The Prism Approach to Mapping Precipitation and Temperature

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1. INTRODUCTION

PRISM (Parameter-elevation Regressions on Independent Slopes Model) is 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 (Daly et al. 1994). Originally developed in 1991 for precipitation estimation, PRISM has been generalized and applied successfully to temperature, snowfall, growing degree-days, and weather generator parameters, among others (Johnson et al.1997, Taylor et al. 1997). It has been used extensively to map precipitation and minimum and maximum temperature over the United States, Canada, and other countries (Kittel et al. 1997, Parzybok et al. 1997). PRISM development and application are the focus of a growing research program at Oregon State University aimed at producing environmental maps with unprecedented accuracy and detail.

The rapid development of new capabilities within the OSU climate analysis program has been due largely to the fact that PRISM is not a statistical "black box" with a restrictive set of numerical routines. Rather, it is a coordinated set of rules, decisions, and calculations, designed to approximate the decision-making process an expert climatologist would invoke when creating a climate map. Humans are incredibly adaptive and changeable creatures, assimilating experience and knowledge at a rapid rate. We have attempted to keep PRISM as open and changeable as possible, so it can continue to reflect our current state of knowledge.

In our ongoing attempts to produce physically realistic and detailed climate maps, PRISM has had to accommodate many difficult situations in innovative ways. Below we present our current approaches to some of these situations and discuss plans for further improvements.

2. EXTRAPOLATION OVER LARGE ELEVATION RANGES

The most common lament of climate analysts is the lack of observations just where they need them most: at high elevations in mountainous areas. In these regions, the analyst must often settle for extrapolating climate over large elevation ranges. Because most climate parameters bear strong relationships with elevation, the ability of a model to extrapolate vertically to elevations beyond those for which stations exist is paramount. PRISM calculates linear parameter-elevation relationships, and the slope of this line changes locally with elevation as dictated by the data points. We currently maintain the simple linear form, because our experience so far has shown that it is more straightforward and robust than others. The local elevation range over which data points are selected can be varied separately in the upward and downward directions, and points nearer to the target elevation can receive greater weight than those further up- or downslope. The overall result may be a non-linear vertical profile within the elevation range of the data. Beyond the lowest or highest station, the profile becomes linear and can be extrapolated as far as needed.

Some cases arise for which an indefinite, monotonic change in a climate parameter with elevation is not realistic. Two examples illustrate this.

(1) In coastal areas, orographic precipitation may result from uplift of a moist, but shallow, boundary layer

advected 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.

(2) 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 2.5-3.0_C/100m 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 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).

To accommodate the spatially and temporally varying strength of inversions and boundary layer integrity, PRISM allows varying amounts of "crosstalk" (sharing of data points) between the vertical layer regressions, depending on the similarity of the regression functions. For example, under strong inversion conditions in winter, the regression functions would be very different, and crosstalk would be minimized. During summer and in well-mixed locations, the regression functions would show similar characteristics, and stations would be shared more freely across the layer 1/layer 2 boundary. If there are no stations in one of the two layers, default regression slopes describing the expected mean behavior of the boundary layer or free atmosphere are invoked.

3. REPRODUCING GRADIENTS BETWEEN DIFFERENT CLIMATIC REGIMES

Regions influenced by varying topography or large water bodies are often characterized by transitions among several climatic regimes. These include rain shadows, and coastal temperature and rainfall effects. While elevation may still be the best explanatory variable for climate locally, it is usually very difficult to combine data from the entire area to form an overall relationship between climate and elevation. Because this problem is so common, a model must have the ability to adapt to shifting relationships between a parameter and elevation. PRISM continually changes its frame of reference by calculating a separate regression for each pixel, selecting stations falling within a local window around the pixel. No overall relationships are required. 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 20_C 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.

Grouping stations on climatically important facets allows the terrain to naturally isolate one regime from another and reproduce the extreme climatic gradients that may occur at their boundaries. Without this feature, transitions among regimes may be poorly delineated, excessively smoothed, and improperly located.

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, simple 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. The current proximity grids define coastal influence only as the shortest distance from a site to the water. Work is now underway on methods that will simulate the advection of coastal influence into areas with complex terrain, where terrain blocking effects and channeled flow are significant.

4. THE VARIABLE EFFECT OF TERRAIN ON PRECIPITATION

An issue encountered when mapping precipitation is the importance of terrain in defining the patterns of precipitation. In the mountainous West, terrain dominates the spatial patterns of precipitation. In flat or gently rolling areas such as the Great Plains, the role of terrain is more subdued and not as clear-cut. Conceptually, the effectiveness of a terrain feature in amplifying precipitation depends on its ability to block and uplift moisture-bearing air. This ability is determined mainly by the profile the feature presents to the oncoming air flow. Large, steep, bulky, features oriented normal to the flow can generally be expected to produce greater precipitation/elevation (P/E) slopes than low, gently rising, features oriented parallel to the flow. 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 which exhibits two-dimensional patterns only. Between these extremes would be a transition between 2D and 3D patterns, for which P/E slopes would range from zero (2D) to values typical of mountainous areas (3D).

In a perfect world, the effectiveness of the terrain would be reflected in the station data, and thus in the empirical P/E regression slopes. In reality, the station data are rarely of sufficient density and reliability to provide such a detailed and accurate picture of the situation. If spatial information on the 2D/3D nature of the terrain were available *a priori*, the range of allowable P/E slopes could be varied to the appropriate degree, providing an independent check and constraint (if necessary) on the empirically-derived P/E slopes.

We have made a simple, first attempt at producing an effective terrain height grid across the U.S. This grid has been used in recent precipitation modeling activities with encouraging results. The effective terrain height for each pixel on a DEM was 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 were considered to have little effect on precipitation, and classed as 2D features. Those rising far above the background field were assumed to be firmly in 3D territory. Prevailing wind direction was not considered in this first attempt. We are currently setting the thresholds for 2D and 3D features empirically, but expect that a combination of theoretical studies and further experience will provide a firmer basis for future settings.

5. CONCLUSIONS

PRISM (Parameter-elevation Regressions on Independent Slopes Model) is 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, reproducing gradients caused by rain shadows and coastal effects, and assessing the varying effects of terrain on precipitation.

Because our knowledge of climate patterns and processes is rapidly evolving, PRISM is necessarily a rapidly changing system. The latest information and product schedules are available online at the PRISM Web site:

http://www.ocs.orst.edu/prism/prism_new.html

6. REFERENCES

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