

# **Development of a 103-Year High-Resolution Climate Data Set for the Conterminous United States**

Comprehensive Final Report for 9/1/97 - 5/31/02

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## **OBJECTIVE**

Produce a high-quality, topographically-sensitive, 103-year data set of monthly temperature and precipitation on a 2.5-min (4-km) grid over the conterminous United States.

## **RESULT**

The high-quality, topographically-sensitive, 103-year data set of monthly maximum and minimum and precipitation on a 2.5-min (4-km) grid over the conterminous United States is now available via the World Wide Web. The gridded data and documentation can be downloaded from <ftp.ncdc.noaa.gov/pub/data/prism100>.

## **USEFULNESS**

These data sets are unprecedented in their combination of high quality, century-long temporal extent, and fine spatial detail. They will enable users to perform a wide variety of analyses, including:

- Transient ecological and natural resource modeling for use in global change assessment;

- Analysis of local and regional trends of climate variations;
- Analysis of frequency, duration, and spatial patterns of extreme climatological events; and
- Investigation of relationships between climatological variability and large-scale forcing mechanisms (e.g., ENSO or QBO).

## **ACCOMPLISHMENTS**

### **Year 1**

- Produced a draft 10,000-station, serially complete data set of observed precipitation for the period 1895-1996.
- Using PRISM, developed draft monthly precipitation grids at 4-km resolution for the conterminous United States over the period 1948-1993.
- Archived draft monthly precipitation grids at NCDC and provided on-line access to users at <ftp.ncdc.noaa.gov/pub/data/prism100>.

### **Year 2**

- Developed a semi-automated, spatially intelligent quality control system for monthly precipitation observations; applied QC system to all precipitation station data.
- Extended the time period of the data set to 103 years by adding data through 1997.
- Added station data for several hundred pre-1948 stations made available through the Midwestern Climate Center's recent digitizing program.
- Made assessment of data quality and limitations in parallel with the in-filling of missing precipitation station data.

### **Year 3**

- Re-applied semi-automated QC system to full precipitation station data set.
- Using PRISM, developed draft monthly precipitation grids at 4-km resolution for the conterminous United States over the period 1895-1997.
- Analyzed gridded precipitation for reasonableness in spatial and temporal trends and variability.

### **Year 4**

- Based on the analysis, completed a major redesign of the process by which missing precipitation data are infilled.
- Re-applied semi-automated QC system to full precipitation station data set.
- Applied the modified infill system to produce a serially complete station precipitation data set for the period 1895-1997
- Using PRISM, developed draft monthly precipitation grids at 4-km resolution for the conterminous United States over the period 1895-1997.
- Constructed a monthly minimum and maximum temperature station data set for the period 1895-1997.

## **Year 5**

- Modified and tested the precipitation QC system for use with the temperature station data set.
- Applied the QC system to the station temperature data set
- Applied the precipitation infill system to produce a serially complete station minimum and maximum temperature data set for the period 1895-1997.
- Using PRISM, developed draft monthly minimum and maximum temperature grids at 4-km resolution for the conterminous United States over the period 1895-1997.
- Analyzed gridded precipitation for reasonableness in spatial and temporal trends and variability.
- Analyzed gridded minimum and maximum temperature for reasonableness in spatial and temporal trends and variability.
- Monthly grids of minimum and maximum temperature for the period 1895-1997 were pronounced final.
- Monthly grids of precipitation for the period 1895-1997 were pronounced final.
- Complete set of monthly grids of precipitation and minimum and maximum temperature were uploaded to the NCDC ftp site at <ftp.ncdc.noaa.gov/pub/data/prism100>.
- Documentation, GIS metadata, and final report were written and uploaded to the ftp site.

## USE IN GLOBAL CHANGE ASSESSMENTS

A precursor to this data set, developed using similar methods, was used by the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP). VEMAP is an intercomparison of predicted changes to vegetation under climate change scenarios. Results from VEMAP were used in the USGCRP assessment. Data sets from the current 103-year project will be used to update and improve the VEMAP climate data sets.

## PUBLICATIONS

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## PROJECT SUMMARY

This project successfully reached its goal of developing a century-long time series of monthly precipitation and temperature grids for the conterminous US. The project was originally envisioned as a 3-year effort. As is sometimes the case with more complex projects, the eventual magnitude of what was to be done required many more man-hours than planned or budgeted. Below is a summary of the work performed.

This 4.5-year project consisted of 4 major tasks. In many cases, a task, or series of tasks, was performed repeatedly to obtain an acceptable final result. For the sake of clarity and brevity, only the methodologies and results that apply to the final products are discussed. Please refer to the list of accomplishments for a chronology of individual tasks performed in each year.

- Task 1:** Obtain monthly precipitation and minimum and maximum temperature station data for the conterminous United States over the period 1895-1997
- Task 2:** Develop and apply a spatial QC procedure to identify erroneous station data
- Task 3:** Develop and apply a statistical infilling procedure to produce a serially complete station data set
- Task 4:** Apply PRISM to the infilled station data to produce a series of monthly spatial grids for the period 1895-1997

### **Task 1- Obtain monthly station data**

Station data for monthly precipitation and minimum and maximum temperature covering the period 1895-1997 were collected for the conterminous United States. Data sources are as follows:

COOP: NWS cooperative stations and station history files

SNOTEL: NRCS SnoTel data. Begins in 1978

AG: Agricultural climate data for southeastern Washington. From Phil Pasteris of USDA-NRCS

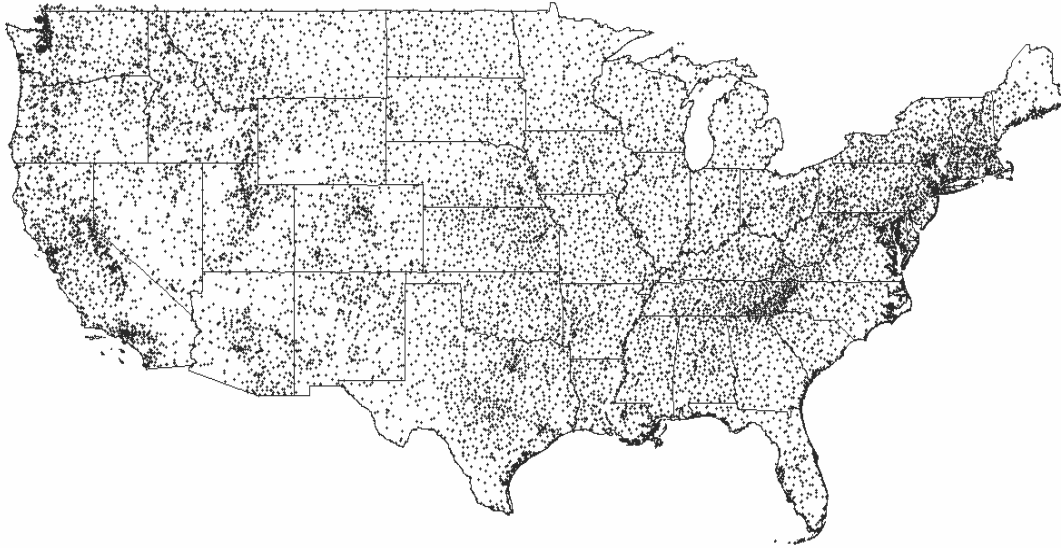
MCC: Midwest Climate Data Center data. Data recently digitized. Mainly for pre 1948 period

HCN: Historical Climate Network data (supercedes COOP data for the same ID code)

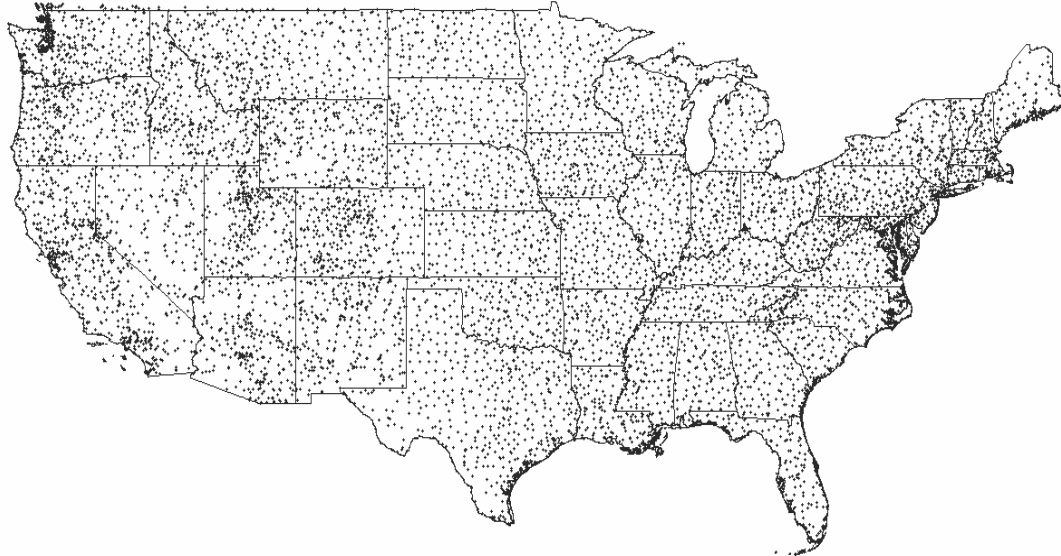
MISC: Miscellaneous data, including storage gauges, snow courses, manually estimated points, and selected Canadian data

The total number of precipitation stations was approximately 12600, and the total number of temperature stations was approximately 8500. All station data were reformatted into PRISM input format for the QC procedure. Station locations are shown in Figure 1.

(a)



(b)



**Figure 1. Locations of stations used to develop the 103-year data set: (a) Precipitation; (b) temperature.**

### **Task 2 - Develop a PRISM-based QC system for monthly station data**

Spatial modeling and mapping of climatic observations is a relatively new science, and is placing higher demands on data quality than traditional, point-based analyses. Previous experience with spatial modeling projects has demonstrated the problems experienced with insufficiently quality-controlled (QC) data sets. A single outlier has the capability of causing

spatial abnormalities, sometimes quite large and obvious. The outlier may not appear unusual in a time series plot for a single station, but spatial analyses can often show the inconsistency of the outlier in relation to values from nearby stations.

While a spatial analysis can be an effective way of identifying outliers, the detection and correction of such errors after the spatial data set has been produced can be time-consuming and inconsistent. Each spatial grid must be visually examined for possible outliers, and special calculations must be made to help show outliers where they may be otherwise hidden, such as areas of complex terrain. In this project, there are 4017 monthly and annual grids, each covering the entire lower 48 states. Examination of such a large number of grids requires many man-weeks of time, and is fraught with inconsistencies inherent in human visual inspection. When possible errors are found, they must be individually verified, and the erroneous grid reproduced without the offending data point.

Our premise was that it is better to use the power of the spatial analysis system (i.e., PRISM) *a priori* to detect errors in the station data in as an objective and automated fashion as possible. Therefore, we developed a semi-automated QC system that is effective at identifying bad monthly data, while leaving good data untouched. Our definition of “bad data” is a value that has experienced an error in transcription somewhere between the observation and the digital value available to us. We did not attempt to identify errors due to gauge undercatch, or subtle inhomogeneities cause by changes in observation method, instrumentation changes, etc.

The QC system incorporated two main types of checks:

- (1) Metadata errors - errors in the location or elevation of a station. Such errors are insidious, in that a station mislocation affects the entire period covered by the erroneous metadata, not just one month.
- (2) Monthly data errors - errors in the actual monthly data values.

## **Metadata Errors**

The metadata checks relied on two strategies to find mislocated stations: direct identification of mislocation; and indirect identification through temporal inconsistencies in the station history file. Direct checks were made using ancillary GIS (geographic information system) data sets. First, each station’s state ID number was compared to that derived from a gridded state code data set at the station location. Mismatches between the metadata- and spatially-derived state codes suggested the station may be in the wrong state. Next, each station’s metadata elevation was compared to that derived from a 15-arc-second (~500m) DEM (digital elevation model) at the station location. Large mismatches in the two elevation values suggested the station was mislocated, or the metadata elevation value was incorrect. Each mismatch was carefully checked to determine whether an error was indeed present.

A reformatted version of NCDC’s station history file was checked for inconsistencies in

location and elevation. For example, a move of more than about 20 km horizontally or 100 m vertically was flagged and checked manually for accuracy. Many times, this check revealed latitude/longitude errors of exactly 1 degree, probably a keypunch problem. Another common erroneous situation was a large change in elevation but no discernable change in horizontal location.

Using the two methods described above, approximately 100 metadata errors were discovered. Errors in the COOP and MCC data sets, and their corrections, were sent to NCDC for incorporation into the official history files. SNOTEL errors were provided to the NRCS. All metadata corrections were made to the data files before the monthly data errors (below) were assessed.

In a related effort, sensitivity tests were made to determine if the spatial QC system described below for monthly error detection could be used to detect locational errors in the metadata. The tests indicated that this system could not detect mis-located stations with a reasonable degree of certainty and consistency.

## **Monthly Data Errors**

Monthly data QC was done using a version of PRISM called ASSAY\_QC, a modified version of ASSAY. ASSAY is essentially a full version of PRISM, except that it makes predictions for individual points in space, rather than producing gridded output. ASSAY is commonly used to produce jackknife cross-validation errors for various model parameterizations. For use in QC, ASSAY\_QC made a prediction for each station for each month, in the absence of that station's data value. Large differences between the predicted and observed values indicated that there was a discrepancy between the station observation and those from surrounding stations. To determine what constitutes a "large" discrepancy or a consistent basis for precipitation, we derived a strong empirical relationship between precipitation and variance from climatology; the higher the precipitation, the larger the expected variance. This relationship was used to normalize differences between predicted and observed precipitation. No relationship between temperature and variance was found, so the variance was held constant for all temperatures.

The confidence in a PRISM prediction for a station also had to be considered. Criteria were developed to identify those situations for which the confidence in the PRISM predictions was low, and no judgement could be reasonably made about the veracity of the station observation.

### Definitions

PC = prediction of standard deviation based on climatology

P = Prediction based on ASSAY

J = Jackknifed station

O = Observation at highest weighted station (determined by ASSAY)

S1 = number of standard deviations for J vs O (5.6)

S2 = number of standard deviations for J vs P (1.19)

Sr = standard deviations of regression model based on all observations

An outlier could be detected in one of two ways: (1) meeting an absolute residual criterion, or (2) meeting a series of comparative criteria. The absolute residual criterion is stated as:

$$| P(x,y) - J(x,y) | \geq \text{Residual cutoff}$$

Where the residual cutoff is 150 mm for precipitation and 15° C for temperature. If the observed value met the absolute residual test, it was considered a candidate outlier. Otherwise, to be deemed a candidate outlier, the outlier must have met all of the criteria outlined below.

#### Distance Confidence Criterion

We have less confidence in the ASSAY\_QC predictions the farther away the surrounding stations are from the predictor location.

$$| J(x,y) - O(x,y) | \leq \text{Distance cutoff}$$

Where distance cutoff for Jan ... Dec is [60,50,40,32,25,21,21,25,32,40,50,60] km. Cutoff values are specified monthly to account for seasonal differences in precipitation spatial scale (i.e., large-scale synoptic storms in winter vs small-scale convection in summer). This criterion was not applied to temperature.

#### Coastal Proximity Criterion

We have less confidence in the ASSAY\_QC predictions if the surrounding stations do not have a similar proximity to a major water body (oceans or Great Lakes) than the predictor location.

$$| J(x,y) - O(x,y) | \leq \text{Proximity cutoff}$$

Where the proximity cutoff is 50 km, for predictor locations within 100 km of a coastline..

#### Elevation Confidence Criterion

We have less confidence in the ASSAY\_QC predictions the larger the elevation differences between the surrounding stations and the predictor location.

$$| J(z) - O(z) | \leq \text{Elevation cutoff}$$

Where the elevation cutoff is 500 m. This criterion was not applied to temperature.

#### Prediction vs Observation Criterion

Does a “large” difference exist between what we expect vs what was modeled?

$$| J - P | \geq S1 * PC(\min(J,P))$$

If the ASSAY\_QC regression function is noisier than climatology predicts, we adjust the criterion for this local increase in variability:

$$| J - P | \geq S1 * PC(\min(J,P)) * S2 * Sr / PC(P), \text{ for } Sr > PC(P)$$

If ASSAY\_QC makes an unexpectedly poor prediction, as evidenced by J and O observations that are similar to each other but different from P, we adjust the criterion.

$$| J - O | \geq 1.4 * PC(\min(J,O))$$

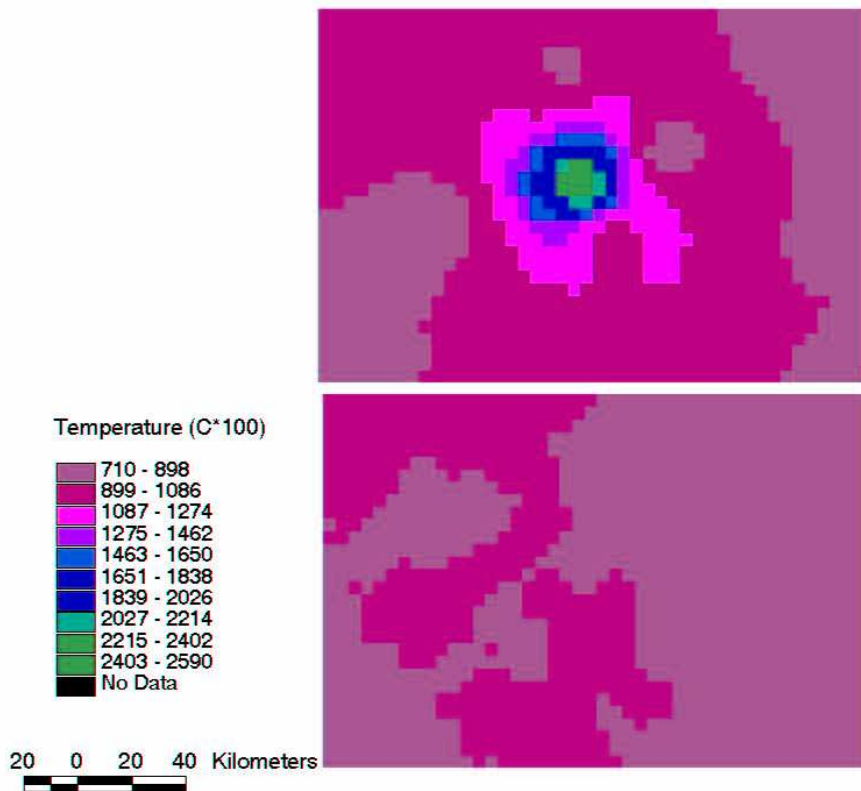
Station observations that satisfied all of these criteria were considered candidate outliers. Using additional software, they were then divided into several groups, including definite outliers, those that appeared to be outliers only because the most highly weighted station was also an outlier, cases that were too close to call, and others. Those that were too close to call were examined manually. Those classified as definite outliers were set to missing.

For precipitation, the spatial QC system detected 2,371 monthly data errors out of 6,345,675 station-months, for an error detection rate of 0.0374%. While this may appear to be a very low error rate, it translates into about two errors per monthly grid, which is not insignificant. Fifty-six outliers were too close to call; after manual checks, 40 were found to be erroneous and 16 could not be proven invalid. This reasonable split between good and bad data in a group that was deemed marginal confirmed that the system was operating as an effective substitute for an expert operator.

The spatial QC system detected 355 monthly errors in 4,978,120 station-months for maximum temperature and 593 errors in 4,938,120 station-months for minimum temperature. These gave error detection rates of 0.0072% and 0.0120%, respectively, which were smaller than the precipitation error detection rate. An example of a minimum temperature outlier is shown in Figure 2.

## Minimum Temperature (Oct 1943)

Station FLORA, Longitude=-90.32, Latitude=32.53



**Figure 2. An example of a minimum temperature outlier at Flora, MS in October 1943. Top panel is a PRISM analysis with the outlier, bottom panel is the analysis with it outlier removed.**

### Task 3 - Produce Serially Complete Station Data Set

The process of infilling missing monthly data, which essentially extended the records of all stations to the full 103-year period, went through several development and testing stages. Precipitation and temperature fields are demanding in the sense that extremely sharp gradients can occur over short distances, such as occurs in the transition zone between the wet (windward) and dry (leeward) sides of a mountain range for precipitation, or along coastal zones for temperature. Early methods used kriging, a distance-based weighting scheme, to select stations to provide information for the infilling of a station with missing data. This method worked well over most of the country, where the closest stations were, indeed, the best suited to provide infilling information. However, in the West, where mountainous terrain and cold ocean waters produces sharply different precipitation and temperature regimes, the closest stations may not be the best suited. For example, precipitation at a station on the windward side of a mountain range

is likely to be more highly correlated with another station on the windward side, than with a station that is closer, but on the leeward side.

The new version of the infilling scheme added, in addition to distance, a second component to the weighting of stations: the historical regressions relationship between stations. That is, a station was given higher weight if it exhibited a historically strong relationship with the station to be infilled. This only works if both stations have valid data that overlap in time for at least 10 years; otherwise, the regression function becomes unstable and cannot be relied upon to accurately estimate historical relationships. These relationships were assessed separately for each month of the year.

Temporal relationships between pairs of stations were calculated in anomaly space, that is, the variations remaining after the means had been subtracted off. While this a generally a more stable way to express precipitation and temperature, it requires that a stable, long-term mean value be available. This not the case for stations with periods of record that a short, and do not represent similar time periods. Therefore, peer-reviewed, gridded analyses of 1961-1990 mean monthly precipitation and temperature created for the USDA-NRCS with the PRISM modeling system was used to provide long-term means for each station (Daly and Johnson 1999, USDA-NRCS 1998). However, because climatology does vary slowly with time and the PRISM analysis did not use station outside the 1961-1990 period, there were a small number of cases in which the PRISM means did not correspond closely with the station means. Such a discrepancy led to biases when cross-validation was used to assess the infilling accuracy. To guard against this problem, a t-statistic was used to flag suspect PRISM means and adjust them towards the observed station means.

A detailed discussion of the final method for infilling missing station data accompanies this report as a pdf document.

#### **Task 4 - Apply PRISM to produce a series of monthly spatial grids**

The PRISM (Parameter-elevation Regressions on Independent Slopes Model) modeling system was used to map precipitation over the continental United States. The regression-based PRISM uses point data, a digital elevation model (DEM), other spatial data sets, a knowledge base, and expert interaction to generate repeatable estimates of annual, monthly, daily, and event-based climatic elements. These estimates are interpolated to a regular grid, making them GIS-compatible. Recent mapping efforts include peer-reviewed, official USDA precipitation and temperature maps for all 50 states and Pacific Islands (Bishop et al. 1998, USDA-NRCS 1998, Daly and Johnson 1999, Vogel et al. 1999, Daly et al 2001); a new official climate atlas for the United States (Plantico et al 2000); precipitation and temperature maps for Canada, China and Mongolia (Daly et al 2000a), and the first comprehensive precipitation maps for the European Alps region (Schwarb et al. 2001a, 2001b).

PRISM adopts the assumption that for a localized region, elevation is the most important factor in the distribution of temperature and precipitation (Daly et al., 2002). PRISM calculates a linear

climate-elevation relationship for each DEM grid cell, but the slope of this line changes locally with elevation as dictated by the data points. Beyond the lowest or highest station, the function can be extrapolated linearly as far as needed. A simple, rather than multiple, regression model was chosen because controlling and interpreting the complex relationships between multiple independent variables and climate is difficult. Instead, weighting the data points (discussed later) controls the effects of variables other than elevation.

The climate-elevation regression is developed from x,y pairs of elevation and climate observations supplied by station data. A moving-window procedure is used to calculate a unique climate-elevation regression function for each grid cell. The simple linear regression has the form

$$(1) \quad Y = \beta_1 X + \beta_0$$

where Y is the predicted climate element,  $\beta_1$  and  $\beta_0$  are the regression slope and intercept, respectively, and X is the DEM elevation at the target grid cell.

Upon entering the regression function, each station is assigned a weight that is based on several factors. In the general PRISM formulation, the combined weight of a station is a function of distance, elevation, cluster, vertical layer, topographic facet, coastal proximity, and effective terrain weights, respectively. A full discussion of the station weighting functions is available in Daly et al. (2002, in press). The combined weight W of a station is a function of the following:

$$(2) \quad W = f \{ W_d, W_z, W_c, W_p, W_l, W_f, W_e \}$$

where  $W_d$ ,  $W_z$ ,  $W_c$ ,  $W_p$ ,  $W_l$ ,  $W_f$ , and  $W_e$  are the distance, elevation, cluster, coastal proximity, vertical layer, topographic facet, 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).

Coastal proximity weighting is used to define gradients in precipitation or temperature that may occur due to proximity to large water bodies (Daly et al. 1997, Daly and Johnson 1999, Daly et al. in press). Vertical layer weighting is used to simulate situations where rapid changes, or even reversals, in the relationship between climate and elevation are possible (i.e., temperature inversions). When the potential for such situations exists, the climate stations entering the regression are divided into two vertical layers, and regressions run on each separately. Layer 1 represents the boundary layer, and layer 2 represents the free atmosphere above it. Topographic facet weighting accounts for discontinuities in the climate field caused by terrain breaks (e.g., rain shadows). A topographic facet is a contiguous terrain slope with a common orientation, delineated at a variety of scales, from the major leeward and windward sides of large mountain ranges, to north- and south-facing hill slopes. At each grid cell, the model 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 (Daly et al., in press). Effective terrain weighting accounts for differences in the ability of terrain features to enhance precipitation

through mechanical uplift of moisture-bearing air. Features having relatively steep, bulky profiles typically produce strong precipitation-elevation relationships; while low, gently rolling features have weaker relationships (Daly et al. 1997, Daly and Johnson 1999, Daly et al. 2002).

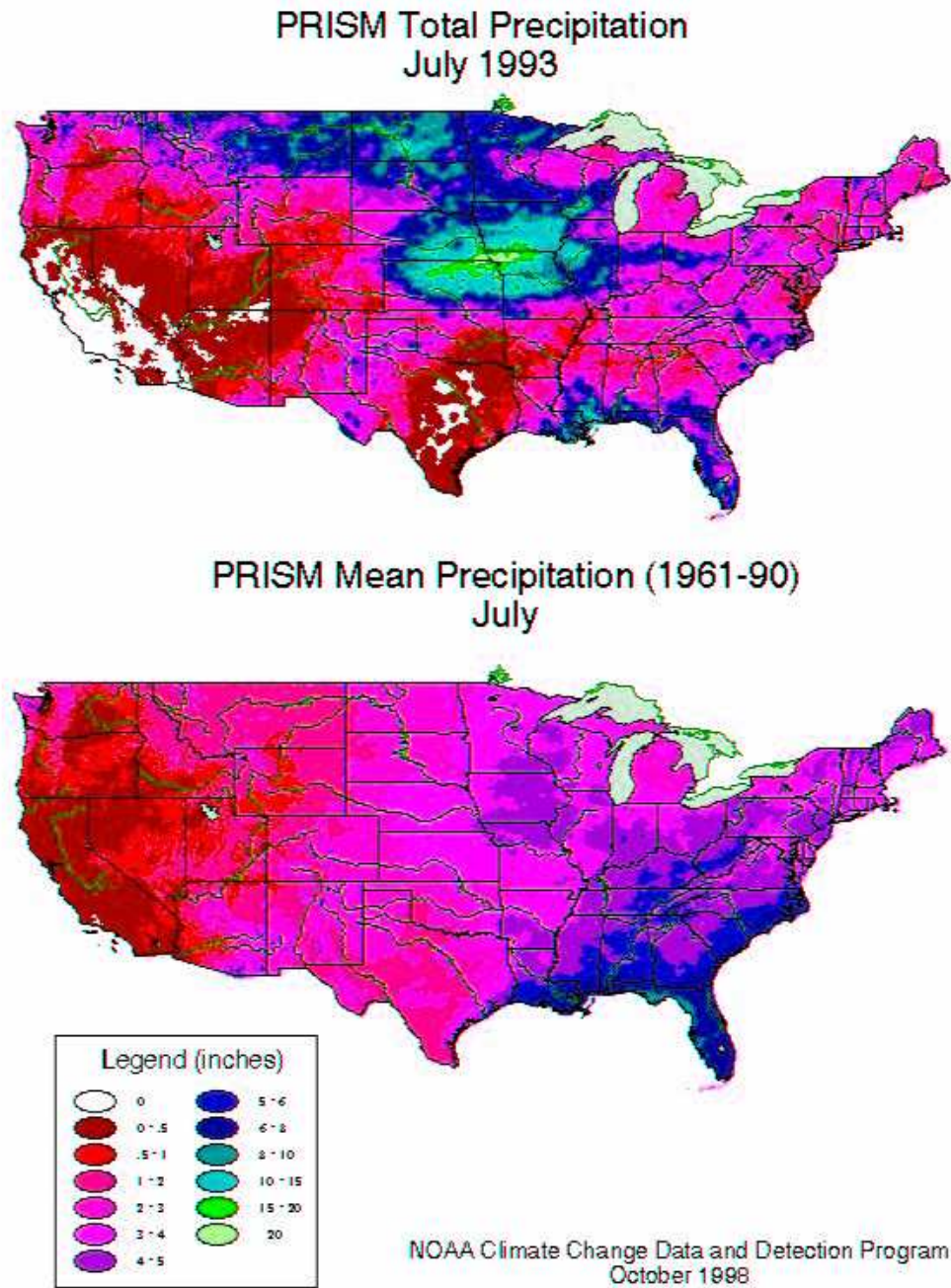
A DEM with grid resolution of 2.5-minutes (approximately 3x5 km at 45N) was used as the base map for all interpolation activities. This DEM was derived from a 15-sec DEM obtained from the EROS Data Center by applying a modified Gaussian filter. A 2.5-min cell size produces a continental grid of manageable size, while still resolving detailed topographic structures that dictate precipitation patterns.

PRISM was parameterized for optimal performance by applying a statistical package that determines optimal model performance from a cross-validation error analysis. PRISM was then applied to a subset of years and months and the parameterization checked and modified, as necessary. The goal was to achieve a robust, universal parameterization that worked well for all months and years. (This was made easier by using station data that were consistent and serially complete through time.)

The continental United States was modeled in three overlapping regions: western, central, and eastern; these regions were then merged together into a single grid. Monthly and annual grids (13 total) were produced for each year, summing to 1336 grids per climate element over the 103-year period. This was done for precipitation, minimum temperature, and maximum temperature, for a grand total of 4017 grids. Each of the grids were visually checked for reasonableness. An example of a precipitation grid for July 1993, compared to the mean July precipitation for 1961-90, is shown in Figure 3.

Once approved, the grids were transferred to NCDC for archival. On-line access to the grids, metadata, and documentation is available through NCDC's anonymous ftp server at:

<ftp.ncdc.noaa.gov/pub/data/prism100>



**Figure 3.** An example of a precipitation grid for July 1993, compared to the mean July precipitation for 1961-90. Extremely high precipitation over the central Mississippi drainage caused major flooding, while drought extending from eastern Texas to the Carolinas resulted in widespread crop failures.

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