

Microclimatic Variability of Cold-Season Minimum Temperatures in Michigan, United States: A Study with Implications for Insect Mortality

MICHAEL T. KIEFER,^a JEFFREY A. ANDRESEN,^a DEBORAH G. MCCULLOUGH,^{b,c} JAMES B. WIEFERICH,^d JUSTIN KEYZER,^c AND STEVE A. MARQUIE^e

^a Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing, Michigan

^b Department of Entomology, Michigan State University, East Lansing, Michigan

^c Department of Forestry, Michigan State University, East Lansing, Michigan

^d Forest Resources Division, Michigan Department of Natural Resources, Lansing, Michigan

^e Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, Michigan

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ABSTRACT: Gridded climate datasets are used by researchers and practitioners in many disciplines, including forest ecology, agriculture, and entomology. However, such datasets are generally unable to account for microclimatic variability, particularly within sites or among individual trees. One such dataset is a recent climatology of extreme minimum temperatures in the U.S. Great Lakes region, based on the Parameter–Elevation Regressions on Independent Slopes Model (PRISM) gridded temperature dataset. Development of this climatology was motivated by interest in the spatiotemporal variability of winter temperatures potentially lethal to the hemlock woolly adelgid (HWA) (*Adelges tsugae* Annand) (Hemiptera: Adelgidae), an invasive insect that causes mortality of eastern hemlock (*Tsuga canadensis*). In this study, cold-season daily minimum temperatures were monitored at six Michigan sites varying in latitude, elevation, Great Lakes proximity, and HWA infestation status, to address two objectives. First, we documented the spatiotemporal variability in daily minimum air temperatures recorded at multiple aspects and heights on selected hemlock trees. Second, this variability was characterized in the context of the PRISM extreme minimum temperature climatology. Tree-sensor air temperatures exhibited minimal relationships with aspect but considerable sensitivity to height. Daily minimum temperatures were higher for some tree sensors positioned ≤ 0.2 m above ground level during some time periods, with overall muted temporal variability, relative to an adjacent ambient sensor. This phenomenon was attributed to the insulating effects of snow cover, because the tree–ambient sensor temperature difference was positively correlated with snow depth. Overall, results indicate that such unresolved variability warrants consideration by gridded climate dataset users.

KEYWORDS: Atmosphere; Inland seas/lakes; Climate; Climate variability; Microscale processes/variability; Local effects

1. Introduction

In broad terms, most insect species are poikilothermic, that is, internal temperatures vary with ambient temperature and are thus sensitive to low environmental temperatures. As environmental temperatures fall below species-specific thresholds, insects sustain an array of metabolic dysfunctions and injuries, culminating in death (e.g., Renault et al. 2002). These insects include the hemlock woolly adelgid (HWA) (*Adelges tsugae* Annand) (Hemiptera: Adelgidae), a tiny, aphid-like insect native to Japan (Havill and Footitt 2007; Havill et al. 2014) that was first reported in eastern North America in 1951 (McClure 1991; Orwig and Foster 1998; Morin et al. 2011; Orwig et al. 2012). To date, HWA is present across approximately one-half of

the eastern hemlock (*Tsuga canadensis*) range in the United States, and localized populations were first detected in western Michigan in 2015 (Michigan Department of Agriculture and Rural Development 2016; Michigan Department of Natural Resources 2023). This sap-feeding insect is relatively unique in that during one of the two annual generations of HWA, the insects feed and develop throughout winter (McAvoy et al. 2017; Parker et al. 1998). A consensus among prior studies of HWA mortality is that winter-season extreme minimum temperature is the most critical limiting factor for HWA distribution (e.g., Paradis et al. 2008; McAvoy et al. 2017; Trotter and Shields 2009). To this end, Kiefer et al. (2022) constructed a 1981–2018 climatology of extreme minimum temperatures in the Great Lakes region of the United States using the Parameter–Elevation Regressions on Independent Slopes Model (PRISM) gridded daily minimum temperature dataset (Daly et al. 2008). Temperatures were examined exclusively during the cold season, defined here as the period from 1 November to 30 April. Cold-season minimum temperatures were found to be sensitive to proximity to water, surface elevation, and latitude, and the modifying influence of the Great Lakes was found to protect locations within about 10–25 km of the lakeshore from severe and potentially lethal temperatures for HWA (approximately from -20° to -30°C).

Marquie's current affiliation: ClimaTEQ, LLC, Okemos, Michigan.

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Corresponding author: Michael T. Kiefer, mtkiefer@msu.edu

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Gridded climate datasets such as PRISM are valuable tools used by researchers and practitioners in numerous sectors including forest ecology, agriculture, and entomology, as well as hydrology and risk management (e.g., [Daly et al. 2008](#); [Rogers et al. 2017](#); [Kiefer et al. 2019, 2022](#)). However, gridded climate datasets are generally unable to account for microclimatic variability (e.g., due to subtle topographic differences, forest versus forest clearing), including variability at the scale of individual trees, reflecting differences in aspect (e.g., south vs east side of tree) or height above ground. In this study, we adopt the American Meteorological Society *Glossary of Meteorology* (<https://glossary.ametsoc.org/>) definition of microclimate: the “fine climatic structure of the air space that extends from the very surface of the earth to a height where the effects of the immediate character of the underlying surface no longer can be distinguished from the general local climate,” which in turn consists of mesoclimate (the “climate of a natural region of small extent, for example, valley, forest, plantation, and park”) and macroclimate (the “general large-scale climate of a large area or country”) ([American Meteorological Society 2012](#)).

Previous studies have characterized microclimatic variability and the potential impact on organisms including insects (e.g., [Andresen et al. 2001](#)), considered the complex relationship between microclimate and organisms under current and future climate scenarios (e.g., [Pincebourde et al. 2016](#)), addressed challenges involved in collecting microclimate measurements (e.g., [Maclean et al. 2021](#)), and related microclimatic variability to variability resolved by gridded datasets (e.g., [Latimer and Zuckerberg 2017](#)). In the first example, [Andresen et al. \(2001\)](#) examined the effects of tree aspect and height above ground on temperatures in spongy moth (*Lymantria dispar* L.; formerly known as gypsy moth) egg masses on oak tree stems during three winter seasons in Michigan. They documented instantaneous egg-mass temperatures up to 30°C higher on the southern aspect relative to the other aspects and related such temperature variations to differences in solar radiative flux between aspects. Furthermore, they documented significant differences in egg mortality among aspects, with less than 25% of eggs surviving on the southern and western aspects, as compared with 53%–73% egg survival on the northern and eastern aspects. Differences in egg-mass temperature among egg masses at different heights above ground level were minimal, but snow cover moderated extreme minimum winter temperatures at the base of the trees. This result is broadly consistent with studies of HWA mortality (e.g., [McClure and Cheah 2002](#); [Cheah 2017](#); [Mausel 2017](#)), soil temperatures in the U.S. Great Lakes region ([Isard et al. 2007](#)), winter mortality of alfalfa in Michigan ([Leep et al. 2001](#)), and winter mortality of cotton bollworm [*Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae)] pupae in Xinjiang, China ([Huang 2016](#)).

Second, [Pincebourde et al. \(2016\)](#) reviewed and synthesized literature on microclimatic variability at spatial scales ranging from that of individual plant elements and insects up to landscape scale (from $\sim 10^{-3}$ to 10^3 m), and the response of organisms to such variability, with climate change implications considered as well. They noted that microclimatic temperature variability reported in the literature is often actually a combination of

variability across space and time and strongly recommended that the spatial resolution of temperature data be reported along with the microclimatic variability. They also observed that environmental and organism temperature spatiotemporal heterogeneity is largely undocumented for the vast majority of species. They concluded that spatial variability of temperatures, along with corresponding temporal variability, is of critical importance for understanding the potential impacts of climate change on organisms.

Third, [Latimer and Zuckerberg \(2017\)](#) compared daily minimum, maximum, and mean temperatures measured by 68 microclimate temperature sensors in forested sites in southern Wisconsin with PRISM gridded temperature estimates during the 2012/13 winter season. They found that daily minimum and maximum temperatures measured at the microclimate sites were on average 0.72° and 4.2°C higher than PRISM temperatures, respectively, and also noted that the closest agreement between PRISM and microclimate-site daily temperatures occurred for locations distant from urban sites, with low topographic relief and greater amounts of forest edge. They found that differences in cooling degree-day accumulations (-18°C base) across their forested study area, approximately 50 km in scale, were comparable to differences between Chicago O’Hare International airport, Illinois, and the Minneapolis–St. Paul airport, Minnesota, located approximately 550 km apart [stated incorrectly as 650 km in [Latimer and Zuckerberg \(2017\)](#)].

Last, [Maclean et al. \(2021\)](#) examined the challenges involved in collecting accurate temperature measurements at microclimates sites in Belgium and the United Kingdom. They noted that the factors that contribute to microclimatic variability (e.g., forest canopy gaps) are the same factors that may contribute to temperature measurement error. In sunlight, the main factors affecting air temperature accuracy are thermal emissivity and reflectivity of the instrument. In the absence of sunlight, however, the primary factors affecting air temperature accuracy are thermal emissivity and conductivity of the instrument. They found that accurate measurements of nighttime air temperatures are more easily achieved than corresponding daytime temperatures in sun-exposed locations, with consumer- and research-grade sensors yielding similar temperature accuracy at night but not during the day.

Although not cited in the preceding literature overview, it is also worth mentioning the importance of microclimatic variability to fields such as forensic entomology and anthropology (e.g., [Archer 2004](#); [Dorel et al. 2010](#); [Dabbs 2015](#); [Chappell et al. 2022](#)), in which accuracy of postmortem interval estimates is affected by temperature differences between off-site weather stations and sites of interest to investigators. Collectively, the studies described herein highlight the need for further investigations of microclimatic variability, including how such spatiotemporal variability may impact the life cycle or survival of an organism.

In this study, daily minimum temperatures are examined during the cold season from 1 November to 30 April at six instrumented sites in Michigan that vary in latitude, elevation, lake proximity, and HWA infestation status [as in [Kiefer et al. \(2022\)](#)]. These dates correspond approximately to the earliest and latest dates in the PRISM extreme minimum temperature climatology, with daily minimum temperatures below the -20°C threshold (often associated with $\geq 90\%$ HWA mortality, as reported in

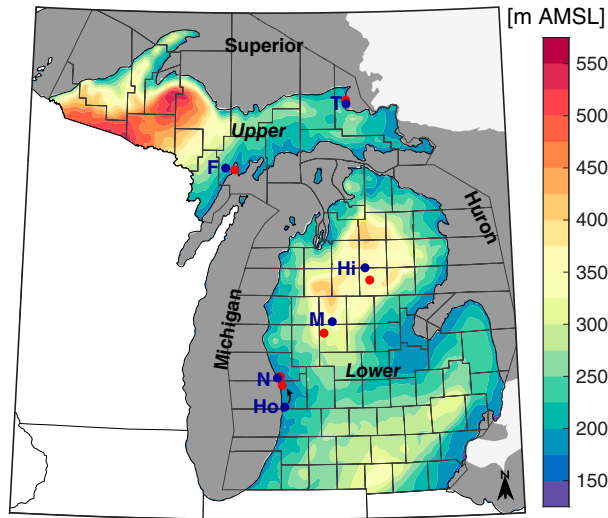


FIG. 1. Contoured map of PRISM surface elevation across Michigan. Blue circles denote the locations of microclimate station sites, and red circles denote the locations of corresponding NWS COOP network sites used for snowfall and/or ambient-temperature measurements; in the case of Holland, the black arrow points to the NWS COOP network site used for snowfall measurements (Grand Haven; see Table 2). Microclimate station sites are labeled as follows: Ho: Holland; N: Norton; M: Meemos; Hi: Higgins; F: FBIC; T: Tahquamenon. Three Great Lakes and the Upper and Lower Peninsulas of Michigan are labeled for reference [Lake Erie (under north compass arrow) is not labeled].

previous studies; e.g., Paradis et al. 2008). Objectives of the current study are twofold. First, we analyze differences in daily minimum air temperatures recorded within and among trees and sites to evaluate macroclimatic through microclimatic temperature variability, including the moderating effects of Lake Michigan on cold-season minimum temperatures. Second, we characterize the spatiotemporal variability observed at the instrumented sites in the context of the PRISM-based U.S. Great Lakes region extreme minimum temperature climatology presented in Kiefer et al. (2022). Although the microclimate sites are limited to Michigan, we expect that these results will be applicable to other areas

of the U.S. Great Lakes region, and indeed, to other regions of the world with similar physiography (e.g., the Mediterranean Sea).

The remainder of this paper is organized as follows: the materials and methods are described in section 2, including descriptions of the station sites (section 2a), data sources (section 2b), data processing steps (section 2c), and analysis method (section 2d); results and discussion are provided in section 3, including analysis of the impacts of tree-sensor aspect and height on daily minimum temperatures (section 3a), analysis of the impact of snow cover on daily minimum temperatures (section 3b), a comparison of PRISM and microclimate-site daily minimum temperatures (section 3c), and an overall assessment of microclimatic variability in the context of the Kiefer et al. (2022) PRISM extreme minimum temperature climatology (section 3d); the paper is concluded in section 4.

2. Materials and methods

a. Station sites

Daily minimum temperatures were evaluated at six microclimate sites across Michigan (Fig. 1; Table 1) during three cold seasons: 2016/17, 2017/18, and 2018/19. Note that during the preliminary 2016/17 season, three trees were instrumented at a single site (Norton). The six sites were chosen to broadly represent variation in latitude, elevation, lake proximity, and HWA infestation status across Michigan. An eastern hemlock tree was selected for temperature monitoring at each location. At two sites, Norton and Holland, infestations of HWA had been detected in 2015 and 2016, respectively. Both sites are in the western Lower Peninsula of Michigan (hereinafter Lower Michigan) along or near the Lake Michigan shoreline. Most hemlocks at the two sites had some level of HWA infestation during this study, but few trees appeared to be declining and no hemlocks had been killed by HWA. At the other four locations [Forestry Biomass Innovation Center (FBIC), Higgins, Meemos, and Tahquamenon], there was no HWA present. Permits or permission from landowners and managers were acquired for all sites. For some sites, the availability of cellular telephone coverage (for data transmission) was

TABLE 1. Microclimate station site information, including latitude and longitude (decimal degrees) and elevation (m), along with tree-sensor height AGL (m) and aspect. For reference, the ambient-sensor height is 1.0 ± 0.1 m. For FBIC, Holland, Meemos, and Tahquamenon, sensor heights shown here are for the 2017/18 season only (sensor heights for 2018/19 are provided in Table S1 of the online supplemental material). For Higgins and Norton (boldface font), sensor heights shown here are valid for the 2017/18 and 2018/19 seasons; sensor heights at Norton during the 2016/17 season are included in Table S1. Here, N, E, S, and W indicate north, east, south, and west, respectively.

| Microclimate sites | | | | Sensor height and aspect | | | | | | | | | | | |
|--------------------|---------------|----------------|------------|--------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| | | | | Low | | | | Middle | | | | High | | | |
| Name | Lat | Lon | Elev | N | E | S | W | N | E | S | W | N | E | S | W |
| FBIC | 45.765 | -87.202 | 230 | 2.8 | 2.6 | 2.3 | 2.6 | 3.2 | 3.6 | 3.5 | 3.6 | 4.5 | 4.0 | 4.4 | 4.0 |
| Higgins | 44.513 | -84.751 | 358 | 0.2 | 0.1 | 0.1 | 0.1 | 2.2 | 1.3 | 1.8 | 1.6 | 3.3 | 3.7 | 3.5 | 3.1 |
| Holland | 42.791 | -86.161 | 184 | 0.3 | 0.2 | 0.2 | 0.3 | 1.8 | 1.6 | 2.0 | 2.0 | 3.0 | 2.9 | 3.1 | 3.8 |
| Meemos | 43.849 | -85.337 | 326 | 2.1 | 2.4 | 2.1 | 2.2 | 3.4 | 4.6 | 3.3 | 3.6 | 4.5 | 5.3 | 5.2 | 4.4 |
| Norton | 43.154 | -86.285 | 196 | 0.0 | 0.1 | 0.1 | 0.1 | 2.1 | 2.4 | 2.1 | 2.3 | 3.4 | 4.0 | 3.3 | 3.4 |
| Tahquamenon | 46.559 | -85.036 | 187 | 0.6 | 0.5 | 0.7 | 0.6 | 1.9 | 2.2 | 1.9 | 2.0 | 3.1 | 3.6 | 3.0 | 3.1 |

considered when selecting sites and trees for temperature monitoring (e.g., Meemos and Tahquamenon).

Holland, the most southerly of the six sites, was a 4-ha woodlot on the outskirts of Holland, Ottawa County, approximately 6.5 km from the Lake Michigan shoreline (Fig. 1). The site was topographically flat, with an overstory dominated by eastern hemlock, along with scattered eastern white pine (*Pinus strobus*), American beech (*Fagus grandifolia*), northern red oak (*Quercus rubra*), and sugar maple (*Acer saccharum*). A dense understory of American beech saplings and raspberry (*Rubus strigosus*) occurred in scattered openings among the trees. Although HWA was detected in 2016, even heavily infested trees appeared healthy, with full canopies at the onset and for the duration of the project. The 16-ha Norton site, near Norton Shores, Muskegon County, was approximately 43 km north of Holland and bordered Lake Michigan (Fig. 1). This site consisted of a flat, central area with semipermanent trailers surrounded by steep, forested dunes. Overstory composition at this site was dominated by eastern hemlock and American beech, with a minor component of white pine, red oak, and sugar maple. HWA was first detected at this site in 2015.

Two of the four sites without HWA were located in Lower Michigan and the other two were in Michigan's Upper Peninsula (hereinafter Upper Michigan). In Lower Michigan, the Meemos site was a 14-ha stand on a private hunting preserve near Evart, Osceola County, 91 km east of Lake Michigan (Fig. 1). A first-order stream wound through the stand, which was fairly flat with ephemerally flooded lowlands. Hemlocks and white pine were abundant on the relatively dry ground, whereas white ash (*Fraxinus americana*) and red maple (*Acer rubrum*) were common along the stream and in the flood-prone areas. The Higgins site, also in Lower Michigan, was a 7.6-ha lowland area north of Higgins Lake in Roscommon County in the north-central region of Lower Michigan (Fig. 1). This area, which experienced occasional flooding, was flat with a dense overstory of pole-sized hemlock and white cedar (*Thuja occidentalis*).

In Upper Michigan, the Tahquamenon site was near the edge of a campground on a 27-ha peninsula extending into the Tahquamenon River in Chippewa County, approximately 4 km from a bay on the southwestern edge of Lake Superior (Fig. 1). In addition to eastern hemlock, the overstory included a mix of beech, paper birch (*Betula papyrifera*), sugar maple, and red maple. The FBIC site was a 12-ha stand in a research forest approximately 9 km west of Escanaba, Delta County, and approximately 12 km west of a bay on the northern edge of Lake Michigan (Fig. 1). This flat, upland site included a minor component of hemlock mixed with abundant beech and sugar maple.

b. Data sources

Temperature sensors were attached to the underside of 12 shoots in a predesignated pattern on a mature hemlock tree at each of the six microclimate sites (e.g., Higgins and Norton, Figs. 2a,b). At FBIC, Holland, Meemos, and Tahquamenon, temperatures on the hemlock trees were monitored with HOBO S-TMB-M017 12-bit temperature sensors (Onset Computer Corporation) attached to shoots with zip ties, whereas at Higgins and Norton, 0.254-mm type E chromel–constantan



FIG. 2. Photographs from microclimate sites. (top) The instrumented hemlock tree and (middle) the ambient weather station at (a),(c) Higgins and (b),(d) Norton. (e) A snow-covered lower branch of the instrumented hemlock tree at Holland. For reference, the Higgins instrumented tree in (a) is immediately left of the birch tree trunk in the image center.

thermocouples (Omega Engineering) were attached to the shoots in the same manner. Instrumented trees were exposed to nearly full sun at the Holland, Norton (Fig. 2b), and Tahquamenon sites, whereas trees at the FBIC, Higgins (Fig. 2a), and Meemos sites were shaded on at least three aspects by adjacent trees. Sensors were installed on each tree at three heights (low, middle, and high categories) and four aspects (north, east, south, and west facing) (Table 1), to measure the air temperatures to which a hypothetical HWA would be exposed. Note that sensor heights varied

TABLE 2. Summary of data sources acquired by site and season, where Ta is air temperature, NC is the NWS COOP network, AP is airport, and WP is water plant. For observations not collected at the microclimate site, the distance from the proxy site to the microclimate site is listed (source: Google Earth). A map of station locations is provided in Fig. 1.

| Season | Microclimate site | Ambient Ta (NC) | Snow depth (NC) |
|---------|-------------------|----------------------------|----------------------------|
| 2016/17 | Norton | Muskegon AP (4.4 km) | Muskegon AP (4.4 km) |
| 2017/18 | FBIC | onsite | Escanaba WP (12.8 km) |
| 2017/18 | Higgins | onsite | Houghton Lake AP (18.2 km) |
| 2017/18 | Holland | onsite | Grand Haven WP (30.2 km) |
| 2017/18 | Meemos | onsite | Big Rapids WP (19.6 km) |
| 2017/18 | Norton | onsite | Muskegon AP (4.4 km) |
| 2017/18 | Tahquamenon | onsite | Paradise (5.1 km) |
| 2018/19 | FBIC | onsite | Escanaba WP (12.8 km) |
| 2018/19 | Higgins | Houghton Lake AP (18.2 km) | Houghton Lake AP (18.2 km) |
| 2018/19 | Holland | onsite | Grand Haven WP (30.2 km) |
| 2018/19 | Meemos | onsite | Big Rapids WP (19.6 km) |
| 2018/19 | Norton | onsite | Muskegon AP (4.4 km) |
| 2018/19 | Tahquamenon | onsite | Paradise (5.1 km) |

considerably among sites, depending on branch distribution, and, with the notable exceptions of Higgins and Norton during the 2017/18 and 2018/19 seasons, varied from one season to the next (cf. Table 1 with Table S1 in the online supplemental material). Homogeneity of instrumentation heights among sites and seasons was a primary factor in the selection of sites for in-depth analysis of tree and ambient temperatures (section 2d).

Ambient air temperature was measured at 1 m above ground level, in open areas several meters away from the instrumented trees, using either the same Onset S-TMB-M0017 sensors used for the tree temperature measurements (FBIC, Holland, Meemos, and Tahquamenon) or Vaisala HMP-155A hygrothermometers (Vaisala Corporation) (Higgins and Norton; Figs. 2c,d). At FBIC, Holland, Meemos, and Tahquamenon, ambient- and tree-sensor temperature data were recorded by Onset Hobo Remote Monitoring System RX3000 dataloggers, which collected 5-min mean temperatures. At Higgins and Norton, Campbell Scientific CR1000 dataloggers collected 5-min, hourly, and daily temperatures and transmitted data to computers on the Michigan State University campus at 12-h intervals. Temperature sensors and weather stations were installed in September or October each year. With the notable exceptions of Higgins and Norton, land-owners or managers required that weather equipment be removed in spring to prevent interference or vandalism by visitors.

National Weather Service (NWS) Cooperative Observer Program (COOP) temperature measurements were used as a proxy for ambient-sensor temperature measurements at two sites (Table 2): Norton, during the 2016/17 season, when no ambient sensor was deployed (proxy: Muskegon airport), and Higgins, during the 2018/19 season, when the ambient-sensor time series exhibited little to no diurnal or seasonal variability, indicative of a sensor malfunction (proxy: Houghton Lake airport). To account for systematic differences between the proxy and microclimate station siting and instrumentation, a least squares linear regression was fit to scatterplots of daily minimum temperatures at the proxy and microclimate sites during the 2017/18 season (when the ambient sensors were available and functioning within normal parameters at all microclimate sites). Separate linear regression equations were developed for daily minimum temperatures at Higgins and

Norton. The coefficient of determination R^2 ranged from 0.94 to 0.95, indicating that the bulk of the temperature variability between the microclimate and NWS COOP sites [separated by 4.4 km (Norton–Muskegon airport) and 18.2 km (Higgins–Houghton Lake airport); Table 2] was captured by the linear regression equations. Equations were subsequently applied to the NWS COOP temperature time series at Muskegon airport (Norton, 2016/17) and Houghton Lake airport (Higgins, 2018/19).

Last, given the substantial insulating effect of snow cover on spongy moth egg-mass temperatures reported by Andresen et al. (2001), we sought to investigate whether a similar relationship might exist for tree-sensor air temperatures at the microclimate sites (see Fig. 2e for an example of a snow-covered lower hemlock branch at Holland). Because snowfall measurements were not collected at the sites, daily snow-depth measurements were obtained from the nearest NWS COOP site with reasonably complete snowfall records during the study period (less than 10% missing). As shown in Table 2, the distance between the microclimate sites and snow-depth proxy sites varied from as little as 4.4 km for Norton to as much as 30.2 km for Holland. Before proceeding, a brief discussion of snow-depth measurement representativeness is in order. In broad terms, snowfall in Michigan results from a combination of larger-scale synoptic weather systems transiting the Great Lakes region and smaller-scale lake-effect systems that are typically activated following the passage of synoptic systems. Given the complex physiography of Michigan, the relative distribution between the two snowfall sources varies substantially across the state but is primarily a function of distance downwind of the lakeshore (Andresen 2012). Using the Scott and Huff (1996) definition of a lake-effect region (i.e., snowbelt) as any location within 80 km of one of the Great Lakes, four of the six sites considered in this study are definitively located in lake-effect snowbelts (FBIC, Holland, Norton, and Tahquamenon) and two are located near or just outside of the snowbelts but are influenced to some degree by lake-effect snow (Higgins and Meemos). Given the focus of this study on Higgins (nonsnowbelt site; weaker snowfall gradients expected) and Norton (snowbelt site; stronger snowfall gradients expected), and the distances to the proxy snow-depth

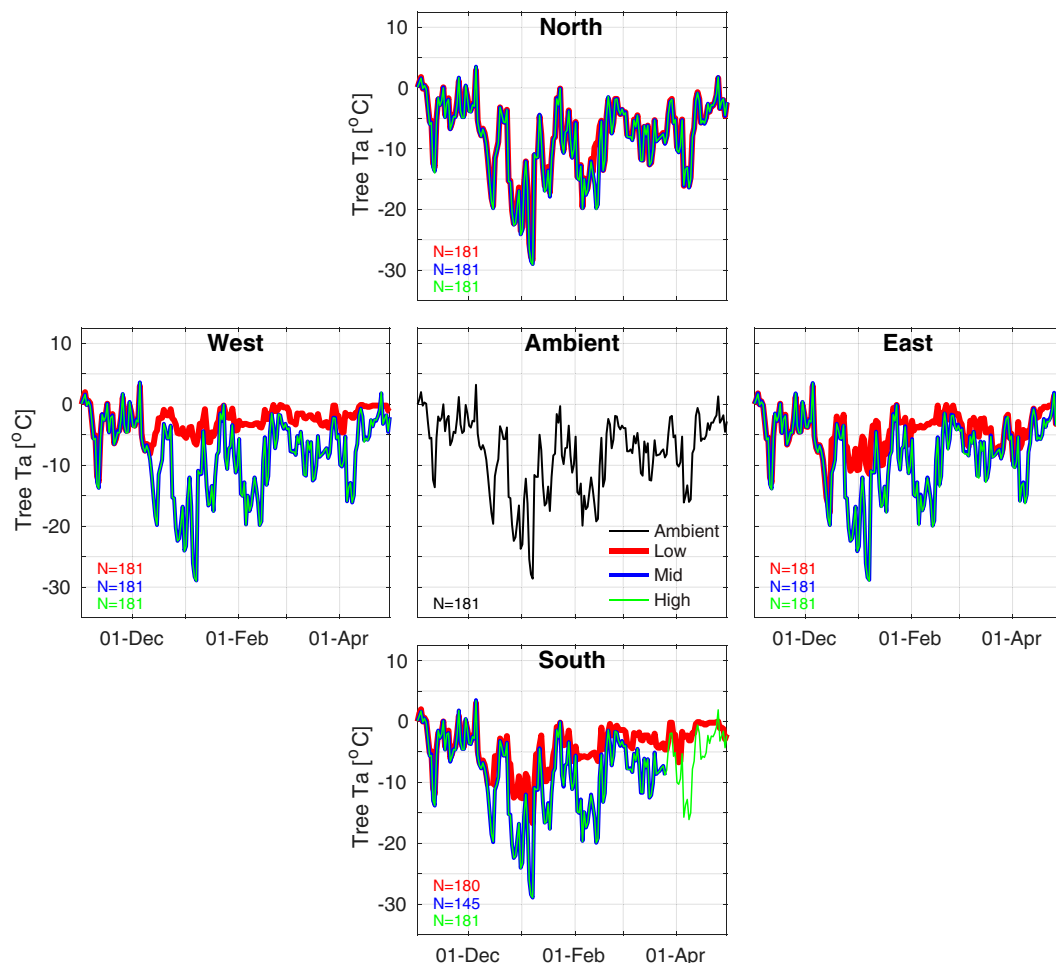


FIG. 3. Time series of daily minimum temperature by aspect at the Higgins microclimate site during the 2017/18 season. Line colors denote sensor type and tree-sensor height category: ambient is black, low tree is red, midtree is blue, and high tree is green. See Table 3 for summary statistics. The number of days N with observations is included for each aspect.

sites of 18.2 and 4.4 km, respectively (Table 2), the unknown amount of representativeness error associated with snow-depth spatial variability was deemed acceptable.

c. Data processing

A series of automated and manual quality assurance (QA)/quality control (QC) steps were applied to the 5-min microclimate-site temperature data downloaded from the dataloggers, based in part on automated procedures applied within the Oklahoma Mesonet-work (Shafer et al. 2000). First, redundant rows in the raw data files were eliminated, missing rows were inserted as strings of “NaN” (i.e., “not a number”), and inconsistent sensor order in the raw data files was standardized. Second, a three-step automated procedure was applied, consisting of a gross range check (temperature must be between -40° and 45°C , inclusive), a step check (temperature change from one time step to another must not exceed 10°C), and an outlier check (temperature at a given tree-mounted sensor must not differ from the mean among the other 11 tree-mounted instruments by more than 3 times the standard

deviation among those instruments); observations failing one or more automated checks were subsequently masked. Note that the outlier check excludes the ambient sensor; during morning–evening transitions, tree sensors warm/cool more rapidly than the free-standing ambient sensor, potentially leading to considerable temperature differences between the two sensor types. Last, manual QA/QC was applied to the data to mask values that passed the automated checks but were judged to be erroneous following a close visual inspection.

Following QA/QC, the temperature time series from 1205 UTC 31 October to 200:00 UTC 30 April were isolated, the lowest 5-min mean value during each 24-h period ending at 1200 UTC [0700 eastern standard time (EST = UTC – 5)] was designated as the daily minimum temperature, and daily values were set to missing if more than 10% of the 288 five-minute observations during that 24-h period were unavailable (either missing or rejected in the preceding QA/QC step). This method ensures that the daily temperatures computed from the microclimate-site data conform to the PRISM day

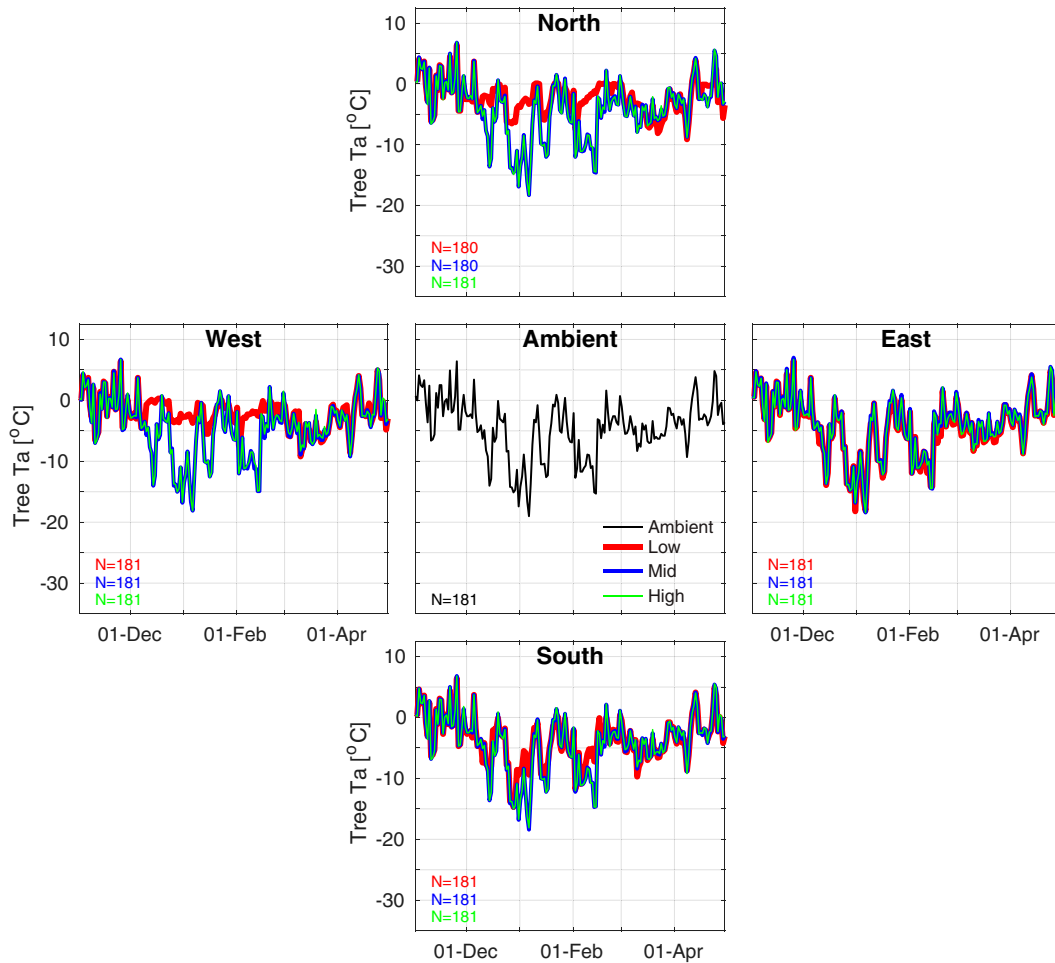


FIG. 4. As in Fig. 3, but for the Norton microclimate site.

definition (1200–1200 UTC; Daly et al. 2008), facilitating a direct comparison of microclimate-site observations and PRISM gridded estimates.

d. Analysis method

Assessment of the microclimate-site temperature time series takes place in two stages. In the first stage, daily minimum temperatures during the 2017/18 season are examined in detail at two microclimate sites, one representative of inland areas without HWA present (Higgins) and one representative of lake-shore areas with HWA present (Norton). The choice of season and sites for this in-depth examination ensures broad homogeneity in sensors, sensor heights, and dataloggers between sites and limits the number of missing and rejected observations. Note that results are generally consistent among seasons; figures and tables for the 2016/17 and 2018/19 seasons are included as online supplemental material and are briefly discussed in section 3, where appropriate. Time series and scatterplots, with corresponding summary statistics, are used to assess relationships between tree- and ambient-sensor temperatures, the heights and aspects of the tree sensors, and snow depths measured at nearby NWS COOP sites. Primary statistical measures utilized

include mean difference (MD), root-mean-square difference (RMSD), Pearson’s correlation coefficient (CORR), and the R^2 and slope S of a least squares linear regression line fit to the data points. To assess the statistical significance of differences between tree and ambient temperatures, p values from a two-tailed t test without equal variance assumption are included.

In the second stage, daily minimum temperatures observed at all six microclimate sites are compared with corresponding PRISM gridded estimates. As a preliminary step, ambient-sensor daily minimum temperatures are compared with PRISM estimates at the nearest grid point to each microclimate site. This preliminary analysis is conducted to evaluate possible systematic differences between the microclimate-site observations and the PRISM gridded estimates used to develop the Kiefer et al. (2022) extreme minimum temperature climatology. Last, daily minimum temperatures from all seasons, sites, and sensors are overlaid on box-and-whisker plots depicting the Kiefer et al. (2022) climatological distribution at the nearest grid point to each site. This final exercise is conducted to place the microclimatic variability identified in this study in the context of the macroclimatic variability contained in the Kiefer et al. (2022) extreme minimum temperature climatology.

TABLE 3. Summary statistics for tree- vs ambient-sensor daily minimum temperatures at the Higgins and Norton microclimate sites for the 2017/18 season. Height refers to the tree-sensor height category (Table 1), aspect refers to the direction toward which the tree sensor faces, N is No. of days (max: 181), MD is mean difference (tree – ambient; °C), t test is the p value for a two-sample t test without equal variance assumption (boldface type indicates p value less than 0.05), RMSD is root-mean-square difference (tree – ambient; °C), CORR is correlation coefficient, and R^2 and S are the coefficient of determination and slope of the linear regression, respectively.

| Station | Height | Aspect | N | MD | t test | RMSD | CORR | R^2 | S |
|---------|--------|--------|-----|-------|------------------|------|------|-------|------|
| Higgins | Low | North | 181 | 0.26 | 0.69 | 1.22 | 0.98 | 0.96 | 0.96 |
| | | East | 181 | 3.85 | <0.001 | 5.86 | 0.72 | 0.52 | 0.40 |
| | | South | 180 | 4.08 | <0.001 | 5.50 | 0.85 | 0.73 | 0.48 |
| | | West | 181 | 5.59 | <0.001 | 7.63 | 0.60 | 0.36 | 0.21 |
| | Middle | North | 181 | –0.08 | 0.90 | 0.36 | 1.00 | 1.00 | 1.02 |
| | | East | 181 | 0.06 | 0.93 | 0.38 | 1.00 | 1.00 | 1.01 |
| | | South | 145 | 0.03 | 0.97 | 0.32 | 1.00 | 1.00 | 1.02 |
| | | West | 181 | 0.07 | 0.92 | 0.32 | 1.00 | 1.00 | 1.02 |
| | High | North | 181 | –0.09 | 0.89 | 0.40 | 1.00 | 1.00 | 1.02 |
| | | East | 181 | –0.03 | 0.96 | 0.39 | 1.00 | 1.00 | 1.02 |
| | | South | 181 | 0.06 | 0.93 | 0.37 | 1.00 | 1.00 | 1.02 |
| | | West | 181 | 0.04 | 0.95 | 0.36 | 1.00 | 1.00 | 1.02 |
| Norton | Low | North | 180 | 2.51 | <0.001 | 4.39 | 0.67 | 0.45 | 0.38 |
| | | East | 181 | 0.23 | 0.65 | 0.51 | 1.00 | 0.99 | 0.98 |
| | | South | 181 | 0.96 | 0.04 | 2.12 | 0.93 | 0.86 | 0.74 |
| | | West | 181 | 2.60 | <0.001 | 4.64 | 0.60 | 0.36 | 0.33 |
| | Middle | North | 180 | 0.51 | 0.31 | 0.55 | 1.00 | 1.00 | 0.99 |
| | | East | 181 | 0.62 | 0.22 | 0.67 | 1.00 | 1.00 | 1.00 |
| | | South | 181 | 0.41 | 0.42 | 0.48 | 1.00 | 1.00 | 0.99 |
| | | West | 181 | 0.25 | 0.62 | 0.41 | 1.00 | 1.00 | 0.99 |
| | High | North | 181 | 0.49 | 0.34 | 0.57 | 1.00 | 1.00 | 0.99 |
| | | East | 181 | 0.43 | 0.39 | 0.55 | 1.00 | 1.00 | 0.99 |
| | | South | 181 | 0.42 | 0.41 | 0.53 | 1.00 | 1.00 | 0.99 |
| | | West | 181 | 0.35 | 0.49 | 0.51 | 1.00 | 0.99 | 0.99 |

3. Results and discussion

a. Impact of tree-sensor aspect and height on daily minimum temperatures

Analysis begins with an assessment of daily minimum temperatures during the 2017/18 season at the inland Higgins site and the Norton site adjacent to the Lake Michigan shoreline. To provide an overview of temperatures at the sites, daily minimum temperature time series at Higgins and Norton are presented in Figs. 3 and 4, respectively, with summary statistics provided in Table 3. Corresponding time series during the 2016/17 (Norton only) and 2018/19 seasons are provided in the online supplemental material (Figs. S1–S3 and Tables S2 and S3). Note that temperatures during the 2017/18 season are intermediate between the warmer 2016/17 and colder 2018/19 seasons (cf. Figs. 3 and 4 and Figs. S1–S3). Focusing on the ambient temperature time series first, a broad seasonal cycle is discernable, with the lowest temperatures in late December and early January and highest temperatures in November and April. Embedded within this broad cycle is a series of valleys and peaks indicative of planetary–synoptic-scale variability on time scales of weeks to days. The lowest temperatures of the entire season occur in early January, with daily minimum temperatures approaching (but not exceeding) -30° and -20°C at Higgins and Norton, respectively, with additional cold-air outbreaks in early November, early- to mid-December, early- to

mid-February, and early April. Unsurprisingly, daily minimum temperatures at the two sites are highly correlated (CORR = 0.90). On average, ambient temperatures at Norton were 3.55°C higher than at Higgins ($p < 0.001$). Such differences in ambient temperature are consistent with macroclimatic differences between Higgins and Norton: Higgins is an interior site at 44.513°N latitude and 358 m above mean sea level, whereas Norton is a lakeshore site at 43.154°N latitude and 196 m above mean sea level (Table 1).

In comparing ambient- and tree-sensor temperatures, negligible differences are seen for the middle and high tree-sensor categories, a finding that is supported by MD values generally in the range of $\pm 0.5^\circ\text{C}$ ($p > 0.05$). Consistently larger MD values at Norton than at Higgins are consistent with the greater sky exposure for the ambient sensor at Norton (and thus more efficient radiative cooling) relative to the ambient sensor at Higgins (Figs. 2a,b). In contrast to the middle and high tree-sensor categories, some of the low-category sensors exhibit noticeably different temperature time series than the ambient sensors. On the west, east, and south aspects at Higgins (Fig. 3), and north, west, and to a lesser degree, south aspects at Norton (Fig. 4), extended periods of higher temperatures and reduced variability (relative to the ambient sensor) are observed. As shown in Table 3, tree–ambient MD values for these sensors are between 0.96° and 5.59°C ($p < 0.05$), with RMSD values between 2.12° and 7.63°C , indicative of large day-to-day variability in ambient-

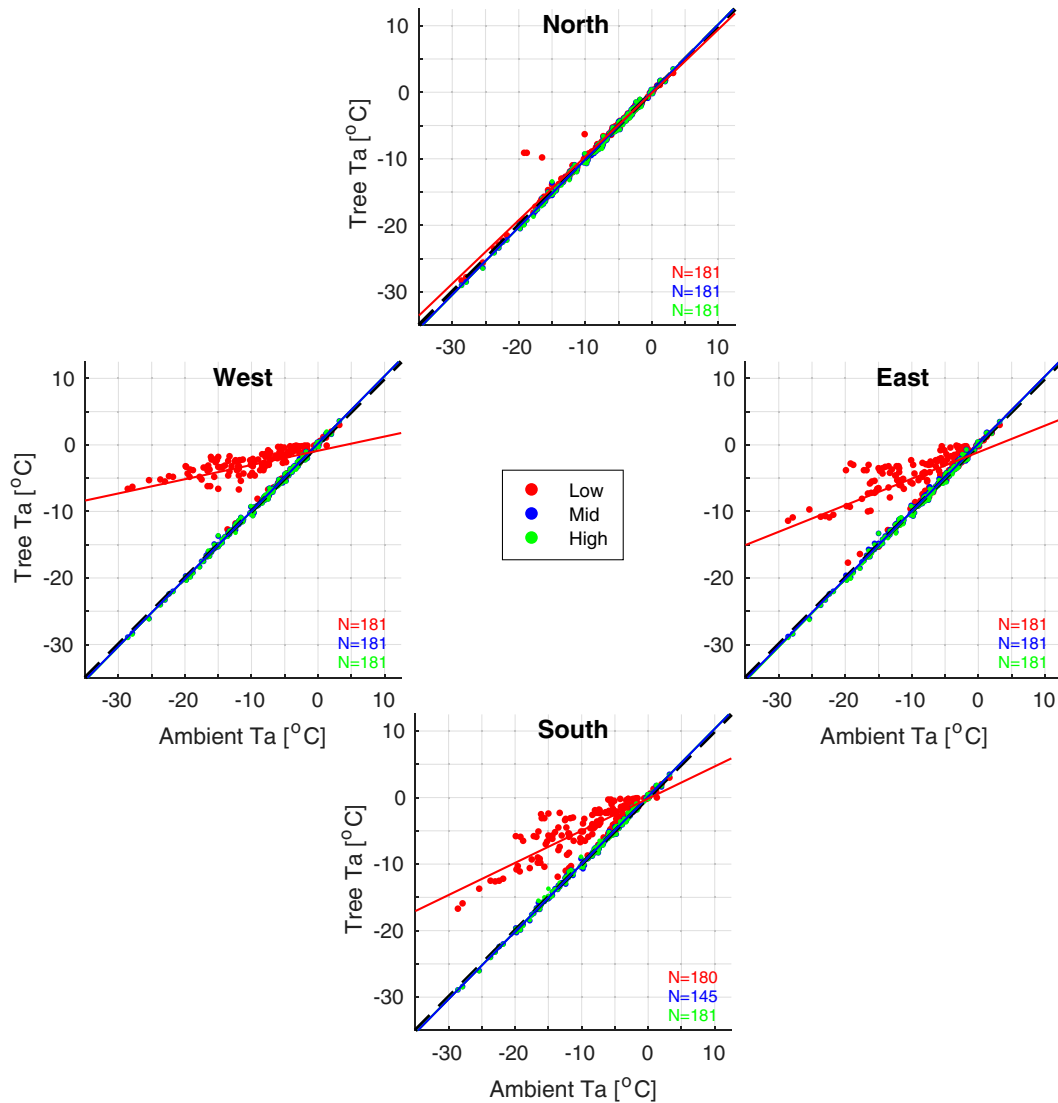


FIG. 5. Scatterplots of daily minimum temperature at the Higgins microclimate site during the 2017/18 season (x axis: ambient sensor; y axis: tree sensor). In each panel, solid lines depict the linear regressions (one per sensor) and the dashed line is the 1:1 line. Line and symbol colors denote tree-sensor height category: low is red; middle is blue, and high is green. See Table 3 for summary statistics.

sensor temperatures (variability that is generally lacking with the tree sensors). Histograms of ambient- and tree-sensor temperatures confirm the results deduced from the time series plots (Figs. S4 and S5 in the online supplemental material). Temperature distributions are considerably narrower for the aforementioned low tree sensors in comparison with the remaining tree sensors, whose temperature distributions closely match the ambient-sensor distribution. With the notable exception of the low-height tree-sensor temperature behavior, no obvious or consistent relationship between tree aspect and temperature time series occurs. However, [Andresen et al.’s \(2001\)](#) observation of a strong correlation between egg-mass temperatures and aspect when measured directly on tree trunks suggests that the

exact location in the tree canopy (e.g., under a branch vs on the trunk) is still a key consideration.

Patterns identified in the time series plots are examined further via scatterplots of ambient- and tree-sensor temperatures (Figs. 5 and 6) and summary statistics in Table 3. Corresponding scatterplots of the 2016/17 (Norton only) and 2018/19 seasons are included in the online supplemental material (Figs. S6–S8; Tables S2 and S3). In the scatterplots, temperatures recorded by the middle and high tree sensors are clustered tightly along the 1:1 (dashed) line, indicating small departures from the corresponding ambient temperatures (Figs. 3 and 4), consistent with the time series plots. In contrast, relationships between low-sensor and ambient temperatures vary considerably among the four tree aspects and between the two sites.

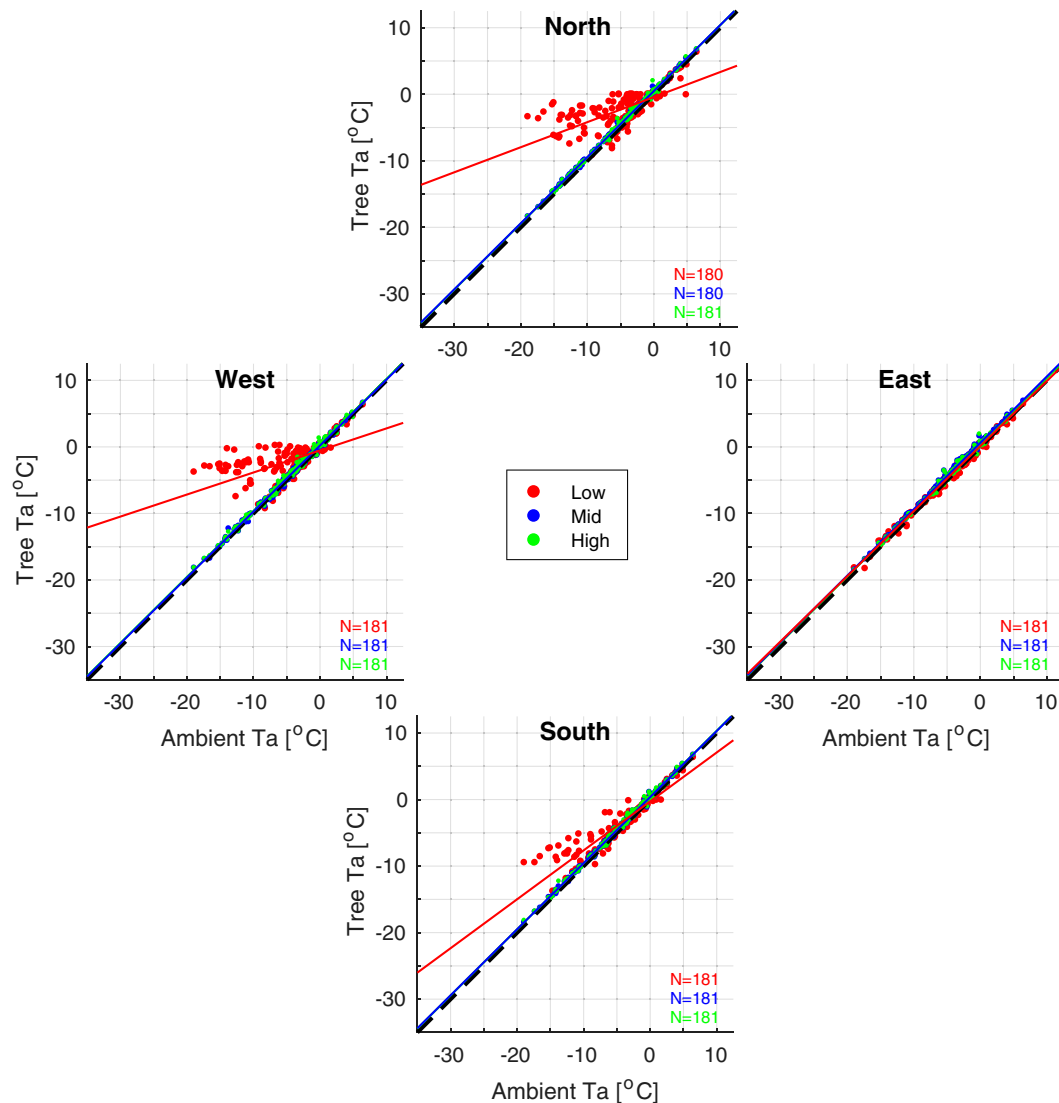


FIG. 6. As in Fig. 5, but for the Norton microclimate site.

At Higgins (Fig. 5), the least squares regression line is at a considerable angle to the 1:1 line on the east, south, and west aspects, and at Norton (Fig. 6), the least squares regression line departs from the 1:1 line on the north, south, and west aspects (with the smallest departure on the south aspect). Corresponding statistics from linear regressions (Table 3) help to quantify this behavior. At Higgins, R^2 and S range from 0.36 to 0.73 and from 0.21 to 0.48, respectively, for the low-height tree sensors on the east, south, and west aspects, as compared with from 0.96 to 1.00 and from 0.96 to 1.02, respectively, for the other nine tree sensors. At Norton, R^2 and S are in the range of 0.36–0.86 and 0.33–0.74 for the north, south, and west aspects, as compared with 0.99–1.00 and 0.98–1.00, respectively, for the other nine tree sensors. In other words, for every 1°C increase or decrease in ambient sensor temperature, the temperature at selected low-height tree sensors increased or decreased by only 0.21° to 0.74°C.

b. Impact of snow cover on daily minimum temperatures

Ameliorating effects of snow cover on winter mortality have been reported for a variety of forest and agriculture pests, including HWA (McClure and Cheah 2002) and cotton bollworm (Huang 2016). In addition, snow cover had a considerable insulating effect on spongy moth egg-mass temperatures (Andresen et al. 2001). Because low-height tree sensors at Higgins and Norton were positioned 0.2 m or less above ground level (AGL), a plausible hypothesis is that the consistently higher (i.e., warmer) temperatures and reduced variability at many of the low-height tree sensors is due to insulation of the thermocouples by snow accumulated on lower branches of the hemlock trees. The photograph of a snow-covered lower branch of the instrumented tree at Holland (Fig. 2e) provides visual confirmation of this phenomenon [note that the lowest sensors at Holland were 0.2–0.8 m AGL (Table 1 and Table S1 in the online supplemental material)].

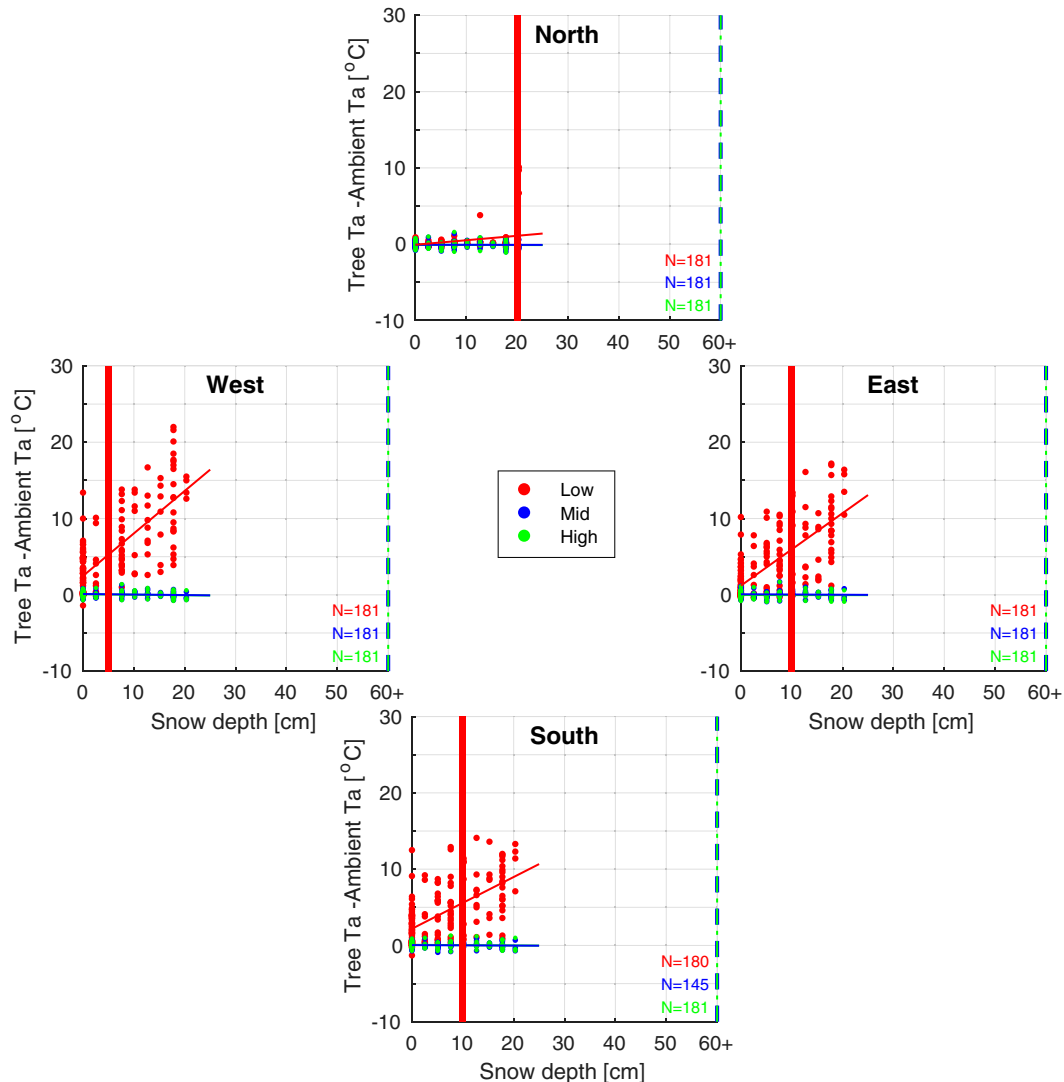


FIG. 7. Scatterplots of daily minimum temperature differences (tree – ambient) at the Higgins microclimate site and daily snow depth measured at the Houghton Lake airport during the 2017/18 season. In each panel, thin solid lines depict the linear regressions (one per sensor) and vertical lines indicate sensor heights. Line and symbol colors denote tree-sensor height category: low is red, middle is blue, and high is green. Number of days N with observations is denoted in the lower-right corner of each panel. See Table 4 for summary statistics.

Note also that this hypothesis applies only to sensors covered by snow, not sensors positioned above the snow wherein enhanced radiative cooling is expected to yield lower (i.e., cooler) temperatures. Potential relationships between tree-ambient temperature differences at the Higgins and Norton microclimate stations and snow cover at nearby proxy sites is explored in scatterplots presented in Figs. 7 and 8 and corresponding summary statistics in Table 4. For corresponding scatterplots of the 2016/17 (Norton only) and 2018/19 seasons, along with some related statistics, see Figs. S9–S11 and Tables S4 and S5 in the online supplemental material. When interpreting the scatterplots, it is important to note that points to the right of the vertical lines with the same color are tree-sensor temperatures collected on days when the proxy site snow depth exceeded the

height of that microclimate-site tree sensor. For reference, maximum snow depth at the proxy sites during the 2017/18 winter was 20.3 and 45.7 cm at Houghton Lake (Higgins) and Muskegon (Norton), respectively.

Taking Figs. 7 and 8 together, relationships between snow depth measured at the proxy site and tree-ambient temperature difference at the microclimate sites occur only for the low-height tree sensors identified earlier (Figs. 3–6). For these sensors, tree-ambient temperature difference increases with increasing snow depth at the proxy site. At Higgins, R^2 and S are in the range of 0.37 to 0.51 and 0.34 to 0.56, respectively, for the low-height tree sensors on the east, south, and west aspects; at Norton, R^2 and S are respectively in the range of 0.60–0.71 and 0.12–0.27 for the north, south, and west aspects (Table 4). Thus, for every 1-cm

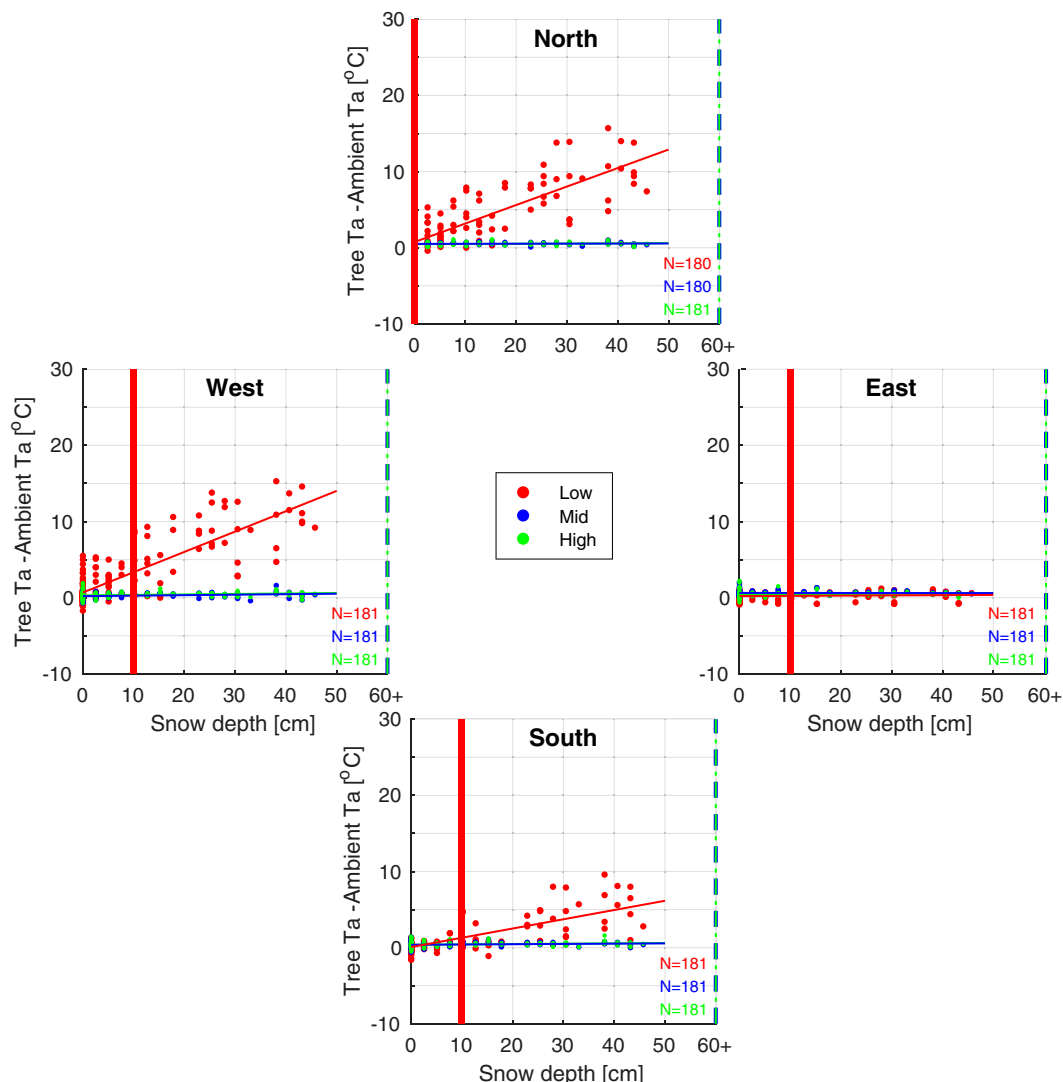


FIG. 8. As in Fig. 7, but the temperature differences are at the Norton microclimate site and snow depth is from the Muskegon airport.

increase in snow depth at the proxy site, the tree–ambient temperature difference at the microclimate site increased by 0.12° to 0.56°C , and differences were largest at Higgins. At the other tree sensors, R^2 and S are mostly below 0.10, indicating little to no relationship between snow depth and tree–ambient temperature difference. This phenomenon was observed at all sites except for FBIC and Meemos, where the lowest sensors were positioned at 2.1–2.8 m AGL, and was observed at two midheight tree sensors at Tahquamenon (1.9–2.2 m AGL) (not shown).

Before proceeding, it is important to emphasize that in the absence of visual verification of the snow-covered sensors, it is not possible to distinguish between isolated clumps of snow covering the sensor and partially or completely buried branches. The lack of any relationship between snow depth at the proxy site and tree–ambient temperature difference at the low height on the north aspect at Higgins and the east aspect at Norton suggests shallower snow depths for those aspects relative to the

other three aspects. Evaluation of the 2018/19 season data at Higgins reveals that unlike the 2017/18 season, all aspects exhibit a robust relationship between snow depth at the proxy site and low-height tree–ambient temperature difference at the microclimate site (cf. Fig. 7 and online supplemental Fig. S9). At Norton, however, the low-height tree–ambient temperature difference on the east aspect again exhibits little to no relationship with proxy site snow depth (cf. Fig. 8 and online supplemental Fig. S11). For reference, the proxy site maximum snow depths during the 2018/19 season were 43.2 and 38.1 cm at Higgins and Norton, respectively. Presumably, the change in north aspect temperature behavior at Higgins between the 2017/18 and 2018/19 seasons is related to the twofold-greater peak snow depth at the proxy site in 2018/19 (43.2 cm) than in 2017/18 (20.3 cm). Note that, during the relatively warm 2016/17 season, there is little to no relationship between tree–ambient temperature difference and snow depth at Norton, with the possible

TABLE 4. Summary statistics for daily minimum temperature differences (tree – ambient) at the Higgins and Norton microclimate sites vs snow depths at the NWS COOP proxy sites (Higgins: Houghton Lake airport; Norton: Muskegon airport) for the 2017/18 season. Columns are defined as in Table 3.

| Station | Height | Aspect | <i>N</i> | CORR | <i>R</i> ² | <i>S</i> |
|---------|--------|--------|----------|-------|-----------------------|----------|
| Higgins | Low | North | 181 | 0.32 | 0.11 | 0.06 |
| | | East | 181 | 0.71 | 0.51 | 0.48 |
| | | South | 180 | 0.61 | 0.37 | 0.34 |
| | | West | 181 | 0.71 | 0.50 | 0.56 |
| | Middle | North | 181 | −0.01 | 0.00 | 0.00 |
| | | East | 181 | −0.06 | 0.00 | 0.00 |
| | | South | 145 | −0.06 | 0.00 | 0.00 |
| | | West | 181 | −0.15 | 0.02 | −0.01 |
| | High | North | 181 | −0.02 | 0.00 | 0.00 |
| | | East | 181 | −0.01 | 0.00 | 0.00 |
| | | South | 181 | −0.08 | 0.01 | 0.00 |
| | | West | 181 | −0.12 | 0.02 | −0.01 |
| Norton | Low | North | 180 | 0.82 | 0.67 | 0.24 |
| | | East | 181 | 0.09 | 0.01 | 0.00 |
| | | South | 181 | 0.78 | 0.60 | 0.12 |
| | | West | 181 | 0.84 | 0.71 | 0.27 |
| | Middle | North | 180 | 0.07 | 0.00 | 0.00 |
| | | East | 181 | −0.02 | 0.00 | 0.00 |
| | | South | 181 | 0.18 | 0.03 | 0.00 |
| | | West | 181 | 0.24 | 0.06 | 0.01 |
| | High | North | 181 | 0.10 | 0.01 | 0.00 |
| | | East | 181 | 0.14 | 0.02 | 0.00 |
| | | South | 181 | 0.17 | 0.03 | 0.00 |
| | | West | 181 | 0.20 | 0.04 | 0.01 |

exception of the low sensor on the north aspect (Fig. S10 and Table S5 in the online supplemental material); note the difference in sensor heights between the 2016/17 and 2017/18 and 2018/19 seasons (Table S1 in the online supplemental material).

c. Comparison of PRISM and microclimate-site daily minimum temperatures

Having addressed the first study objective, evaluating macroclimatic through microclimatic temperature variability across Michigan, including the potential moderating effects of Lake Michigan on cold-season minimum temperatures, we now proceed to the second objective, placing the aforementioned variability in the context of the Kiefer et al. (2022) PRISM extreme minimum temperature climatology. Before proceeding, it is important to examine both systematic and random differences between PRISM gridded estimates and point observations at the six microclimate sites. To accomplish this task, PRISM daily minimum temperature estimates at the closest grid point to each microclimate site are compared with corresponding ambient-sensor temperatures at the six microclimate sites (Fig. 9). Corresponding plots of the 2016/17 (Norton only) and 2018/19 seasons are provided in the online supplemental material (Figs. S12 and S13). For reference, PRISM temperatures are valid at 1.5 m AGL, whereas hemlock ambient temperatures are taken at 1.0 ± 0.1 m AGL.

Examining scatterplots and summary statistics in Fig. 9 as a whole indicates PRISM temperature estimates during the 2017/18

season are generally consistent with the microclimate-site observations. Across the six sites, MD and RMSD range from −0.7° to 1.6°C and from 1.1° to 2.1°C, respectively, with the largest differences occurring at Norton. Despite the larger systematic and random differences at Norton, *R*² = 0.94, still suggesting close agreement between the least squares linear regression and the data points. Note that Holland also exhibits an *R*² of 0.94 (tied with Norton for the lowest *R*²), indicating slightly larger variability in PRISM estimate accuracy at the two lakeshore sites than at the four inland sites where *R*² ranged from 0.96 to 0.98.

In comparing contingency tables for daily minimum temperatures below −20°C [the primary temperature threshold examined in Kiefer et al. (2022)], it is seen that PRISM estimates and observations at the microclimate sites are consistent on the majority of nights. However, PRISM exhibits a potentially concerning tendency at Higgins and Tahquamenon to incorrectly estimate subthreshold temperatures about as frequently as it correctly estimates such temperatures, indicated by green “false alarms” and blue “hits” in Fig. 9. Furthermore, at FBIC and Tahquamenon, there are two–three nights during the 2017/18 season when PRISM fails to capture observed subthreshold temperatures, indicated as yellow “misses” in Fig. 9. Scatterplots for the 2018/19 season (Fig. S13 in the online supplemental material) are broadly similar to the 2017/18 plots in Fig. 9, with two notable exceptions: subthreshold temperatures occur more frequently during the 2018/19 season, and the high false alarm ratios (number of false alarms/sum of hits and false alarms) noted during the 2017/18 season are not present during the 2018/19 season. A likely reason for the inconsistency in false alarm occurrence between seasons is that the PRISM cold bias present at Higgins and Tahquamenon in both seasons (MD is from −0.5° to −0.9°C) is less impactful on the −20°C contingency table during the overall colder 2018/19 season.

d. Impact of microclimatic variability on PRISM extreme minimum temperature climatology

With the PRISM temperature assessment complete, we proceed to addressing the second study objective, placing the spatiotemporal variability identified in this study in the context of the PRISM extreme minimum temperature climatology presented in Kiefer et al. (2022). Put another way, we wish to examine how the distribution of daily minimum temperatures observed at the microclimate sites relates to the climatological distribution of PRISM temperature estimates at the nearest grid point to each site. In Fig. 10, box-and-whisker plots depict cold-season daily minimum temperatures (Fig. 10a) and the number of nights during the same period with daily minimum temperatures below −20°C (Fig. 10b), from the PRISM 1981–2018 extreme minimum temperature climatology, overlaid with observations from the six microclimate sites during the three seasons. As noted in section 1, use of the −20°C threshold is based on previous studies linking this temperature with ≥90% HWA mortality (e.g., Paradis et al. 2008). Examining the two panels of Fig. 10 as a whole, the microclimate-site observations generally fall within the range of values in the PRISM climatology. Temperatures during the 2017/18 season generally fall between the 25th and 50th percentiles for cold-season minimum temperatures in

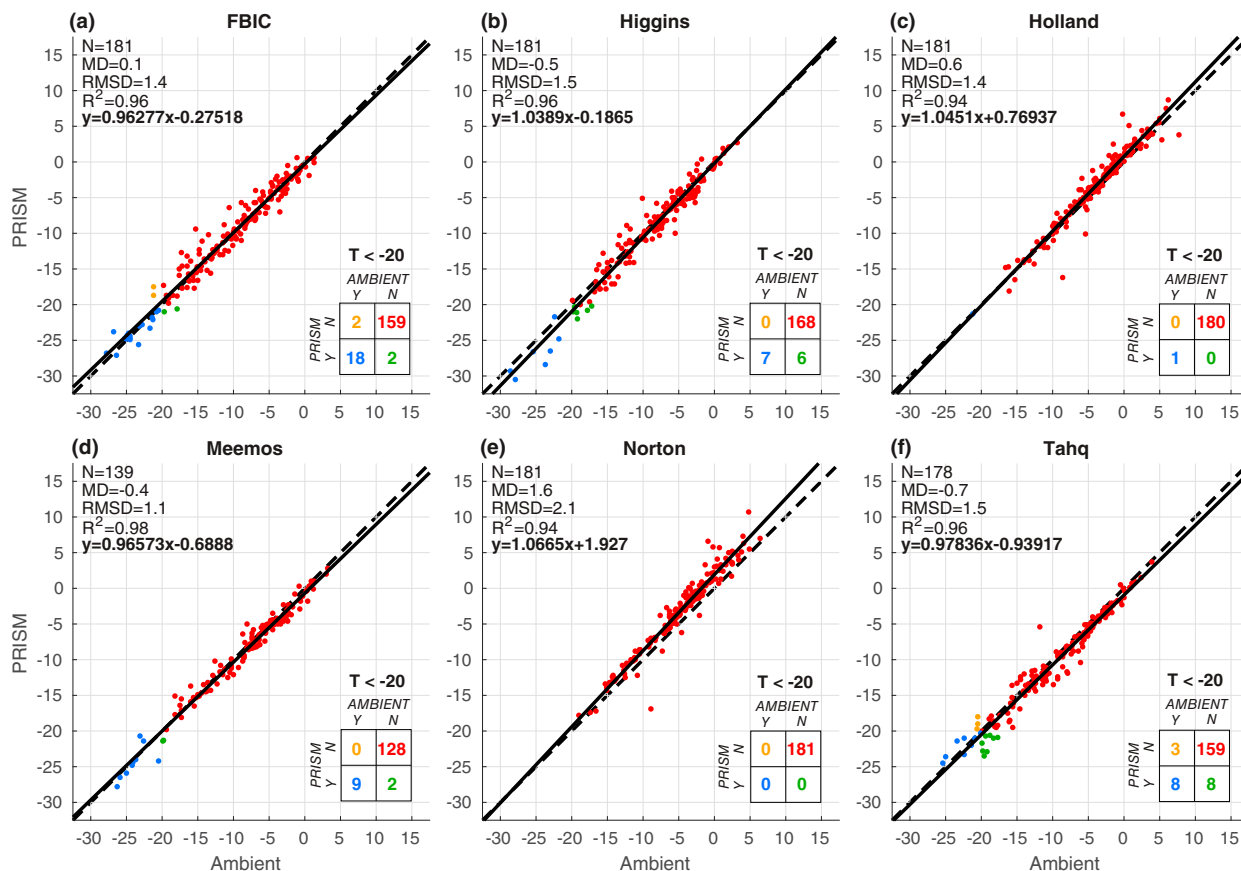


FIG. 9. Scatterplots of daily minimum temperature, with microclimate-site ambient-sensor measurements on the x axis and PRISM estimates on the y axis, at the six microclimate sites during the 2017/18 season. Symbols and contingency-table values are color coded on the basis of whether the minimum temperature for the day is below the -20°C threshold [blue: hit (observed and estimated temperatures below threshold); red: correct negative (observed and estimated temperatures at or above threshold); yellow: miss (observed temperature below threshold and estimated temperature at or above threshold); and green: false alarm (observed temperature at or above threshold and estimated temperature below threshold)]. In each panel, the solid line is the linear regression, the dashed line is the 1:1 line, and summary statistics include number of days N , mean difference MD (PRISM – ambient), root-mean-square difference RMSD (PRISM – ambient), coefficient of determination R^2 of the linear regression, and the linear regression equation (in boldface font).

the PRISM climatology (Fig. 10a) and between the 25th and 75th percentiles for number of nights per season with minimum temperature below the -20°C threshold (Fig. 10b). Temperatures during the 2018/19 season are mostly lower (i.e., colder) than during the 2017/18 season, generally placing near the 10th percentile for cold-season minimum temperatures in the PRISM climatology (Fig. 10a) and between the 50th and 90th percentiles for number of nights per season with minimum temperature below the -20°C threshold (Fig. 10b). For comparison, temperatures during the 2016/17 season at Norton were above the 90th percentile for cold-season minimum temperatures (Fig. 10a), with all daily minimum temperatures above the -20°C threshold (Fig. 10b).

However, some cold-season minimum temperatures observed at the Higgins, Norton, and Tahquamenon sites fall entirely outside the nearest-grid point PRISM climatological distributions. These cold-season minimum temperatures are approximately $2^\circ\text{--}8^\circ\text{C}$ higher (i.e., warmer) than the highest cold-season minimum temperature in the 38-yr PRISM climatology (Fig. 10a). These

measurements are from snow-covered sensors (section 3b), as may be deduced for Higgins and Norton from close inspection of tree-sensor temperatures in Figs. 3–6 (2017/18) and Figs. S1, S3, S6, and S8 in the online supplemental material (2018/19). Interestingly, for the same season, some of the sensors at the interior Higgins site measured cold-season minimum temperatures that were higher (i.e., warmer) than most of the cold-season minimum temperatures observed at the two lakeshore sites, Holland and Norton. In other words, snow-covered sensors at the colder interior site recorded higher (i.e., warmer) cold-season minimum temperatures than exposed sensors at the warmer lakeshore sites. Thus, in certain circumstances, microclimatic variability (e.g., snow covered vs exposed branches) can overwhelm macroclimatic variability (e.g., lakeshore vs interior siting). One implication of this finding is that insulation provided by snow cover may provide refuges that facilitate survival of HWA or other insects during periods of otherwise lethal winter temperatures. The frequency and extent of such microclimatic variability warrants consideration when utilizing gridded climate

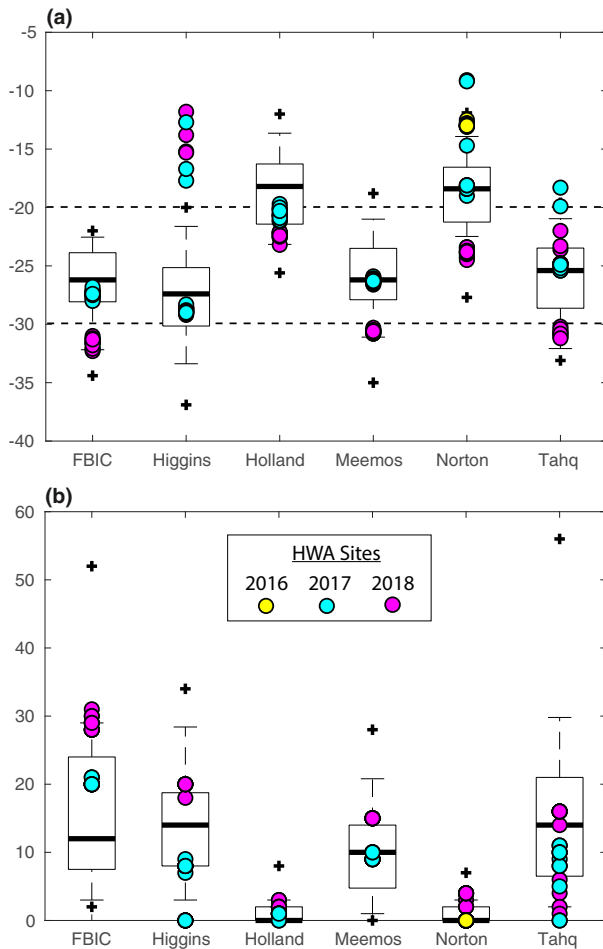


FIG. 10. Plots of (a) cold-season minimum temperatures and (b) the number of nights per season with daily minimum temperature below the -20°C threshold. Box-and-whisker plots depict the PRISM 1981–2018 extreme minimum temperature climatology at the nearest grid point to each microclimate site (thick lines: median; boxes: interquartile range; whiskers: 10th–90th percentiles; plus signs: maximum and minimum values), and the colored symbols denote the values observed at each microclimate site [yellow: 2016/17 (Norton only); cyan: 2017/18; magenta: 2018/19]. Horizontal dashed lines in (a) denote the -20° and -30°C thresholds.

datasets to assess the suitability of current or future conditions for insect pests or other organisms (e.g., Kiefer et al. 2022).

4. Summary and conclusions

In this study, cold-season (November–April) daily minimum temperatures were assessed at six forested sites in Michigan chosen to broadly represent variation in latitude, elevation, lake proximity, and HWA infestation status across the state, to characterize macroclimatic through microclimatic temperature variability and provide important context for the PRISM-based U.S. Great Lakes extreme minimum temperature climatology presented in Kiefer et al. (2022). Winter temperatures were monitored at three heights and four aspects on an eastern hemlock tree at each microclimate site during three seasons, with a single season (2017/18) and two

sites (Higgins and Norton) serving as the primary focus of the analysis. Tree and ambient air temperatures were compared among sites, aspects, and sensor heights and were also related to snow depth measured at nearby NWS COOP sites.

Daily minimum temperatures recorded by tree sensors exhibited only weak sensitivity to tree aspect (e.g., north versus south) but considerable sensitivity to the height of the sensor above the ground. At Higgins and Norton, periods were observed with muted variability of daily minimum temperatures at some of the low-height tree sensors ($\sim 0\text{--}0.2$ m above ground level). Daily minimum temperatures were higher (i.e., warmer) at these sensors, with overall muted variability, than at the ambient sensor and other tree sensors. Daily minimum temperatures at the microclimate sites were subsequently compared with daily snow depths at the closest NWS COOP sites. In general, the greater the snow depth is, the larger is the difference in daily minimum temperature between the tree (warmer) and ambient (cooler) sensors. Higher temperatures and reduced temporal variability were attributed to the insulating effect of snow cover, similar to results from a previous study of spongy moth egg mortality in Michigan (Andresen et al. 2001). Given the knowledge that this and other studies of microclimatic variability provide regarding relationships between air temperatures (off site proxy, on site ambient, and tree sensor) and snow depth, potential may exist for the accurate prediction of air temperatures that HWA and other cold-intolerant insect species are exposed to using off-site proxy temperature and snow measurements.

Insulating effects of snow cover identified at the microclimate sites suggest that even in areas where the Kiefer et al. (2022) PRISM-based extreme minimum temperature climatology indicates that winter temperatures lethal to HWA are common (e.g., interior northern Lower Michigan), mortality of HWA reduced by snow cover may be lower than expected. Notably, the cold-season minimum temperatures measured by the snow-covered sensors at the Higgins, Norton, and Tahquamenon sites fell entirely outside the nearest-grid point PRISM climatological distributions. We recommend that users of gridded climate datasets such as the Kiefer et al. (2022) climate dataset keep such unresolved microclimatic variability in mind, given that snow cover may provide refuges for some portion of an insect population that would otherwise experience lethal temperatures. Additionally, those applying our study findings in the context of HWA mortality should note that Elkinton et al. (2017) found HWA cold hardiness varied regionally, seasonally, and interannually, which we did not address herein. For example, HWA exposed to near-lethal temperatures in December or January may exhibit some degree of tolerance to lethal temperatures in February; seasonal snow cover variability is likely to further complicate this process. It is also important to highlight the potential broader applicability of our results beyond HWA mortality, for example, to the field of forensic entomology, wherein microclimatic variability can impact postmortem interval estimates. Despite the progress documented herein, much work remains in characterizing microclimatic variability. Future work will involve analysis of data collected at Higgins and Norton during additional seasons and the organization of one

or more new field campaigns with additional stations and a larger suite of instruments that together will allow us to further characterize microclimatic variability in Michigan and across the U.S. Great Lakes region.

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Data availability statement. Datasets and software code associated with this study have been uploaded to the Harvard Dataverse (Kiefer et al. 2023). Data are available under the terms of the Creative Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).

REFERENCES

- American Meteorological Society, 2012: Microclimate. Glossary of Meteorology, <https://glossary.ametsoc.org/wiki/Microclimate>.
- Andresen, J. A., 2012: Historical climate trends in Michigan and the Great Lakes region. *Climate Change in the Great Lakes Region*, T. Dietz and D. Bidwell, Eds., Michigan State University Press, 17–34.
- , D. G. McCullough, B. E. Potter, C. N. Koller, L. S. Bauer, D. P. Lusch, and C. W. Ramm, 2001: Effects of winter temperatures on gypsy moth egg masses in the Great Lakes region of the United States. *Agric. For. Meteorol.*, **110**, 85–100, [https://doi.org/10.1016/S0168-1923\(01\)00282-9](https://doi.org/10.1016/S0168-1923(01)00282-9).
- Archer, M. S., 2004: The effect of time after body discovery on the accuracy of retrospective weather station ambient temperature corrections in forensic entomology. *J. Forensic Sci.*, **49**, JFS2003258, <https://doi.org/10.1520/JFS2003258>.
- Chappell, T. M., T. W. Rusch, and A. M. Tarone, 2022: A fly in the ointment: How to predict environmentally driven phenology of an organism that partially regulates its microclimate. *Front. Ecol. Evol.*, **10**, 837732, <https://doi.org/10.3389/fevo.2022.837732>.
- Cheah, C. A. S.-J., 2017: Predicting hemlock woolly adelgid winter mortality in Connecticut forests by climate divisions. *North-east. Nat.*, **24**, B90–B118, <https://doi.org/10.1656/045.024.s713>.
- Dabbs, G. R., 2015: How should forensic anthropologists correct National Weather Service temperature data for use in estimating the postmortem interval? *J. Forensic Sci.*, **60**, 581–587, <https://doi.org/10.1111/1556-4029.12724>.
- Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris, 2008: Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *Int. J. Climatol.*, **28**, 2031–2064, <https://doi.org/10.1002/joc.1688>.
- Dourel, L., T. Pasquerault, E. Gaudry, and B. Vincent, 2010: Using estimated onsite ambient temperature has uncertain benefit when estimating postmortem interval. *Psyche*, **2010**, 610639, <https://doi.org/10.1155/2010/610639>.
- Elkinton, J. S., J. A. Lombardo, A. D. Roehrig, T. J. McAvoy, A. Mayfield, and M. Whitmore, 2017: Induction of cold hardiness in an invasive herbivore: The case of hemlock woolly adelgid (Hemiptera: Adelgidae). *Environ. Entomol.*, **46**, 118–124, <https://doi.org/10.1093/ee/nwv143>.
- Havill, N. P., and R. G. Foottit, 2007: Biology and evolution of Adelgidae. *Annu. Rev. Entomol.*, **52**, 325–349, <https://doi.org/10.1146/annurev.ento.52.110405.091303>.
- , L. C. Vieira, and S. M. Salom, 2014: Biology and control of hemlock woolly adelgid. USDA Forest Service Forest Health Technology Enterprise Team Rep. 2014-05, 29 pp., <https://www.fs.usda.gov/foresthealth/technology/pdfs/HWA-FHTET-2014-05.pdf>.
- Huang, J., 2016: Effects of soil temperature and snow cover on the mortality of overwintering pupae of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae). *Int. J. Biometeor.*, **60**, 977–989, <https://doi.org/10.1007/s00484-015-1090-y>.
- Isard, S. A., R. J. Schaetzl, and J. A. Andresen, 2007: Soils cool as climate warms in the Great Lakes region: 1951–2000. *Ann. Assoc. Amer. Geogr.*, **97**, 467–476, <https://doi.org/10.1111/j.1467-8306.2007.00558.x>.
- Kiefer, M. T., J. A. Andresen, D. Doubler, and A. Pollyea, 2019: Development of a gridded reference evapotranspiration dataset for the Great Lakes region. *J. Hydrol. Reg. Stud.*, **24**, 100606, <https://doi.org/10.1016/j.ejrh.2019.100606>.
- , —, D. G. McCullough, W. J. Baule, and M. Notaro, 2022: Extreme minimum temperatures in the Great Lakes region of the United States: A climatology with implications for insect mortality. *Int. J. Climatol.*, **42**, 3596–3615, <https://doi.org/10.1002/joc.7434>.
- , —, —, J. B. Wierich, J. Keyzer, and S. A. Marquie, 2023: Microclimatic variability of cold-season minimum temperatures in Michigan, United States: A study with implications for insect mortality, version 2. Harvard Dataverse, accessed 17 April 2023, <https://doi.org/10.7910/DVN/XVAMSQ>.
- Latimer, C. E., and B. Zuckerberg, 2017: Forest fragmentation alters winter microclimates and microrefugia in human-modified landscapes. *Ecography*, **40**, 158–170, <https://doi.org/10.1111/ecog.02551>.
- Leep, R. H., J. A. Andresen, and P. Jeranyama, 2001: Fall dormancy and snow depth effects on winterkill of alfalfa. *Agron. J.*, **93**, 1142–1148, <https://doi.org/10.2134/agronj2001.9351142x>.
- Maclean, I. M. D., and Coauthors, 2021: On the measurement of microclimate. *Methods Ecol. Evol.*, **12**, 1397–1410, <https://doi.org/10.1111/2041-210X.13627>.
- Mausel, D. L., 2017: Subnivean survival of hemlock woolly adelgid (*Adelges tsugae*) in New England. *Arboric. Urban For.*, **43**, 199–201, <https://doi.org/10.48044/jauf.2017.017>.

- McAvoy, T. J., J. Régnière, R. St-Amant, N. F. Schneeberger, and S. M. Salom, 2017: Mortality and recovery of hemlock woolly adelgid (*Adelges tsugae*) in response to winter temperatures and predictions for the future. *Forests*, **8**, 497, <https://doi.org/10.3390/f8120497>.
- McClure, M. S., 1991: Density-dependent feedback and population cycles in *Adelges tsugae* (Homoptera: Adelgidae) on *Tsuga canadensis*. *Environ. Entomol.*, **20**, 258–264, <https://doi.org/10.1093/ee/20.1.258>.
- , and C. A. S.-J. Cheah, 2002: Important mortality factors in the life cycle of hemlock woolly adelgid, *Adelges tsugae* Anand (Homoptera: Adelgidae) in the northeastern United States. *Proc. Hemlock Woolly Adelgid in the Eastern United States Symp.*, East Brunswick, NJ, The State University of New Jersey, 13–22, <http://hwa.ento.vt.edu/hwa/wp-content/uploads/publications/2002proceedings/important.pdf>.
- Michigan Department of Agriculture and Rural Development, 2016: Hemlock woolly adelgid in Michigan, recommendations for landowners. State of Michigan, 3 pp., https://www.michigan.gov/-/media/Project/Websites/mdard/documents/pesticide-plant-pest/planthealth/hwa_in_mi_recommendations_for_landowners.pdf.
- Michigan Department of Natural Resources, 2023: Known extent of hemlock woolly adelgid in Michigan. Accessed 17 April 2023, https://www.michigan.gov/invasives/-/media/Project/Websites/invasives/Documents/ID-Report-resources/Statewide_imagery_HWA.pdf.
- Morin, R. S., S. N. Oswalt, R. T. Trotter III, and A. M. Liebhold, 2011: Status of hemlock in the eastern United States. United States Forest Service Southern Research Station e-Science Update SRS-038, 4 pp., https://www.srs.fs.usda.gov/pubs/su/su_srs038.pdf.
- Orwig, D. A., and D. R. Foster, 1998: Forest response to the introduced hemlock woolly adelgid in southern New England. *J. Torrey Bot. Soc.*, **125**, 60–73, <https://doi.org/10.2307/2997232>.
- , J. R. Thompson, N. A. Povak, M. Manner, D. Niebyl, and D. R. Foster, 2012: A foundation tree at the precipice: *Tsuga canadensis* health after the arrival of *Adelges tsugae* in central New England. *Ecosphere*, **3**, 1–16, <https://doi.org/10.1890/ES11-0277.1>.
- Paradis, A., J. Elkinton, K. Hayhoe, and J. Buonaccorsi, 2008: Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (*Adelges tsugae*) in eastern North America. *Mitigation Adapt. Strategies Global Change*, **13**, 541–554, <https://doi.org/10.1007/s11027-007-9127-0>.
- Parker, B. L., M. Skinner, S. Gouli, T. Ashikaga, and H. B. Teillon, 1998: Survival of hemlock woolly adelgid (Homoptera: Adelgidae) at low temperatures. *For. Sci.*, **44**, 414–420, <https://doi.org/10.1093/forestscience/44.3.414>.
- Pincebourde, S., C. C. Murdock, M. Vickers, and M. W. Sears, 2016: Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integr. Comp. Biol.*, **56**, 45–61, <https://doi.org/10.1093/icb/icw016>.
- Renault, D., C. Salin, G. Vannier, and P. Vernon, 2002: Survival at low temperatures in insects: What is the ecological significance of the supercooling point? *Cryo Lett.*, **23**, 217–228.
- Rogers, B. M., P. Jantz, and S. J. Goetz, 2017: Vulnerability of eastern US tree species to climate change. *Global Change Biol.*, **23**, 3302–3320, <https://doi.org/10.1111/gcb.13585>.
- Scott, R. W., and F. A. Huff, 1996: Impacts of the Great Lakes on regional climate conditions. *J. Great Lakes Res.*, **22**, 845–863, [https://doi.org/10.1016/S0380-1330\(96\)71006-7](https://doi.org/10.1016/S0380-1330(96)71006-7).
- Shafer, M. A., C. A. Fiebrich, D. S. Arndt, S. E. Fredrickson, and T. W. Hughes, 2000: Quality assurance procedures in the Oklahoma Mesonet. *J. Atmos. Oceanic Technol.*, **17**, 474–494, [https://doi.org/10.1175/1520-0426\(2000\)017<0474:QAPITO>2.0.CO;2](https://doi.org/10.1175/1520-0426(2000)017<0474:QAPITO>2.0.CO;2).
- Trotter, R. T., III, and K. S. Shields, 2009: Variation in winter survival of the invasive hemlock woolly adelgid (Hemiptera: Adelgidae) across the eastern United States. *Environ. Entomol.*, **38**, 577–587, <https://doi.org/10.1603/022.038.0309>.