EFFECTS OF WINTER WEATHER CONDITIONS ON SOIL FREEZING IN SOUTHERN MICHIGAN

Scott A. Isard
Department of Geography
University of Illinois
220 Davenport Hall
Urbana, Illinios 61801

Randall J. Schaetzl
Department of Geography
Michigan State University
315 Natural Science Building
East Lansing, Michigan 48824
e-mail: schaetzl@pilot.msu.edu

Abstract: We examined climatic and (modelled) soil-temperature data from five winters in southern Michigan to ascertain the spatial variability in soil-freezing and freeze-thaw cycles at 5 cm. The five winters chosen for study (1951–1952, 1952–1953, 1953–1954, 1976–1977, and 1979–1980) represent the extremes of weather (e.g., cold and snowy, warm and dry) for the 1951–1980 period. We chose this study area because it lies on an ecotone between the cold, snowy climates of southern Canada and the warmer climates of the Ohio Valley where persistent snowpacks are rare, and because virtually no data on soil freezing exist for this area. Soil freezing in winter in southern Michigan is more dependent on snowpack persistence and thickness, especially in mid-winter, than on air temperatures. Here, even in warm winters, soils freeze to 5 cm, provided that snowpacks are thin or absent. Conversely, in even the coldest winters, soils rarely freeze where deep snows accumulate. Thus, freezing is least frequent, and in some years nonexistent, in the lake-effect snowbelt region, where deep, reliable snowpacks insulate the soil. Conversely, soil-freezing and freeze-thaw activity are most common in dry winters, almost regardless of temperature. On average, less than two freeze-thaw cycles a year can be expected in the snowbelt region; 3 to 5 cycles a year are typical in eastern and southeastern southern Michigan. Soil freezing is likely to increase in Michigan's lower peninsula, under a doubled-CO_2 climate that is warmer and drier. [Key words: soil frost, freeze-thaw cycles, lake-effect snow, climate, Michigan.]

INTRODUCTION

Soil temperatures are affected by numerous meteorologic and pedologic variables, such as air temperature, insulating effects of a snowpack and the O horizon, wind, solar radiation, soil moisture content, texture, and various other soil-related thermal properties (Linell and Kaplar, 1959; Smith et al., 1964; Goetz and Müller, 1969; Lascano and Van Bavel, 1983). The temperature of the upper soil horizons

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affects not only plant growth (Green et al., 1984), but also many processes of weathering and pedogenesis, especially those that involve water and/or ice (Smith et al., 1964; Burt and Williams, 1976; Schaetzl and Isard, 1991). Soil temperature has perhaps its most pronounced impact on pedogenic processes, and biota rooted within, when it drops below freezing (Baker, 1971; Boyd, 1973; Schmidlin et al., 1987). Because soil temperature and freezing are dependent on so many variables, their spatial and temporal variation can be quite complex (e.g., Russell, 1943, Boyd, 1973; Schmidlin et al., 1987). Explaining this spatial complexity, at all scales, can be done only if the process linkages between the atmosphere and the lithosphere are fully understood, and the ranges of the variation in soil temperature and freezing are known (Hart and Lull, 1963; Baker, 1971; Isard and Schaetzl, 1995; Schaetzl and Isard, 1996).

This study uses a hydrologic/soil-temperature model to examine patterns of winter soil temperatures across southern Michigan, and in so doing sheds light on the meteorologic variables that affect soil freezing. Southern Michigan is uniquely suited to this type of analysis because it lies on a major climatic ecotone between the cold winter–cool summer climate of southern Canada, where thick O horizons act in concert with deep snowpacks to insulate soils from freezing, and the warmer humid climate of the Ohio River Valley, where persistent snowpacks are rare and O horizons are thin. Additionally, the region contains a prominent lake-effect snowbelt, which parallels the Lake Michigan shore and extends some 10 to 80 km inland (Thomas, 1964; Eichenlaub, 1970). The deep snowpacks of low-density lake-effect snow have been shown to mollify significantly wintertime soil-temperature extremes and, on average, inhibit soil freezing (Isard and Schaetzl, 1995). Because of overlying east-west and north-south environmental gradients, the region exhibits complex patterns of soil freezing (Russell, 1943; Isard and Schaetzl, 1995).

This study also has a temporal focus. Spatial patterns of soil freezing were studied for five uniquely different winter seasons that represent the extremes of weather for the region: various combinations of cold versus warm, snowy versus dry. This approach provides information not only on spatial patterns of soil freezing, but also on the interannual variability and, most importantly, pedo-climatic extremes.

On long time scales, General Circulation Models (GCMs) are used to predict the future temperature and precipitation patterns based on a number of climate scenarios including a doubling of greenhouse gases in the atmosphere (e.g., Wilks, 1988; Grotch and MacCracken, 1991). Establishing the relationships between winter-time air temperature and precipitation regimes and soil processes, which are currently unclear (Buol et al., 1990), could be used to project the likelihood of soil frost in a future, possibly warmer, climate. GCM data have already been used to predict daily temperature cycles at the regional scale (e.g., Palutikof et al., 1997); data and methods employed here could be used in conjunction with such studies to link potential changes in the atmosphere to soil freeze-thaw cycling. On shorter time scales, forecasts of temperature and precipitation up to one year in advance are currently being provided by the U.S. National Weather Service, and these values could be used to determine risks of soil freezing for the upcoming winter.

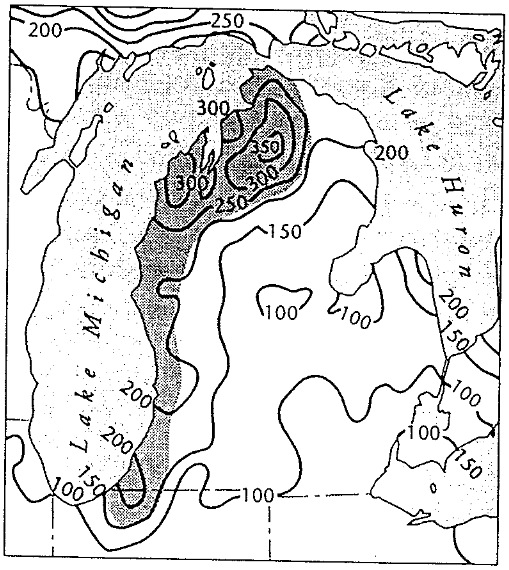

Fig. 1. Mean annual snowfall (mm) in the southern peninsula of Michigan for the period 1951–1980. The Lake Michigan snowbelt is shown as the shaded area in the lee of Lake Michigan. After Norton and Bolsenga (1993).

STUDY AREA

Extratropical cyclones are the primary cause of winter precipitation in southern Michigan. These large storms are characterized by circulations that advect moist air masses poleward from the Gulf of Mexico and can produce copious snowfall. In winter, cyclones that form to the lee of the Rocky Mountains often track across the Great Lakes region, while others follow a more southerly route across the Ohio River Valley or southeastern United States (Harman et al., 1980; Harman and Schwartz, 1987). Different paths among winter-time cyclones result in large temporal and spatial variations in snowfall across the southern peninsula (Bolsenga, 1967; Norton and Bolsenga, 1993).

The Great Lakes themselves, because of their large surface area, also have an important impact on snowfall patterns and amounts. Rapid advection of cold air masses over the comparatively warm water in winter, often following the passage of an extratropical cyclone, leads to instability and heavy lake-effect snowfall in the lee of the lakes (Muller, 1966; Braham and Dungey, 1984). Southern Michigan's lake-effect snowbelt runs the entire length of Lake Michigan, where it is most pronounced about 40 km inland from the lake (Eichenlaub, 1970; Eichenlaub et al., 1990; Norton and Bolsenga, 1993; Fig. 1). Snowfall in the lake-effect region tends to accumulate earlier in winter than at sites elsewhere (Dewey, 1971), and the snowcover often persists longer than elsewhere in southern Michigan (i.e., mid-winter melt events are less common than elsewhere owing to the moderating effects of the lake). Snowfall in the snowbelt is driven both by convergence uplift to the lee of the open lake waters and by orographic uplift over uplands in the northern part of lower Michigan (Strommen and Harman, 1978).

Southern Michigan contains widespread areas of sandy soils, which are the type modeled in this study. Almost all of southern Michigan was forested prior to European settlement, except for some scattered prairie areas in the southwestern parts of the peninsula (Veatch, 1927; Manogaran, 1983). Previous work (Isard and Schaetzl, 1995) suggested that soils in northeastern parts of lower Michigan frequently freeze to 10 cm or more, from December through February, owing to thin snowpacks and cold temperatures. In many parts of the state, where heavy clay soils are farmed for grain and sugar beets, wintertime freezing is essential to agriculture, because the frost breaks up the clods and renders the soil more manageable in the spring.

MATERIALS AND METHODS

Data

We used 1951–1980 National Weather Service data that contained daily maximum and minimum temperatures and daily precipitation data for 56 class-one weather stations, more or less uniformly scattered across the southern peninsula of Michigan (see Schaetzl and Isard [1990] for a map of station locations). Because the focus of the study was on wintertime weather, data for the first six months of 1951 and for the last six months of 1980 were not analyzed, leaving 29 full years of record.

The Hydrologic/Soil-Temperature Model

The data were entered into a previously developed computer algorithm that was designed to calculate the vertical profile of temperature for coarse-textured, well-drained, forested soils (Isard and Schaetzl, 1993, 1995). The algorithm (model) combines a Thornthwaite-based water budget model (Thornthwaite and Mather, 1955) and the NRCS (Natural Resources Conservation Service) runoff and snowmelt models (USDA-SCS, 1971) with a one-dimensional heat-conduction equation (Carslaw and Jaeger, 1959). Details of an earlier version of the model without the heat-conduction component are provided elsewhere (Schaetzl and Isard, 1991). The model requires daily maximum (Tmax) and minimum (Tmin) air temperatures (°C) and precipitation data as inputs.

The temperature profile within the mineral soil was calculated at 30-minute intervals using a finite difference formulation with nine soil layers that increase in thickness with increasing depth (0.05, 0.1, 0.3, 0.5, 1.0, 1.5, 3.5, and 8.0 m thick), one litter layer (0.05 m thick), and up to five snowpack layers (all 0.1 m thick) (Isard and Schaetzl, 1995). The soil temperature at 15 m was held constant at 2°C above the mean annual air temperature (Geiger, 1959). For each 30-minute interval, the temperature at the soil surface (Tt) was calculated using a truncated harmonic function of time around the Tmean for daytime:

$$\mathrm{Tt} = (\mathrm{Tmax} - \mathrm{Tmin}) \sin[(\pi m)/(D + 1)] + \mathrm{Tmin}$$

and an exponential function for nighttime:

$$\mathrm{Tt} = \mathrm{Tmin} + (\mathrm{Tss} - \mathrm{Tmin})e^{-1.81 n/N}$$

where D and N are day and night length (hr), respectively (Parton and Logan, 1981). Tss is the soil-surface temperature (°C) calculated for sunset, m is the number of hours between the current time interval and sunset, and n is the number of hours between sunset and the current time interval. Thermal properties for the soil, litter, and snowpack are discussed elsewhere (Isard and Schaetzl, 1995).

The model also has a water-balance component (Schaetzl and Isard, 1996). Precipitation that falls when the mean daily temperature (Tmean) is ≥0°C was assumed to be rain; other precipitation was snow, using a 10:1 conversion for liquid to solid precipitation.* We wanted to examine the "natural" patterns of soil temperature, and thus assumed forested soil conditions. The model was designed to eliminate precipitation that is intercepted by the forest canopy and later lost to evaporation (canopy interception loss; see Mahendrappa and Kingston, 1982). The amount of water reaching the forest floor via throughfall was therefore computed from liquid-equivalent precipitation data, but it also was affected by forest type (mixed versus deciduous), season of the year (leaf-on versus leaf-off), and precipitation type (snow versus rain). Schaetzl and Isard (1991) provide the relevant equations and a review of the hydrologic literature. The model temporarily stores water as a snowpack if throughfall and air-temperature conditions allow. When the Tmean is >0°C and a snowpack is present, snowmelt is calculated as a function of mean daily air temperature (Tmean):

$$\text{Melt (mm day}^{-1}\text{)} = 1.27 \text{ Tmean}$$

(Garstka, 1964) and made available for storage in the litter. On days when snowcover was absent and Tmean was >0°C, evaporation of water from the litter layer was calculated as a linear function of Tmean (Thornthwaite and Mather, 1955; Baier and Robertson, 1966; Willmott, 1977).

Site-specific input parameters are needed to operationalize the algorithm: (1) latitude is used to calculate evaporation and soil-surface temperature, (2) forest type (deciduous versus mixed) is used in throughfall calculations, and (3) water-retention capacity of the litter layer affects water-balance calculations.

Model Accuracy

In a previous paper (Isard and Schaetzl, 1995), detailed data on the error statistics for the hydrologic/soil-temperature model were reported; we summarize that information here. We have little information with which to estimate the accuracy of the hydrologic component of the model. Actual soil-temperature data for different sites across the lower peninsula, which we have been collecting at forested sites for nearly a decade, compare remarkably well to modeled values. The coefficient of

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*Our model uses a 10:1 conversion of liquid precipitation to solid. Our snowfall maps (Figs. 2 through 6) essentially report mm of liquid equivalence, converting easily to cm of snow; we suggest a 10:1 ratio of liquid water to snow. In lake-effect areas, however, the dry, low-density snow may have a ratio closer to 17:1 (pers. comm., R. Van De Kopple, University of Michigan Biological Station, Pellston, MI, 1996). Thus, our snowfall maps may underrepresent the actual amount of snow measured by NWS personnel, although the liquid equivalents are the same.

Table 1. Climatic Characteristics of the Five Winters Studied for Southern Michigan (Peninsula-Wide)

Winter	Early-winter temp	Late-winter temp	Early-winter snow	Late-winter snow	Comments
1951–1952	Cool	Warm	High	Normal	High amounts of early-season snowfall
1952–1953	Warm	Warm	Low	Low	Warm and dry
1953–1954	Warm	Normal	Low	Normal	Warm with low snowfall, especially in the snowbelt
1976–1977	Cold	Cool	Normal–high	Low	Very cold with high amounts of lake-effect snow
1979–1980	Normal–warm	Normal	Low	Low	Normal temperatures coupled with low snowfall

determination (r^2) between actual and modeled soil temperatures for the cold season is about 0.47 at the 5 cm depth. Inspection of the root mean square error statistics (RMSE) reveals that the expected errors in the computed soil temperatures are 2.3°C at 5 cm. The model generally *under*estimates cold-season soil temperatures at 5 cm by about 1.6°C (i.e., it has a "cold bias" in winter; Isard and Schaetzl, 1993). These errors are well within the limits required for the present study and are actually quite remarkable, considering that the meteorologic data used to drive the model were taken from NWS shelters that are not in forested settings and, in most instances, are several km away from our soil-temperature observation sites.

Modeling Procedures

Our model was run on the daily climate data for each of the 56 NWS stations, for the 29 winters. Data on several climatic variables for each of the five winters (above) were then printed to a file, one file for each of the 56 stations. Using the ArcView 3.0 GIS package (ESRI, 1996), the data for each of these variables were plotted and a series of choropleth maps created.

The 29 winter seasons then were ranked on the basis of three different climatic parameters: (1) mean air temperature for November through March, (2) early-season snowfall (November–December), and (3) total snowfall (November–March). These rankings were examined in order to ascertain which winter best represented an "extreme." Table 1 shows the climatic characteristics of the winter seasons used in this study.

RESULTS AND DISCUSSION

Warm and Dry: The Winter of 1952–1953

The winter of 1952–1953 was the warmest winter of the 29-year timespan for 48 of the 56 NWS stations in the lower peninsula. The winter started out very dry (Table 2). The lower peninsula averaged only 27% of its normal precipitation for October (Winston, 1952b). Although the winter began cold (colder than normal

Table 2. Climatic Deviations from Normal for the Five Winters Studied for Southern Michigan[a]

	1951–1952	1952–1953	1953–1954	1976–1977	1979–1980
General characteristics	Cold early, then warm, with very high amounts of early-season snowfall	Very warm, with low snowfall	Generally warm, with normal snowfall, but low snowfall in the snowbelt	Very cold, with high amounts of lake-effect snowfall	Near-normal temperatures, with low snowfall
Temperature deviation (°C)[b]					
October	+1.2	−2.3	+2.0	−3.3	−1.1
November	−3.6	+2.2	+2.7	−3.5	+0.6
December	−0.5	+2.8	+2.3	−4.9	+2.7
January	+2.8	+2.2	−0.5	−5.7	+1.1
February	+3.4	+2.3	+4.9	−0.8	−1.7
March	+0.6	+1.6	−1.0	+4.7	−1.2
Precipitation (snowfall) deviation; % of normal					
October	160 (na)	10 (na)	50 (na)	75 (na)	95 (na)
November	110 (350)	110 (45)	50 (60)	45 (80)	130 (80)
December	110 (275)	100 (75)	100 (100)	60 (125)	110 (40)
January	130 (120)	100 (80)	100 (125)	70 (125)	95 (60)
February	65 (95)	100 (55)	125 (95)	80 (70)	75 (90)
March	100 (120)	100 (50)	150 (180)	150 (65)	80 (100)

[a] Data summarized from: Hawkins (1951), Klein (1951a, 1951b), Martin (1952), Winston (1952a, 1952b), Hawkins (1952a, 1952b), Smith (1953a, 1953b), Hawkins (1953), Klein (1953), Winston (1953a, 1953b), Hawkins (1954), Krueger (1954a, 1954b), Dickson (1977a, 1977b), Taubensee (1977a, 1977b), Wagner (1977a, 1977b), Dickson (1980a, 1980b), Livezey (1980), Taubensee (1980), Wagner (1980a, 1980b).

[b] Temperature and precipitation deviations are averaged for the entire lower peninsula, based on data supplied on maps in *Monthly Weather Review*.

temperatures, by about 3°C, in October accompanied the lingering drought in lower Michigan [Winston, 1952b]), by November, positive temperature anomalies had set into the region. As is typical of warm autumns, lower-than-normal snowfall totals also accrued (Hawkins, 1952a; Table 2). December's warmth, ranging from 2.2° to 4.4°C above normal, was especially concentrated in the snowbelt region, where on December 30, only about 10 cm of snowpack was present and less than 60 cm had fallen to date (Hawkins, 1952b; Table 2; Fig. 2A). Across the entire lower peninsula, snowfall was at or less than the 29-year mean value (Fig. 2B). January 1993 was one of the warmest on record for the United States, with few if any invasions of cold arctic air masses (Smith, 1953a; Table 2). By late January, most locations in the southern half of the lower peninsula lacked a continuous snowcover (Smith, 1953a). February continued warm across most of the nation (Smith, 1953b;

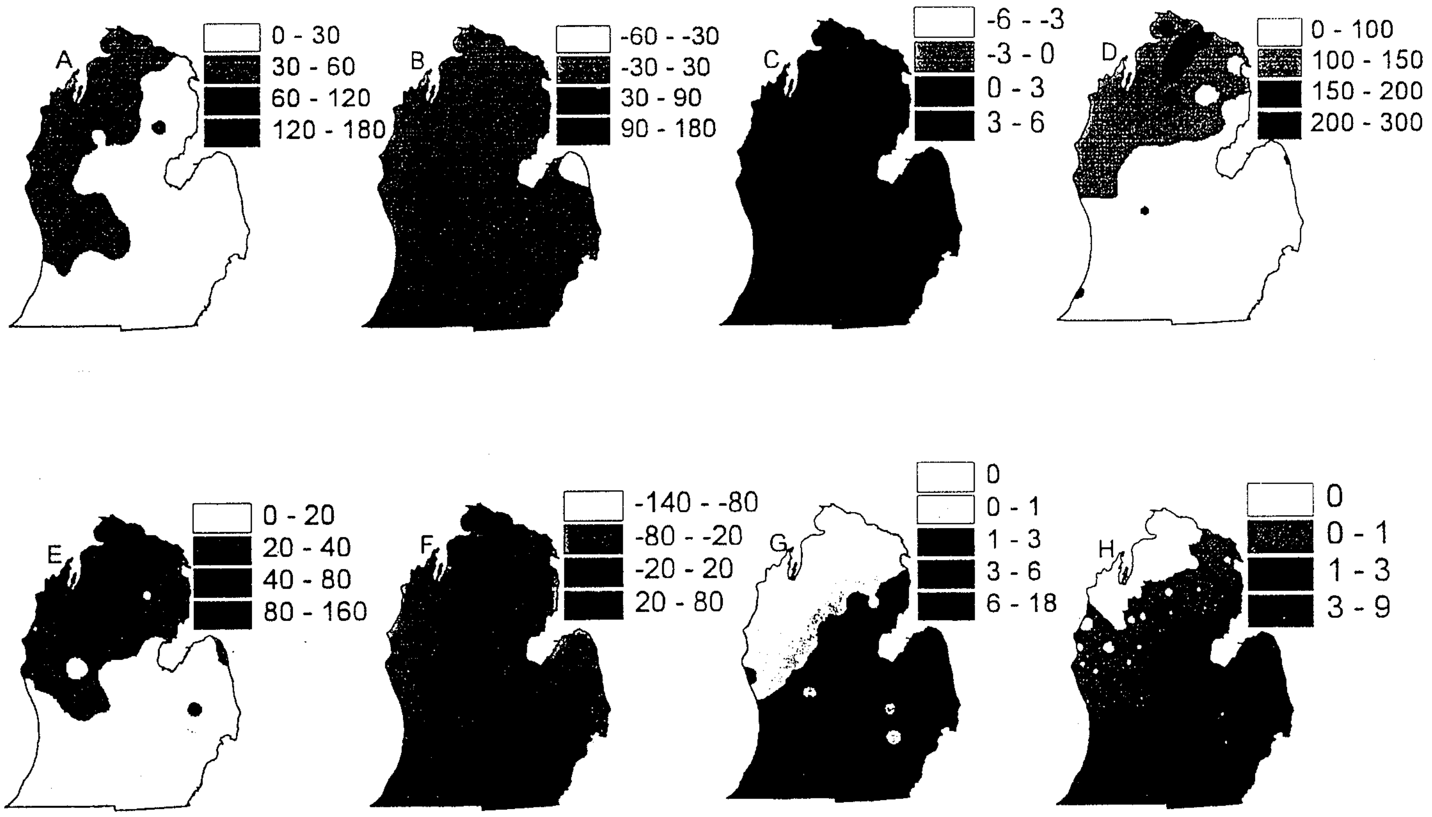

Fig. 2. Climatic and soil data for the southern peninsula of Michigan for the winter of 1952–1953. (A) Early-season (November–December) snowfall (cm). (B) Difference (cm) between the early-season snowfall of 1952 and the 30-year mean. Negative numbers imply that the station received less snowfall in November–December 1952 than it normally does. (C) Temperature deviation from the 30-year mean, for the entire winter. (D) Total snowfall (cm) for November–March. (E) Total number of "snow days" (defined as a day on which the snowpack was ≥10 cm). (F) Difference between the number of snow days in 1952–1953 and the 30-year mean. Negative numbers imply that the station had fewer snow days in 1952–1953 than it normally does. (G) Total number of "freeze days" (defined as a day in which the soil temperature at 5 cm stays below 0°C all day [24 hours]). (H) Total number of freeze-thaw cycles (defined by −1° [lower] and 0°C [upper] temperature thresholds).

Table 2). Snowbelt snowpacks, which are normally >50 cm thick at this time of the winter, were less than 30 cm thick almost everywhere in the lower peninsula (Smith, 1953b). Extreme southern Michigan had no snow on the ground by late in the month. Another warm month, March 1953, ended what was the warmest winter in the United States since 1933–1934 (Klein, 1953; Table 2).

As for most of the winter, the entire southern peninsula averaged well above normal for temperature, while at the same time precipitation was near normal (Table 2). Only four stations in the lower peninsula did *not* average *at least 3°C* above normal for the winter (Fig. 2C). Total snowfall was generally <120 cm over most of the southern peninsula; heavy lake-effect snowfall was not common, especially in the southern snowbelt region (Fig. 2D). Over the winter as a whole, snow days in the lower peninsula (defined as a day on which the snowpack was ≥10 cm) were maximal in the highlands of the extreme north (Fig. 2E). Most stations in the southern snowbelt had less than 190 cm of snowfall and less than 40 snow days. When compared to the 29-year mean values for snow days, similar patterns, all associated with extremely low snowfall totals, especially in the snowbelt, emerge (Fig. 2F).

Despite the warm winter temperatures, most sites in the lower peninsula had at least one freeze day (defined as a day in which the soil temperature at 5 cm stays below 0°C all day) (Fig. 2G). Extreme northwestern lower Michigan, where snow days were maximal and generally >40, experienced no freeze days (Fig. 2G). In the southeastern part of the peninsula, most sites had 3 to 5 freeze days. Similarly, most sites south and east of the snowbelt had at least one freeze-thaw cycle during the winter, but nowhere was there a great abundance of freeze-thaw activity (Fig. 2H). In sum, this warm dry winter did not exclude soil freezing, though the total amount of soil frost across the peninsula was minimal. Snowbelt sites were essentially frost free.

Warm with Low Snowfall in the Snowbelt: The Winter of 1953–1954

The winter of 1953–1954 followed an extreme drought throughout much of the United States (Hawkins, 1953). October was a cool, dry month (Table 2). November issued in warmth that would generally continue throughout the winter (Table 2). Late November was especially warm, while early November was also very dry over southern Michigan (Winston, 1953a). Hence, snow cover was essentially nil over the snowbelt areas, even in late November (Winston, 1953a). Although snow began to accumulate in the snowbelt in December, by the 29th most of the snowbelt had less than 8 cm on the ground, and extreme southern Michigan was snow free. Most sites outside the snowbelt received less than 20 cm of snowfall during November–December (Winston, 1953a; Fig. 3A). At only one NWS station was this *not* the least-snowy early winter in the 1951–1980 period (Fig. 3B). January 1954 was slightly colder than normal, especially in the extreme north (Krueger, 1954a; Table 2). Most of the peninsula had near-average precipitation, although the cold temperatures led to slightly elevated snowfall totals in the central snowbelt. By late January, snowpacks exceeded 30 cm in most of the northern snowbelt areas, and most of the southern Michigan had at least some measurable snow on the ground (Krueger, 1954a). Lake-effect snowfall was accentuated by several polar outbreaks during

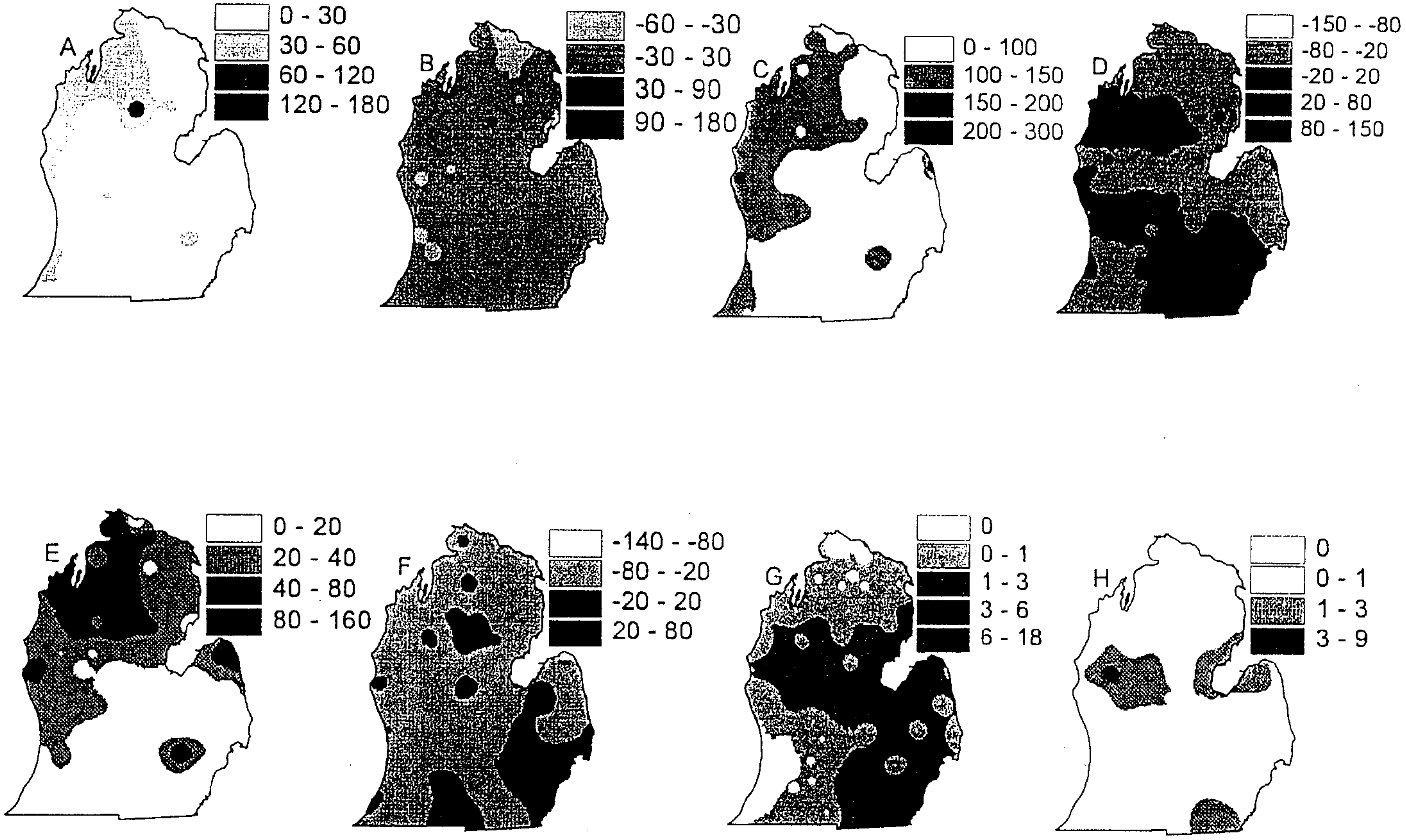

Fig. 3. Climatic and soil data for the southern peninsula of Michigan for the winter of 1953–1954. (A) Early-season (November–December) snowfall (cm). (B) Difference (cm) between the early-season snowfall of 1953 and the 30-year mean. Negative numbers imply that the station received less snowfall in November–December 1953 than it normally does. (C) Total snowfall (cm) for November–March. (D) Difference (cm) between total snowfall in 1953–1954 and the 30-year mean. Negative numbers imply that the station received less snowfall in 1953–1954 than it normally does. (E) Total number of "snow days." (F) Difference between the the number of snow days in 1953–1954 and the 30-year mean. Negative numbers imply that the station had fewer snow days in 1953–1954 than it normally does. (G) Total number of "freeze days." (H) Total number of freeze-thaw cycles.

January (Krueger, 1954a). In February, record warmth in the northern United States fueled an early snowmelt season and thus, the moderately deep snowpacks in the snowbelt were quickly lost. February temperatures averaged near or above freezing for much of the lower peninsula: a nearly 5°C positive anomaly (Krueger, 1954b; Table 2). Low precipitation and snowfall totals, especially in the north, led to snowpack depths of 15 cm or less throughout the snowbelt (Krueger, 1954b). Although March was a comparatively cool month with high amounts of precipitation and snowfall, the larger accumulations were in the southern three tiers of counties, while the northern lower peninsula had below-normal snowfall totals (Hawkins, 1954). As a result, on March 30 the snowbelt region was snow free while extreme southern Michigan lay under snowpacks in excess of 25 cm.

In sum, the winter of 1953–1954 was similar to the warm, dry winter of the previous year in many respects. However, snowfalls totals were generally less in 1953–1954 than in 1952–1953 (cp. Figs. 2C and 3C). Most of the lower peninsula received less than 150 cm of snowfall, which often equated to a negative anomaly of 40 cm or more (Figs. 3C, 3D). The most notable negative snowfall anomalies were located in the far northern snowbelt (Fig. 3D). Snow-day patterns revealed similar low values, especially in the southern snowbelt (Fig. 3E). Negative snow-day anomalies were present for all but one site, surpassing even the previous winter in the scarcity of low snowpacks (cp. Figs. 3F and 2E). In most cases, snow days were about 25–35 lower than normal.

Low snowfall totals and warm temperatures again, as in the previous winter, resulted in little soil freezing in the snowbelt proper (Fig. 3G). Northerly sites that had more than one freeze day also had <40 snow days (Figs. 3E, 3G). In the southeastern lower peninsula, freeze days occurred where total snowfall was less than about 80 cm. At some sites in the extreme southern and extreme northern parts of the snowbelt, soils did not freeze to 5 cm depth even once (Fig. 3G). Maximal freezing occurred in eastern and southeastern Michigan, where freeze-day totals of 2 and 3 were common. Freeze-thaw cycles were also low, generally less than 1, and showed spatial patterns similar to those for freeze days (Fig. 3H).

Low Snowfall: The Winter of 1979–1980

The winter of 1979–1980 began cold and wet (Wagner, 1980b; Table 2). Precipitation totals (as rain) were especially high in the snowbelt, where positive anomalies topped 150%. November's near-normal temperatures combined with slightly wetter than normal precipitation totals (Dickson, 1980b; Table 2). Little snow fell in southern Michigan (Fig. 4A), however, as most of the precipitation occurred during the warm parts of the month. Invasions of cold cP air were infrequent during December (Taubensee, 1980), leading to warmer than normal temperatures and near-normal precipitation totals (Table 2). Thus, peninsula-wide snowfall totals were very low, with Grand Rapids, Michigan recording its third-least snowy December and Muskegon, Michigan its least snowy December since 1940 (Taubensee, 1980). Parts of extreme northern lower Michigan had more than 40 cm of snowfall (Fig. 4A), but this too had melted by late December, as the last week of the month averaged over 6°C above normal across most of southern Michigan. Nega-

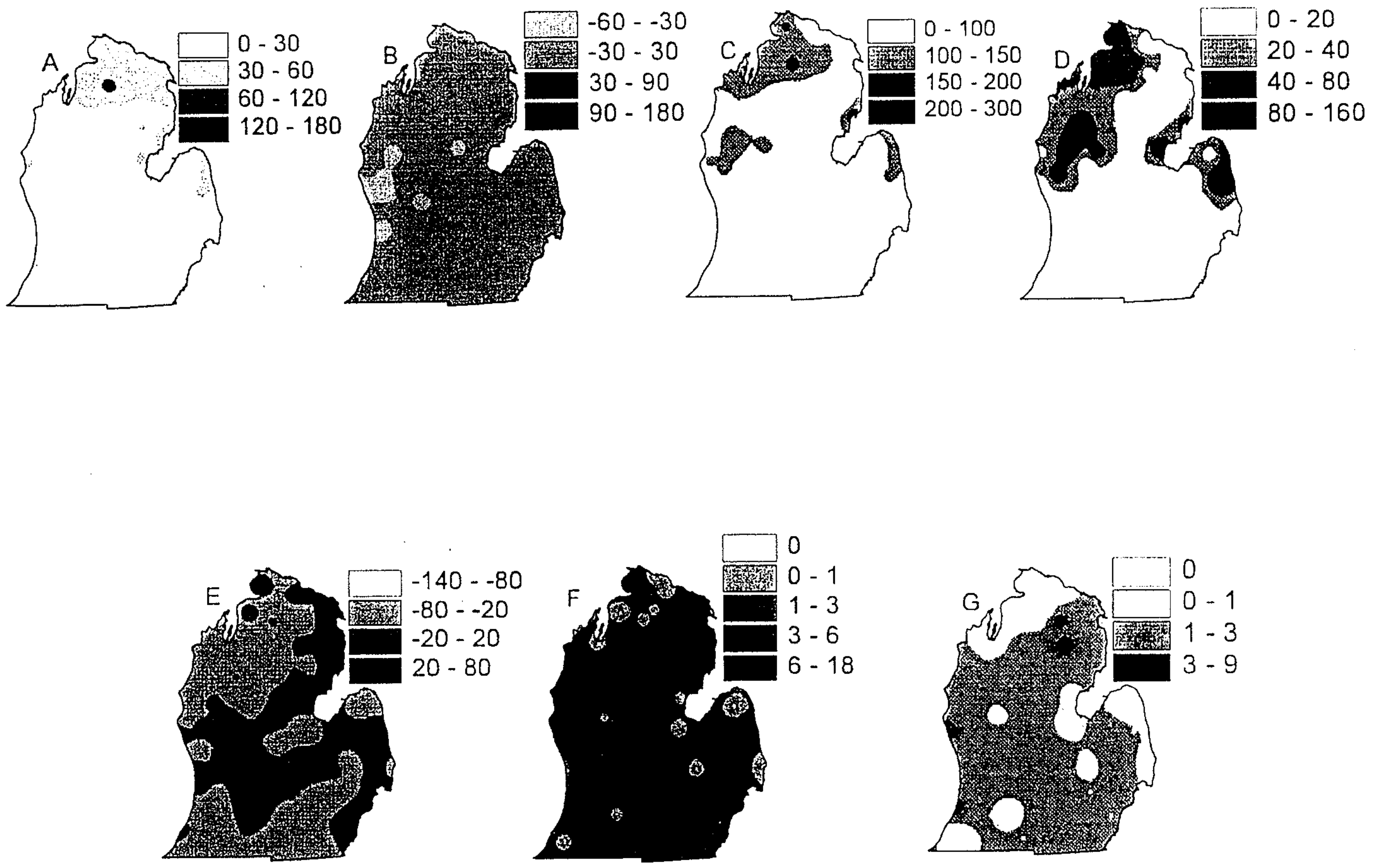

Fig. 4. Climatic and soil data for the southern peninsula of Michigan for the winter of 1979–1980. (A) Early-season (November–December) snowfall (cm). (B) Difference (cm) between the early-season snowfall of 1979 and the 30-year mean. Negative numbers imply that the station received less snowfall in November–December 1979 than it normally does. (C) Total snowfall (cm) for November–March. (D) Total number of "snow days." (E) Difference between the number of snow days in 1979–1980 and the 30-year mean. Negative numbers imply that the station had fewer snow days in 1979–1980 than it normally does. (F) Total number of "freeze days." (G) Total number of freeze-thaw cycles.

tive early-season snowfall anomalies were most pronounced in the middle snowbelt (Fig. 4B). January temperatures were again slightly above normal and snowfall was only 60% of normal (Table 2), although some snow did accumulate in the snowbelt where precipitation totals were 100% to 160% of normal (Wagner, 1980a). Most of this total, however, occurred as rain. The general lack of large lake-effect snowfall episodes continued into February, as temperatures cooled (Dickson, 1980a; Table 2), but deep snowpacks failed to develop. March 1980 was a cool, dry month in lower Michigan (Table 2). Snowbelt precipitation totals were less than half of normal (Livezey, 1980).

In sum, the winter of 1979–1980 brought low snowfall totals to much of the lower peninsula (Figs. 4C, 4D), a phenomenon usually associated with abnormally warm temperatures. In this case, however, near-normal temperatures prevailed (Table 2). Total snowfall was even less than in 1952–1953 or 1953–1954 (cp. Figs. 2D, 3C, and 4C). Negative snowfall anomalies were commonly in excess of 50 cm (Fig. 4D). Snow days were fewer than 30 over most of the peninsula, except for some northern snowbelt sites and the eastern "thumb" region (Fig. 4E). Snow-day anomalies were in the –20 to –50 range throughout the snowbelt (Fig. 4F).

Low snowfall totals combined with cold temperature anomalies in early and late winter produced significant numbers of freeze days (Fig. 4G) but seldom more than one or two freeze-thaw cycles (Fig. 4H) across most of southern Michigan. Most of the interior peninsula experienced 3 to 8 freeze days. Again, the extreme northern snowbelt, where snow days exceeded 40, had the fewest freeze events (cp. Figs. 4E and 4G).

High Amounts of Early-Season Snowfall: The Winter of 1951–1952

The winter of 1951–1952 began mild and wet, as October brought above-normal temperatures and precipitation to the Great Lakes region (Hawkins, 1951; Table 2). In November, below-normal temperatures prevailed across the upper midwest, with negative temperature anomalies exceeding 4°C over parts of the region (Klein, 1951a; Table 2). Early cold weather associated with Arctic outbreaks usually brings heavy lake-effect snow, and in November most of the lower peninsula experienced snowfall totals >200% of normal (Klein, 1951a). More than 60 cm of snow fell on parts of the snowbelt. However, most of this early-season snow melted as a result of mild weather in late November, such that by early December snowpacks were nearly nonexistent across most of southern Michigan. December was another cold and snowy month, especially in southwest lower Michigan (Klein, 1951b). Snowbelt locations had accumulated another 20 to 25 cm by the end of the month; sites in the eastern part of the peninsula had still deeper snowpacks. Most of the major snowfall events were cyclonic, rather than lake-effect, in nature, resulting in large-scale snowfall events (rather than isolated, lake-effect squalls), and as a result snowfall totals in southwest lower Michigan exceeded 400% of normal (Klein, 1951b). In sum, the early-season snowfall regime in 1951–1952, which included strong lake-effect snows in early November as well as cyclonically driven snowfall in December, resulted in widespread snows across the entire peninsula (Fig. 5A). By January 1, most of southern Michigan had already received from 30 to 70 cm more

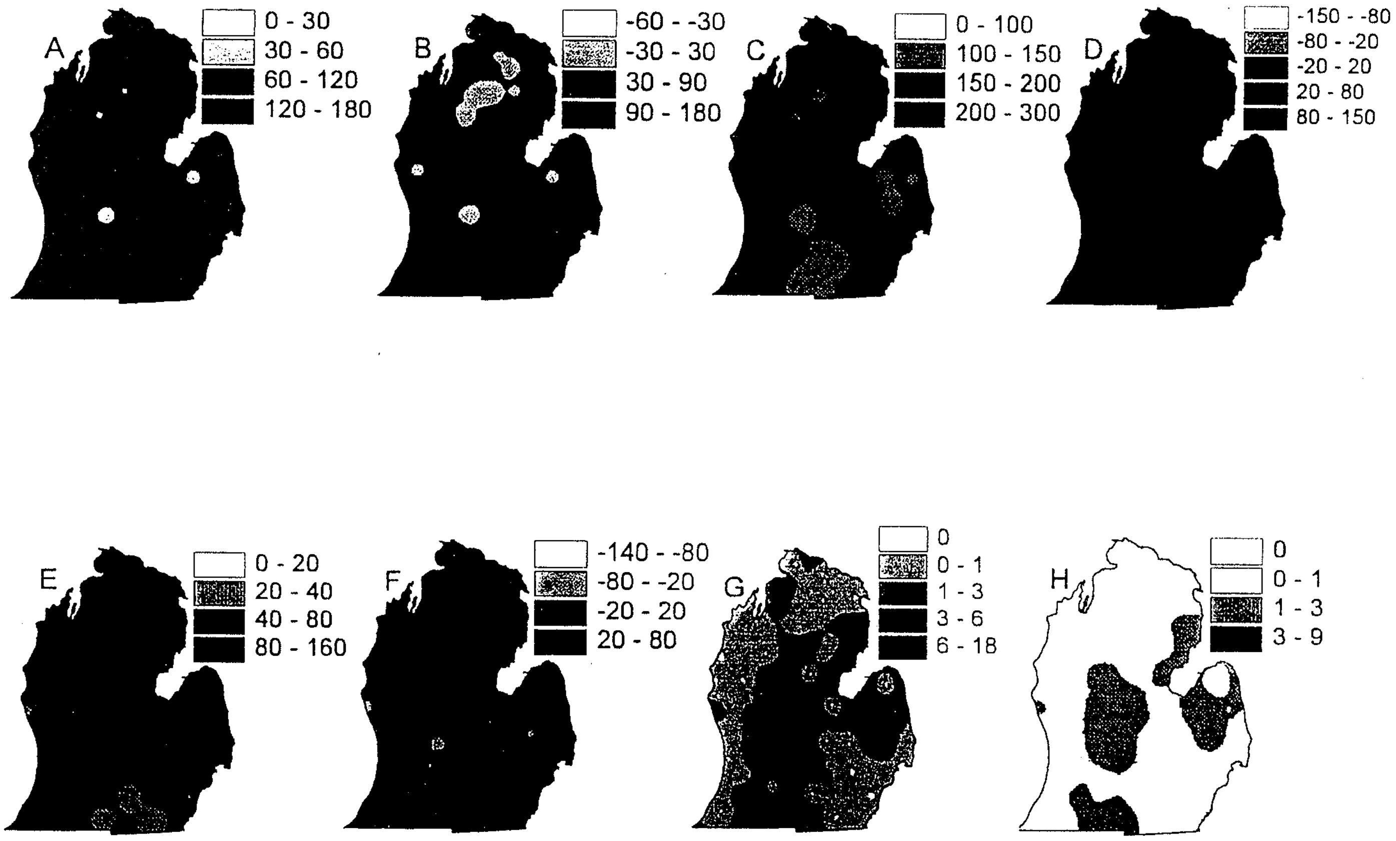

Fig. 5. Climatic and soil data for the southern peninsula of Michigan for the winter of 1951–1952. (A) Early-season (November–December) snowfall (cm). (B) Difference (cm) between the early-season snowfall of 1951 and the 30-year mean. Negative numbers imply that the station received less snowfall in November–December 1951 than it normally does. (C) Total snowfall (cm) for November–March. (D) Difference (cm) between total snowfall in 1951–1952 and the 30-year mean. Negative numbers imply that the station received less snowfall in 1951–1952 than it normally does. (E) Total number of "snow days." (F) Difference between the number of snow days in 1979–1980 and the 30-year mean. Negative numbers imply that the station had fewer snow days in 1979–1980 than it normally does. (G) Total number of "freeze days." (H) Total number of freeze-thaw cycles.

snowfall than normal (Fig. 5B). Snowy weather dominated again in January (Winston, 1952b; Table 2). By late in the month, most of southern Michigan had a measurable snowpack; in the snowbelt over 30 cm of snow was on the ground. An abnormally warm February coupled with below-normal snowfall totals caused these snowpacks to thin markedly (Winston, 1952a; Table 2). Only 8 cm of snow remained on the ground by late February in the northern snowbelt. Continued warmth in March led to a complete loss of snowpacks in southern Michigan by the end of the month (Martin, 1952).

In sum, 1951–1952 saw deep, early snowpacks, followed by a complete melt in December, and then finally a reestablishment of near-normal snowpack conditions later in the winter. Most of the peninsula received more than 150 cm of snowfall (Fig. 5C), which, in most instances, was ≥50 cm above normal (Fig. 5D). Snow days were very high (>90) across all of the northern lower peninsula (Fig. 5E), and positive snow-day anomalies generally exceeded 25 (Fig. 5F).

Soil-freeze days were commonly in the range of 1 to 4 across most of the peninsula (Fig. 5G). Most sites in the snowbelt had one or no freeze days, demonstrating that deep, early snowpacks do retard soil freezing (Isard and Schaetzl, 1995). Unlike other years wherein sites with >40 snow days had little soil frost, many sites in 1951–1952 that had 90 or more snow days still had notable numbers of freeze days, owing to the inconsistent nature of the snowpack. Frequent melt events early and again late in winter led to soil frost across much of central and eastern lower Michigan (Fig. 5G). Most sites underwent only one freeze-thaw cycle, although notable exceptions did occur (i.e., the Saginaw Bay region and central lower Michigan) (Fig. 5H).

Very Cold with High Amounts of Lake-Effect Snow: The Winter of 1976–1977

The winter of 1976–1977 began with record cold over the midwest, as frequent polar outbreaks invaded the region during October (Wagner, 1977a). November continued cold, with over 30 cities in the eastern United States recording their coldest November ever (Dickson, 1997b; Table 2). Consistent northwest-southeast upper-air trajectories over the Great Lakes region resulted in heavy lake-effect snows for Michigan's upper peninsula and for extreme southwest portions of the lower peninsula; the rest of southern Michigan remained quite dry (Dickson, 1977b). Some sites in the interior peninsula recorded near-record dryness for November. The record cold continued into December; several stations experienced their coldest December (Taubensee, 1977a). Precipitation totals were well below normal, especially along the eastern parts of the peninsula that do not get lake-effect snow (Table 2; Fig. 6A). This snowfall pattern, with heavy snowfall in the snowbelt but significantly less in eastern lower Michigan (Fig. 6A), is typical for early winter; Figure 6B shows that most of the southern peninsula in November and December 1977 had near-normal snowfall totals (see also Fig. 1). The Ohio Valley experienced its coldest January ever in 1977 (Wagner, 1977b). In southern Michigan, temperature anomalies were –4 to –6°C (Table 2). Lake-effect snows were strong and frequent, while the eastern side of the peninsula was again dry. Although February averaged less than 1°C below normal (Table 2), it contained two weeks

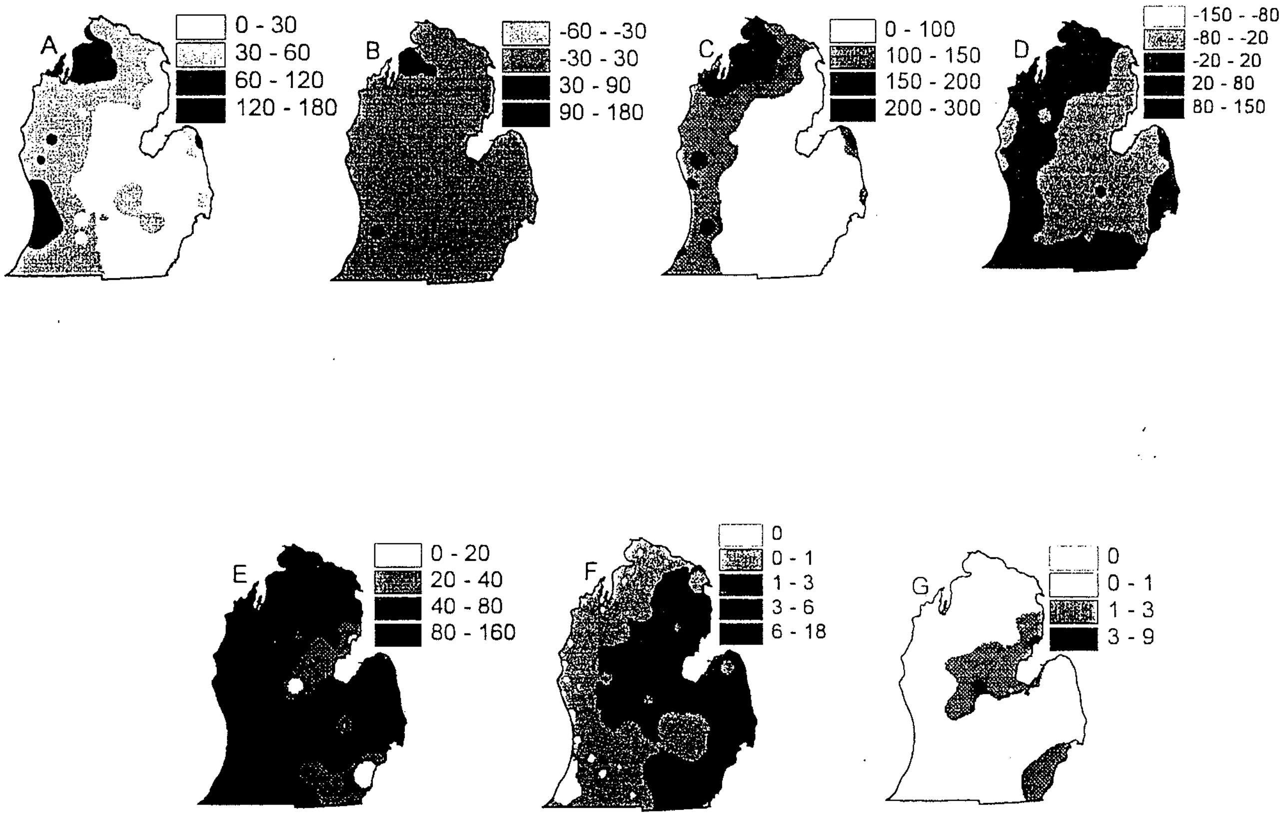

Fig. 6. Climatic and soil data for the southern peninsula of Michigan for the winter of 1976–1977. (A) Early-season (November–December) snowfall (cm). (B) Difference (cm) between the early-season snowfall of 1976 and the 30-year mean. Negative numbers imply that the station received less snowfall in November–December 1976 than it normally does. (C) Total snowfall (cm) for November–March. (D) Difference between total snowfall in 1976–1977 and the 30-year mean. Negative numbers imply that the station received less snowfall in 1976–1977 than it normally does. (E) Total number of "snow days." (F) Total number of "freeze days." (G) Total number of freeze-thaw cycles.

of anomalously cold weather (Dickson, 1977a). Snow was again frequent in the snowbelt, especially in the extreme north. Snowmelt was extremely rapid in 1977, owing to high positive temperature anomalies throughout March; by week two, temperatures were nearly 9°C above normal in southern Michigan (Taubensee, 1977b; Table 2).

The cold 1976–1977 winter is best characterized by heavy lake-effect snows in the snowbelt, coupled with lower than normal snowfall totals in eastern lower Michigan (Figs. 6C, 6D). Heavy snowfall began early in the winter and continued throughout. Snowfall totals were near normal across most of the snowbelt, while negative departures in the –50 cm range were common in eastern lower Michigan (Fig. 6D). Snow-day totals exceeded 60 throughout the snowbelt, with the extreme northern snowbelt accumulating snow-day totals in excess of 100 (Fig. 6E).

This cold, snowy winter provides an excellent opportunity to examine the interplay between soil freezing, air temperatures, and snowpack. Although atmospheric conditions were much colder than normal (Table 2), the heavy lake-effect snows effectively insulated the soil from freezing across almost the entire snowbelt (Fig. 6F). Freeze days were maximal in eastern lower Michigan, especially in the Saginaw Bay lowlands, where snowpacks were thinner than normal. Similarly, freeze-thaw cycles were, in most places, less than one for the entire winter (Fig. 6G).

SUMMARY AND CONCLUSIONS

Our model's wintertime "cold bias" of approximately 1.6°C must be taken into account when discussing the data above. This bias implies that sites shown to be freezing in Figures 2 through 6 may, in fact, be near freezing but unfrozen. The modeled data suggest that at least one 24-hour period of soil freezing is encountered at most sites in southern Michigan in even the snowiest (Fig. 6F) winters; only in some winters, in the heart of the snowbelt, can soil freezing be truly discounted (e.g., Figs. 2G and 3G). The rarity of soil frost in the snowbelt region has been noted before and linked to especially strong pedogenesis—specifically, podzolization (Schaetzl and Isard, 1991). However, if soil-freeze days are conservatively reexamined for the five winters, knowing that the model's cold bias is 2°C, a more restricted area of soil freezing emerges. Figure 7 conservatively shows patterns of soil freezing and illustrates that most sites in southern Michigan probably do not freeze often (bear in mind the model is designed for forested soils and may not be representative of urban areas or windswept agricultural fields). Sites that froze in *every one of the five modeled years* (Fig. 7C) are indeed rare, and sites that did not freeze for more two days in *at least one year* are commonplace (Fig. 7A).

The warm winter of 1952–1953 warrants a second look; soils did freeze (to at least 5 cm) in the southern peninsula, except for snowbelt sites that had at least 30 to 40 snow days. Some of the sites that did not experience soil freezing were the coldest with regard to air temperature, but lacked soil frost because of a more persistent and deeper snowpack—as, for example, the far northern snowbelt areas (Isard and Schaetzl, 1995). Early-season snowfall, previously thought to be important in inhibiting soil freezing (Schaetzl and Isard, 1991), does not appear to be an important variable (Fig. 5G). There are two explanations for the lack of correlation between deep, early-season snowfall and soil freezing: (1) deep snowpacks usually

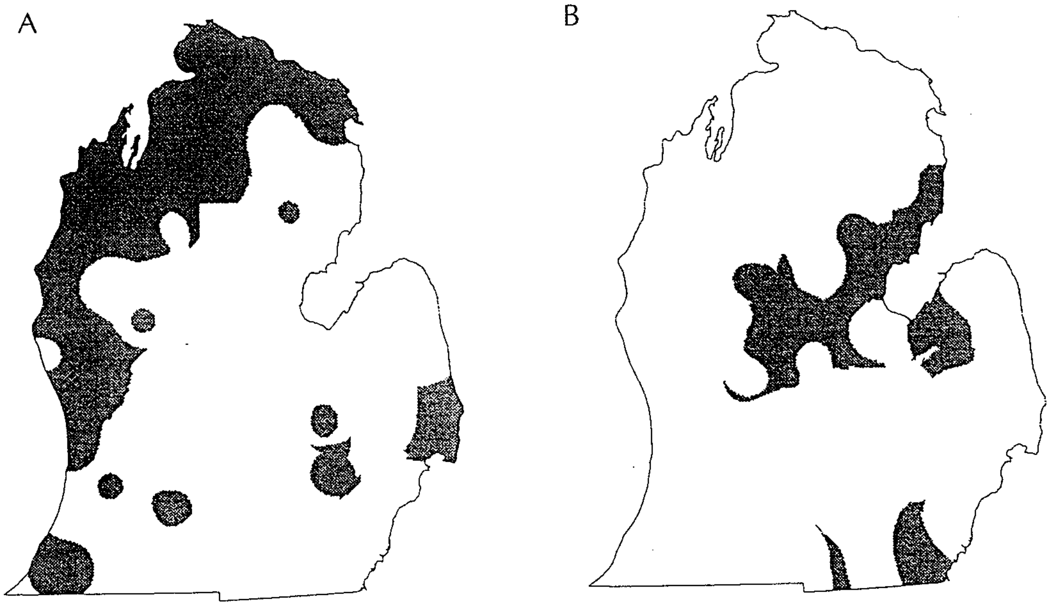

Fig. 7. (A) Areas, in gray, where the soil froze in *one or none* of the five winters studied. (B) Areas, in gray, where the soil froze in *four or five* of the winters studied.

experience at least one episode of melt, and the cold meltwater pulse from that melt event probably cools soils down faster than might an early outbreak of cold dry air; and (2) the coldest air temperatures occur in mid-winter, such that snowpack status *at that time* may be most important in the determination of whether the soil freezes. Mid-winter melt events, which render the soil bare, are therefore most important in promoting soil frost, and these events are fairly predictable spatially: the likelihood of a thin snowpack in mid-winter in the snowbelt is less than elsewhere. Thus, in winters that have several warm periods, soil frost may occur in snowbelt areas, but sites in eastern lower Michigan will probably have more frost events and more freeze-thaw cycles.

For these reasons, southeastern lower Michigan and the Saginaw Bay lowlands have the maximum numbers of days with continuous subzero soil temperatures and the highest numbers of freeze-thaw cycles (Figs. 7 and 8). Previously, we had predicted maximal soil-frost activity in northeast lower Michigan (Isard and Schaetzl, 1995), as had R. J. Russell in 1943. Minimal freezing occurs in the two snowbelt areas where deep snowpacks are most frequently observed: the far northern "tip of the mitten" and southwest lower Michigan (cp. Figs. 1 and 8). Only in winters where snowfall amounts are very low, as in 1979–1980 or 1952–1953, does widespread soil frost occur in these areas. And even in winters such as these, in which soil freezing is most likely, freeze days rarely exceed five or six in any other part of southern Michigan.

Scenarios of future climates that involve significant greenhouse warming generally predict that winters in central North America are likely to be 1° to 6°C warmer than at present (Kattenberg et al., 1996). Warmer winters typically are accompanied by lowered winter precipitation in Michigan, a trend supported by past climate data as well as GCM runs of future climate (e.g., Giorgi et al., 1994). Thus, the results of

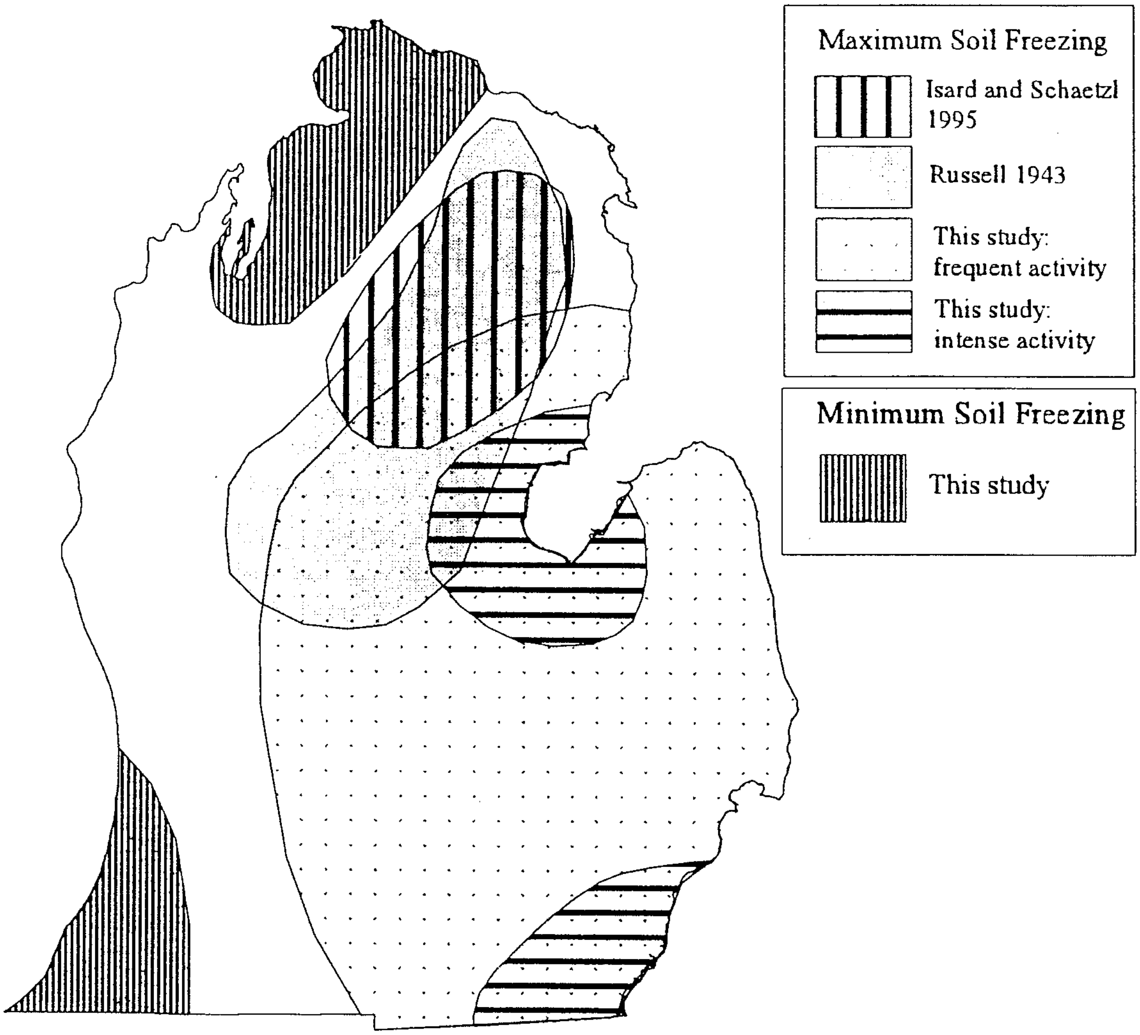

Fig. 8. Areas of maximal and minimal freezing in southern Michigan, based on conclusions drawn from this study and others.

this study indicate that soil freezing in southern Michigan, and the Great Lakes region as a whole, is likely to increase under a warmer, drier, 2 × CO_2 climate. An increased incidence of soil freezing, both spatially (more areas frozen) or temporally (soils stay frozen longer), could lead to more runoff from these landscapes and less groundwater recharge. Deforestation of the Great Lakes drainage basin certainly has led to an increase in runoff (relative to run-in), "flashier" hydrographs, and lowered base-flow values for streams in the region. This trend may be further exaggerated under a 2 × CO_2 climate.

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