# Development of a New USDA Plant Hardiness Zone Map for the United States

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ABSTRACT

In many regions of the world, the extremes of winter cold are a major determinant of the geographic distribution of perennial plant species and of their successful cultivation. In the United States, the U.S. Department of Agriculture (USDA) Plant Hardiness Zone Map (PHZM) is the primary reference for defining geospatial patterns of extreme winter cold for the horticulture and nursery industries, home gardeners, agrometeorologists, and plant scientists. This paper describes the approaches followed for updating the USDA PHZM, the last version of which was published in 1990. The new PHZM depicts 1976–2005 mean annual extreme minimum temperature, in 2.8°C (5°F) half zones, for the conterminous United States, Alaska, Hawaii, and Puerto Rico. Station data were interpolated to a grid with the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) climate-mapping system. PRISM accounts for the effects of elevation, terrain-induced airmass blockage, coastal effects, temperature inversions, and cold-air pooling on extreme minimum temperature patterns. Climatologically aided interpolation was applied, based on the 1971–2000 mean minimum temperature of the coldest month as the predictor grid. Evaluation of a standard-deviation map and two 15-yr maps (1976–90 and 1991–2005 averaging periods) revealed substantial vertical and horizontal gradients in trend and variability, especially in complex terrain. The new PHZM is generally warmer by one 2.8°C (5°F) half zone than the previous PHZM throughout much of the United States, as a result of a more recent averaging period. Nonetheless, a more sophisticated interpolation technique, greater physiographic detail, and more comprehensive station data were the main causes of zonal changes in complex terrain, especially in the western United States. The updated PHZM can be accessed online (http://www.planthardiness.ars.usda.gov).

## 1. Introduction

Accurate prediction of winter injury is a key component to the successful cultivation and survival of long-lived woody and herbaceous perennial plants in many regions of the world. The frequency and severity of winter injury are also important determinants in the natural distributions of many temperate plants (George et al. 1974; Sakai and Weiser 1973; Sakai and Larcher 1987). Low-temperature injury typically occurs at three stages in the annual cycle (Larcher 2005): during autumn, when plants begin to harden or acclimate to winter conditions; during late winter and early spring, when plants may de-harden, having satisfied physiological rest requirements; and during the lowest temperatures of midwinter, when unusually frigid temperatures may overwhelm a plant's maximal degree of cold acclimation. Of course, there are unusual circumstances when even relatively mild, but atypical, freeze events cause significant damage to unacclimated plants actively growing during the normal growing season.

In many temperate woody plants, adaptation responses often involve physiological changes that lower the freezing point of cellular contents. In most plants, adaptation

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responses to cold have finite limits, usually at or above the homogeneous nucleation point of water in cell solutes, from −41° to −47°C (Sakai and Larcher 1987). However, boreal and arctic species that rely on dehydration and extraorgan freezing can survive to even lower temperatures (Sakai and Larcher 1987).

Of the three stages when injury may occur, the frequency and severity of midwinter, low-temperature events have historically received considerable attention by plant scientists. Heinze and Schreiber (1984) presented an overview of the use of long-term climatological data to relate patterns of woody-plant adaptation to low-temperature injury. One relatively simple method to visualize geographic patterns of the severity of low-temperature events is to map a climatological variable closely correlated with patterns of plant survival. The first such map for the United States was developed by Rehder (1927), who created a mapped zonation system to relate winter minimum temperatures to the hardiness of specific woody plants. He roughly divided the temperate portion of the conterminous United States and southern Canada into eight zones based on the mean temperature of the coldest month, each zone spanning a range of 2.8°C (5°F).

Shortly thereafter, Kincer (1928) produced a similar map for the conterminous United States for the U.S. Department of Agriculture (USDA), but based on mean annual extreme minimum temperature [the lowest temperature recorded in a year, herein referred to as the plant hardiness (PH) statistic] scaled by 5.6°C (10°F) intervals and lacking formal zone designations. In 1936, a slightly different approach was taken by Wyman, who drew a revised plant hardiness map based on the PH statistic averaged over 1895–1935. However, Wyman's zones were not based on consistent temperature intervals; some were 2.8°C (5°F), and others were 5.6°C (10°F) or 8.3°C (15°F). Wyman's map and subsequent updates using more recent meteorological data were published in 1951, 1967, and 1971 (see Wyman and Flint 1985).

Lack of uniformity in zone intervals prompted the USDA Agricultural Research Service (ARS) to develop its own "Plant Hardiness Zone Map" (PHZM) with uniform 5.6°C (10°F) zones based on the PH statistic (USDA 1960, 1965). Discrepancies between the zone designations of Wyman's and USDA's maps caused some confusion, but the USDA's consistent zone designations became the standard for assessing plant hardiness in the United States.

The most recent comprehensive update of the USDA PHZM was released in 1990 (Cathey 1990; Cathey and Heriteau 1990). This version was based on the PH statistic for the United States, Canada, and Mexico. The map included 10 zones of 5.6°C (10°F), with zones 2–10 subdivided into 2.8°C (5°F) half zones. Zone 11 was introduced to represent areas with PH > 4.4°C (40°F) that are essentially freeze free. Little information is available describing mapping protocols applied to develop the 1990 PHZM. It was based on approximately 8000 stations in the United States, Canada, and Mexico. In the United States, the map relied on National Weather Service (NWS) Cooperative Observer Program (COOP) stations. Extreme annual minimum temperatures were averaged over 1974–1986 in the United States and Canada and from 1971 to 1984 in Mexico (Cathey and Heriteau 1990). The map was not prepared digitally (it was manually drawn), limiting its distribution to paper copy and scanned graphics. An attempt was made to update the 1990 PHZM in 2003 (Ellis 2003), but preliminary efforts relied on outdated methods, leading to a draft map that was not adopted by USDA-ARS.

In 2004, USDA-ARS renewed efforts to update the 1990 map, with a goal of meeting modern standards of geostatistical analysis, accuracy, and resolution. A technical review team (TRT)—including representatives from the horticulture and nursery industries, public gardens, agro-meteorologists, climatologists, and plant scientists—was convened to develop technical guidelines and suggest ways to present the resulting information, maximizing its value to researchers, the green industry, and gardeners. Once guidelines were established, the TRT also reviewed all draft map products, and additional plant scientists and climatologists with specialized regional expertise were added to the team to ensure complete geographic coverage. The TRT took a flexible, multidisciplinary approach, incorporating input, through physical meetings, conference calls, and electronic media, from horticultural industry and professional organizations, such as the American Horticultural Society, the American Nursery and Landscape Association, and the American Public Gardens Association, as well as from within USDA and academic communities.

The TRT recommended that a new PHZM be created by incorporating the most recent and accurate meteorological data and applying the most advanced interpolation methods and that it focus only on plant hardiness in the United States, as measured by the PH statistic. The TRT recognized that many other datasets were available, offering considerable insight into the geographic patterning of factors related to plant adaptation, but decided to retain the PH statistic, given its widespread adoption, including the availability of estimates of winter hardiness for thousands of plants and the extent of compatible hardiness-zone maps available internationally [e.g., Australia (Dawson 1991), China (Widrlechner 1997), Europe (Heinze and Schreiber 1984), Japan (Hayashi 1990), and Ukraine (Widrlechner et al. 2001)]. In 2007, Oregon State University's Parameter-Elevation Regressions on Independent Slopes Model (PRISM) Climate Group was subsequently given the task of developing the updated PHZM by USDA-ARS.

This paper describes the technical aspects of this project to develop an updated PHZM. Section 2 defines the plant hardiness statistic and averaging periods analyzed. Section 3 describes the sources and processing of station data. Section 4 discusses the interpolation method applied and summarizes the modeling, review, and revision process. Section 5 presents the resulting PHZM, discusses model performance, compares the new PHZM with that from 1990, and discusses variability and trends in the PH statistic. Section 6 presents concluding remarks.

## 2. Definitions and averaging periods

The PHZM update retains the annual extreme minimum temperature (i.e., lowest daily minimum temperature of the year), averaged over a given period of years, as its PH statistic. The averaging period 1976–2005 was chosen because it represented the most recent 30-yr period for which there were reasonably complete data at the time. This had certain advantages over the standard 1971–2000 climatological period in that it included five years of record for more recently installed stations, and better reflected recent conditions. A 30-yr period was chosen instead of a shorter period because it is more stable statistically, samples recent climatological variation more completely, and yields a clearer picture of the role that past winters have played in the survival of long-lived plants.

To enable reviewers to assess temporal trends and variability, the TRT requested that three ancillary maps be prepared: two 15-yr PH statistic maps based on 1976–1990 and 1991–2005, respectively, and a standard-deviation map of the 1976–2005 PH statistic. Information gleaned from the ancillary maps is summarized in section 5. The annual period (“PH year”) is defined as 1 July of year 1 through 30 June of year 2. The PH year is designated by the ending year (e.g., 1 July 1975 through 30 June 1976 is PH year 1976). Therefore, the actual period covered by the 1976–2005 PHZM is 1 July 1975–30 June 2005. The updated PHZM is divided into 13 5.6°C (10°F) “full” zones and 26 2.8°C (5°F) “half” zones (Table 1), an expansion of zones offered in the 1990 PHZM.

TABLE 1. Comparison of the updated and 1990 PHZM zone temperature ranges. Full 5.6°C (10°F) zones are defined by the numbers 1–13. These are separated into 2.8°C (5°F) half zones, denoted by an a or b.

| 1990 zones | Updated zones | Temperature range °C | Temperature range °F |
|---|---|---|---|
| 1 | 1a | −51.1 to −48.3 | −60 to −55 |
| 1 | 1b | −48.3 to −45.6 | −55 to −50 |
| 2a | 2a | −45.6 to −42.8 | −50 to −45 |
| 2b | 2b | −42.8 to −40.0 | −45 to −40 |
| 3a | 3a | −40 to −37.2 | −40 to −35 |
| 3b | 3b | −37.2 to −34.4 | −35 to −30 |
| 4a | 4a | −34.4 to −31.7 | −30 to −25 |
| 4b | 4b | −31.7 to −28.9 | −25 to −20 |
| 5a | 5a | −28.9 to −26.1 | −20 to −15 |
| 5b | 5b | −26.1 to −23.3 | −15 to −10 |
| 6a | 6a | −23.3 to −20.6 | −10 to −5 |
| 6b | 6b | −20.6 to −17.8 | −5 to 0 |
| 7a | 7a | −17.8 to −15 | 0–5 |
| 7b | 7b | −15 to −12.2 | 5–10 |
| 8a | 8a | −12.2 to −9.4 | 10–15 |
| 8b | 8b | −9.4 to −6.7 | 15–20 |
| 9a | 9a | −6.7 to −3.9 | 20–25 |
| 9b | 9b | −3.9 to −1.1 | 25–30 |
| 10a | 10a | −1.1 to 1.7 | 30–35 |
| 10b | 10b | 1.7–4.4 | 35–40 |
| 11 | 11a | 4.4–7.2 | 40–45 |
| 11 | 11b | 7.2–10.0 | 45–50 |
| — | 12a | 10.0–12.8 | 50–55 |
| — | 12b | 12.8–15.6 | 55–60 |
| — | 13a | 15.6–18.3 | 60–65 |
| — | 13b | 18.3–21.1 | 65–70 |

## 3. Station data

### a. Sources

Station observations of daily surface minimum temperature were obtained for the United States, Mexico, and Canada (Table 2; Fig. 1). Data sources in the United States included stations from the following networks: NWS COOP and Weather Bureau–Army–Navy (WBAN), USDA Natural Resources Conservation Service Snow Telemetry (SNOTEL), USDA Forest Service and Bureau of Land Management Remote Automatic Weather Stations (RAWS), and Bureau of Reclamation AgriMet. Canadian data were obtained from Environment Canada. Mexican data were obtained from the National Climatic Data Center (NCDC) Global Historical Climatology Network (daily and global summary of the day) and the International Research Institute’s climate data library. The COOP network had by far the most stations, which are operated primarily by volunteer observers and are typically located in habitable areas. The SNOTEL automated network is designed to observe conditions in the snow zones of the western United States and provided critical data for high-elevation regions. The RAWS automated network focuses primarily on fire-weather conditions and provided much-needed data at middle elevations between COOP and SNOTEL stations. AgriMet automated stations provided high-quality data in agricultural regions of the Pacific Northwest. In total, data from 7983 stations were accepted for analysis: 6418 in the conterminous United States, 32 in Puerto Rico, 52 in Hawaii, 145 in Alaska, 1111 in Canada, and 225 in Mexico (Table 2).

TABLE 2. Stations used in the PHZM, by mapping region. See text for definitions of source acronyms.

| Source | No. of stations | URL |
|---|---|---|
| Conterminous United States | | |
| COOP | 5686 | http://cdo.ncdc.noaa.gov/CDO/cdo/ |
| SNOTEL | 583 | http://www.wcc.nrcs.usda.gov/snow/ |
| RAWS | 105 | http://www.wrcc.dri.edu/ |
| Agrimet | 44 | http://www.usbr.gov/pn/agrimet/ |
| Canada (border areas) | 1046 | http://climate.weatheroffice.ec.gc.ca |
| Mexico (border areas) | 225 | ftp://ftp.ncdc.noaa.gov/pub/data/ghcn<br>ftp://ftp.ncdc.noaa.gov/pub/data/gsod<br>http://iridl.ldeo.columbia.edu |
| Total | 7689 | |
| Puerto Rico | | |
| COOP | 32 | http://cdo.ncdc.noaa.gov/CDO/cdo/ |
| Total | 32 | |
| Hawaii | | |
| COOP | 49 | http://cdo.ncdc.noaa.gov/CDO/cdo/ |
| WBAN | 3 | http://cdo.ncdc.noaa.gov/CDO/cdo/ |
| Total | 52 | |
| Alaska | | |
| COOP | 133 | http://cdo.ncdc.noaa.gov/CDO/cdo/ |
| SNOTEL | 12 | http://www.wcc.nrcs.usda.gov/snow/ |
| Canada | 65 | http://climate.weatheroffice.ec.gc.ca |
| Total | 210 | |
| Grand total | 7983 | |

### b. *Data processing*

Station data were obtained mainly at a daily time interval. Valid annual minimum temperature values were calculated only for stations with at least 24 nonmissing days (80%) during each of the months of October–March. Our 80% monthly data completeness criterion resembles those used by NCDC (NCDC 2003) and the World Meteorological Organization (WMO; WMO 1989) in developing monthly temperature statistics. Stations having fewer than 10 years of data satisfying these monthly criteria were rejected. Station data passing the completeness tests were subjected to several quality-control (QC) procedures, as outlined in Daly et al. (2008, their section 3.2).

Subsequent to QC, station data were averaged to create 1976–2005 monthly means and standard deviations. A 1976–2005 mean annual minimum temperature calculated from at least 23 of these 30 years (75% data coverage) was considered to be sufficiently characteristic and was called a ''long term'' station. However, many stations had a period of record (POR) with fewer than 23 years. It was advantageous to retain such stations for analysis because they often contributed to the interpolation process at critical locations. To minimize temporal biases, POR means for short-term stations were adjusted to the 1976–2005 period. The same adjustment procedure was used to adjust means for the two 15-yr periods, except that the data completeness threshold was set to 12 years. A full discussion of the adjustment process is given in Daly et al. (2008, their appendix A). As a final step, 30-yr average and standard deviation station files and 15-yr average station files were cross-checked; stations that did not appear in all files were removed. Incorporating a common set of stations for all maps ensured that differences among maps for different time periods would be primarily climate driven rather than resulting from differences in station selection or interpolation.

A data deletion exercise was performed to ensure that that our data completeness criteria did not introduce substantial errors into the PH statistic calculations. We started with 83 stations from our dataset having valid data for every day for every month (during October–March) for the entire 1976–2005 period. Omitting all possible combinations of years to achieve 12 valid years in each 15-yr period (24 in a 30-yr period, similar to our 23-of-30-yr criterion) resulted in a mean absolute error (MAE) of 0.22°C when compared with the full dataset. The same yearly deletion exercise was then repeated, but with days randomly omitted from each month to achieve 24 valid days per month; this was done 30 times and the results were averaged. The MAE for the same yearly deletion dataset (12 of 15 and 24 of 30 years) increased from 0.20° to 0.62°C when compared with the full dataset, indicating that our data completeness criteria introduced relatively small errors into the PH calculations.

## 4. Mapping methods

### a. *The PRISM climate-mapping system*

The 1976–2005 PHZM and ancillary maps were produced with the latest version of PRISM, a well-known climate-mapping technology that has been used to generate official USDA 1961–90 digital climate normal grids and 1971–2000 updates (Daly et al. 1994, 2002, 2008; Daly 2006). PRISM develops local regression functions (one for each grid cell) between a predictor grid of an explanatory variable, such as elevation, and the climate element being modeled, for every grid cell in a domain. Surrounding stations, weighted by their physiographic similarity to the grid cell being modeled, populate the regression function. PRISM accounts for the effects of elevation, terrain-induced airmass blockage, coastal proximity, temperature inversions, and cold-air pooling on extreme minimum temperature patterns (Daly et al. 2008). More information on PRISM can be obtained online (see http://prism.oregonstate.edu).

### b. *Climatologically aided interpolation*

There is a very strong correlation between coldest-month mean minimum temperature and the PH statistic (e.g., Fig. 2). This correlation is much stronger than that

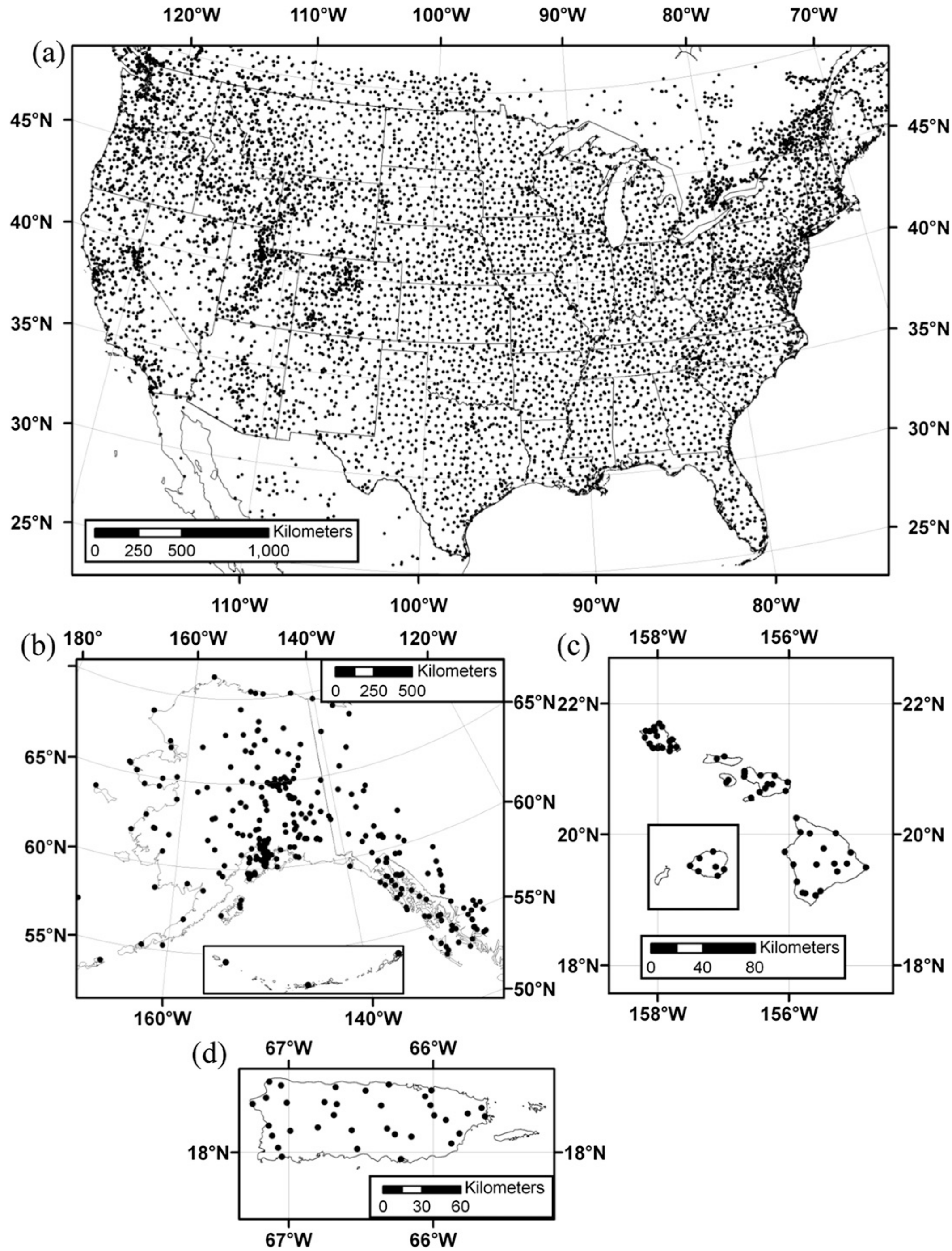


FIG. 1. Locations of stations providing data for the PHZM: (a) conterminous United States, (b) Alaska, (c) Hawaii, and (d) Puerto Rico.

between the PH statistic and elevation (e.g., Fig. 3), because the mean minimum temperature already reflects complex minimum temperature interactions with elevation (e.g., varying lapse rates, cold-air pooling, inversions, and coastal effects). Therefore, a procedure known as climatologically aided interpolation (CAI; Willmott and Robeson 1995; Daly 2006) was applied to develop the new PHZM. CAI involves using a high-quality mean climatological dataset as the predictor grid (independent variable in the moving-window regression function) instead of a digital elevation model. This method relies on the assumption that local spatial patterns of the element

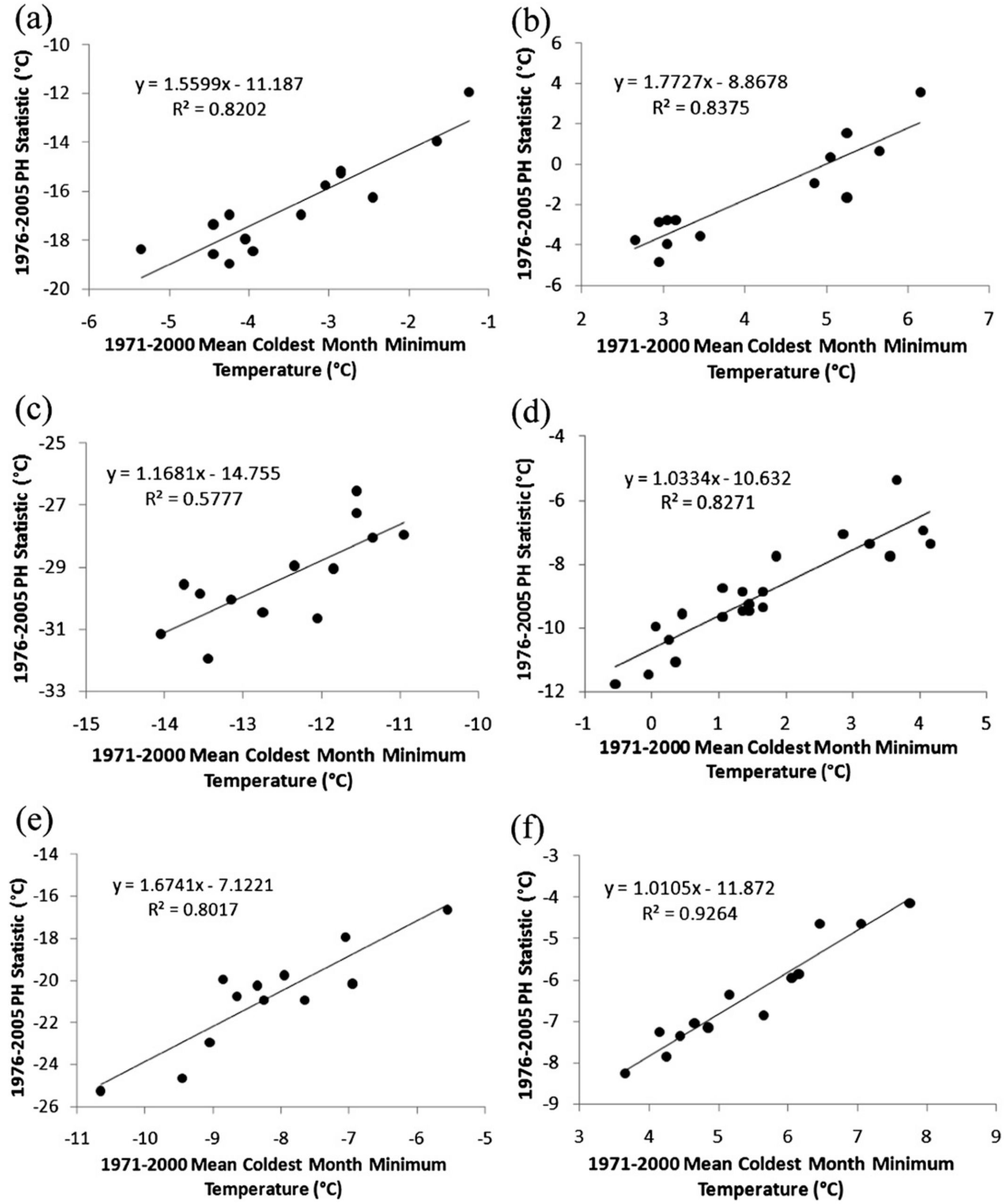


FIG. 2. Local linear relationships between observed 1976–2005 PH statistic (mean annual extreme minimum temperature) and 1971–2000 mean coldest-month minimum temperature from an 800-m PRISM grid, for stations in the vicinity of (a) the Columbia River east of The Dalles, OR; (b) Sonoma, CA; (c) Rapid City, SD; (d) San Antonio, TX; (e) Allentown, PA; and (f) Jacksonville, FL. These relationships are stronger than those between the PH statistic and elevation (see Fig. 3, below).

being interpolated closely resemble those of an existing climatic grid. This method is useful for interpolating climatic variables for which station data may be relatively sparse. In the conterminous United States, the predictor grid for PHZM interpolation was derived from the latest (May 2007) version of the PRISM 30-arc-s (~800 m) resolution, 1971–2000 mean monthly minimum-temperature grids (Daly et al. 2008). These peer-reviewed grids incorporate the complex variations in minimum temperature caused by cold-air pooling, coastal effects, terrain blocking and others, and thus are effective predictor grids for interpolation. The final predictor grid was created by finding the lowest mean monthly minimum temperature for each cell. This

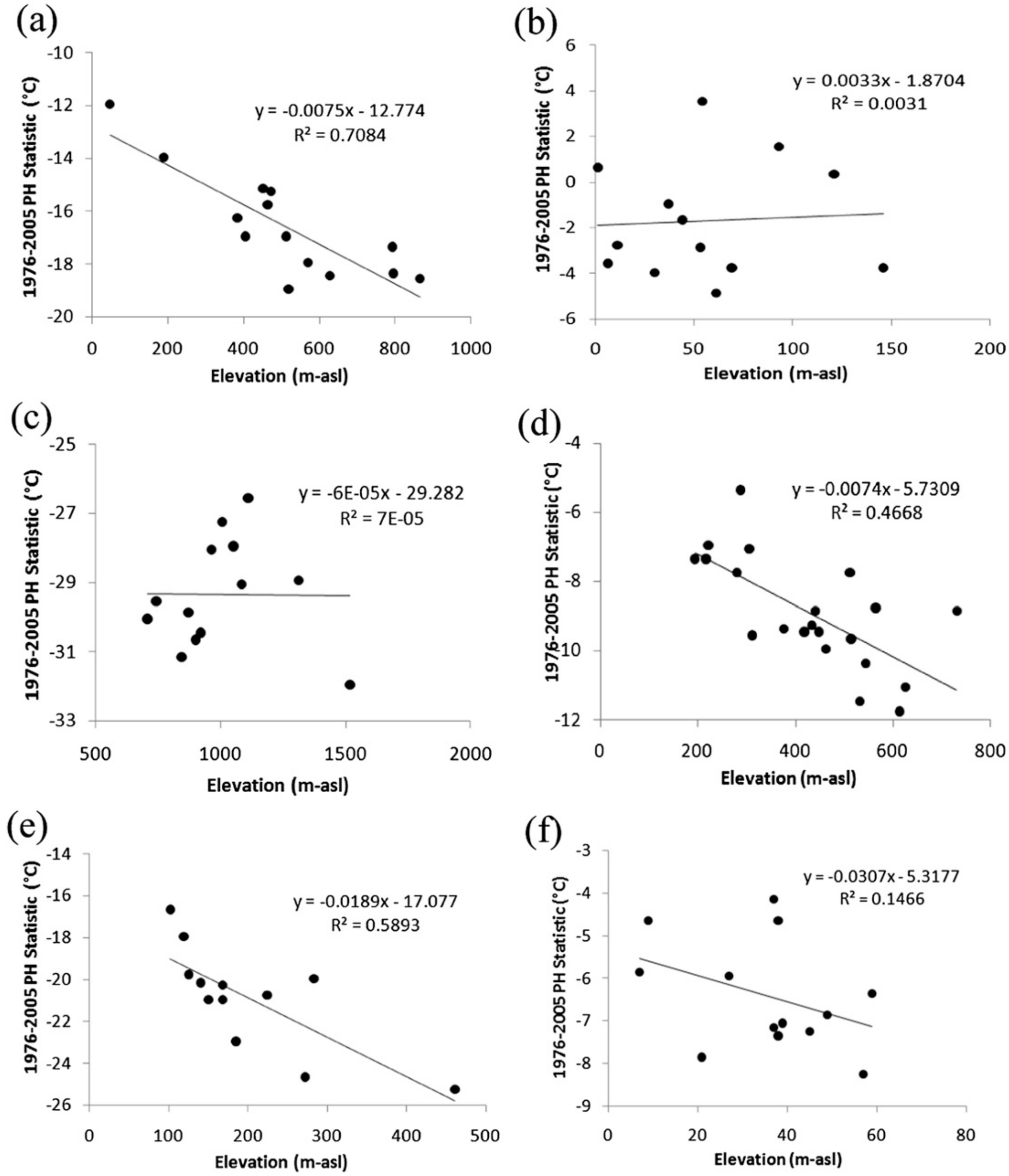


FIG. 3. As in Fig. 2, but for local linear relationships between the observed 1976–2005 PH statistic (mean annual extreme minimum temperature) and elevation from an 800-m digital elevation model. These relationships are not as strong as those between the PH statistic and the coldest-month minimum temperature (see Fig. 2).

typically occurred in December or January but was occasionally in February or March.

### c. *Mapping regions*

Interpolation for the conterminous-U.S. PHZM was performed separately for the western, central, and eastern United States, and the resulting grids were merged to form a conterminous-U.S. grid at 30-arc-s (~800 m) resolution. The extent of gridded data coverage matched that of the 1971–2000 mean coldest-month minimum temperature grid (Daly et al. 2008).

Interpolation was performed separately for Puerto Rico, Hawaii, and Alaska. Puerto Rico mapping used a 15-arc-s (~400 m) PRISM 1963–95 mean coldest-month minimum temperature dataset (Daly et al. 2003) as the CAI predictor grid, and Hawaii used a 15-arc-s 1971–2000 mean coldest-month minimum temperature grid (http://nrinfo.nps.gov). Alaska mapping was based on a 2.5-arc-min

(~4 km) 1961–90 mean coldest-month minimum temperature grid (Simpson et al. 2005, 2007). Variation in averaging periods among the predictor grids is insignificant because only relative spatial variation in the predictor grid is used in CAI, and these spatial patterns are not likely to vary appreciably among overlapping 30-yr averaging periods.

### d. 15-yr maps

Maps of the PH statistic with averaging periods of 1976–90 and 1991–2005, respectively, were produced for the conterminous United States, Puerto Rico, Hawaii, and Alaska. The same stations, POR adjustment procedures, and interpolation methods used in the 1976–2005 PHZM development were also applied in these analyses to ensure maximum comparability.

### e. Standard deviation maps

Maps of the standard deviation of the 1976–2005 PH statistic were produced for the conterminous United States, Puerto Rico, Hawaii, and Alaska, on the basis of the same stations included in the PHZM interpolation. Standard deviations were calculated from the frequency distribution of the PH statistic for 1976–2005 and were adjusted for short POR as described in section 3b herein and in Daly et al. (2008, their appendix A).

A preliminary interpolation of the standard deviation map was performed with the CAI PRISM method based on the 1971–2000 mean coldest-month minimum temperature grid, the same method used for interpolation of the PH statistic. This was compared with PRISM interpolation using elevation as the predictor variable. The standard deviation was more strongly correlated to the coldest-month minimum temperature and resulted in lower interpolation errors; thus, the 1971–2000 mean coldest-month minimum temperature grid was used for interpolation of the PH standard deviation. The relationship between the minimum-temperature grid and PH standard deviation was not nearly as strong as its relationship with the mean PH statistic but was sufficiently associated for mapping purposes. For example, Fig. 4 shows a negative relationship between 1971–2000 mean January minimum temperature and standard deviation in the southwestern Wyoming lowlands, where cold-air pooling and temperature inversions are common. In the intermountain region, where cold-air pooling is frequent, the standard deviation was often relatively high in the cold lowland areas and was lower in adjacent and warmer highlands near and above inversion layers (see section 5e for an example).

### f. Map review and revision

Draft PHZMs were developed for each region (conterminous United States, Puerto Rico, Hawaii, and Alaska) and were presented to the TRT and selected local experts for review. Comments from the TRT, submitted electronically via Internet map server, led to many refinements, including adding Canadian and Mexican stations to improve zone definitions near national borders, modifying the PRISM interpolation parameters to increase local detail, and sharpening the delineation of coastal zones.

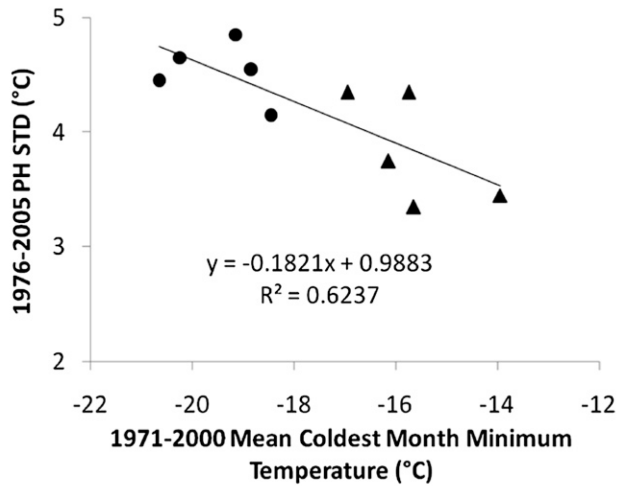


FIG. 4. Local linear relationship between the standard deviation of the 1976–2005 PH statistic (mean annual extreme minimum temperature) and the 1971–2000 mean coldest month minimum temperature, observed at stations in the vicinity of Big Piney, WY. Relatively cold valley-bottom stations (dots), subject to cold-air pooling, exhibit somewhat greater variability in the PH statistic than do nearby mountain stations (triangles) above the cold-air pool.

## 5. Results and discussion

### a. General features

The 1976–2005 PHZM for all regions is shown in Fig. 5; a key to the zones is given in Table 1 and zone designations for major metropolitan areas are given in Table 3. This updated PHZM can be accessed online (http://www.planthardiness.ars.usda.gov). The latitudinal delineation of zones can be clearly seen in the central part of the conterminous United States. The eastern United States has somewhat similar latitudinal patterns, but they are mediated by elevational and coastal influences. For example, zone 6a extends southward along the Appalachian Mountains into northern Georgia but also extends along the Atlantic coastline as far north as Maine. A combination of latitudinal and coastal influences allows for extremely mild zones that are essentially freeze free in southern Florida.

Zone patterns in the western United States are dominated by relatively mild marine influences along the West Coast, elevational effects in the mountains, and cold-air

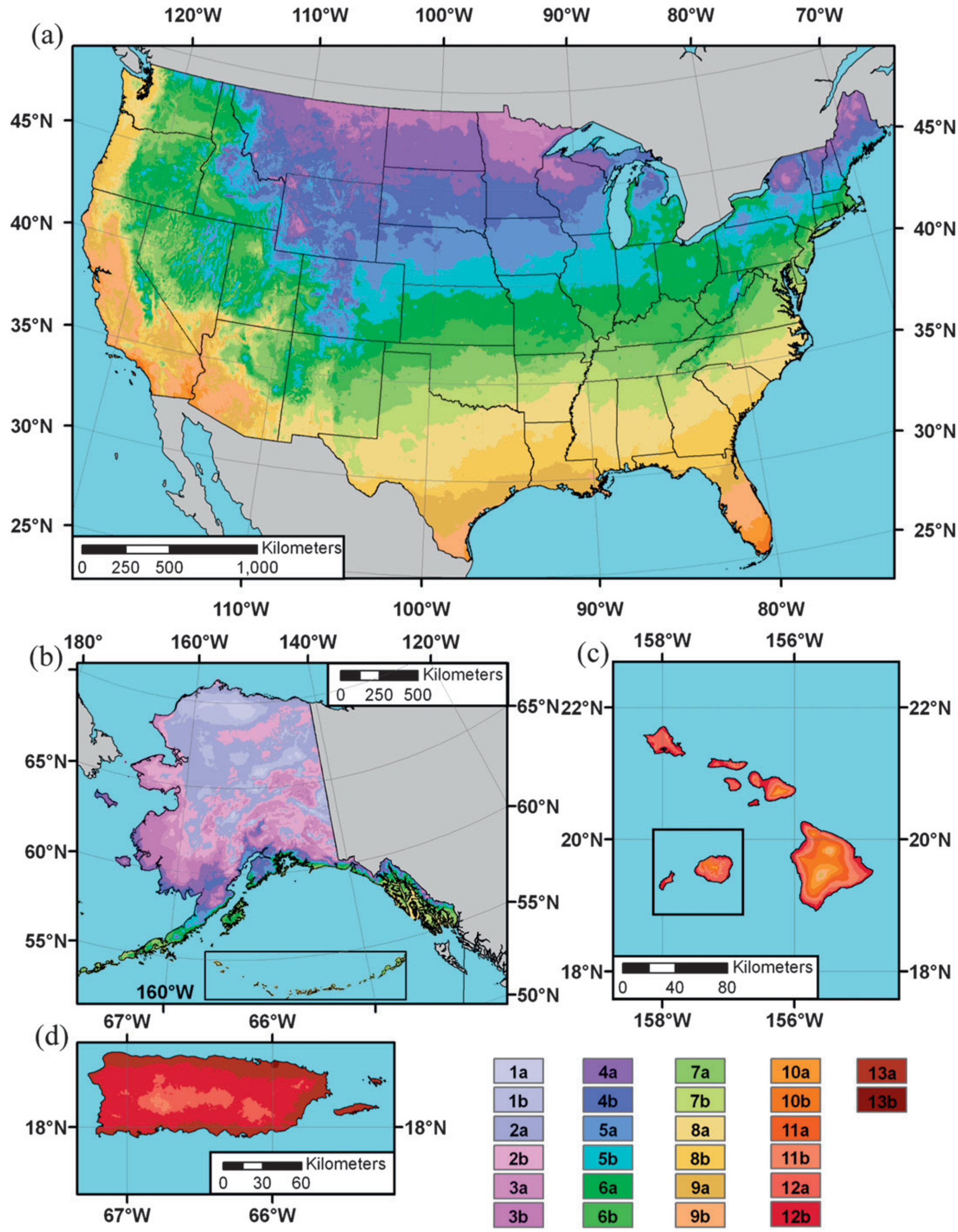


FIG. 5. PRISM 1976–2005 Plant Hardiness Zone Maps: (a) conterminous United States, (b) Alaska, (c) Hawaii, and (d) Puerto Rico. The zone color key is given at the lower right. See Table 1 for temperature ranges of zones.

pools in many interior valleys. The Cascade Range in the Pacific Northwest and the Sierra Nevada in California serve as effective barriers to the eastward flow of mild Pacific Ocean air, creating sharp zonal contrasts along their crests. The Rocky Mountains act as a barrier to Arctic outbreaks that occasionally move southward from Canada during winter, resulting in milder zones west of the Rockies than to the east. The coldest zones in the western United States are located not at the highest elevations, but rather in interior valleys where persistent cold-air pooling occurs (cf. Daly et al. 2008, their Figs. 4 and 5). These effects are discussed in more detail in section 5e.

Not surprising is that the coldest zones occur in the Alaskan interior (Fig. 5b). However, zones as warm as

TABLE 3. Plant hardiness zones for the 11 largest metropolitan statistical areas (MSA) (data taken from the U.S. Census Bureau; see http://www.census.gov/population/www/cen2000/phc-t29.html) in the recently revised Plant Hardiness Zone Map. Temperature ranges for each zone are given in Table 1.

| MSA | Zone |
|---|---|
| New York–Northern New Jersey–Long Island, NY–NJ–PA | 7a–7b |
| Los Angeles–Long Beach–Santa Ana, CA | 10a–11a |
| Chicago–Naperville–Joliet, IL–IN–WI | 5b–6a |
| Philadelphia–Camden–Wilmington, PA–NJ–DE | 7a–7b |
| Dallas–Fort Worth–Arlington, TX | 8a |
| Miami–Fort Lauderdale–Miami Beach, FL | 10b |
| Washington–Arlington–Alexandria, DC–VA–MD | 7a–7b |
| Houston–Baytown–Sugar Land, TX | 9a |
| Detroit–Warren–Livonia, MI | 5b–6b |
| Boston–Cambridge–Quincy, MA–NH | 6a–6b |
| Atlanta–Sandy Springs–Marietta, GA | 7b–8a |

those of southern Alabama occur along the Gulf of Alaska coastline and Aleutians. In southern Alaska, the Chugach Mountains present a formidable barrier between dominant coastal and interior air masses, creating strong gradients between the coastal strip and adjacent inland regions. The warmest zones are found in Hawaii and Puerto Rico (Figs. 5c,d). Elevation and coastal influence are the dominant factors controlling spatial distribution. Puerto Rico, owing to its location in the relatively warm Caribbean Sea and southern latitude, has the warmest zones of all of the regions mapped.

As discussed previously, the type of plant injury resulting from extreme cold can vary depending on the timing of the cold event. A plot of the month having the greatest number of occurrences of the annual extreme minimum temperature illustrates the spatial variation in the timing of extreme cold events (Fig. 6). January is easily the month with the most occurrences. A December maximum predominates in the southwestern United States, whereas a February maximum is common at the higher elevations of the Rockies. In Hawaii and Puerto Rico, the maximum occurs in January–March.

### b. *Statistical uncertainty analysis*

Estimating the true errors associated with the PHZM, and with spatial climate datasets in general, is difficult and subject to its own set of errors (Daly 2006). This is because the true climate field is unknown, except at a relatively small number of observed points, and even these are subject to measurement and siting uncertainties. A performance statistic often reported in climate-interpolation studies is the cross-validation (CV) error (Daly et al. 1994, 2008; Willmott and Matsuura 1995; Gyalistras 2003). The CV error is a measure of the difference between one or more station values and a model's estimates for those stations, when they have been removed from the dataset (Harrell 2001).

In the common practice of single-deletion jackknife CV, the process of removal and estimation is performed for each station individually, with the station returned to the dataset after estimation (Legates and McCabe 1999). Once the process is complete, overall error statistics, such as MAE and bias, are calculated (e.g., Willmott et al. 1985; Legates and McCabe 1999). The obvious disadvantage to CV error estimation is that it is limited to locations where there are stations. Notwithstanding these shortcomings, CV does serve as a valuable estimate of interpolation uncertainty.

Jackknife CV was performed for the three conterminous-U.S. modeling regions (west, central, and east) and for Puerto Rico, Hawaii, and Alaska. After each CV exercise, prediction–observation differences were calculated, and means of the signed differences (bias) and unsigned differences (MAE) were calculated.

Overall biases were near zero, indicating that PRISM did not systematically over- or underpredict the PH statistic (Table 4). MAE values were also small, typically averaging $<1.1°C$ (2°F). MAEs were greatest in the western United States and Alaska because 1) the region is physiographically and climatically complex, characterized by steep spatial gradients and temperature inversions; 2) the station dataset included SNOTEL and RAWS stations that are typically difficult to estimate when omitted during CV because of their remote, mountainous locations; and 3) these regions are relatively undersampled. The 1976–2005 standard deviation MAE was notably small in Puerto Rico, a reflection of the low temporal variability in the PH statistic for this region (see section 5c).

An alternative measure of uncertainty produced by PRISM at each grid cell is the regression prediction interval. Since PRISM uses weighted linear regression to interpolate climatic variables, standard methods for calculating prediction intervals for the dependent variable $Y$ are used. Unlike a confidence interval, the prediction interval takes into account both the variation in the possible location of the expected value of $Y$ for a given $X$ (since the regression parameters must be estimated), and variation of individual values of $Y$ around the expected value (Neter et al. 1989). The mean 70% prediction interval (PI70), which approximates 1 standard error around the model prediction, was 1.19°, 0.88°, and 0.93°C for the western, central, and eastern United States, respectively. These are similar to the CV MAEs reported in Table 4, which is in agreement with the findings of Daly et al. (2008) that the two error measures are comparable over large regions.

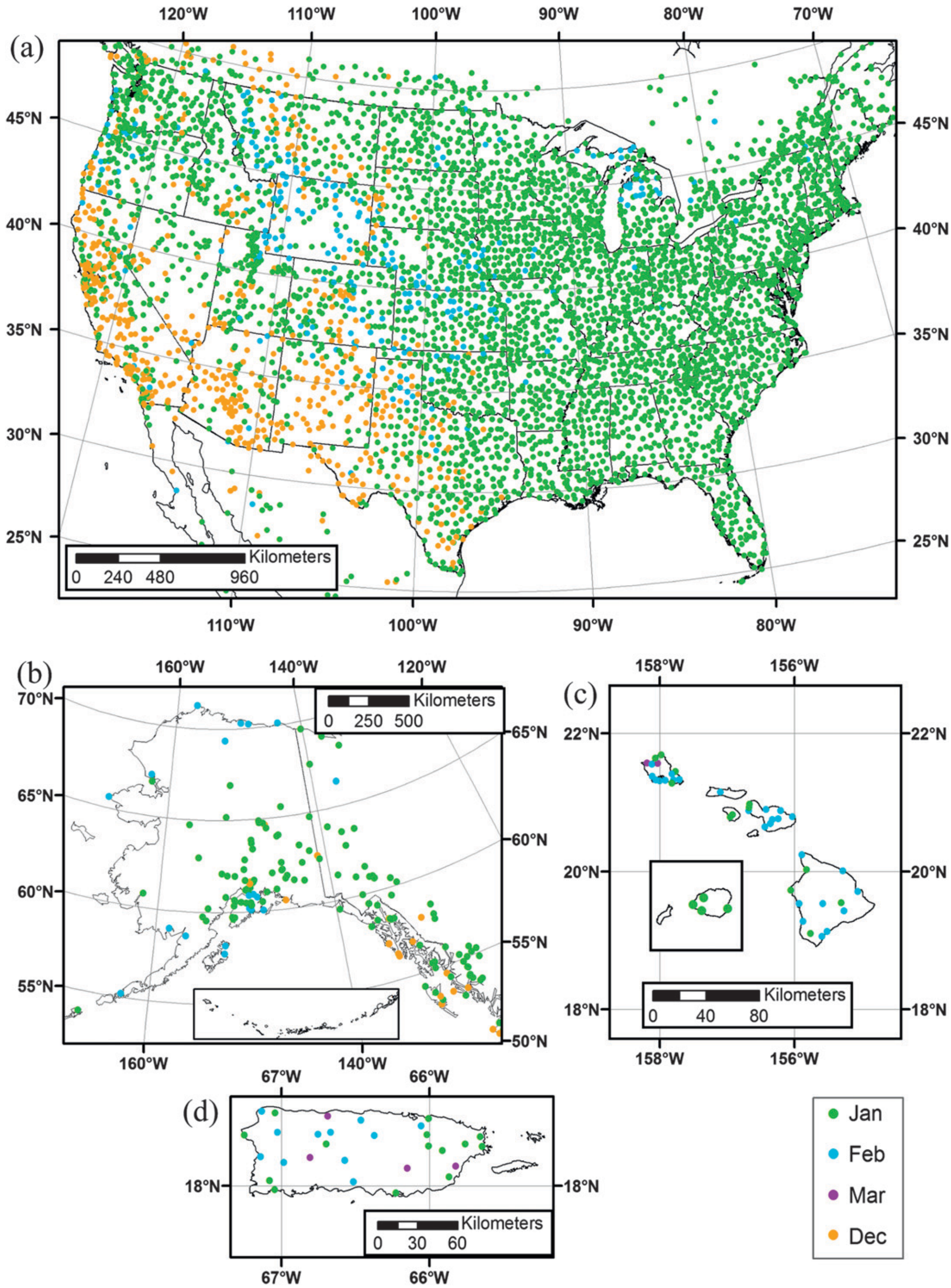


FIG. 6. Month of the year having the greatest number of occurrences of the annual extreme minimum temperature: (a) conterminous United States, (b) Alaska, (c) Hawaii, and (d) Puerto Rico. Stations shown are those used in the PHZM that have a total of at least 25 occurrences of the extreme annual minimum temperature during the period 1976–2005, including repeats (ties) within a month or year.

TABLE 4. Cross-validation results for PRISM interpolation of the PH statistic and standard deviation of the 1976–2005 PH statistic (STD). Bias is the mean of the signed errors and MAE is the mean of the unsigned errors.

| Region | Bias (°C/°F) | MAE (°C/°F) |
|---|---|---|
| U.S. West | | |
| 1976–2005 PH | −0.01/−0.02 | 1.04/1.84 |
| 1976–90 PH | −0.01/−0.02 | 1.11/2.00 |
| 1991–2005 PH | 0.0/0.0 | 1.07/1.89 |
| 1976–2005 STD | 0.0/0.0 | 0.43/0.76 |
| U.S. Central | | |
| 1976–2005 PH | 0.01/0.02 | 0.69/1.22 |
| 1976–90 PH | 0.01/0.02 | 0.74/1.31 |
| 1991–2005 PH | 0.02/0.03 | 0.76/1.35 |
| 1976–2005 STD | 0.0/0.0 | 0.32/0.56 |
| U.S. East | | |
| 1976–2005 PH | −0.01/−0.02 | 0.77/1.35 |
| 1976–90 PH | −0.01/−0.02 | 0.83/1.46 |
| 1991–2005 PH | −0.01/−0.02 | 0.82/1.44 |
| 1976–2005 STD | 0.0/0.0 | 0.33/0.58 |
| Puerto Rico | | |
| 1976–2005 PH | 0.03/0.05 | 0.52/0.92 |
| 1976–90 PH | 0.03/0.05 | 0.50/0.88 |
| 1991–2005 PH | 0.03/0.05 | 0.58/1.03 |
| 1976–2005 STD | 0.0/0.0 | 0.02/0.04 |
| Hawaii | | |
| 1976–2005 PH | 0.0/0.0 | 0.76/1.35 |
| 1976–90 PH | 0.01/0.02 | 0.91/1.60 |
| 1991–2005 PH | −0.02/−0.04 | 0.71/1.26 |
| 1976–2005 STD | 0.01/0.02 | 0.22/0.40 |
| Alaska | | |
| 1976–2005 PH | 0.0/0.0 | 1.04/1.85 |
| 1976–90 PH | −0.01/−0.02 | 1.05/1.86 |
| 1991–2005 PH | 0.01/0.01 | 1.03/1.83 |
| 1976–2005 STD | −0.01/−0.01 | 0.29/0.51 |

The CV and prediction interval MAEs reported here likely underestimate the true interpolation error of the PH statistic for several reasons. First, areas with the greatest uncertainty are likely to be in remote, mountainous regions, but these areas are undersampled by station data. Second, the CAI method used for interpolation of the PH statistic relies on a previously developed predictor grid that is not completely independent from the predictand, in that they share data from many of the same stations. A joint jackknife cross-validation exercise, wherein each station is omitted from the predictor and predictand interpolations simultaneously, could provide information on the effect of these dependencies on error but was beyond the scope of this study. The CV MAEs for 1971–2000 mean January minimum temperature (commonly used as the predictor grid) were reported in Daly et al. (2008) as 1.12°, 0.75°, and 0.72°C for the western, central, and eastern United States, respectively, similar to those reported for the PH interpolation in Table 4.

How these estimated interpolation errors translate into uncertainties in the delineation of zone boundaries depends on local gradients in the PH statistic. In the central United States, where gradients are gentle, a given MAE translates into the largest horizontal distance in zone placement. Given a representative gradient in this region of about one half zone per 150 km, an error of 1°C (1.76°F) in the PH statistic along a zone boundary would translate into a change of about 35 km in the boundary's placement. In regions with complex terrain, where gradients can be one half zone per kilometer or greater, the same error could translate into a change of only a few hundred meters. When estimating the zone designation at a specific point, there is clearly a need for greater positional accuracy in areas of high gradient than in areas of low gradient.

### c. *Comparison with the 1990 PHZM*

As mentioned previously, the 1990 PHZM was not prepared digitally, limiting its distribution to paper copy and scanned graphics. For our analysis, a scanned, digitized version of the conterminous-U.S. portion of the 1990 PHZM was obtained from the University of Nebraska (Vogel et al. 2005). It was preclassified into 2.8°C (5°F) half zones (Fig. 7). The map somewhat resembles the updated PHZM in the central United States (Fig. 5) but is highly smoothed and simplified. Patterns associated with terrain in the western United States are largely absent, except for some coastal effects. Given the number of bull's-eyes around what appear to be individual stations, it appears that contours were drawn in a largely two-dimensional fashion, incorporating relatively little physiographic information. Spatial detail is therefore determined by the density of the stations sampled and variations in their values rather than by the physiographic features that actually control spatial temperature patterns.

Differences between the updated PHZM and the 1990 PHZM were substantial in some regions but minimal in others (Fig. 8; Table 5). Differences can be attributed to three main factors: 1) the stations selected, 2) the averaging periods used, and 3) the interpolation techniques. Although it was impossible to examine the effect of each factor separately, we were able to separate the combined influence of station selection and interpolation technique from that of time period. Figure 8a shows differences between the 1990 PHZM and the 1976–90 15-yr map. The 1990 PHZM averaging period of 1975–86 overlaps substantially with the 1976–90 period, suggesting that differences between the two maps are due mainly to station selection and interpolation method. Across the central and eastern United States, about two-thirds of the land area had no zonal changes and about one-third had a change of one half zone (Table 5). Differences were likely a result of station data differences, except for the

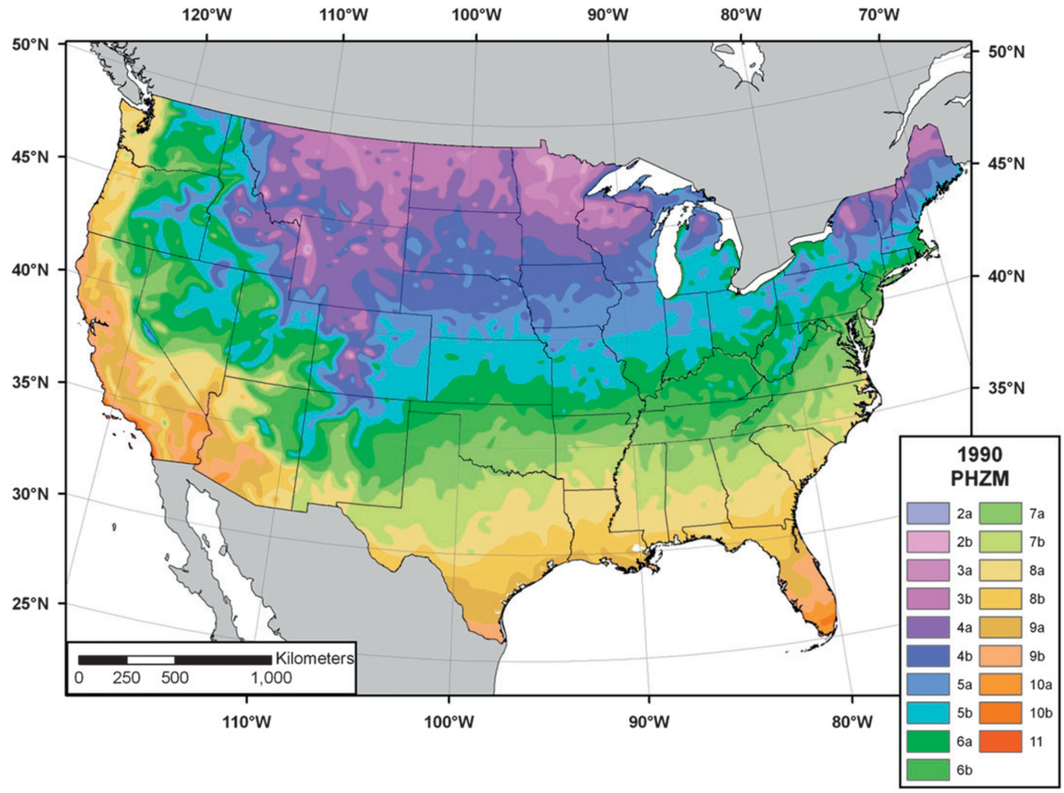


FIG. 7. The 1990 USDA PHZM for the conterminous United States. Station data were averaged over the period 1974–86.

Appalachian Mountains and along the Great Lakes, where steep elevational and coastal gradients could not be adequately reproduced in the 1990 map by simply drawing contours around the station values. Differences were more pronounced in the western United States; about one-half of the land area showed no zonal differences, 40% had differences of one half zone, and about 10% had differences of two or more half zones (Table 5). Overall, the west accounted for most of the 400 000-km$^2$ area with differences of at least two half zones. Many mountain areas not represented by COOP stations were depicted as too warm in the 1990 map; in the most extreme case, the 1976–90 map was cooler by as much as seven half zones than the 1990 PHZM in the southern Sierra Nevada. Much of the northern intermountain region was depicted by the 1990 PHZM as too cold. This was the result of a tendency for COOP stations, which employ human observers, to be located primarily in valley bottoms where most people live. These are excellent locations for cold-air pooling, yielding a low-temperature bias relative to surrounding uplands. Given that the 1990 PHZM did not include mountain networks, such as SNOTEL, nor did it incorporate terrain guidance during interpolation, these cold values were not restricted to valleys; instead, they were extrapolated to warmer uplands, yielding a map that was locally too cold by as much as six half zones.

Differences between the updated PHZM and the 1990 PHZM illustrate differences users of the old map will now encounter. Because of the later (and warmer) averaging period, the updated PHZM is warmer by one half zone than the old map over nearly one-half of the United States (Fig. 8b; Table 5). A similar, but opposite zone shift was experienced during the transition between the 1990 PHZM and its 1965 predecessor (cf. Cathey and Heriteau 1990). In the central and eastern United States, the more recent averaging period is likely the main source of zonal change, whereas in the western United States, a more sophisticated interpolation technique, greater physiographic detail, and a more comprehensive set of stations, especially in the mountains, are key sources of zonal change. In the West, about 16% of the land area shifted two or more half zones (Table 5).

### *d. Variability and trends*

Clearly, plant hardiness zones are dynamic, and the magnitude of this temporal variability varies across the United States. A map of the standard deviation of

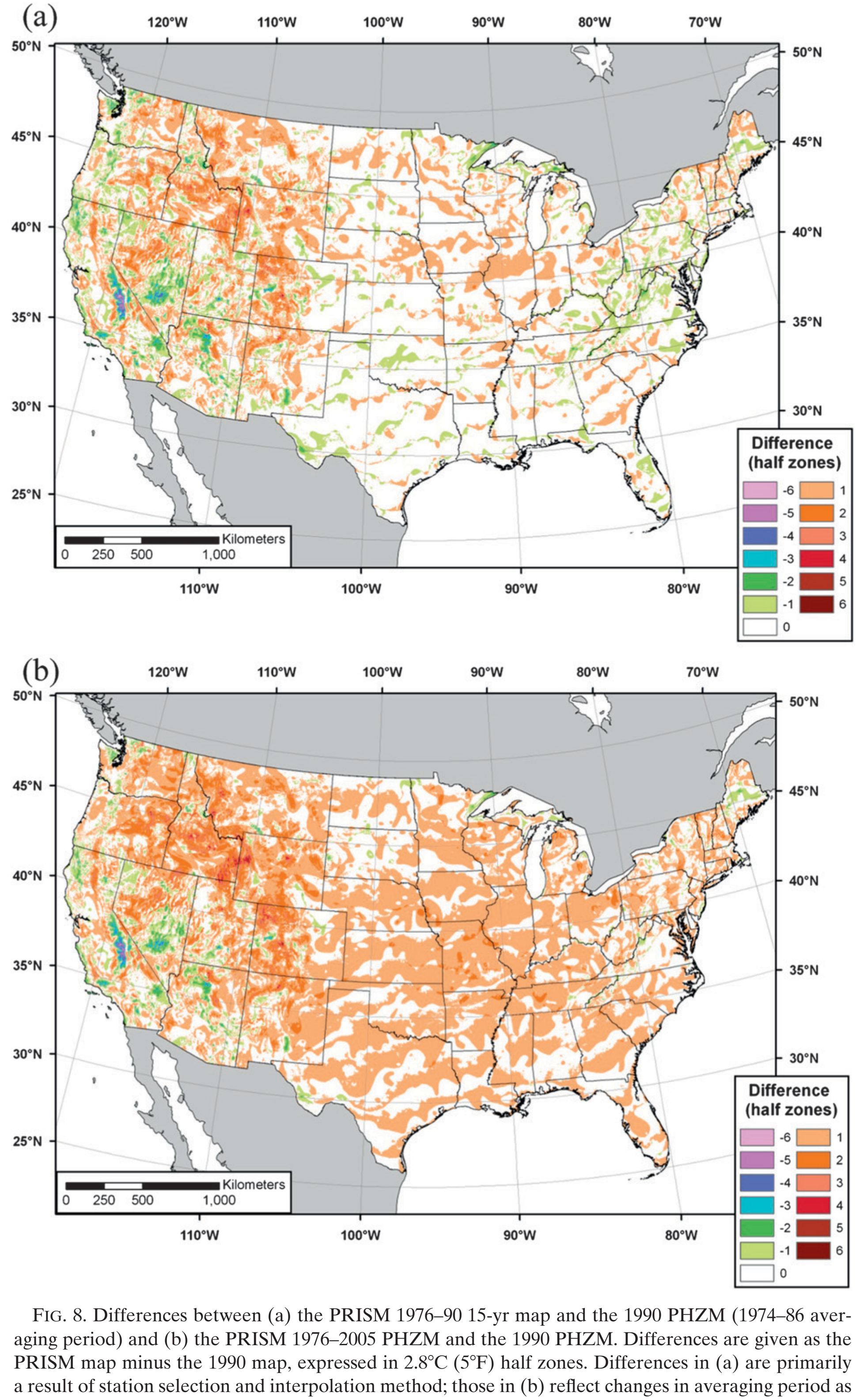


FIG. 8. Differences between (a) the PRISM 1976–90 15-yr map and the 1990 PHZM (1974–86 averaging period) and (b) the PRISM 1976–2005 PHZM and the 1990 PHZM. Differences are given as the PRISM map minus the 1990 map, expressed in 2.8°C (5°F) half zones. Differences in (a) are primarily a result of station selection and interpolation method; those in (b) reflect changes in averaging period as well as station selection and interpolation method.

TABLE 5. Differences between the 1976–90 15-yr map and the 1990 PHZM, and the updated 1976–2005 PHZM and the 1990 PHZM, for the conterminous United States (CONUS). Differences are expressed regionally as percent of land area and as both percent of land area and total kilometers squared for CONUS.

| | 1976–90 minus 1990 | | | | | 1976–2005 minus 1990 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Difference (half zones) | U.S. west (%) | U.S. central (%) | U.S. east (%) | CONUS (%) | CONUS ($\times$1000 km$^2$) | U.S. west (%) | U.S. central (%) | U.S. east (%) | CONUS (%) | CONUS ($\times$1000 km$^2$) |
| −7 | <0.1 | 0.0 | 0.0 | <0.1 | <0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| −6 | <0.1 | 0.0 | 0.0 | <0.1 | 0.3 | <0.1 | 0.0 | 0.0 | <0.1 | 0.1 |
| −5 | 0.1 | 0.0 | 0.0 | <0.1 | 2.0 | <0.1 | 0.0 | 0.0 | <0.1 | 1.5 |
| −4 | 0.2 | <0.1 | 0.0 | 0.1 | 5.7 | 0.1 | 0.0 | 0.0 | 0.1 | 4.5 |
| −3 | 0.5 | <0.1 | <0.1 | 0.2 | 19.2 | 0.4 | <0.1 | <0.1 | 0.2 | 12.4 |
| −2 | 2.5 | 0.2 | 0.4 | 1.3 | 97.6 | 1.6 | 0.1 | 0.1 | 0.8 | 59.1 |
| −1 | 13.0 | 6.9 | 11.1 | 11.0 | 858.2 | 7.3 | 1.2 | 2.1 | 4.2 | 324.4 |
| 0 | 49.0 | 73.1 | 69.3 | 62.0 | 4834.3 | 35.4 | 38.5 | 42.5 | 38.9 | 3034.4 |
| 1 | 27.5 | 19.0 | 19.0 | 21.9 | 1709.7 | 41.3 | 56.9 | 53.3 | 48.7 | 3795.7 |
| 2 | 6.3 | 0.7 | 0.3 | 3.0 | 230.0 | 11.3 | 3.0 | 2.0 | 6.1 | 472.4 |
| 3 | 1.0 | 0.1 | <0.1 | 0.4 | 34.0 | 2.2 | 0.2 | <0.1 | 1.0 | 77.2 |
| 4 | 0.1 | <0.1 | 0.0 | <0.1 | 3.3 | 0.3 | <0.1 | <0.1 | 0.2 | 11.9 |
| 5 | <0.1 | <0.1 | 0.0 | <0.1 | 0.3 | <0.1 | <0.1 | 0.0 | <0.1 | 1.0 |
| 6 | <0.1 | <0.1 | 0.0 | <0.1 | <0.1 | <0.1 | <0.1 | 0.0 | <0.1 | <0.1 |

the 1976–2005 PH statistic shows that variability is greatest (>5°C; 9°F) in the intermountain region of the western United States and also in the southeastern Midwest (Fig. 9a). A 5°C standard deviation translates into about a 70% chance that, in any given year, the actual zone could be plus/minus one half zone from the mean. In a few locations in the intermountain west, standard deviations exceeded 7°C (12.6°F). These areas experienced such large annual fluctuations in the PH statistic that winter conditions for long-lived plants were likely much harsher than in other regions sharing that zone. In contrast, the standard deviation is lowest (≤2°C; 3.6°F) in the Central Valley of California and the desert Southwest; there, it is unlikely that the zone varies significantly from the mean. Patterns of variability appear to be partly related to variation in the frequency and intensity of Arctic air penetration. Variability is greatest in areas that experience inconsistent exposure to Arctic air masses each winter, the strength and frequency of which depend on upper-air flow pattern and strength. In the interior Pacific Northwest, for example, a relatively infrequent northerly or northeasterly flow pattern is required for Arctic air masses to bypass the Rocky Mountain barrier and penetrate the region. In contrast, the typical northwest-to-southeast trajectory of cold-air outbreaks across the northern United States all but guarantees that the northern plains and upper Midwest will experience at least one annual outbreak, and the southwestern United States, remote from typical Arctic airflow and effectively shielded by several mountain ranges, experiences only mild and infrequent cold events.

In Alaska, variability is greatest in the southern interior and least on the North Slope and southern coast (Fig. 9b). The North Slope sees relatively low variability primarily because it is firmly entrenched under Arctic air each winter. Along the south coast, mountain barriers block the entry of cold continental air, and the ocean moderates what cold air does penetrate, keeping variability relatively low. Hawaii and Puerto Rico, located far from cold air masses and surrounded by water, exhibit little variability.

Trends in the PH statistic over the past 30 years were estimated by taking the difference between the 1976–90 and 1991–2005 15-yr maps (Fig. 10). As discussed earlier, significant warming in the PH statistic has occurred in many parts of the conterminous United States. The PH statistic has generally warmed at least one half zone, except for the northern plains, northern Maine, and small parts of the Southwest. A warming of two half zones has occurred over large parts of the central and eastern United States, as well as the Pacific Northwest. The modal zone in the conterminous United States has shifted a full zone from 5b in 1976–90 to 6b in 1991–2005 (Table 6). Alaska experienced warming of one half zone, evenly distributed over about one-half of its area (Fig. 10b), while Hawaii and Puerto Rico had only small changes (Figs. 10c,d). Alaska, Hawaii, and Puerto Rico did not have a shift in the modal zone (not shown).

### *e. Northeastern Utah case study*

A detailed analysis of PH zone patterns in the Uinta Mountains and adjacent Green River Valley in northeastern Utah provides a useful perspective on the extreme spatial and temporal heterogeneity that can occur in the PH statistic. The Uinta Mountains (encompassing Lakefork Basin in Fig. 11) is an east–west-oriented

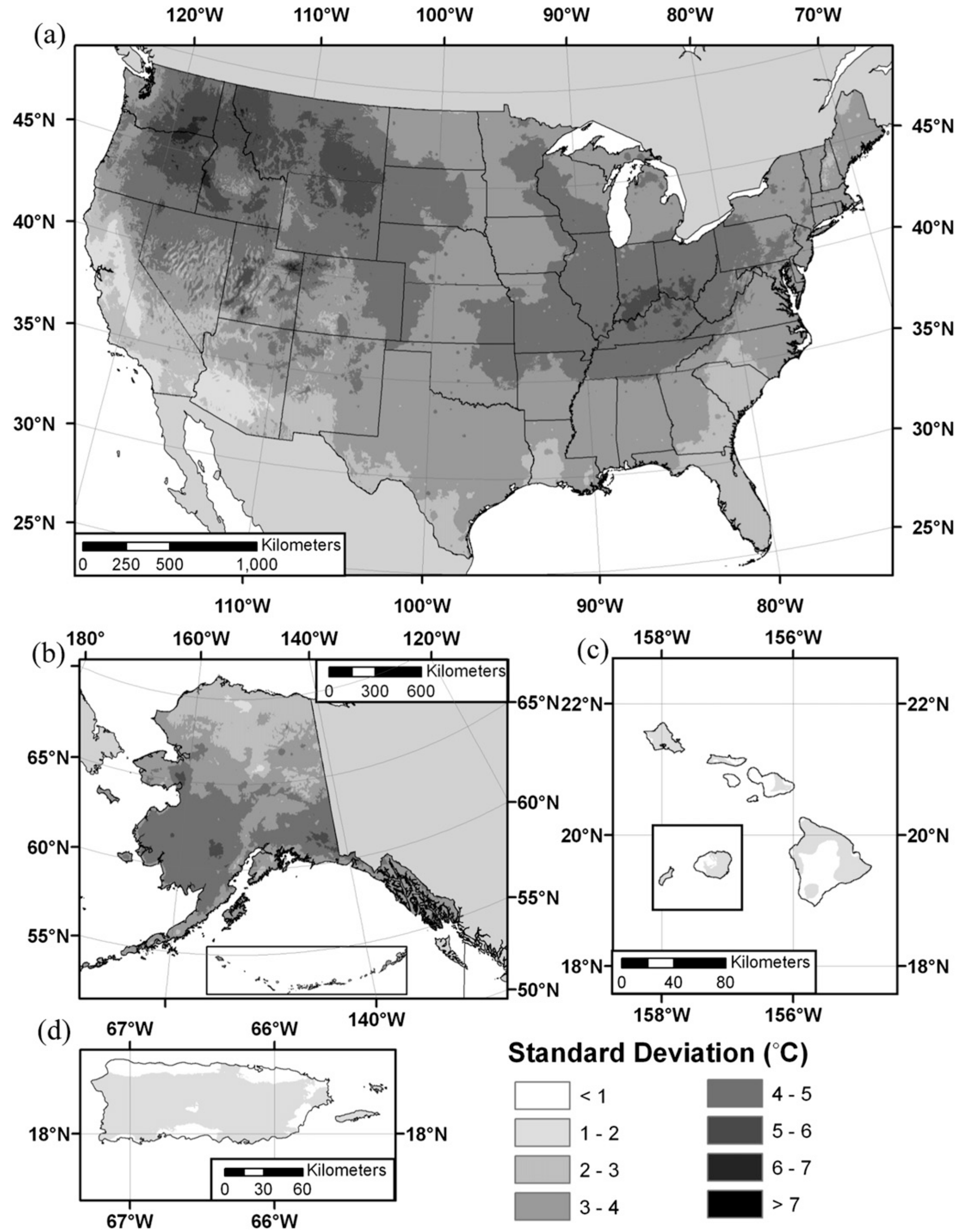


FIG. 9. PRISM maps of the standard deviation of the 1976–2005 PH statistic: (a) conterminous United States, (b) Alaska, (c) Hawaii, and (d) Puerto Rico.

range rising to 3500–4000+ m MSL at the crest. A broad basin to the south rises gently from 1400 m MSL along the Green River (vicinity of Ouray) to about 2100 m MSL at the base of the Uintas. Nearly surrounded by mountains, this basin is susceptible to cold-air pooling throughout the winter, most strongly during periods of low solar radiation, high atmospheric pressure, and light synoptic winds (Barr and Orgill 1989; Beniston 2006; Lundquist and Cayan 2007).

Unlike the 1990 PHZM, which did not account for terrain effects, the updated PHZM exhibits significant vertical gradients in this region (Figs. 11a,b). The basin

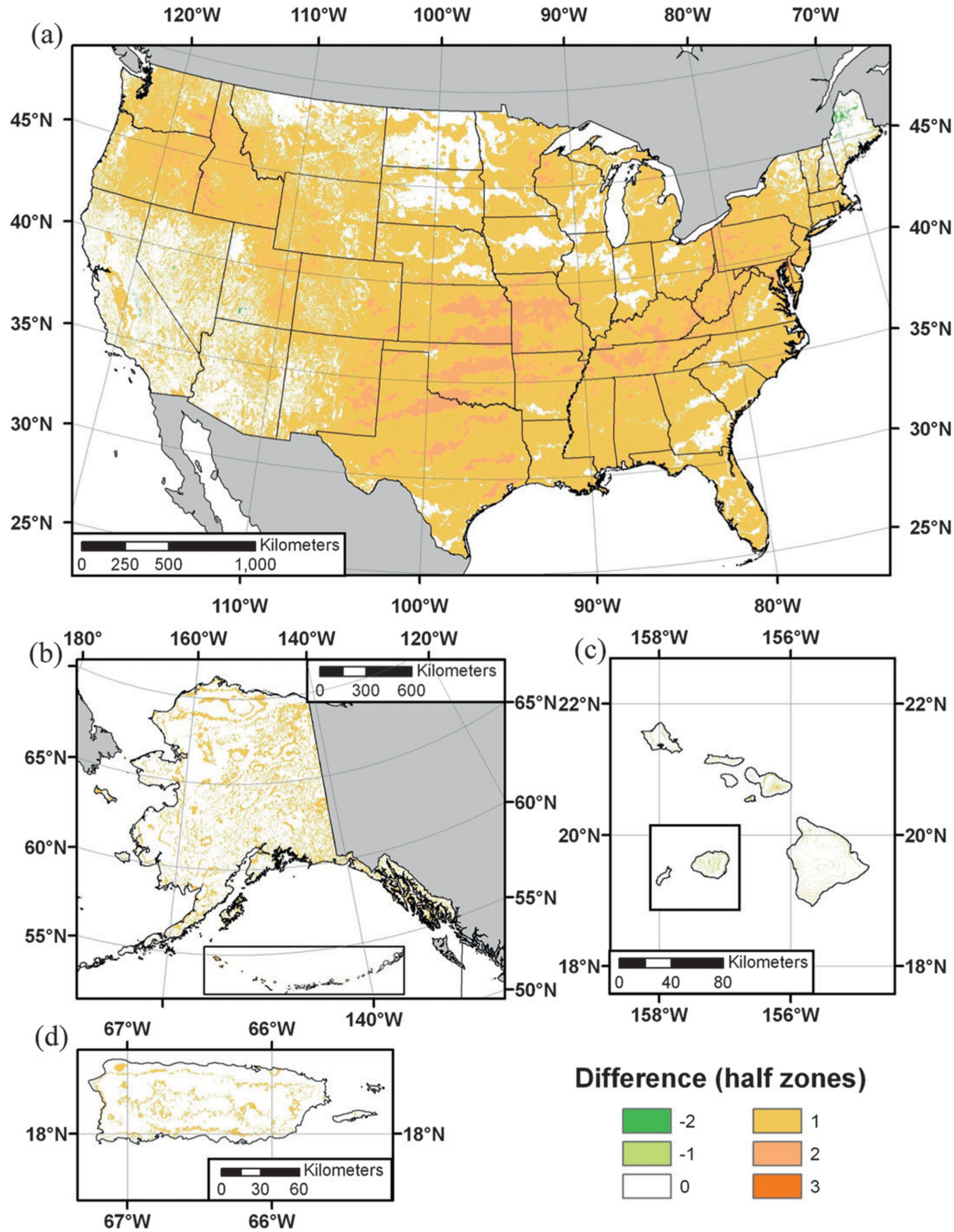


FIG. 10. Difference between the PRISM 1991–2005 and 1976–1990 15-yr maps (1991–2005 minus 1976–1990) for (a) the conterminous United States, (b) Alaska, (c) Hawaii, and (d) Puerto Rico. Differences are expressed in 2.8°C (5°F) half zones.

floor (e.g., Ouray) is in zone 5a, nearly as cold as much of the Uintas. At midelevation (e.g., Altamont), a thermal belt is warmer by one to two (locally up to four) half zones than the basin floor, on exposed terrain not susceptible to cold-air pooling (Fig. 11b). To illustrate the effect of interpolation uncertainty on the 1976–2005 mean zone boundaries, the lower and upper bounds of the 95% prediction interval (within 2 standard errors, approximated by 2 times the PI70 statistic) of the PRISM regression functions were plotted (Figs. 11c,d). At many locations in this region, the 95% prediction interval encompasses two possible half zones. Clearly, what appear

TABLE 6. Percent of conterminous-U.S. land area falling into each PH zone, for the PRISM 1976–2005 PHZM and the PRISM 1976–90 and 1991–2005 15-yr maps. The modal zone for each map is boldfaced.

| Zone | Averaging period | | |
|---|---|---|---|
| | 1976–90 | 1976–2005 | 1991–2005 |
| 2a | 0.0 | 0.0 | 0.0 |
| 2b | <0.1 | <0.1 | 0.0 |
| 3a | 0.8 | 0.4 | 0.1 |
| 3b | 3.8 | 2.7 | 1.9 |
| 4a | 7.8 | 6.8 | 5.8 |
| 4b | 9.0 | 8.1 | 6.8 |
| 5a | 8.1 | 7.8 | 8.4 |
| 5b | **12.4** | 9.3 | 7.7 |
| 6a | 11.6 | **12.2** | 11.1 |
| 6b | 9.6 | 11.1 | **11.6** |
| 7a | 7.2 | 8.4 | 9.7 |
| 7b | 8.4 | 7.4 | 7.1 |
| 8a | 8.1 | 9.6 | 9.0 |
| 8b | 5.7 | 7.0 | 9.2 |
| 9a | 4.0 | 4.7 | 5.5 |
| 9b | 2.7 | 3.3 | 4.2 |
| 10a | 0.7 | 1.0 | 1.4 |
| 10b | 0.1 | 0.2 | 0.3 |
| 11a | <0.1 | <0.1 | 0.1 |
| 11b | <0.1 | <0.1 | <0.1 |

to be clearly defined zone boundaries on the mean map (Fig. 11b) are, in reality, imprecisely defined transitional areas.

In this region, temporal variation in the PH statistic exhibits significant vertical gradients. The standard deviation of the PH statistic at the basin floor is 2–3 times that in the mountains, and the difference between the 1991–2005 and 1975–90 PH statistics is about 4 times that in the mountains (Figs. 11e,f). Three representative stations were selected to highlight these differences: Ouray 4 NE COOP station (40.13°N, 109.64°W), located at 1423 m MSL near the Green River and the basin floor; Altamont COOP station at 1942 m MSL on an alluvial fan near the base of the mountains (40.36°N, 110.28°W); and Lakefork Basin SNOTEL station at 3322 m MSL high in the Uinta Mountains (40.74°N, 110.62°W; Fig. 11). During 1975–2005, the interannual variability of the PH statistic was much greater at Ouray 4 NE than at Altamont and was greater at Altamont than at Lakefork Basin (Fig. 12). Variability at high-elevation Lakefork Basin was associated closely with the variability in the free airmass temperature, whereas Ouray 4 NE was affected by both airmass temperature and the occurrence of local cold-air pooling and inversions, thus increasing overall variability. Temperatures at Ouray 4 NE tended to be colder than at Altamont or Lakefork Basin during extreme minimum temperature events in relatively cold years but warmer during relatively warm events, suggesting that the basin's coldest extreme events are typically accompanied by well-developed cold-air pools and inversions whereas warmer extreme events are not. This is exemplified in daily time series plots of a relatively cold and a relatively warm annual extreme minimum temperature event in Fig. 13. In addition to the three surface stations, the mean daily temperature at 700 hPa from the National Centers for Environmental Prediction (NCEP) Reanalysis 2 is shown (Kanamitsu et al. 2002). The cold event occurring in mid-January 1984 was characterized by a combination of a cold air mass originating in the Arctic and a strongly inverted lapse rate, resulting in an extreme minimum temperature of −40°C at Ouray 4 NE. This extreme was recorded on 20 January, three days after Lakefork Basin recorded its extreme minimum of −29.6°C and two days after Altamont recorded its −30.6°C extreme minimum. Such a delay in timing is not unusual; cold-air pooling and resulting inversions are often strongest after the cold air mass has arrived, when winds have calmed and vertical mixing of the free air mass (which has already begun to warm; see Fig. 13a) is minimal.

In contrast to the January 1984 cold event, the relatively warm extreme minimum temperature event occurring in late November and December 2004 was characterized by the lack of an extremely cold air mass or strong inversions. Because there was no pronounced cold event, the timing of the extreme minimum temperature differed among sites and sometimes occurred repeatedly.

Temporal trends also differed among sites (Fig. 12). At Ouray 4 NE, there were four occurrences of annual extreme minimum temperatures below −10°C between 1975 and 1991 but none after that, resulting in a noticeable warming trend in the PH statistic over the 1976–2005 period. Altamont shows a similar but smaller trend due to an overall lower variability. Lakefork Basin exhibits the least trend, with the lowest variability. It appears that a recent lack of Arctic airmass outbreaks into this area, accompanied by fewer strong cold-air pooling and inversion events, has contributed to a local warming in the PH statistic.

## 6. Conclusions

The extremes of winter cold are a major determinant of natural plant distributions and the successful cultivation and survival of long-lived plants. In the United States, the USDA Plant Hardiness Zone Map is the primary reference for defining and communicating the geospatial patterns of extreme winter cold to the horticulture and nursery industries, agrometeorologists, and plant scientists. This paper describes an update to the 1990 PHZM for the conterminous United States, Alaska, Hawaii, and Puerto

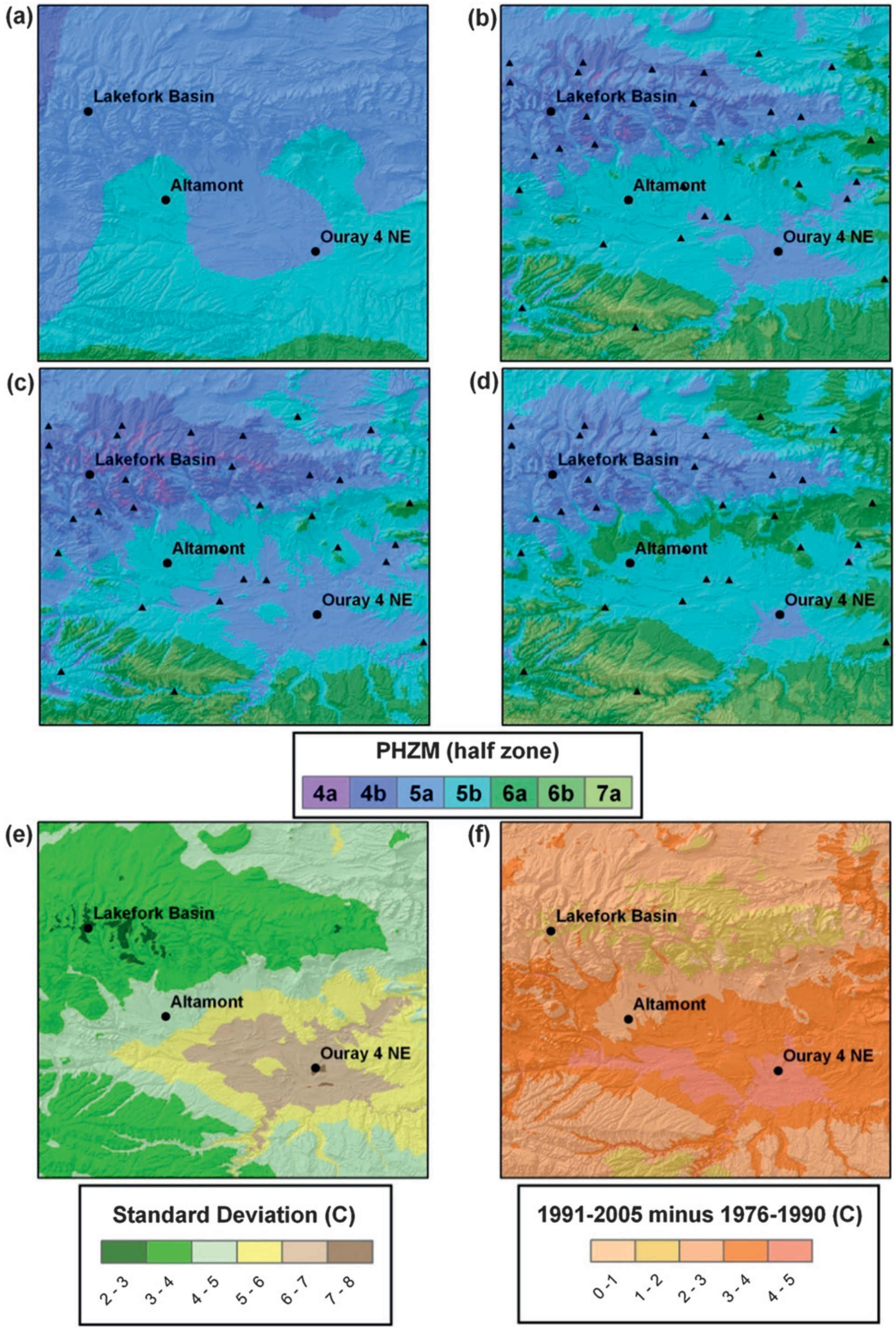


FIG. 11. Plant hardiness and ancillary maps for the Uinta Mountains/Green River area of northeastern Utah: (a) 1990 PHZM (1974–86 data), (b) PRISM 1976–2005 PHZM, (c) 1976–2005 PHZM realization at the lower bound of the PRISM regression 95% prediction interval, (d) 1976–2005 PHZM realization at the upper bound of the PRISM regression 95% prediction interval, (e) standard deviation of the 1976–2005 PH statistic, and (f) difference between the two PRISM 15-yr maps (1991–2005 minus 1976–90). Stations used in the interpolation of the 1976–2005 PHZM are shown as black triangles in (b)–(d). Locations of stations highlighted in Figs. 12 and 13 are shown in all panels.

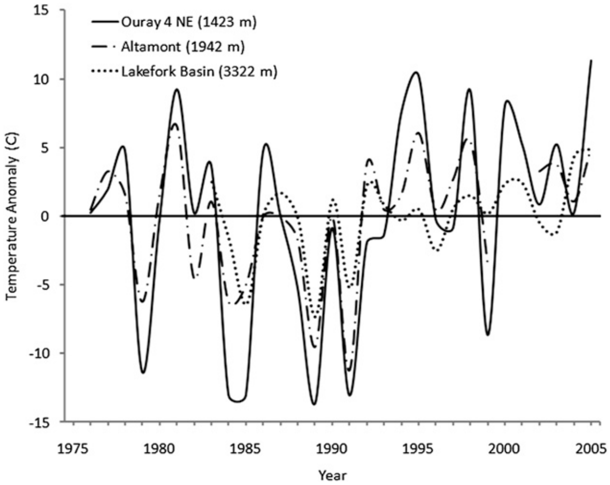


FIG. 12. Time series plot of annual extreme minimum temperature anomalies from their respective means for three stations in the Uinta Mountains/Green River area of northeastern Utah. Means are −27.0°, −24.4°, and −27.9°C for Ouray 4 NE, Altamont, and Lakefork Basin, respectively. See Fig. 11 for station locations. (Temperatures were plotted with the Microsoft Excel software smooth-line option to improve readability).

Rico. The updated map can be accessed online (http://www.planthardiness.ars.usda.gov). The new PHZM was developed at fine grid resolution—800 m in the conterminous United States, 4 km in Alaska, and 400 m in Hawaii and Puerto Rico—and was divided into 13 5.6°C (10°F) full zones and 26 2.8°C (5°F) half zones. A 1976–2005 averaging period was chosen to reflect recent climatic conditions in a statistically stable manner.

In the updated PHZM, PH-zone patterns in the central and eastern United States are dominated by latitudinal and coastal influences, with some terrain effects apparent in the Appalachian Mountains. Zone patterns in the western United States and Alaska exhibit a relatively indistinct latitudinal gradient and are instead dominated by relatively mild marine influences along the coasts, elevational effects in the mountains, and cold-air pools in many interior valleys. In Hawaii and Puerto Rico, terrain and coastal influences are again the dominant factors controlling the spatial distribution of PH zones.

The CV biases were nearly zero in all regions. MAEs for the PH interpolation were also small, typically averaging less than 1.1°C (2°F). MAEs were greatest in the western United States and Alaska because of the complexity of the landscape and the relatively sparse station coverage. The standard prediction error of the PRISM regression function was similar to the CV MAEs on a regional basis. The added error due to uncertainty in the interpolation of the predictor grid (1971–2000 coldest-month minimum temperature) was difficult to quantify; CV MAEs for the predictor grid were similar to those of the PH interpolation.

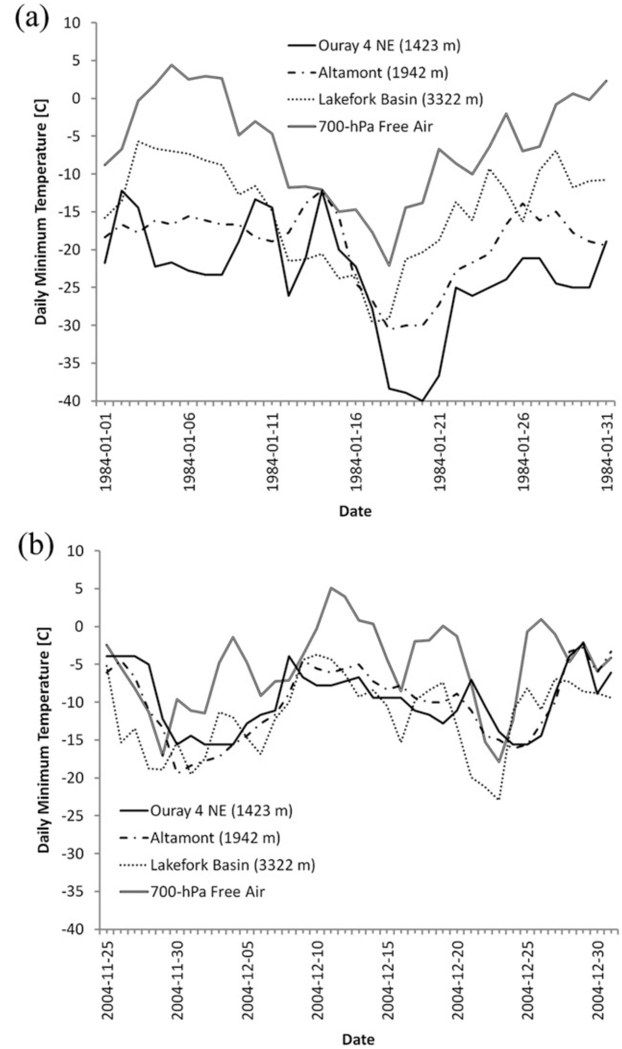


FIG. 13. Daily minimum temperature at three stations in the Uinta Mountains/Green River area of northeastern Utah and 700-hPa mean daily temperature from the NCEP Reanalysis 2 (40°N, 110°W grid point) for two periods, each encompassing an annual extreme minimum temperature event: (a) 1–31 Jan 1984 and (b) 25 Nov–31 Dec 2004. The definition of a ''day'' differs among the four data sources: 1800–1800 local standard time (LST) at Ouray 4 NE and Altamont, 0000–0000 LST at Lakefork Basin, and 0500–0500 LST for the NCEP Reanalysis 2; therefore, a daily temperature event could be shifted by ±1 day among these time series. See Fig. 11 for station locations.

The updated PHZM is generally warmer by one half zone than the 1990 PHZM map over much of the United States. In the central and eastern United States, the more recent averaging period is the main source of zonal change, whereas in the western United States a more sophisticated interpolation technique, greater spatial detail, and more comprehensive station set, especially in the mountains, are key sources of zonal change between the 1990 PHZM and the current PHZM.

The standard deviation map indicated that variability of the PH statistic is greatest in areas with transient Arctic airmass exposure, the strength and frequency of which are related to upper-air flow pattern and strength. Trends in the PH statistic over the past 30 years, estimated by 1976–90 versus 1991–2005 difference maps, indicate that the frequency of extreme cold events has decreased across much of the conterminous United States. The PH statistic generally warmed at least one half zone, with a warming of two half zones occurring over large parts of the central and eastern United States, as well as the Pacific Northwest. The modal zone in the conterminous United States has shifted a full zone from 5b in 1976–1990 to 6b in 1991–2005. Alaska experienced warming of one half zone, evenly distributed over about one-half of its area, whereas Hawaii and Puerto Rico had only small zonal changes.

A detailed analysis in northeastern Utah's Uinta Mountains and adjacent Green River Valley exemplified the complex vertical gradients that can occur in the mean, variability and trends of the PH statistic. In this region, warming of the PH statistic over the past thirty years has been greatest in the valley floor, because of a decrease in the frequency and intensity of Arctic outbreaks and accompanying cold-air pooling and inversions. In addition, maps of the range of possible zone boundaries within the 95% prediction interval of the PRISM regression function illustrated that zonal boundaries should be thought of as fuzzy and indistinct rather than as hard and precise.

Although winter low-temperature events reflected by the PH statistic are a major determinant of plant adaptation, other climatic factors also influence plant survival and performance (Widrlechner 1994). Thus, USDA PH zones are more effectively applied in conjunction with data that reflect these additional factors, which may vary by plant species or location (Vogel et al. 2005). Common factors include measures of high temperature, such as heat-unit accumulation, required for plant growth and reproduction (e.g., Pigott 1981; Pigott and Huntley 1981), or extreme, high-temperature events (Cathey 1997) and high nighttime temperatures (Deal and Raulston 1989), both of which can cause physiological injury; measures of water relations (Stephenson 1990, 1998), as quantified through various moisture-balance indices (Mather and Yoshioka 1968); and consistency of cloud and snow cover (Sabuco 1989).

An extreme example in which PH zones are clearly best interpreted in light of other climatic factors was described in section 5a, where the Gulf of Alaska coastline and Aleutians were noted as being assigned to the same zone as southern Alabama. The American Horticultural Society's Plant Heat-Zone Map (Cathey 1997) highlights this difference: the areas in Alaska experience less than one day of temperatures above 30°C (86°F) each year whereas those in Alabama typically experience more than 120 days. Even where both hardiness zones and summer temperatures are roughly equivalent, such as in northwestern Kansas and southeastern Indiana, dry prairie and rangeland predominate in northwestern Kansas, very different from the native and cultivated flora in the diverse hardwood forests of southeastern Indiana. This can be explained mainly by regional differences in annual moisture balance (Widrlechner 1999), essential to the long-term survival of plants across the region (Widrlechner et al. 1992, 1998).

The development of geographic information systems (GIS) has enabled the simultaneous presentation of multiple variables, and various software packages have been developed to apply "climate envelopes," or known ranges of suitable climatic conditions, to describe or predict geospatial patterns of plant adaptation (Sutherst and Maywald 1999; Houlder et al. 2000; McKenney et al. 2007). However, such tools are generally most applicable to the characteristics of individual species and not for circumscribing zones that apply broadly across many different species. A challenge for the future development of hardiness zonation is how best to enlist GIS tools and sophisticated interpolation techniques for creating PHZMs that incorporate and weight appropriately all of the climatic factors that are key to the adaptation of a wide spectrum of perennial plants. In Canada, multivariate analysis has been applied to generate a modern PHZM (McKenney et al. 2001), building upon the pioneering work of Ouellet and Sherk (1967) and DeGaetano and Shulman (1990).

As our body of research on relationships among climatic factors and patterns of plant adaptation grows, opportunities will undoubtedly arise for the creation and refinement of the next generation of plant hardiness zone maps. We look forward to working with the horticultural research community to build upon those opportunities and create such maps for the United States.

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