So, how much of the Earth's surface *is* covered by rain gauges?

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Summary Capsule:

The total area measured globally by all currently available rain gauges is surprisingly small, equivalent to less than half a football field or soccer pitch.

Abstract

The measurement of global precipitation, both rainfall and snowfall, is critical to a wide range of users and applications. Rain gauges are indispensable in the measurement of precipitation, remaining the *de facto* standard for precipitation information across the Earth's surface for hydro-meteorological purposes. However, their distribution across the globe is limited: over land their distribution and density is variable, while over oceans very few gauges exist and where measurements are made, they may not adequately reflect the rainfall amounts of the broader area. Critically, the number of gauges available, or appropriate for a particular study, varies greatly across the Earth due to temporal sampling resolutions, periods of operation, data latency and data access. Numbers of gauges range from a few thousand available in near real time, to about a hundred thousand for all 'official' gauges, and to possibly hundreds of thousands if all possible gauges are included. Gauges routinely used in the generation of global precipitation products cover an equivalent area of between about 250 m^2 and 3,000 m^2. For comparison, the center circle of a soccer pitch or tennis court is about 260 m^2. Although each gauge should represent more than just the gauge orifice, auto-correlation distances of precipitation vary greatly with regime and the integration period. Assuming each Global Precipitation Climatology Centre (GPCC) -available gauge is independent and represents a surrounding area of 5 km radius, this represents only about 1% of the Earth's surface. The situation is further confounded for snowfall which has a greater measurement uncertainty.

Precipitation, including both rainfall and snowfall, is a key component of the energy and water cycle influencing the Earth's climate system. Its measurement is not only fundamental in specifying the current state of the distribution and intensity of precipitation that help define our climate, but also for monitoring the changes in our climate. Precipitation is considered to be an essential global variable (NASA 1988) and an Essential Climate Variable (GCOS 2010), and thus requires adequate measurement. Fundamental to this must be high quality, long term observations at fine temporal and spatial resolutions. Trenberth et al. (2003) emphasized the need to be able to assess and quantify the changing character of precipitation through better documentation and processing of all aspects of precipitation. In particular, Stephens et al. (2010) noted that precipitation is not well represented in climate-scale models. Precipitation is also of great interest to a number of different scientific disciplines beyond the atmospheric community, including the hydrological, oceanic, cryospheric, environmental, ecological and biological communities. Not only is precipitation a critical component of the Earth System, but also essential to life on Earth, impacting not only humanity, but also the natural environment around us. Over land, precipitation is ultimately the source of all fresh water. The monitoring and measurement of precipitation is of economic value for agriculture through agro-businesses such as crop forecasting, water resource management, civil defense through mitigation of droughts or floods, and through more benign economic returns through, for example, the removal of particulate matter from the atmosphere (Thornes et al. 2010).

The measurement of precipitation (defined as deposition of water from the atmosphere in solid or liquid form) might at first appear to be straightforward; however, precipitation is relatively rare, highly variable, and consequently poorly monitored as an environmental parameter particularly on a global basis. Instantaneously, precipitation occurs globally probably less than 1% of the time (Barrett and Martin, 1981). When precipitation does occur, intensities may range from very light to very heavy; the range of intensities for instantaneous precipitation is highly skewed towards lighter intensities. Furthermore it has significant spatial and temporal variability, making it difficult to measure satisfactorily; dense observational networks are necessary to adequately capture this variability, particularly at fine temporal and spatial scales. Averaging over time and space generally results in accumulated precipitation being more normally distributed and more representative (Bell et al. 1990); climatological-scale accumulations require less dense networks, although these may not necessarily faithfully capture small scale, extreme events or the variability over complex terrain.

Thus, the adequate measurement of precipitation is necessary at a number of scales and for a number of users. For flash flood studies precipitation measurements are required at local, fine scales with rapid access to the data (low latency) while for drought, longer term measurements will suffice, with less stringent spatial, temporal and latency requirements. For climate studies the accuracy of the measurements and the homogeneity of the data record are perhaps paramount over other criteria to enable the assessment of the subtleties due to climate change.

Gauge numbers

The number of gauges cited in the literature varies somewhat. In their *Catalogue of National Standard Precipitation Gauges,* Sevruk and Klemm (1989b) put the number of gauges worldwide at more than 150,000, while Groisman & Legates (1995) estimated the number of ‘different’ gauges to be as many as 250,000. However, New et al. (2001) put the number closer to the figure of 150,000 stations of Sevruk and Klemm. The figure was quantified by Strangeways (2003) who identified at least 123,014 monthly accumulation gauges (summarized in Table 1). These variations are largely dependent upon on the criteria used to count the number of gauges; for example, some of these numbers will include all the ‘stations’ that have existed and have provided some precipitation measurements at some time in their observational record, while others will only report locations which currently return precipitation measurements. Thus, while it is certain that many gauges exist, not all gauges have operated continuously or simultaneously.

Not all gauge observations are available to the public or even to researchers. Those observations that are available, are not necessarily available for all temporal samples (i.e. 3-hourly, daily, etc), or with adequate data latency; flood monitoring and forecasting requires the timely delivery of data to be truly useful, whereas climate application can accommodate longer data delivery times. The availability of data from different countries/regions often depends upon the organization within the country, region or locality. Often more than one agency within each country is tasked with the collection of rainfall data; these agencies are not necessarily consistent from one country to the next. An additional and potentially large number of gauge observations are available from commercial networks (e.g. water companies) although such data may be deemed to be commercially sensitive and therefore access to such data is often restricted.

Global meteorological data (including precipitation) is available through the World Meteorological Organisation (WMO) Global Telecommunication System (GTS), collected from between 8,000 and 12,000 “first class” stations (WMO, 2011). The precipitation information contained with the SYNOP report is collected for 3-hourly and daily periods at the fixed synoptic hours and distributed in near real time, although the records for each station may not always be complete for an entire monthly record. Figure 1 illustrates the coverage of these measurements by mapping the distance from each of the GTS stations across the globe; it can be seen that the data coverage for near real-time data on a global scale is relatively poor. While some regions such as Europe and eastern Asia (including Japan) have reasonable coverage, elsewhere gauges are sparse. This means that applications such as flash flood monitoring that require fine temporal and spatial resolutions generally rely upon gauge and radar (where available) observations obtained from local or regional meteorological organizations, or satellite-based infrared estimates (Arkin and Xie, 1989)

At the daily scale, the situation is somewhat better. A more comprehensive set of daily gauge data is organized through the Global Precipitation Climatology Project (GPCP) at the Global Precipitation Climatology Centre (GPCC; Becker et al. 2013) which provides perhaps the foremost repository of global precipitation data derived from gauges. Access to existing data sets hitherto unavailable to the GPCC has been improved through the WMO-implemented Global Terrestrial Network for Hydrology (GTN-H) observing system since 2001. Although the data released by the GPCC is restricted to a gridded product, it reveals the number of rain gauges operating across the globe that report information on a regular and reliable basis. As of 2013 (2015) a total of 180 institutions contribute data to the GPCC from about 85,000 (100,000) gauge locations that have provided observations at least once since the start of the dataset in 1901. Initial daily and monthly products are available a few days after the end of the integration period, with a more complete ‘monitoring’ product after about 8 weeks and full daily and monthly products available after about 2 years. For this full, long-term or climatological analysis it is critical to ensure continuous records of precipitation from any single station, consequently the GPCC imposes a 10-year minimum constraint. This restricts the number of available stations as of 2013 (2015) to 67,298 (75,165) for the best month, or 67,149 (75,033) for the worst, or a total 65,335 (73,586) stations across all 12 months of the year (Becker et al. 2013; Schneider et al., 2015). Figure 2 shows the coverage of the GPCC gauge data. Most of Germany lies within 10 km of the nearest rain gauge, while large areas of Europe, the US, eastern South America, India and the more populated regions of Australia are less than 25 km from a gauge. Other regions with lesser, but still good coverage include Turkey and Iran, parts of Africa (South Africa in particular) and the Andes in South

America. Some of the GTS stations ‘disappear’ in the GPCC dataset primarily due the fragmented nature of their observational record.

A number of other key gauge data products exist that provide a greater range of precipitation products at varying temporal and spatial resolutions. It should be noted that many of these data products utilize the same gauge information as the GPCC product, rather than providing information from additional gauges. Such global data sets include the CPC Gauge-Based Analysis of Global Daily Precipitation (Xie et al. 2010) and the Global Historical Climatology Network (GHCN; Menne et al. 2012), both of which provide daily gridded precipitation products derived from meteorological observations worldwide. The number of available gauges varies considerably by year (and by region/year) with a maximum (for precipitation observations) of just over 30,000 stations, about half of which are in the US. The GHCN also collects information on snow depth from about 17,000 stations, again virtually all in the US. The Climate Research Unit at the University of East Anglia gauge product (Mitchell and Jones 2005) aims to provide a consistent precipitation data set exploiting historical precipitation records. Regional data sets, such as the APHRODITE product (Yatagi et al. 2012) and the China Gauge-based Daily Precipitation Analysis (CGDPA; Shen and Xiong 2016) are often able to obtain a greater number of regional gauges through local sources.

It is therefore clear that the number of gauges used in creating precipitation products varies considerably. The numbers of sub-daily rainfall gauge observations available in near real-time is small, although more observations are available if the user is willing to wait longer for the data to become available. Daily gauge accumulations, although hindered by non-uniform reporting times globally, represent perhaps the greatest number of official data entries since this is in line with the WMO recommendations and most easily implemented by the individual meteorological agencies. At longer time scales the potential number of stations declines slowly, not least if a complete data record is required since some stations might not report precipitation (including zero-rain) 100% of the time.

Gauge Representativeness

If the rain gauges alone are considered, the surface area of the orifices is surprisingly small. The most common gauges, as noted in Table 1, provide a total surface area estimated to cover just 3,026 m^2 from 123,014 gauges. Scaling the GTS and GPCC data sets using an average orifice size of 246 cm^2 would result in equivalent surface areas of about 295 m^2 and 1,612 m^2 respectively. For comparison, Table 2 provides the areas of pitches/courts/fields for common sporting activities; the comparisons between the GTS and GPCC against the equivalent areas are illustrated in Figure 3. For the 3-hourly GTS data set, assuming that the maximum number of gauges report data, an area just greater than that of the center circle of a soccer pitch is actually measured; in reality less than half of the GTS stations regularly report rainfall measurements. The GPCC gauges provide an area equivalent to about 4 basketball courts.

However, fundamental to the measurement of precipitation using rain gauges is that they are accurate at the location and are representative of their surrounding area.The ‘capture’ of precipitation, particularly solid precipitation, by a rain gauge is largely affected by the wind-effect around the orifice, an effect that is exacerbated with increased exposure (Duchon and Essenberg, 2001; Goodison et al, 1998), together with losses or errors that may also arise from the mechanical construction of the gauge. However, despite errors associated with rain gauges, they remain arguably the most accurate instrument by which to measure rainfall. The measurement of snowfall is more difficult than the measurement of rainfall due to nature of falling (and blowing) snow, the variety of snow gauges used and the catchment (in)efficiencies of the gauges and is the focus of the WMO Solid Precipitation

Intercomparison Experiment (SPICE) project (Nitu and Wong, 2010b, ; Rasmussen et al, 2012). The majority of these measurements are now made by automated systems (Nitu and Wong 2010a), predominantly by weighing or tipping bucket gauges, the latter being poor at measuring snowfall (Goodison et al. 1998). Despite the measurement accuracy for snowfall being strongly affected by the wind due to the collector-snow particle flow dynamics, only about 28% of precipitation gauges are equipped with shields to modify the air flow over the gauge, although most automated snow gauges are heated in order to prevent snow accumulating on the rim or sides of the collector (Nitu and Wong, 2010a). While rainfall can be usually be measured to within 10-20% (Vuerich et al, 2009), wind-effects may result in less than 25% of the snowfall being caught (Goodison et al. 1998). However, errors and uncertainties associated with such precipitation measurements for manual gauges are reasonably well understood and corrections (or quality control) can be applied. The SPICE project is currently addressing corrections necessary for automatic gauges.

Spatially, at the very local scale, the gauge should at least represent the rainfall falling in its immediate vicinity, over scales of a few metres and preferably a few kilometres. However, gauge measurements have their limitations given the spatial and temporal variability of precipitation and the fact that gauges are (small) point measurements. Standards set by the WMO (2008) are designed to ensure consistency between gauge measurements to reduce some of the inherent errors, such as those caused by siting or exposure. However, even under ideal situations the representativeness or auto-correlation length of precipitation is surprisingly small; Habib et al. (2001) showed that for instantaneous precipitation over the mid-western US the correlation coefficient between adjacent gauges fell to less than 0.5 just 4 km away; similar results were found for frozen precipitation. Furthermore, this correlation length is dependent upon the meteorology of the precipitation event and the local topography. Fortunately, accumulating precipitation over time, increases the correlation length (Bell et al. 1990); over longer periods, the gauges become more representative of the regional precipitation regime. Although many schemes exist for the interpolation of precipitation, care is needed since the same interpolation scheme applied to instantaneous or monthly precipitation data could produce undesired results: Indeed, the interpolation of instantaneous gauge data should be avoided where possible due to the inherent heterogeneity of precipitation at fine temporal and spatial scales.

Considering the representativeness of gauges on a global scale, Figure 4 illustrates the area of the Earth within the defined distances from the GTS and GPCC gauge locations, divided into four regions, ocean or land and 60°-polewards or 60°S-60°N. It is clear that the vast majority of the Earth's surface closest to gauges are (not surprisingly) concentrated over the land areas between 60°S-60°N, with relatively few gauges over land polewards of 60°. Over the oceans only a very small area is within 100 km of a gauge, and most of this area would be deemed 'coastal waters'. Considering the GPCC data globally, only 1.6% of the Earth's surface lies within 10 km of a rain gauge, although 5.9% lies within 25 km; over 60°S-60°N land areas this improves to 6.5% and 23.0% respectively. This contrasts with less than 4% of the Earth's oceans lying within 100 km of a gauge.

Filling the gaps

It is clear that gaps exist within the currently available gauge networks over the various temporal scales which require additional information if the representativeness of the precipitation measurements are sufficiently adequate to meet user requirements. Despite significant progress having been made in addressing some of the larger data gaps resulting from non-availability of regional gauge data sets, it is also clear that not all existing rain gauges that could be used are currently exploited. The gauges incorporated into the GPCC database derive from meteorological agencies which adhere to the requirements laid down by the WMO to ensure consistent measurements between different sites and regions. Perhaps the next great challenge will be whether to, and how to incorporate observations and/or measurements from non-traditional sources.

Citizen science or *crowdsourcing* offers one such source of additional information generated through addressing an underlying curiosity and interest in the weather (see Muller et al. 2015). An increasing number of internet-enabled, low-cost sensors and instrumentation are now easily available for personal, research and operational use. A number of these devices are capable of measuring precipitation, e.g. tipping bucket gauges or rainfall disdrometers (see Minda and Tsuda 2012) connected to small computers (Goodwin 2013). The data collected (manually or electronically) by these devices can be transmitted via a range of communication techniques, making a large amount of data available in near real time. Numerous websites have been set up to crowdsource data from these devices; these include the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS: http://www.cocorahs.org/; Cifelli *et al.* 2005), Weather Underground (http://www.wunderground.com/), UK Met Office Weather Observation Website (WOW: http://wow.metoffice.gov.uk; Tweddle *et al.* 2012), the NOAA Citizen Weather Observer Program (CWOP: http://wxqa.com/) and gauge-enabled Netatmo weather stations (www.netatmo.com). Social media holds potential for providing information on the phase of precipitation. The National Oceanic and Atmospheric Administration's (NOAA) Precipitation Identification Near the Ground (PING) project (Binau 2012) and the mobile PING (mPING; Elmore *et al.* 2014) project provide information on the phase of precipitation to directly improve radar estimates of precipitation, while the 'UK snow map' (http://uksnowmap.com/#/) was set up to monitor and map snowfall across the UK with citizens giving the snowfall a rating out of ten which, in conjunction with a range of specific hash-tags (e.g. #UKSnowMap, #UKSnow), whilst Muller (2013) used social media to obtain higher-resolution snow-depths across Birmingham, UK.

The potential of harvesting amateur weather data from thousands of sites, which may now outnumber those of standard measurement sites, does have drawbacks however. Although the crowdsourced data has the potential to overcome the spatial and temporal representativeness of standard data sets, issues arise from utilising non-traditional sources of data, i.e. calibration, exposure and other quality assurance/quality control (QA/QC) issues (Muller et al. 2015). For example, Bell et al. (2015) found variations in annual rainfall totals from low-cost weather stations ranged from about 76% to 111% of standard co-located gauges, although after correction differences throughout the year rarely exceeded 5%. Another issue is that the locations of crowdsourced observations are population-centric (see Elmore et al. 2014); while these additional data observations are not necessarily useful at the global-scale, the fine temporal observations and the fact that they are population-centric makes them ideal for certain applications, such as urban flood monitoring, by filling in information about particularly variations over short distances.

Radar networks, although not a direct measurement, provide another important source of large scale rainfall information. Weather radars offer the advantage of providing frequent spatial observations of precipitation over relatively large areas compared to gauge observations. This spatial information provides additional insights into the variability of precipitation, particularly in the gaps between gauge observations. Although radars are capable of producing reasonable estimates of rainfall, they do suffer from a number of artefacts, not least persistent errors related to beam blockage and range effects, as well as transient errors resulting from imperfect backscatter to rainfall relationships. The spatial distribution of operational radars is also somewhat limited on a global scale, being limited primarily to the US/Canada, Europe/Western Russia and Japan/Korea/Australia and New Zealand; these are regions where the density of gauge data are generally adequate. Despite the drawbacks and some repetition of gauge coverage, radars can provide spatial measurements at time scales that fulfil a niche in the measurement of precipitation, at least on a local to regional scale.

Satellite observations of remotely-sensed precipitation have been available over much of the globe for almost four decades and have the potential to be available on a truly global scale (Arkin and Ardunay, 1989). In particular, satellite estimates have a distinct advantage for assessing precipitation over data-sparse regions such as the world's oceans. Satellite observations from visible, infrared, and in particular, passive and active microwave systems are used to generate precipitation estimates using a number of techniques (see Kidd and Huffman 2011), although techniques differ in performance regionally and temporally. The Tropical Rainfall Measuring Mission (TRMM; Kummerow et al. 1998) Precipitation Radar (PR) and the Global Precipitation Measurement (GPM) mission (Hou et al. 2014) Dual-frequency Precipitation Radar (DPR) provide more direct measurements of precipitation. Although the PR and DPR provide intermittent measurements covering 36°S-36°N and 66°S-66°N respectively, the detailed information they provide is proving invaluable for a number of applications including hurricane monitoring and forecasting, as well as acting as a calibrator for other satellite precipitation measurements.

The potential for *repurposing* data from non-meteorological networks has also shown potential. Numerous municipal networks exist and collect routine data for various applications and may have the potential to be used as proxies for monitoring variables such as precipitation. For example, Overeem et al. (2013) used the received signal level data from microwave links in cellular communication networks to monitor precipitation in the Netherlands. Furthermore, multi-observational precipitation products have been developed to exploit the information from individual data sources. In particular, a number of mature satellite-based precipitation techniques incorporate surface precipitation data sets, allowing good spatial and temporal resolution precipitation products to be generated with the accuracy of surface measurements (e.g. Huffman et al. 2009): surface gauge measurements provide the anchor points for remotely-sensed products.

Conclusions

The surface area that is equivalent to the orifice area all of the worldwide operational rain gauges is surprisingly small, amounting to only 0.000000000593% of the Earth's surface. There are clearly a large number of gauges in existence, but the actual number of gauges available to the user is highly variable depending upon the period of study and latency requirements. The GPCC rain gauge data set, arguably the most comprehensive currently available global gauge dataset, comprises of a little over 65,000 gauges whose combined area is roughly equivalent to less than half a soccer pitch. If the number of gauges that provide near real time data is considered, as available through the WMO GTS network, the gauges could easily fit into a tennis court or the center circle of a soccer pitch. However, since gauges represent more than just the actual point location of the orifice, it may be assumed that a greater part of the Earth's surface might be covered: if each GPCC gauge represented an area extended to 5 km from each gauge (assuming no overlap) this still only represents about 1% of the Earth's surface.

Improving worldwide information on precipitation is fundamentally important. Information utilizing crowdsourced precipitation measurements (as opposed to just observations) from 'amateur' gauge networks has potential for many applications, including meteorology, but is probably more difficult to achieve due to timely access to the data, continuity and absolute calibration of the measurements. Furthermore, the spatial availability of both amateur and crowdsourced information tends to mimic that of existing precipitation information due to being population-centric. Great efforts have been made in obtaining gauge data in data sparse regions; however additional high-quality measurements are still needed to fill gaps in certain regions. In particular, the continental interiors of South America, Africa and Australia together with the northern regions of the continental land masses in the Northern Hemisphere and Antarctica are deficient in precipitation gauges. Projects such as the Trans-African HydroMeteorological Observatory (TAHMO; http://tahmo.org) are now beginning to address this need.

Ultimately gauge data has a critical role to play in not only the observation and monitoring of the Earth's climate, but also for enabling and improving other means of estimating global precipitation, whether through numerical models or through satellite observations.

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SIDEBAR:

WHAT IS A RAIN GAUGE? Fundamentally, a rain gauge may be described as any object that collects rain(water) which can be measured. The most common gauges have historically been 'simple cans' that accumulate rain water over a set period of time; evidence of such gauges may be traced back over two thousand years ago (see Strangeways 2010). While the basic concept of the gauge is simple, the practical implementation necessary to meet user requirements has led to a great diversity of gauge types; Sevruk and Klemm (1989a) identified more than 50 different manual gauge types alone. These can be categorized into the physical design of the gauge, the mechanisms used to collect and quantize the rainfall and the technology necessary to report the rainfall.

Design: The vast majority of gauges share one common feature; the orifice. This is usually circular with the rim and interior designed to ensure an accurate catch of the precipitation. The differences in the size of the orifice do not appear to critically affect the accuracy of the catch (Stangeways 2003), most official gauges having orifices typically between about 127 cm^2 and 400 cm^2: Figure S1a shows a Casella tipping bucket rain gauge with a 400 cm^2 orifice together with a Snowdon MkII accumulation gauge with a 127 cm^2 orifice However, the wind flow over the orifice, affects the accuracy of the catch often resulting in an under-measurement for light intensity precipitation and stronger winds (Strangeways 2004). A number of designs therefore make the gauges more aerodynamic to reduce this under-catch (Robinson and Rodda 1969). An example of the adaptation of a rain gauge for measuring snowfall is shown in Figure S1b which shows an OTT-Hydromet Pluvio2 200 weighing gauge with a heated rim, an inner Tretykov shield and an outer alter fence.

Mechanical: Despite the simplicity of the accumulation gauge the variability of precipitation over short time scales cannot be adequately captured by such gauges. Numerous mechanisms have therefore been devised to enable the precipitation collected to be suitably quantized over time. These include mechanically recording gauges such as the siphon gauge and weighing gauges, electrically recording such as tipping bucket gauges, electronic weighing gauges, capacitance gauges and drop counting gauges (see Strangeways 2010).

Technological: The cost of manual or mechanically recorded gauges together with the development of electrically recording gauges has led to the development of (quasi-) automatic gauges that can measure, record and report the rainfall in near real time through the use of electronic data loggers and communication systems (satellite or phone networks). The availability of gauge measurements in near real time greatly enhances the usefulness of such measurements for meteorological and hydrological applications.

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Table 1: Monthly manually-read gauges by type (after Strangeways 2003)

Country of origin	Number	Countries deployed	Orifice area	Total
Germany (Hellmann)	30,080	30	200 cm^2	601.6 m^2
China	19,676	3	314 cm^2	617.8 m^2
United Kingdom (Mk2/Snowdon)	17,856	29	127 cm^2	226.7 m^2
Russia	13,620	7	200 cm^2	272.4 m^2
United States	11,342	6	324 cm^2	367.5 m^2
India	10,975	1	200 cm^2	219.5 m^2
Australia	7,539	3	324 cm^2	247.5 m^2
Brazil	6,950	1	400 cm^2	278.0 m^2
France	4,876	23	400 cm^2	195.0 m^2
Total	123,014			3,026 m^2

Table 2: Dimensions and areas of common sporting fields/pitches/courts together with numbers of gauges with the equivalent area.

	Dimensions	Area	Equivalent gauges*
Soccer pitch	105 x 68 m	7140.0 m^2	178,500 - 562,204
Centre circle of soccer pitch	9.15 m radius	263.0 m^2	6,575 - 20,709
American Football	109.7 x 48.8 m	5353.4 m^2	133,834 - 421,524
Tennis Court	23.78 x 10.97 m	260.9 m^2	6,522 - 20,541
Basketball (FIBA)	28.0 x 15.0 m	420.0 m^2	10,500 - 33,071

*range based upon to 400 cm^2 to 127 cm^2 orifice areas.

Figure captions:

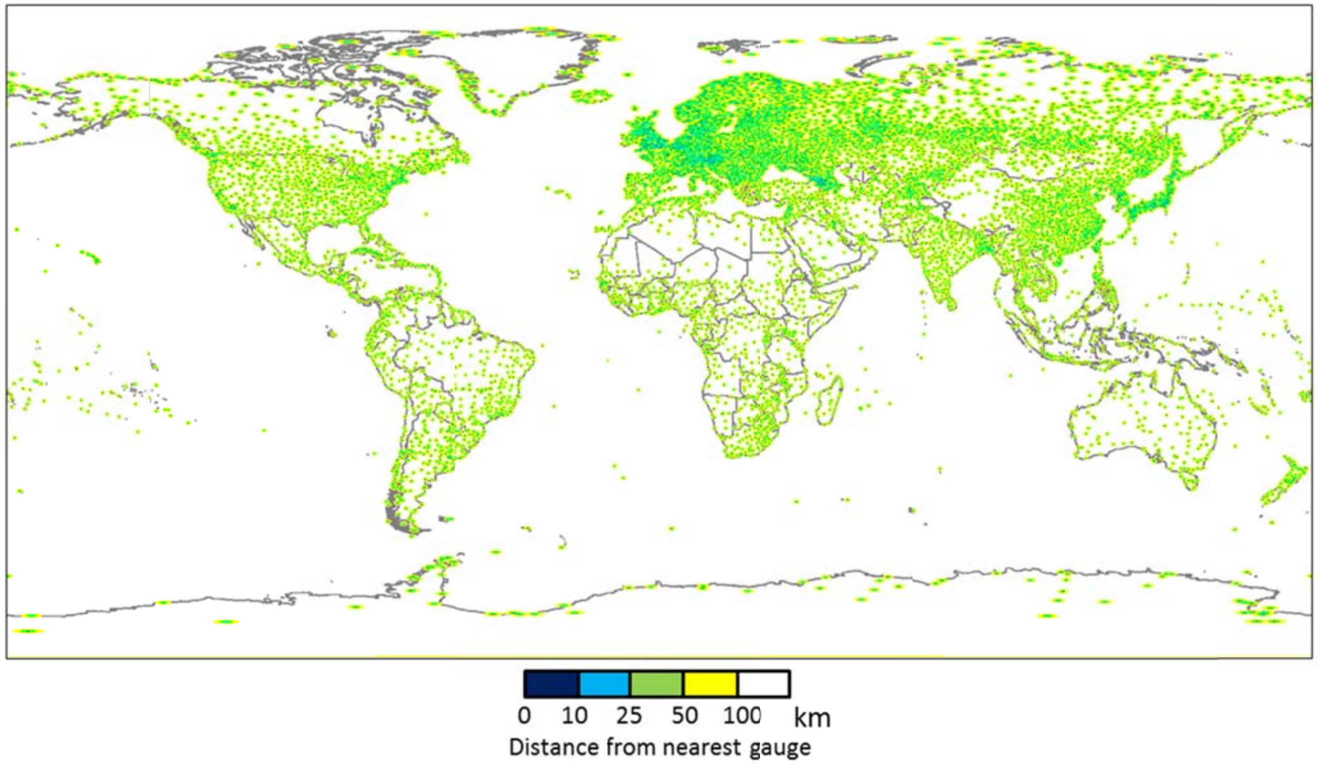
Figure 1: Map showing the distance to nearest GTS gauge, typical of 3-hourly/daily measurements available in near real time; blank areas in the figure are beyond 100 km from the nearest gauge.

Figure 2: Map showing the distance to nearest GPCC gauge, typical of all regular and reliable gauge measurements; blank areas in the figure are beyond 100 km from the nearest gauge.

Figure 3: Equivalent areas of common sports pitches and courts compared with the total areas of orifices of all GTS and GPCC gauges.

Figure 4. Areas of the Earth within certain distances from the nearest precipitation gauge for the GTS network (left) and the GPCC dataset (right). The whole square represents the whole of the Earth's surface, while the subdivisions are for land and ocean and 60°-polewards and 60°S-60°N.

Figure S1 a) Two Casella tipping bucket rain gauges (green) and Snowdon MkII accumulation gauge (copper-color) at the University of Birmingham (UK) Winterbourne II climate station, and b) an OTT-Hydromet Pluvio2 200 weighing gauge with a heated rim, an inner Tretykov shield and an outer alter fence during the GPM Cold-season Precipitation Experiment (GCPEx) in Canada.



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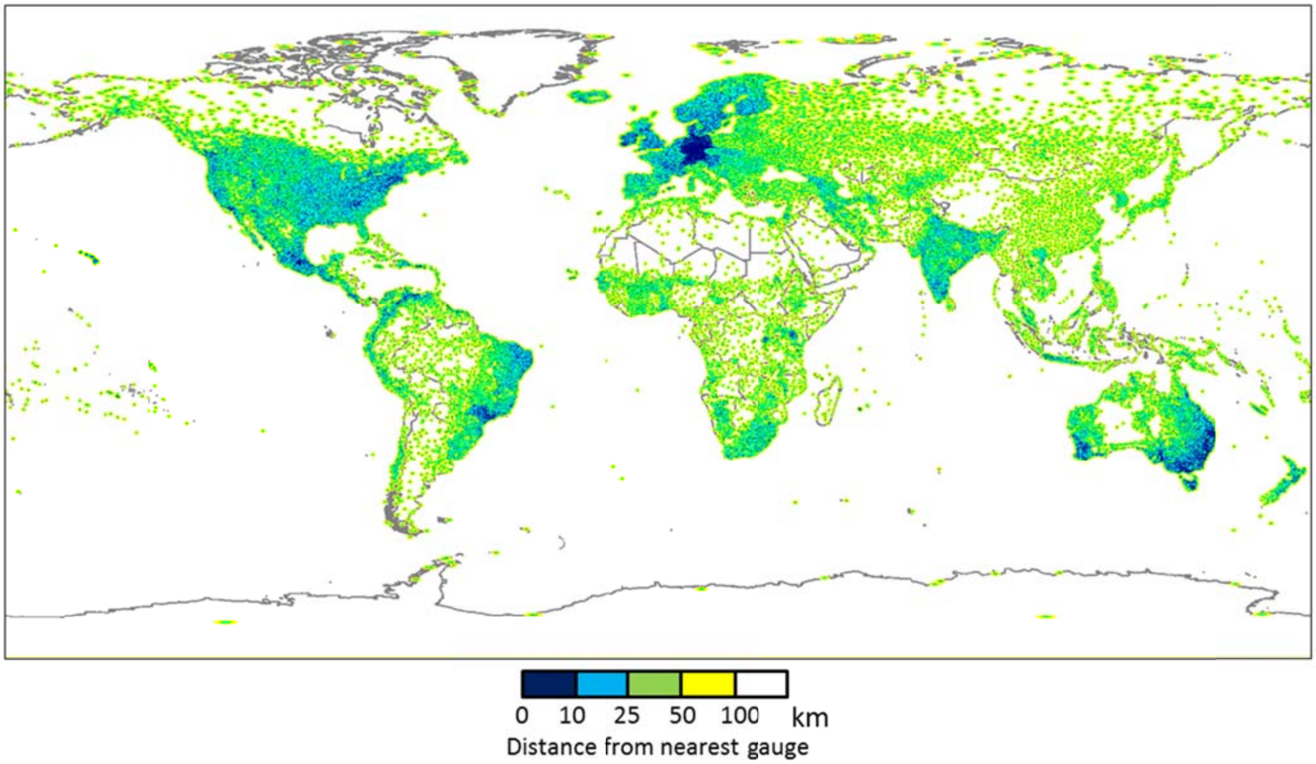
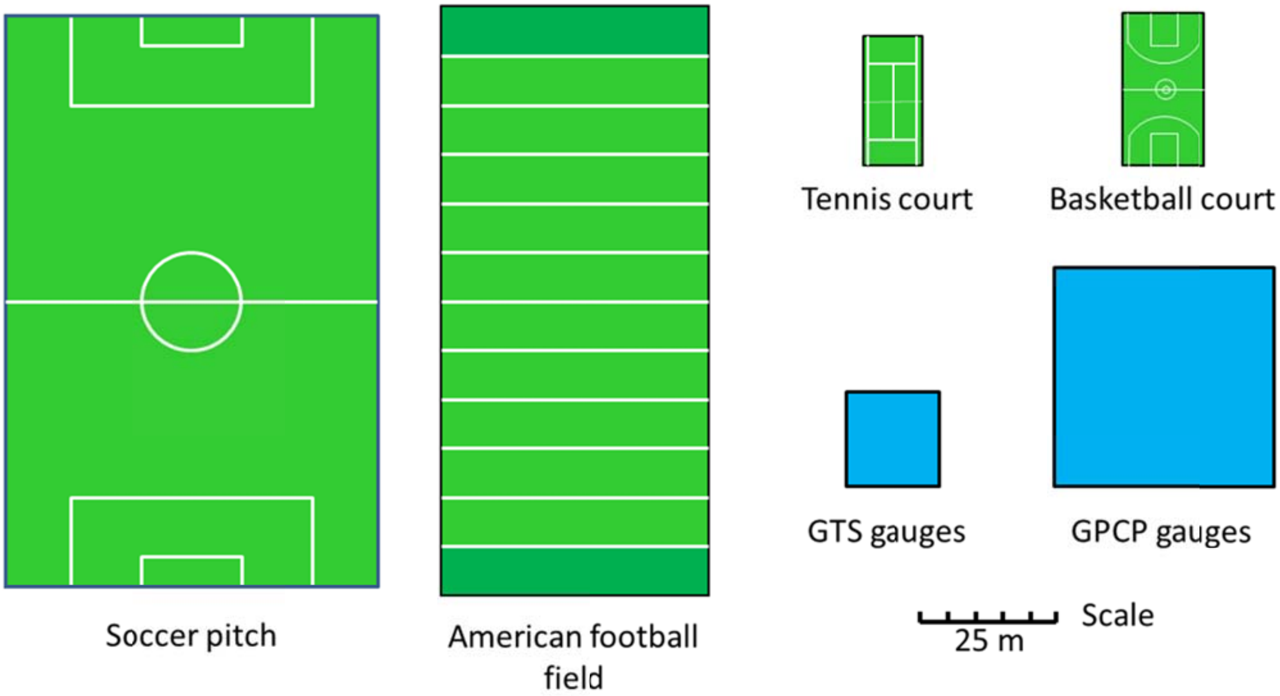


Figure 2: Map showing the distance to nearest GPCC gauge, typical of all regular and reliable gauge measurements; blank areas in the figure are beyond 100 km from the nearest gauge.



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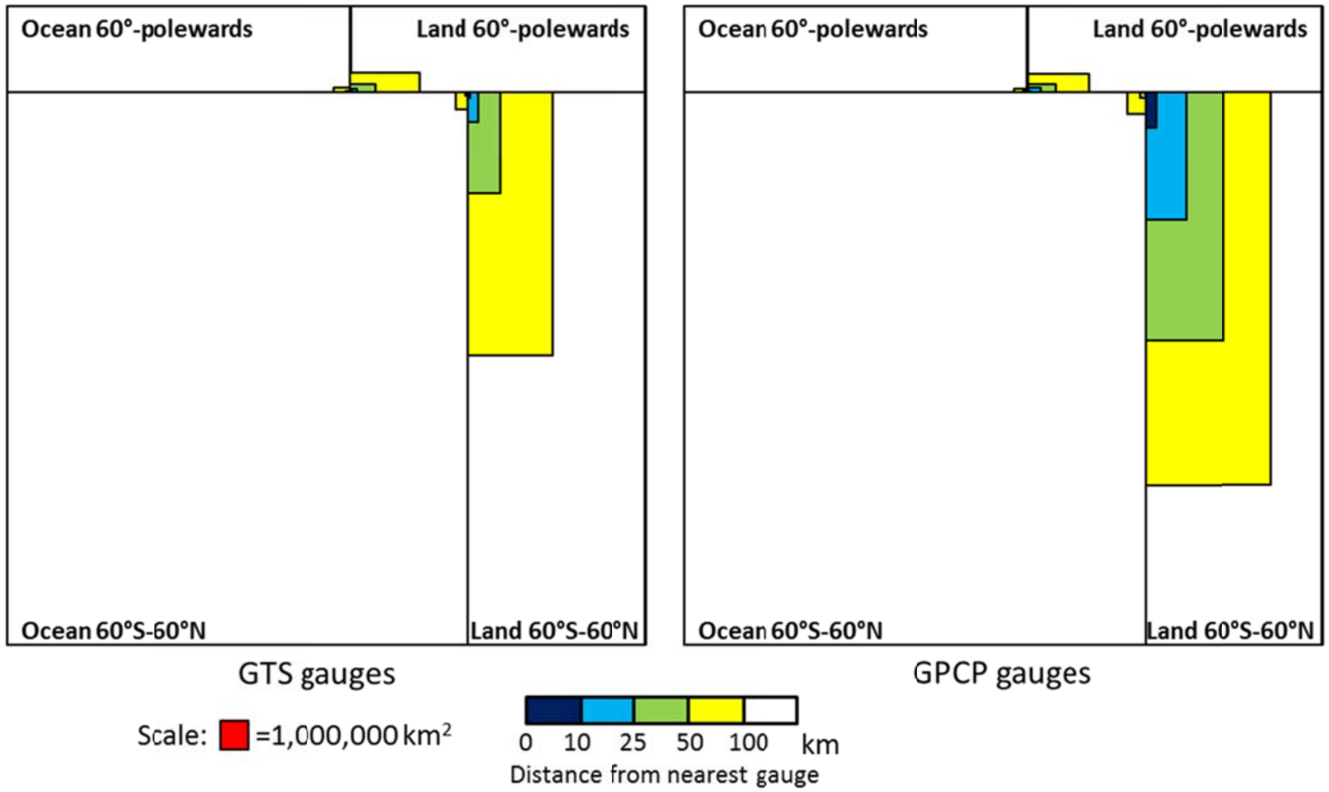

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a)

b)

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