

HIGH-QUALITY SPATIAL CLIMATE DATA SETS FOR THE UNITED STATES AND BEYOND

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ABSTRACT. A number of peer-reviewed, spatial climate data sets of excellent quality and detail for the United States are now available. The data sets are suitable for a variety of modeling, analysis, and decision-making activities. These products are the result of collaboration between Oregon State University's Spatial Climate Analysis Service and USDA NRCS, NOAA Office of Global Programs, NOAA National Climatic Data Center, NASA, Environment Canada, and other agencies. The development of these high-quality maps was made possible through the development and use of PRISM, a knowledge-based climate analysis system that uses point climate data, a digital elevation model, and other spatial data sets to generate gridded, GIS-compatible estimates of annual, monthly and event-based climatic elements. Mapped elements currently available for the United States include 1961-1990 mean monthly and annual precipitation, maximum and minimum temperature, dew point temperature, relative humidity, snowfall, heating and cooling degree days, growing degree days, median last spring and first fall frost dates, median freeze-free season length, and others. In addition, century-long gridded time series of monthly precipitation and minimum and maximum temperature for the lower 48 states will be available in 2001. Map products for other countries, including China and Canada, are nearing completion.

Keywords. Climate maps, Spatial climate, Precipitation, Temperature, GIS, PRISM.

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 agricultural, hydrological, ecological, and natural resource models and expert systems to be linked to geographic information systems (GIS) (e.g., Bishop et al., 1998a; 1998b; Vogel et al., 1999). 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 (Johnson et al., 1998; 1999).

Over the past several years, innovative methods for mapping climatic elements have been developed at Oregon State University's Spatial Climate Analysis Service (SCAS). The ultimate goal of the SCAS is to describe the climatic environment of the world in a spatially detailed, physically realistic manner. A major focus has been the ongoing development and enhancement of PRISM (Parameter-elevation Regressions on Independent Slopes Model), a knowledge-based approach to mapping climate that seeks to combine the strengths of human-expert and statistical methods (Daly and Neilson, 1992; Daly et al.,

1994; 1997; 1998a; Daly and Johnson, 1999; Johnson et al., 2000). PRISM uses point data, a digital elevation model (DEM), other spatial data sets, a knowledge base, and expert interaction to generate estimates of annual, monthly and event-based climatic elements that are gridded and GIS-compatible (Daly et al., 1994; 1997).

Originally developed for precipitation estimation, PRISM has been generalized and applied successfully to temperature, dew point, and weather generator parameters, among others (Daly and Johnson, 1999; Johnson et al., 2000;). It has been used extensively to map precipitation and temperature over the United States, Canada, and other countries (Kittel et al., 1997; Parzybok et al., 1997; Huffman et al., 1997). Current and recent mapping efforts include peer-reviewed precipitation and temperature maps for all 50 states (Bishop et al., 1998b; Daly et al., 1998b; USDA NRCS, 1998; Vogel et al., 1999; Daly and Johnson, 1999); a new official climate atlas for the United States (Plantico et al., 2000); a high-resolution, 103-year series of monthly temperature and precipitation maps for the conterminous 48 states (Daly et al., 1999; 2000b); and detailed precipitation and temperature maps for western Canada, China, Mongolia, and the European Alps (Schwarb et al., 1999; Daly et al., 2000a). PRISM climate maps are of high quality because of a rigorous peer-review process, and attention to developing new tools that faithfully reproduce climate patterns in the most demanding regions and situations.

This article 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, PRISM digital map products available from the World Wide Web are presented.

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THE PRISM MODELING SYSTEM

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 (Vuglinski, 1972; Whitmore, 1972; Hibbert, 1977; Houghton, 1979; Hanson et al., 1980; Osborn, 1984; Briggs and Cogley, 1996).

A common lament of climatologists is the lack of observations just where they need them most: at high elevations and in remote, rural areas. In these regions, the analyst must often settle for extrapolating climate over large distances and 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. 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:

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

where

Y = predicted climate element
 β_1 and β_0 = regression slope and intercept, respectively
X = 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.

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:

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

where W_d , W_z , W_c , W_l , W_f , W_p , and W_e 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). Discussions concerning vertical layer, topographic facet, coastal proximity, and effective terrain weights follow.

THE TWO-LAYER ATMOSPHERE

As discussed previously, it is important that a model be able to extrapolate climate vertically to elevations beyond those for which stations exist. However, some cases arise for which an indefinite, monotonic extrapolation of a climate element with elevation is unrealistic. Here are two examples:

- Enhanced precipitation often results from uplift of a moist, but vertically limited, 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. Parts of the western U.S., as well as areas in the subtropics, such as Central America and Hawaii, experience this effect (e.g., Giambelluca and Nullet, 1991).
- In all seasons, but predominantly during winter, inland valleys can experience persistent temperature inversions that are easily seen in the climatic record. In Colorado's San Luis Valley and Montana's Bighorn Valley, for example, increases in January minimum and maximum temperatures of 25 to 30°C/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 (Daly et al., 1997; Daly and Johnson, 1999). 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. Simple 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 (inversion height may vary by month or season). 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., 2000).

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 phenomenon is so common, a successful 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 (Daly and Neilson, 1992; Daly et al., 1994; 1997; Daly and Johnson, 1999). 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:

- Abrupt rain shadows, occurring on the leeward slopes of mountain ranges. Precipitation may drop by more than 75% within a zone of just 10 to 20 km.
- Coastal effects on temperature and precipitation. For example, summer maximum temperature gradients can exceed 20°C across thin coastal strips.

To accommodate such gradients, PRISM takes advantage of DEM information that goes beyond a simple estimate of elevation. It is recognized 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 (Daly and Johnson, 1999). 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 (Daly et al., 1997; Daly and Johnson, 1999).

ABILITY OF TERRAIN TO ENHANCE PRECIPITATION

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 which exhibits 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. In areas of orographically-effective terrain, PRISM operates in three-dimensional fashion with a fully functional climate-elevation regression function. In noneffective terrain situations (low relief), PRISM becomes a two-dimensional

interpolator, for which all station weighting factors become negligible, 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.

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.

STATISTICAL PARAMETERIZATION

PRISM utilizes a technique whereby the lowest possible prediction error is achieved. This is done through jackknife cross-validation with replacement, in which each 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 (Daly et al., 1994). In a pre-processing step, PRISM varies the values of radius of influence, minimum number of stations entering into the regression function, and minimum number of stations on the target grid cell's topographic facet, and performs cross-validation for each combination of input parameter values. The combination of values that produces the lowest mean absolute prediction error can be automatically adopted by PRISM for use in modeling. Alternatively, because cross-validation is a measure of predictive skill only at station locations, the user can elect to use other values of any input parameter for final map production (Daly et al., 1994).

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 (Natural Resources Conservation Service) Water and Climate Center, PRISM was used to prepare detailed maps of 1961-1990 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 methods 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 (NCDC) representative, a National Weather Service representative, and engineers, hydrologists, GIS (Geographic Information System) 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.

CLIMATE MAPPING PROJECTS

The SCAS is engaged in many projects to prepare detailed climate maps for the United States. Five of these projects are discussed below.

USDA NRCS CLIMATE MAPPING PROJECT

The USDA NRCS Water and Climate Center initiated a project with SCAS in 1993 to produce peer-reviewed maps of major climatic elements for the United States and its possessions (Johnson et al., 1998, 1999). 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 developed using standard monthly and annual normal observations from National Weather Service cooperative stations and NRCS Snotel sites for the period 1961-1990.

Monthly and annual precipitation maps for all 50 states were reviewed and have been distributed to NRCS offices throughout the nation (USDA NRCS, 1998). These were distributed in a variety of media, including via the worldwide web (<http://www.ftw.nrcs.usda.gov/prism/prism.html>), and as a set of three compact discs that included these digital spatial data sets for the 48 continental states, as well as map viewing software. Mean monthly and annual minimum, maximum and average temperature maps for all 50 states also have been completed, and are being distributed primarily to NRCS GIS staff. Draft maps of monthly mean daily minimum and maximum dew point, freeze dates, freeze-free season length, growing degree days and related elements were being completed. Projects to be completed in 2001 include a new rainfall erosivity (so-called R-factor in the Revised Universal Soil Loss Equation) map of the United States, and a new plant hardiness (mean annual extreme minimum temperature) map. In addition, the NRCS is utilizing the baseline PRISM precipitation and temperature data sets to generate several critically-needed maps on their own. These include soil climate maps (monthly and annual soil temperature and moisture) and new soil climate taxonomy maps. These will replace outdated, hand-drawn maps that are not digital and provide erroneous values in mountainous areas. The contact for this project is Greg Johnson at the NRCS Water and Climate Center (gjohnson@wcc.nrcs.usda.gov).

NOAA NCDC CLIMATE ATLAS

The NCDC is working with SCAS to develop a new climate atlas for the United States, last produced in 1968 (Plantico et al., 2000). The completed atlas will be available on the Web and CD-ROM, and include hundreds of national maps of many climatic elements. The project is divided into two phases. Phase one involved successfully developing and testing statistical methods that can be used to derive maps of climate elements from existing high-quality maps of mean precipitation and temperature (produced for the USDA NRCS). Examples are the derivation of mean growing degree days from mean monthly temperature and median freeze dates from minimum monthly temperature. Statistical derivation precluded a costly mapping effort for each of the many elements involved, and promoted consistent mapping of related climate elements. The strength of the regression relationships between the predictive element (precipitation

or temperature) and the derived element varied. Typically, the strongest regression relationships were achieved when a mean value, such as mean growing degree days, was predicted. Relationships were less strong when deriving extreme or record elements, such as record monthly precipitation from mean monthly precipitation. To account for regionally varying relationships, residuals from the U.S.-wide regression function were mapped and used to correct the final map product. Phase 2, nearing completion, has involved the application of derivation procedures to produce national maps for many climate elements. The NCDC contact for this project is Marc Plantico (MPLANTIC@ncdc.noaa.gov).

NOAA/NASA HIGH RESOLUTION, 103-YEAR TIME SERIES

Under joint funding from NASA (National Aeronautics and Space Administration) and NOAA's (National Oceanographic and Atmospheric Administration) Climate Change Data and Detection Program; SCAS, NCAR (National Center for Atmospheric Research), and NCDC are engaged in an effort to produce 103 years of monthly precipitation and minimum and maximum temperature for the lower 48 states (Daly et al., 1999; 2000b). These data sets are high-resolution (~4 km) grids. Station data used are National Weather Service cooperative sites and USDA NRCS Snotel stations. A PRISM-based spatial quality control system was developed by SCAS to improve data quality for mapping purposes (Daly et al., 2000b). Missing monthly data were infilled via statistical methods developed by NCAR (Kittel et al., 1997). PRISM was then applied to the infilled station data to produce monthly climate grids. A draft precipitation data set for the years 1950-1993 with limited station data screening is currently available. Final, screened, precipitation and temperature data sets for the entire 103-year period will be available in 2001. It is envisioned that the final data sets will be distributed by NCDC via the Web and on CD-ROM. These climate grids will provide a vast resource to climate researchers, modelers, ecologists, agricultural interests, and natural resource managers. 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 Christopher Daly, at SCAS (daly@oce.orst.edu).

OSC/USDA/STATE OF OREGON

CLIMATE MAPS FOR CHINA

The Oregon Seed Council (OSC) is a consortium of Oregon grass seed companies whose purpose is to develop new seed products and market them worldwide. OSC received funding from USDA's Market Access Program and the State of Oregon to develop new markets in the Peoples' Republic of China for Oregon grass seed products. Grass is increasingly being used in China in various ways, including turf, forage, and erosion control. Unfortunately, no accurate species adaptation maps existed to assist OSC in planning their marketing activities. For the past several years there have been several field tests in China to assess the performance of grass cultivars, but it was not possible to extrapolate those tests to other areas because of the complexity of China's climate. SCAS is producing detailed (~4 km) gridded climate maps of China, Taiwan, and

Mongolia to aid in the extrapolation of the field trials and the mapping of species adaptation zones. SCAS obtained mean 1961-1990 data for from over 1,500 Chinese stations, and is completing monthly and annual maps of precipitation and average maximum and minimum temperature. The contact for this project is Christopher Daly, at SCAS (daly@oce.orst.edu).

ENVIRONMENT CANADA CLIMATE MAPS

Environment Canada is supporting SCAS to develop peer-reviewed, high-quality minimum and maximum temperature and precipitation maps for the provinces of British Columbia, Yukon, Alberta, Saskatchewan, and Manitoba. PRISM is being applied to 1961-1990 mean station data collected by Canada's Atmospheric Environment Service, plus a small number of mountain stations in British Columbia maintained by BC Hydro. Grid resolution is the same as that of the U.S. data sets (~4km), and the grids are coincident with the NRCS U.S. grids discussed above. Canadian and U.S. grids are being merged to produce coverages that are consistent across boundaries with the lower 48 states and Alaska. Maps for southern British Columbia and Yukon Territory have been completed. The remainder of British Columbia and the Prairie Provinces will be completed by spring 2001. The contact for this project is Eric Taylor, Natural Resources Canada, (Eric.Taylor@nrcan.gc.ca).

PRISM PRODUCTS ON THE WORLD WIDE WEB

Many of the digital data sets described above are now being made available to the general public via the World Wide Web. The most comprehensive sources of information on how to obtain these data sets are the SCAS PRISM Web site, <http://www.ocs.orst.edu/prism/>, and the Climate Source, <http://www.climatesource.com>. The largest selection of maps is available in ASCII grid form, the native format of PRISM. Grid format is typically ARC/Info ASCII GRID, which is compatible with most GIS packages. Some maps are available in other formats, such as ARC/Info color polygon coverage, GIF graphic representation, and hard copy. Accompanying documentation includes metadata files that are compliant with Federal Geographic Data Committee (FGDC) standards, and details on materials and methods used for each climatic element.

The USDA NRCS spatial climate Web site, <http://www.ftw.nrcs.usda.gov/prism/prism.html>, offers downloadable postscript files containing cartographic-quality maps of PRISM mean annual precipitation for each state in the U.S. It also offers the precipitation and temperature data sets mentioned previously, as well as all future NRCS products, primarily for USDA use only.

Draft monthly precipitation grids for 1950-1993 from the NOAA-NASA time series project are available for download from the NCDC ftp site: <ftp.ncdc.noaa.gov/pub/data/prism100/>. In 2001, these grids will be superseded and the time series extended to the full 1895-1997 period. When completed in late 2001, it is anticipated that the monthly minimum and maximum temperature time series will be posted to this site.

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, NOAA Office of Global Programs, NOAA National Climatic Data Center, NASA, Environment Canada and other agencies, Oregon State University's Spatial Climate Analysis Service has produced a number of spatial data sets of excellent quality and detail, most of which are peer reviewed. Many of these data sets are, or will soon be, available via the World Wide Web. Elements include 1961-1990 mean monthly and annual precipitation, maximum, minimum, and average temperature, dew point temperature, relative humidity, snowfall, heating and cooling degree days, and growing degree days; median last spring freeze and first fall freeze (0°C) dates; median freeze-free season length, and others. Data sets were modeled in gridded form at a resolution of 2.5 min (~ 4 km) or less. Currently under development is a high-resolution (2.5-min), 103-year time series of monthly precipitation and minimum and maximum temperature for the U.S. In addition to the United States data sets, high-quality temperature and precipitation data sets for western Canada and the People's Republic of China are also nearing completion. The most comprehensive sources of information on how to obtain these data sets are the SCAS PRISM Web site, <http://www.ocs.orst.edu/prism/>, and the Climate Source, <http://www.climatesource.com>.

These map products are being developed using PRISM (Parameter-elevation Regressions on Independent Slopes Model), a knowledge-based approach to mapping climate that seeks to combine the strengths of human-expert and statistical methods. PRISM uses point data, a digital elevation model, other spatial data sets, a knowledge base, and expert interaction to generate estimates of annual, monthly and event-based climatic elements that are gridded and GIS-compatible. PRISM 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 ability of terrain to enhance precipitation. PRISM climate maps are of high quality because of a rigorous peer-review process, and attention to developing new tools that faithfully reproduce climate patterns in the most demanding regions and situations.

REFERENCES

- Bishop, G. D., M. R. Church, J. D. Aber, R. P. Neilson, S. V. Ollinger, and C. Daly. 1998a. A comparison of mapped estimates of long-term runoff in the northeast United States. *J. Hydrol.* 206: 176-190.
- Bishop, G. D., M. R. Church, and C. Daly. 1998b. Effects of improved precipitation estimates on automated runoff mapping: eastern United States. *J. Am. Water Resour. Assoc.* 34(1): 159-166.
- Briggs, P. R., and J. G. Cogley. 1996. Topographic bias in mesoscale precipitation networks. *J. Clim.* 9: 205-218.
- Daly, C., W. P. Gibson, D. Hannaway, and G. H. Taylor. 2000a. Development of new climate and plant adaptation maps for China. In *Proc., 12th Conf. on Applied Climatology*, 8-11 May, Asheville, N.C.: American Meteorological Society.

- Daly, C., and G. L. Johnson. 1999. PRISM spatial climate layers: their development and use. Short Course on Topics in Applied Climatology. Dallas, Tex. 10-15 January. <<http://www.ocs.orst.edu/prism/prisguid.pdf>>. Boston, Mass.: Am. Meteorological Society.
- Daly, C., T. G. F. Kittel, A. McNab, J. A. Royle, W. P. Gibson, T. Parzybok, N. Rosenbloom, G. H. Taylor, and H. Fisher. 1999. Development of a 102-year high-resolution climate data set for the conterminous United States. In *Proc., 10th Symp. on Global Change Studies*, 480-483. Dallas, Tex. 10-15 January. Boston, Mass.: Am. Meteorological Society.
- Daly, C., T. G. F. Kittel, A. McNab, W. P. Gibson, A. Royle, D. Nychka, T. Parzybok, N. Rosenbloom, and G. H. Taylor. 2000b. Development of a 103-year high-resolution climate data set for the conterminous United States. In *Proc., 12th Conference on Applied Climatology*, 249-252. Asheville, N.C. 8-11 May. Boston, Mass.: Am. Meteorological Society.
- Daly, C., and R. P. Neilson. 1992. A digital topographic approach to modeling the distribution of precipitation in mountainous terrain. In *Interdisciplinary Approaches in Hydrology and Hydrogeology*, eds. M. E. Jones, and A. Laenen, 437-454. Minneapolis, Minn.: American Institute of Hydrology.
- Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.* 33: 140-158.
- Daly, C., G. H. Taylor, and W. P. Gibson. 1997. The PRISM approach to mapping precipitation and temperature. In *Proc., 10th AMS Conf. on Applied Climatology*, 10-12. Reno, Nev. 20-23 Oct. <<http://www.ocs.orst.edu/prism/amsac97.pdf>>. Boston, Mass.: Am. Meteorological Society.
- _____. 1998a. The PRISM approach to mapping precipitation and temperature. In *Proc., Modeling for Crop-Climatology-Soil-Pest System and Its Applications in Sustainable Crop Production*, 150-152. Jaingsu Academy of Agricultural Sciences. Nanjing, China. 22-26 June.
- Daly, C., G. H. Taylor, W.P. Gibson, T. Parzybok, G. L. Johnson, and P. A. Pasteris. 1998b. Development of high-quality spatial climate datasets for the United States. In *Proc., 1st Int. Conf. on Geospatial Information in Agriculture and Forestry*, I-512 - I-519. Lake Buena Vista, Fla. June 1-3.
- Giambelluca, T. W., and D. Nullet. 1991. Influence of the trade-wind inversion on the climate of a leeward mountain slope in Hawaii. *Clim. Res.* 1: 207-216.
- Gibson, W. P., C. Daly, and G. H. Taylor, 1997. Derivation of facet grids for use with the PRISM model. In *Proc., 10th AMS Conf. on Applied Climatology*, 208-209. Reno, Nev. 20-23 Oct. <http://www.ocs.orst.edu/prism/facet_ac1997.html>. Boston, Mass.: Am. Meteorological Society.
- Hanson, C. L., R. P. Morris, R. L. Engleman, D. L. Coon, and C. W. Johnson. 1980. Spatial and seasonal precipitation distribution in southwest Idaho. U.S. Department of Agriculture, Science and Education Administration Agricultural Reviews and Manuals. Washington, D.C.: GPO.
- Hibbert, A. R. 1977. Distribution of precipitation on rugged terrain in central Arizona. *Hydrol Water Resour Ariz Southwest* 7: 163-173.
- Houghton, J. G. 1979. A model for orographic precipitation in the north-central Great Basin. *Mon. Wea. Rev.* 107: 1462-1475.
- Huffman, G. J., R. F. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider. 1997. The Global Precipitation Climatology Project (GPCP) combined precipitation dataset. *Bull., Amer. Meteor. Soc.* 78: 5-20.
- Johnson, G. ., C. Daly, C. L. Hanson, Y. Y. Lu, and G. H. Taylor. 2000. Spatial variability and interpolation of stochastic weather simulation model parameters. *J. Appl. Meteorol.* 39: 778-796.
- Johnson, G. L., P. A. Pasteris, C. Daly, and G. H. Taylor. 1998. Climate information for natural resource management in a spatial world. In *Proc., 1st Int. Conf. on Geospatial Information in Agriculture and Forestry*, II-255 - II-257. Lake Buena Vista, Fla. 1-3 June. Ann Arbor, Mich.: ERIM International, Inc.
- Johnson, G. L., P. A. Pasteris, G. H. Taylor, and C. Daly. 1999. Spatial climate products: A new dimension for climate applications. In *Proc., 11th Conf. on Applied Climatology*, 107-114. Dallas, Tex. 10-15 January. Boston, Mass.: Am. Meteorological Society.
- Kittel, T. G. F., J. A. Royle, C. Daly, N. A. Rosenbloom, W. P. Gibson, H. H. Fisher, D. S. Schimel, L. M. Berliner, and VEMAP2 Participants. 1997. A gridded historical (1895-1993) bioclimate dataset for the conterminous United States. In *Proc., 10th AMS Conf. on Applied Climatology*, 219-222. Reno, Nev. 20-23 Oct. Boston, Mass.: Am. Meteorological Society.
- Osborn, H. B. 1984. Estimating precipitation in mountainous regions. *J. Hydr. Eng* 110: 1859-1863.
- Parzybok, T., W. P. Gibson, C. Daly, and G. H. Taylor. 1997. Quality assurance of climatological data for the VEMAP project. In *Proc., 10th AMS Conf. on Applied Climatology*, 215-216. Reno, Nev. 20-23 Oct. Boston, Mass.: Am. Meteorological Society.
- Plantico, M., L. A. Goss, C. Daly, and G. H. Taylor. 2000. A new U.S. climate atlas. In *Proc., 12th Conf. on Applied Climatology*, 247-248. Asheville, N.C. 8-11 May. Boston, Mass.: Am. Meteorological Society.
- Schwarb, M., C. Daly, and C. Frei. 1999. Precipitation climate maps for the Alpine region. Poster presented at Mesoscale Alpine Program Meeting, Appenzell, Switzerland, June.
- USDA NRCS. 1998. PRISM Climate Mapping Project—Precipitation. Mean monthly and annual precipitation digital files for the continental U.S. USDA-NRCS National Cartography and Geospatial Center, Ft. Worth Tex. December. CD-ROM.
- Vogel, R. M., I. Wilson, and C. Daly. 1999. Regional regression models of annual streamflow for the United States. *ASCE J. Irrig. & Drain. Eng.* 125: 148-157.
- Vuglinski, V. S. 1972. Methods for the study of laws for the distribution of precipitation in medium-high mountains (illustrated by the Vitim River Basin). *Distribution of Precipitation in Mountainous Areas, WMO Pub.* 326(2): 212-221.
- Whitmore, J. S. 1972. The variation of mean annual rainfall with altitude and locality in South Africa, as determined by multiple curvilinear regression analysis. *Distribution of Precipitation in Mountainous Areas, WMO Pub.* 326(2): 188-200.