Development of High-Quality Spatial Climate Datasets for the United States*

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ABSTRACT

A number of peer-reviewed, spatial climate datasets of excellent quality and detail for the United States are now available. The datasets are suitable for a variety of modeling, analysis, and decision-making activities. These products are the result of collaboration between Oregon State University, USDA-NRCS, and other agencies. The development of high-quality maps was made possible through the use of PRISM, a climate analysis system that uses point climate data, a digital elevation model, and other spatial datasets to generate gridded, GIS-compatible estimates of annual, monthly and event-based climatic elements. Mapped elements currently available include 1961-90 mean monthly and annual precipitation, maximum temperature, minimum temperature, snowfall, heating and cooling degree days, growing degree days, median last spring and first fall frost dates, and mean growing season length. In addition, century-long time series of monthly precipitation and minimum and maximum temperature will soon be available for the lower 48 states.

1. INTRODUCTION

The demand for spatial data sets of climate elements in digital form has risen dramatically over the past several years. This demand has been fueled by the maturation of computer technology enabling a variety of hydrologic, ecological, and natural resource models and expert systems to be linked to geographic information systems (GIS). In turn, the use of such model/GIS linkages has stemmed partially from the increasingly complex nature of today's environmental issues, requiring multiple layers of spatial information to be analyzed in a relational manner.

Over the past several years, innovative methods for mapping climatic elements have been developed at Oregon State University (OSU). The ultimate goal of this work is to describe the climatic environment of the world in a detailed, scientifically defensible manner. A major focus has been the ongoing development and enhancement of PRISM (Parameter-elevation Regressions on Independent Slopes Model), a hybrid statistical-geographic approach to mapping climate (Daly and Neilson 1992, Daly et al. 1994, 1997). PRISM retains many of the predictive advantages of statistical techniques, while emphasizing a geographic approach that is lacking in the more generalized statistical methods. PRISM uses point data, a digital elevation model (DEM), and other spatial datasets to generate estimates of annual, monthly and event-based climatic parameters that are gridded and GIS-compatible (Daly et al. 1994, 1997). PRISM is not a static system of equations; rather, it is a coordinated set of rules, decisions, and calculations, designed to accommodate the decision-making process an expert climatologist would invoke when creating a climate map. Because information is gathered each time PRISM is applied to a new region or climatic element, PRISM is kept as open-ended and flexible as possible to reflect our current state of knowledge.

Originally developed for precipitation estimation, PRISM has been generalized and applied successfully to temperature and weather generator parameters, among others (Johnson et al. 1997). It has been used extensively to map precipitation and temperature over the United States, Canada, and other countries. PRISM is unique in that it has been used to produce the highest quality maps available; maps that represent the state of knowledge via rigorous peer review. This is primarily due to the emphasis on tools that faithfully reproduce climate patterns in the most demanding regions and situations.

This paper provides an introduction to the PRISM modeling system, an overview of the PRISM evaluation process, and a discussion of several climate mapping projects underway. Finally, digital map products available for download from our Web site are presented. Further information on PRISM map products available through the USDA-NRCS are given in a companion paper by Johnson et al. (1998).

2. INTRODUCTION TO PRISM

In our ongoing attempts to produce physically realistic and detailed climate maps, PRISM has had to accommodate many difficult situations in innovative ways. Model features discussed here include a weighted linear regression for the vertical extrapolation of climate, a two-layer model that allows for temperature inversions and mid-slope precipitation maxima, methods for incorporating hillslope orientation to handle rain shadows, and a coastal proximity measure for reproducing extreme climate gradients near coastlines.

2.1 CLIMATE EXTRAPOLATION OVER LARGE ELEVATION RANGES

The most common lament of climatologists is the lack of observations just where they need them most: at high elevations in remote, mountainous areas. In these regions, the analyst must often settle for extrapolating climate over large elevation ranges. Because most climate elements bear strong relationships with elevation, the ability of a model to extrapolate vertically to elevations beyond those for which stations exist is of paramount importance. PRISM calculates linear climate-elevation relationships, and the slope of this line changes locally with elevation as dictated by the data points. Beyond the lowest or highest station, the profile becomes linear and can be extrapolated as far as needed. Station observations entering into the regression are weighted by distance, elevation, atmospheric vertical layer, hillslope orientation (i.e., topographic facet), proximity to a coastline, and other factors.

Some cases arise for which an indefinite, monotonic extrapolation of a climate element with elevation is unrealistic. Here are two examples:

In coastal areas, enhanced precipitation may result from uplift of a moist, but shallow, boundary layer by mountainous terrain as it moves inland, causing increasing precipitation with increasing elevation. Above this layer, the atmosphere becomes drier, causing precipitation to decrease with elevation. The west coast of the U.S., as well as areas in the subtropics, such as Central America and Hawaii, experience this effect.

During winter, inland valleys often experience persistent temperature inversions that are easily seen in the climatic record. In Colorado's Alamosa Valley and Montana's Bighorn Valley, for example, increases in January minimum and maximum temperatures of 25-30EC/km elevation are not uncommon. If one were to extrapolate these lapse rates upwards into the surrounding mountains, the predicted temperature would be wildly unrealistic.

To simulate these situations, PRISM allows climate stations to be divided into two vertical layers, with regressions done on each separately. Layer 1 represents the boundary layer and layer 2 the free atmosphere. The thickness of the boundary layer may be prescribed to reflect the height of the marine boundary layer for precipitation, or the mean wintertime inversion height for temperature. Preliminary methods have been developed to spatially distribute the height of the boundary layer to a grid. For temperature, the elevation of the top of the boundary layer is estimated by using the elevation of the lowest DEM pixels in the vicinity as a base, and adding a climatological inversion height to this elevation. As a result, large valleys tend to fall within the boundary layer, while local ridge tops and other elevated terrain jut into the free atmosphere (Johnson et al. 1997).

2.2 RAIN SHADOWS AND COASTAL EFFECTS

Regions influenced by varying topography or large water bodies are often characterized by transitions among several climatic regimes. In these situations, the relationship between a climate element and elevation is not constant across the landscape. Because this problem is so common, a model must be able to adapt to these shifting relationships. PRISM continually changes its frame of reference by calculating a separate climate-elevation regression for each pixel, selecting stations falling within a local window around the pixel. This method is especially valuable for preserving locally unusual regimes that would otherwise be considered "noise" in an all-encompassing statistical relationship.

Even the moving-window approach described above is insufficient to capture certain gradients in climate regime. These fall into two main categories:

(1) Abrupt rain shadows, occurring on the leeward slopes of mountain ranges. Precipitation may drop by more than 75% within a zone of just 10-20 kilometers.

(2) Coastal effects on temperature and precipitation. For example, summer maximum temperature gradients can exceed 20EC within thin coastal strips.

To accommodate such gradients, PRISM takes advantage of DEM information that goes beyond a simple estimate of elevation. We recognize that in complex terrain, climatic patterns are defined and delineated by topographic barriers, creating a mosaic of hill slopes, or "facets," each potentially experiencing a different climatic regime (Gibson et al. 1997). Topographic facets can be delineated at a variety of scales, ranging from the major leeward and windward sides of large mountain ranges, to north- and south-facing hill slopes experiencing different radiation and temperature regimes. At each pixel, PRISM chooses the topographic facet scale that best matches the data density and terrain complexity, and assigns the highest weights to stations on the same topographic facet. PRISM also attempts to assess the climatic significance of the facets, merging those that have little significance.

While highly effective in reproducing rain shadows, topographic facets can be of limited usefulness along coastal strips. Sites along and near a coastline might typically be seen as belonging to one facet orientation, separated from sites on the inland side of coastal hills or mountains. However, within this coastal facet, it is the proximity to the water body that determines the climate regime. Therefore, coastal proximity grids have been developed that inform PRISM of the proximity of each pixel to the water. Stations are selected and weighted according to their similarity in coastal proximity to the grid cell being predicted. PRISM then tends to search along, rather than across, a coastline to find stations for its regression calculations.

3. PRISM EVALUATION

The PRISM modeling system and the climate maps it produces are routinely evaluated for climatological and statistical accuracy. Methods used to obtain and ensure optimum performance are summarized below.

3.1 STATISTICAL PARAMETERIZATION

PRISM predictions utilize a technique whereby the lowest possible prediction error is achieved. This is done through jackknife cross-validation with replacement, in which a station is omitted from the prediction equation, a new prediction is made for the station location, and the station is then replaced in the equation. This process is repeated for all stations. The combination of PRISM input parameter values that produces the lowest overall mean absolute prediction error (for the whole map) is typically used for final map production.

3.2 PEER REVIEW

While statistical optimization is a fairly routine procedure, it is rare to see climate map products and the methods used to prepare them evaluated for climatological reasonableness and accuracy. This is a critical part of the process, because observed climate data are very sparse or unavailable in many remote, mountainous regions. Experts are needed to provide skillful assessments based on a thorough meteorological knowledge of a given region, synthesized with information from sources such as short-term intensive observations, vegetation maps, and streamflow analyses.

In a project sponsored by the USDA NRCS Water and Climate Center, PRISM was used to prepare detailed maps of 1961-90 mean monthly and annual precipitation for all 50 states. An initial pilot project was conducted in which PRISM was applied to several western states, and the methodology and results rigorously peer-reviewed. The review was conducted by establishing a PRISM Evaluation Group, composed of State and Regional Climatologists, a National Climatic Data Center representative, a National Weather Service representative, and engineers, hydrologists, GIS experts and a meteorologist from the NRCS. Once PRISM was found to be a viable method for precipitation distribution, each state and regional climate office participated in map reviews as subsequent maps were produced. This was an in-depth process spanning several years in which each map was prepared in draft form, peer-reviewed, and revised to the satisfaction of the reviewers. A similar process is underway to evaluate draft PRISM minimum and maximum temperature maps.

4. CLIMATE MAPPING PROJECTS

Oregon State University is engaged in several projects to prepare detailed climate maps for the United States. Four of these projects are discussed below.

4.1 USDA-NRCS CLIMATE MAPPING PROJECT

The USDA-NRCS Water and Climate Center initiated a project with OSU several years ago to produce peer-reviewed maps of major climatic elements for the United States and its possessions. These maps were to be of sufficient accuracy and detail to be suitable for use by field offices and decision-makers, and for scientific modeling and analysis. All maps were to be based on standard monthly and annual normal observations from National Weather Service cooperative stations and NRCS Snotel sites for the period 1961-1990. As of February 1998, monthly and annual precipitation maps for the lower 48 states have been reviewed and finalized. Maps for Hawaii and Alaska, Puerto Rico, and the Pacific Islands are under development. Draft minimum and maximum temperature maps for the lower 48 states have been completed, and are in peer-review. Finalized temperature and precipitation maps for all states and possessions are expected to be completed by the end of 1998. Draft maps of mean monthly dew point, frost dates, extreme minimum temperature and related elements will also be completed by the end of the year. Further information on this project can be found in a companion paper by Johnson et al. (1998). The contact for this project is Greg Johnson at the NRCS Water and Climate Center, in Portland, Oregon (gjohnson@storm.wcc.nrcs.usda.gov).

4.2 NOAA-NCDC CLIMATE ATLAS

The National Climatic Data Center is working with OSU to develop a new climate atlas for the United States, last produced in 1968. The completed atlas will be available on the Web and CD-ROM, and include thousands of national maps of many climatic elements. The project is divided into three phases. Phase one, recently completed, involved successfully developing and testing simple statistical methods that can be used to derive maps of climate elements from existing high-quality maps of precipitation and temperature (produced under the NRCS project). Examples are the derivation of growing degree days from mean monthly temperature and frost dates from minimum monthly temperature. Developing these relationships precludes a costly mapping effort for each of the many elements involved. Phase 2, beginning this spring and ending in early 1999, will see the production of national maps for many climate elements. Phase 3, to be performed in 1999, will complete the atlas. The NCDC contact for this project is Marc Plantico (MPLANTIC@ncdc.noaa.gov).

4.3 VEMAP 99-YEAR BIOCLIMATE TIME SERIES

VEMAP (Vegetation-Ecosystem Modeling and Analysis Project) is a multi-institutional, international effort addressing the response of ecosystems to environmental variability. A main objective of VEMAP is to compare and contrast the responses of various ecological models to changing climate and elevated carbon dioxide concentrations. Such a comparison requires a common input climate dataset as a driver. Further, this climate dataset must be a true time series, not a long-term mean. To this end, OSU developed 0.5-degree resolution grids of monthly precipitation and minimum and maximum temperature for the years 1895-1993. A complete station dataset, with all missing months infilled, was prepared by the National Center for Atmospheric Research (NCAR). The gridded climate maps are now in beta-test, and will be released to the public in late 1998. The contact for this project is Tim Kittel at NCAR (Tim_Kittel@qgate.ucar.edu).

4.4 NOAA-NASA HIGH-RESOLUTION, 100-YEAR TIME SERIES

OSU, NCAR, and NCDC are in the first year of a three-year effort to produce 100 years of monthly precipitation and minimum and maximum temperature for the lower 48 states. These datasets are similar to those produced for VEMAP, except that they are high-resolution (~4 km) grids. A draft precipitation dataset will be available in September 1998. Final precipitation and draft temperature datasets will be produced in September 1999, and the temperature datasets will be finalized in September 2000. It is envisioned that the final datasets will be distributed by NCDC on CD-ROM. These climate grids will provide a vast resource to climate researchers, modelers, and managers who wish to assess how the climate of their region has varied over the past century. At 4-km resolution, topographic details are preserved, giving an unprecedented glimpse of past climate in remote, mountainous regions. The contact for this project is Chris Daly at OSU (daly@fsl.orst.edu).

5. PRISM PRODUCTS ON THE WORLD WIDE WEB

Many national and state climate maps are available from the PRISM Web site maintained by the Oregon Climate Service:

http://prism.oregonstate.edu

Maps are available in four formats: gridded ASCII, ARC/Info color polygon coverages, GIF graphic representation, and hard copy. The largest selection of maps is available in gridded form, the format used by PRISM. Grid resolution is 2.5-min latitude/longitude (~4 km). As of February 1998, gridded national maps could be downloaded for 1961-90 mean monthly precipitation, minimum and maximum temperature, temperature range, snowfall, growing degree days, heating and cooling degree days, and median first and last frost dates; more elements will undoubtedly been added this spring. Both ARC/Info and GRASS GIS grid formats are available. Accompanying readme files provide details on material and methods for each climatic element, and give important information on the developmental status of the maps. State and regional maps for 1961-90 mean monthly precipitation are also available in gridded form. State temperature maps, plus other elements, will be added when finalized. State ARC/Info color polygon coverages are now available for mean annual precipitation, with more elements to follow. These coverages are high-quality representations with labeled contours and color-filled intervals. State, regional and national color GIF images of mean annual precipitation can also be downloaded for use in printing and display. Hard copy maps of mean annual precipitation for a state, region, or the United States can be ordered from the Oregon Climate Service. Information on maps sizes, regions, costs, and ordering can be found on the PRISM Web site.

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6. SUMMARY

The demand for spatial data sets of climate elements in digital form has risen dramatically over the past several years. As a result of collaboration with the USDA-NRCS Water and Climate Center and other agencies, Oregon State University has produced a number of peer-reviewed, spatial datasets of excellent quality and detail. Many of these datasets are available via the World Wide Web. Elements include 1961-90 mean monthly and annual precipitation, maximum temperature, minimum temperature, average temperature, and snowfall; heating and cooling degree days, growing degree days (at various base temperatures), median last spring frost and first fall frost (0C) dates, and mean growing season length (in days). Datasets were modeled in gridded form at a resolution of 2.5 minutes (~ 4 km). In addition, a 99-year time series of monthly precipitation and minimum and maximum temperature at 0.5-degree (~ 50 km) resolution was constructed as part of the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP). Currently under development is a high-resolution (2.5-min), 100-year time series of monthly precipitation for the U.S.

These map products are being developed using PRISM (Parameter-elevation Regressions on Independent Slopes Model), a climate analysis system that uses point data, a digital elevation model (DEM), and other spatial datasets to generate gridded estimates of annual, monthly and event-based climatic parameters. It has been designed to accommodate difficult climate mapping situations in innovative ways. These include vertical extrapolation of climate well beyond the lowest or highest station, and reproducing gradients caused by rain shadows and coastal effects. PRISM is not a static system of equations; rather, it is a coordinated set of rules, decisions, and calculations, designed to accommodate the decision-making process an expert climatologist would invoke when creating a climate map. Because information is gathered each time PRISM is applied to a new region or climatic element, PRISM is kept as open-ended and flexible as possible to reflect our current state of knowledge.

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