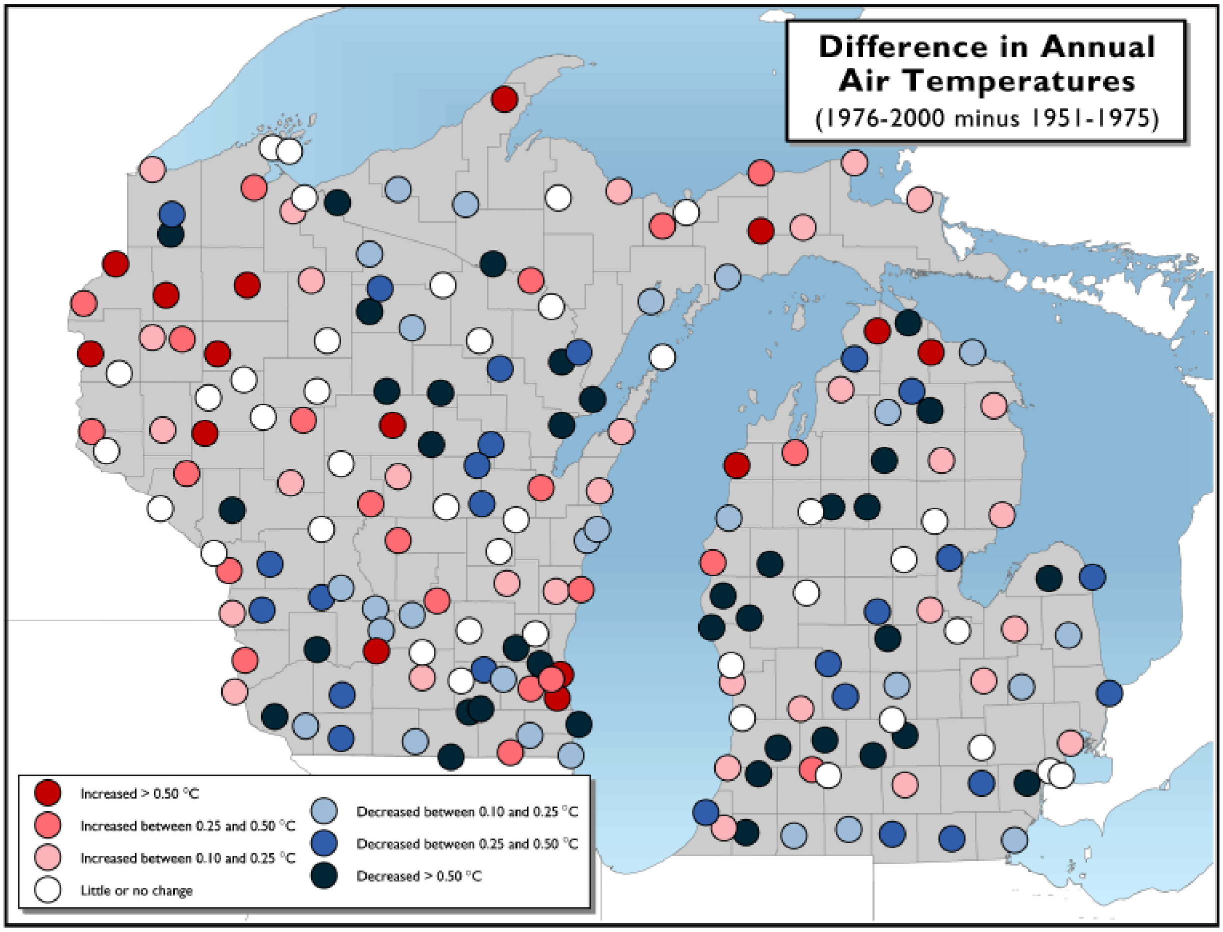

Figure 2. Mean annual air temperatures for 194 sites within the study area, compiled by comparing 1976–2000 data to data for 1951–1975.

Beginning in 1997, our manually operated soil temperature network (Isard and Schaetzl 1993, 1995; Schaetzl and Isard 1996) was replaced by an automated network of soil temperature stations; this network would eventually grow to include thirty nine stations throughout northern Michigan. At each site, a representative upland, forested location on a slope of <5 percent was first identified, then a copper-constantan thermocouple was installed at 50 cm by placing it $\approx$ 15-cm horizontally into the face of a small pit. The 50-cm depth was chosen because it is the depth below which diurnal temperature fluctuations are damped out (Smith et al. 1964). The thermocouple was connected to a small data logger, set to record the soil temperature at two-hour intervals. Data were downloaded annually in the field to a laptop computer. Missing data due to equipment failure or vandalism were common, but gaps in the data set did not greatly affect the research because we only used these data to establish the accuracy of the model. The actual, instantaneous soil temperature data, totaling 22,401 observations from 1997–2000, were then compared to output from the soil temperature model as a means of establishing its accuracy and bias.

The Model

The physically based model uses vertical profiles of soil water content and temperature, calculated using a modified form of a soil water and temperature algorithm (Schaetzl and Isard 1991, 1996; Isard and Schaetzl 1993, 1995). It uses a Newhall-based, water budget component (Van Wambeke, Hastings, and Tolomeo 1986), combined with a snowmelt model (USDA-SCS 1971) and a one-dimensional heat conduction equation (Carslaw and Jaeger 1959). It is formulated with twenty 5-cm-thick soil layers, five additional soil layers that increase in thickness with increasing depth, one litter layer, and up to ten snowpack layers. Basic to the model are its use of soil hydrologic and thermal properties for coarse-textured soils, which dominate large parts of the region. The state (liquid vs. solid) and amount of precipitation reaching the forest floor via stemflow and throughfall is calculated as a function of air temperature, precipitation amount, and various forest hydrology equations (Schaetzl and Isard 1996). This water is stored in a snowpack if air temperatures are below freezing; otherwise it is immediately made available to the soil. Snowmelt is calculated as a function of air temperature; meltwater and precipitation are made available for storage in the litter and/or soil layers. Liquid throughfall can be stored in the forest litter; the water storage capacity of the litter and soil layers are specified in Schaetzl and Isard (1996). Thornthwaite and Mather's (1955) formula for potential evapotranspiration (PE) was used to determine the daily amount of water removed from the litter and soil layers. Water stored in the litter and uppermost soil layer is used in the PE calculation. When PE exceeds the amount of water stored in the litter and uppermost soil layer, the excess water is removed from lower layers (Van Wambeke, Hastings, and Tolomeo 1986). Water is sequentially withdrawn from the layers by assuming a linear relationship between the ratio of water removal to PE and available water (Baier and Robertson 1966).

Temperature in the deepest (7–15 m) soil layer is held at 2°C above the mean annual air temperature (Smith et al. 1964; Geiger 1965). Temperatures at the litter or snow surface are calculated using a truncated harmonic function of time for daytime and an exponential function of time for nighttime (Parton and Logan 1981). Thermal properties for soil, litter, and snowpack are taken from van Wijk and de Vries (1963). Thermal conductivities and volumetric heat capacities for the soil layers are specified as a function of soil water (Lowrey and Lowrey 1989). A finite difference formulation is used to calculate the temperature profile within the mineral soil at 20-minute intervals.

Results and Discussion

In our distinctly geographic and qualitative modeling approach, patterns are determined and then interpreted in light of the processes that have driven them. Previously published results indicate that our model accurately predicts soil temperatures for northern Michigan, and that it is essentially unbiased (Isard and Schaetzl 1995; Schaetzl and Isard 1996; Schaetzl, Knapp, and Isard 2005). We see no reason that it cannot function equally well and be extrapolated across both Wisconsin and the upper peninsula of Michigan, where climate and soils are reasonably similar (Schaetzl, Knapp, and Isard 2005).

Mean bias errors of the model show only a small "cold" bias in summer—that is, the model predicts soil temperatures to be, on average, 0.1°C colder in summer than they actually are (Table 1). Important to this study is the absence of a bias in the annual soil temperature series, and in winter (Schaetzl, Knapp, and Isard 2005).

Because our period of record is longer than many climate studies (50 vs. 30 years), we felt that a comparison of the first and last twenty-five years of record would be a reasonable way of examining temporal trends in soil and atmospheric climate. This type of analysis, when done over only thirty years of record, could potentially be overinfluenced by decadal-length trends in climate. We assumed that the fifty-year climate record used in our study would minimize that potential problem and allow us to ascertain "real" longer-term temporal trends in the regional climate.

Annual air temperature differences between the first twenty-five and last twenty-five years of the fifty-year period of record suggest no clear spatial trends, and exhibit the expected amount of spatial "noise" (Figure 2). Of the seven temperature change categories in Figure 2, the largest is "little or no change" (thirty-nine stations), and each category had a minimum of fifteen stations that fit within it. A spatio-temporal trend of decreasing temperatures in the eastern part of the region (81 percent of the stations in lower Michigan exhibited decreased air temperatures or "no change"), coupled with increasing air temperatures in the west (64 percent of the stations in Wisconsin exhibited increased air temperatures or "no change") may exist, but the pattern is not convincing, largely because each of these two regions includes many stations that exhibit the *opposite* temperature trend.

Wintertime (Dec–Mar) air temperature trends are, however quite clear; increases in temperature have occurred across the region, especially in western and southern Wisconsin (Figure 3). Winters in the region appear to be warming, although, again, while rising air temperatures appear to be more prominent in the western part of the region, all areas in the region show generally higher air temperatures. Only 29 percent of the stations in the study area exhibited decreasing wintertime air temperatures—most of these are in southern Michigan (Figure 3). Remarkably, at ten stations the wintertime trend of increasing air temperatures exceeded 1.0°C over the past fifty years. If the 1984–2000 winter air temperature data are compared to those for 1951–1966 (data not shown), the trend is even more obvious; air temperatures at forty-six stations increased by >1°C, and at thirteen stations air temperatures were >1.5°C higher. Thus, it is clear that wintertime air temperatures are increasing across the Great Lakes region.

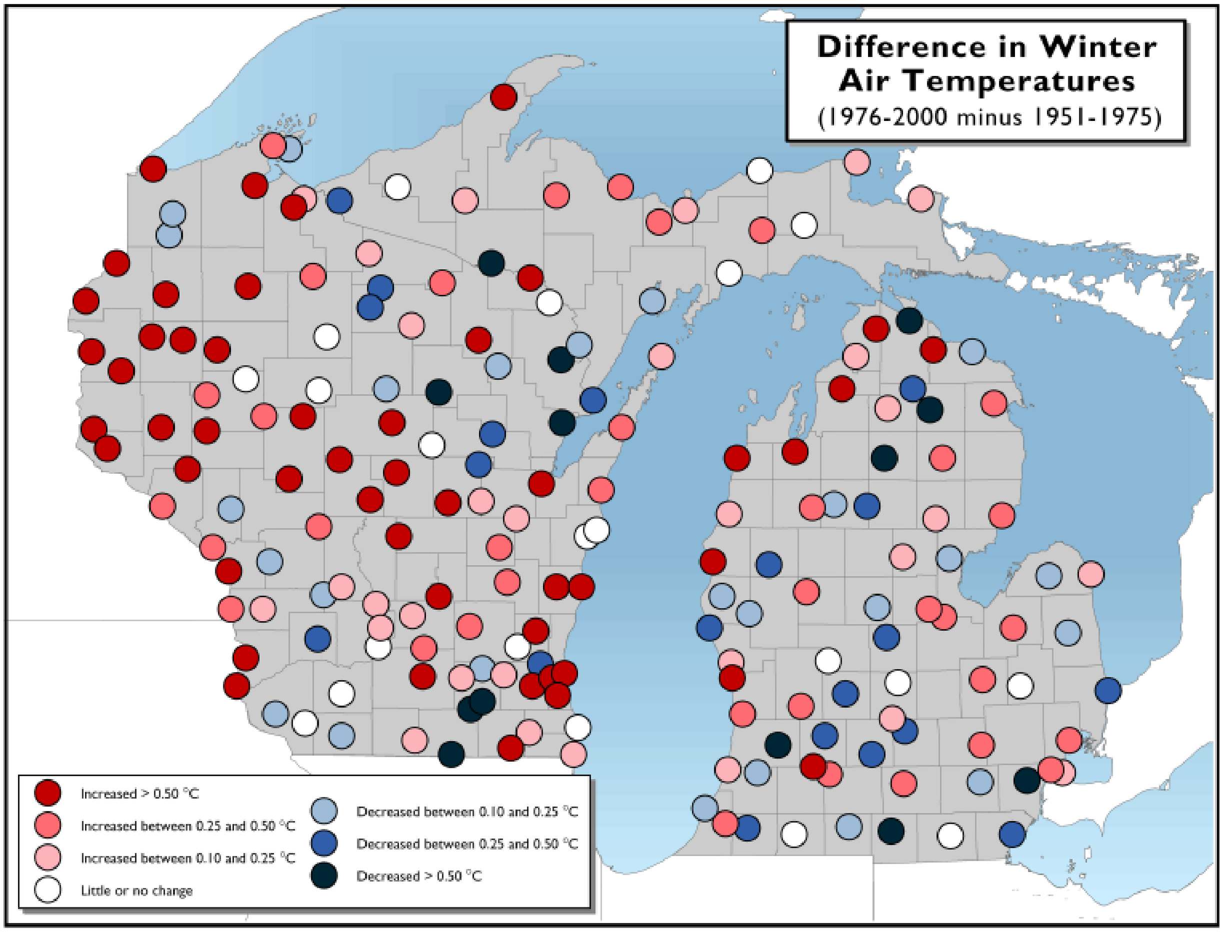

Figure 3. Mean winter (December–March) air temperatures for 194 sites within the study area, compiled by comparing 1976–2000 data to data for 1951–1975.

The response of *soil* temperatures to the changing *air* temperatures in this region is complex, being largely dependent on snowpack thicknesses and persistence, and in our study area the response was somewhat unexpected. At most (86 percent) of the NWS sites, annual soil temperatures had either decreased or exhibited "little or no change" (Figure 4). An increase of >0.5°C was found at only one site, whereas thirty-eight sites showed decreasing soil temperatures of this magnitude or greater. Although decreases in annual soil temperatures are widespread across the region, they are most pronounced in southern Michigan, where at only five sites (out of seventy) had soil temperatures fallen by >0.10°C. Thus, the general trend in annual soil temperatures across the region during the 1951–2000 period appears to be mixed, with many sites showing some cooling, but we emphasize that there is some evidence for possible warming soil temperatures in southern Michigan (Figure 4).

It is clear that for many stations in the study area most of the decrease in *annual* soil temperatures (Figure 4) is due to cooling *during the winter season* (Figure 5). Lower wintertime soil temperatures are especially pronounced in the eastern two-thirds of the region and in southern Michigan, where fifty-two of the seventy NWS sites exhibited decreased soil temperatures (Figure 5). Stations that exhibited the greatest increases in wintertime soil temperatures were almost exclusively located along the western edge of the region, near the Mississippi River (Figure 5). Many of the Michigan stations that showed the largest soil temperature decreases are located in the Lake Michigan and Lake Superior snowbelts, just to the east and south of the lakes, implicating snowfall totals and snowpack thicknesses as likely explanatory variables for the lower wintertime soil temperatures (Isard and Schaetzl 1995, 1998).

In order to evaluate temporal trends in soil temperature more robustly, we plotted the mean wintertime soil temperature for each station for each of the fifty years of

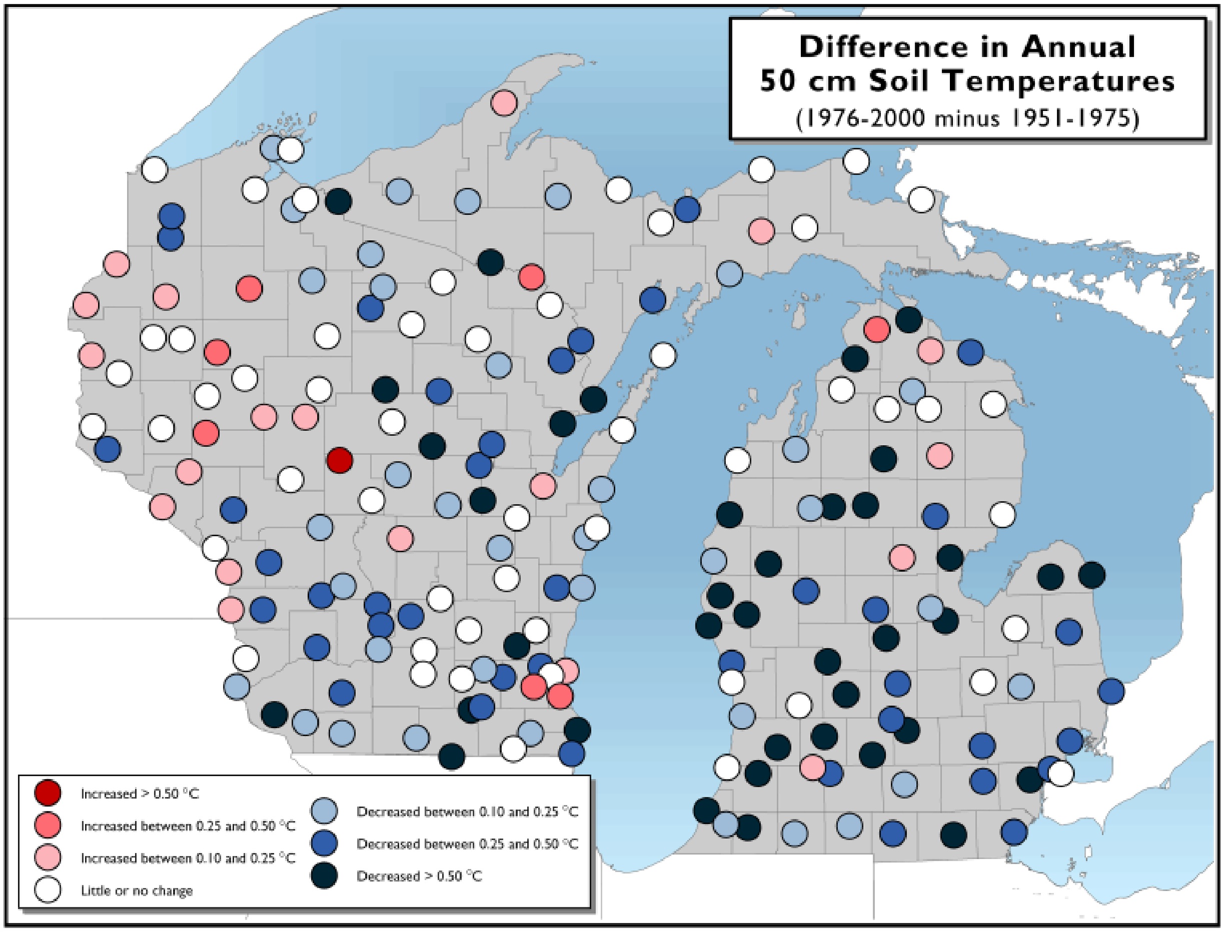

Figure 4. Mean annual soil temperatures, modeled for 50-cm depth, for 194 sites within the study area, compiled by comparing 1976–2000 data to data for 1951–1975.

record, and we fitted a least squares bivariate regression line to the scatter of points. We then evaluated the null hypothesis that the slope of these lines was equal to zero. Stations for which the hypothesis of zero slope was rejected—the slope was significantly different from zero at $P = 0.05$—are shown in Figure 6. For most stations (the open circles in Figure 6), the slope of the regression line was not significantly different from zero. Only two stations exhibited a positive slope for wintertime soil temperature, whereas sixty-one stations, most of which are in Michigan, showed a cooling trend. This analysis documents the cooling trend in soil temperatures during the period 1951–2000, especially for wintertime, across the eastern and northern parts of the region.

Of the possible reasons for the decreasing wintertime soil temperatures, the most likely cause is thinning, more variable snowpacks (Male and Granger 1981; Isard and Schaetzl 1995, 1998), since lower wintertime air temperatures can be eliminated as a cause (Figure 3). This hypothesis is supported by the distribution of sites that have had decreased wintertime soil temperatures; most are in snowbelt, or at least snowy, locations (Figure 6). Under warmer climatological conditions in winter, lake-effect snowfall amounts tend to decrease, and incidences of melting increase, leading to thinner snowpacks overall (Kunkel, Wescott, and Kristovich 2000). Thick, persistent snowpacks insulate the soil from subfreezing atmospheric conditions, but when they are thin or absent, soils can cool rapidly and deeply, especially in late winter and spring (Baker 1971; Schaetzl and Tomczak 2002). Climatological snowpack data are notoriously unreliable, with many missing data in the individual series, which thwarted our attempts to establish a statistical relationship between soil and air temperatures, and snow cover thickness and/or continuity. Nonetheless, it seems highly likely that increasing wintertime air temperatures across the region (Figure 3) have led to decreased incidence of thick snowpacks, or even continuous but thin snowpacks, which in turn has caused soils to cool, based both on inference and on our knowledge of the soil-atmo-

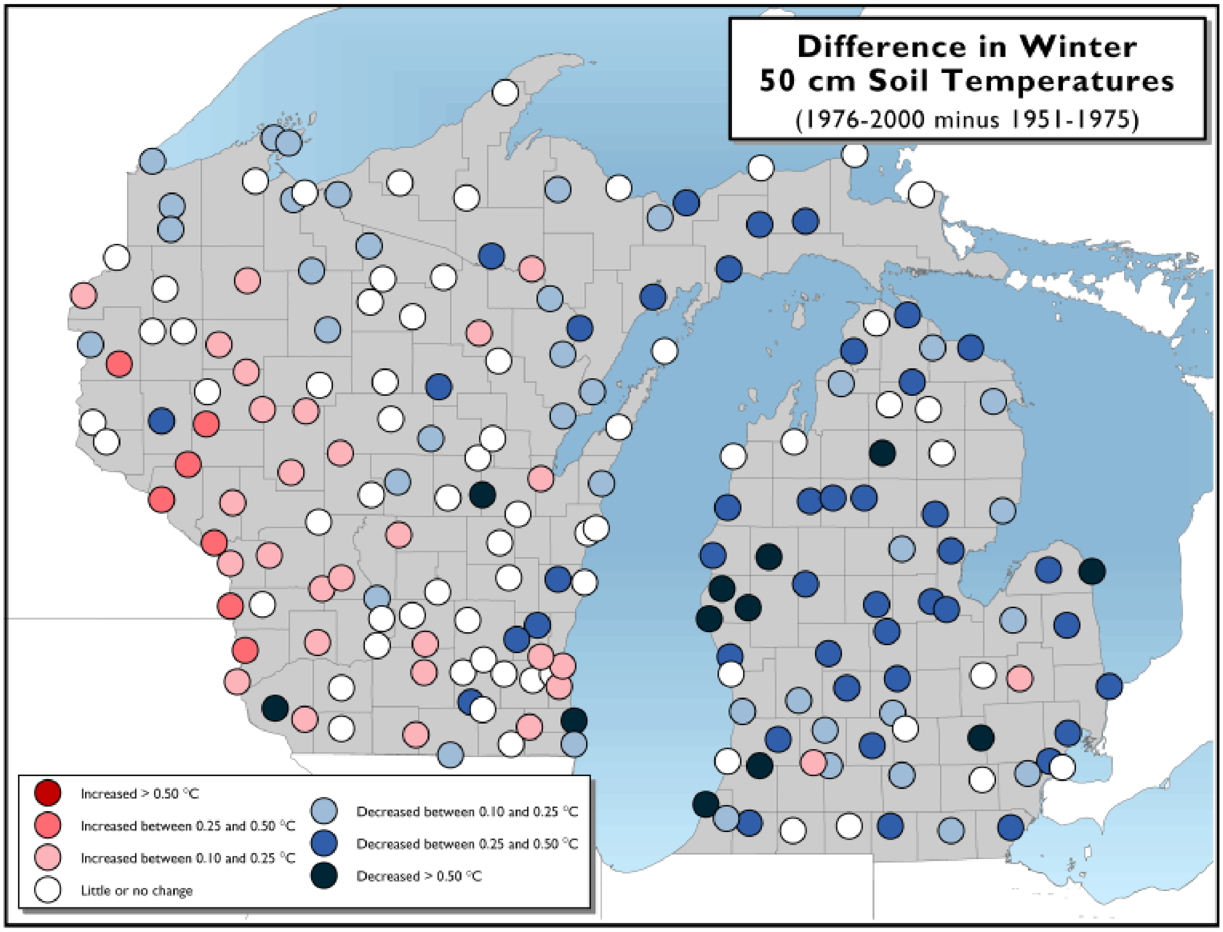

Figure 5. Mean winter soil temperatures, modeled for 50-cm depth, for 194 sites within the study area, compiled by comparing 1976–2000 data to data for 1951–1975.

sphere system. In this regard, the Great Lakes region is not unique; similar findings (thinner snowpacks) have been reported for mountainous regions of the United States and Europe, which have in turn led to decreased soil temperatures and reduced soil respiration (Monson et al. 2006).

Colder wintertime soil temperatures in the Great Lakes region, especially in areas where soils normally do not freeze due to reliable and thick snowpacks (Isard and Schaetzl 1998), suggest that contemporary (and future) soil freezing may be more widespread and deeper than in the past. Implications for this are myriad. Colder and more frequently frozen soils will favor runoff and soil erosion over infiltration and soil/groundwater recharge (Burt and Williams 1976; Schaetzl and Tomczak 2002). Colder soil temperatures may lessen respiration rates and release of CO_2 from soils in the region, and dramatically change soil carbon sequestration rates (Monson et al. 2006). Finally, some fauna (many of which are pathogens) that spend part or all of their life cycle in the soil and act as vectors for the spread of plant and animal diseases, may be impacted by the colder soils (Leather 1996). For example, insects such as the Japanese beetle (*Popilla japonica*), which overwinter in the soil as instars and are geographically limited by cold winter temperatures, may find their geographic ranges restricted or significantly altered (Fleming 1976; Allsopp 1996). Similar impacts may obtain for earthworms (Holmstrup 2003) and other soil fauna. Changes in wintertime soil temperatures may also influence crop disease risk, as exemplified by the corn flea beetle (*Chaetocnema pulicaria*), which serves as a vector for Stewart's bacterial wilt (a foliar disease of maize) and typically is a problem in the region following winters characterized by mild temperatures and relatively high insect survival rates (Esker and Nutter, 2002). In sum, soils appear to be cooling across the region, and especially in snowbelt areas. The implications of this trend, however small it may be, might be more complex and widespread than currently envisioned.

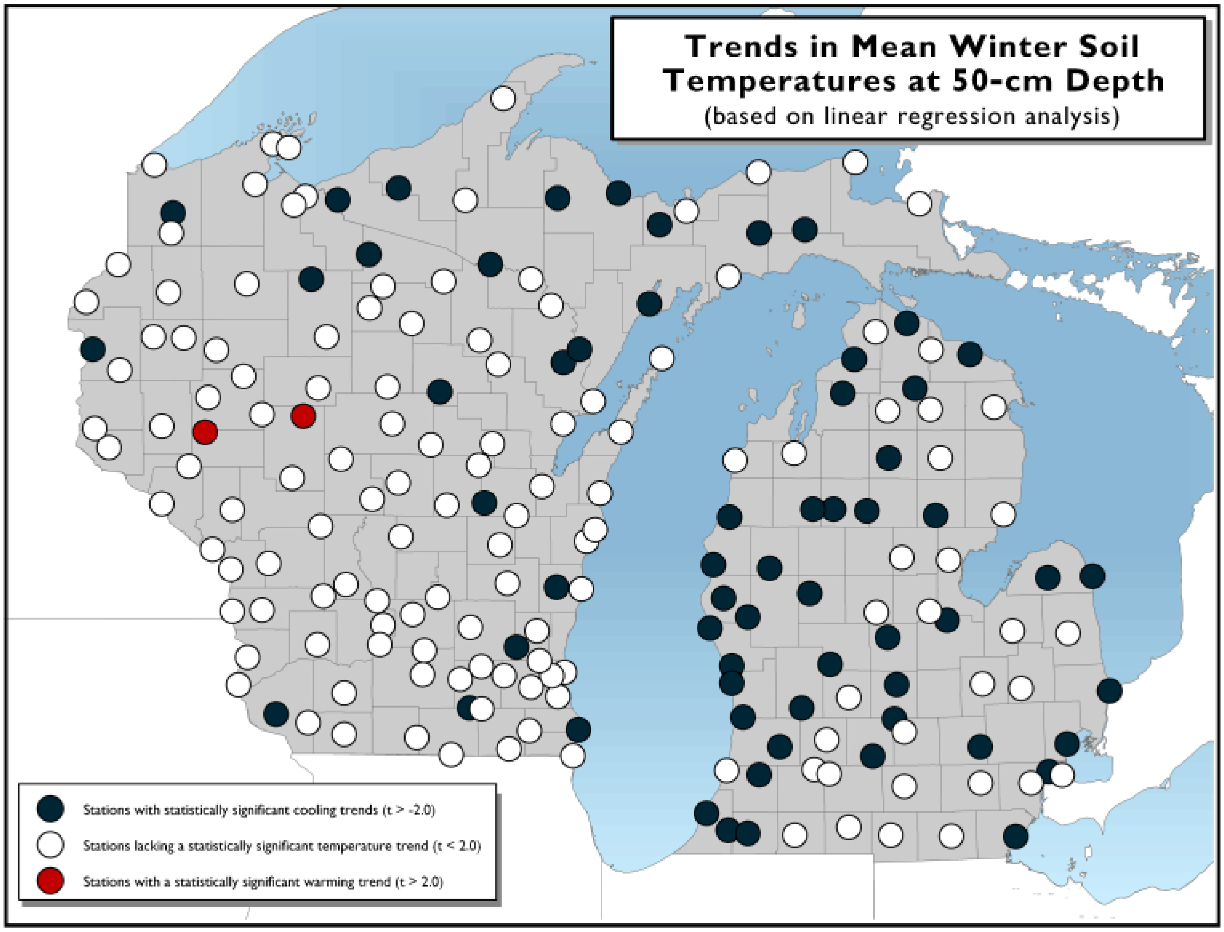

Figure 6. Statistical trends in mean wintertime (December–March) soil temperatures for 50-cm depth, based on regression analysis of the 1951–2000 data (fifty data points per station). Stations shown in red exhibit a warming trend (the slope of the least-squares, bivariate regression line is positive and significantly different from zero at $P = 0.05$). Stations shown in black exhibited a significant cooling trend, using the same analysis.

Conclusions

One of the more insightful ways to examine and interpret climate data is to view them *spatially*, an approach that forces questions (and answers) about spatial interdependence that might not otherwise arise. In our study, we examined soil and air temperature data across Michigan and Wisconsin—states that lie on the windward and lee sides of Lake Michigan and its major snowbelt. On the whole, the region shows no clear temporal trends in *annual* air temperatures over the 1951–2000 period, although many sites in southern Michigan show evidence of warming. Wintertime air temperatures are, however, increasing at most sites in the region. Likewise, temporal and spatial trends in *wintertime soil temperatures* in the region are even more clear: soils are getting colder, especially in the northern and eastern parts of the region. The correspondence between decreased wintertime soil temperatures (especially in snowy areas and in snowbelts) and increased wintertime air temperatures for the same areas points to a response mechanism that has set up across the Great Lakes. During warmer winters there tends to be less lake-effect snow and less snow in general, and the snow that falls melts faster and sooner. Thinner snowpacks are poorer insulators, allowing soils to release heat to the atmosphere faster and more completely, thereby cooling to a great extent. This cooling trend is most apparent, and of the greatest magnitude, in areas where soils are normally insulated from the cold winter air temperatures (in the snowbelts). Our work has clearly shown that soil temperatures are decreasing in the Great Lakes region, but the trend is not uniform, and that using a geographic approach to tease out the spatial patterns can be highly revealing as to probable cause.

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