

# Potential Effects of Climate Change on *Emydoidea blandingii* (Blanding's Turtle)

Open-File Report 2021–1104–D



# **Potential Effects of Climate Change on *Emydoidea blandingii* (Blanding's Turtle)**

By Marta P. Lyons, Catherine A. Nikiel, Olivia E. LeDee, and Ryan Boyles

Open-File Report 2021–1104–D

**U.S. Department of the Interior  
U.S. Geological Survey**

## U.S. Geological Survey, Reston, Virginia: 2023

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## Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)

Temperature in degrees Celsius ( $^{\circ}\text{C}$ ) may be converted to degrees Fahrenheit ( $^{\circ}\text{F}$ ) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Temperature in degrees Fahrenheit ( $^{\circ}\text{F}$ ) may be converted to degrees Celsius ( $^{\circ}\text{C}$ ) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

## Abbreviations

MACAv2	Multivariate Adaptive Constructed Analogs version 2
RCP4.5	representative concentration pathway 4.5
RCP8.5	representative concentration pathway 8.5

# Potential Effects of Climate Change on *Emydoidea blandingii* (Blanding's Turtle)

By Marta P. Lyons,<sup>1</sup> Catherine A. Nikiel,<sup>2</sup> Olivia E. LeDee,<sup>1</sup> and Ryan Boyles<sup>1</sup>

## Abstract

*Emydoidea blandingii* (Holbrook, 1838; Blanding's turtles) are a species of medium-sized, long-lived, semiaquatic, freshwater turtles with a wide distribution across the northern and eastern United States and southern Canada. They have an annual activity cycle consisting of late autumn and winter overwintering and spring emergence, spring movement and foraging, spring and summer nesting, and summer and autumn foraging and nonnesting movement. In response to changes in average and extreme temperatures, Blanding's turtles are likely to experience increased physiological stress and reduced reproductive success. Variability in precipitation may affect the availability of freshwater habitats for overwintering, shelter, and feeding; however, projected changes in precipitation vary widely. This analysis presents anticipated climate conditions and effects on the species; the complex life history and expansive geographic range of this species require additional analysis at local scales.

## Purpose and Scope

*Emydoidea blandingii* (Holbrook, 1838; Blanding's turtles) are medium-sized, long-lived, semiaquatic, freshwater turtles inhabiting the northern United States and southern Canada. Their distribution spans east to west from Nova Scotia to Nebraska and north to south from Ontario to Illinois. The domain is largely forested in the east, Upper Midwest, and Great Lakes. Large areas of cropland and pastureland predominate in eastern Nebraska and the Dakotas, Iowa, and southern Minnesota (fig. 1). In the western part of their distribution, agricultural land is mixed with grassland and herbaceous wetland, especially in western Nebraska and the

Dakotas. The largest populations of Blanding's turtle have been detected around the U.S. and Canadian Great Lakes (NatureServe, 2022; GBIF, 2023).

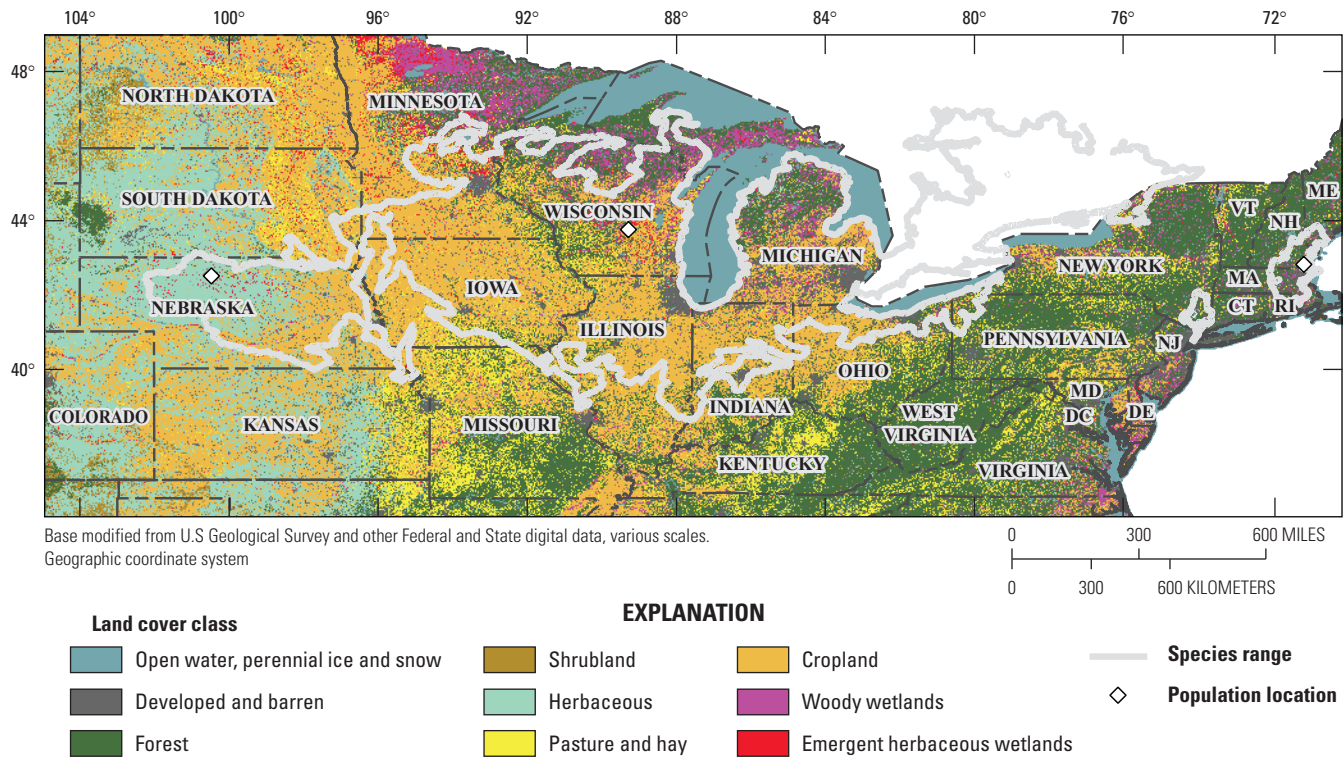
Blanding's turtles require a mosaic of habitat, including (1) cool, freshwater wetlands and ponds for residency and overwintering; (2) open terrestrial habitat with well-drained soil for nesting; and (3) small wetlands, vernal pools, and marshes adjacent to upland areas for movement between residency areas and nesting (Congdon and Keinath, 2006). Land use change, including urbanization and agricultural development, is the primary threat to viable habitat and connectivity between wetlands and open low-vegetation uplands (Dahl, 2014; Johnston and McIntyre, 2019). Past wetland drainage and conversion of prairies for agriculture likely decreased populations of Blanding's turtles in Iowa, Illinois, and Kansas (Congdon and Keinath, 2006). Although future land use and agricultural expansion are uncertain, the largest risk of this land conversion is in the Dakotas (Sohl and others, 2016).

The purpose of this report is to provide an overview, based on peer reviewed literature, government reports, and analysis of regional climate data, of the direct and indirect effects of climate change on Blanding's turtles. In alignment with Blanding's turtles' annual cycle, this report is structured by seasonal climate—winter (December–February), spring (March–May), summer (June–August), and autumn (September–November)—and corresponding seasonal activity—late autumn and winter overwintering and spring emergence, spring movement and foraging, late spring and summer nesting, and summer and autumn emergence, foraging, dispersal (fig. 2). This analysis focuses on the full historical range of the species in the United States (36–49 °N, 256–290 °E; NatureServe, 2022; GBIF, 2023; fig. 1).

In this report, effects of changes in precipitation on wetland hydrology are inferred using cool season water year precipitation (October–March) and warm season water year precipitation (April–September). A water year is the period from October 1 to September 30 and is designated by the year in which it ends. This seasonal divide captures trajectories of wetland wetting and drying through the year and the corresponding seasonal behavior of Blanding's turtles (table 1).

<sup>1</sup>U.S. Geological Survey.

<sup>2</sup>Oak Ridge Institute for Science and Education Research Participation Program.



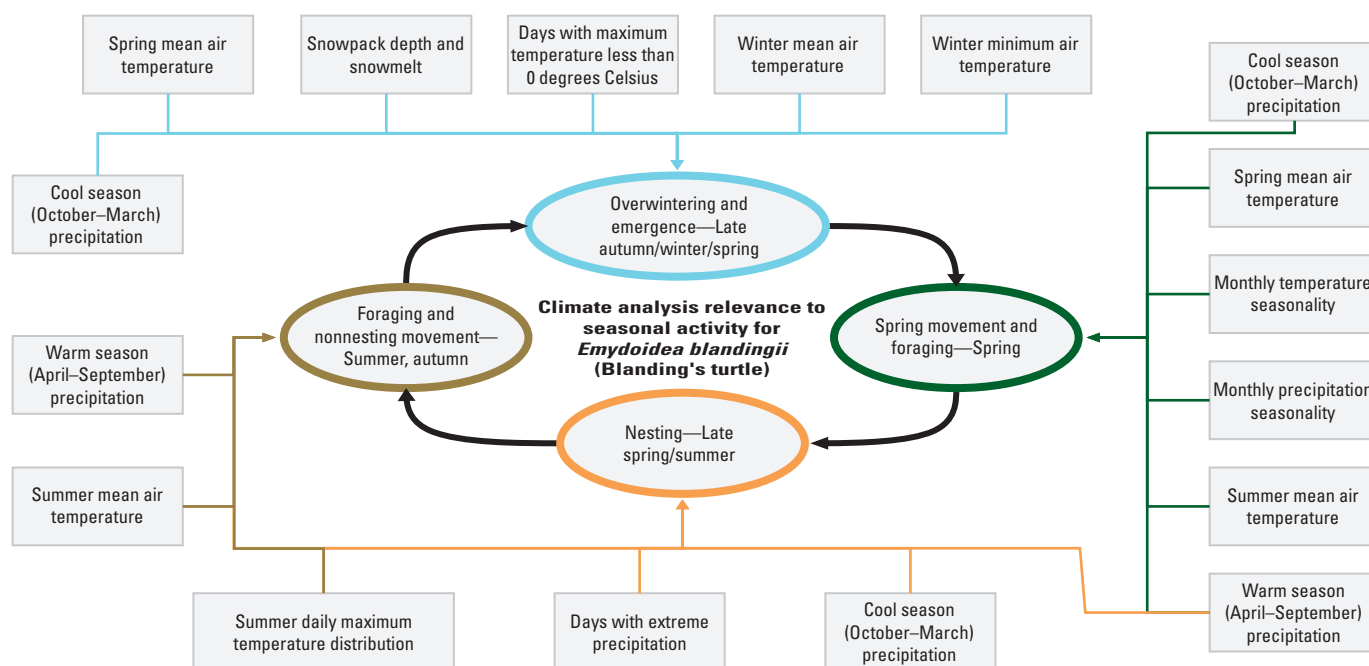
**Figure 1.** Study area with full analysis domain and locations for three populations (white diamonds). Shading indicates land cover classes in 2019 from the National Land Cover Database (Dewitz and U.S. Geological Survey, 2021). Species range is marked in light gray (CRF, 2013).

Historical (1979–2008) seasonal temperatures across this domain follow a latitudinal gradient with lower temperatures in the north of the domain and along the high elevation areas of the Appalachians (not shown) and mountainous regions in the east (fig. 3A–H). The northern parts of North Dakota, Minnesota, and Wisconsin also are generally several degrees Celsius cooler than the Lower Peninsula of Michigan and areas at the same latitude farther east. Average annual total precipitation is higher in the south and east of the domain with lower average precipitation in the Upper Midwest around the Great Lakes. Summer (June–August) precipitation has a regional maximum in the Midwest, centered on Iowa, with pockets of high precipitation in high elevation areas. Extremely cold days are greatest in the north of the domain, especially in the Upper Midwest near the Great Lakes and in the far Northeast. Conversely, extremely hot days greater than 38 degrees Celsius (°C) are rarely experienced in recent history in most of the historical range; however, a few areas in the central and southern plains historically experience these temperatures, on average as many as 20 days a year (fig. 3H).

Additional grid-cell level analysis is presented for three locations in Nebraska (42.5 °N, 100.5 °W), Wisconsin (43.75 °N, 89.25 °W), and Massachusetts (42.81 °N,

71.03 °W), which are marked in figure 1. These locations capture relevant climate variations within the domain and coincide with reported species and research locations and areas of appropriate habitat described previously. Historical averages for observed annual and summer temperatures at the three population locations are listed in table 2, and figure 4 presents the seasonal climatology of minimum and maximum temperature and monthly precipitation at each population location. Location 1 in central Nebraska has the warmest summer (June–August) average temperatures with a pronounced seasonal cycle of precipitation that peaks in late spring/early summer. Location 2 in central Wisconsin has a similar seasonal cycle of precipitation with higher annual totals; temperatures are colder on average across the full year. Location 3 in eastern Massachusetts has the highest total annual precipitation and annual average temperature with a less pronounced seasonal cycle marked by a small dip in precipitation in the summer; the temperature distribution is similar to location 2 in central Wisconsin but with warmer winters on average (fig. 4).





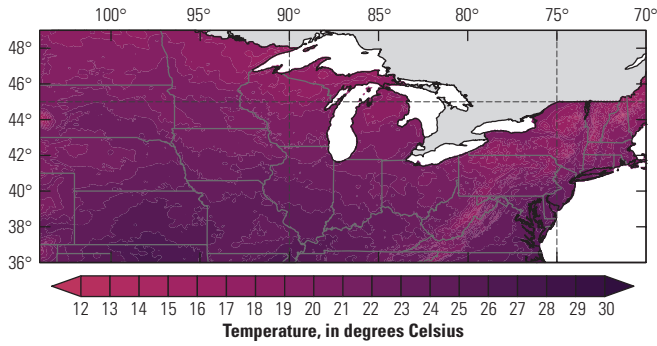
**Figure 2.** Yearly cycle of ecological life period and the corresponding season (center ovals and colors), and the climate analysis included in this report (gray boxes).

**Table 1.** Link among ecological period, season, species wetland requirements, and climate effect.

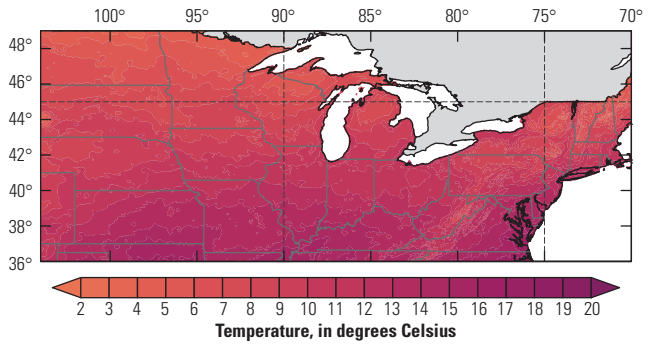
Activity	Season	Wetland type	Climate effect
Overwintering and emergence	Late autumn, winter, spring	Cool freshwater ponds and wetlands	Cool season precipitation; snowmelt
Movement and foraging	Spring	Connected wetlands and ponds	Cool season precipitation; warm season precipitation
Nesting	Late spring, summer	Freshwater bodies adjacent uplands	Cool season precipitation; warm season precipitation
Foraging and nonnesting movement	Summer, autumn	Connected wetlands and ponds	Warm season precipitation

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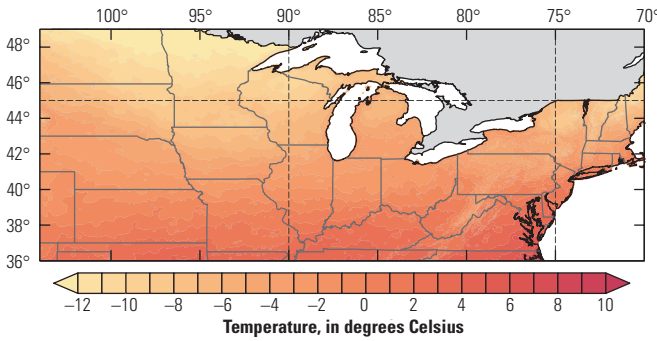
**A. Average June–August air temperature**



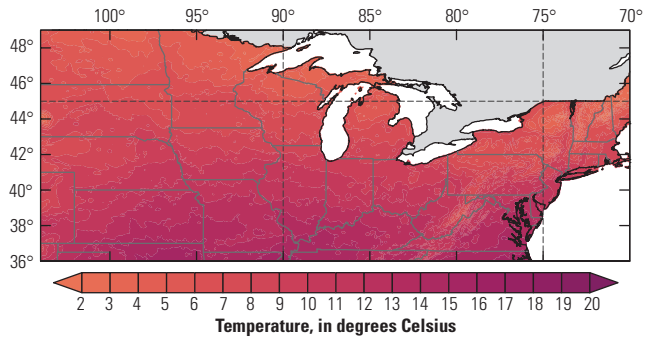
**B. Average September–November air temperature**



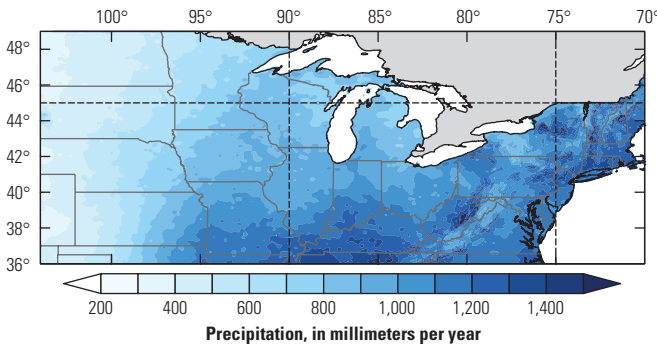
**C. Average December–February air temperature**



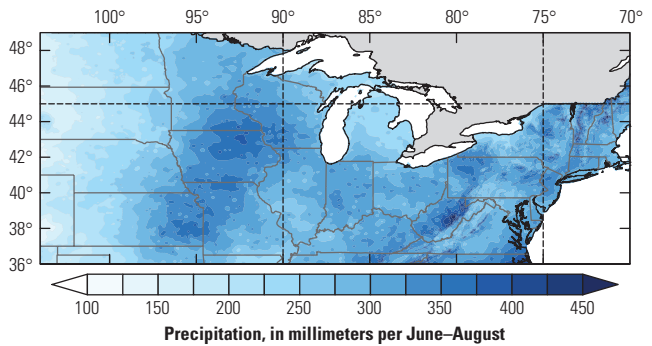
**D. Average March–May air temperature**



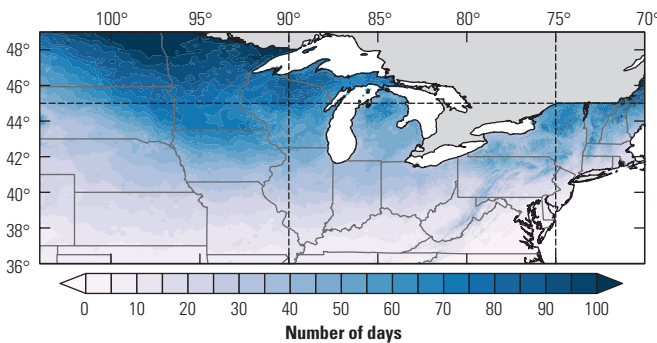
**E. Average annual total precipitation**



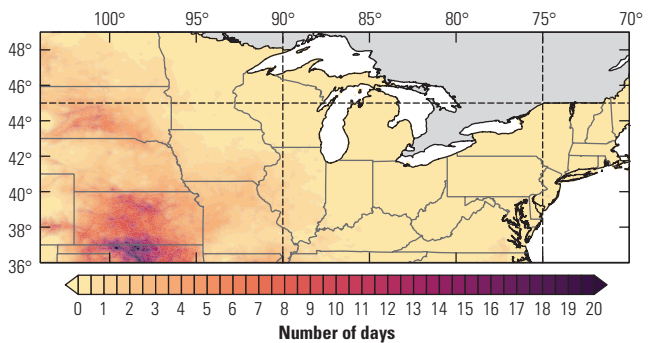
**F. Average June–August total precipitation**



**G. Historical days with maximum temperature less than 0 degrees Celsius**



**H. Historical days with maximum temperature greater than 38 degrees Celsius**



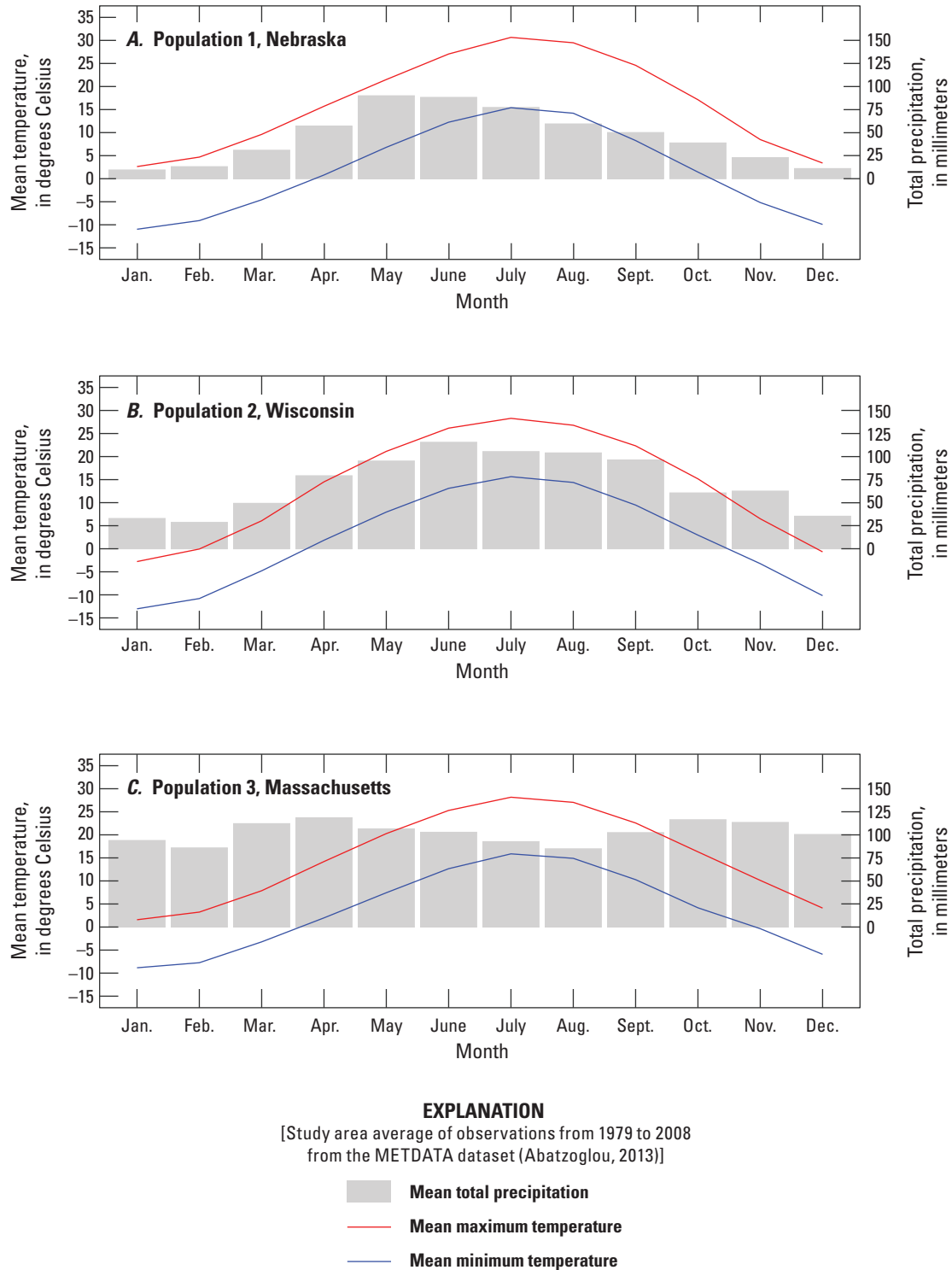
**Figure 3.** Historical climate of the analysis domain from 1979 to 2008 in METDATA (Abatzoglou, 2013). *A*, average summer (June–August) air temperature (in degrees Celsius); *B*, average autumn (September–November) air temperature (in degrees Celsius); *C*, average winter (December–February) air temperature (in degrees Celsius); *D*, average spring (March–May) air temperature (in degrees Celsius); *E*, average annual total precipitation (in millimeters per year); *F*, average summer total precipitation (in millimeters per season); *G*, average annual historical days with maximum temperature less than 0 degrees Celsius; *H*, average annual historical days with maximum temperature greater than 38 degrees Celsius.

**Table 2.** Historical (1979–2008) location ([figure 1](#)) averages of annual and summer mean temperature and total precipitation in METDATA (Abatzoglou, 2013).

[°C, degree Celsius; JJA, summer, June–August; mm, millimeter; yr, year; NE, Nebraska; WI, Wisconsin; MA, Massachusetts]

Annual mean air temperature (°C)	JJA mean air temperature (°C)	Annual total precipitation (mm/yr)	JJA total precipitation (mm/season)
Location 1 (NE)			
8.9	21.5	548	225
Location 2 (WI)			
7.8	20.7	865	325
Location 3 (MA)			
9.3	20.7	1,229	280

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**Figure 4.** Historical climatology from 1979 to 2008 for population locations. *A*, population 1 in Nebraska (42.5 °N, 100.5 °W); *B*, population 2 in Wisconsin (43.75 °N, 89.25 °W); *C*, population 3 in Massachusetts (42.81 °N, 71.03 °W). Values are shown for the grid cell containing the coordinate.

## Data and Methods

To explore the potential range of future climate changes, we used downscaled projections for this region based on the Intergovernmental Panel on Climate Change Coupled Model Intercomparison Project Phase 5 models for two emissions scenarios: a moderate emissions scenario (representative concentration pathway 4.5 [RCP4.5]) and a high emissions scenario (representative concentration pathway 8.5 [RCP8.5]) (Taylor and others, 2012). The output from 20 global climate models with the necessary variables is statistically downscaled using Multivariate Adaptive Constructed Analogs version 2 (MACAv2) method; this multistep constructed analog approach establishes relations between global climate model output and historical climate observations. Outputs are bias corrected by climate variable to develop higher resolution and localized projections with about a 4-kilometer spatial resolution. The first realization (r1i1p1) of each model is used except for CCSM4, where the sixth realization (r6i1p1) is used. Output can be accessed through [https://climate.northwestknowledge.net/MACA/data\\_portal.php](https://climate.northwestknowledge.net/MACA/data_portal.php) (Abatzoglou and Brown, 2012), and the full list of models used is provided in [table 3](#). MACAv2 was chosen because it is widely vetted and used for impact studies, is available at the appropriate spatial and temporal resolution for the region of interest, and has been demonstrated to better capture signals in rainfall extremes and frequency as compared to other downscaled products (Wang and others, 2020; Wootten and others, 2021). Although the distribution of Blanding's turtle extends into Canada, this report focuses on climate changes and effects in the United States.

Current modeling efforts have difficulty in modeling climate changes in the Great Lakes region mainly because of poor representation of lakes in the global climate models (Mallard and others, 2014; Briley and others, 2021) and a lack of integrated lake models in dynamical modeling setups (Sharma and others, 2018). We acknowledge the availability of one dynamically downscaled product (Notaro and others, 2015); however, this product does not cover the full domain of interest. A comparison between the two products determined that for measures of annual and seasonal mean temperature and precipitation, the full spread of MACAv2 simulations largely captures the high-end (hot and dry) projections produced in the dynamical products. Therefore, we continue with the MACAv2 product as a conservative estimate of the full range of potential risk despite concerns about the

applicability of traditional statistical downscaling methods and assumptions in and around the Great Lakes (Notaro and others, 2013; Briley and others, 2021).

The observational dataset used here is the METDATA/gridMET dataset, which is available daily from 1979 to 2022 at equivalent resolution to the MACAv2 data and can be accessed through <https://www.northwestknowledge.net/metdata/data/> (Abatzoglou, 2013). This dataset was developed using PRISM and NLDAS-2 gridded data (Daly and others, 2008).

Climate data are presented over four period averages—a historical period (1971–2000) and three future periods (2010–39, 2040–69, and 2070–99). These 30-year periods provide a long enough climate window to complete a robust analysis of period means and changes. The historical period was chosen to align with the available period of the historical simulation while retaining a 30-year analysis period. Note that the historical METDATA observations are presented from 1979 to 2008 because of data availability. At each period, projections are provided for two Intergovernmental Panel on Climate Change emissions scenarios: RCP4.5 and RCP8.5. Neither of these scenarios is presented as more likely than the other and both are considered plausible. All 20 downscaled models are considered with 5 models selected for each future period and emissions scenario to illustrate the spread of future potential climate conditions for each emissions scenario. These chosen models indicate a spatially consistent projection from an individual model rather than presenting an amalgamated median and range calculated at the individual grid cells. This presentation highlights how the magnitude and the spatial pattern of changes vary among model projections. Models are ranked based on changes for a given variable averaged over a central area that contains all three population locations (40–46 °N, 101–70 °W), and the minimum, 25th percentile, median, 75th percentile, and maximum change models are presented as a paneled figure with the same scale. Thus, for example, the driest or warmest model in the early future period (2010–39) may not be the same as the driest or warmest model in the late period (2070–99) and reflects the different rates of change among models and over the full future period. Additionally, the area averaged driest or warmest model may not present the driest or warmest projection for a given location. For full model spread for individual locations, refer to the tables included within the text. For clarity, the model used in each panel is marked by a letter in the bottom right-hand corner of each panel, and the corresponding model is detailed in [table 3](#).

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**Table 3.** Downscaled global climate models from Multivariate Adaptive Constructed Analogs version 2-METDATA used in this study (Abatzoglou and Brown, 2012).

[NOAA, National Oceanic and Atmospheric Administration]

Letter <sup>1</sup>	Model	Group	Citation
A	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University (GCESS)	Ji and others (2014)
B	CCSM4	National Center for Atmospheric Research (NCAR)	Gent and others (2011)
C	CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Européen de Recherche et Formation Avancées en Calcul Scientifique (CNRM-CERFACS)	Voldoire and others (2013)
D	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)	Rotstayn and others (2010)
E	CanESM2	Canadian Centre for Climate Modeling and Analysis (CCCma)	Arora and others (2011)
F	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory (NOAA-GFDL)	Dunne and others (2012)
G	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory (NOAA-GFDL)	Dunne and others (2012)
H	HadGEM2-CC365	Met Office Hadley Centre (MOHC)	Collins and others (2011)
I	HadGEM2-ES365	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) (MOHC)	Collins and others (2011)
J	IPSL-CM5A-LR	Institut Pierre-Simon Laplace (IPSL)	Marti and others (2010)
K	IPSL-CM5A-MR	Institut Pierre-Simon Laplace (IPSL)	Marti and others (2010)
L	IPSL-CM5B-LR	Institut Pierre-Simon Laplace (IPSL)	Marti and others (2010)
M	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies (MIROC)	Watanabe and others (2010)
N	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies (MIROC)	Watanabe and others (2010)
O	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies (MIROC), and Japan Agency for Marine-Earth Science and Technology	Watanabe and others (2010)
P	MRI-CGCM3	Meteorological Research Institute (MRI)	Yukimoto and others (2012)
Q	NorESM1-M	Norwegian Climate Centre (NCC)	Bentsen and others (2013)
R	bcc-csm1-1-m	Beijing Climate Center, China Meteorological Administration (BCC)	Xiao-Ge and others (2013)
S	bcc-csm1-1	Beijing Climate Center, China Meteorological Administration (BCC)	Xiao-Ge and others (2013)
T	inmcm4	Institute for Numerical Mathematics (INM)	Volodin and others (2010)

<sup>1</sup>Letters index the models and are used to identify panels in [figures 5–7, 9, and 12–16](#).



# Overwintering and Emergence

## Adult and Juvenile Habitat Requirements

Adult and juvenile Blanding's turtles overwinter in a variety of freshwater habitats including marshes, bogs, fens, ponds, creeks, and the edges of lakes and rivers. Movement to these overwintering sites typically is done in September and October (Edge and others, 2009).

## Precipitation

Timing and volume of precipitation are in part responsible for maintaining suitable overwintering habitat (Park and others, 2022; Shannon and others, 2022). Precipitation, including delayed input from snowmelt, is necessary to replenish and maintain wetland habitat after summer dry downs (Park and others, 2022), and increases in precipitation may increase habitat area and connectivity. However, substantial increases in precipitation also can decrease habitat availability by increasing the number of deep-water ponds where overwintering turtles may experience anoxic conditions (Congdon and Keinath, 2006). Lack of suitable overwintering habitat can lead to increased mortality through exposure and predation (Edge and others, 2009).

Annual total precipitation has increased across the Midwest and Northeast from 1901–1960 to 1986–2015, and increases are distributed among all seasons (fig. 7.1 in Easterling and others, 2017). Large parts of the Blanding's turtle range have seen an increase in historical annual precipitation of more than 10 percent, especially the upper Northeast and Upper Midwest.

Analysis of the MACAv2 ensemble of projections indicates uncertainty in the projected future cool season (October–March) precipitation across the species' range, with a large spread for models under emissions scenarios RCP4.5 and RCP8.5 (fig. 5A–F). Most models indicate that precipitation amounts will generally be greater, but several plausible models indicate future precipitation could be less than the period of 1971–2000, especially in the Midwest in the winter. Additionally, models have variable projections about what parts of the range will become wetter or drier relative to others. The presentation of a five-model spread of projections and average changes at individual locations aims to demonstrate this spatial variability. Cool season precipitation change ranges for the three population locations in all periods and emissions scenarios are given in table 4. This precipitation projection is consistent with the average model mean seasonal precipitation projections under RCP8.5 in the Fourth National Climate Assessment where winter and spring are shown to have strong increases of greater than 10 percent across the northern United States and autumn has a smaller and more uncertain increase (fig. 7.5 in Easterling and others, 2017).

The spread of projected cool season precipitation increases throughout the 21st century and is higher in the high emissions (RCP8.5) scenario than in the moderate (RCP4.5) scenario. Given widespread precipitation increases of 15 percent among more of the domain in the 20th century, these moderate future decreases projected by some plausible models are not likely to usher in unprecedented dryness for the region. However, with the coincident changes in land use and habitat distribution over the 20th century, the ability for species to adapt to a return to widely drier conditions may be limited. Additionally, the increased potential for severe droughts and dry spells in any given year can affect habitat availability from year to year (Dahl, 2014).

## Hatchling Overwintering

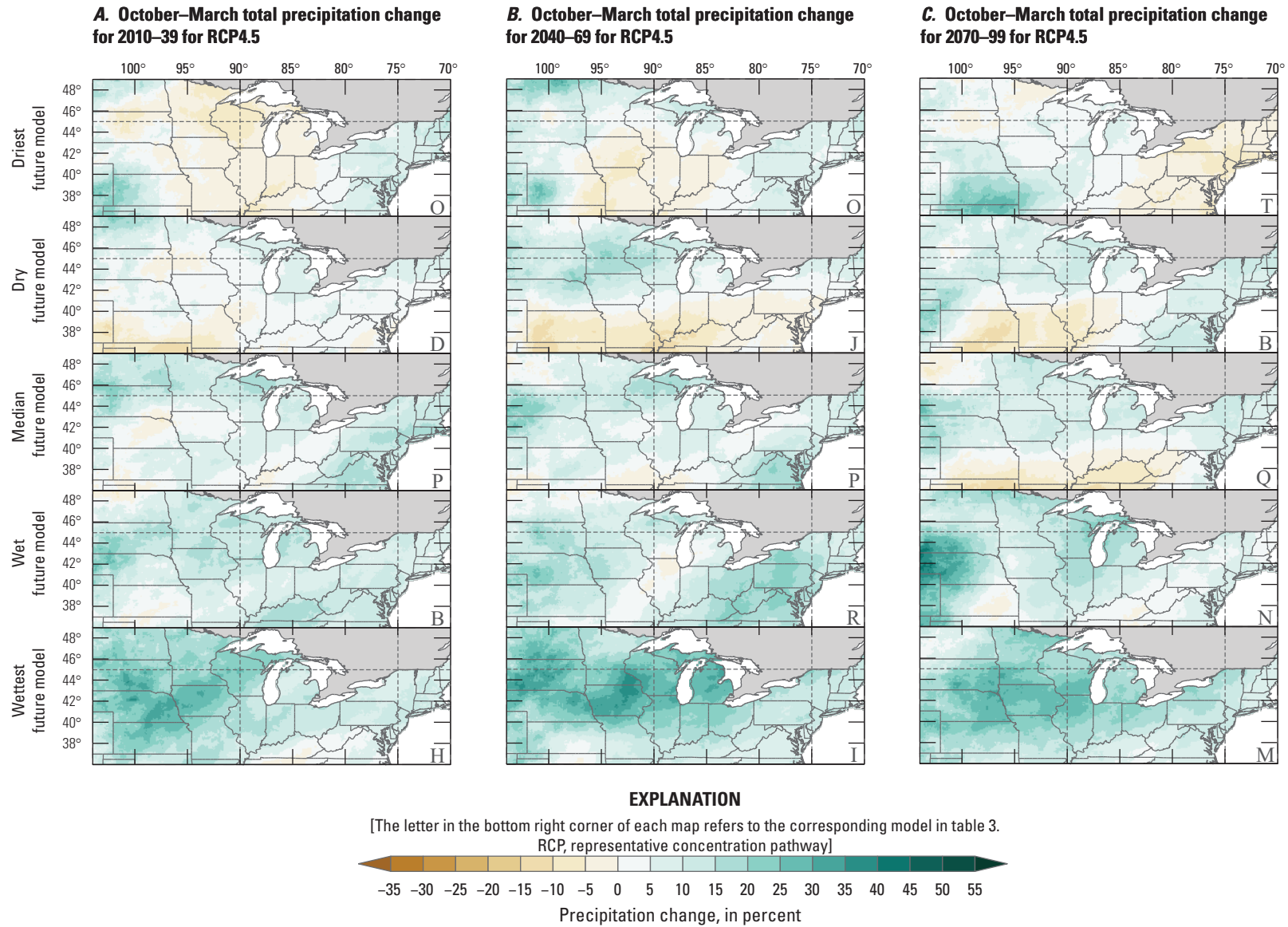
Unlike adults and juveniles, hatchlings may overwinter in their nest cavity or a new location on land. By overwintering on land, hatchlings are at increased risk of freezing (Pappas and others, 2009) or desiccating (Ruane and others, 2008). Snow provides insulation from low temperatures and protection from cold exposure/thermal stress (Pappas and others, 2009). Climate-driven change in snow conditions (for example, reduced depth, earlier melt) could increase exposure and mortality risk for hatchling turtles overwintering on land.

## Winter Temperature and Snow

Winter temperatures are projected to increase across the region, with more warming in the north and surrounding the Great Lakes (fig. 6A–F). Even with increased precipitation (fig. 5A–F), warmer winter temperatures will likely contribute to reduced snowpack depth and earlier melt time, especially in northern areas like northern Wisconsin where temperature increases are projected to be higher (Notaro and others, 2011, 2014; Shrestha and others, 2022). Research indicates that the number of days with at least 1 centimeter of snowpack across the region is projected to decrease (Notaro and others, 2014). Winter temperature change ranges for the three population locations in all periods and emissions scenarios are given in table 5.

## Movement During Winter

Movement during winter is positively correlated with temperature (Newton and Herman, 2009), and warm or variable winters increase energy demands on overwintering turtles. In a Massachusetts population, when water temperatures reached greater than 6 °C, turtles were recorded moving as many as 13 meters (m) between surveys, but when temperatures dropped to less than 3 °C, movement decreased to only 1–2 m (Kofron and Schreiber, 1985). Increased temperatures in the winter may increase deleterious movement in winter.



**Figure 5.** October–March mean total precipitation change (in percent) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5.



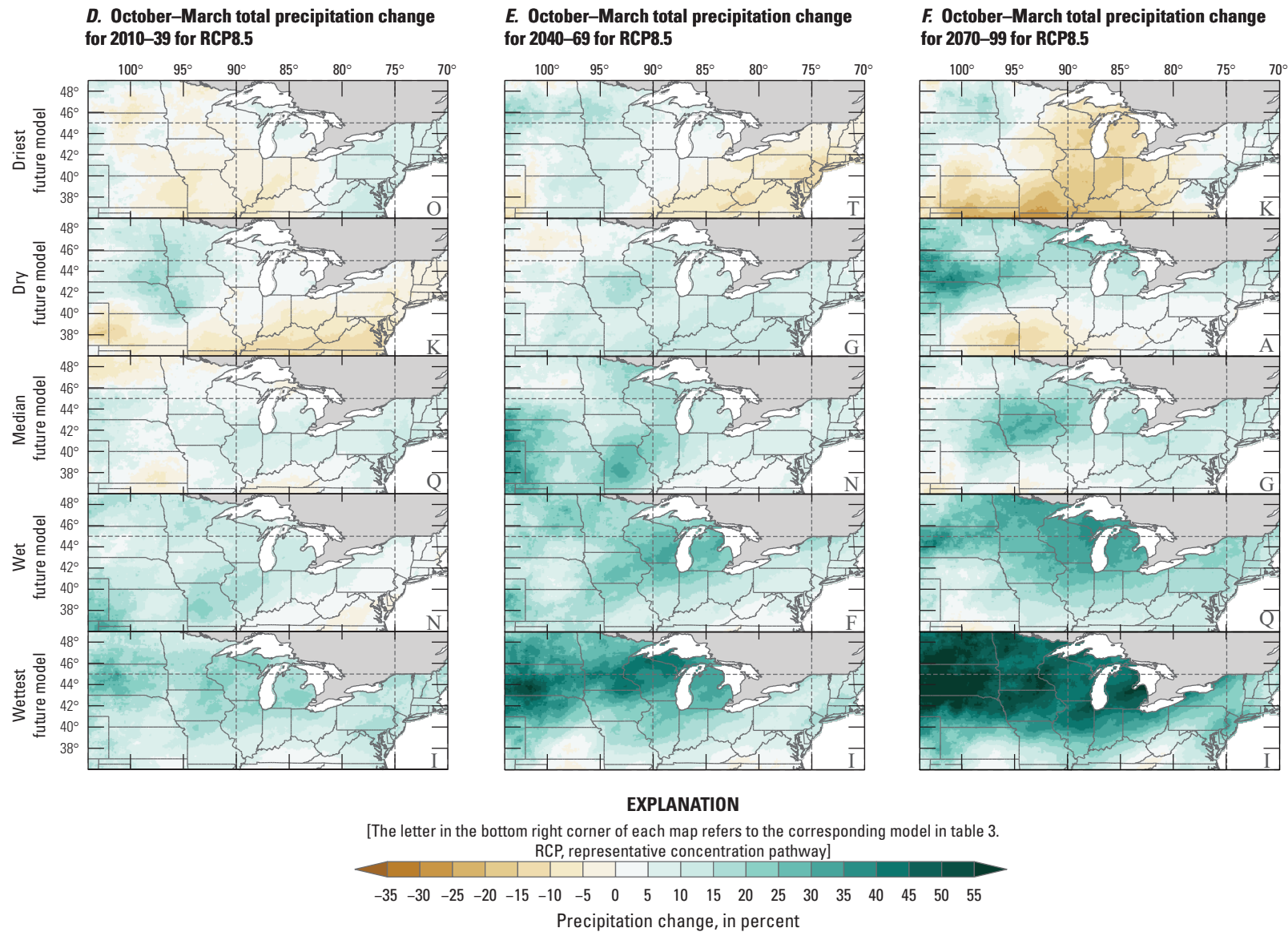


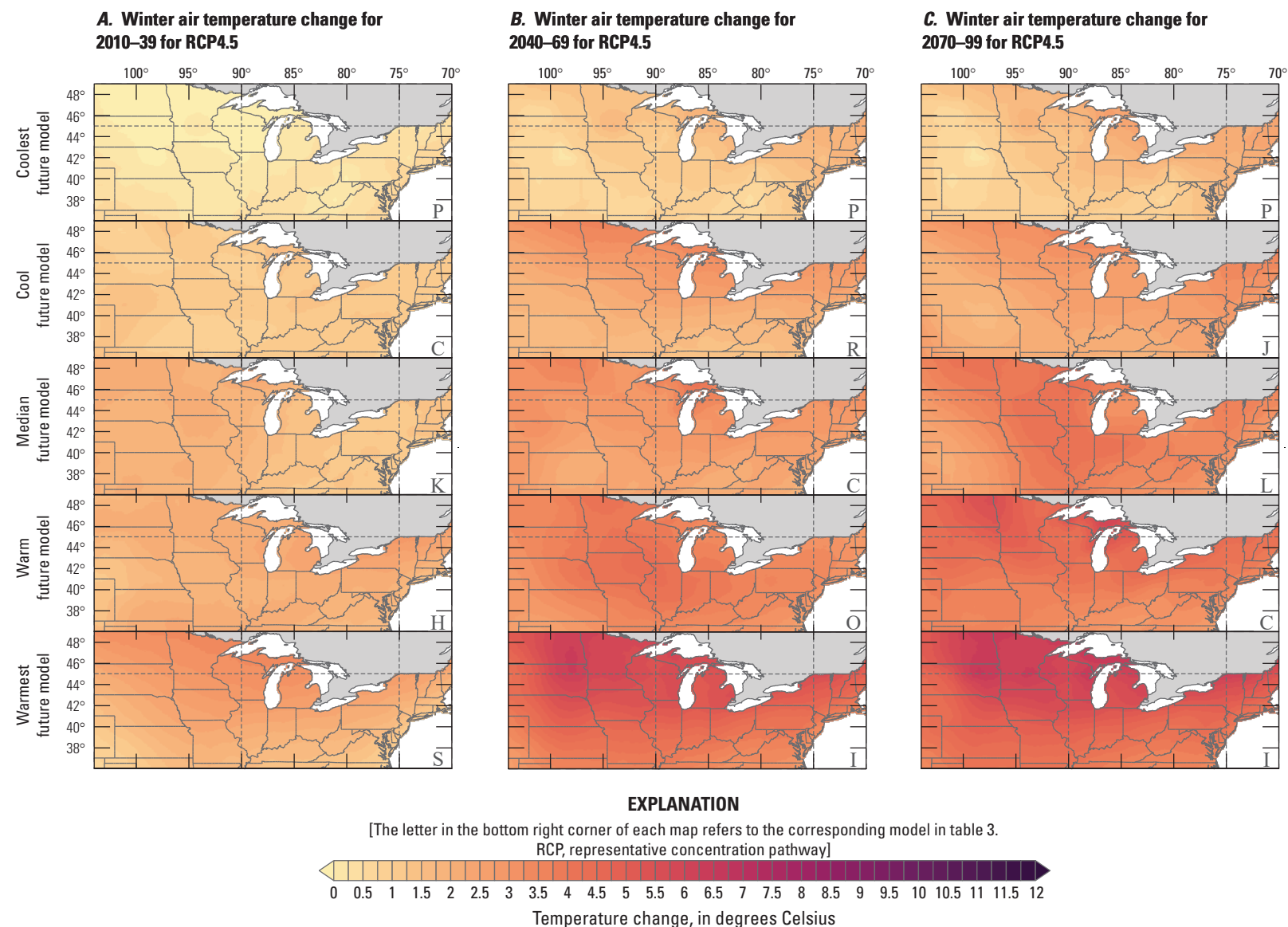
Figure 5.—Continued

## 12 Potential Effects of Climate Change on *Emydoidea blandingii* (Blanding's Turtle)

**Table 4.** Change in cool season (October–March) precipitation (in percent) from the historical period (1971–2000) for the three future periods under representative concentration pathways 4.5 and 8.5 using Multivariate Adaptive Constructed Analogs version 2-METDATA downscaled global climate model data (Abatzoglou and Brown, 2012). Median model values are given, and the range between the driest and wettest model is given in parentheses. Models are ranked for each location individually. Values are for the Multivariate Adaptive Constructed Analogs version 2 grid cell containing the location coordinate.

[Italics indicate the range is positive. RCP, representative concentration pathway; NE, Nebraska; WI, Wisconsin; MA, Massachusetts]

RCP4.5			RCP8.5		
2010–39	2040–69	2070–99	2010–39	2040–69	2070–99
Location 1 (NE)					
+6.9 (0.7, 33.3)	+14.1 (0.0, 31.7)	+13.7 (–7.4, 28.8)	+10.5 (–3.0, 21.6)	+12.5 (–0.9, 40.6)	+18.9 (1.6, 57.4)
Location 2 (WI)					
+7.9 (–6.7, 18.5)	+9.7 (–1.7, 31.2)	+12.0 (–1.8, 26.0)	+8.4 (0.3, 19.8)	+11.9 (–0.3, 35.0)	+18.3 (–13.9, 42.4)
Location 3 (MA)					
+2.9 (0.0, 13.6)	+6.9 (–4.0, 18.7)	+7.0 (–3.5, 19.5)	+3.0 (–5.0, 14.5)	+9.6 (–3.9, 25.4)	+11.1 (–2.4, 31.7)



**Figure 6.** Winter mean 2-meter air temperature change (in degrees Celsius) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5.

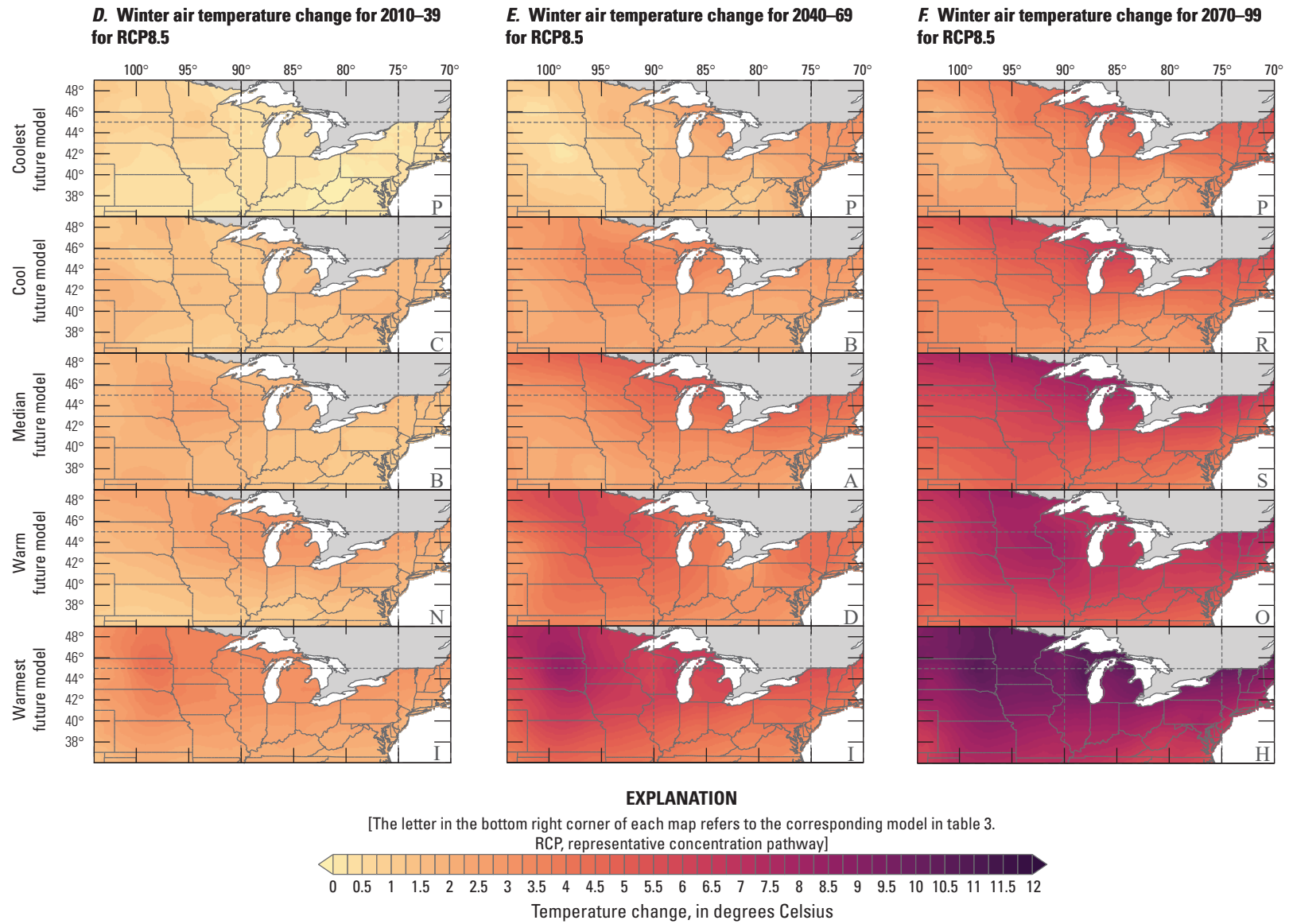


Figure 6.—Continued

**Table 5.** Change in winter (December–February) temperature (in degrees Celsius) from the historical period (1971–2000) for the three future periods under representative concentration pathways 4.5 and 8.5 using Multivariate Adaptive Constructed Analogs version 2-METDATA downscaled global climate model data (Abatzoglou and Brown, 2012). Median model values are given, and the range between the coolest and warmest model is given in parentheses. Models are ranked for each location individually. Values are for the Multivariate Adaptive Constructed Analogs version 2 grid cell containing the location coordinate.

[Italics indicate the range is positive. RCP, representative concentration pathway; NE, Nebraska; WI, Wisconsin; MA, Massachusetts]

RCP4.5			RCP8.5		
2010–39	2040–69	2070–99	2010–39	2040–69	2070–99
Location 1 (NE)					
+1.5 (+0.1, +2.3)	+2.6 (+0.6, +5.0)	+2.8 (+0.6, +4.8)	+1.7 (+0.1, +3.1)	+3.4 (+0.6, +6.7)	+5.4 (+1.9, +8.9)
Location 2 (WI)					
+1.8 (−0.3, +3.0)	+2.9 (+1.0, +5.7)	+3.8 (+1.3, +6.7)	+2.0 (+0.3, +3.6)	+4.1 (+1.3, +6.7)	+6.1 (+3.4, +10.2)
Location 3 (MA)					
+1.4 (+0.5, +2.6)	+2.6 (+1.2, +4.2)	+3.0 (+1.9, +4.6)	+1.8 (+0.5, +3.1)	+3.3 (+2.0, +4.9)	+5.5 (+3.6, +7.9)

## Winter Temperature

Along with increasing average winter temperatures and reductions in snow pack and snowfall (Notaro and others, 2014), extreme cold events are projected to be less frequent. There has been a historical increase in the coldest daily temperature of the year from 1901–60 to 1986–2016 (fig. 6.3 in Vose and others, 2017), especially in the Upper Midwest and the far Northeast. In the future, models agree that days with maximum air temperature less than 0 °C are projected to decrease across the region. This decrease in the number of freezing days is most pronounced in the Upper Midwest around the Great Lakes and in the Northeast (fig. 7.4–F).

## Emergence Cue

Spring emergence for Blanding’s turtles is associated with spring warming and ice loss. Movement from overwintering sites is rapid (Newton and Herman, 2009). Because of this rapid emergence following warming cues, variable winter temperatures (for example, false spring) can lead to premature emergence of Blanding’s turtles and exposure to lethal conditions (that is, freezing temperatures; Markle and Chow-Fraser, 2014).

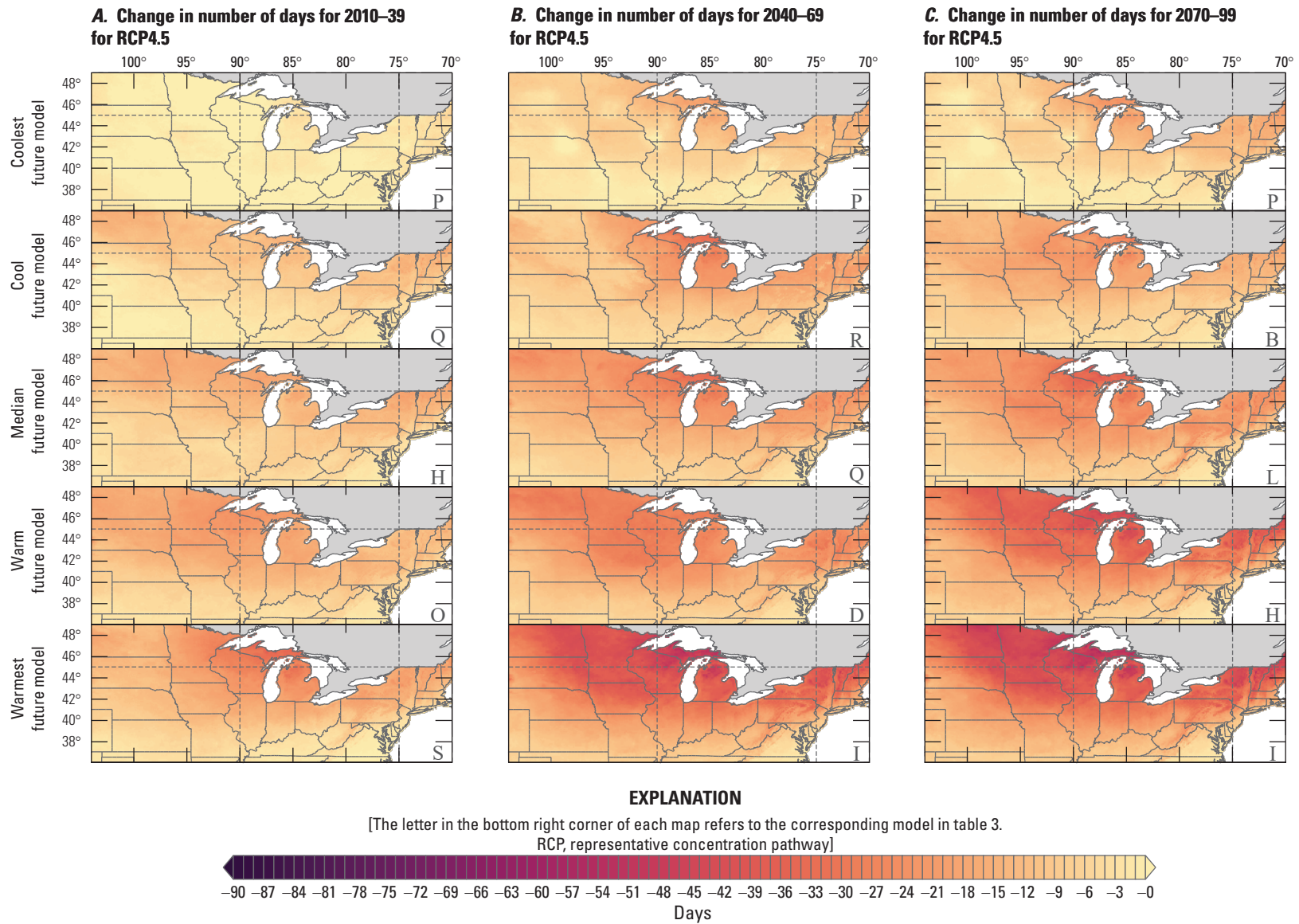
## Minimum Temperature Variability and Spring Warming

Future increases in seasonal air temperature in the winter and spring months may spur earlier movement from overwintering sites (fig. 8.4–F). Spring mean temperature,

similar to winter, is projected to increase in every period under every emissions scenario over the full spread of models with larger increases in the north and near the Great Lakes (fig. 9.4–F). Spring temperature change ranges for the three population locations in all periods and emissions scenarios are given in table 6.

Without a set threshold or exposure duration required for cessation of hibernation, two measures of daily minimum temperature are presented as proxies for winter intensity and variability. The climatology of 14-day running mean daily minimum of air temperatures at 2 m above the surface demonstrates that winters are projected to be milder under the climate scenarios presented here (fig. 10). The timespan does not capture shorter snaps of cold temperatures, and the near-surface temperature data are used as the closest available proxy for surface skin temperature with the understanding that local microclimate variations may affect the experienced temperature for individuals at ground level. The overall increase in daily minimum temperature across the full year is combined with a trend towards reduction in winter daily minimum temperature variability with time (fig. 11.4–F). The mean of 14-day moving average ranges of daily minimum temperature indicates the average range in temperatures across a 2-week period averaged to a monthly climatology and captures the variability of minimum temperatures. This warming and reduced variability in the daily minimum temperatures is most pronounced in location 2 (Wisconsin). Although anomalous cold events are still possible, the combination of these two metrics points to a reduced chance of exposure danger.





**Figure 7.** Change in number of days with daily maximum temperatures less than 0 degrees Celsius in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. A, early 21st century (2010–39) for RCP4.5; B, mid-21st century (2040–69) for RCP4.5; C, late 21st century (2070–99) for RCP4.5; D, early 21st century (2010–39) for RCP8.5; E, mid-21st century (2040–69) for RCP8.5; F, late 21st century (2070–99) for RCP8.5.

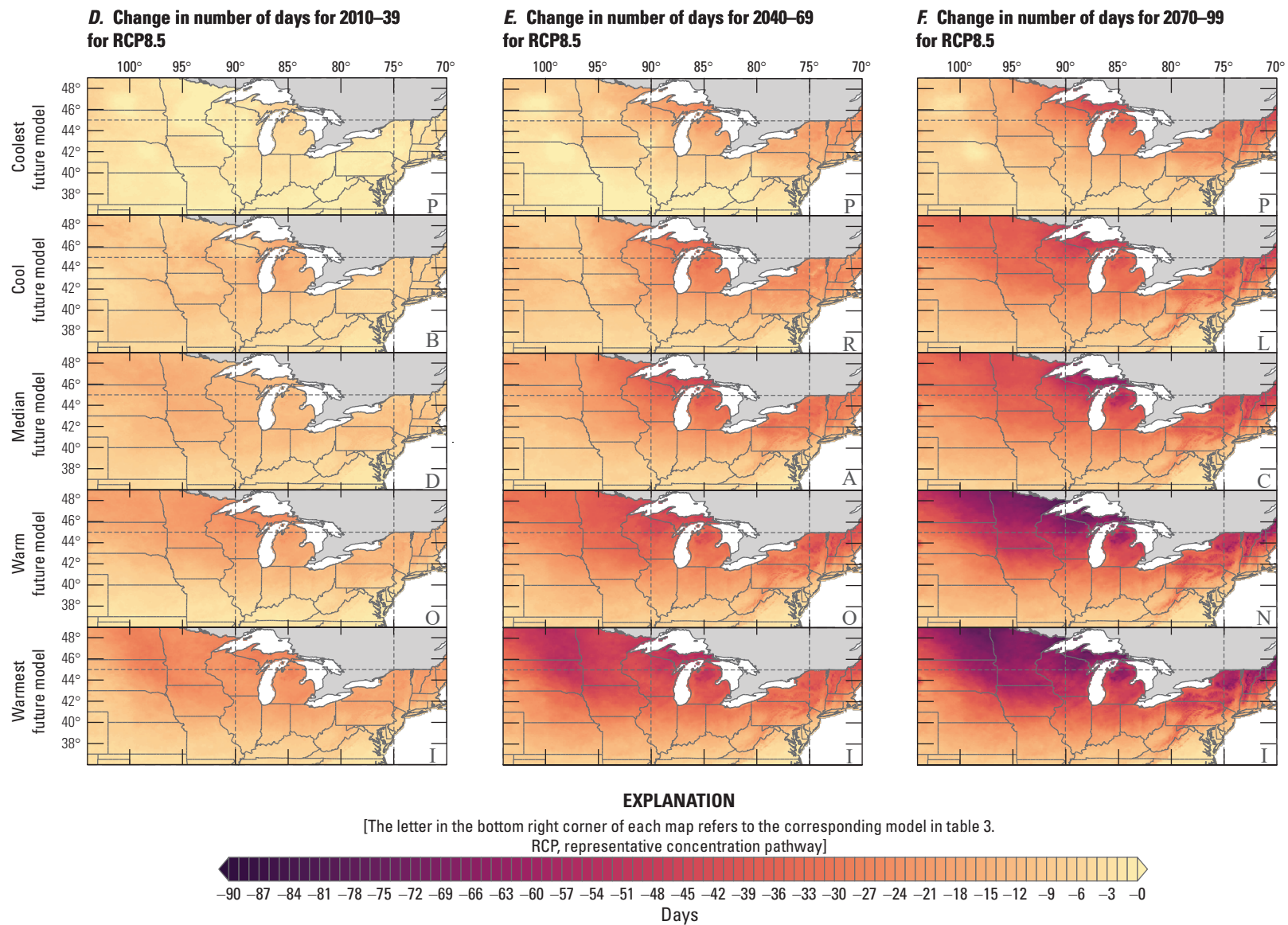
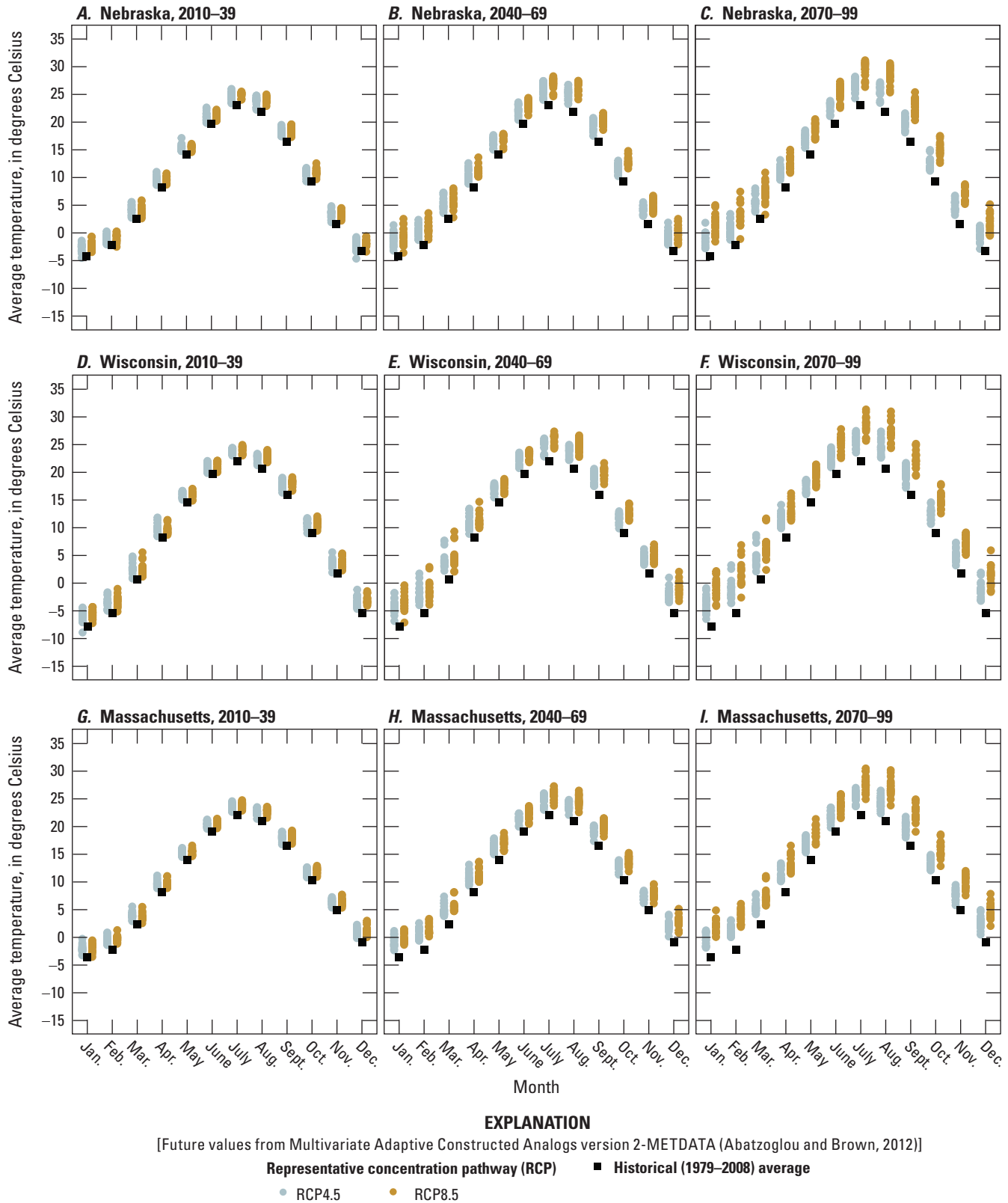
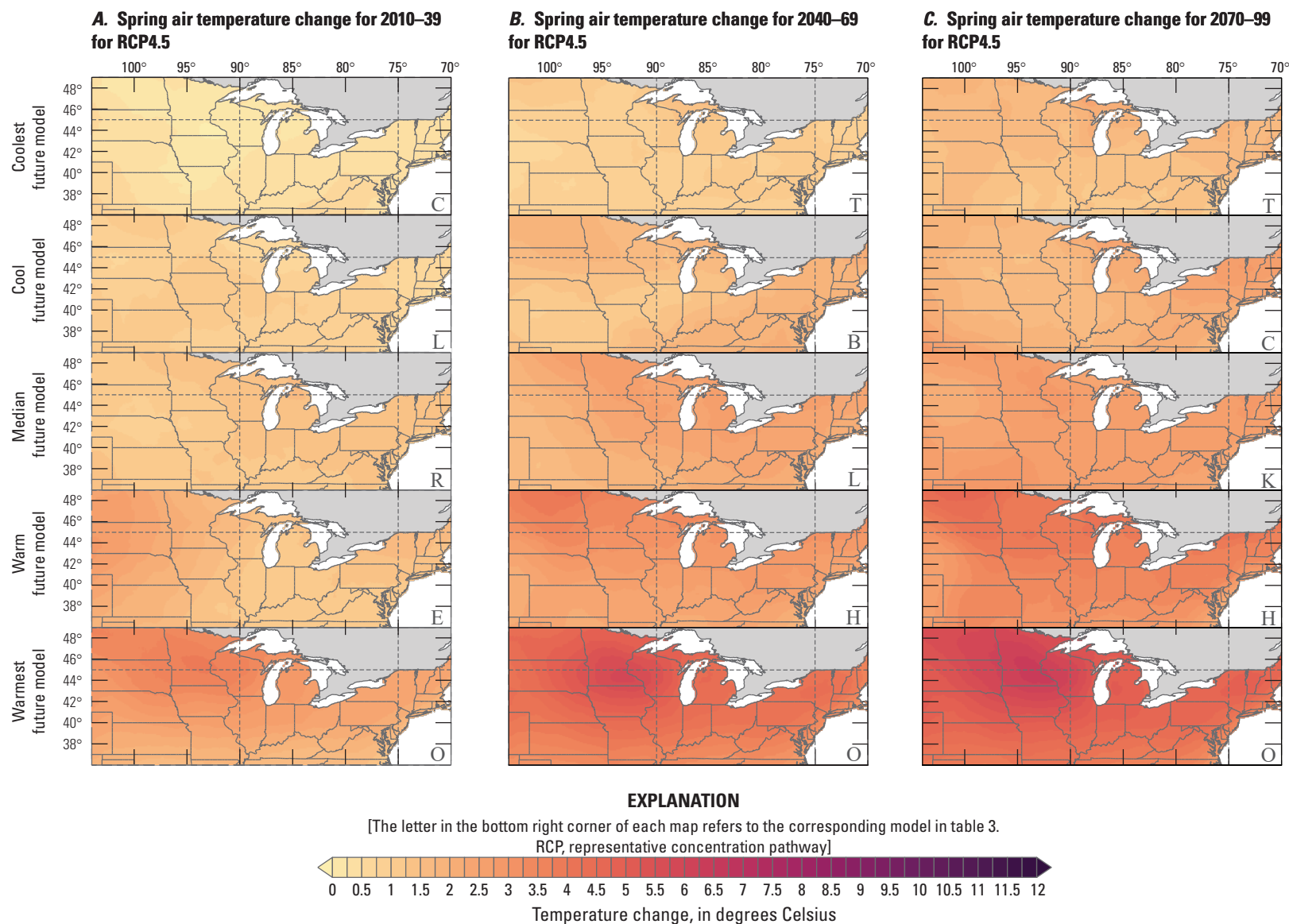


Figure 7.—Continued



**Figure 8.** Mean monthly 2-meter air temperature climatology (in degrees Celsius) in the downscaled climate simulations for the three population areas under emissions scenarios for representative concentration pathway 4.5 (RCP4.5; blue) and representative concentration pathway 8.5 (RCP8.5; brown). A, 2010–39 for Nebraska; B, 2040–69 for Nebraska; C, 2070–99 for Nebraska; D, 2010–39 for Wisconsin; E, 2040–69 for Wisconsin; F, 2070–99 for Wisconsin; G, 2010–39 for Massachusetts; H, 2040–69 for Massachusetts; I, 2070–99 for Massachusetts. Black squares show the historical (1979–2008) average for the population area in the METDATA observations.





**Figure 9.** Spring mean 2-meter air temperature change (in degrees Celsius) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5.

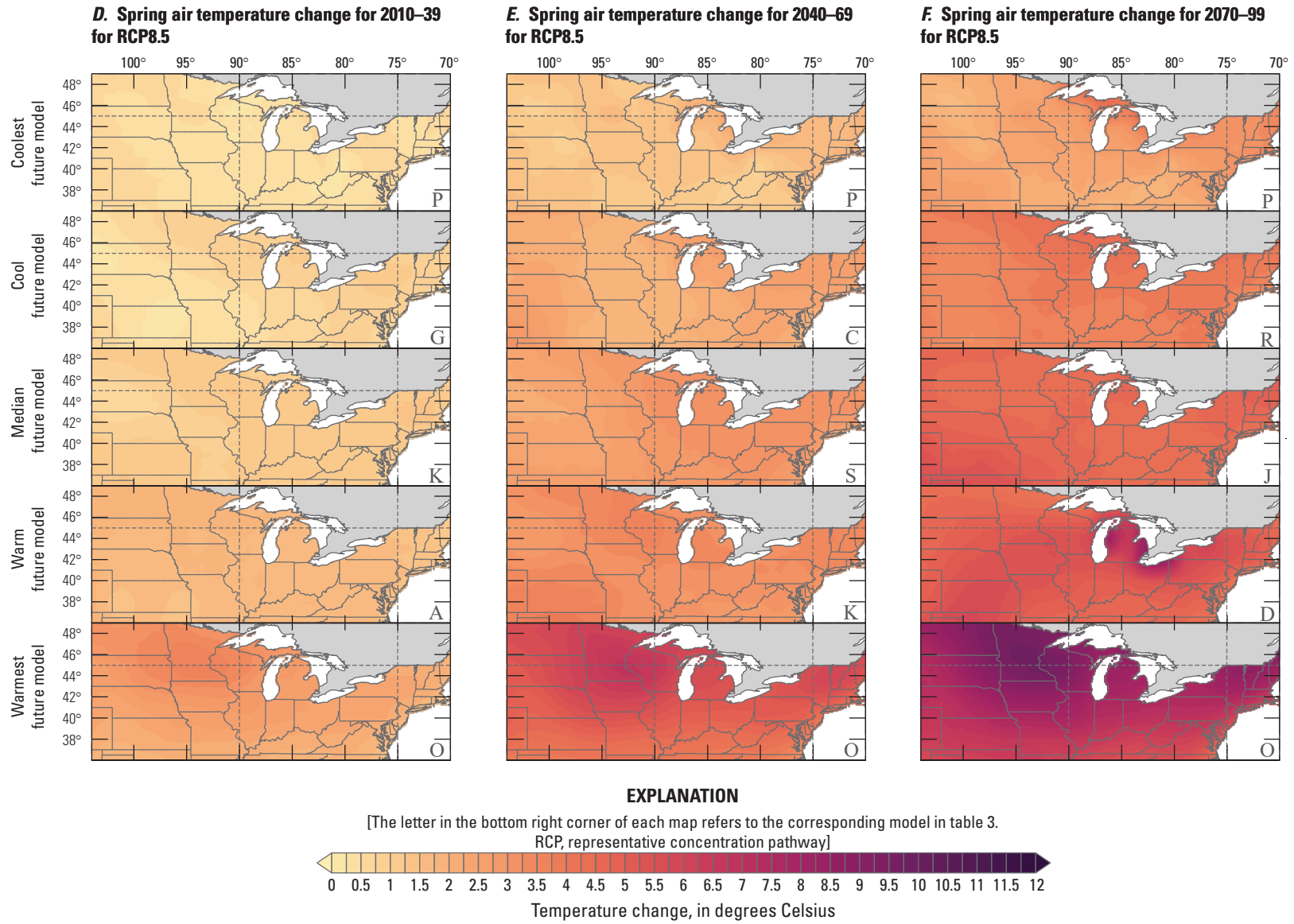
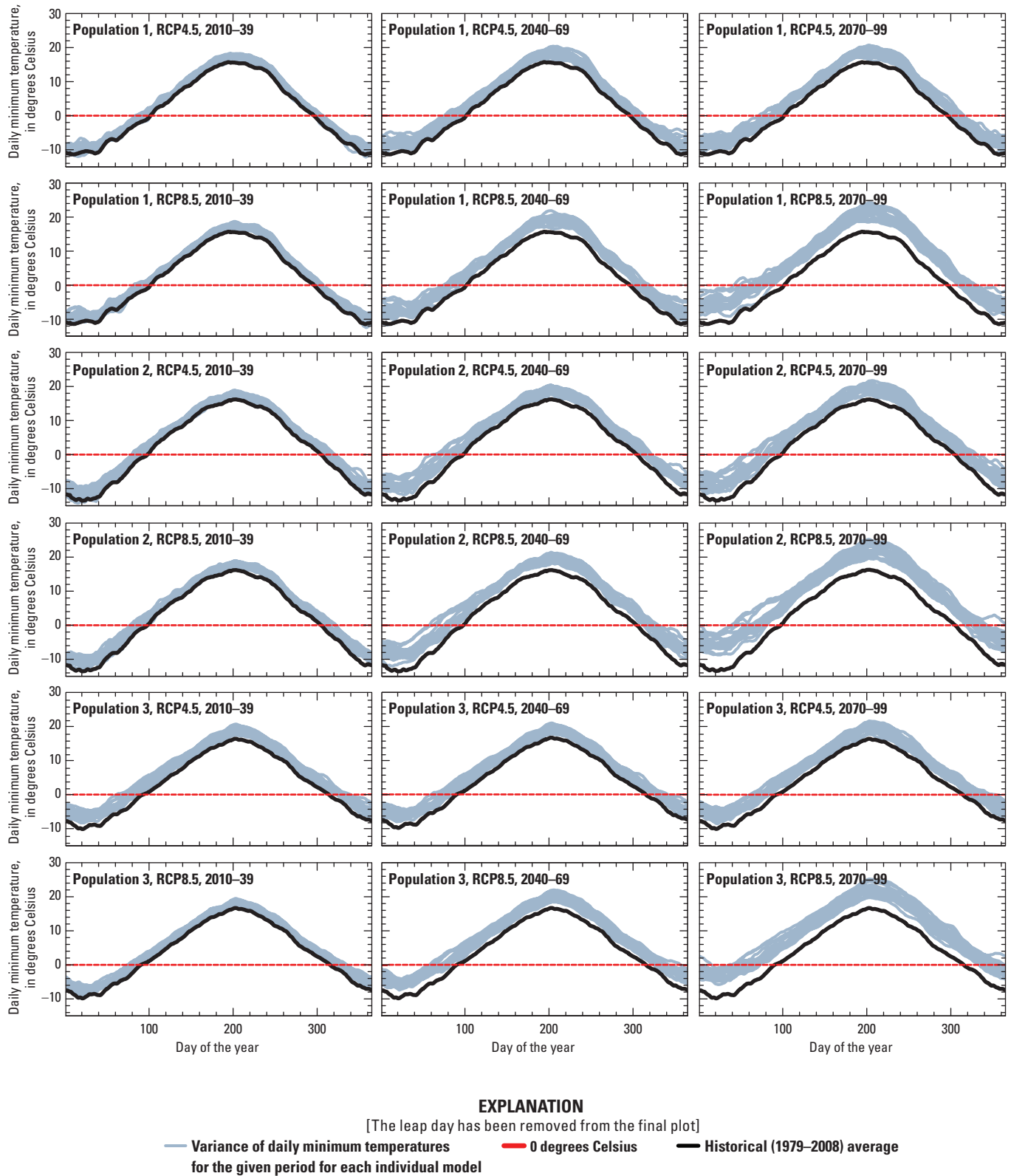


Figure 9.—Continued

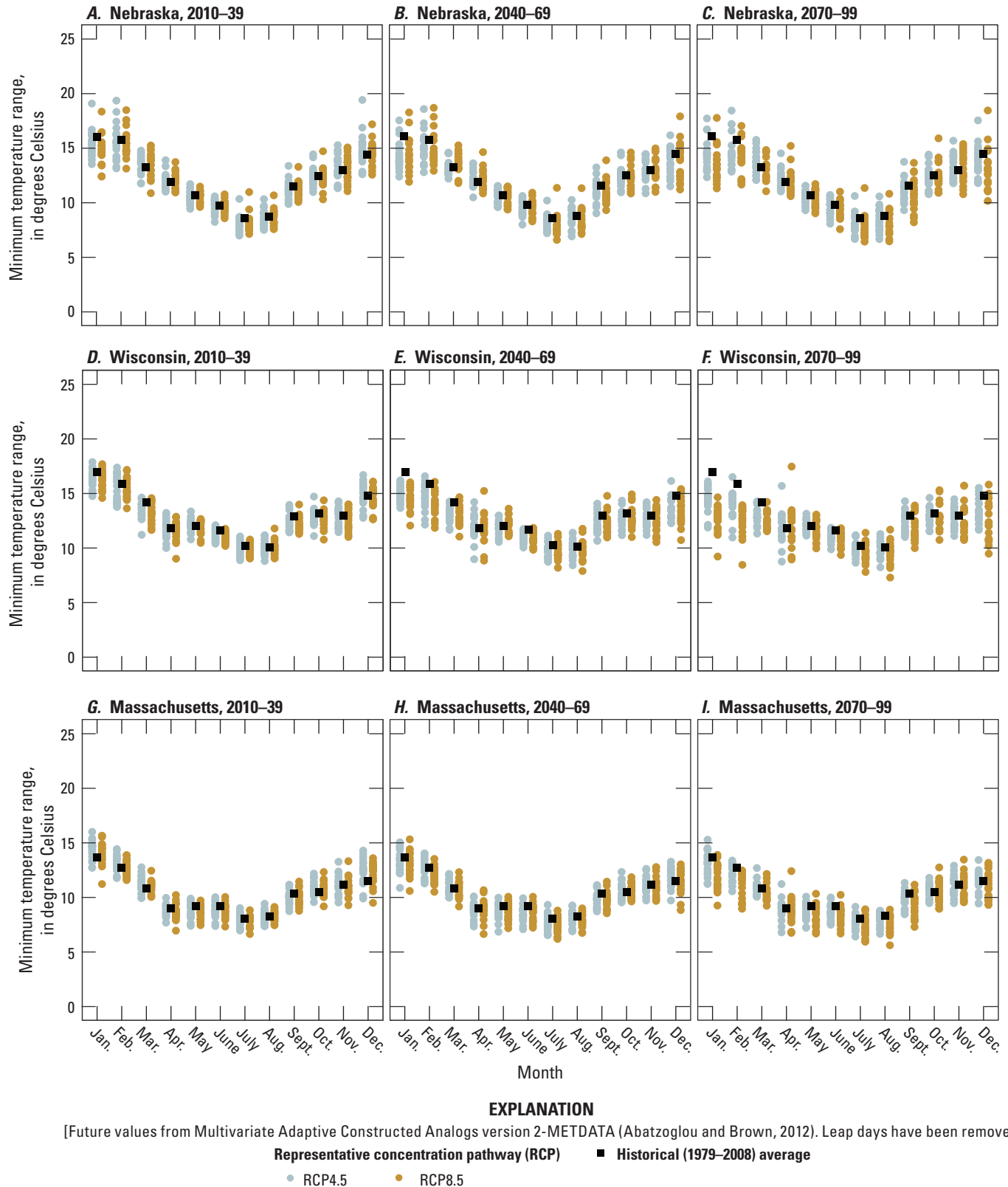
**Table 6.** Change in spring (March–May) temperature (in degrees Celsius) from the historical period (1971–2000) for the three future periods under representative concentration pathways 4.5 and 8.5 using Multivariate Adaptive Constructed Analogs version 2-METDATA downscaled global climate model data (Abatzoglou and Brown, 2012). Median model values are given, and the range between the coolest and warmest model is given in parentheses. Models are ranked for each location individually. Values are for the Multivariate Adaptive Constructed Analogs version 2 grid cell containing the location coordinate.

[Italics indicate the range is positive. RCP, representative concentration pathway; NE, Nebraska; WI, Wisconsin; MA, Massachusetts]

RCP4.5			RCP8.5		
2010–39	2040–69	2070–99	2010–39	2040–69	2070–99
Location 1 (NE)					
<i>+1.0</i> (+0.4, +2.9)	<i>+1.9</i> (+0.7, +4.4)	<i>+2.5</i> (+1.6, +5.1)	<i>+1.0</i> (+0.3, +2.7)	<i>+2.7</i> (+1.0, +5.2)	<i>+4.6</i> (+2.2, +7.5)
Location 2 (WI)					
<i>+1.4</i> (+0.1, +3.3)	<i>+2.4</i> (+1.1, +5.2)	<i>+2.7</i> (+1.6, +5.7)	<i>+1.1</i> (+0.3, +3.1)	<i>+2.8</i> (+1.4, +6.2)	<i>+4.6</i> (+2.6, +8.8)
Location 3 (MA)					
<i>+1.3</i> (+0.3, +2.5)	<i>+2.2</i> (+1.0, +4.4)	<i>+2.6</i> (+1.7, +4.7)	<i>+1.1</i> (+0.5, +2.6)	<i>+2.6</i> (+1.8, +5.1)	<i>+4.5</i> (+3.2, +7.9)



**Figure 10.** Climatology of 14-day running mean daily minimum 2-meter air temperatures (in degrees Celsius) in the downscaled climate simulations for the three population areas. The black distribution shows the historical (1979–2008) average for the population area in the METDATA observations.



**Figure 11.** Mean monthly climatology of 14-day moving average ranges of daily minimum temperature in the downscaled climate simulations for the three population areas under emissions scenarios for representative concentration pathway 4.5 (RCP4.5; blue) and representative concentration pathway 8.5 (RCP8.5; brown). *A*, 2010–39 for Nebraska; *B*, 2040–69 for Nebraska; *C*, 2070–99 for Nebraska; *D*, 2010–39 for Wisconsin; *E*, 2040–69 for Wisconsin; *F*, 2070–99 for Wisconsin; *G*, 2010–39 for Massachusetts; *H*, 2040–69 for Massachusetts; *I*, 2070–99 for Massachusetts. Black squares show the historical (1979–2008) average for the population area in the METDATA observations.

## Overwintering and Emergence Conclusions

Changes in precipitation may affect availability of future suitable wetland habitat. Given projected increases in precipitation across many models, broad wetland availability may not be threatened by reduced precipitation and may even experience benefits to area and connectivity from increased rainfall. However, low rainfall in a given year may still lead to reduced habitat. Additionally, increased precipitation and heavy precipitation events may yield more unsuitable deep-water ponds. Increasing winter temperatures may decrease snowpack and increase movement within and away from overwintering sites; decreased thermal insulation from snow is of special concerns for hatchlings. However, given projected changes in minimum temperatures, the likelihood of mortality from extreme cold events will likely be reduced. In addition, this increase in temperature also is likely to lead to earlier emergence, earlier nesting activity, and increased energetic demands.

## Spring Movement and Foraging

In the spring and early summer, female Blanding's turtles disperse to upland areas with low vegetation and well-drained soils for nesting. During dispersal, Blanding's turtles typically move among multiple wetlands, and females make 7.9 interwetland movements on average in a year (Beaudry and others, 2010). Male Blanding's turtles make a similar number of interwetland movements (Beaudry and others, 2010), but this is not concentrated in a single season (Piepgras and Lang, 2000). Dispersal to nesting areas may increase female Blanding's turtles' risk of road mortality and lead to sex bias in the population (Reid and Peery, 2014). Because Blanding's turtles often move among wetlands (Beaudry and others, 2009), changes in early spring and summer wetland availability may alter movement and further increase the risk of mortality for adult females.

## Precipitation

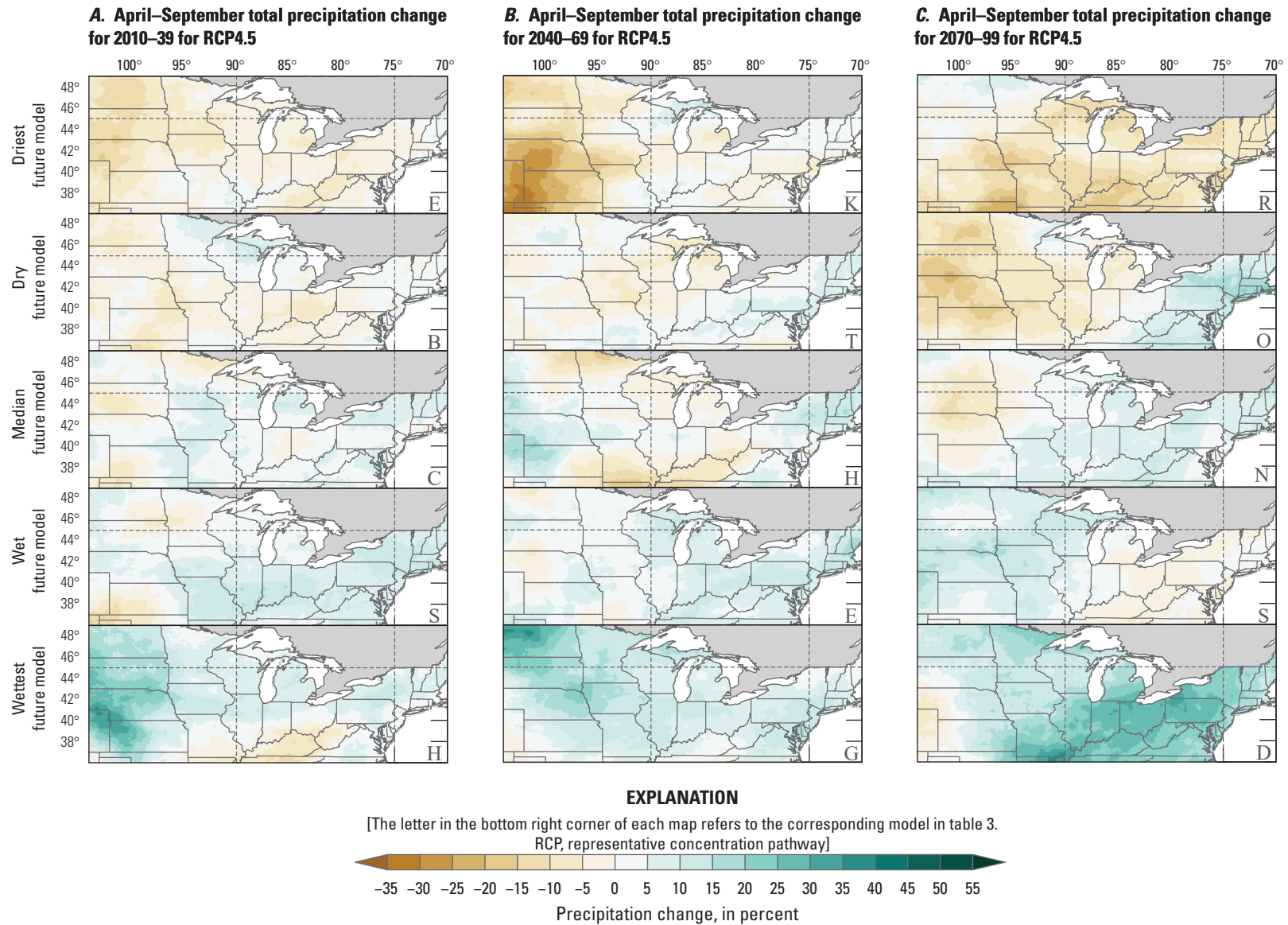
Successful spring dispersal of females to nesting sites depends on the availability of small waterbodies on the landscape for feeding and shelter. As already noted, cool season precipitation affects the availability and suitability of ponds, lakes, rivers, and wetlands on the landscape for overwintering after summer dry downs. Late cool season and warm season precipitation also may support pond persistence throughout the spring—despite warming temperatures—especially for populations in the center and west of the range. Increases in precipitation have the potential benefit of increasing habitat area and connectivity.

## Aridity

Although warm season (April–September) precipitation is projected to increase in some models and emissions scenarios, projected precipitation across the full model spread indicates a general trend towards decreases, especially in the west and center of the domain (fig. 12A–F). Again, models indicate variable projections about what parts of the range will become wetter or drier relative to others. The presentation of a five-model spread of projections and average changes at individual locations aims to demonstrate this spatial variability. This tendency towards reduced precipitation, coupled with consistent temperature increases across all periods under all emissions scenarios in the full spread of models, may contribute to increased drying in the summer months and may contribute to habitat drying earlier in the year (May–July) if not offset by changes in other seasons (Dahl, 2014; Renton and others, 2015; fig. 13A–F). Again, we note the projected drying in the context of historical summer precipitation increases, where the central Midwest and Northeast saw precipitation increases of greater than 15 percent. Warm season precipitation and summer temperature change ranges for the three population locations in all periods and emissions scenarios are given in tables 7–8.

Although average annual precipitation may be projected to increase in some areas, droughts and floods remain likely given a trend towards more extreme precipitation events and higher temperatures (Easterling and others, 2017; Vose and others, 2017).





**Figure 12.** April–September mean total precipitation change (in percent) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. A, early 21st century (2010–39) for RCP4.5; B, mid-21st century (2040–69) for RCP4.5; C, late 21st century (2070–99) for RCP4.5; D, early 21st century (2010–39) for RCP8.5; E, mid-21st century (2040–69) for RCP8.5; F, late 21st century (2070–99) for RCP8.5.

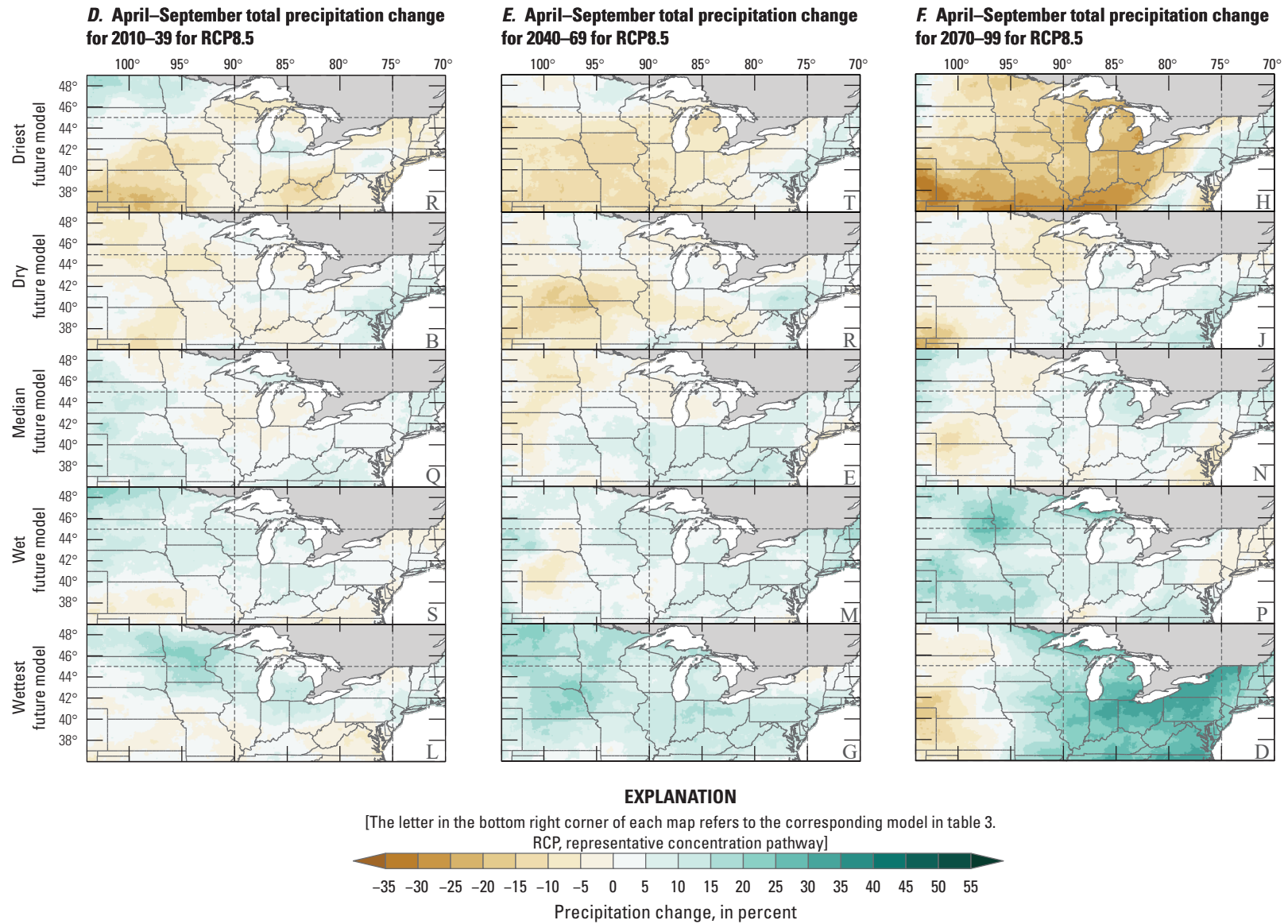
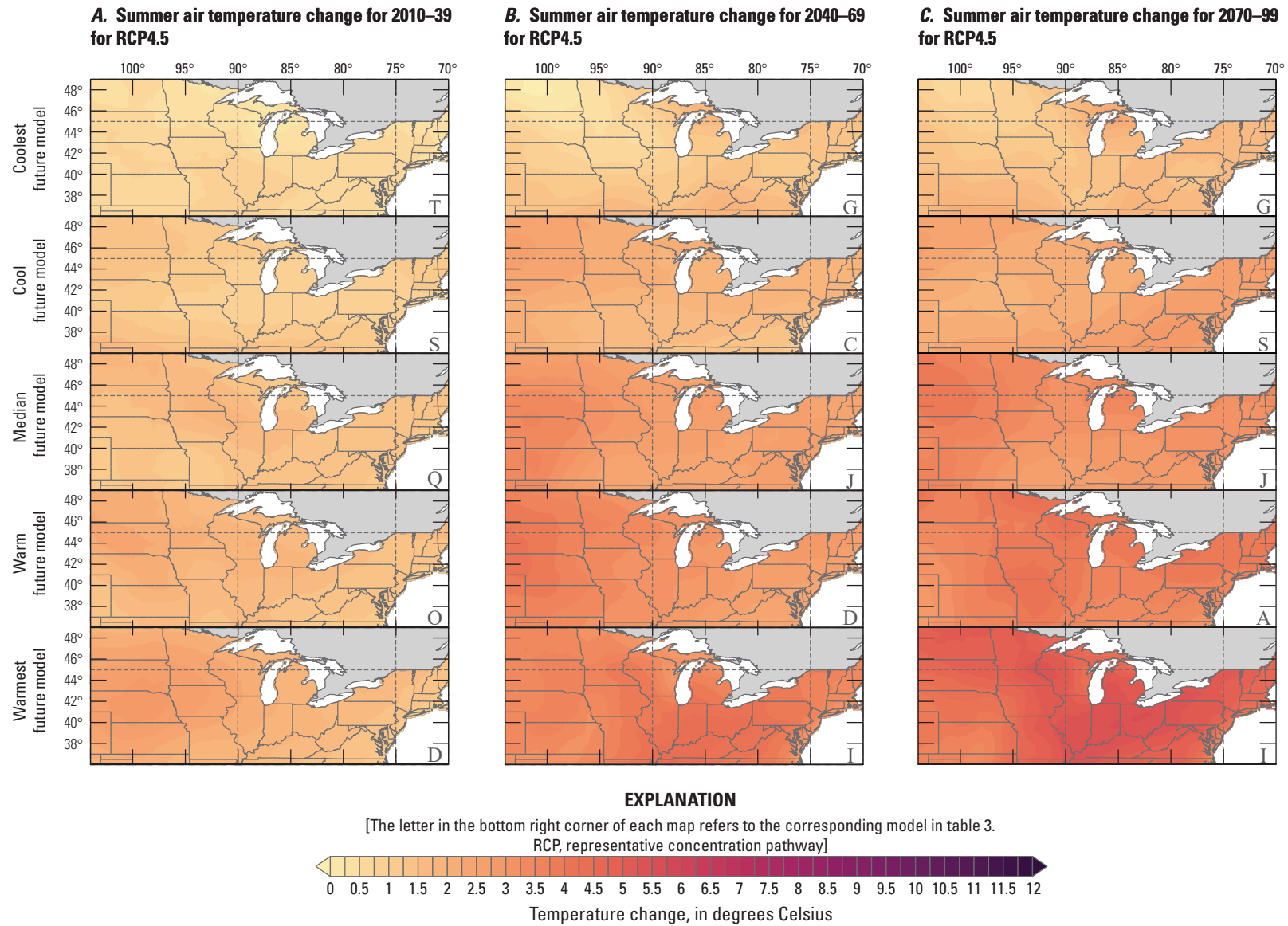


Figure 12.—Continued





**Figure 13.** Summer mean 2-meter air temperature change (in degrees Celsius) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5.

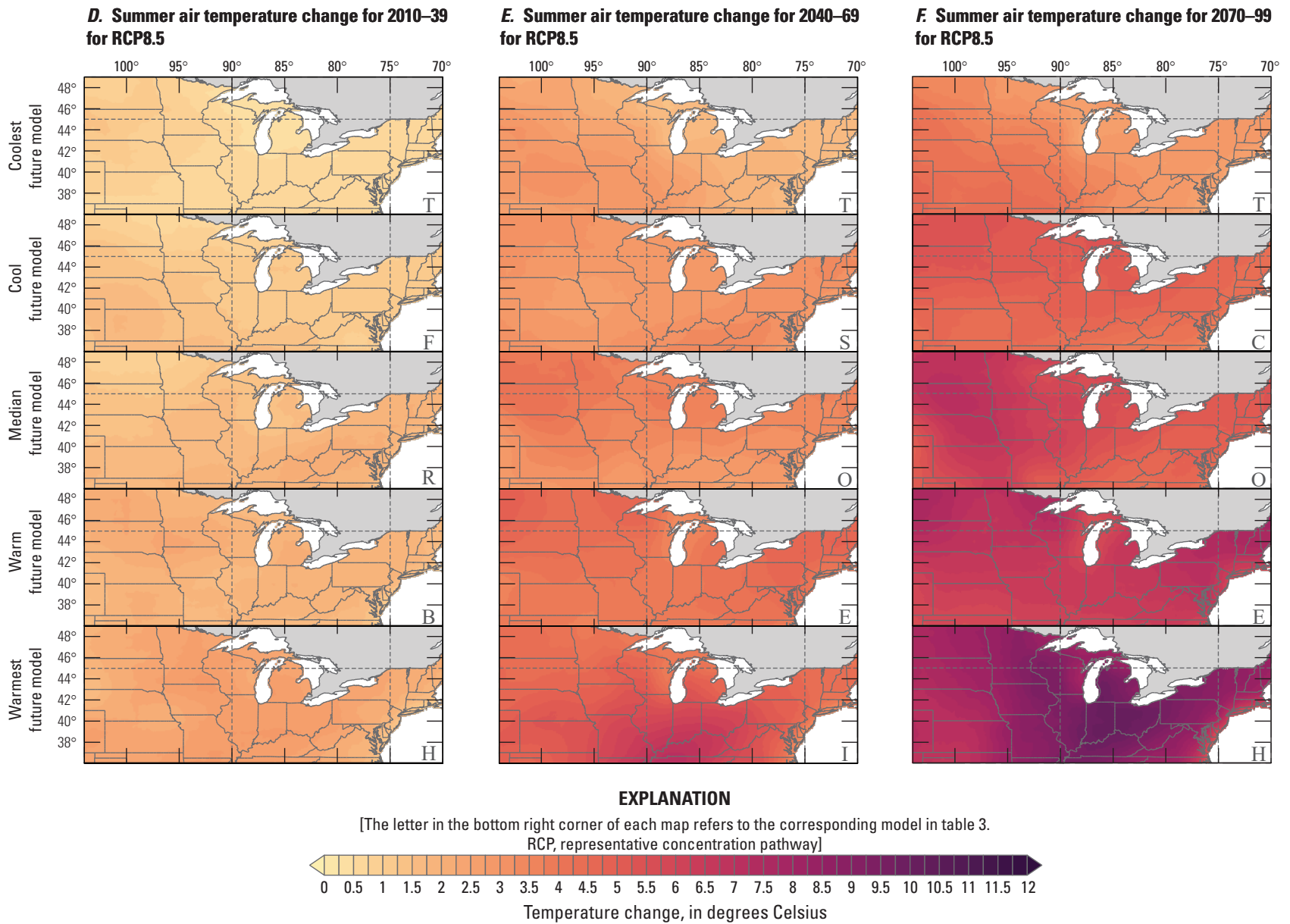


Figure 13.—Continued

**Table 7.** Change in warm season (April–September) precipitation (%) from the historical period (1971–2000) for the three future time periods under RCP4.5 and RCP8.5 using Multivariate Adaptive Constructed Analogs version 2-METDATA downscaled global climate model data (Abatzoglou and Brown, 2012). Median model values are given with the range between the driest and wettest model given in parentheses.

RCP4.5			RCP8.5		
2010–39	2040–69	2070–99	2010–39	2040–69	2070–99
Location 1 (NE)					
–0.8 (–11.9, 24.6)	+1.2 (–22.8, 17.5)	+2.9 (–20.1, 20.0)	+2.7 (–8.2, 13.2)	–1.7 (–17.9, 21.2)	–1.9 (–22.8, 16.0)
Location 2 (WI)					
+3.4 (–7.9, 12.9)	+3.1 (–9.4, 17.7)	+1.3 (–14.8, 13.7)	+0.3 (–4.5, 9.6)	+1.7 (–8.7, 18.5)	+2.5 (–20.0, 18.3)
Location 3 (MA)					
+4.6 (–8.3, 13.5)	+5.0 (–13.6, 17.0)	+7.4 (–5.6, 16.7)	+2.9 (–5.5, 15.4)	+5.8 (–13.6, 12.3)	+8.7 (–5.6, 16.1)

**Table 8.** Change in summer (June–August) temperature (in degrees Celsius) from the historical period (1971–2000) for the three future periods under representative concentration pathways 4.5 and 8.5 using Multivariate Adaptive Constructed Analogs version 2-METDATA downscaled global climate model data (Abatzoglou and Brown, 2012). Median model values are given, and the range between the coolest and warmest model is given in parentheses. Models are ranked for each location individually. Values are for the Multivariate Adaptive Constructed Analogs version 2 grid cell containing the location coordinate.

[Italics indicate the range is positive. RCP, representative concentration pathway; NE, Nebraska; WI, Wisconsin; MA, Massachusetts]

RCP4.5			RCP8.5		
2010–39	2040–69	2070–99	2010–39	2040–69	2070–99
Location 1 (NE)					
<i>+1.6</i> <i>(+0.2, +2.8)</i>	<i>+2.6</i> <i>(+0.8, +4.1)</i>	<i>+3.5</i> <i>(+1.2, +4.8)</i>	<i>+1.7</i> <i>(+0.8, +2.6)</i>	<i>+3.9</i> <i>(+1.8, +4.9)</i>	<i>+5.9</i> <i>(+3.1, +8.0)</i>
Location 2 (WI)					
<i>+1.5</i> <i>(+0.4, +2.2)</i>	<i>+2.7</i> <i>(+0.7, +3.5)</i>	<i>+3.2</i> <i>(+1.3, +5.0)</i>	<i>+1.7</i> <i>(+0.5, +2.4)</i>	<i>+3.7</i> <i>(+2.1, +4.6)</i>	<i>+5.9</i> <i>(+3.0, +8.8)</i>
Location 3 (MA)					
<i>+1.3</i> <i>(+0.5, +2.0)</i>	<i>+2.5</i> <i>(+1.0, +3.3)</i>	<i>+2.9</i> <i>(+1.2, 4.6)</i>	<i>+1.5</i> <i>(+0.7, +2.2)</i>	<i>+3.3</i> <i>(+1.5, +4.6)</i>	<i>+5.1</i> <i>(+2.7, +7.8)</i>

## Spring Movement and Foraging Conclusions

Cool season precipitation is necessary to establish and maintain wetlands during the winter and early spring, and warm season precipitation is crucial for wetland maintenance through the summer. Several plausible models indicate increasing warm season precipitation, especially in the spring, reducing the likelihood of habitat loss early in the year. Anomalous temperatures and low precipitation may vary pond availability by region and year. Local reduction in habitat availability may increase female movement and, in turn, increase mortality.

## Nesting

### Temperature

Nesting is historically between late May and early July (Joyal and others, 2000) when temperatures are greater than 18.9 °C (Buckardt and others, 2020), and incubation lasts 69–128 days (Joyal and others, 2000). Warmer temperatures correspond to earlier nesting (Buckardt and others, 2020) and shorter incubation (Joyal and others, 2000). An increase in spring temperature will likely shift nesting earlier in the year (Byer and others, 2020). In all three sample locations, April mean temperatures may reach historical May mean temperatures by midcentury (2040–69) under the high emissions scenario RCP8.5 and under emissions scenarios RCP4.5 by the end of the century (2070–99; [fig. 8B, C, E, F, H, and I](#)). Under the high emissions scenario RCP8.5, average May temperatures may exceed 20 °C on average by the end of the century across the population distribution.

Blanding's turtles, like most other ectotherms, have a narrow optimal temperature window for successful embryo development. At temperatures less than 22 °C, nest failure is complete (Gutzke and Packard, 1987). At temperatures greater than 31 °C, hatchling success decreases, but the maximum thermal threshold is unknown (Gutzke and Packard, 1987). After a warm summer in Massachusetts, with nest temperatures recorded between 35 and 40 °C for 17 days during incubation, nest failure was either partial or complete (Compton, 2007). Additionally, sex determination in Blanding's turtles is temperature dependent; incubation temperatures greater than 30 °C produce primarily females, and incubation temperatures less than 28 °C produce primarily males (Gutzke and Packard, 1987). In many populations, hatchlings already seem to be female biased (Congdon and Keinath, 2006); however, evidence for the temperature thresholds for sex determination and for nest success is mixed (Reid and Peery, 2014). Warmer daily average and daily maximum temperatures in nesting regions, as noted in the spring ([fig. 9A–F](#)) and summer ([fig. 13A–F](#)), may be important.

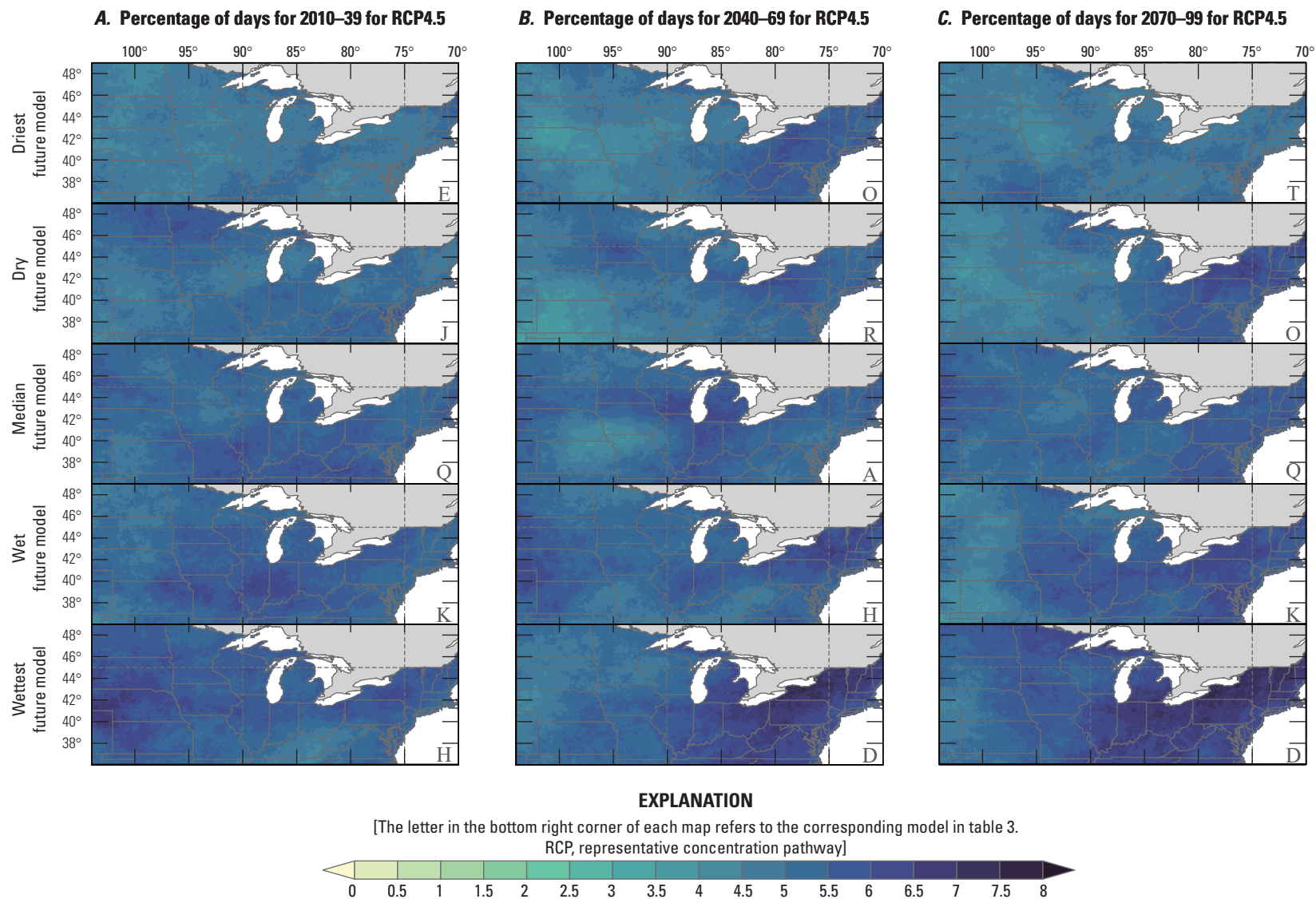
Individual nest exposure to increased temperatures varies based on factors including vegetation, timing, and substrate; Blanding's turtles may demonstrate adaptive capacity (Roberts and others, 2023) to buffer nests from the effects of climate change. In response to warming air temperatures, reptiles will nest at a greater depth (*Chrysemys picta* [Schneider, 1783; painted turtles; Refsnider and Janzen, 2012] and two species of Australian lizards, *Acrisoscinus duperreyi* [Gray, 1838; three-lined skink] and *Intellagama lesueurii* [Gray, 1838; eastern water dragon; Doody, 2009; Telemeco and others, 2009]). However, because of the magnitude of climate change, an increase in nest depth for Blanding's turtles is unlikely to offset warming (Reid and Peery, 2014). Other freshwater turtle species compensate for warming environmental conditions with behavioral plasticity, selecting more shaded nesting locations (Refsnider and Janzen, 2012; Topping and Valenzuela, 2021; Roberts and others, 2023). However, female Blanding's turtles consistently choose warm nesting sites, preferring sites that are south facing with low vegetation and sandy soils (Congdon and others, 2000; Ruane and others, 2008). For nesting Blanding's turtles, earlier nesting seasons and potential changes to nesting microhabitats are likely the primary mechanisms to compensate for ambient warming.

### Flooding

Heavy precipitation events may cause nest failure (Congdon and others, 2000). In heavy precipitation years, Standing and others (2000) determined that flooding was the main cause of nest failure. Given the preference for sandy nesting sites with low vegetation, heavy rainfall events also may increase erosion of Blanding's turtle nests (Congdon and others, 2000).

Extreme precipitation events have been increasing in the historical period in the Midwest and Northeast, especially in the autumn ([fig. 7.2](#) in Easterling and others, 2017). During 1958–2016, the 99th percentile precipitation increased 42 percent in the Midwest and 55 percent in the Northeast ([fig. 7.4](#) in Easterling and others, 2017). Because of the importance of local factors and antecedent conditions, it is difficult to directly link extreme precipitation events to certain flooding levels or effects. The frequency of heavy precipitation and flooding events (in areas where flooding is driven primarily by excess precipitation) in the historical period has been increasing more than the magnitude of those events in most regions of the Midwest/Great Lakes (Mallakpour and Villarini, 2015; Berghuijs and others, 2016; Hodgkins and others, 2019). Analysis of the percentage of future days with precipitation greater than the historical 95th percentile of daily precipitation indicates a broad increase in annual extreme precipitation days ([fig. 14A–F](#)). This analysis aligns with studies indicating extreme precipitation is expected to increase in the future, especially in the spring (Basile and others, 2017; Easterling and others, 2017; Byun and Hamlet, 2018; Byun and others, 2019).





**Figure 14.** Percentage of days with precipitation greater than the historical 95th percentile of daily precipitation in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5.

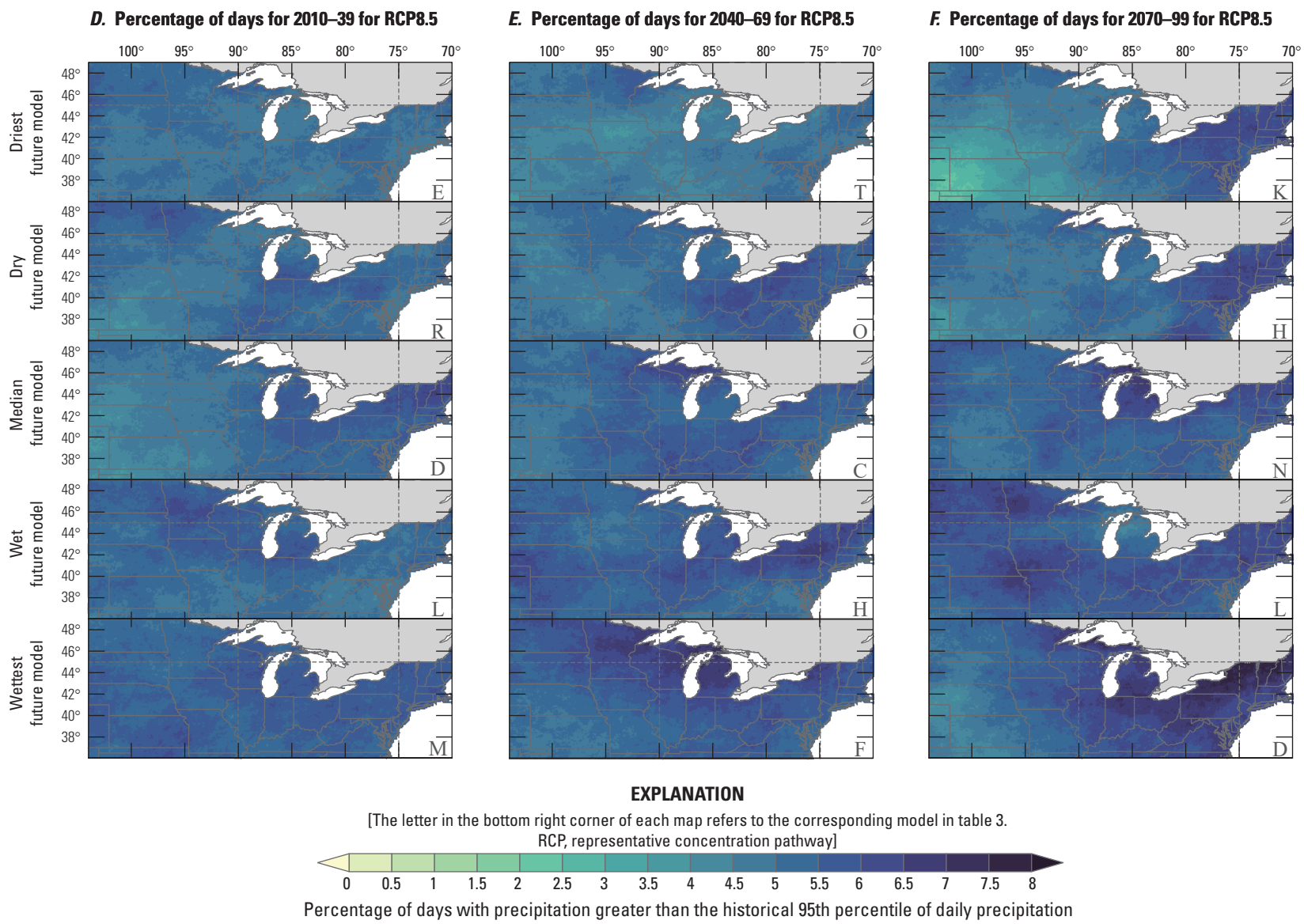


Figure 14.—Continued

Climate models have been determined to underestimate extreme precipitation in the historical period, especially after the 1980s, with observed extreme events exceeding the full model spread of historical simulations in the Midwest and Northeast (fig. 8 in Janssen and others, 2014). Variation among and within models can be affected by downscaling and bias correction methodology (Wang and others, 2020). In a comparison of dynamical and statistical downscaling products for the region introduced in the “Data and Methods” section, the dynamical product produced much higher projections of extreme daily rainfall events (greater than 3 inches); therefore, the projections from the statistical downscaling presented here are a conservative estimate. Modeling of extreme precipitation in this region is further complicated by spring and summer mesoscale convective events (Feng and others, 2018; Schumacher and Rasmussen, 2020), internal variability, and sea surface temperature teleconnections (Hoerling and others, 2012; Huang and others, 2021).

## Aridity

Increasing aridity may affect the ability of Blanding’s turtles to construct nests and nest success. Dry soils hinder nest construction and increase likelihood of nest collapse (Congdon and others, 2000). In arid environments, embryo failure and hatchling mortality from desiccation also are possible (Congdon and others, 2000). Populations in Nebraska seem to be adapted to the more arid environment (Ruane and others, 2008). In the Nebraska Sandhills region, egg size increases with female carapace length (Ruane and others, 2008); larger eggs yield larger hatchlings and have lower desiccation rates. In the rest of the species distribution, female carapace length is correlated with clutch size rather than egg size.

Increased summer drying coupled with decreased summer precipitation increases the aridity of a region given a changing ratio between precipitation and evapotranspiration. However, given moisture balance changes in other seasons, it is not certain that increased aridity in the summer months would have important consequences on Blanding’s turtles. Additionally, the projection of evaporation is not necessarily driven only by temperature increase. Byun and others (2019) indicate little change in actual evapotranspiration during the summer months in the Midwest despite warming.

## Nesting Conclusions

Changing conditions across the distribution of Blanding’s turtles are likely to decrease nest success. In the southern part of the species’ range, temperatures are likely to exceed those necessary for successful incubation (Hamilton and others, 2018). Across the full range, increasing temperatures will likely foster sex bias. Female sex bias may benefit population

growth in the short term if a sufficient number of males is produced to sustain the population (Roberts and others, 2023). In the Midwest, increased cycling between drought and flooding will likely increase nest mortality. In response to warmer spring temperatures, Blanding’s turtles may advance nesting. Additionally, warmer temperatures may reduce the incubation period and, in turn, reduce the risk of desiccation in the late summer.

## Foraging and Nonnesting Movement

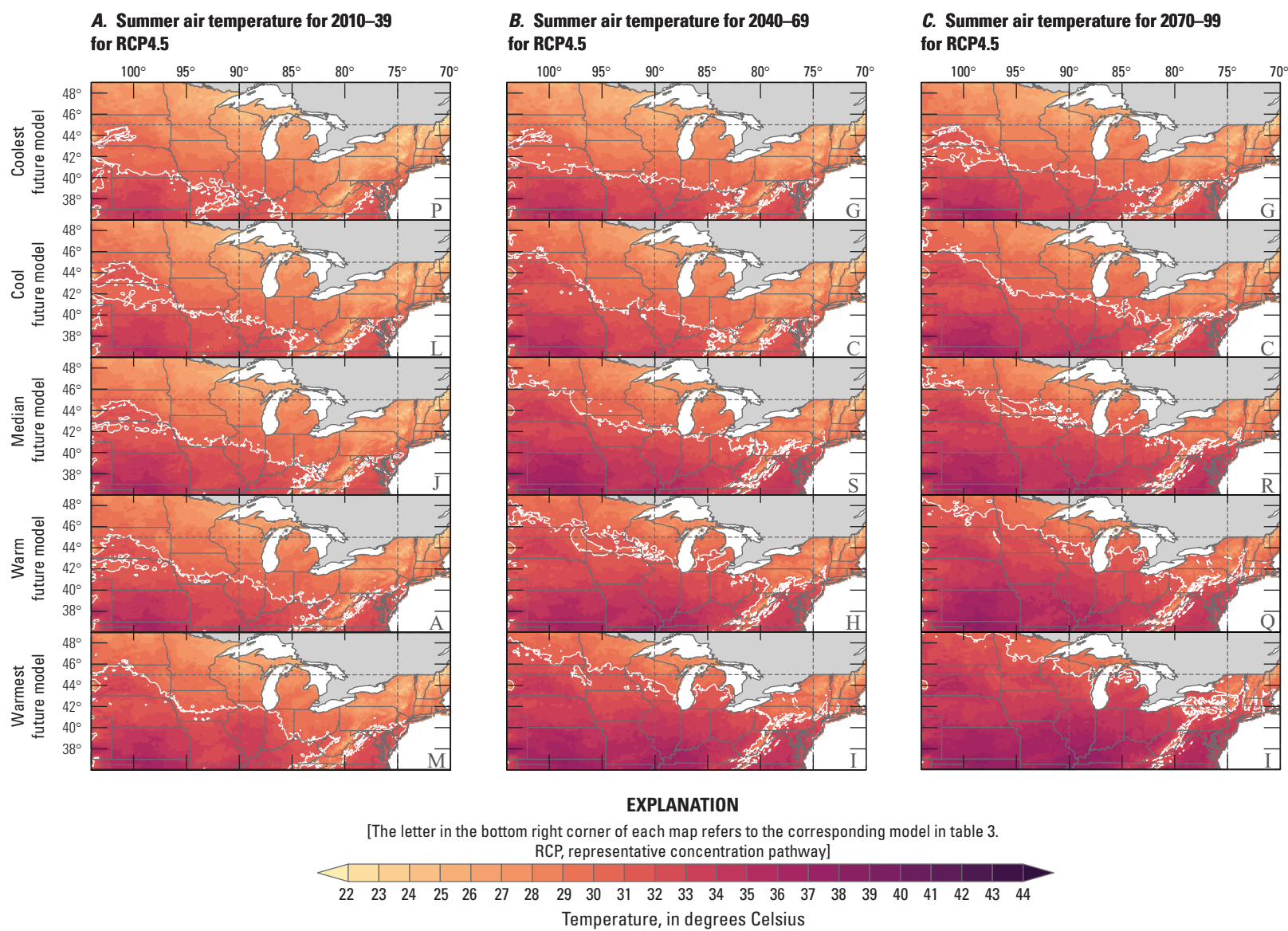
Compared to other freshwater turtles, Blanding’s turtles have a low critical thermal maximum between 38.2 and 40.6 °C (Compton, 2007). Blanding’s turtles seem to primarily forage for food in two pulses—spring to early summer and late summer to early fall. Foraging starts when water temperatures exceed 18 °C and pauses in late July and early August when temperatures are likely too high (Kofron and Schreiber, 1985). Annual and geographic variation in aestivation length and timing may be considerable and likely depend on local variations in temperature (Compton, 2007).

## Temperature

Increasing exposure to lethal temperatures will be an issue for Blanding’s turtles, especially in the southern extent of their range. Distributions of daily maximum temperature during the summer months are expected to widen and shift towards hotter temperatures with time and under higher emissions scenarios (fig. 15A–F). When looking at the 95th percentiles of the summer daily maximum air temperature, the region of potentially deadly temperatures extends farther north (fig. 16A–F). Under the highest emissions scenario at the end of century, the warmest model projections indicate large parts of Blanding’s turtles’ range are at summer 95th percentile daily maximum temperatures of greater than 38 °C, noted here as the lower bound of the critical thermal tolerance range. Increasing daily maximum temperatures may affect successful development and bias sex distributions but may be mitigated by microclimate refugia and other protections. However, as historical extreme events become closer to future normals, adaptation to extreme temperature effects may be less viable.

Extreme temperatures that approach the critical thermal maximum are expected to increase in frequency with time and under higher emissions scenarios (figs. 17–18). For example, literature indicates a projected increase in extreme heat events in the Great Lakes region under climate change (Lopez and others, 2018). Again, individual exposure to temperatures may vary and adaptive capacity, plasticity of thresholds, and critical exposure duration are unknown.





**Figure 15.** Summer mean daily maximum 2-meter air temperature (in degrees Celsius) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. *A*, early 21st century (2010–39) for RCP4.5; *B*, mid-21st century (2040–69) for RCP4.5; *C*, late 21st century (2070–99) for RCP4.5; *D*, early 21st century (2010–39) for RCP8.5; *E*, mid-21st century (2040–69) for RCP8.5; *F*, late 21st century (2070–99) for RCP8.5. White lines mark the 31-degree-Celsius contour.



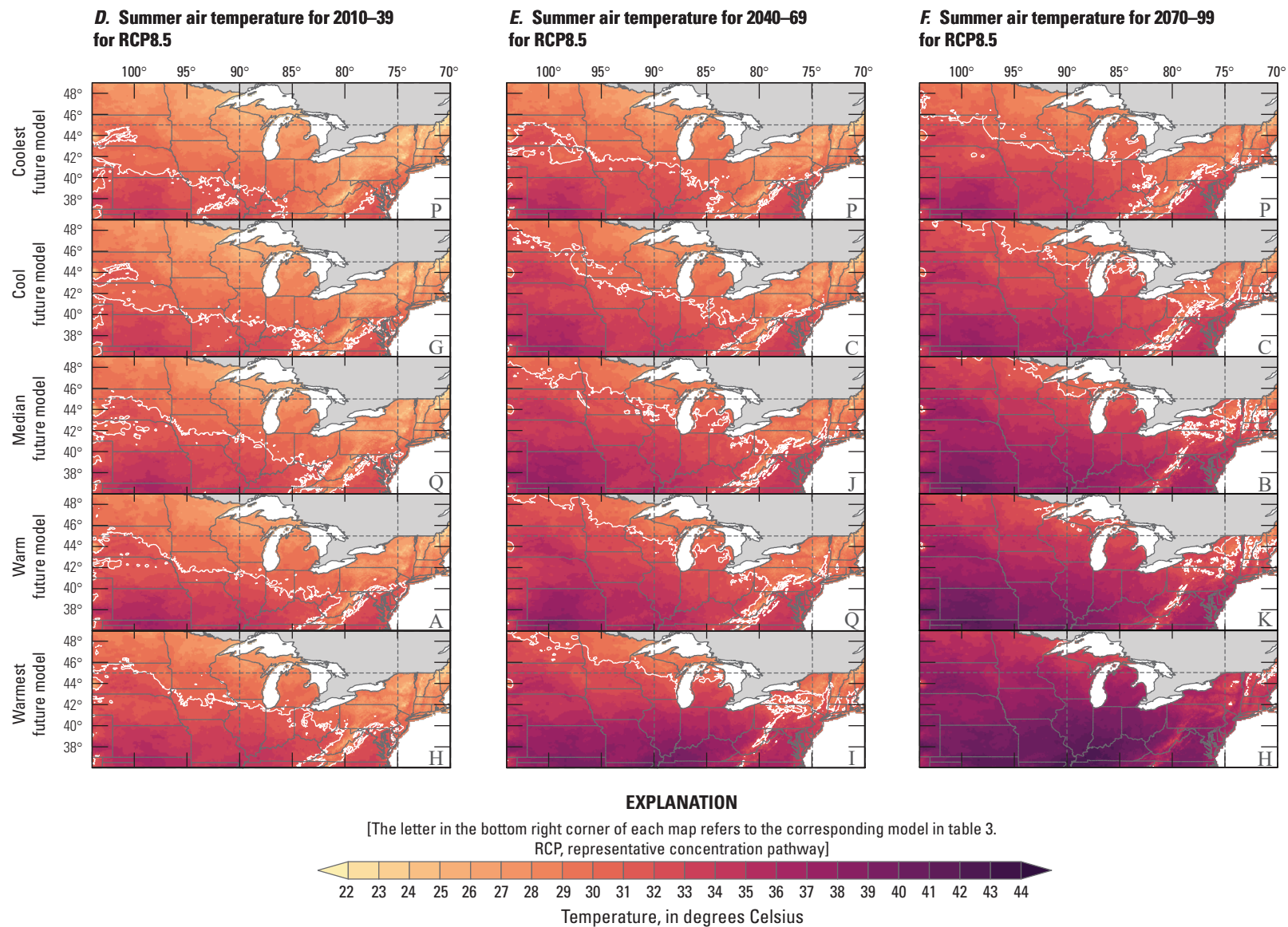
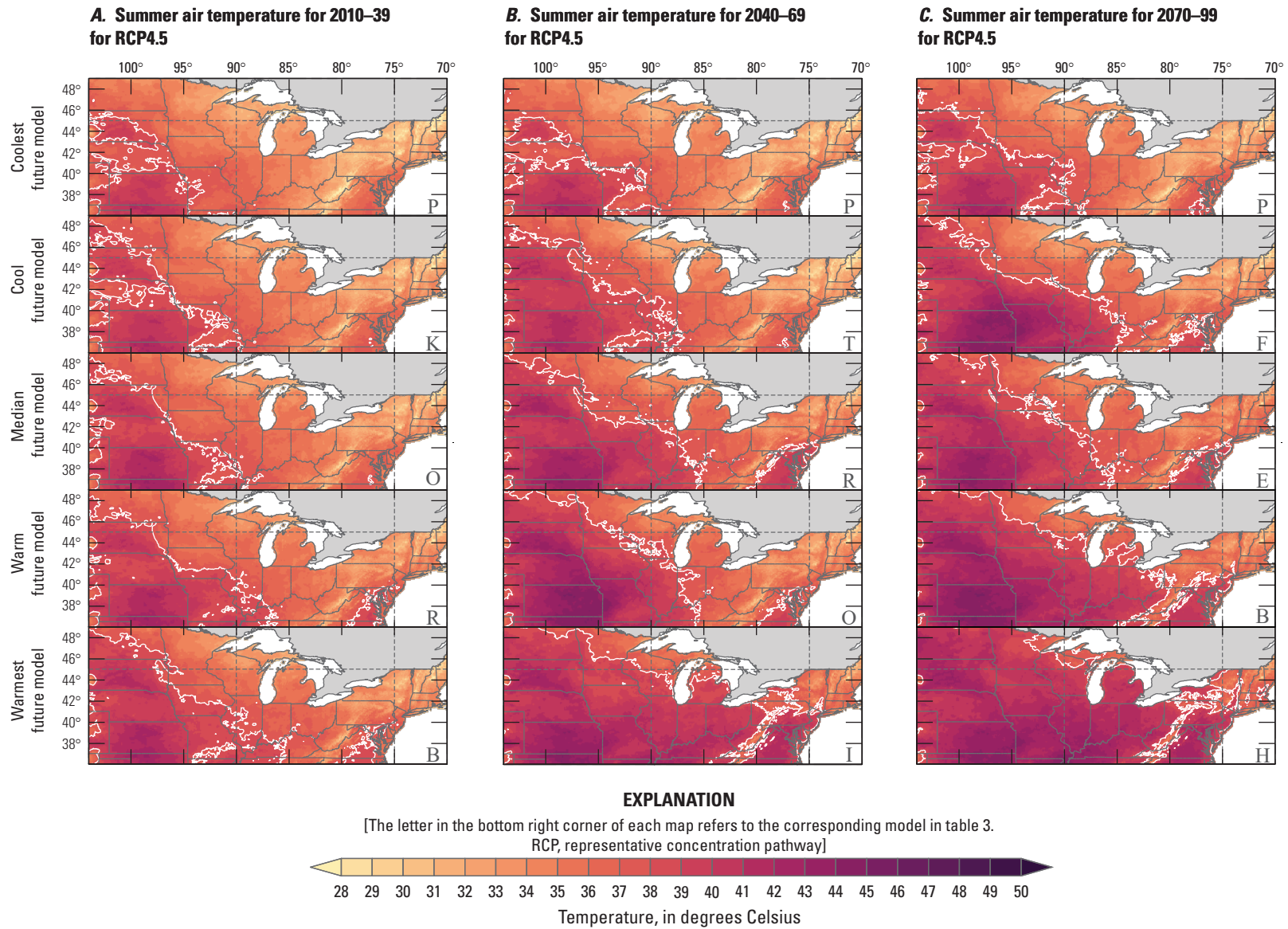
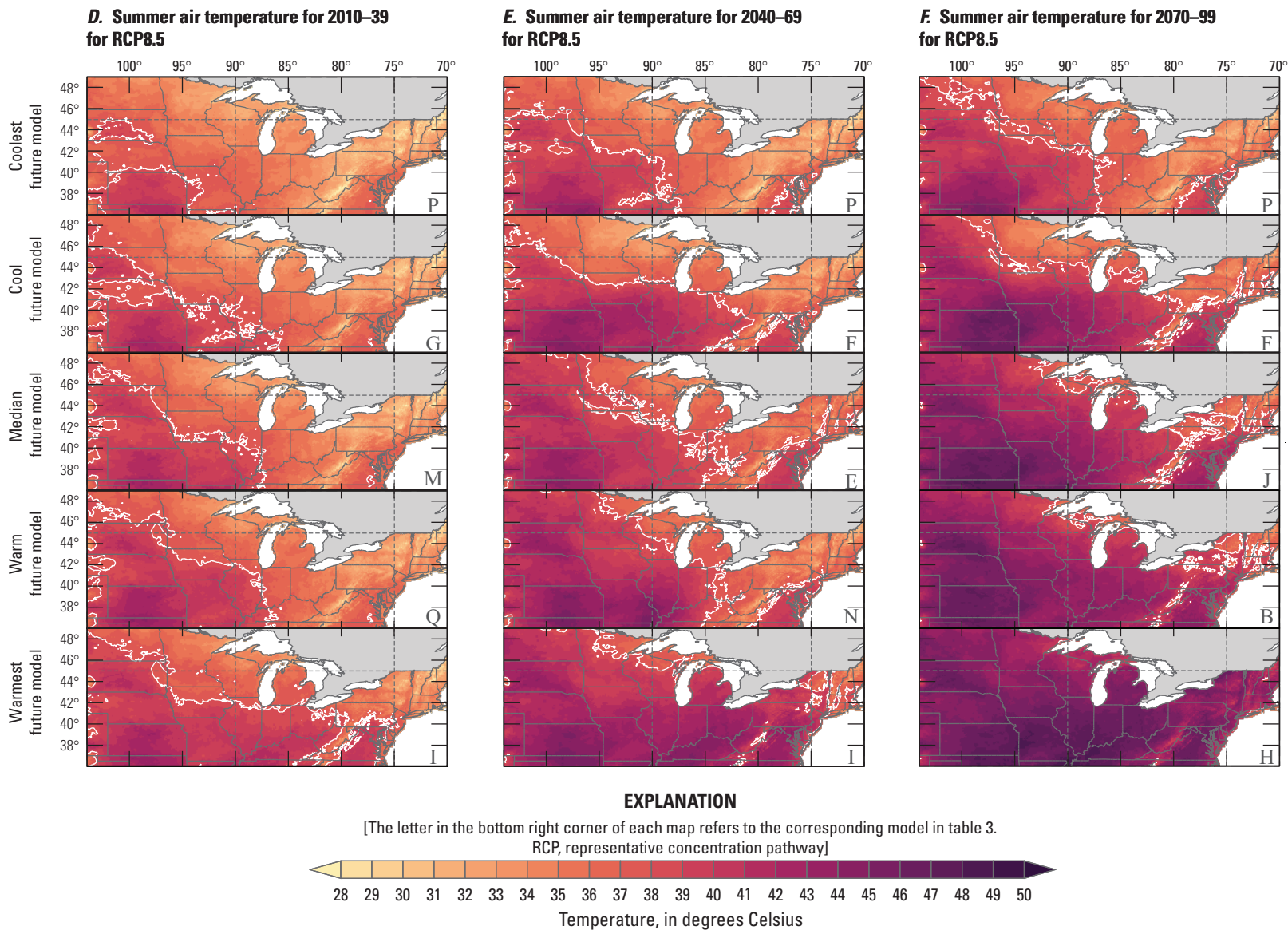


Figure 15.—Continued

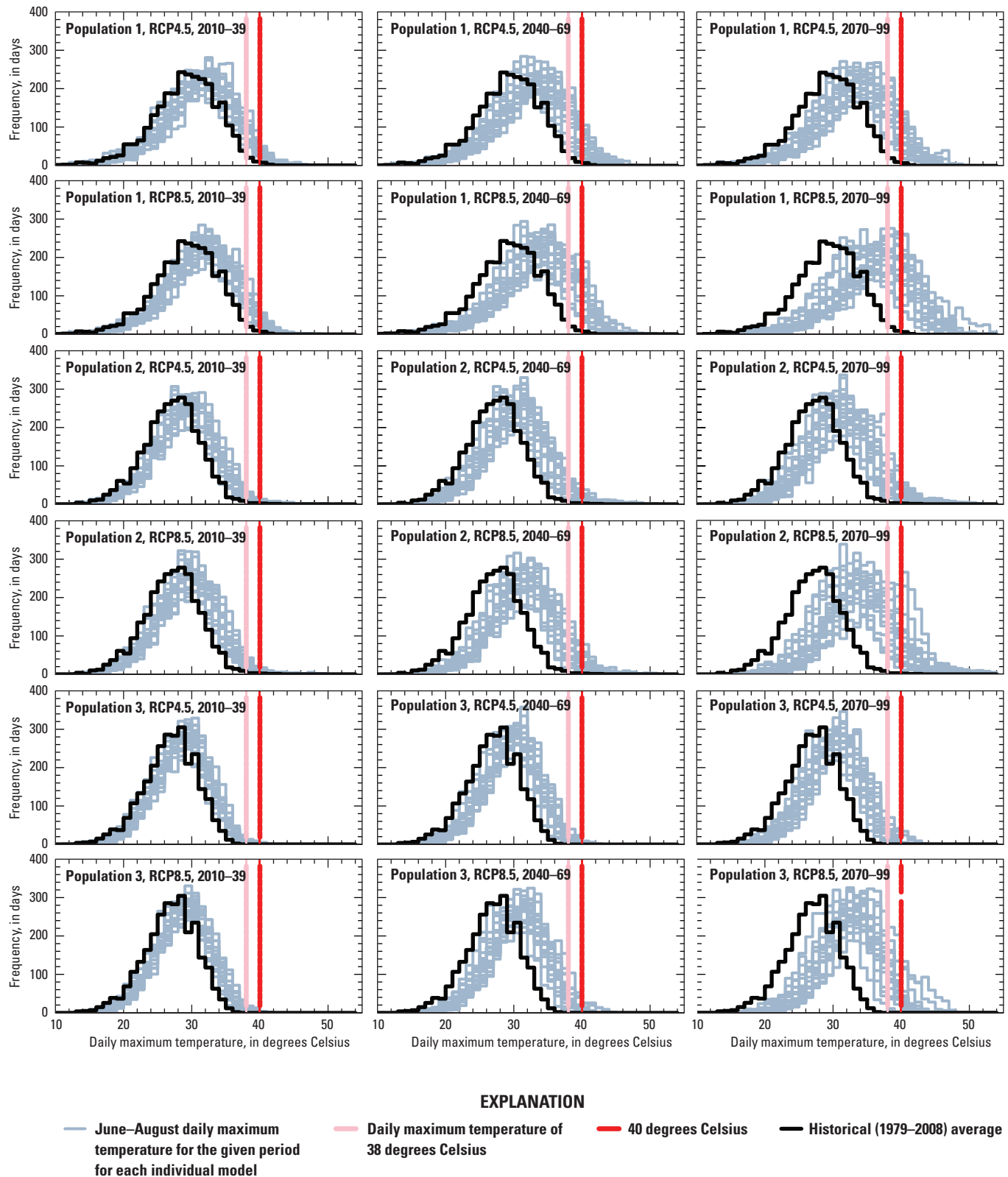


**Figure 16.** Summer 95th-percentile daily maximum 2-meter air temperature (in degrees Celsius) in the downscaled climate simulations under emissions scenarios for representative concentration pathway 4.5 (RCP4.5) and representative concentration pathway 8.5 (RCP8.5) from the historical period (1971–2000) to the future periods. A, early 21st century (2010–39) for RCP4.5; B, mid-21st century (2040–69) for RCP4.5; C, late 21st century (2070–99) for RCP4.5; D, early 21st century (2010–39) for RCP8.5; E, mid-21st century (2040–69) for RCP8.5; F, late 21st century (2070–99) for RCP8.5. White lines mark the 38-degree-Celsius contour.

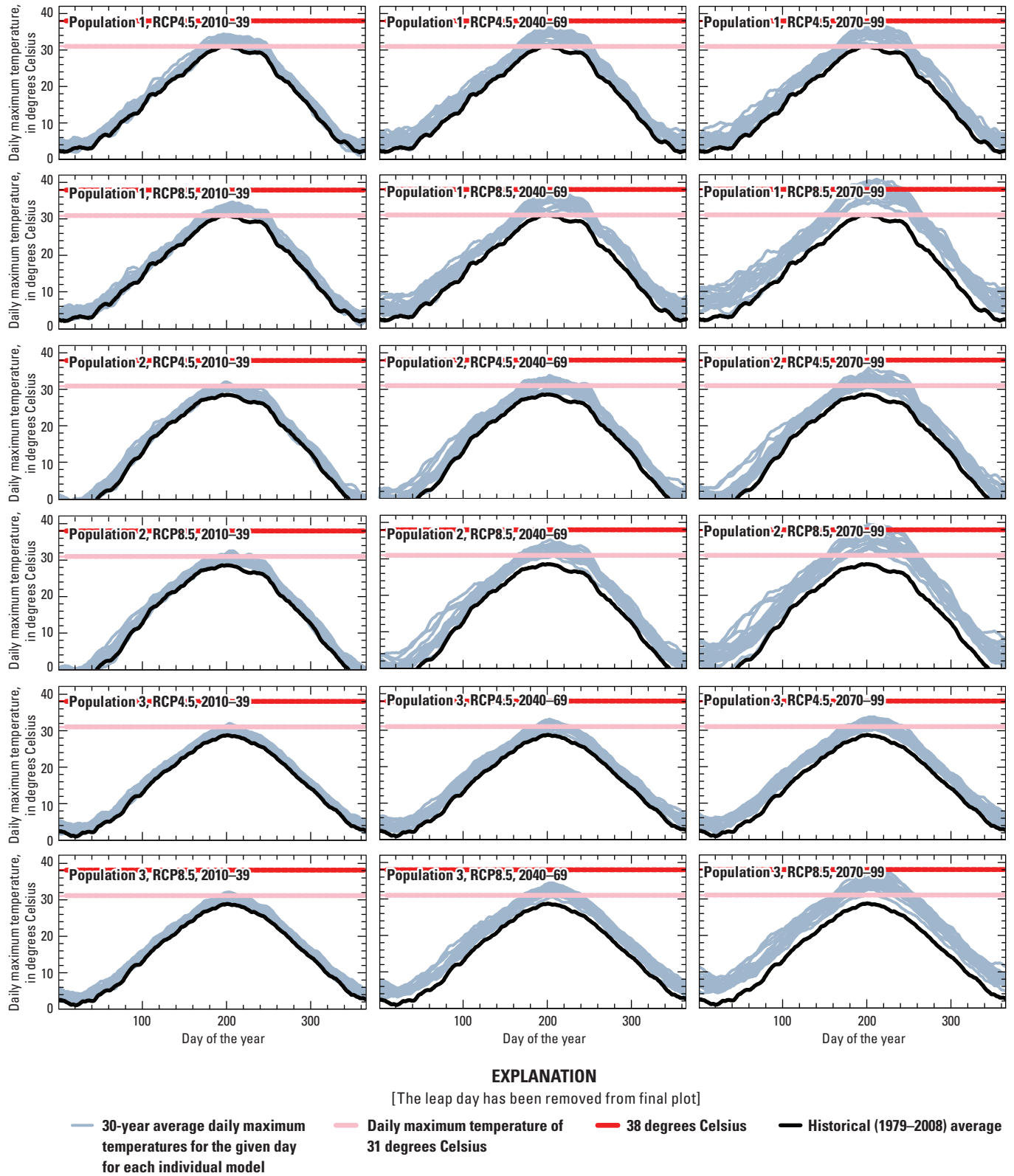


**Figure 16.**—Continued





**Figure 17.** Distribution of summer daily maximum 2-meter air temperatures (in degrees Celsius) in the downscaled climate simulations for the three population areas. The black distribution shows the historical (1979–2008) average for the population area in the METDATA observations. Each blue line shows the June–August daily maximum temperatures for the given period for each individual model. The pink line marks a daily maximum temperature of 38 degrees Celsius, and the red line marks 40 degrees Celsius.



**Figure 18.** Climatology of 14-day running mean daily maximum 2-meter air temperatures (in degrees Celsius) in the downscaled climate simulations for the three population areas. The black distribution shows the historical (1979–2008) average for the population area in the METDATA observations. Each blue line shows the 30-year average daily maximum temperatures for the given day for each individual model. The pink line marks a daily maximum temperature of 31 degrees Celsius, and the red line marks 38 degrees Celsius.

## Aridity

Dry periods in the summer can have multiple effects on Blanding's turtle behavior by limiting foraging habitat, leading to potential reduction in energetic stores and mortality. During food shortages, some Blanding's turtles have been observed to increase movement; this is especially true in females that may require more resources for reproduction (Rowe and Moll, 1991). In search for food resources, Blanding's turtles may be forced to move more among small wetlands rather than remaining in residence in a larger wetland. Low water levels and increased movement increase mortality risks because of road collisions (Ruane and others, 2008) and exposure to predators (Gasbarrini and others, 2021). Hall and Cuthbert (2000) determined that after a summer wetland dry down, Blanding's turtles were significantly more likely to emigrate compared to a control population; half of the radio-tagged turtles from the dried wetland died, compared to no mortality in the control wetland.

## Foraging and Nonnesting Movement Conclusions

Projected higher summer and autumn temperatures may increase the probability or duration of aestivation for adult and juvenile Blanding's turtles. These changes are likely to be costly to energy stores and lead to physiological stress and potential mortality if turtles are forced to forgo important foraging time. In contrast, dry conditions may increase movement by forcing turtles to travel to access suitable foraging or sheltering locations. High summer temperatures, including increases in daily average and extreme (95th percentile) daily maximum temperature, may threaten Blanding's turtles because of their comparatively low thermal tolerance.

## Shifting Distributions

### Blanding's Turtles

Blanding's turtles have low natal dispersal (Reid and others, 2016) and high wetland fidelity (Congdon and others, 2011), and females have nesting site fidelity (Reid and others, 2016). This strong site fidelity, combined with long generation times, may limit adaptive capacity (Hamilton and others, 2018). However, when conditions are poor, Blanding's turtles demonstrate increased movement and wetland seeking behavior (Hall and Cuthbert, 2000), and based on levels of gene flow and documented movement, Blanding's turtles are capable of long-distance dispersal (Reid and others, 2016). Projected northward shifts in suitable habitat, driven by climate and land use change, are anticipated (Hamilton and others, 2018). If accessible, Blanding's turtles may expand their distribution northward, although this process is likely to

be slow; populations at the southern edge of the range may be at higher risk of mismatch between occupancy and suitable habitat (Hamilton and others, 2018).

## Predators, Competitors, Parasites, and Wetland Plants

Other species are likely to shift distributions when tracking suitable climate, leading to new biotic interactions for Blanding's turtles. Gutzke and Packard (1987) hypothesized that the Blanding's turtle southern range limit may result from competitive interactions with other freshwater turtles. These other turtle species may shift northward and compete with Blanding's turtles for wetland habitat and food resources. Mesopredators including *Procyon lotor* (Linnaeus, 1758; raccoons), *Mephitis* (Schreber, 1776; striped skunks), and *Martes americana* (Turton, 1806; American marten) are expected to expand in population size with climate change (Pandey and Papeş, 2018), potentially increasing depredation pressure. *Dasypus novemcinctus* (Linnaeus, 1758; nine-banded armadillos), a species known for turtle nest depredation, already seems to be shifting northward into Illinois (Taulman and Robbins, 2014). Biotic interactions with pathogens also may change with changing climate; stress from warming temperatures and dry conditions may make turtles more vulnerable to disease (Mumm and others, 2019) and parasites (Hall and Cuthbert, 2000). Finally, shifting species distributions also may alter the wetland habitats that Blanding's turtles rely on for foraging and overwintering. Blanding's turtles seem to avoid wetlands with invasive *Phragmites australis* ([Cav.] Trin.ex Steud.; common reeds). Common reed seedlings have greater establishment with warming conditions (Brisson and others, 2008) and are expected to continue spreading in the wetlands used by Blanding's turtles.

## Shifting Distribution Conclusions

Warming is likely to lead to novel biotic interactions among Blanding's turtles and competitors, predators, pathogens, and invasive wetland plants, especially in the southern part of the species' range. Turtles, already physiologically stressed from warming, may be at increased risk in some of these interactions.

## Conclusions

Blanding's turtles demonstrate an annual activity cycle with potential climate-driven changes across all seasons. The main climate drivers, ecological effects, and mechanisms through which they operate are summarized in [table 9](#).

During the overwintering and emergence period (late autumn and winter), changes in cool season precipitation, including snowfall, affect the availability of suitable



overwintering locations and may leave turtles vulnerable to exposure. However, higher winter and spring average and minimum temperatures, a reduction in freezing days, and reduced variability in minimum temperatures may reduce the likelihood of adverse exposure effects on Blanding's turtles. Still, increases in temperature during this period may induce deleterious movement and early emergence. Further study on physiological thresholds in hibernation would aid understanding of climate effects during the overwintering period.

Cool season and warm season precipitation affect the availability and persistence of suitable habitat for spring activity. Reductions in optimal wetland conditions can spur movement, resulting in reduced survival from predation and road mortality. Although increased average precipitation across this region is projected, advanced modeling of wetland dynamics under climate change would inform future availability of optimal habitat for overwintering, foraging, and movement.

For nesting turtles (late spring and summer), extreme precipitation can pose a risk to nests from flooding. Furthermore, as temperatures warm, including higher mean

and maximum summer temperatures, nest success, incubation times, and sex ratios of clutches may all be affected. Turtles also may be exposed to temperatures near their thermal tolerance. Blanding's turtles may demonstrate adaptive capacity, shifting nesting dates, or changing nesting locations. More studies on adaptive capacity across various life stages and the population outcomes of changing sex ratios would inform vulnerability assessments and planning.

This risk from extreme temperatures continues into the summer and autumn foraging and nonnesting movement period. If temperatures are too warm, turtles may enter a period of aestivation during the foraging period. However, if conditions are too dry, increased movement may be necessary and lead to increased predation and road mortality. As predators and pathogens respond to increased temperatures, the risk of negative interspecies interactions increases. More information on shifting community assemblages would inform conservation outcomes for Blanding's turtles and related species.

**Table 9.** Direct and indirect potential effects of climate change on *Emydoidea blandingii* (Holbrook, 1838; Blanding's turtles).

Effect	Climate factor	Direct mechanisms	Indirect mechanisms	Citations
Distribution shift	Changing precipitation amounts and seasonality Increased average temperatures	Thermal tolerance	Habitat availability Road mortality Increased predation	Edge and others (2009); Beaudry and others (2010); Reid and Peery (2014); Hall and Cuthbert (2000); Gutzke and Packard (1987)
Physiological stress	Reduced snowpack depth Minimum winter temperatures and variability Increased winter and spring average temperatures Changing precipitation amounts and seasonality	Exposure (freezing/desiccation) Cost of movement	Overwintering habitat availability	Pappas and others (2009); Ruane and others (2008); Newton and Herman (2009); Markle and Chow-Fraser (2014)
Reproductive stress	Spring and summer temperature increases Extreme precipitation events	Shorter incubation periods Skewed sex ratios • Buffered by earlier nesting and choice in nesting site Reduced nest success • Buffered by earlier nesting and choice in nesting site	Habitat suitability Increased predation • Buffered by shorter incubation Increased flooding/drought	Buckardt and others (2020); Joyal and others (2000); Byer and others (2020); Gutzke and Packard (1987); Congdon and Keinath (2006); Congdon and others (2000); Reid and Peery (2014); Ruane and others (2008); Pandey and Papeş (2018); Taulman and Robbins (2014); Roberts and others (2023)
Reduced survival	Changing precipitation amounts and seasonality Increased summer temperatures	Thermal tolerance Increased aestivation	Habitat availability/suitability Road mortality • Buffered by increased wetland connectivity in wet years Interspecific dynamics	Beaudry and others (2010); Reid and Peery (2014); Compton (2007); Kofron and Schreiber (1985); Mumm and others (2019)

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