The Accuracy of United States Precipitation Data

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Abstract

Precipitation measurements in the United States (as well as all other countries) are adversely affected by the gauge undercatch bias of point precipitation measurements. When these measurements are used to obtain areal averages, particularly in mountainous terrain, additional biases may be introduced because most stations are at lower elevations in exposed sites.

Gauge measurements tend to be underestimates of the true precipitation, largely because of wind-induced turbulence at the gauge orifice and wetting losses on the internal walls of the gauge. These are not trivial as monthly estimates of this bias often vary from 5% to 40%. Biases are larger in winter than in summer and increase to the north in the United States due largely to the deleterious effect of the wind on snowfall.

Simple spatial averaging of data from existing networks does not provide an accurate evaluation of the area-mean precipitation over mountainous terrain (e.g., over much of the western United States) since most stations are located at low elevations. This tends to underestimate area averages since, in mountainous terrain, precipitation generally increases with elevation.

Temporal precipitation trends for the United States, as well as seasonal and annual averages, are presented. Estimates of unbiased (or less biased) precipitation over the northern Great Plains provide a regional analysis.

1. Introduction

Currently, the U.S. meteorological network consists of about 8000 cooperative stations and 278 first-order stations (located mainly at airports) that record precipitation on at least a daily basis. Of these, hourly totals are recorded at 241 first-order stations and about 2600 cooperative stations. Many of these stations have been in operation for more than 100 years and the data are routinely archived at the National Climatic Data Center (NCDC) at Asheville, North Carolina. At NCDC, these data have been largely distributed in two regular publication series—the *Local Climatological Data* (LCD) and the *Hourly Precipitation Data* (HPD) bulletins (published since 1948 and 1950, respectively)—as well as the *Historical Climatology Network* (HCN) (Quinlan et al. 1987; Karl et al. 1990) and the contiguous U.S. Climate Division Data Base (CDDB) archives. Additional precipitation data can be obtained from regional and state networks located particularly in the western United States.

The LCD contains monthly summaries of 272 of the 278 first-order stations. Although these stations constitute a small percentage of the total number of stations at which precipitation is measured in the United States, they nevertheless provide the main source of data that the National Weather Service (NWS) transmits over the Global Telecommunication System (GTS) of meteorological observations and are published in the *Monthly Climatic Data for the World* (Karl et al. 1993b). Precipitation gauges at many of these stations are not shielded, but since the late 1940s, from 20% to 40% of the gauges at first-order stations have been equipped with Alter wind shields. This varying use of wind shields has thus introduced an inhomogeneity into many of the precipitation time series in the LCD (Karl et al. 1993b). This, coupled with the fact that most first-order stations were relocated from downtown locations to suburban airports during the 1930s, 1940s, and 1950s, introduces potential biases into the first-order network (and thus the LCD) that can be problematic when these data are used for climatological studies (Groisman 1991, 1993; Legates 1992a, b).

By contrast, the HCN consists of data from 1221 cooperative and first-order stations evenly distributed over the contiguous United States. Station selection criteria included an availability of a relatively long precipitation time series, a predominantly undisturbed environment around the gauge, and limited relocations of the meteorological site based on the recommendations of state climatologists (Quinlan et al. 1987). These data have been subjected to strict quality control procedures (Karl et al. 1990; Easterling and

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Peterson 1992) and widely used in studies of contemporary climate change (cf. Intergovernmental Panel on Climate Change 1990, 1992; Boden et al. 1991).

Areally averaged precipitation for 344 spatially quasi-homogeneous climatological divisions for the contiguous United States from 1895 through 1993 are contained in the CDDB. Data from more than 6000 stations (first-order and cooperative weather stations) are used in the averaging process. A potential homogeneity problem may be introduced, however, since different station networks were used to compute monthly averages during the period of record. Routine publications of monthly climate summaries based on the CDDB are widely distributed by the NCDC.

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Over the contiguous United States, the HCN and, to a lesser extent, the CDDB are likely the best available sources of historical precipitation data. The question we address here, however, is: Is the absolute accuracy of these data adequate to meet the diverse needs of scientists who use historical precipitation data? We believe that for many applications, the answer is no. Consider, for example, estimates of long-term mean annual precipitation for Colorado obtained from the data of the HCN and CDDB databases compared to those obtained by digitizing climatological maps produced by U.S. (U.S. Department of Commerce 1968) and Russian (World Water Balance 1974) climatologists (Table 1). These maps, although they have been subjectively compiled by experienced climatologists, indicate that mean annual precipitation is 15% to 35% higher than station (point) estimates, which can be significant for long-term annual averages. Similar results were obtained by Legates (1987) and Legates and Willmott (1990) using objectively developed bias estimation techniques. These differences can be attributed to both the systematic biases associated with point precipitation measurements and to inaccuracies associated with obtaining area averages from point precipitation measurements over rough terrain.

Unfortunately, these problems are not specific to Colorado but affect precipitation estimates to some degree for all regions of the world.

In this paper, we further examine these two sources of inaccuracies in areal precipitation estimates. In particular, we will address the question of whether these subjective estimates are reasonable in light of more recent, objective methodologies. A more detailed example for the northern Great Plains also is given.

TABLE 1. Estimates of the long-term mean areally averaged annual precipitation for Colorado from databases and maps.

	Time period	
	1891(5)–1970	1931–60
Historical Climatology Network	385 mm	375 mm
Climate Division Data Base	405 mm	380 mm
U.S. Dept. of Commerce Map (1968)	—	435 mm
World Water Balance Map (1974)	520 mm	—

2. Inaccuracies in precipitation data

a. Point precipitation measurements

To accurately evaluate the influence of anthropogenic modifications to the hydrologic cycle (e.g., changes in land use) or the impact of climate change, regional-scale fluctuations in precipitation must be separated from the effects of local changes that directly affect gauge measurements of precipitation. Such discontinuities in precipitation time series may be induced by changes in instrumentation and recording practices, siting characteristics, and station location (Eischeid et al. 1991).

Changes in instrumentation may introduce a discontinuity into a precipitation time series since the gauge measurement is affected by gauge design and whether the gauge is equipped with a shield. Such discontinuities were introduced in the 1940s by the adoption of Alter wind shields at some U.S. stations primarily in the western United States (U.S. Department of Commerce 1963; Groisman 1991; Groisman et al. 1991b).

Changes in the environment surrounding the gauge may occur with time. This includes, for example, vegetation growth and removal, construction and demolition of buildings and fences near the gauge, and urbanization of the local area. Since each of these changes affect the flow of the wind, it may influence the gauge catch (cf. Brown and Peck 1962; Eischeid et al. 1991). Gauge siting also is affected by stations that have been periodically relocated. In particular, the movement of downtown (urban) stations to airports and the relocation of gauges from or to the roofs of buildings have introduced discontinuities into precipitation time series (Eischeid et al. 1991; Groisman 1991; Groisman et al. 1991b).

In addition to inhomogeneity problems, gauge measurements are biased estimates of the true precipitation. It has long been demonstrated that the catch of a precipitation gauge decreases with increasing wind speed, which, in turn, increases with height (Neff 1977). A practical approach to overcome this effect is to affix a wind shield to the gauge to reduce the turbulence over the orifice. Most gauges in the United States are unshielded—only about 200 stations that record daily precipitation use Alter shields (Karl et al. 1993a) that do not entirely eliminate the wind-induced bias (cf. Goodison 1981; Sevruk and Hamon 1984).

Systematic errors also are induced by other factors including wetting and evaporative losses, automatic recording techniques, and the treatment of trace precipitation as zero. Wetting losses include moisture that adheres to the funnel during precipitation and subsequently evaporates without being measured. Evaporation also may occur from nonrecording storage gauges during the time between the end of precipitation and the manual reading.

Errors also may be introduced by the mechanisms of recording gauges. Some moisture may be lost during the time it takes for tipping-bucket mechanisms to "tip" and the other "bucket" to be positioned under the funnel—particularly during high-intensity rainfall (Parsons 1941). In addition, double tips also are frequently encountered when a tipping bucket gauge is out of level. To measure snowfall, some tipping-bucket gauges are equipped with small, electrical heaters that melt the falling snow and allow its measurement by the tipping bucket mechanism. This design, however, significantly enhances both the evaporation of melted snow and the sublimation of newly fallen snow, which greatly increases the evaporative loss. Heated gauges therefore are not accurate for the measurement of snowfall (cf. Metcalfe and Goodison 1992). It is unfortunate that these gauges have been proposed for use in the Automated Surface Observing System (ASOS) in the United States. Frictional drag produced by the weighing mechanism of weighing gauges and the recording pens of most recording gauges also result in a slight decrease in the measured precipitation. Some self-emptying designs also inaccurately measure precipitation during the few moments it takes to empty the gauge (Linsley et al. 1982).

Random errors may be caused by the gauge (e.g., leakage from or damage to the gauge), by the observer (e.g., inaccuracies in measuring and recording procedures), or by tampering. These errors are considered to be unsystematic biases since they may result in either an increase or a decrease in the gauge catch (Sevruk 1979).

Since the wind field deformation affects the total gauge catch—which includes both the wetting and evaporative losses as well as mechanically induced effects—and all other losses are additive, Legates (1992b) modified Sevruk's (1979) general model for precipitation correction to

$$\begin{aligned} P_c = {} & k_r(P_{gr} + \Delta P_{wr} + \Delta P_{er} + \Delta P_{mr}) \\ & + k_s(P_{gs} + \Delta P_{ws} + \Delta P_{es} + \Delta P_{ms}), \end{aligned} \tag{1}$$

where k is the wind deformation coefficient (usually $k \geq 1$), P_g is the gauge-measured precipitation; ΔP_w, ΔP_e, and ΔP_m are the corrections for wetting, evaporation, and mechanical errors, respectively; and the additional subscripts r and s denote the correction for liquid (rain or drizzle) and solid (snow) precipitation. Here splashing and random errors are ignored. To obtain an unbiased (or less biased) estimate of the actual precipitation, each of the terms in Eq. (1) must be estimated. The wind field deformation coefficient, k, depends on the type of gauge and shield used, whether the precipitation falls as rain or snow, and the wind speed during precipitation at gauge orifice height. Equations for estimating this coefficient have been developed from field studies and gauge intercomparison projects. The WMO Solid Precipitation Measurement Intercomparison studies (Goodison et al. 1988, 1989, 1992), presently nearing completion, will provide more reliable equations to estimate this wind-induced bias.

Wetting and evaporative losses are usually small. The wetting loss correction depends on the gauge design and the form and frequency of precipitation (Sevruk 1979, 1982). Average values of the wetting loss per precipitation event for gauges commonly used in the United States have been determined to be 0.15 mm for snowfall and 0.03 mm for rainfall (cf. Sevruk 1982; Golubev et al. 1992). For the United States, the evaporative loss from the gauge collector is much smaller than the wetting loss and can usually be ignored (Legates 1987; Legates and DeLiberty 1993a,b).

As a direct result of the wind-induced bias and wetting losses, gauges in the United States exhibit an undercatch bias between 3% and 10% for rainfall events (Sevruk and Hamon 1984; Golubev et al. 1992); that varies considerably but may exceed 50% for snowfall events (Larkin 1947; Larson and Peck 1974; Goodison 1978, 1981). In northern Alaska, additional biases of up to 400% in the measurement of

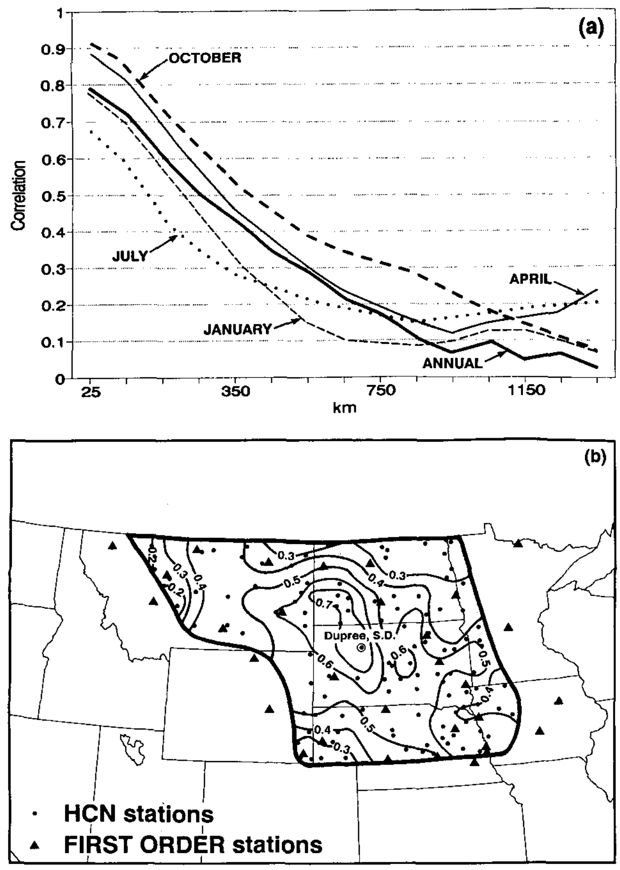

FIG. 6. Spatial correlation of monthly and annual precipitation over the northern Great Plains illustrating (a) the mean spatial correlation function by season and (b) the spatial correlation structure of annual precipitation totals for Dupree, South Dakota.

annual precipitation obtained from two global climatologies where gauge-induced biases were estimated and removed (World Water Balance 1974; Legates 1987). This 1% precision for annual precipitation totals over the northern Great Plains also is a theoretical estimate derived from Eqs. (4) and (5). These small differences illustrate the agreement between considerably different adjustment methods used over level terrain for the correction of precipitation data for annual time scales and regional spatial scales.

TABLE 5. Parameters of the spatial statistical structure of monthly and annual precipitation for the northern Great Plains. The correlation radius, ρ_0, and C_0 are parameters of the spatial correlation function [Eq. (2)].

	Correlation radius (in km)	C_0	Coefficient of variation
January	340	0.85	0.6–0.9
April	470	0.95	0.5–0.8
July	575	0.60	0.6–0.9
October	680	0.90	0.8–1.0
Annual	440	0.90	0.2–0.25

4. Summary and conclusions

Standard precipitation gauges used in the U.S. meteorological network produce underestimates of the actual precipitation owing largely to the effect of wind on snowfall. Over the past century, these biases have changed due to changes in instrumentation and measurement practices, thus introducing countrywide inhomogeneities in precipitation time series over the United States (cf. Karl et al. 1993a,b). Climate change studies that do not account for these inhomogeneities may produce misleading results. In addition, the prevalence of measurements at lower elevations in mountainous terrain necessitates further research to determine reliable estimates of snowfall changes in the United States. Results of the northern Great Plains analyses presented here show that areally averaged annual precipitation is well described by both simple and more detailed correction methods, and the accuracy of averaging (the relative root-mean-square error) for this region is about 1%.

Concerning the reliability of the U.S. precipitation archive, we can conclude as a result of our analyses and experience the following:

- Gauge measurement biases are not trivial and for annual totals, these biases range from 5% to 25% with larger biases in higher elevations and higher latitudes. Seasonally, the bias is greater in winter and smaller in summer owing to the increased effect of wind on snowfall. It should be noted, however, that these biases are not a constant and may exhibit considerable interannual variability.
- Adjustments to conventional precipitation measurements, such as those discussed here, can be used to obtain reliable unbiased (or at least less biased) estimates of absolute amounts of monthly precipitation totals for the U.S. observational network. These adjustments, however, require considerable station information (metadata) and additional meteorological information (i.e., wind and air temperature) for their implementation.
- Areal averaging over rough terrain, which is required for hydrological applications and the creation of gridded precipitation datasets, can be accomplished using models that account for orography (not shown here). Several such models of varying complexity exist although they have not yet