



SCC Publishing
Michelets vei 8 B
1366 Lysaker Norway

ISSN: 2703-9072

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Vol. 6.3 (2026)

pp. 117-125

Issues Associated with the Measurement of Precipitation for Climate Change Assessment

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Abstract

Long-term assessments of climate change depend upon observations that are accurate, representative, and consistent through time. Precipitation presents particular difficulties because it is highly variable both spatially and temporally and because observational networks are unevenly distributed across the globe. Stations tend to be concentrated in developed, populated, low-elevation regions, while large areas of the tropics, high latitudes, mountains, and oceans remain poorly sampled. Moreover, station locations, environments, instrumentation, and observing practices change through time, potentially introducing artificial discontinuities into climate records.

Precipitation gauges themselves are subject to substantial measurement biases. Wind-induced undercatch is particularly important because airflow around a gauge can deflect precipitation away from the gauge, evaporation, gauge height, shielding, splash, and instrument design. These biases are generally systematic rather than random and can affect hydrological and climatological analyses.

Changes in instrumentation can also produce apparent climatic trends. For example, the transition of portions of the U.S. observing network to the Automated Surface Observing System (ASOS) during the early 1990s introduced gauges with different siting and catch characteristics. An examination of a U.S. extreme-precipitation index shows relatively little trend before and after this transition but an apparent discontinuity coincident with network modernization, raising questions about how much of the long-term increase represents climatic change versus observational change.

Consequently, precipitation trends, particularly small trends over large spatial scales, must be interpreted in the context of measurement uncertainty, network evolution, land-use change, and observational inhomogeneity. Robust climate-change assessment requires distinguishing genuine climatic signals from artifacts introduced by the observing system itself.

Keywords: Precipitation measurement; climate change; observational uncertainty; precipitation trends; extreme precipitation; rain-gauge undercatch; climate data homogeneity; instrumentation change; climate trend detection.

Submitted 2026-08-09, Accepted 2026-08-13. <https://doi.org/10.53234/scc202608/03>

1. Introduction

The measurement of climate seems, at first glance, to be a relatively straightforward undertaking. Meteorologists have been measuring temperature and precipitation for well over a century, and modern climate assessments routinely use these observations to identify long-term changes in climate. Yet the apparent simplicity of these measurements conceals a much more difficult

problem. Before trends in precipitation can confidently be attributed to climate change, we must first determine whether the observations themselves are sufficiently accurate, representative, consistent, and homogeneous to reveal the climatic signal we are attempting to detect.

Precipitation presents an especially difficult challenge. It is considerably more variable in both space and time than air temperature. A person can drive through an intense thunderstorm and emerge into completely dry conditions within a short distance. Whether it ‘rained’ at a particular location on a particular day may therefore depend simply upon where the rain gauge happened to be located. In mountainous terrain, where precipitation changes dramatically with elevation and exposure, the problem becomes still more difficult.

These difficulties are important because climatologists frequently combine thousands of individual observations to estimate regional, national, and even global precipitation. The resulting datasets can create an impression of precision that may greatly exceed the precision of the underlying observations.

2. The Global Precipitation Network

One of the fundamental problems is the geographic distribution of precipitation gauges. Weather stations are not distributed randomly or uniformly across Earth’s surface. Dense networks exist in countries such as Germany, while enormous regions of the planet have relatively sparse coverage. Furthermore, the number and location of stations change through time. Stations enter and leave the observational network because of economic circumstances, political changes, wars, institutional decisions, and many other factors unrelated to climate.

The distribution of observations consequently contains several systematic biases. Weather stations tend to be concentrated where developed populations live. They are more common near populated areas and coastlines than in remote interiors, more common at lower elevations than on mountain peaks, more numerous in the middle latitudes than in the tropics or polar regions, and vastly more numerous over land than over the oceans. The resulting observational network therefore has urban, economic, geographic, and elevation biases built into it.

More importantly, these biases are not necessarily constant through time. Historical events can dramatically alter a country’s observing network. Japanese stations, for example, disappeared from one historical dataset around 1945, while the collapse of the Soviet Union disrupted a large observational system that researchers had hoped would provide valuable historical precipitation data. Consequently, a global precipitation record constructed for one period may not be spatially comparable with the network available several decades later.

Even where station density is relatively high, the actual area being sampled is extraordinarily small. Germany provides an instructive example. If *Deutscher Wetterdienst* operates approximately 2,000 precipitation gauges and each has an opening of about 200 square centimeters, the total area collecting precipitation across Germany is only about 40 square meters. That is roughly 40 percent of the six-yard box on a soccer field. And Germany possesses one of the world’s comparatively dense observational networks. The sampled area in countries with sparse meteorological networks is dramatically smaller.

This creates another important statistical issue. Researchers may treat thousands of observations as though they were independent measurements, allowing uncertainty to decrease rapidly as sample size increases. But neighboring gauges frequently measure the same meteorological systems and therefore are not statistically independent. The true effective sample size may be considerably smaller than the raw number of stations suggests.

3. What Does “Representative” Mean?

A second problem concerns representativeness. Meteorological stations are normally expected to

occupy open locations away from buildings, trees, air-conditioning exhausts, furnaces, and other artificial influences. Such standards make sense when the objective is to obtain comparable climatological measurements.

But real landscapes frequently do not resemble ideal meteorological observing sites. Cities such as Berlin, for example, consist largely of buildings, streets, trees, vehicles, and other obstructions. If the objective is to determine how much precipitation falls in Berlin, where should the rain gauge be located? A pristine open site might satisfy climatological standards while simultaneously failing to represent the environment in which most residents actually live.

Thus, there can be a distinction between **climatological representativeness** and **hydrological representativeness**. The former seeks standardized measurements under controlled conditions; the latter may seek to understand what is actually occurring across a heterogeneous landscape.

4. The Requirement for Consistency

Long-term climate analysis requires something else: consistency. Ideally, if precisely the same meteorological conditions occurred today and again several decades from now, the observing system would record the same value both times.

In practice, observing systems rarely remain unchanged. Stations move. Buildings are constructed. Trees grow or are removed. Airports expand. Instruments are replaced. Observational procedures change. Some changes occur suddenly, while others evolve gradually and therefore do not create an obvious discontinuity in the record.

The transformation of Washington Dulles International Airport provides an illustration (Figure 1). Photographs from the early airport era show sheep grazing around largely undeveloped land. The modern airport is surrounded by extensive pavement, roads, terminals, parking facilities, and urban development. Even if a meteorological station remains geographically close to its original position, its surrounding environment may bear little resemblance to what existed when the climate record began.



Figure 1: Washington's Dulles International Airport (USA) shortly after its construction in 1962¹ and in 2011².

For temperature, urbanization generally introduces a predictable influence toward warming. The effects on precipitation are less straightforward. Does replacing fields with pavement make measured precipitation greater, smaller, or simply more variable? How should such effects be identified and corrected? And if surrounding stations have undergone similar urbanization, comparing

¹ https://www.reddit.com/r/nova/comments/t2t7d9/history_sundays_dulles_airport_when_it_first/

² https://en.wikipedia.org/wiki/Dulles_International_Airport

one station with its neighbors may not solve the problem.

5. Climate Change Versus Land-Use Change

The distinction between climate change and land-use change becomes particularly important when examining floods and droughts.

Northern Delaware provides a useful case study. The region has become much more urbanized over the past century and has experienced increased problems associated with both flooding and water shortages. It is tempting to attribute such changes immediately to climate. But dramatic changes in land use can produce similar effects without any corresponding change in precipitation.

Talleyville, Delaware, illustrates the process. In 1937, the community was surrounded largely by farmland and vegetation. Rain falling on the landscape infiltrated into the soil and moved relatively slowly toward the Brandywine River. Over the following 85 years, Talleyville became part of the suburbanized Wilmington metropolitan area.

Rain falling on the modern landscape encounters roads, parking lots, rooftops, and other impervious surfaces. Streets and storm drains efficiently transport water toward streams, increasing runoff and the potential for urban flooding. At the same time, population growth and economic development increase water consumption. More households, businesses, landscaping, and other water-intensive activities place greater demands upon available supplies during dry periods.



Figure 2: Talleyville, Delaware (USA) in 1937 (left) and 2022 (right).

Thus, human activity unquestionably can increase both flood and drought problems. But the relevant human activity may be urbanization and land-use change rather than anthropogenic climate change. The distinction matters because the appropriate policy responses are very different.

6. The Surprisingly Primitive Raingauge

Precipitation measurement appears deceptively simple. At its most basic level, a rain gauge

consists of a container and a ruler. Indeed, despite sophisticated modern alternatives—including optical, acoustic, weighing, hot-plate, and electronic gauges—much of the world's precipitation network still depends upon devices that are fundamentally variations on the traditional container-and-measuring-stick design.

The problem is that countries have historically used different gauges. Designs differ in shape, construction, shielding, and particularly in the height of the gauge opening above the ground. These differences affect the amount of precipitation that actually enters the gauge.

6.1 Wind-induced Errors

The greatest source of error is **wind**. A precipitation gauge is a physical obstruction placed in moving air. Wind accelerates around and over the instrument. This produces turbulence, vertical motion, and pressure differences around the opening. Falling raindrops—and especially snowflakes—can consequently be deflected away from the gauge rather than entering it.

The result is systematic **undercatch**. For rainfall the error can be significant. For snowfall it can become enormous. Under windy conditions, a gauge may capture less than one-quarter of the snow that actually falls.

One solution is to place gauges at ground level in pits, thereby reducing their exposure to wind. Such installations can provide useful reference measurements but are inconvenient for routine observations. Another approach surrounds the gauge with a windshield designed to reduce aerodynamic distortion. Different countries have developed different shield designs, including fixed and movable slats. These improve catch efficiency but do not completely eliminate the problem.

6.2 Wetting-Loss and Evaporation Errors

Wind is not the only source of precipitation loss. Some water adheres to the inside walls of the instrument—a phenomenon known as **wetting loss**—and is therefore never measured. Water can also evaporate from a gauge before the observer records it.

Based upon the global precipitation analysis developed for my dissertation, wind produces an average global underestimate of roughly 8 percent, wetting contributes approximately another 2 percent, and evaporation about 1 percent. Together these effects imply that gauges globally may measure only about 89 percent of the precipitation that actually falls. Crucially, this error is not random. The bias is overwhelmingly toward measuring too little precipitation rather than too much.

6.3 Additional Sources of Measurement Error

Even after accounting for wind, precipitation gauges remain subject to numerous other problems.

Very small rainfall events may wet the internal surfaces of the gauge without producing enough measurable water to be recorded. Evaporation losses become particularly important in hot and dry climates. Installing gauges close to the ground reduces wind effects but can introduce splash-in, as raindrops strike the surrounding surface and rebound into the gauge. Poor gauge designs can also allow splash-out.

Tipping-bucket gauges introduce another difficulty during exceptionally intense rainfall: the mechanism may not tip rapidly enough to record all the incoming water. Snow creates still more complications. Blowing and drifting snow may enter a gauge even though it is not actually falling from the atmosphere at that moment. Converting accumulated snow to its liquid-water equivalent introduces another potential source of uncertainty, and gauges can freeze or become blocked by snow, ice, debris, or birds.

These errors differ according to precipitation type, climate, gauge design, wind speed, installation height, shielding, observational procedure, and local environment. They also change through time as networks evolve.

6.4 The Impact of These Errors on Hydrological Analyses

This bias also propagates through hydrological analyses. If precipitation input into a water-balance calculation is underestimated, some other component of the hydrologic cycle must compensate. Evapotranspiration or soil-moisture estimates may therefore appear anomalously low because the original precipitation input was already biased downward.

Gauge height further complicates matters. Wind speed generally increases with height above the ground. Consequently, raising a precipitation gauge increases its exposure to wind and tends to reduce catch efficiency. Yet countries experiencing heavy snowfall often need to raise gauges so that they are not buried by accumulating snow. Different national observing practices can therefore create artificial discontinuities across political boundaries. Apparent changes in precipitation at an international border may have nothing whatsoever to do with meteorology; they may simply reflect differences in instrumentation and observing procedures.

7. When Better Instruments Create an Artificial Climate Trend

These measurement issues become particularly important when examining trends in extreme precipitation. The NOAA Climate Extremes Index shows the proportion of precipitation associated with extreme one-day events. The series appears to rise over the twentieth and early twenty-first centuries. Viewed without additional information, the graph seems to provide straightforward evidence that heavy precipitation has become more common or intense.

But the history of the observing network complicates that interpretation. Until the late twentieth century, many National Weather Service precipitation observations involved traditional gauges read manually. An observer physically measured the accumulated water, emptied the gauge, and repeated the procedure at specified intervals.

During the late 1980s and early 1990s, the National Weather Service began modernizing its network with the Automated Surface Observing System, or ASOS. Among the new technologies were automated precipitation gauges. Tipping-bucket gauges, for example, use small, calibrated buckets that tip after collecting a predetermined amount of water—usually 1 mm. Each tip is electronically recorded, providing both precipitation totals and much more detailed information about rainfall timing and intensity.

Automation offered obvious operational advantages. But the transition also changed the physical characteristics of the observing system. Because human observers no longer needed convenient access to the instruments, gauges could be installed closer to the ground. Lower placement meant reduced wind speed and therefore improved catch efficiency. Shields were also installed around the gauges, further reducing wind-induced undercatch.

The result was an observational system introduced around 1990–1993 that was more efficient at catching precipitation than much of the system it replaced. That change becomes highly significant when the long-term heavy-precipitation index is divided into periods.

According to the analysis presented, the record from approximately 1910 through 1990 is essentially flat. Likewise, the record after the modernization period—from roughly 1993 onward—is also essentially flat. The apparent century-long increase emerges primarily because the later, more efficient observing system records a higher level than the earlier system.

In other words, two relatively flat periods are separated by a **jump discontinuity** occurring at approximately the same time that the precipitation observing network was modernized (Figure 3).

Climate generally does not change through abrupt nationwide jumps synchronized with changes in meteorological instrumentation. Such discontinuity is therefore a warning that the observational system itself may have changed.

Regional comparisons provide further support for this interpretation in the presentation. The apparent increase is larger in the northeastern United States, where more airport stations underwent the ASOS transition, and smaller in the Southwest, where cooperative observer gauges that did not undergo the same modernization constitute a larger portion of the network.

The argument, therefore, is that at least part of what appears to be an increase in heavy precipitation may actually be a **gauge-change signal rather than a climate-change signal**. Yet the discontinuity remains embedded in the observational record and consequently can be interpreted as evidence of increasing precipitation intensity.

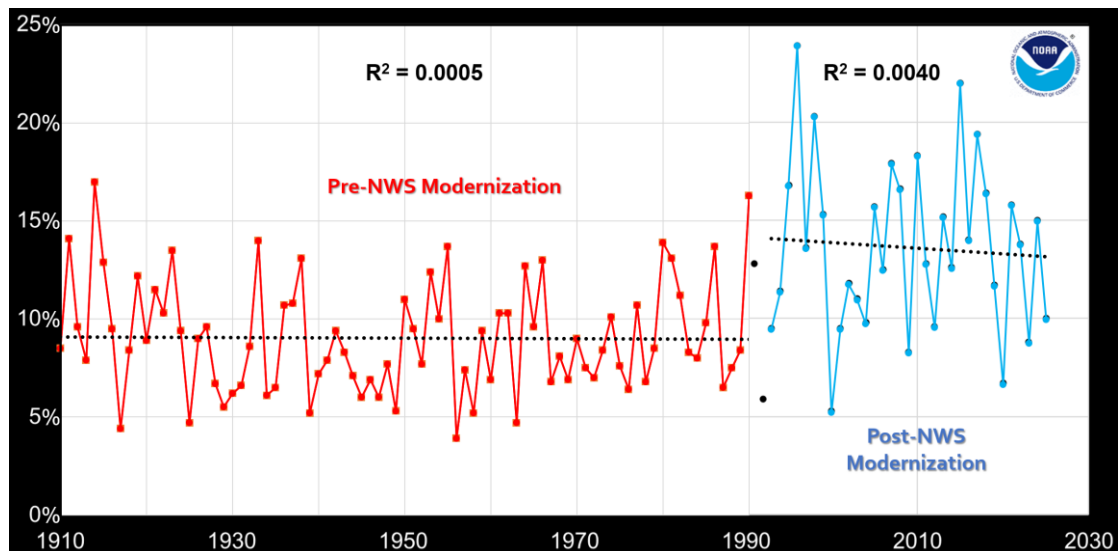


Figure 3: NOAA's Climate Extremes Index (Step 4 – Extremes in one-day precipitation)³ showing the period before the ASOS modernization (in red) and after the ASOS modernization (in blue).

8. The Larger Lesson for Climate Assessment

The central message of this presentation is not that precipitation cannot be measured, nor that precipitation patterns cannot change. Rather, it is that detecting relatively small long-term climatic trends requires a level of observational consistency that is extraordinarily difficult to achieve.

This problem becomes increasingly serious as the geographic scale of the analysis expands. Global mean surface temperature is routinely calculated, plotted, and discussed. Global mean precipitation is much less commonly presented. There is a reason for that difference: precipitation is spatially heterogeneous, difficult to measure, poorly sampled across large portions of the planet, affected by numerous systematic gauge biases, and observed using instruments and procedures that have changed through time.

Consequently, apparently precise precipitation trends can conceal substantial uncertainty.

The basic climatological question should therefore not simply be: **Does the graph show an increase or decrease?** Instead, we must first ask what produced the graph.

Were the same places sampled throughout the period? Did the number of stations change? Are the observations independent? Are they spatially representative? Did urbanization alter the surrounding landscape? Were stations relocated? Did trees grow around them or buildings appear nearby? Did national observing practices change? Were gauges raised or lowered? Were windshields introduced? Did the network transition from manual to automated observations? Did the new instruments catch precipitation more efficiently than the instruments they replaced?

³ <https://www.ncei.noaa.gov/access/monitoring/cei/graph>

Only after addressing these questions can researchers determine whether an apparent trend represents a genuine change in climate or a change in the observing system.

This distinction becomes particularly important when changes are small. If the climatic signal is large compared with observational uncertainty, imperfect measurements may still reveal it. But when the trend being interpreted is comparable to—or smaller than—the uncertainties introduced by station distribution, instrumentation, siting, gauge undercatch, land-use change, and network modernization, strong conclusions become much more difficult to justify.

That is ultimately the reason for pessimism about precipitation trends. The problem is not merely that rain gauges are imperfect. Scientists have known for many decades that gauges suffer from wind loss, wetting loss, evaporation, siting effects, and other biases. The deeper problem is that these biases are neither spatially nor temporally constant. The observing system itself changes while researchers are attempting to measure change in the climate.

A century-long climate record is therefore not necessarily a century-long record produced by a single stable instrument under unchanging conditions. It is more often a composite assembled from stations that opened and closed, instruments that were replaced, locations that changed, cities that grew, observational procedures that evolved, and national networks that expanded, contracted, or disappeared.

The final warning is therefore one of appropriate scientific caution. Maps and graphs showing small changes in precipitation over decades can appear authoritative, particularly when they are produced by major scientific or government institutions. But the visual precision of a graph should not be confused with the precision of the underlying observations.

When precipitation trends are presented as evidence of climate change, the associated observational uncertainty must be considered alongside the trend itself. In some cases, that uncertainty may be relatively modest. In others, it may be comparable to the observed change. And in still others, particularly at very large spatial scales, the uncertainty may overwhelm the signal researchers are attempting to interpret.

The fundamental lesson is therefore straightforward: **before asking what precipitation observations tell us about climate change, we must first understand exactly what our precipitation observations can tell us.** The instrument, its surroundings, its history, its exposure to wind, its location, and changes in the observing network are not peripheral technical details. They are integral parts of the climate record itself.

This is why global precipitation trends deserve considerably more caution than they often receive. Small apparent changes can acquire considerable scientific and public significance, yet the uncertainties behind those changes are rarely as visible as the trend lines drawn through them. In precipitation measurement especially, those uncertainties can be sufficiently large that they overwhelm the very signal we are trying to detect.

Funding

No funding was provided to produce this discussion.

Co-Editor: Stein Storlie Bergsmark

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