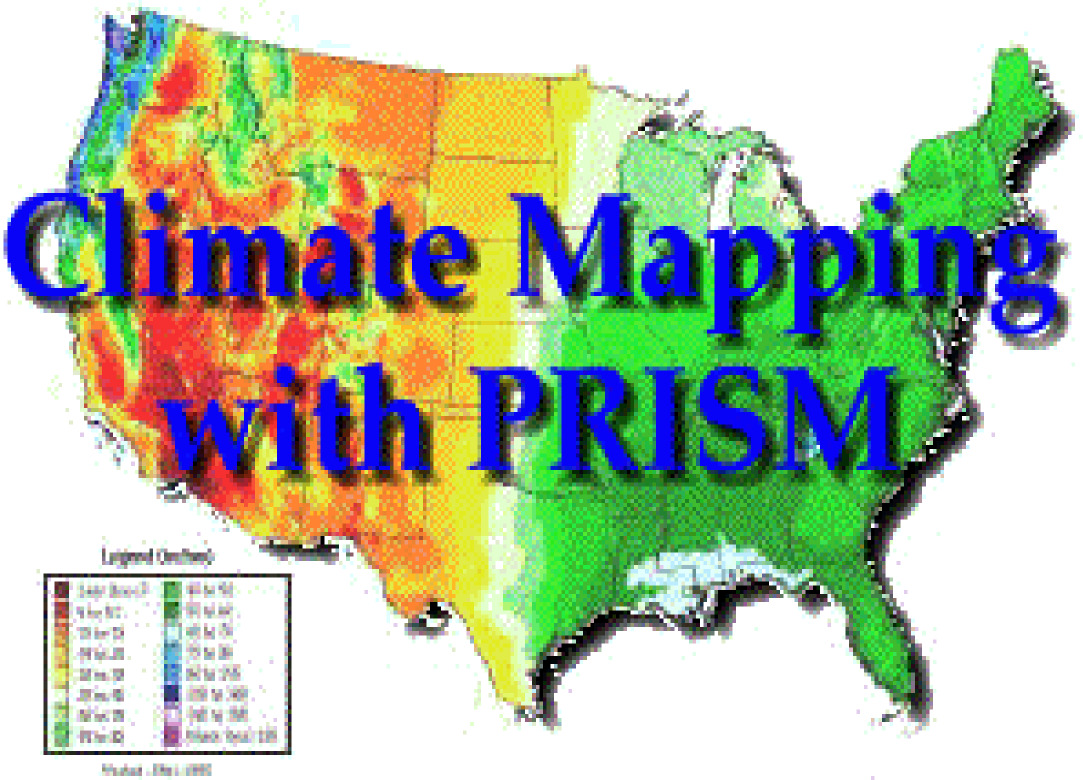
PRISM Spatial Climate Layers



An introduction to PRISM (Parameter-elevation Regressions on Independent Slopes Model), developed by the Spatial Climate Analysis Service at Oregon State University and used to produce spatial climate products

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I. Development of the PRISM Climate Layers

The overall objective in developing the PRISM climate layers for the United States was to use station data and other spatial data sets to estimate patterns of climate in a spatially representative and physically meaningful way. The resulting climate layers are unprecedented in their combination of physically realistic detail and comprehensive spatial extent. In this section, we give an overview of the PRISM modeling system and how it addresses major climate mapping issues; then summarize the methods used to construct the PRISM climate grids, which are the basis for all of the digital map layers.

I.A. Background

PRISM was developed to help meet the rising demand for spatial data sets of climate elements in digital form. This demand has been fueled by the maturation of computer technology, enabling a variety of hydrologic, ecological, and natural resource models 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.

Historically, methods for mapping climate from point observations have fallen into two main categories: geographical and statistical. Geographical techniques dominated climate mapping for the first three-fourths of this century. They involve the manual preparation of climate maps, primarily of precipitation, and topographic analyses involving the correlation of point climate data with an array of topographic and synoptic parameters. During the late 1970s, methods of climate distribution became largely statistical. Such methods include distance-weighting algorithms, kriging, splining, and multivariate analyses. The switch to statistical methods corresponded to the advent of the computer as a common workplace tool.

In 1991, computerized GIS and visualization technology had developed sufficiently to allow the development 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. This technique seeks to integrate into a predictive system the vast store of information concerning climate processes, variation and pattern accumulated from geographical studies.

I.B. PRISM Overview

PRISM uses point data, a digital elevation model (DEM), and other spatial data sets to generate estimates of annual, monthly and event-based climatic elements that are gridded and GIS-compatible. 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, it is kept as open-ended and flexible as possible to reflect our current state of knowledge.

1.B.1 Governing Equation - The General Elevation Regression Function

The strong variation of climate with elevation is the main premise underlying the model formulation. PRISM adopts the assumption that for a localized region, elevation is the most important factor in the distribution of temperature and precipitation. Observations from many parts of the world show the altitudinal variations of temperature and precipitation to approximate a linear form.

Available station data often do not span the complete range of elevations in an area, especially in mountainous regions. Therefore, vertical extrapolation is required. This is accomplished in PRISM at each DEM grid cell (termed the target grid cell) through a simple linear climate-elevation regression. This regression function serves as the main predictive equation in the model. A linear regression was chosen over nonlinear methods such as polynomial regression and curve-fitting functions such as splining, because: (1) altitudinal variations of climate often approximate a linear form; (2) the linear function can be extrapolated in a stable fashion far beyond the elevational range of the data; and (3) the linear function can be easily manipulated to compensate for inadequacies in the data, which are rarely sufficient to fully represent the vertical distribution of the climate element. A simple, rather than multiple, regression model was chosen because it is difficult to control and interpret the complex relationships between multiple independent variables and climate. Instead, much effort has gone into controlling for the effects of variables other than elevation by weighting the data points based on numerous factors, as will be discussed later.

The simple linear regression has the form

$$Y = \beta_1 X + \beta_0$$

where Y is the predicted climate element, β_1 and β_0 are the regression slope and intercept, respectively, and X is the DEM elevation at the target grid cell. The climate-elevation regression is developed from x,y pairs of elevation and climate observations supplied by station data in the local area.

1.B.2 Station Weighting

Upon entering the regression function, each station is assigned a weight that is based on several factors. The combined weight W of a station is a function of the following:

$$W = f \{ Wd , Wz , Wc , Wl , Wf , Wp , We \}$$

where Wd , Wz , Wc , Wl , Wf , Wp and We are the distance, elevation, cluster, vertical layer, topographic facet, coastal proximity, and effective terrain weights, respectively. Distance, elevation, and cluster weighting are relatively straightforward in concept. A station is down-weighted when it is relatively distant or at a much different elevation than the target grid cell, or when it is clustered with other stations (which leads to over-representation). Vertical layer, topographic facet, coastal proximity and effective terrain weights are discussed below.

I.C. Climate Mapping Issues

The level of sophistication necessary to accurately map a climate element depends on the characteristics of the region and the element to be mapped. Below is a list of questions that were asked when developing and applying PRISM for precipitation and temperature for the United States. Accompanying each question is a description of how PRISM handles the situation.

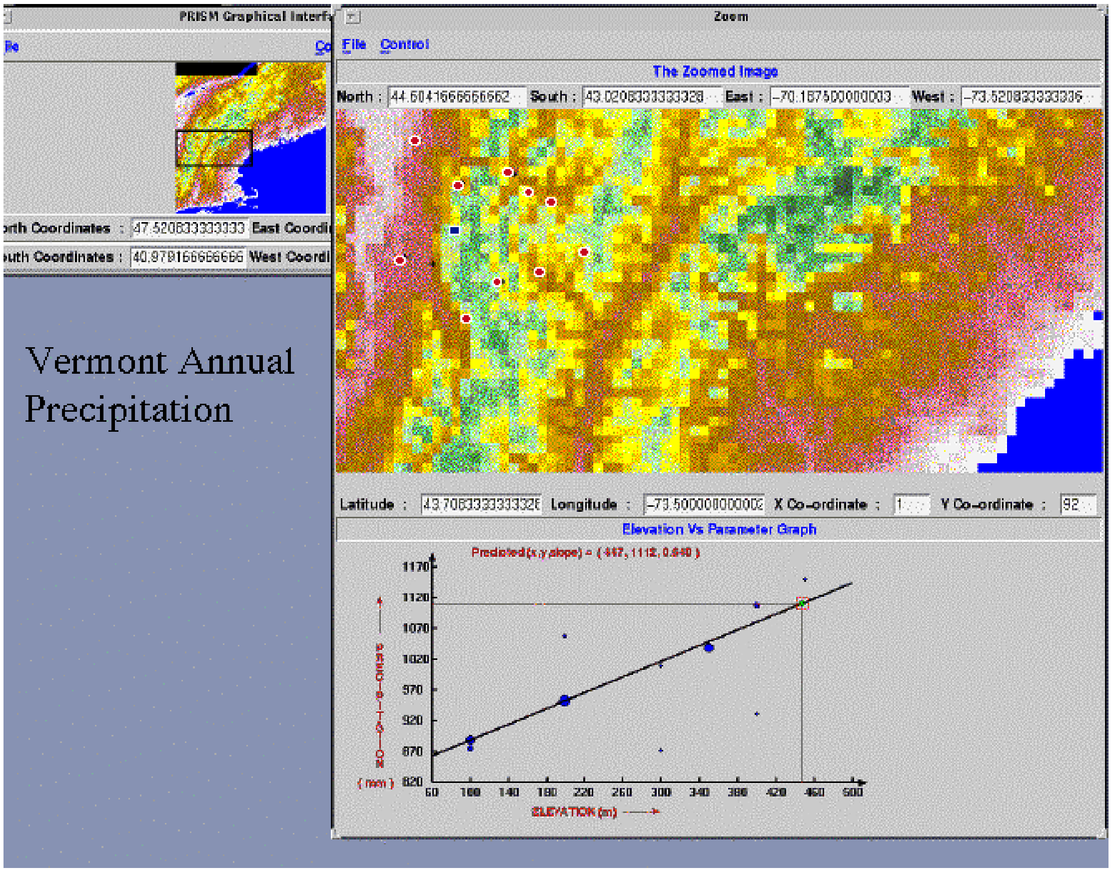
1. <u>Does the region contain any hills or mountains</u>?

This is the most basic question to be asked; it determines whether a two-dimensional mapping approach is adequate, or whether a three-dimensional approach is required. We have found that most regions have at least some terrain features, thus requiring a 3D approach. In fact, the governing equation in PRISM is a climate-elevation regression function. When low-relief (2D) situations are encountered within a region and precipitation is being modeled, PRISM transitions to a 2D interpolater. This is discussed further under the _low relief/high relief_ question. 3D interpolation is always assumed for temperature, because even minor terrain features are important to the thermal climate.

If yes to Question 1:

1a. <u>Does the climate-elevation relationship vary across the region</u>?

It is uncommon to encounter a region of any size that can be easily characterized with one overall relationship between climate and elevation, or even a multi-variate relationship between climate and elevation, latitude, and longitude. There are always numerous additional factors that need to be considered, such as coastal influence, barriers to moisture, etc. that are difficult to account for in a domain-wide manner. PRISM deals with this by localizing the climate-elevation relationship to a relatively small moving window. Each grid cell has its own, unique relationship (Figure 1-1).



orth Coordinates : 47.520833333333 East Coordi

uth Coordinates : 40.979166666666 West Coordi

North : 44.6041666666662 South : 43.0208333333328 East : -70.1675000000003 West : -73.5208333333336

Latitude : 43.7083333333332 Longitude : -73.500000000000 X Co-ordinate : 1 Y Co-ordinate : 92

Figure 1-1. Screen capture from the PRISM graphical user interface (GUI) showing a local mean annual precipitation-elevation relationship for stations (red dots) surrounding a grid cell (blue square) in the Green Mountains of Vermont. Sizes of the blue dots on the scatterplot indicate a station's relative weight in the regression function.

1b. Is there evidence of sharply-defined climate regimes delineated by terrain features?

The most common of these features is the rain shadow, caused by blockage of moisture-bearing air flow by topographic features. Rain shadows occur on the lee sides of many mountain ranges in the western U.S., as well as in interior valleys of the Appalachians. Mixing stations from windward and leeward exposures when creating the local climate-elevation regression function gives a very muddied and inaccurate picture of the situation. To identify stations that have a similar exposure as the target grid cell, PRISM divides the terrain into major topographic orientations, or facets, based on an eight-point compass. Facets are delineated at six different spatial scales to accommodate varying station density and terrain complexity (Figure 1-2). Stations on the same facet as the modeled grid cell are given the highest weight in the regression function. Others are downweighted accordingly (Figure 1-3).

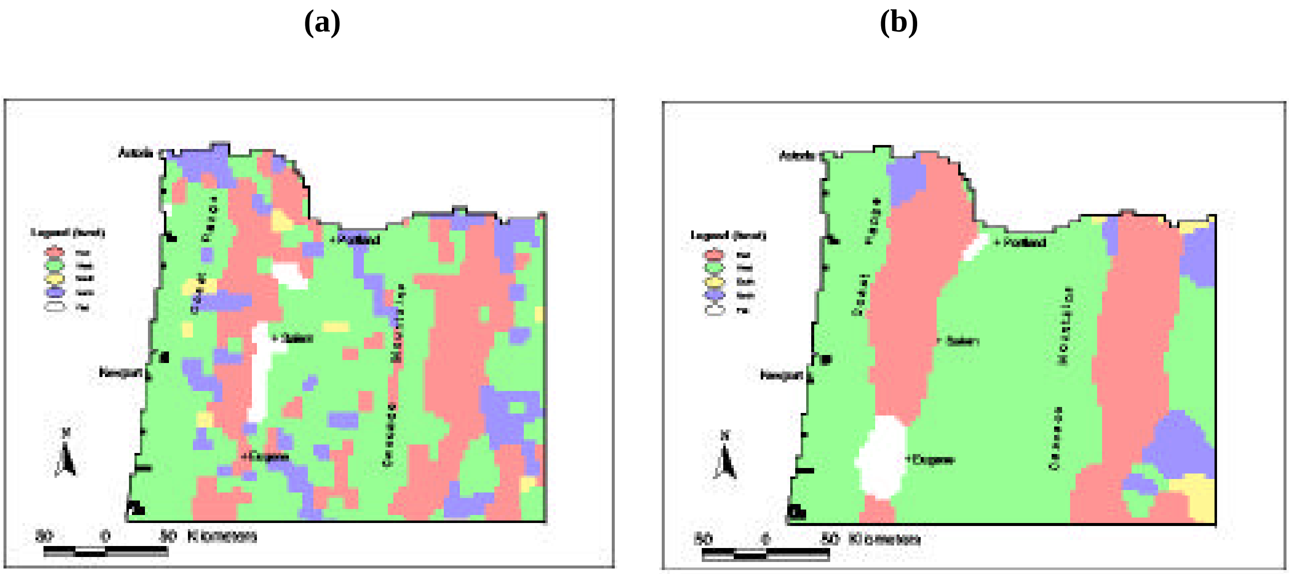


Figure 1-2. Topographic facet grids for
northwestern Oregon delineated at two spatial scales:
a) 2.5 minutes (~4 km); and b) 40 minutes (~60 km). The 8-point facet orientations are condensed into 4 classes - north, south, east, and west - to increase readability of the diagram.

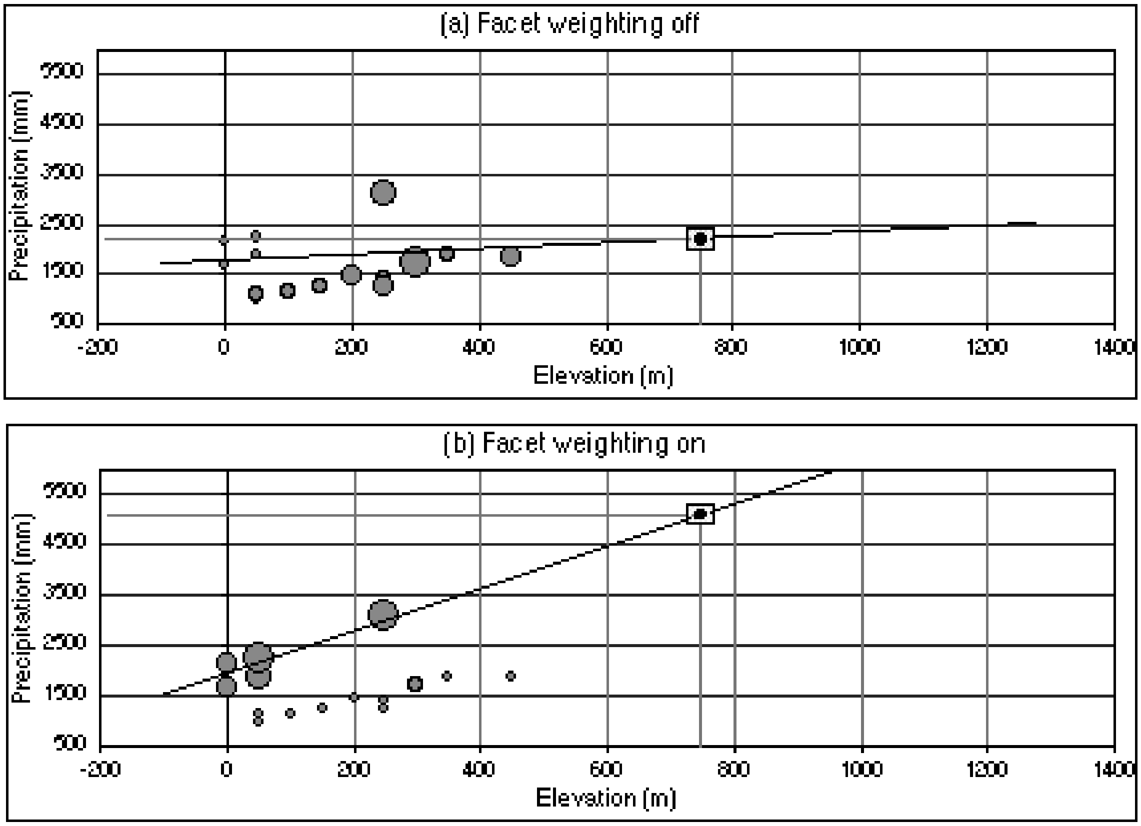


Figure 1-3. PRISM scatterplots and estimated regression lines for 1961-90 mean annual precipitation vs. elevation for a windward grid cell near the crest of the Coast Range in northwestern Oregon; a) without facet weighting; b) with facet weighting.

The Coast Range in northwestern Oregon, one of the wettest places in the continental United States, presents an example of a rain shadow. Figure 1-3 shows PRISM scatterplots of 1961-90 mean annual precipitation vs. elevation for a target grid cell at 775 m-asl, near the crest of the range on its windward exposure. Two distinct groups of stations representing different precipitation regimes are evident: a relatively wet, windward group, and a drier, leeward group. When the facet weighting is not used, PRISM mixes the two groups and predicts about 2250 mm for the target grid cell, which is well below that of windward stations at lower elevations. When facet weighting is used, the regression line moves into the windward position, largely ignoring the leeward influence (Figure 1-3). The precipitation prediction rises dramatically to over 5000 mm, which matches well with observed stream flow in nearby watersheds.

1c. <u>Is the climate-elevation relationship largely monotonic</u>?

It is not always sufficient to assume a monotonic change in climate with elevation. In coastal regions, orographic precipitation may result from uplift of a shallow boundary layer, causing mid-slope precipitation maxima to occur, with drying at higher altitudes. This has been documented in subtropical locations dominated by the trade wind inversion (e.g., Hawaii), but is also thought to occur in mid-latitude coastal areas, where the moist, marine layer is relatively shallow. Mid-elevation maxima can also occur in the case of temperature. For example, inland valleys often experience persistent temperature inversions during winter. In Colorado's San Luis Valley and Wyoming's Bighorn Valley, increases in mean January minimum and maximum temperatures of 2.5-3.0EC/100 m 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 divides climate stations entering the regression into two vertical layers. Layer 1 represents the boundary layer and layer 2 the free atmosphere above it. Stations in the same layer as the target grid cell receive full weight, while those in the adjacent layer receive lower weights. In essence, the layer weighting scheme limits the ability of stations in one layer to influence the regression function of the other.

Simple methods were used to create a potential wintertime inversion height grid for the U.S., which was used in the temperature mapping height grid was created by generating a grid of smoothed "base", or valley-bottom elevations, then adding a constant climatological inversion height to the base elevations (Figure 1.4).

Analyses of radiosonde data from several cities in the United States with persistent wintertime inversions indicated that the inversion top typically occurred at 200-300 m above ground level. The inversion top was quite consistent; when an inversion formed, it tended to do so at about the same height each time. Therefore, 250 m was added to the base elevation at each pixel to obtain the potential inversion height above sea level.

For precipitation mapping, a constant height of 2500 m was used for marine-dominated regions along the West Coast. In recent mapping work in Hawaii, a constant height of 1000 m was used (Figure 1-5, Figure 1-6).

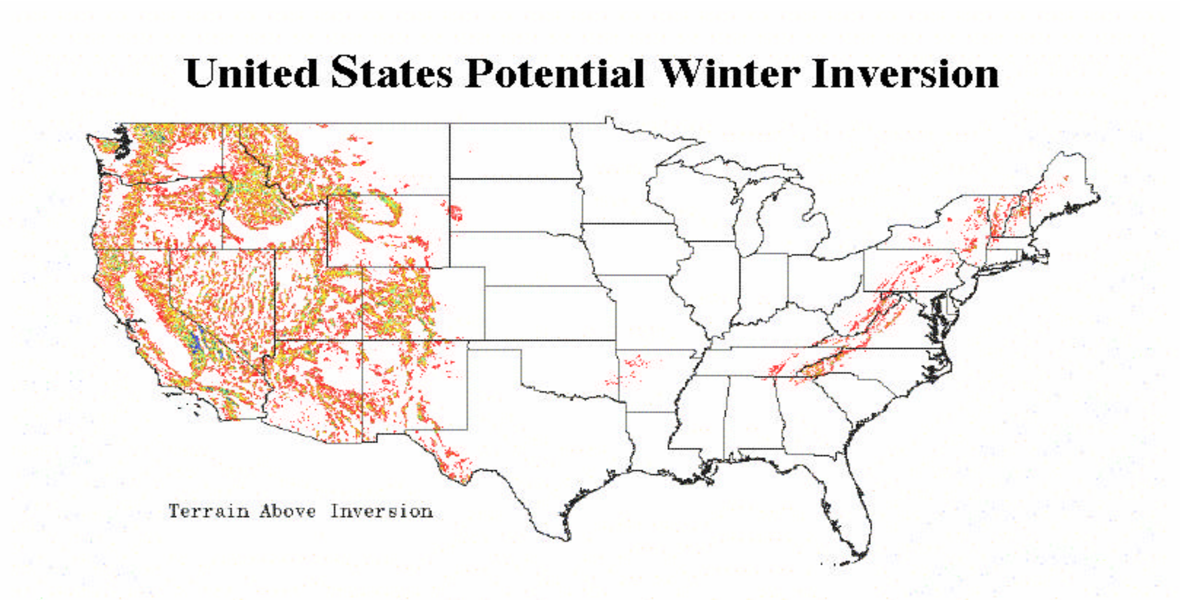


Figure 1-4. Estimated wintertime inversion layer grid for the U.S. Shaded areas denote terrain estimated to be in the free atmosphere (layer 2) under winter inversion conditions, should they develop. Unshaded areas are expected to be within the boundary layer (layer 1). Grid resolution is 2.5 minutes (~ 4 km).

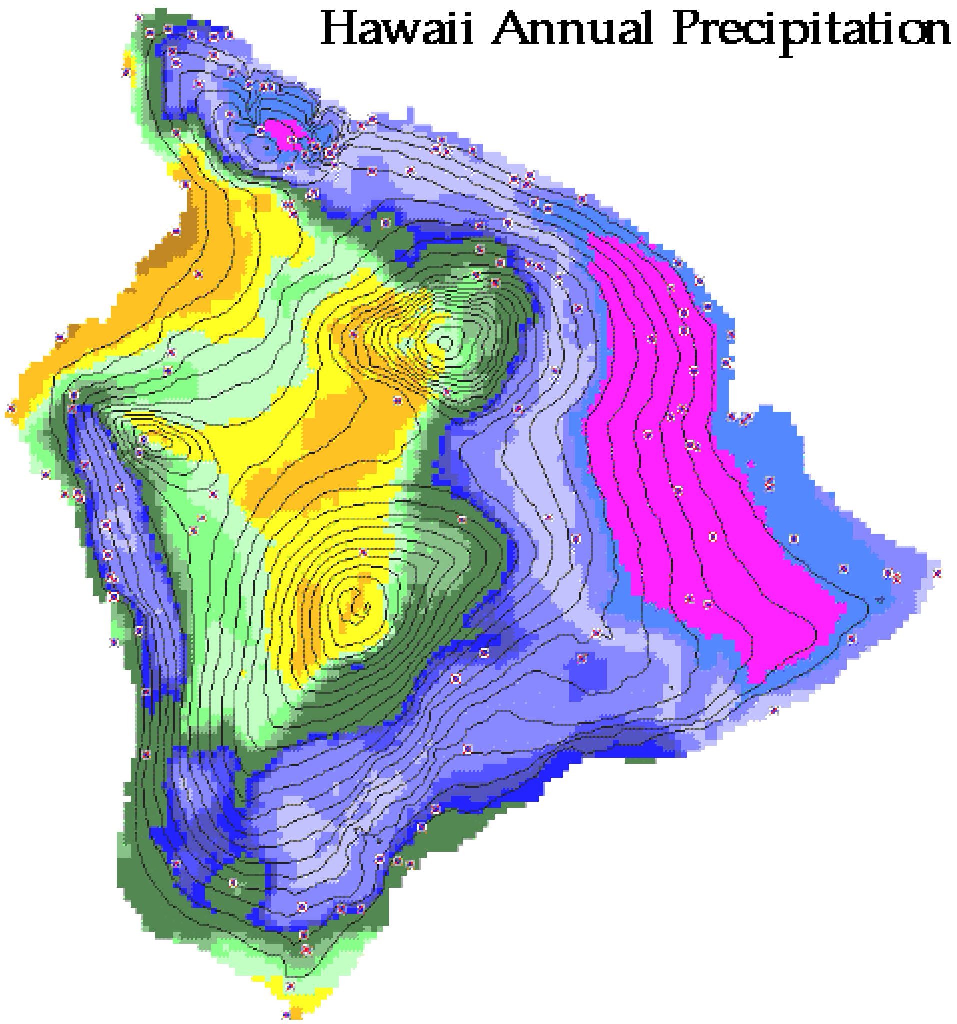


Figure 1-5. PRISM mean annual precipitation for Hawaii. Magenta area on the eastern side of the Mauna Kea and Mauna Loa volcanoes is the area of maximum precipitation. Mauna Kea is the northern volcano. Black lines are elevation contours; dots are climate station locations.

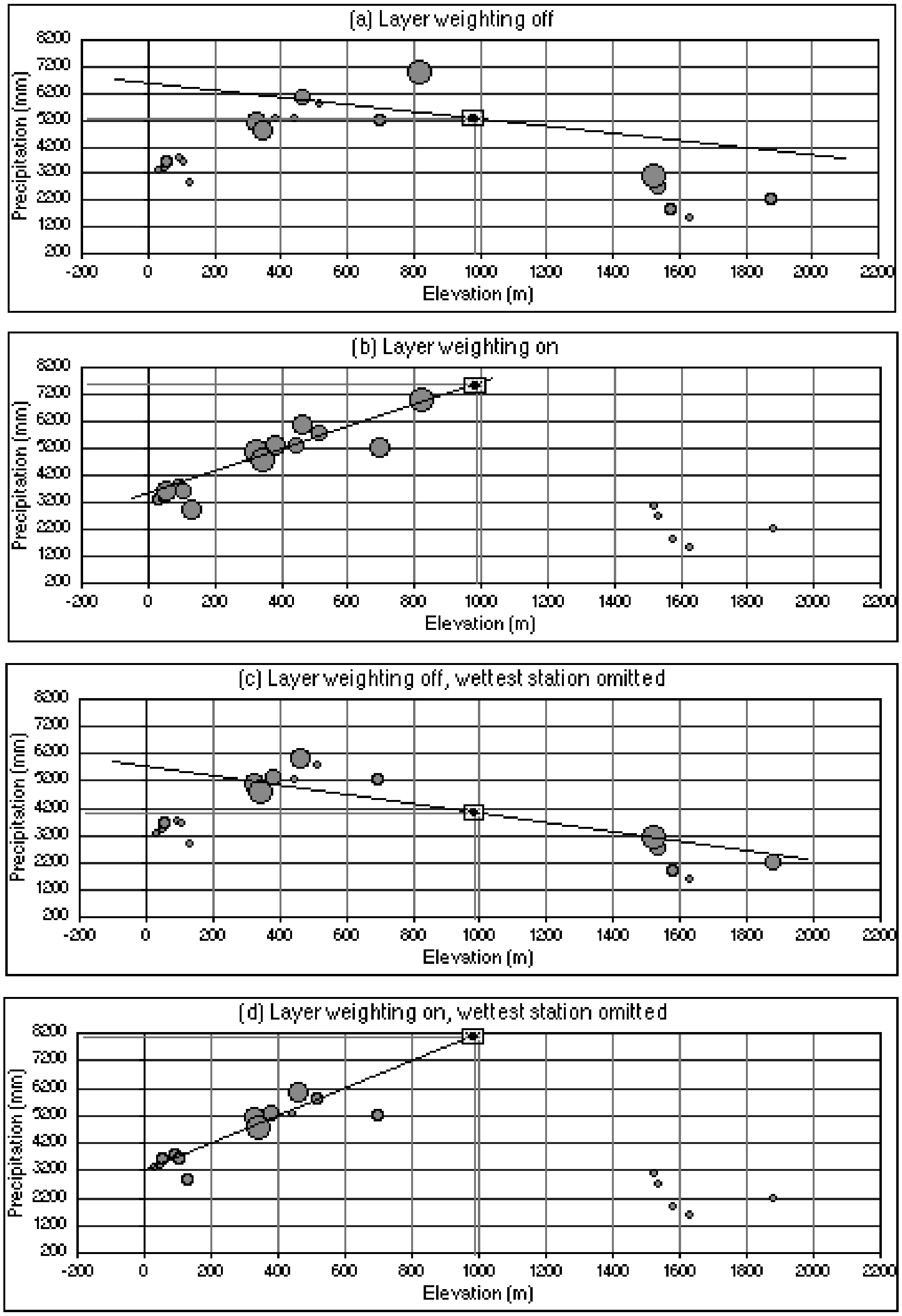


Figure 1-6. PRISM scatterplot and estimated regression lines for 1961-90 mean annual precipitation vs. elevation for the windward (eastern) slope of Mauna Kea, island of Hawaii; a) without vertical layer weighting; b) with vertical layer weighting; c) without vertical layer weighting and the wettest station omitted from the data set; d) with vertical layer weighting and the wettest station omitted from the data set. The wettest station is predicted accurately only when layer weighting is used. Size of symbol indicates the relative total weight of the observation.

1d. <u>Does the region contain low relief as well as high-relief topography</u>?

Not all terrain features are alike in their ability to produce orographic enhancement of precipitation. Conceptually, the effectiveness of a terrain feature in amplifying precipitation depends on its ability to block and uplift moisture-bearing air. One might imagine a spectrum of "effective" terrain heights, ranging from large features that produce highly three-dimensional precipitation patterns, to a nearly flat condition exhibiting two-dimensional patterns only.

Simple methods have been developed for producing effective terrain height grids for a given region, and passing this information to PRISM. The effective terrain height for each pixel on a DEM is estimated by comparing the height of the DEM pixel to that same pixel on a smoothed, large-scale representation of the terrain. Features rising only slightly above the large-scale _background_ terrain are considered to have little effect on precipitation, while those rising far above the background field are assumed to have a significant effect. (Figure 1-7). In areas of orographically-effective terrain, PRISM operates in a full 3D fashion. In non-effective terrain situations (low relief), PRISM becomes a 2D interpolater, for which all station weighting factors become meaningless, except for distance, clustering, and coastal proximity. The result is precipitation maps that vary smoothly in flat terrain, and increase in complexity only when the terrain is significant (Figure 1-8).

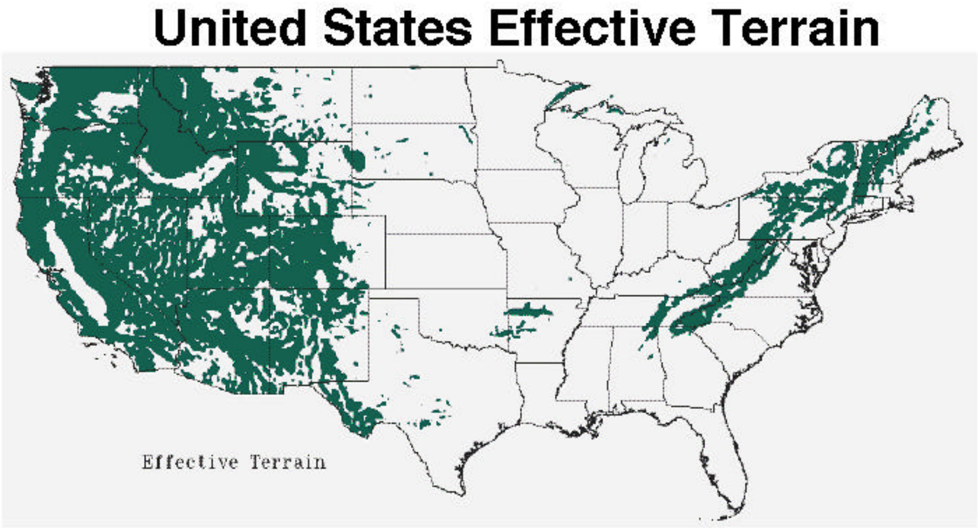
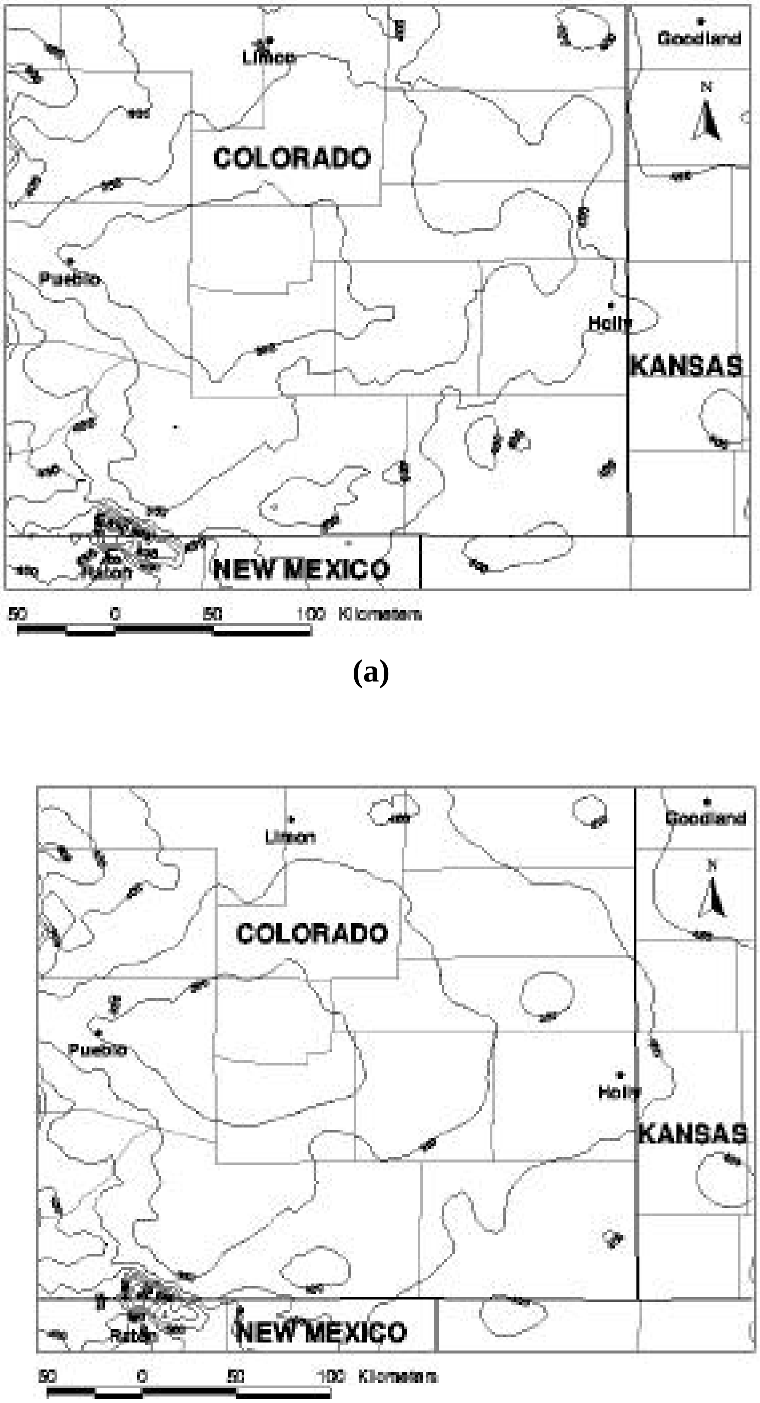


Figure 1-7. Effective terrain grid for the U.S. Shaded areas denote terrain features that are expected to produce significant terrain-induced (3D) precipitation patterns. Grid resolution is 2.5 minutes (~ 4 km).



(a)

(b)

Figure 1-8. PRISM contour maps of mean annual precipitation for southeastern Colorado a) in 3D mode everywhere; b) in varying 2D/3D mode using the effective terrain height grid.

2. Does the region contain climatically-significant water bodies?

Sites near a large water body such as the oceans or Great Lakes may experience climatic conditions that are significantly different than those just a short distance inland. For example, summer maximum temperature gradients can exceed 20C within thin coastal strips, and coastal precipitation is sometimes different than over adjacent inland areas. Therefore, coastal proximity grids have been developed that estimate the proximity of each pixel to the water (Figure 1-9). PRISM uses this information to select and weight stations according to their similarity in coastal proximity to the target grid cell. The result is a more consistent coastal regime that is less sensitive to relative differences in the density and placement of coastal and inland stations (Figure 1-10). In flat terrain, the proximity measure typically represents the shortest distance from a site to the water. In complex terrain, more sophisticated measures have been developed that account for the blocking and channeling effects of terrain on coastal proximity.

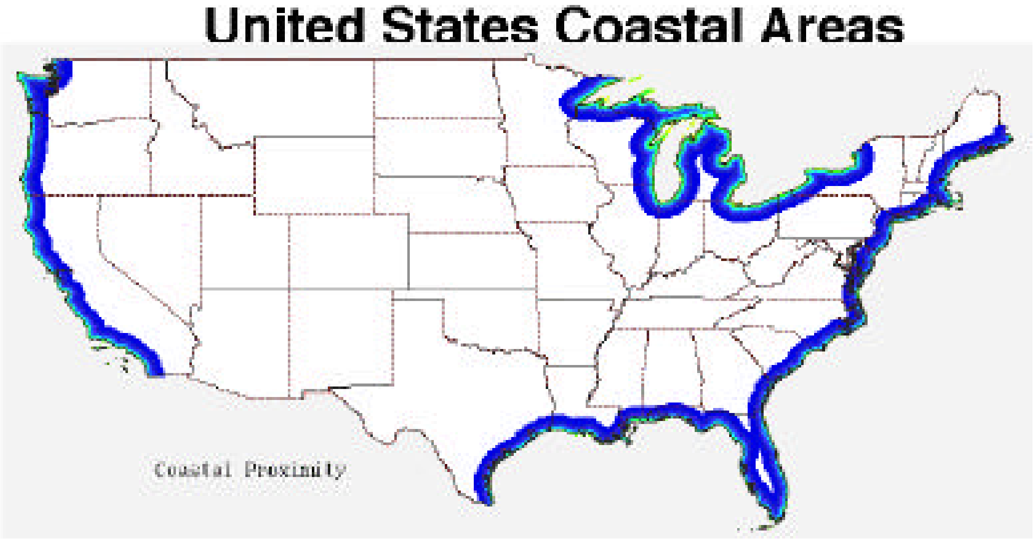
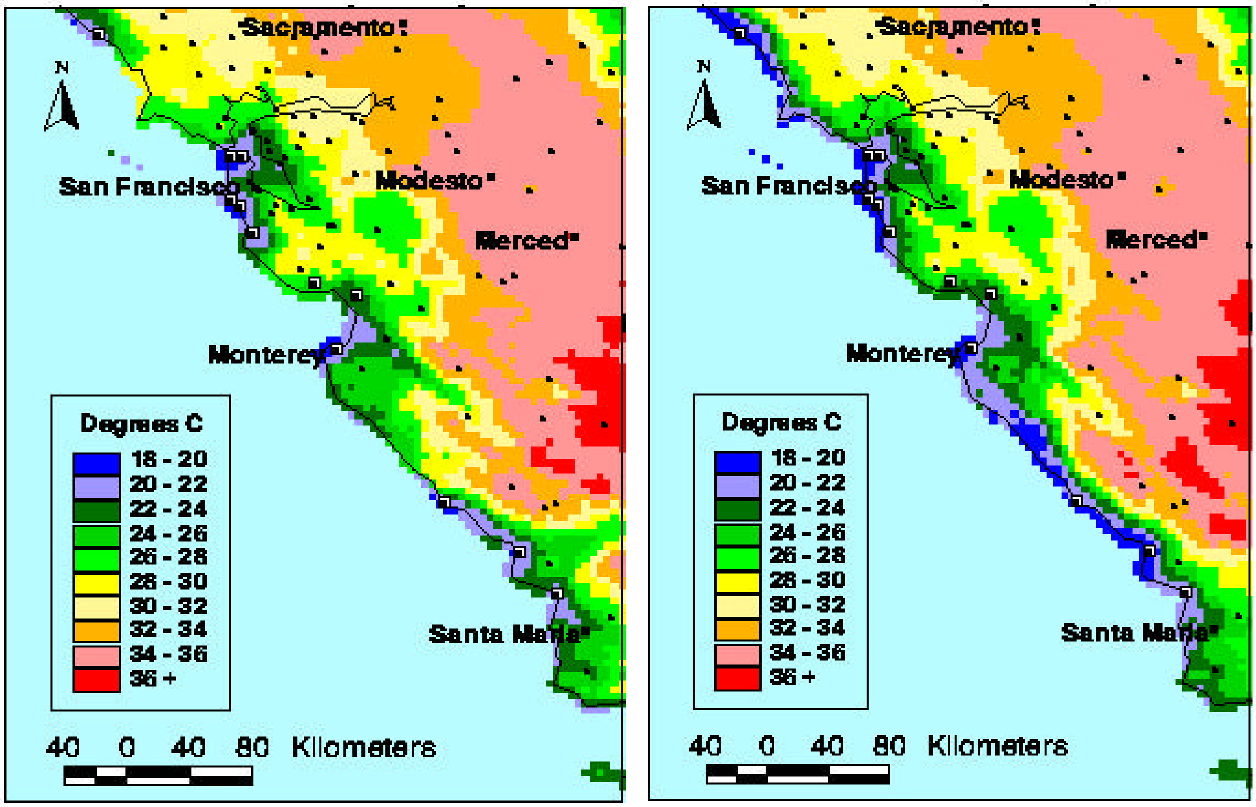


Figure 1-9. Coastal proximity grid for the U.S. Shaded areas denote zone that may experience significant gradients in spatial climate associated with coastline proximity. Grid resolution is 2.5 minutes (~ 4 km).



(a) (b)

Figure 1-10. PRISM map of 1961-90 mean July maximum temperature for the coast of central California; a) without coastal proximity weighting; and b) with coastal proximity weighting. White squares denote locations of coastal stations. Black dots denote inland stations. Grid resolution is 2.5 minutes (~ 4 km).

I.D. Construction of the PRISM Climate Grids

The preparation of the basic PRISM precipitation and temperature grids for the conterminous United States consisted of a sequence of steps that were iterated several times: (1) collect station data; (2) develop PRISM climate grids; and (3) subject PRISM grids to peer review and make improvements. These steps are discussed below.

I.D.1 Collect Station Data

Observed precipitation and temperature data were collected from the National Weather Service cooperative network, the NRCS SNOTEL network, storage gauges, snow courses, and estimated "pseudo" stations. April 1 mean snow water equivalent measurements from snow course sites were processed into estimates of mean annual precipitation. All observations were normalized to the 1961-90 period (monthly and annual). A small number of estimated data points, or pseudo-stations, were used in areas where a climate expert believed the station data to be insufficient to adequately represent a precipitation regime. Typically, pseudo-station estimates were based on vegetation type, short-term observations, or stream flow records.

Annual-only precipitation data from storage gauges, snow courses, and pseudo-stations were processed into mean monthly values based on a subjectively chosen "anchor" station, a nearby monthly station that was believed to possess a representative monthly precipitation distribution. These annual-only stations were used sparingly, when the benefits of a better-defined precipitation regime far outweighed the costs associated with potentially inaccurate values.

Temperature data were also collected from the Global Gridded Upper Air Statistics (GGUAS) data set, available on CD-ROM from NCDC. The data consisted of 2.5-degree grid-cell estimates of mean monthly temperature from the ECMWF model, given as 1980-1995 means. Grid cell values for the 500-mb surface were used over the western U.S., and the 700-mb surface was used over the central and eastern parts of the country. The pressure levels were chosen to be far above the highest terrain, so that the grid cell estimates never conflicted with the surface-based observations. The GGUAS data provided useful high-altitude anchor points for the estimation of temperature in the mountains during months when there was little communication between PRISM layers 1 and 2 for vertical extrapolation (i.e., winter inversions), and when observations were sparse. Mean monthly temperatures were processed into minimum and maximum temperatures by developing spatial grids of monthly temperature range for stations residing in layer 2 and applying these ranges to the gridded mean temperatures.

I.D.2 Develop PRISM Climate Grids

Precipitation

The conterminous United States was divided into the following regions to be modeled individually with PRISM: Each of the eleven western states, including separate northern and southern California regions; central U.S.; eastern U.S.; and New England. Choosing these regions was based on several considerations. First, the PRISM evaluation process was performed on a state-by-state basis in the West, so the mapping naturally began there as a state-oriented activity. Second, the great variation in precipitation patterns and station density and placement among states made it preferable to parameterize the model runs at the state level. The central and eastern U.S. could be done in larger chunks because of the relatively modest variation in precipitation pattern and complexity. The exception was New England, where better results were obtained through a somewhat different parameterization than was used for the greater eastern U.S. region.

Spatial input data sets necessary for modeling were prepared for the conterminous United States super-region, then windowed for each modeling region using GIS. A 2.5-minute DEM served as the base gridded coverage. It was carefully constructed by using a Gaussian filter to degrade the resolution of a quality-controlled 15-sec DEM obtained from the USGS EROS Data Center. A mask that delineated the boundaries of the modeling area was made through a combination of political and physical boundary files. This mask was then _grown_ by several km to provide a buffer of valid precipitation values in near-shore coastal areas and along political boundaries with Canada and Mexico. Topographic facet grids were prepared using PRISM software. A layer 1/layer 2 boundary height grid was developed that estimated the height of the moist marine layer at 2500 m for areas west of the Cascades and Sierra Nevada. All other areas were assumed to be within the boundary layer (layer 1) for precipitation. A coastal proximity grid included the Atlantic and Pacific Oceans and the Great Lakes. An effective terrain height grid was also prepared.

Model runs were made repeatedly for each region over a period of several years as the model was developed and reviewed, and additional data were collected. Monthly grids for the U.S. super-region were prepared by knitting together output from the many modeling regions. Each state region was modeled with 1 degree of overlap with the adjacent region to minimize edges effects. PRISM predictions were highly consistent between one region and another, so very little overlap was actually used in the knitting process. This was fortunate, because the state-specific review process in the West made getting approval of overlapping changes to the grids awkward. Annual precipitation grids were generated by summing the monthly grids.

Temperature

The conterminous United States was divided into three overlapping regions to be modeled individually with PRISM: western, central, and eastern. Just three regions were justified because temperature is a more straightforward element to model than precipitation, and the map review was to be done on a regional, rather than state, basis.

Most of the same spatial input grids used in precipitation modeling were used here. The exception was replacing the layer 1/layer 2 boundary grid with a potential wintertime inversion height grid. Model runs for mean monthly minimum and maximum temperature were made over a period of several months. Monthly grids from each of the three regions were knitted together with at least 0.5-degree of overlap. Annual temperature grids were produced by averaging the monthly grids.

I.D.3. Subject Grids to Peer Review and Make Improvements

From the outset, it was recognized that the final PRISM digital climate layers would quickly become the baseline climatology for a variety of applications, including natural resources management, hydrologic modeling and forecasting, ecological simulations, and educational activities. It was, therefore, of the utmost importance that the PRISM technology and resulting map products represent the state-of-the-science. The way to ensure this was through rigorous and repeated peer-review of all map products. Peer-review of digital climate maps is uncommon; in fact, digital GIS layers of any kind are rarely subjected to a formal peer-review process. However, as will be seen in the discussion below, many significant enhancements to PRISM were made as a result of peer-review responses to the map products.

In 1993, a committee of climatologists and hydrologists from several state and federal agencies was formed by USDA-NWCC to evaluate the PRISM methodology for mapping precipitation in the United States. Four western states were chosen as test areas: Oregon, Idaho, Nevada, and Utah. Each of these states was represented by State Climatologists who had a strong interest in the process, and, in the cases of Idaho and Utah, had recently-completed state precipitation maps to serve as evaluation benchmarks. It was believed that the West would serve as an "acid test" for the U.S., because it possessed the most spatially complex precipitation regimes in the country.

Each member of the committee, termed the PRISM Evaluation Group (PEG), was asked to evaluate a draft PRISM mean annual precipitation map for his or her area of interest by doing the following: (1) inspect precipitation patterns for accuracy, reasonableness and detail; (2) inspect high and low precipitation amounts and their locations; (3) inspect the interrelationships between extremes; and (4) produce factual evidence supporting major differences between PRISM and PEG member viewpoints.

The evaluation process lasted two years, and resulted in several significant improvements in the PRISM methodology, including increasing the grid resolution from 5 minutes to 2.5 minutes, and delineating topographic facet orientation on a 8-point compass, rather than 4. At the conclusion of the PEG review, all members formally sanctioned PRISM as able to produce precipitation maps of equivalent or superior quality than precipitation maps manually prepared by expert climatologists for the regions studied.

After all suggestions and comments from the PEG evaluation had been addressed and incorporated, PRISM draft monthly and annual precipitation maps for the entire U.S. were produced by the OSU Spatial Climate Analysis Service. A mean annual precipitation map for each state was sent to climatologists in that state for review. This review, begun in 1995, required an additional two years, and resulted in useful responses from most states. Improvements made to PRISM based on these responses included adding the effective terrain height algorithms and the coastal proximity measure. "Final" precipitation grids were produced during summer 1997. These were updated one additional time in spring 1998 when efforts to contour-plot monthly values produced blocky contours. This was remedied by producing PRISM grids at higher numerical precision.

Peer review of the temperature maps was conducted at the regional level. Mean January minimum and July maximum temperature maps for each of the climatological regions in the U.S., and one representative state within each region, were sent to the six Regional Climate Offices for review. These reviews were incorporated into the final PRISM temperature maps produced in January 1999.

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