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Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States

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ABSTRACT: Spatial climate data sets of 1971–2000 mean monthly precipitation and minimum and maximum temperature were developed for the conterminous United States. These 30-arcsec (~800-m) grids are the official spatial climate data sets of the U.S. Department of Agriculture. The PRISM (Parameter-elevation Relationships on Independent Slopes Model) interpolation method was used to develop data sets that reflected, as closely as possible, the current state of knowledge of spatial climate patterns in the United States. PRISM calculates a climate–elevation regression for each digital elevation model (DEM) grid cell, and stations entering the regression are assigned weights based primarily on the physiographic similarity of the station to the grid cell. Factors considered are location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain. Surface stations used in the analysis numbered nearly 13 000 for precipitation and 10 000 for temperature. Station data were spatially quality controlled, and short-period-of-record averages adjusted to better reflect the 1971–2000 period.

PRISM interpolation uncertainties were estimated with cross-validation (C-V) mean absolute error (MAE) and the 70% prediction interval of the climate–elevation regression function. The two measures were not well correlated at the point level, but were similar when averaged over large regions. The PRISM data set was compared with the WorldClim and Daymet spatial climate data sets. The comparison demonstrated that using a relatively dense station data set and the physiographically sensitive PRISM interpolation process resulted in substantially improved climate grids over those of WorldClim and Daymet. The improvement varied, however, depending on the complexity of the region. Mountainous and coastal areas of the western United States, characterized by sparse data coverage, large elevation gradients, rain shadows, inversions, cold air drainage, and coastal effects, showed the greatest improvement. The PRISM data set benefited from a peer review procedure that incorporated local knowledge and data into the development process.

KEY WORDS physiography; spatial climate; PRISM; interpolation; temperature; precipitation; rain shadow; cold air drainage; temperature inversion; coastal proximity; elevation; Daymet; WorldClim

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1. Introduction

Spatial climate data sets in digital form are currently in great demand. The most commonly used spatial climate data sets are gridded estimates of mean daily minimum and maximum temperature and total precipitation on a monthly time step, averaged over a nominal 30-year period. The demand for these data sets has been fueled in part by the linking of geographic information systems (GIS) to a variety of models and decision support tools, such as those used in agriculture, engineering, hydrology, ecology, and natural resource conservation.

Spatial climate data are often key drivers of computer models and statistical analyses, which form the basis for scientific conclusions, management decisions, and other important outcomes. It is therefore imperative that these data sets provide a realistic representation of the major forcing factors that affect spatial climate patterns. To achieve this high level of realism, methods used to create the data sets must explicitly account for these factors. A detailed discussion of these factors is given in Daly (2006), and a brief overview is provided here.

General circulation patterns are largely responsible for large-scale climate variations, and include the positions of storm tracks, prevailing wind directions, monsoonal circulations, and other defining features of a region's climate. It is assumed that most of these patterns occur at scales large enough to be adequately reflected in the station data, and therefore are not explicitly accounted for by interpolation methods. Physiographic features on the earth's surface, namely water bodies and terrain, modulate these large-scale climate patterns. Water bodies provide moisture sources for precipitation, and create

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complex temperature gradients along coastlines and in adjacent inland areas. Terrain effects include the direct effect of altitude on climate conditions, the blockage and uplift of major flow patterns by terrain barriers, and cold air drainage and pooling in valleys and depressions.

The relationship between elevation and precipitation is highly variable, but precipitation generally increases with elevation (Oke, 1978; Barry and Chorley, 1987). Exceptions are when terrain rises above the height of a moist boundary layer or trade wind inversion (Mendonca and Iwaoka, 1969). Blocking and uplifting of moisture-bearing winds amplifies precipitation on windward slopes, especially those with steep windward inclines, and can sharply decrease it on leeward slopes downwind, producing rain shadows (Smith, 1979; Daly *et al*., 1994, 2002).

Temperature exhibits a strong, predictable decrease with elevation when the atmosphere is well mixed, such as occurs on summer days in inland areas (e.g. Willmott and Matsuura, 1995). The main summer exception is in coastal regions with well-defined marine layers, where maximum temperatures often increase with elevation above the marine inversion. Winter temperatures, and minimum temperatures in all seasons, have a more complex relationship with elevation. In the absence of solar heating or significant winds to mix the atmosphere, temperatures stratify quickly, and cool, dense air drains into local valleys and depressions to form pools that can be hundreds of metres thick (Geiger, 1964; Hocevar and Martsolf, 1971; Bootsma, 1976; Gustavsson *et al*., 1998; Lindkvist *et al*., 2000; Daly *et al*., 2003). This results in temperature inversions, in which temperature sharply increases, rather than decreases, with elevation (Clements *et al*., 2003). In Polar regions, widespread regional inversions hundreds of kilometres in extent can dominate wintertime temperature patterns (Milewska *et al*., 2005; Simpson *et al*., 2005). Terrain can also serve as a barrier between air masses, creating sharply defined horizontal temperature gradients.

Coastal effects on temperature are most noticeable in situations where the water temperature is significantly different from the adjacent land temperature (Haugen and Brown, 1980; Atkinson and Gajewski, 2002). Along the California coastline during summer, the contrast between the cool Pacific Ocean and the adjacent warm land mass can create daytime air temperature gradients of more than 10 °C in just a few kilometres across the coastal strip (Daly *et al*., 2002).

The above factors are most important at scales from less than 1 km to 50 km or more (Daly, 2006). Several additional spatial climate-forcing factors are most important at relatively small scales of less than 1 km, but can have influences at larger scales as well. These factors include slope and aspect (McCutchan and Fox, 1986; Barry, 1992; Bolstad *et al*., 1998; Lookingbill and Urban, 2003; Daly *et al*., 2007), riparian zones (Brosofske *et al*., 1997; Dong *et al*., 1998; Lookingbill and Urban, 2003), and land use/landcover (Davey and Pielke, 2005). Land use/landcover variations are a major consideration in the spatial representativeness of climate stations at much larger scales. For example, stations located near parking lots, buildings, or other heat-absorbing surfaces may have very different temperature regimes than those in open grasslands or heavily vegetated areas (Davey and Pielke, 2005). In data-sparse regions, a single station, and its particular land use/landcover regime, may influence the interpolated climate conditions for tens of kilometres around that station.

This paper describes the development of spatial climate data sets of 1971–2000 mean monthly total precipitation and daily minimum and maximum temperature across the conterminous United States, using methods that strive to account for the major physiographic factors influencing climate patterns at scales of 1 km and greater. These data sets, created at 30-arcsec (∼800-m) grid resolution, were commissioned by the U.S. Department of Agriculture through the Natural Resources Conservation Service (USDA-NRCS) to serve as the official spatial climate data sets of the USDA. They are updates of the 2.5-arcmin (∼4-km) 1961–1990 spatial climate data sets developed in the 1990s (USDA-NRCS, 1998). The new data sets were interpolated using the latest version of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system. Section 2 of this paper describes the study area and the digital elevation model (DEM) used. In Section 3, the preparation of station data is described. Section 4 provides an overview of the PRISM climate mapping system for this application, and summarizes the modelling, review, and revision process. Section 5 presents the resulting gridded data sets, discusses model performance, and compares and contrasts the PRISM data sets to two other spatial climate data sets. Concluding remarks are given in Section 6.

2. Study area and digital elevation model

Climate data sets were developed at 30-arcsec resolution in geographic (lat./long.) coordinates. A 30-arcsec grid cell is approximately 900 × 700 m at 40°N latitude, and is referred to as '800 m' after the discussion of the elevation grid in the next section. The boundaries of the grid were 22 and 50°N and 65 and 125 °W. Memory, CPU, and model parameterization considerations required that interpolation be performed separately in three regions: western, central, and eastern United States, and the resulting grids merged to form a complete conterminous U.S. grid.

Care was taken to include as many islands offshore the U.S. mainland as possible, but undoubtedly some very small islands were missed. To accommodate GIS shoreline data sets of varying quality and resolution, the modelling region was extended offshore several kilometres and generalized to include bays and inlets (Table I). However, the gridded climate estimates are valid over land areas only.

The DEM was the single most important grid input to the interpolation; it provided the independent variable for the PRISM elevation regression function and served as

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