

**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.

## 24    **Abstract**

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

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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 agribusinesses 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

92 observational record, while others will only report locations which currently return precipitation  
93 measurements. Thus, while it is certain that many gauges exist, not all gauges have operated  
94 continuously or simultaneously.

95  
96 Not all gauge observations are available to the public or even to researchers. Those observations that  
97 are available, are not necessarily available for all temporal samples (i.e. 3-hourly, daily, etc), or with  
98 adequate data latency; flood monitoring and forecasting requires the timely delivery of data to be truly  
99 useful, whereas climate application can accommodate longer data delivery times. The availability of  
100 data from different countries/regions often depends upon the organization within the country, region or  
101 locality. Often more than one agency within each country is tasked with the collection of rainfall data;  
102 these agencies are not necessarily consistent from one country to the next. An additional and potentially  
103 large number of gauge observations are available from commercial networks (e.g. water companies)  
104 although such data may be deemed to be commercially sensitive and therefore access to such data is  
105 often restricted.

106  
107 Global meteorological data (including precipitation) is available through the World Meteorological  
108 Organisation (WMO) Global Telecommunication System (GTS), collected from between 8,000 and  
109 12,000 “first class” stations (WMO, 2011). The precipitation information contained with the SYNOP  
110 report is collected for 3-hourly and daily periods at the fixed synoptic hours and distributed in near real  
111 time, although the records for each station may not always be complete for an entire monthly record.  
112 Figure 1 illustrates the coverage of these measurements by mapping the distance from each of the GTS  
113 stations across the globe; it can be seen that the data coverage for near real-time data on a global scale  
114 is relatively poor. While some regions such as Europe and eastern Asia (including Japan) have  
115 reasonable coverage, elsewhere gauges are sparse. This means that applications such as flash flood

116 monitoring that require fine temporal and spatial resolutions generally rely upon gauge and radar  
117 (where available) observations obtained from local or regional meteorological organizations, or  
118 satellite-based infrared estimates (Arkin and Xie, 1989)

119

120 At the daily scale, the situation is somewhat better. A more comprehensive set of daily gauge data is  
121 organized through the Global Precipitation Climatology Project (GPCP) at the Global Precipitation  
122 Climatology Centre (GPCC; Becker et al. 2013) which provides perhaps the foremost repository of  
123 global precipitation data derived from gauges. Access to existing data sets hitherto unavailable to the  
124 GPCC has been improved through the WMO-implemented Global Terrestrial Network for Hydrology  
125 (GTN-H) observing system since 2001. Although the data released by the GPCC is restricted to a  
126 gridded product, it reveals the number of rain gauges operating across the globe that report information  
127 on a regular and reliable basis. As of 2013 (2015) a total of 180 institutions contribute data to the  
128 GPCC from about 85,000 (100,000) gauge locations that have provided observations at least once since  
129 the start of the dataset in 1901. Initial daily and monthly products are available a few days after the end  
130 of the integration period, with a more complete ‘monitoring’ product after about 8 weeks and full daily  
131 and monthly products available after about 2 years. For this full, long-term or climatological analysis it  
132 is critical to ensure continuous records of precipitation from any single station, consequently the GPCC  
133 imposes a 10-year minimum constraint. This restricts the number of available stations as of 2013  
134 (2015) to 67,298 (75,165) for the best month, or 67,149 (75,033) for the worst, or a total 65,335  
135 (73,586) stations across all 12 months of the year (Becker et al. 2013; Schneider et al., 2015). Figure 2  
136 shows the coverage of the GPCC gauge data. Most of Germany lies within 10 km of the nearest rain  
137 gauge, while large areas of Europe, the US, eastern South America, India and the more populated  
138 regions of Australia are less than 25 km from a gauge. Other regions with lesser, but still good  
139 coverage include Turkey and Iran, parts of Africa (South Africa in particular) and the Andes in South

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

142

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

157

158 It is therefore clear that the number of gauges used in creating precipitation products varies  
159 considerably. The numbers of sub-daily rainfall gauge observations available in near real-time is small,  
160 although more observations are available if the user is willing to wait longer for the data to become  
161 available. Daily gauge accumulations, although hindered by non-uniform reporting times globally,  
162 represent perhaps the greatest number of official data entries since this is in line with the WMO  
163 recommendations and most easily implemented by the individual meteorological agencies. At longer

164 time scales the potential number of stations declines slowly, not least if a complete data record is  
165 required since some stations might not report precipitation (including zero-rain) 100% of the time.

166

### 167 **Gauge Representativeness**

168 If the rain gauges alone are considered, the surface area of the orifices is surprisingly small. The most  
169 common gauges, as noted in Table 1, provide a total surface area estimated to cover just 3,026 m<sup>2</sup> from  
170 123,014 gauges. Scaling the GTS and GPCC data sets using an average orifice size of 246 cm<sup>2</sup> would  
171 result in equivalent surface areas of about 295 m<sup>2</sup> and 1,612 m<sup>2</sup> respectively. For comparison, Table 2  
172 provides the areas of pitches/courts/fields for common sporting activities; the comparisons between the  
173 GTS and GPCC against the equivalent areas are illustrated in Figure 3. For the 3-hourly GTS data set,  
174 assuming that the maximum number of gauges report data, an area just greater than that of the center  
175 circle of a soccer pitch is actually measured; in reality less than half of the GTS stations regularly  
176 report rainfall measurements. The GPCC gauges provide an area equivalent to about 4 basketball  
177 courts.

178

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



188 Intercomparison Experiment (SPICE) project (Nitu and Wong, 2010b, ; Rasmussen et al, 2012). The  
189 majority of these measurements are now made by automated systems (Nitu and Wong 2010a),  
190 predominantly by weighing or tipping bucket gauges, the latter being poor at measuring snowfall  
191 (Goodison et al. 1998). Despite the measurement accuracy for snowfall being strongly affected by the  
192 wind due to the collector-snow particle flow dynamics, only about 28% of precipitation gauges are  
193 equipped with shields to modify the air flow over the gauge, although most automated snow gauges are  
194 heated in order to prevent snow accumulating on the rim or sides of the collector (Nitu and Wong,  
195 2010a). While rainfall can be usually be measured to within 10-20% (Vuerich et al, 2009), wind-effects  
196 may result in less than 25% of the snowfall being caught (Goodison et al. 1998). However, errors and  
197 uncertainties associated with such precipitation measurements for manual gauges are reasonably well  
198 understood and corrections (or quality control) can be applied. The SPICE project is currently  
199 addressing corrections necessary for automatic gauges.

200

201 Spatially, at the very local scale, the gauge should at least represent the rainfall falling in its immediate  
202 vicinity, over scales of a few metres and preferably a few kilometres. However, gauge measurements  
203 have their limitations given the spatial and temporal variability of precipitation and the fact that gauges  
204 are (small) point measurements. Standards set by the WMO (2008) are designed to ensure consistency  
205 between gauge measurements to reduce some of the inherent errors, such as those caused by siting or  
206 exposure. However, even under ideal situations the representativeness or auto-correlation length of  
207 precipitation is surprisingly small; Habib et al. (2001) showed that for instantaneous precipitation over  
208 the mid-western US the correlation coefficient between adjacent gauges fell to less than 0.5 just 4 km  
209 away; similar results were found for frozen precipitation. Furthermore, this correlation length is  
210 dependent upon the meteorology of the precipitation event and the local topography. Fortunately,  
211 accumulating precipitation over time, increases the correlation length (Bell et al. 1990); over longer

212 periods, the gauges become more representative of the regional precipitation regime. Although many  
213 schemes exist for the interpolation of precipitation, care is needed since the same interpolation scheme  
214 applied to instantaneous or monthly precipitation data could produce undesired results: Indeed, the  
215 interpolation of instantaneous gauge data should be avoided where possible due to the inherent  
216 heterogeneity of precipitation at fine temporal and spatial scales.

217

218 Considering the representativeness of gauges on a global scale, Figure 4 illustrates the area of the Earth  
219 within the defined distances from the GTS and GPCC gauge locations, divided into four regions, ocean  
220 or land and 60°-polewards or 60°S-60°N. It is clear that the vast majority of the Earth's surface closest  
221 to gauges are (not surprisingly) concentrated over the land areas between 60°S-60°N, with relatively  
222 few gauges over land polewards of 60°. Over the oceans only a very small area is within 100 km of a  
223 gauge, and most of this area would be deemed 'coastal waters'. Considering the GPCC data globally,  
224 only 1.6% of the Earth's surface lies within 10 km of a rain gauge, although 5.9% lies within 25 km;  
225 over 60°S-60°N land areas this improves to 6.5% and 23.0% respectively. This contrasts with less than  
226 4% of the Earth's oceans lying within 100 km of a gauge.

227

## 228 **Filling the gaps**

229 It is clear that gaps exist within the currently available gauge networks over the various temporal scales  
230 which require additional information if the representativeness of the precipitation measurements are  
231 sufficiently adequate to meet user requirements. Despite significant progress having been made in  
232 addressing some of the larger data gaps resulting from non-availability of regional gauge data sets, it is  
233 also clear that not all existing rain gauges that could be used are currently exploited. The gauges  
234 incorporated into the GPCC database derive from meteorological agencies which adhere to the  
235 requirements laid down by the WMO to ensure consistent measurements between different sites and

236 regions. Perhaps the next great challenge will be whether to, and how to incorporate observations  
237 and/or measurements from non-traditional sources.

238

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

259

260 The potential of harvesting amateur weather data from thousands of sites, which may now outnumber  
261 those of standard measurement sites, does have drawbacks however. Although the crowdsourced data  
262 has the potential to overcome the spatial and temporal representativeness of standard data sets, issues  
263 arise from utilising non-traditional sources of data, i.e. calibration, exposure and other quality  
264 assurance/quality control (QA/QC) issues (Muller et al. 2015). For example, Bell et al. (2015) found  
265 variations in annual rainfall totals from low-cost weather stations ranged from about 76% to 111% of  
266 standard co-located gauges, although after correction differences throughout the year rarely exceeded  
267 5%. Another issue is that the locations of crowdsourced observations are population-centric (see  
268 Elmore et al. 2014); while these additional data observations are not necessarily useful at the global-  
269 scale, the fine temporal observations and the fact that they are population-centric makes them ideal for  
270 certain applications, such as urban flood monitoring, by filling in information about particularly  
271 variations over short distances.

272

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

283 gauge coverage, radars can provide spatial measurements at time scales that fulfil a niche in the  
284 measurement of precipitation, at least on a local to regional scale.

285

286 *Satellite observations* of remotely-sensed precipitation have been available over much of the globe for  
287 almost four decades and have the potential to be available on a truly global scale (Arkin and Ardunay,  
288 1989). In particular, satellite estimates have a distinct advantage for assessing precipitation over data-  
289 sparse regions such as the world's oceans. Satellite observations from visible, infrared, and in  
290 particular, passive and active microwave systems are used to generate precipitation estimates using a  
291 number of techniques (see Kidd and Huffman 2011), although techniques differ in performance  
292 regionally and temporally. The Tropical Rainfall Measuring Mission (TRMM; Kummerow et al. 1998)  
293 Precipitation Radar (PR) and the Global Precipitation Measurement (GPM) mission (Hou et al. 2014)  
294 Dual-frequency Precipitation Radar (DPR) provide more direct measurements of precipitation.  
295 Although the PR and DPR provide intermittent measurements covering 36°S-36°N and 66°S-66°N  
296 respectively, the detailed information they provide is proving invaluable for a number of applications  
297 including hurricane monitoring and forecasting, as well as acting as a calibrator for other satellite  
298 precipitation measurements.

299

300 The potential for *repurposing* data from non-meteorological networks has also shown potential.  
301 Numerous municipal networks exist and collect routine data for various applications and may have the  
302 potential to be used as proxies for monitoring variables such as precipitation. For example, Overeem et  
303 al. (2013) used the received signal level data from microwave links in cellular communication  
304 networks to monitor precipitation in the Netherlands. Furthermore, multi-observational precipitation  
305 products have been developed to exploit the information from individual data sources. In particular, a  
306 number of mature satellite-based precipitation techniques incorporate surface precipitation data sets,

307 allowing good spatial and temporal resolution precipitation products to be generated with the accuracy  
308 of surface measurements (e.g. Huffman et al. 2009): surface gauge measurements provide the anchor  
309 points for remotely-sensed products.

310

## 311 **Conclusions**

312 The surface area that is equivalent to the orifice area all of the worldwide operational rain gauges is  
313 surprisingly small, amounting to only 0.000000000593% of the Earth's surface. There are clearly a  
314 large number of gauges in existence, but the actual number of gauges available to the user is highly  
315 variable depending upon the period of study and latency requirements. The GPCC rain gauge data set,  
316 arguably the most comprehensive currently available global gauge dataset, comprises of a little over  
317 65,000 gauges whose combined area is roughly equivalent to less than half a soccer pitch. If the  
318 number of gauges that provide near real time data is considered, as available through the WMO GTS  
319 network, the gauges could easily fit into a tennis court or the center circle of a soccer pitch. However,  
320 since gauges represent more than just the actual point location of the orifice, it may be assumed that a  
321 greater part of the Earth's surface might be covered: if each GPCC gauge represented an area extended  
322 to 5 km from each gauge (assuming no overlap) this still only represents about 1% of the Earth's  
323 surface.

324

325 Improving worldwide information on precipitation is fundamentally important. Information utilizing  
326 crowdsourced precipitation measurements (as opposed to just observations) from 'amateur' gauge  
327 networks has potential for many applications, including meteorology, but is probably more difficult to  
328 achieve due to timely access to the data, continuity and absolute calibration of the measurements.  
329 Furthermore, the spatial availability of both amateur and crowdsourced information tends to mimic that  
330 of existing precipitation information due to being population-centric. Great efforts have been made in

331 obtaining gauge data in data sparse regions; however additional high-quality measurements are still  
332 needed to fill gaps in certain regions. In particular, the continental interiors of South America, Africa  
333 and Australia together with the northern regions of the continental land masses in the Northern  
334 Hemisphere and Antarctica are deficient in precipitation gauges. Projects such as the Trans-African  
335 HydroMeteorological Observatory (TAHMO; <http://tahmo.org>) are now beginning to address this need.

336

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

340

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344 agencies for their continued provision of gauge data to regional and global data sets; their data is  
345 invaluable in furthering precipitation science.

346

347

#### 348 **SIDEBAR:**

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

355 can be categorized into the physical design of the gauge, the mechanisms used to collect and quantize  
356 the rainfall and the technology necessary to report the rainfall.

357

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

369

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

376

377 *Technological:* The cost of manual or mechanically recorded gauges together with the development of  
378 electrically recording gauges has led to the development of (quasi-) automatic gauges that can measure,



379 record and report the rainfall in near real time through the use of electronic data loggers and  
380 communication systems (satellite or phone networks). The availability of gauge measurements in near  
381 real time greatly enhances the usefulness of such measurements for meteorological and hydrological  
382 applications.

383

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551

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

553

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

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555

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

558

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

559 <sup>\*</sup> range based upon to 400 cm<sup>2</sup> to 127 cm<sup>2</sup> orifice areas.

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562 Figure captions:

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

566

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

569

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

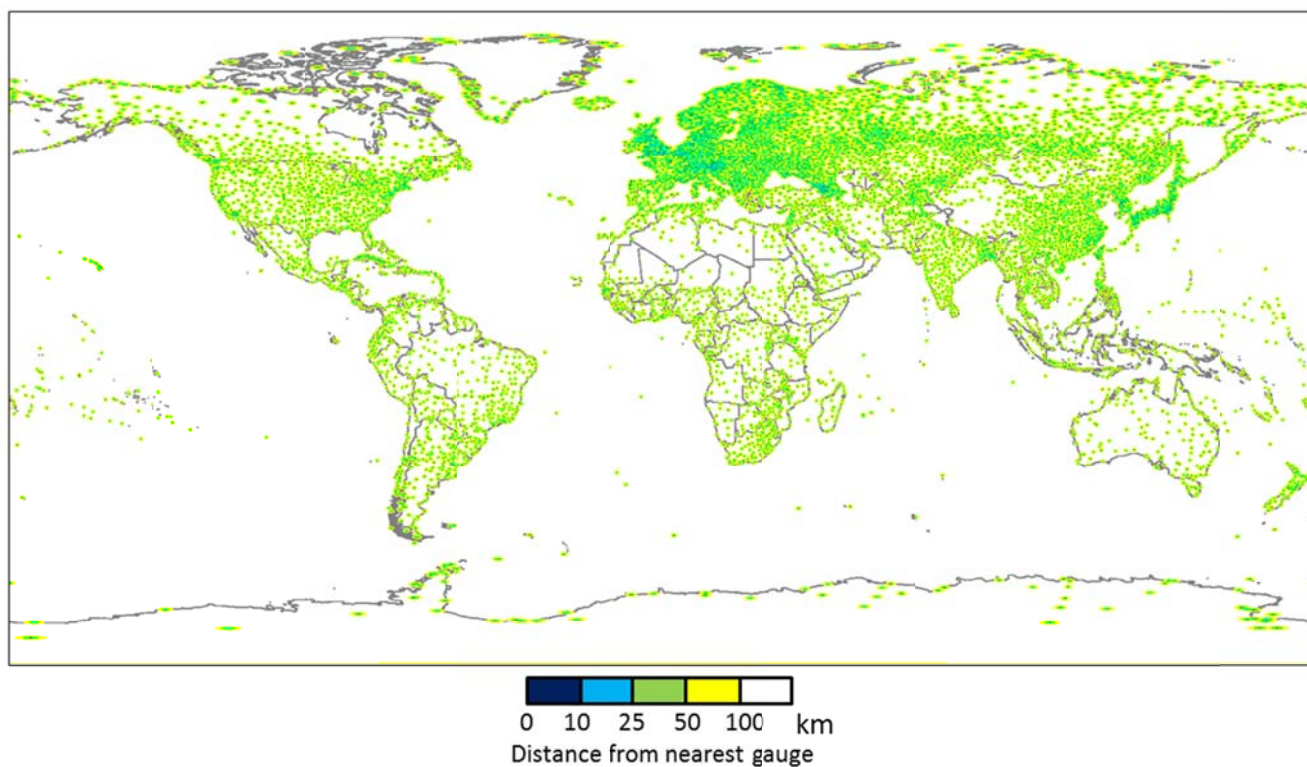
572

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

576

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

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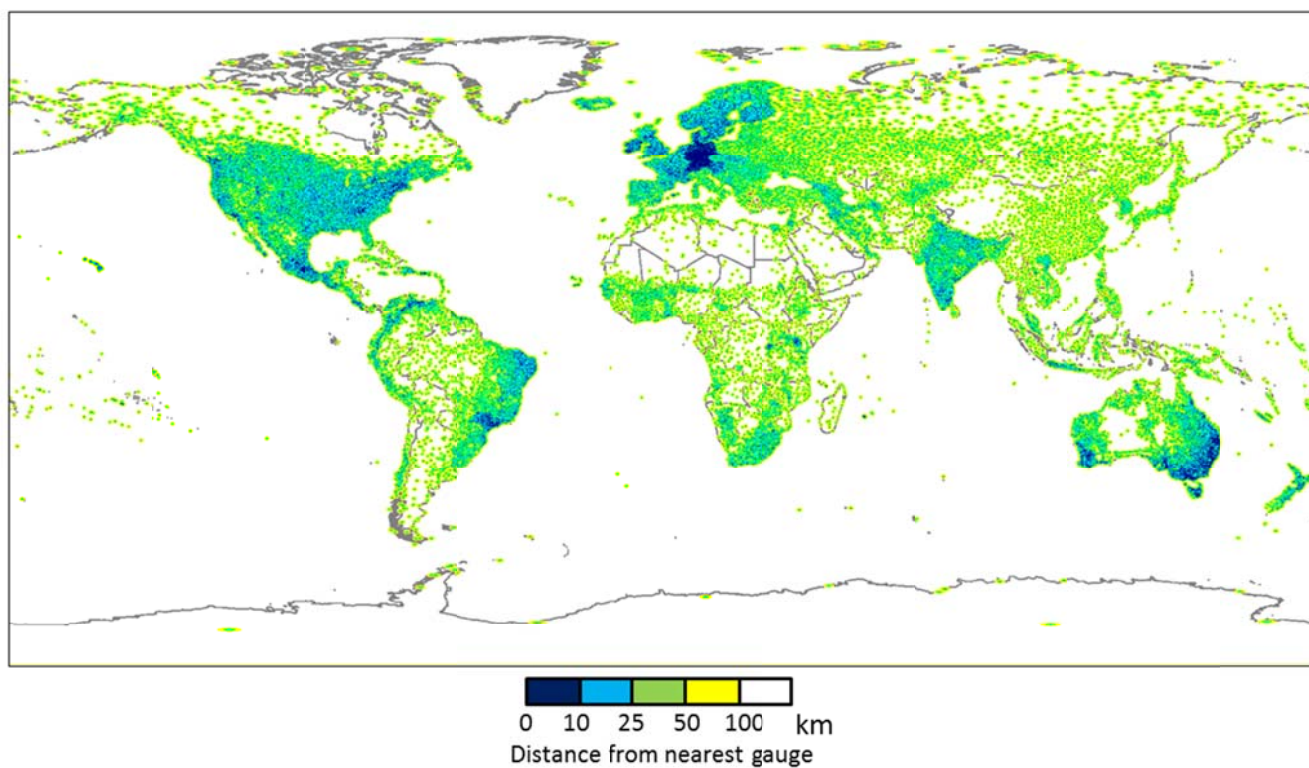


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583 Figure 1: Map showing the distance to nearest GTS gauge, typical of 3-hourly/daily measurements  
584 available in near real time; blank areas in the figure are beyond 100 km from the nearest gauge.

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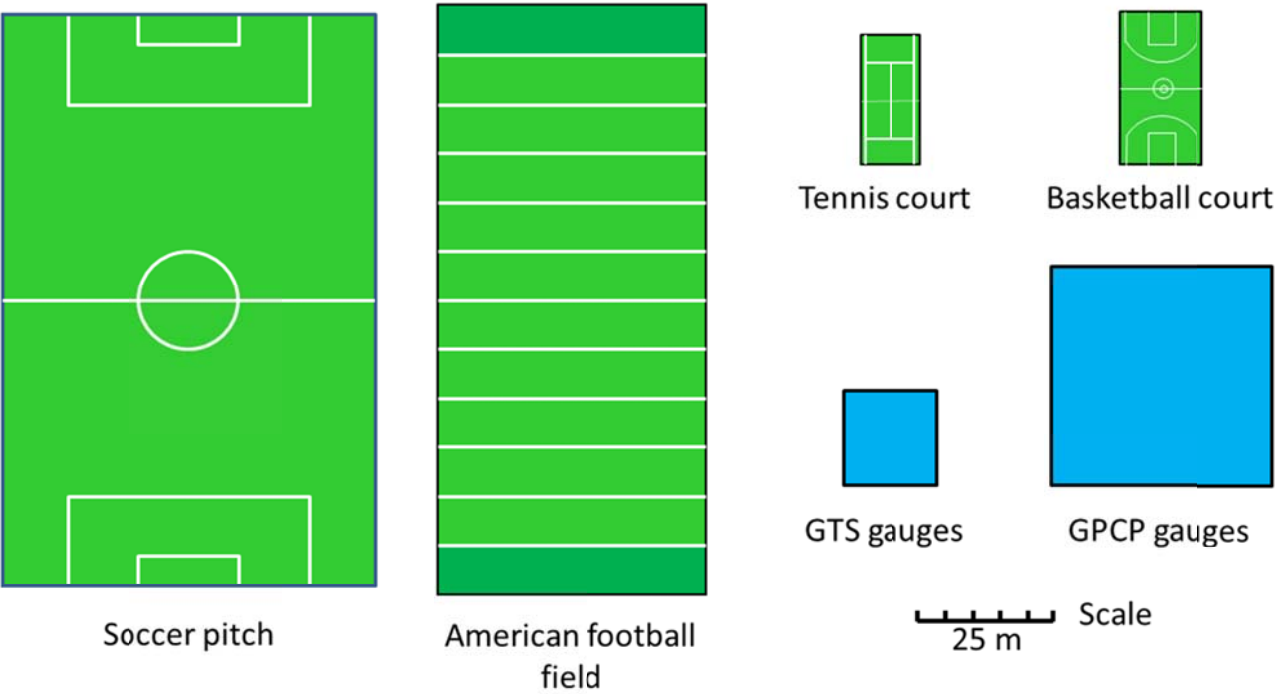


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588 Figure 2: Map showing the distance to nearest GPCP gauge, typical of all regular and reliable gauge  
589 measurements; blank areas in the figure are beyond 100 km from the nearest gauge.

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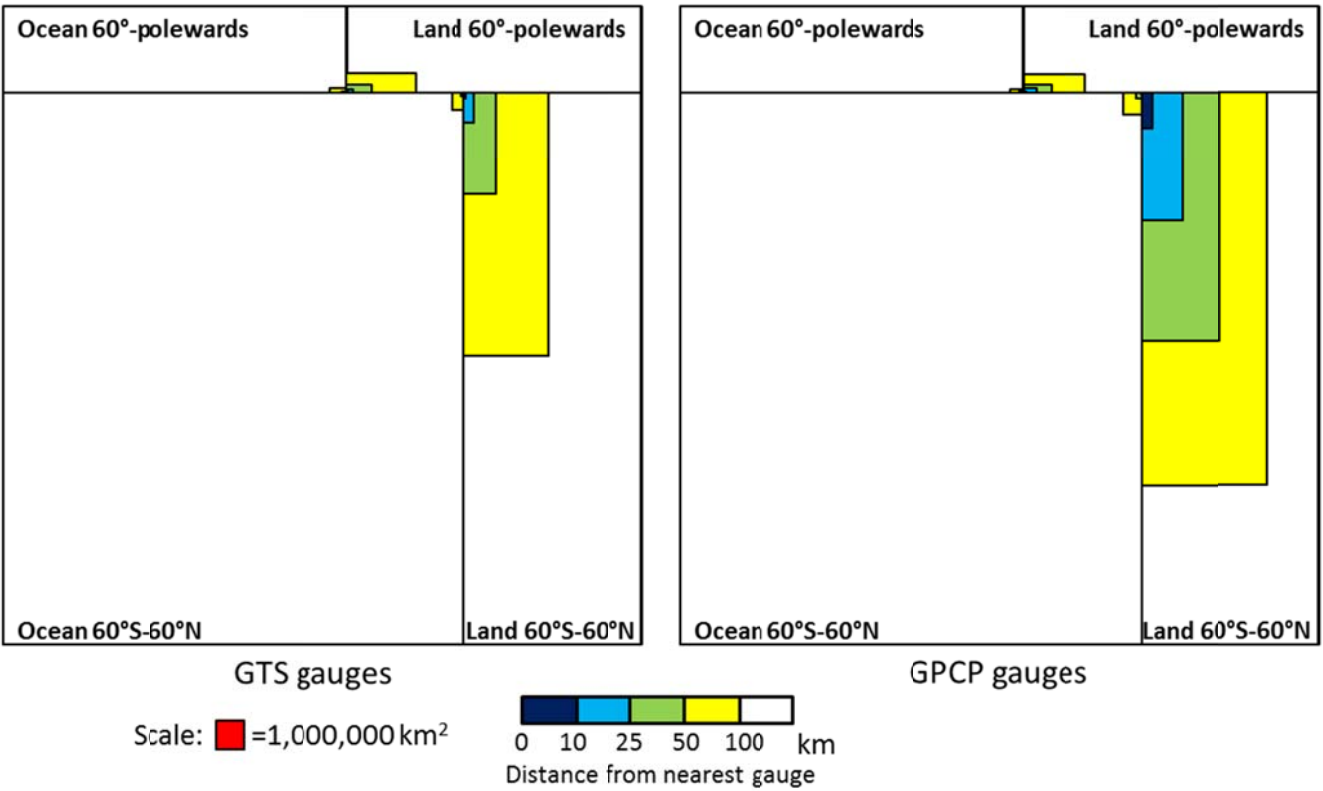
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593 Figure 3: Equivalent areas of common sports pitches and courts compared with the total areas of  
594 orifices of all GTS and GPCC gauges.

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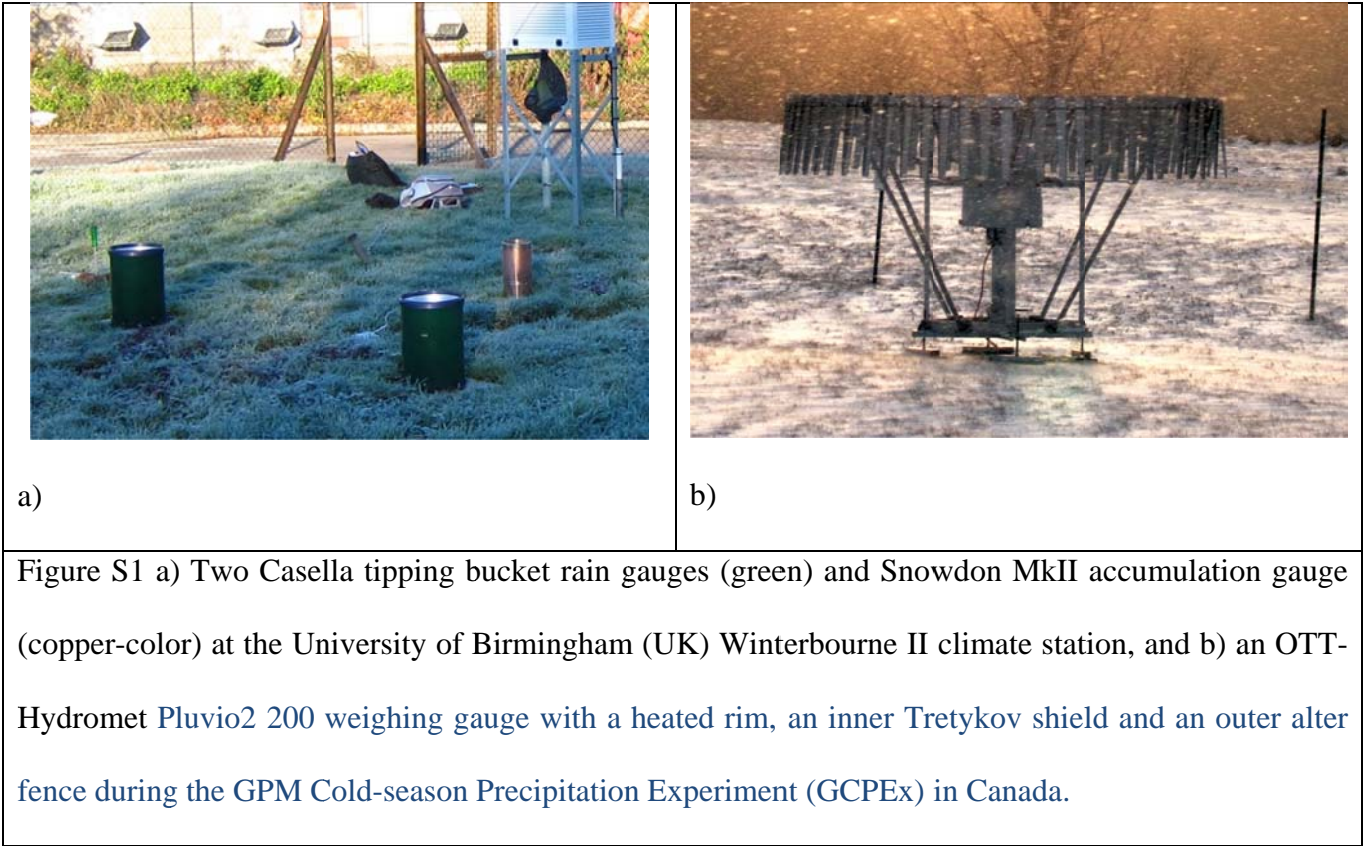
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599 dataset (left) and the GPCC dataset (right). The whole square represents the whole of the Earth’s  
600 surface, while the subdivisions are for land and ocean and 60°-polewards and 60°S-60°N.

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