

1 **Improving the Global Precipitation Record: GPCP Version 2.1**

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20 **Abstract**

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22 The GPCP has developed Version 2.1 of its long-term (1979-present) global Satellite-Gauge
23 (SG) data sets to take advantage of the improved GPCC gauge analysis, which is one key input.
24 As well, the OPI estimates used in the pre-SSM/I era have been rescaled to 20 years of the
25 SSM/I-era SG. The monthly, pentad, and daily GPCP products have been entirely reprocessed,
26 continuing to enforce consistency of the submonthly estimates to the monthly. Version 2.1 is
27 close to Version 2, with the global ocean, land, and total values about 0%, 6%, and 2% higher,
28 respectively. The revised long-term global precipitation rate is 2.68 mm/d. The corresponding
29 tropical (25°N-S) increases are 0%, 7%, and 3%. Long-term linear changes in the data tend to be
30 smaller in Version 2.1, but the statistics are sensitive to the threshold for land/ocean separation
31 and use of the pre-SSM/I part of the record.

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33 **1. Introduction**

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35 The Global Precipitation Climatology Project (GPCP) is charged with developing global
36 long-term records of precipitation for the international community on behalf of the World
37 Meteorological Organization/World Climate Research Programme/Global Energy and Water
38 Experiment (WMO/WCRP/GEWEX). GPCP is one of several GEWEX global analyses of
39 components of the water and energy cycle organized under the GEWEX Radiation Panel. Such
40 data are essential for quantifying the global water cycle, supporting verification of numerical
41 models, and providing the background climate statistics for many operational water-resource
42 activities. The GPCP datasets are developed and maintained as an international activity. Input
43 datasets are provided by several contributing groups: Retrievals from Special Sensor
44 Microwave/Imager data (Defense Meteorological Satellite Program, U.S.) are provided by L.
45 Chiu (Chinese Univ. of Hong Kong and George Mason Univ., U.S.) and R. Ferraro (National
46 Environmental Satellite Data and Information Service, NESDIS, U.S.). Merged
47 geosynchronous- and low-orbit–satellite infrared data are provided by P. Xie (National Oceanic
48 and Atmospheric Administration/Climate Prediction Center, NOAA/CPC, U.S.) using data
49 contributed by NESDIS, the Japanese Meteorological Agency, and the European Organisation
50 for the Exploitation of Meteorological Satellites. J. Susskind (National Aeronautics and Space
51 Administration/Goddard Space Flight Center, NASA/GSFC, U.S.) contributes estimates based
52 on the Television Infrared Observation Satellite Operational Vertical Sounder (provided by
53 NESDIS) and the Advanced Infrared Sounder (provided by NASA). Global precipitation-gauge
54 analyses are provided by B. Rudolf and U. Schneider (Global Precipitation Climatology Centre,
55 GPCC, hosted at the Deutscher Wetterdienst) using data from most countries around the world.
56 The final computations are carried out by the group led by G. Huffman and R. Adler
57 (NASA/GSFC) and the primary archive is hosted by World Data Center A (National Climatic
58 Data Center, U.S.).

59 It is critical that the dataset be carefully monitored for changes in the input data sources
60 that might cause inhomogeneities in the long-term record. Recently, such an instance arose
61 when the GPCC upgraded their precipitation gauge analysis scheme to a climatology-anomaly
62 approach. This should provide better results, particularly in undersampled, but it also would
63 have introduced a jump discontinuity in the GPCP products that was judged unacceptable. To
64 maintain homogeneity, the GPCP determined that the entire record should be reprocessed with
65 the new gauge analysis. After sketching the reprocessing steps, a short analysis of the changes
66 from Version 2 to Version 2.1 of the monthly satellite-gauge (SG) product is presented. The
67 same information about the GPCP pentad and daily products ([Xie et al. 2003] and [Huffman et
68 al. 2001], respectively) is not necessary because they have not changed beyond being rescaled to
69 the Version 2.1 monthly product. Throughout, “Version 2” and “Version 2.1” refer to the GPCP
70 products unless otherwise specified.

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72 **2. Revisions for Version 2.1**

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74 The processing strategy for Version 2.1 is substantially the same as described for Version
75 2 in Adler et al. [2003], so the summary here focuses on the differences. In general terms,
76 multiple sources of satellite data are combined, according to their periods of availability and
77 estimated accuracies, then the monthly satellite-gauge (SG) product is computed by combining
78 the multi-satellite estimate with a precipitation gauge analysis provided by the GPCC.

79 The primary reason for the upgrade to Version 2.1 is GPCP's shift to a new climatology-
80 anomaly analysis technique for precipitation gauge data [Schneider et al. 2008]. Precipitation
81 gauge reports are archived from a time-varying collection of over 70,000 stations around the
82 globe, both from Global Telecommunications System (GTS) reports, and from other world-wide
83 or national data collections. The extensive quality-control system, featuring both an automated
84 screening and then a manual check, feeds into a two-step analysis. First, a long-term climatology
85 is assembled from all available gauge data, focusing on the period 1951-2000. The lack of
86 complete consistency in period of record for individual stations has been shown to be less
87 important than the gain in detail, particularly in complex terrain. Then for each month, the
88 individual gauge reports are converted to deviations from climatology, and are analyzed into
89 gridded values using a variant of the SPHEREMAP spatial interpolation routine [Willmott et al.
90 1985]. Finally, the month's analysis is produced by superimposing the anomaly analysis on the
91 month's climatology.

92 The GPCP creates multiple products, and two are used in the GPCP Version 2.1. The
93 Full Data Reanalysis (Version 4) is a retrospective analysis that covers 1901-2007, and it is used
94 in GPCP for 1979-2007. Thereafter we use the GPCP Monitoring Product (Version 2), whose
95 data source is limited to GTS reports. The advantages of these changes are that: 1) we no longer
96 need to use the separate and differently prepared gauge analysis based on the Global Historical
97 Climate Network and Climate Analysis and Monitoring System (GHCN+CAMS) for 1979-1985,
98 and 2) the numbers of gauges used are much higher for much of the record. When the Full Data
99 Reanalysis is updated to a longer record we expect to reprocess the GPCP datasets to take
100 advantage of the improved data. We continue the GPCP's long-standing practice of correcting
101 all gauge analysis values for climatological estimates of systematic error due to wind effects,
102 side-wetting, evaporation, etc., following Legates [1987].

103 During the period before SSM/I data became available the GPCP uses the Outgoing
104 Longwave Radiation (OLR) Precipitation Index (OPI) product [Xie and Arkin 1998], calibrated
105 to an overlap period with the GPCP monthly product in the SSM/I era. The OPI depends on the
106 correlation of colder OLR radiances to higher cloud tops, and thus increased precipitation rates.
107 It is necessary to define "cold" locally, so a regression relationship is developed for anomalies in
108 both OLR and precipitation. In use, the total precipitation inferred is the estimated anomaly plus
109 the local climatological value. A backup direct OLR-precipitation regression is used when the
110 anomaly approach yields unphysical values. In Version 2 the calibration was computed for
111 1988-1995, but for Version 2.1 it was extended to 1988-2007. This spatially and seasonally
112 varying climatological calibration is then applied to the independent OPI data covering the span
113 1979-1987 to fill all months lacking SSM/I data.

114 Our work in developing Version 2 for the pre-SSM/I era showed calibration-induced
115 biases for the OPI precipitation from TIROS-N (January 1979 – January 1980) and NOAA-6
116 (February 1980 – August 1981). This is true even though the biases in the OLR itself are small
117 (less than 1%), and this continued to be true for Version 2.1. Accordingly, we re-applied the
118 scheme used in Version 2 to adjust the bias of the first two satellites. The precipitation was
119 averaged for each satellite separately over all gridboxes having a valid OPI value, at least one
120 gauge/gridbox, and a gauge estimate of at least 50 mm/month, for all months of TIROS-N,
121 NOAA-6, and NOAA-7 (September 1981 – February 1985). The same averaging is applied to
122 the corresponding gauge estimates for the three periods and compared with the three satellite
123 estimates. The ratios of the satellite averages versus the gauge data were computed. Using the
124 NOAA-7 OPI-gauge ratio as representative, since it appears to be minimally biased, and

125 assuming that the OPI bias over ocean is similar to that over land, a ratio correction was applied
126 for all grid boxes to the TIROS-N and NOAA-6 data to match the ratio of the NOAA-7 period.
127 Comparison to an alternative OLR data set [Lee et al. 2007] shows very similar results, and
128 confirms that biases are consistent between land and ocean. Nonetheless, the first two satellites
129 still appear to be biased low and will be re-examined in the next upgrade. The new Version 2.1
130 adjustments for the TIROS-N and NOAA-6 periods are +8% and +0.4%, compared to +12% and
131 +3% in Version 2.

132 The Version 2.1 reprocessing also provided an opportunity to apply several corrections to
133 input datasets. These include:

- 134 • substituting a full month of AIRS data for a partial month of TOVS data in February 2004;
- 135 • including 5°x5° SSM/I emission-based estimates (i.e., over ocean) for July 1990 through
136 December 1991, completing the 5°x5° time series for use as fill-in when the usual 2.5°x2.5°
137 product failed to converge; and
- 138 • corrections in the mid-Pacific overlap region between geo-IR satellites for October and
139 November 1994.

140 On the other hand, we continue to use the same OPI estimation scheme for Version 2.1 as in
141 Version 2, so the spatial and temporal variances are still underestimated in months when SSM/I
142 data are unavailable.

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144 **3. Comparison of Versions 2 and 2.1**

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146 The global climatologies for the two versions are quite similar, so only Version 2.1 is
147 displayed in Fig. 1a, while the mean difference map is shown in Fig. 1b. Differences over
148 oceanic regions are generally small, representing a compromise between essentially-zero
149 differences in the SSM/I era and the mean differences during the pre-SSM/I era. The freckles of
150 difference in the oceans mostly correspond to island locations used in the previous GPCP
151 Monitoring Product that have been eliminated from the new Full Data Reanalysis. Land regions
152 have more substantial differences, mostly due to the mean differences between the versions of
153 the gauge analyses throughout the period of record. The largest differences occur in
154 northwestern South American and Mesoamerica. The new gauge analysis is attributing as much
155 as 50% more precipitation to parts of this region, which is characterized by large gradients in
156 topography. Such gradients typically feature higher precipitation at higher elevations (within the
157 limits of the 2.5° resolution), which the previous GPCP Monitoring Product tended to miss.
158 Similar tropical topographic regimes are highlighted in Papua New Guinea, the Himalayas, and
159 along the east coast of the Bay of Bengal. The change in central Africa is an improvement over
160 the Version 2 data set, in which persistent gaps in gauge coverage over central Africa coincided
161 with the climatological maximum. Under such conditions, the previous GPCP analysis scheme,
162 and therefore the GPCP satellite-gauge product, tended to underestimate the climatological
163 maximum month after month. At higher latitudes the major increases occur in steep terrain on
164 coasts that intersect storm tracks – the Pacific coasts of northwestern North America and
165 southern Chile, and New Zealand. Finally, the new GPCP analyses do not cover Antarctica, so
166 the satellite adjustments in the high southern latitudes continue to be based on the (very
167 approximate) mean gauge precipitation climatology computed in Version 2 from these gauges as
168 contained in the previous GPCP Monitoring Product.

169 The time series of global and tropical averages for all, land, and ocean regions (Fig. 2)
170 give insight into the aggregate time variation of these differences. Experience has shown that

171 such regionalization is somewhat sensitive to the choice of regions. Although the most realistic
172 land/water distribution is provided by a threshold for coverage by water of 75%, we wish to
173 provide a clean “open ocean” comparison of the data sets. Thus, throughout this paper “ocean”
174 and “land” regions are defined as having 100% and <100% coverage by water, respectively. A
175 seven-point boxcar running smoother has been applied to suppress short-interval noise. As in
176 previous GPCP versions, we see that the seasonal cycle over land, primarily driven by the boreal
177 seasons, is almost exactly balanced by changes over the ocean on the global scale (Fig. 2a), with
178 some seasonality apparent in total precipitation for the tropics (Fig. 2b).

179 In the pre-SSM/I era (i.e., before mid-1987) the revised scaling for the OPI raises the
180 oceanic mean for most of the period. The exception is for the first two satellites (January 1979 –
181 August 1981). Even though the same bias adjustment procedure is used in both Versions 2 and
182 2.1, as described above, we find that the revised OPI scaling and the replacement of the
183 GHCN+CAMS gauge analysis with the new GPCC Full Data Reanalysis work together to
184 produce almost no change from Version 2 to Version 2.1, unlike the following OPI satellites.
185 Over land, Version 2 contains a data boundary at the start of 1986, when the GHCN+CAMS was
186 replaced by the then-current GPCC Monitoring Product. Reasonable continuity in the Version 2
187 time series itself, as well as comparison with the Version 2.1 time series, reveals that the change
188 in gauge analysis in January 1986 is relatively unimportant at the tropical or global scale,
189 although locally there can be noticeable differences (not shown). However, within the
190 GHCN+CAMS record there is an issue. The first few years of GPCP Version 2 are closer to the
191 corresponding Version 2.1 data for the global-average land (Fig. 2a) than any other years,
192 confirming earlier impressions that the GHCN+CAMS was making the Version 2 land estimates
193 in those years somewhat inconsistent with the rest of the record.

194 The total, land, and ocean averages for each of the Versions are given in Table 1. The
195 global and tropical regions are consistent in showing modestly higher values in Version 2.1, with
196 essentially all of the change occurring over land (and coast, since the threshold is 100%).

197 One convenient way to summarize time changes in the data sets is to compute the long-
198 term linear rate of change for each grid box. Fig. 3 displays the most certain results, namely
199 Version 2.1 during the SSM/I era, while all the fields summarized below are shown in the
200 Electronic Data Supplement. Note that we compute the linear-change statistic with no
201 assumption or implication of a particular dynamic or secular trend. Furthermore, the shift in
202 input satellite data from OPI to SSM/I led us to compute the linear changes both for the entire
203 data set, and for the SSM/I era (1988-2007). In general, there is consistency both between the
204 longer and shorter period results and between the Version 2 and 2.1 results. The more precise,
205 somewhat shorter, and more recent SSM/I-era data mostly show larger linear change values than
206 the entire data record, while Version 2.1 shows smaller linear changes than in Version 2. See Gu
207 et al. [2007], and Adler et al. [2008] for analyses of the Version 2 results. The global- and
208 tropical-average linear changes for both versions are listed in Table 2. The increase in linear
209 change from Version 2 to Version 2.1 for global ocean across the entire data set, which is the
210 only such increase in Table 2, is driven by the somewhat questionable behavior of the OPI in the
211 first 2.5 years of the data record. The revisions to the linear change over land from Version 2 to
212 2.1 are driven by the gauge data and tend to be focused in the regions previously noted for
213 having large mean differences between the two Versions. As stated previously, the statistics
214 under discussion are somewhat sensitive to the definition of land and ocean. These subtle, but
215 important changes in the data set will be the subject of further analysis.

216

217 **4. Concluding Remarks**

218

219 It was necessary to develop Version 2.1 of the GPCP data sets to prevent a discontinuity
220 due to changes to the new GPCC gauge analysis scheme that forms a key part of the GPCP input
221 data. The only substantive changes were: use of the new GPCC Full Data Reanalysis (Version
222 4) for 1979-2007 and the new GPCC Monitoring Product (Version 2) thereafter, and
223 recalibration of the OPI data to a longer record of the new SSM/I-era GPCP data. All GPCP
224 products have been reprocessed for their entire periods of record, including the monthly, pentad,
225 and daily products. The pentad and daily GPCP data sets are now considered to be at Version
226 1.1, since this is the first reprocessing since they were released. Version 2.1 provides an estimate
227 of the global total of 2.68 mm/d, about 2% higher than in Version 2, with changes almost entirely
228 over land. Linear changes over the data set tend to be smaller, particularly for the more certain
229 SSM/I era.

230 Development work in GPCP will now focus on the upcoming Version 3, which is
231 planned to feature finer time and space resolution. At the same time, it is likely that the Version
232 2.1 products will continue to be produced for some time after the release of Version 3 to provide
233 continuity for the user community.

234

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265 **Table Captions**

266

267 Table 1 Global- and tropical-average land, ocean, and total precipitation for Versions 2.1 and 2
268 in mm/d. The percentage increase of Version 2.1 over Version 2 is given in parentheses.
269 “Ocean” and “land” regions are defined by 100% and <100% coverage by water.

270 Table 2 Global- and tropical-average linear changes in mm/d/decade a) for the entire study
271 period (1979-2007), and b) for the SSM/I era (1988-2007). “Ocean” and “land” regions
272 are defined by 100% and <100% coverage by water.

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274 **Figure Captions**

275

276 Fig. 1 a) Thirty-year (1979-2008) climatology for GPCP Version 2.1 in mm/d, and b) (Version
277 2.1 – Version 2) difference averaged over 1979-2007 in mm/d.

278 Fig. 2 Time series of a) global-average and b) tropical-average land, ocean, and total
279 precipitation (red, blue, black) for Versions 2.1 (solid) and 2 (dashed) for the entire study
280 period (1979-2007) in mm/d. “Ocean” and “land” regions are defined by 100% and
281 <100% coverage by water, and the monthly data have been smoothed with a seven-point
282 running boxcar filter.

283 Fig. 3 Map of linear change for Version 2.1 for the SSM/I era (1988-2007) in mm/d/decade.

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285 Table 1 Global- and tropical-average land, ocean, and total precipitation for Versions
 286 2.1 and 2 in mm/d. The percentage increase of Version 2.1 over Version 2 is given in
 287 parentheses. "Ocean" and "land" regions are defined by 100% and <100% coverage by
 288 water.
 289

1979-2007	Global 90°N-90°S		Tropical 25°N-25°S	
Version	2	2.1	2	2.1
Land and Ocean	2.62	2.68 (+2%)	3.12	3.22 (+3%)
Land	2.39	2.53 (+6%)	3.49	3.73 (+7%)
Ocean	2.78	2.78 (+0%)	2.88	2.88 (+0%)

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293 Table 2 Global- and tropical-average linear changes in mm/d/decade a) for the entire
 294 study period (1979-2007), and b) for the SSM/I era (1988-2007) . “Ocean” and “land”
 295 regions are defined by 100% and <100% coverage by water.
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a)

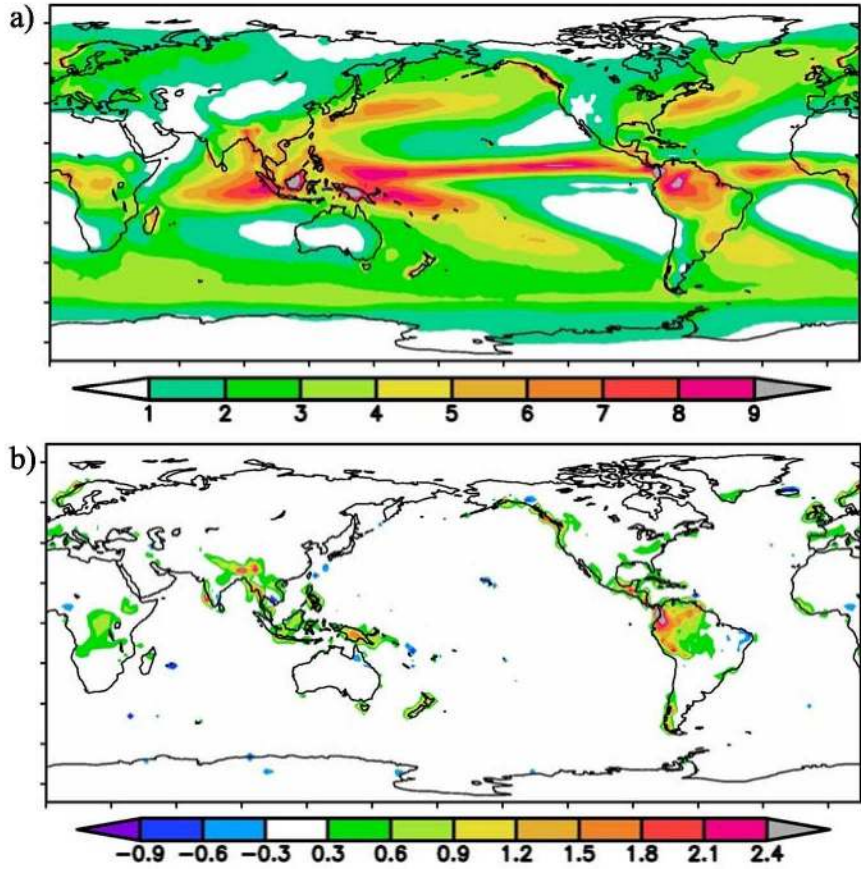
1979-2007	Global 90°N-90°S		Tropical 25°N-25°S	
Version	2	2.1	2	2.1
Land and Ocean	+0.0115	+0.0069	+0.0480	+0.0252
Land	+0.0018	-0.0118	+0.0432	-0.0030
Ocean	+0.0184	+0.0199	+0.0511	+0.0438

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b)

1988-2007	Global 90°N-90°S		Tropical 25°N-25°S	
Version	2	2.1	2	2.1
Land and Ocean	+0.0343	+0.0169	+0.0714	+0.0497
Land	+0.0630	+0.0252	+0.1327	+0.0889
Ocean	+0.0144	+0.0111	+0.0308	+0.0238

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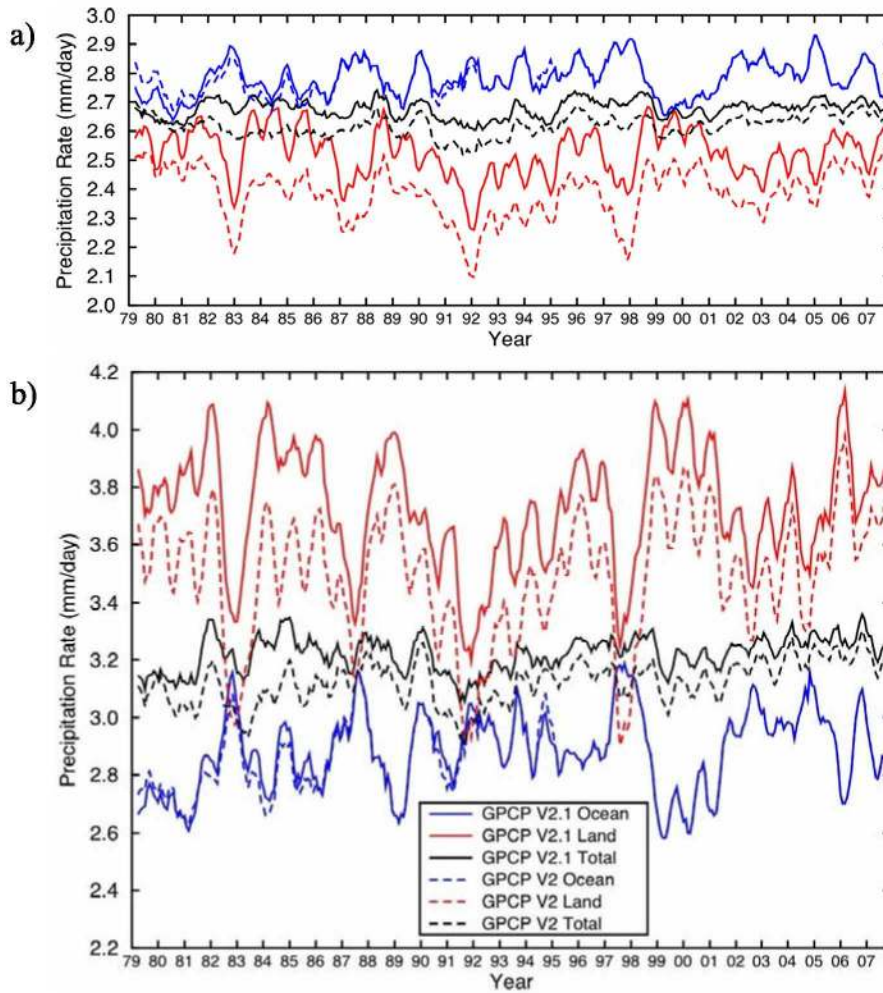
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Fig. 1 a) Thirty-year climatology for GPCP Version 2.1 in mm/d, and b) (Version 2.1 – Version 2) difference averaged over 1979-2007 in mm/d.

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Fig. 2 Time series of a) global-average and b) tropical-average land, ocean, and total precipitation (red, blue, black) for Versions 2.1 (solid) and 2 (dashed) for the entire study period (1979-2007) in mm/d. “Ocean” and “land” regions are defined by 100% and <100% coverage by water, and the monthly data have been smoothed with a seven-point running boxcar filter.

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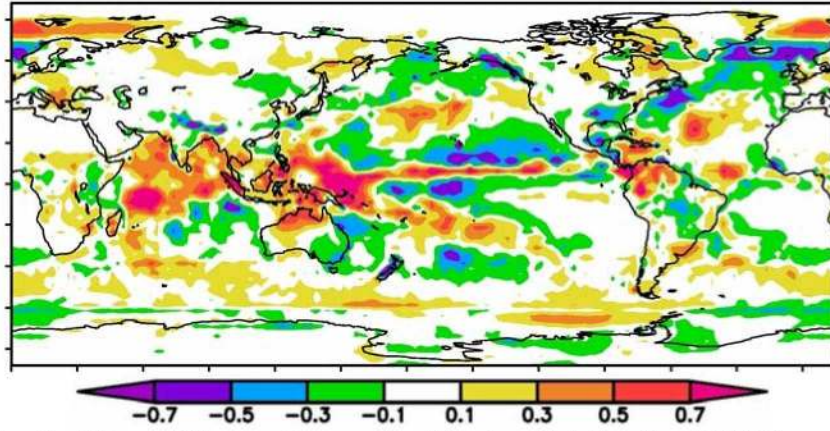


Fig. 3 Map of linear change for Version 2.1 for the SSM/I era (1988-2007) in mm/d/decade.

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**Electronic Data Supplement to:
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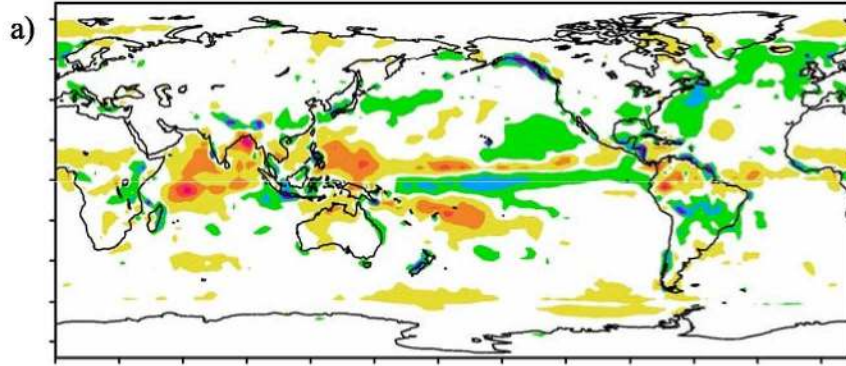
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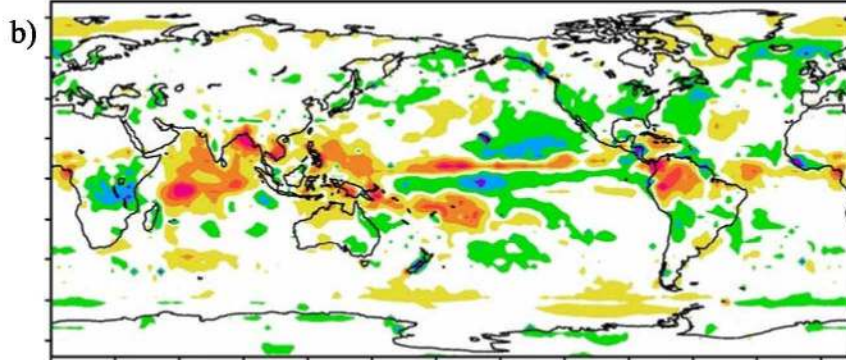
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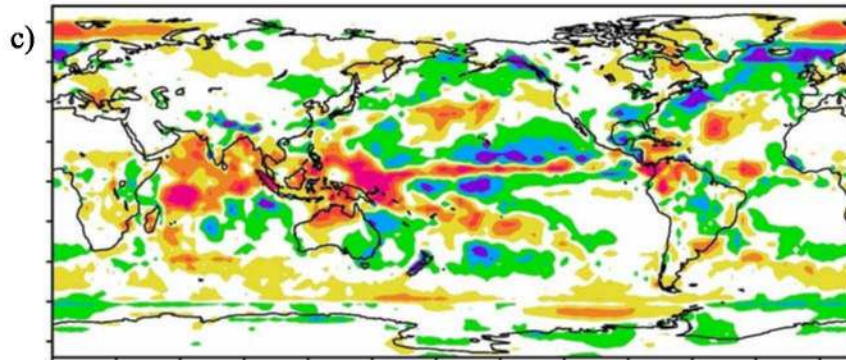
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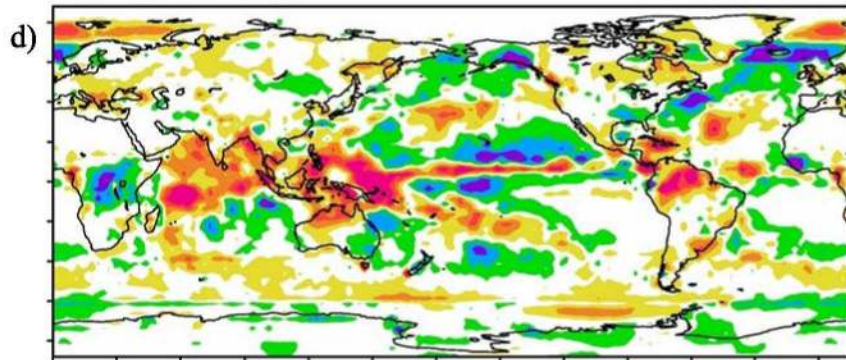
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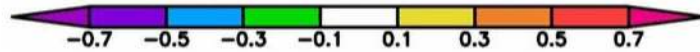
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Fig. EDS-1 Maps of linear change for Versions 2.1 and 2 for the entire study period (1979-2007; a and b, respectively), and for the SSM/I era (1988-2007, c and d, respectively), all in mm/d/decade.

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Popular Summary

How much precipitation fell last month around the entire globe? What's the long-term average? It might surprise most Americans that these are hard questions because they are accustomed to flicking on the television to watch weather reports that detail daily accumulations from numerous weather stations and feature composite radar movies of the current precipitation patterns. Globally, the situation is much different, with a nearly total lack of surface data over the oceans, which cover about 2/3 of the globe, and large gaps in many land areas. It has been clear from the dawn of the Space Age that satellites provide an excellent platform to address this problem, but it was not until the late 1970's that the first generation of sensors was continuously available in space to start the precipitation record. It took another 15 years and a second generation of satellite-based sensors, starting in mid-1987, for scientists to develop the first long-term global precipitation data set that took advantage of these then-new satellite data, while still incorporating raingauge data where available. The Global Precipitation Climatology Project (GPCP) was created by the World Climate Research Program (part of the World Meteorological Organization) to carry out the necessary innovative international cooperation among the operational weather satellite agencies in the U.S., Europe, and Japan, as well as the international precipitation science community.

Now, almost two decades later, the GPCP continues to extend and improve the global record of precipitation. Recently, the Global Precipitation Climatology Centre, a companion organization based in the Deutscher Wetterdienst (German Weather Service), released a new long-term archive of raingauge data. The improvements include a much higher number of stations and a better analysis scheme, and resolve some deficiencies that had been affecting the GPCP analysis. The GPCP has now adopted this new gauge analysis and recomputed the entire record of global precipitation, from 1979 to the present. During the reprocessing, special attention was paid to ensuring consistency among the various sensor types so that the entire record, now spanning 30 years, can be used for climate studies.

So, what is the long-term global average? This new "Version 2.1" dataset averages 2.68 mm per day (a tad over an inch a day), which is about 2% higher than for the old "Version 2". The change essentially all comes from changes over land due to the new gauge analysis. The important point, of course, is that the estimated values over particular locations at particular times can vary by a great deal more. Notably higher values are now analyzed in tropical

mountain regions (northwestern South America, Papua New Guinea, the Himalayas, and along the east coast of the Bay of Bengal), along the mountainous Pacific coasts of northwestern North America and southern Chile, in New Zealand, and in central Africa. These are all high-precipitation areas that lacked sufficient gauge coverage in the previous analysis to capture the highest values.

Note that the various data sets produced in the highly successful Tropical Rainfall Measuring Mission (TRMM, a joint NASA – Japanese Aerospace Exploration Agency satellite mission) are created at much finer time and space scales than the GPCP data, but for a shorter period and only the tropical and subtropical regions. Both TRMM and GPCP have benefited greatly from intercomparing datasets and exchanging analysis concepts since the start of TRMM, and this is expected to continue with the development of the Global Precipitation Measurement (GPM) satellite mission. One important new area of comparison will arise from GPM's coverage over polar latitudes.