

Supporting Information for “Global partitioning of precipitation in the terrestrial water cycle”

Text S1. Reference excerpts

Here, we provide the original excerpts of the studies referenced in our study. Data sets or software cited in the manuscript are not included.

Abramowitz et al. (2019): *In the absence of easy and agreed-upon alternatives, many studies still use the traditional “model democracy” approach; indeed, it seems unlikely that a “one size fits all” approach or list of good and independent models would be meaningful. (...) Nonetheless, we discourage the use of weighting or sub-sampling without out-of-sample testing, as the risks may well outweigh the potential benefits (Weigel et al., 2010; Herger et al., 2018b).*

Bromwich et al. (2011): *1989–2009 average values for P , E , and $P - E$ (mm yr⁻¹) from the reanalyses, spatially averaged over the grounded ice sheet (12.35×10^6 km²)*

Bhuiyan et al. (2019): *To overcome the limitations of individual satellite and reanalysis precipitation products, researchers have developed different merging techniques that combine these global precipitation products (from satellite and/or reanalysis) with in situ observations (Sinclair and Pegram 2005; Woldemeskel et al. 2013; Huffman et al. 2015; Beck et al. 2017a,b; Bhuiyan et al. 2017, 2018; Beck et al. 2019).*

Daly (2006): *There is no one satisfactory method for quantitatively estimating errors in spatial climate data sets, because the field that is being estimated is unknown between data points. Perhaps the best overall way to assess errors is to use a combination of ap-*

proaches, involve data that are as independent from those used in the analysis as possible, and use common sense in the interpretation of results.

Eyring et al. (2019): *This suggests that the ensemble has been unintentionally skill weighted by the inclusion of multiple versions of better-performing models.*

Oki and Kanae (2006): *Fig. 1. Global hydrological fluxes (1000 km³/year) and storages (1000 km³) with natural and anthropogenic cycles are synthesized from various sources (1, 3–5).*

Průhálíe (2016): *It is unanimously agreed that drylands total 41% of the Earth's surface, where 2 billion people live, of which approximately 90% in developing countries.*

Rodell et al. (2015): *Observed and optimized (boldface text) mean annual fluxes (mm day⁻¹) of P, ET or ocean evaporation E, Q, and C for the continents, major ocean basins and seas, world land, World Ocean, and world.*

Schlesinger & Jasechko (2014): *Weighting T/ET to either ecozone P or ET (Mu et al., 2011) yields a global T/ET estimate of $61 \pm 15\%$ (s.d.; Table 1).*

Trenberth et al. (2007): *(...) for precipitation P we prefer to use the newer version 2 of the Global Precipitation Climatology Project (GPCP) data (Adler et al. 2003) that are a blend of satellite and gauge data and provide global coverage. We also make use of two other land precipitation datasets. The University of East Anglia Climatic Research Unit (CRU) TS 2.1 land precipitation dataset is from Mitchell and Jones (2005). The PREC/L dataset is from Chen et al. (2002) and includes both Global Historical Climatology Network (GHCN) and synoptic data from NOAA/CPC's Climate Anomaly Monitoring System (CAMS). (...) The seasonal variation of E over land is taken from a stand-alone integration of the Community Land Model version 3 (CLM3) (Bonan et al. 2002; Qian et al. 2006). (...) The E - P has been computed from the moisture budget from ERA-40 (Uppala et al. 2005).*

Fig. 1. The hydrological cycle. Estimates of the main water reservoirs, given in plain font in 103 km³, and the flow of moisture through the system, given in slant font (103 km³ yr⁻¹), equivalent to Eg (1018 g) yr⁻¹.

Vargas Godoy et al. (2021): Table 1 and Figure 5.

Early attempts to quantify the global water cycle date back to the early 1900s [Brückner 1905]. To date, despite tremendous advances in terms of data and technology, accuracy regarding the components of the global water cycle has not increased accordingly. Ultimately, unquantified uncertainties on remote sensing satellite products [Sheffield et al. 2009], limitations of climate model simulations [Trenberth et al. 2011], short and heterogeneous observational data records [Schneider et al. 2017], and the natural fluctuations of water cycle components [Markonis et al. 2018] keep the understanding of the global water cycle ambiguous and human contribution unattributed.

Text S2. Data sets

This study has used five observational (gauge-based), five reanalysis, and seven satellite-based products to get precipitation data sets. The observational products are CPC-Global, CRU-TS v4.06, EM-EARTH, GPCC v2020, 20, and PREC/L. We selected the CPC-Global products because its high-resolution datasets are available on a 0.5° latitude-longitude grid with global (mainly land) spatial coverage at a daily temporal scale (Xie et al., 2010a). This observational data is the product of the NOAA-CPC Unified Precipitation Project, which is collected from more than 30,000 stations from multiple sources and then interpolated to create daily precipitation, retaining orographic effects. Another observational data, i.e., CRU-TS, refers to Climatic Research Unit gridded Time Series. This data has global (over land) spatial coverage of 0.5° latitude-longitude grid, except Antarctica (Harris et al., 2020). However, the temporal resolution for this data is at a monthly scale. The monthly climate anomaly from a series of weather station-based observations are interpolated using angular distance weighting (ADW) to achieve CRU-TS data with improved traceability and more informative diagnostics.

The next gauge-based data is EM-Earth, which is the abbreviation of the Ensemble Meteorological Dataset for Planet Earth. This EM-Earth dataset includes precipitation, daily air temperature range, dew-point temperature, and daily mean air temperature with higher spatial resolution at 0.1° over the globe focusing only on land areas (Tang et al., 2022). The temporal resolution of this data is from 1950 to 2019. We selected the GPCC observational dataset because it delivers data on monthly precipitation with the temporal record from 1891 to the present (Schneider et al., 2011). The GPCC refers to the Global Precipitation Climatology Centre, and the source of this dataset is quality-controlled station data. The Full Data Product (V2020), the version used herein, covers a reduced period from 1891 to 2019, but it is based on 67200 stations whose record duration

is ten years or longer. The PREC/L is the NOAA's Precipitation Reconstruction over Land, providing monthly averaged precipitation from 1948 to 2022 from over 17 000 gauge stations. The spatial coverage of this data is a 0.5° latitude-longitude global grid (Chen et al., 2002). The major advantage of this data is that it shows good agreement with other gauge-based observations.

The five reanalysis products we have used are ERA5, NCEP/NCAR R1, and NCEP/DOE R2. The ERA5 data is the real-time monthly quality-assured data that cover the temporal scale from 1959 to the present (Hersbach et al., 2020). This data is carried out with the Integrated Forecasting System model cycle CY41r2 and combined with multiple historical observations and data assimilation systems to achieve global estimates. The spatial resolution of this data is 0.25° . The NCEP/NCAR Reanalysis (R1) temporally covers data format with daily, 4-times daily, and monthly scales from 1948 to 2023. The spatial extent of this data covers 2.5° latitude-longitude global grids at 17 atmospheric pressure levels and 28 Sigma levels (Kalnay et al., 1996). The NCEP/DOE Reanalysis 2 (R2) is the improved model version of NCEP/NCAR R1. The measurement error and assimilation issues have been minimized in this new NCEP/DOE R2 and include updated parameterization schemes to achieve precise data (Kanamitsu et al., 2002). The temporal coverage of this data is from 1979 to 2023 with monthly values and from 1981 to 2010 with long-term monthly means. The spatial extent of this data is the 2.5° latitude-longitude global grid.

The JRA-55 is the global atmospheric reanalysis product of the Japan Meteorological Agency. This real-time JRA-55 product has been available from 1958 to the present. The incorporation of data assimilation and prediction system (such as radiation scheme, 4D-variational data assimilation with Variational Bias Correction, and the addition of greenhouse gases with time-varying concentrations) makes this product (JRA-55) more

reliable to use. This product is available at 1.25° spatial resolution (JMA, Japan, 2013). Another product, i.e., the MERRA-2, is also a global atmospheric reanalysis product by the NASA Global Modeling and Assimilation Office. This product contains satellite observations from 1980 to the present, with a spatial resolution of $0.625^\circ \times 0.5^\circ$ (longitude, latitude) (Bosilovich et al., 2016). The MERRA-2 product combines observations from satellites, radiosondes, and surface data, to accurately simulate the atmosphere.

In our analysis, we analyzed seven satellite-based products: CHIRPS v2.0, CMAP, CMORPH, GPCP v2.3, GPM IMERG v06, MSWEP v2.8, and PERSIANN-CDR. The CHIRPS v2.0 refers to Climate Hazards Group InfraRed Precipitation with Station data. CHIRPS estimated using the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (3B42) product and a ‘smart interpolation’ approach (Funk et al., 2015). This product contains a quasi-global data set of gridded rainfall spanning 50°S to 50°N , including all longitudes. The spatial resolution of this product is 0.05° . With the daily, pentadal, and monthly rainfall data, the time scale for this dataset ranges from 1981 to the present. Another dataset, i.e., CMAP refers to the CPC Merged Analysis of Precipitation, which contains monthly and pentad precipitation data sets (Xie & Arkin, 1997). Here we used monthly values, which range from 1979 to 2022. This monthly averaged precipitation dataset is the combined product of gauge and satellite estimates. The spatial resolution of CMAP is 2.5° latitude-longitude global grid.

The CMORPH is short for Climate Prediction Center morphing method. This product uses cloud motion vectors estimated from geostationary satellite IR imagery at half-hourly intervals to reproduce the high-quality precipitation estimates from passive microwave data (Joyce et al., 2004). The CMORPH covers 60°S to 60°N at the spatial resolution of 0.25° latitude-longitude globe grid. Having daily scale data, CMORPH covers the temporal scale from 1998 to 2021. The Global Precipitation Climatology Project (GPCP)

version 2.3 is the monthly global precipitation generated by integrating satellite data (over land and ocean) and rain gauge-based data over land (Adler et al., 2018). This high spatial resolution data, i.e., on a 2.5° global grid, covers the temporal scale from 1979-present. The Integrated Multi-satellitE Retrievals for GPM (IMERGM) version-06 provides multi-satellite monthly precipitation (Huffman et al., 2019). The spatial resolution of data is at 0.1° latitude-longitude grid with global coverage from 2000-present. The IMERG v06 product integrates early precipitation estimations from the TRMM satellite (i.e., from 2000 - 2015) with more recent precipitation estimates of the GPM satellite (i.e., from 2014 - present). The Multi-Source Weighted-Ensemble Precipitation (MSWEP) version 2.8 is the global precipitation product available from 1979 to the present (Beck et al., 2019). This dataset has a spatial resolution of 0.1° latitude-longitude with real-time about three hourly temporal scales. The MSWEP is the high-quality precipitation data obtained by integrating gauge, reanalysis, and satellite data. The Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR) (Ashouri et al., 2015). This dataset is developed from the PERSIANN algorithm employing GridSat-B1 infrared data. This dataset provides high spatial-resolution daily rainfall rates at $0.25^\circ \times 0.25^\circ$ resolution, with spatial coverage from 60°S - 60°N . The temporal length for this dataset is available from 1983 to the present.

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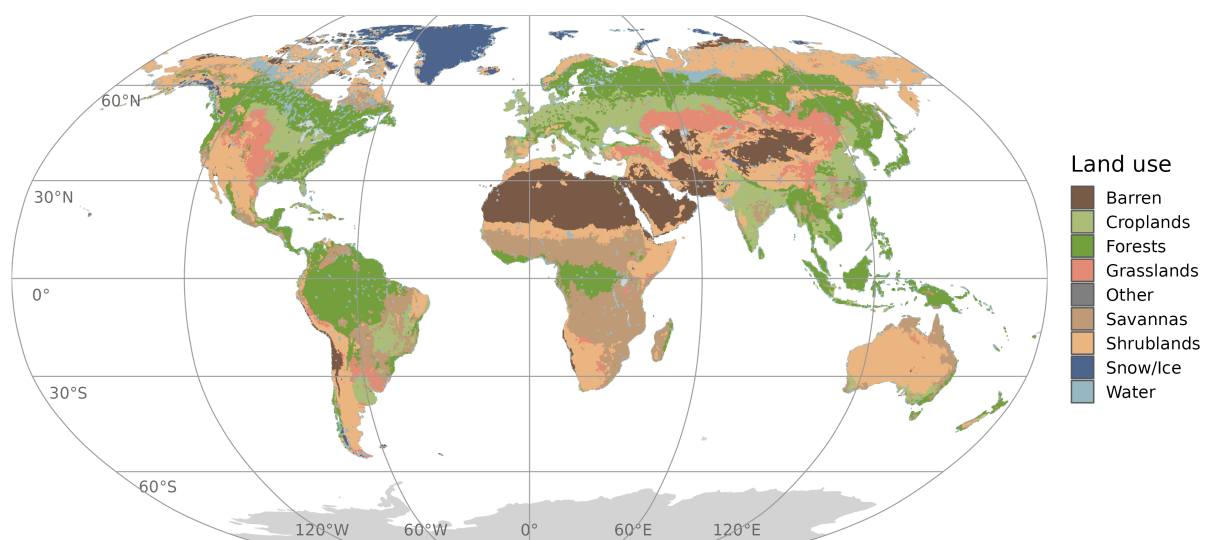


Figure S1. Land cover types according to “MODIS MOD12C1 0.25 Degree Land Cover” data product (Friedl & Sulla-Menashe, 2010).

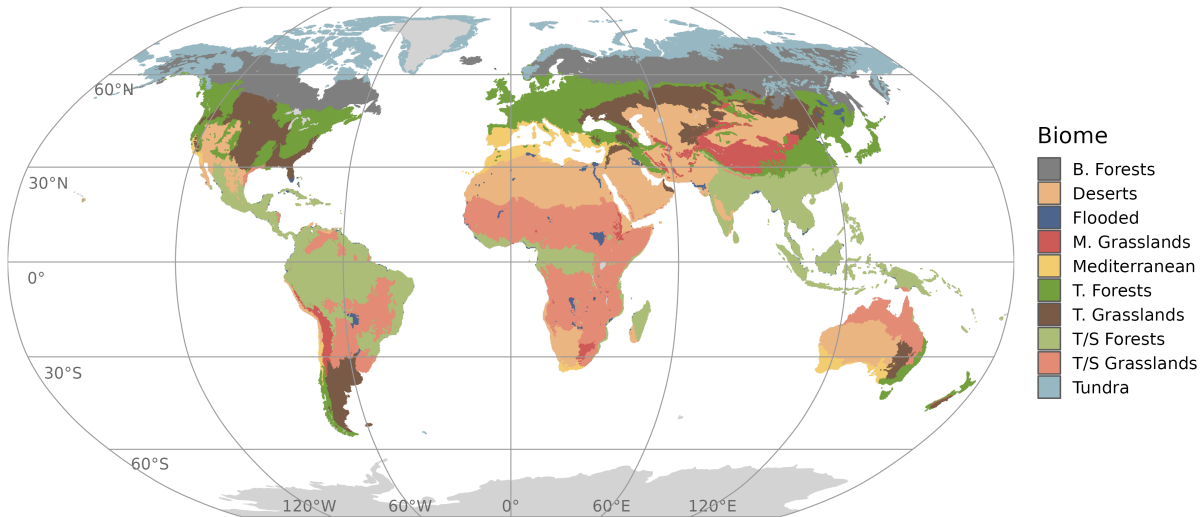


Figure S2. Biomes adapted from Dinerstein et al. (2017). T/S Forests: Tropical & Subtropical Forests, T/S Grasslands: Tropical & Subtropical Grasslands, Savannas & Shrublands, T. Forests: Temperate Forests, B. Forests: Boreal Forests/Taiga, T. Grasslands: Temperate Grasslands, Savannas & Shrublands, Savannas & Shrublands, Deserts & Xeric Shrublands, Tundra, M. Grasslands: Montane Grasslands & Shrublands, Flooded: Mangroves & Flooded Grasslands/Savannas, Mediterranean: Mediterranean Forests, Woodlands & Scrublands.

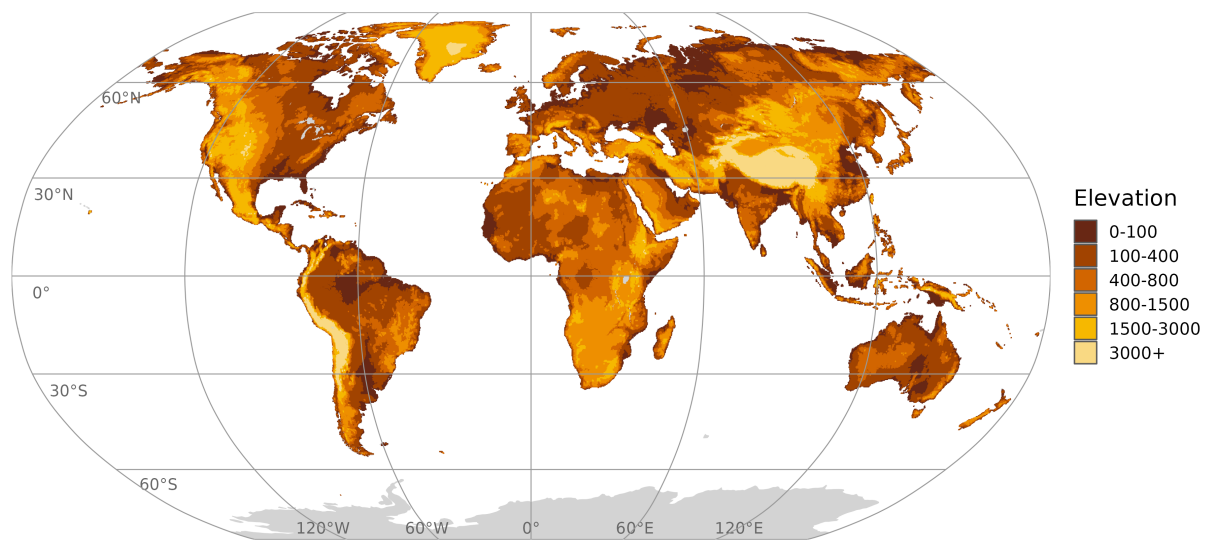


Figure S3. Elevation zones from ERA5 reanalysis (Hersbach et al., 2018).

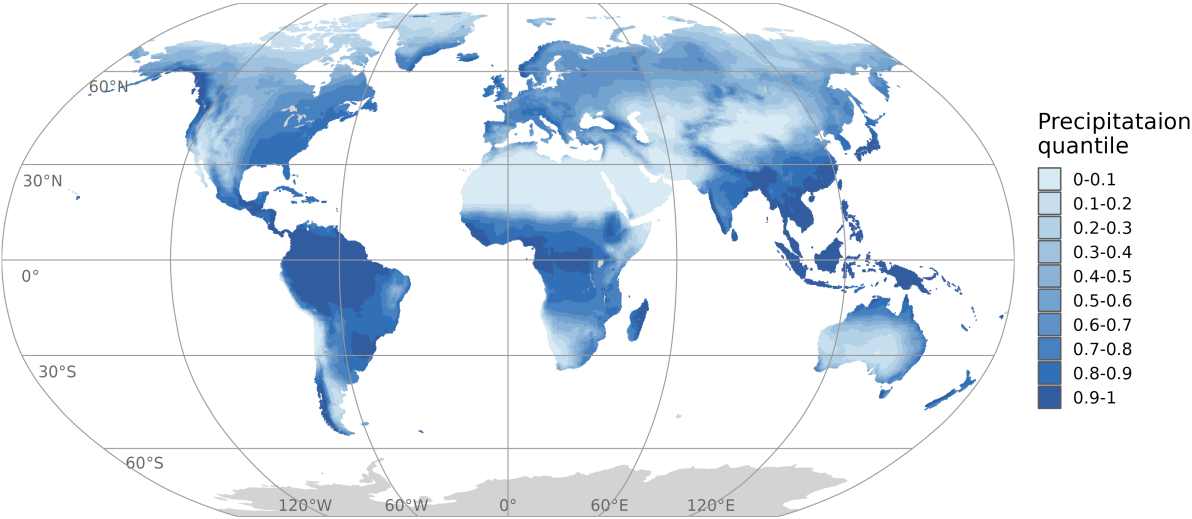


Figure S4. Ensemble mean annual precipitation intensity classes.

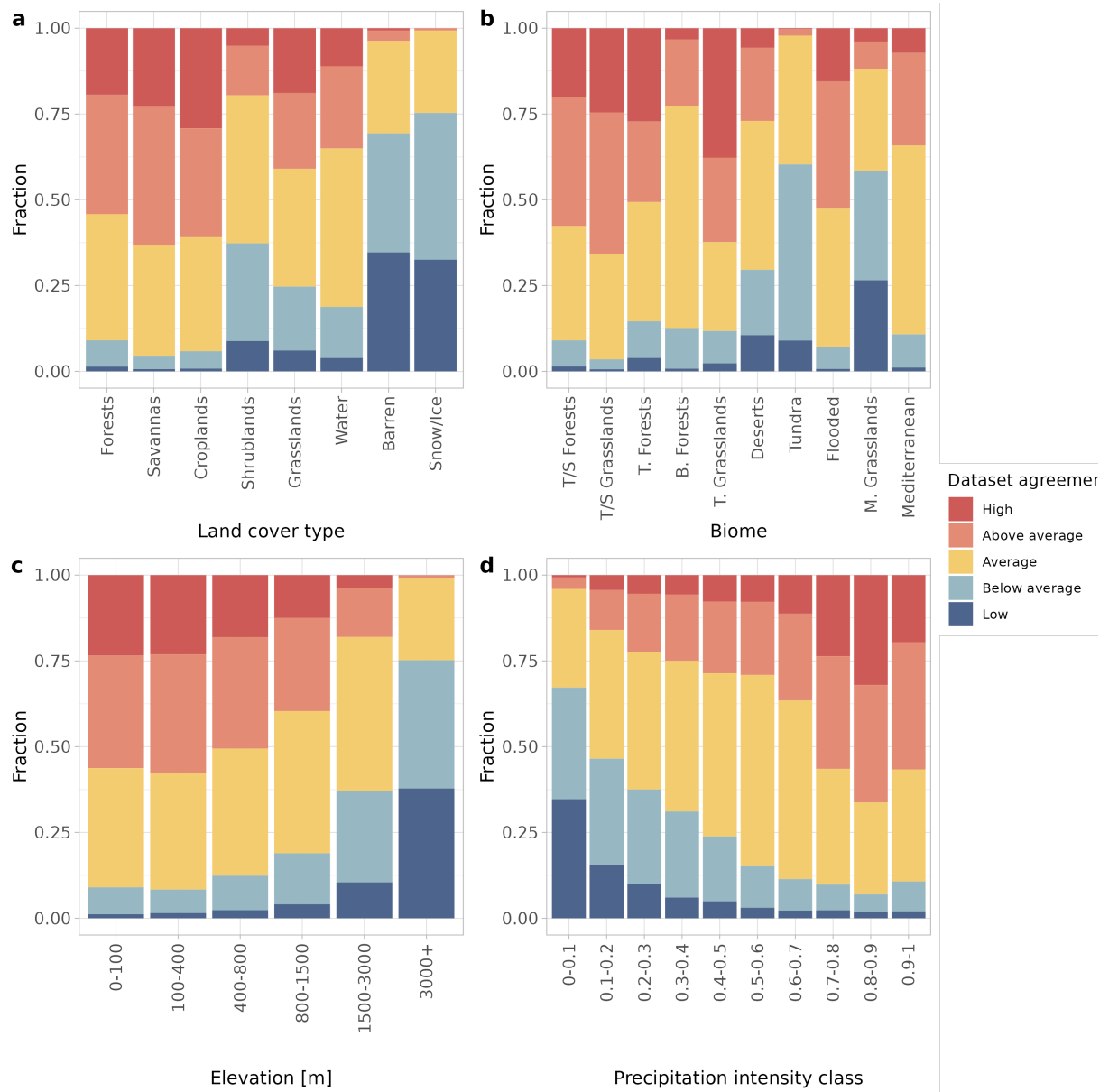


Figure S5. Dataset agreement of global precipitation volume per year for different (a) land cover types, (b) ecosystem classes, (c) elevation zones, and (d) precipitation intensity classes. Abbreviations as in Figure 1.

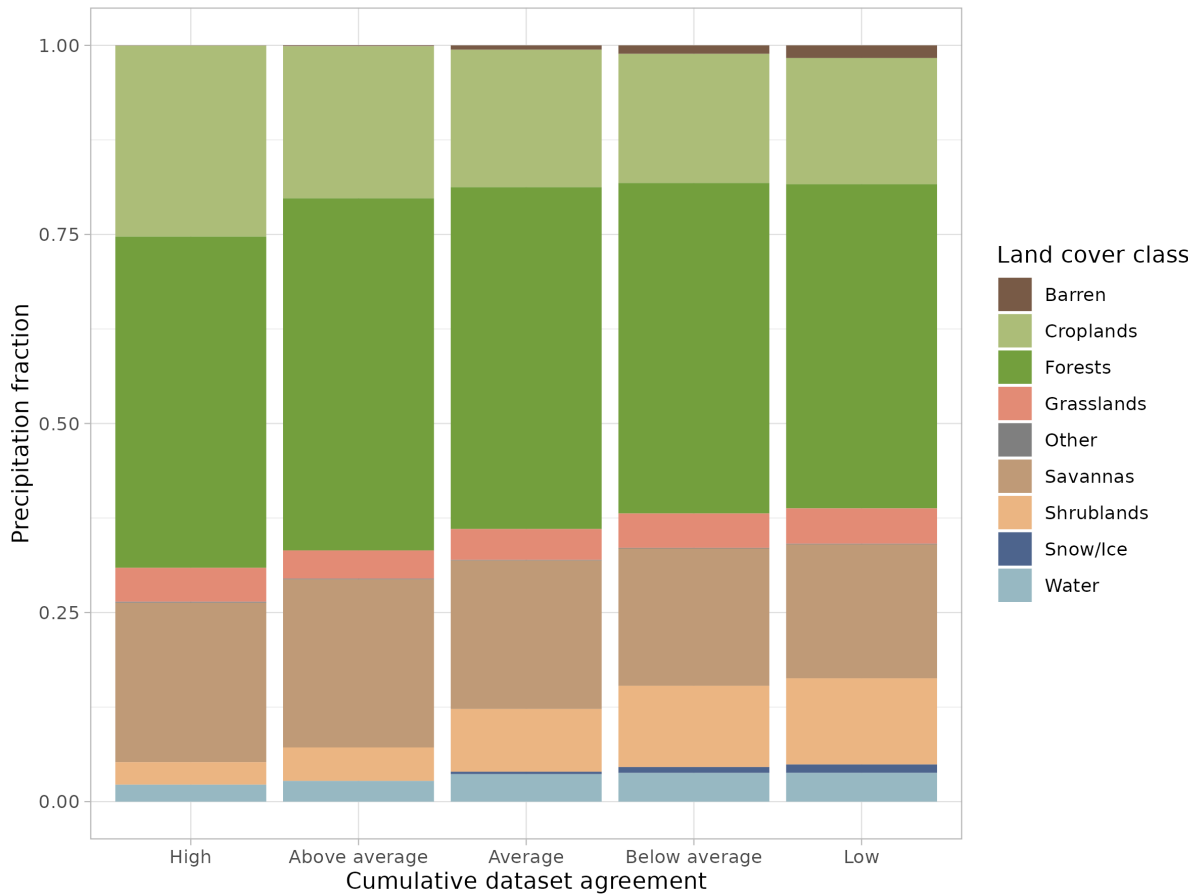


Figure S6. Cumulative dataset agreement partitioned over land cover classes. The left-most bar consists of only grid-cells with high agreement, while the right-most consists of all the datasets.



Figure S7. Cumulative dataset agreement partitioned over biome classes. The left-most bar consists of only grid-cells with high agreement, while the right-most consists of all the datasets.

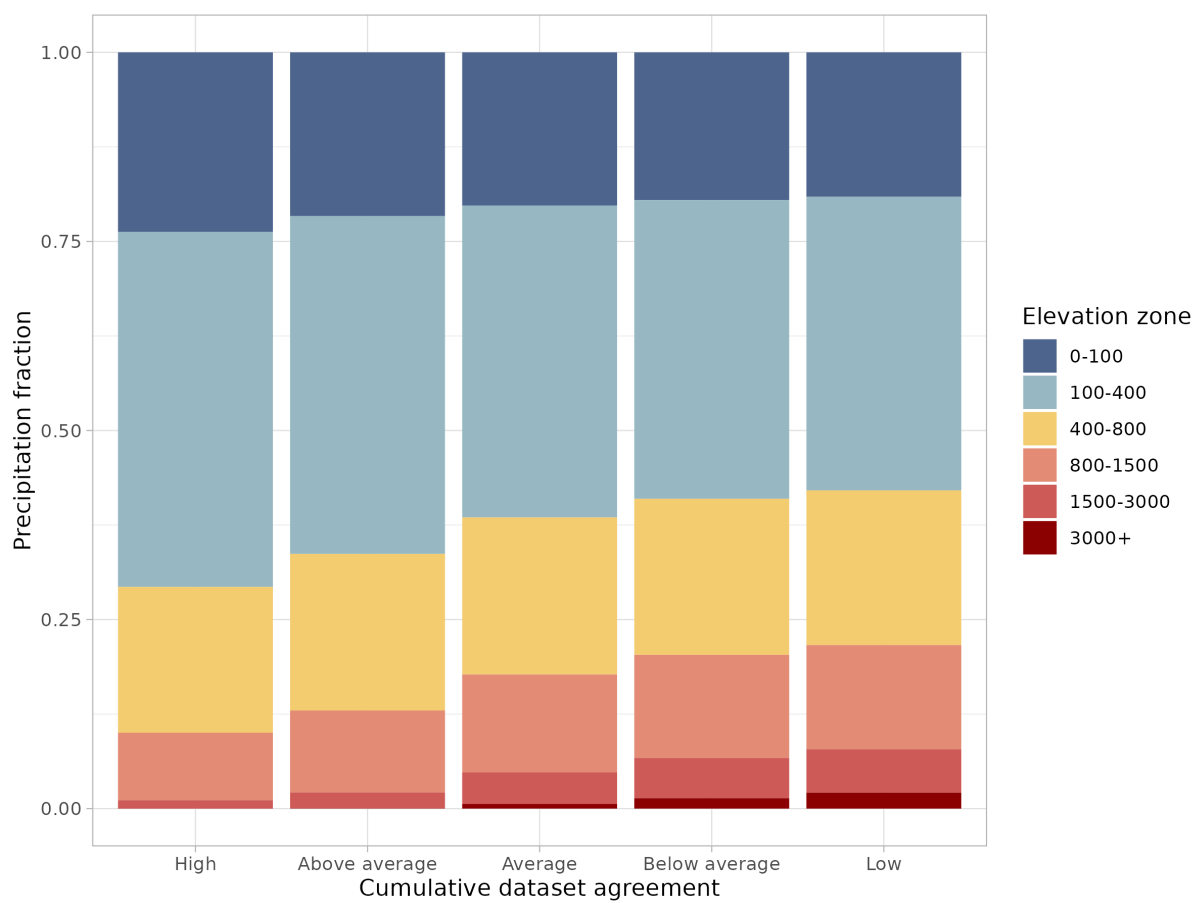


Figure S8. As in S6, but for elevation zones.

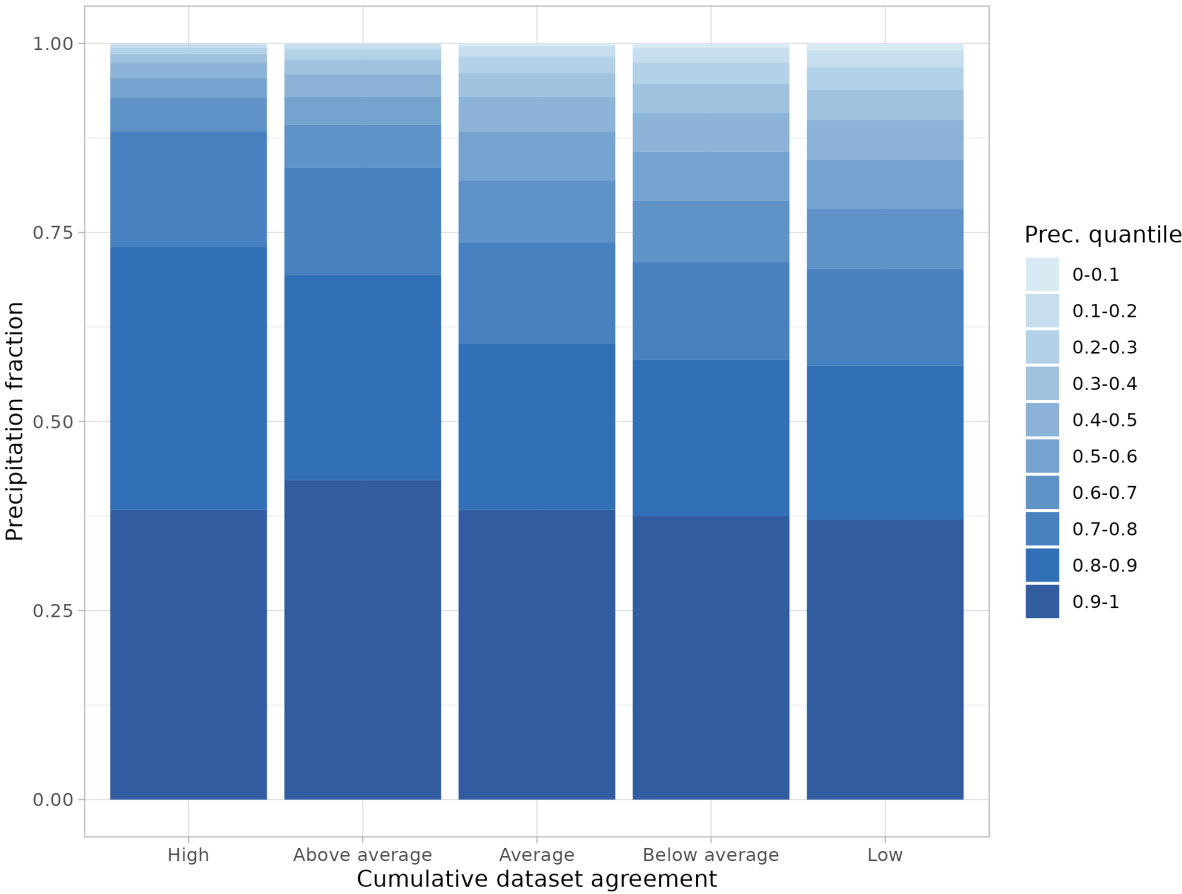


Figure S9. As in S8, but for precipitation intensity classes.

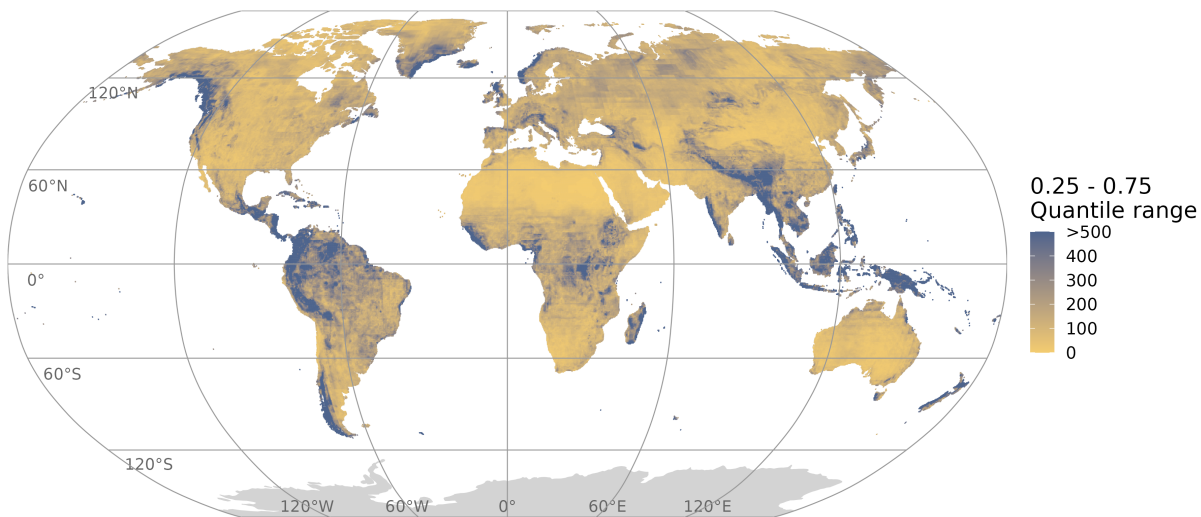


Figure S10. Difference of Q_{75} to Q_{25} of mean precipitation of data set ensemble.

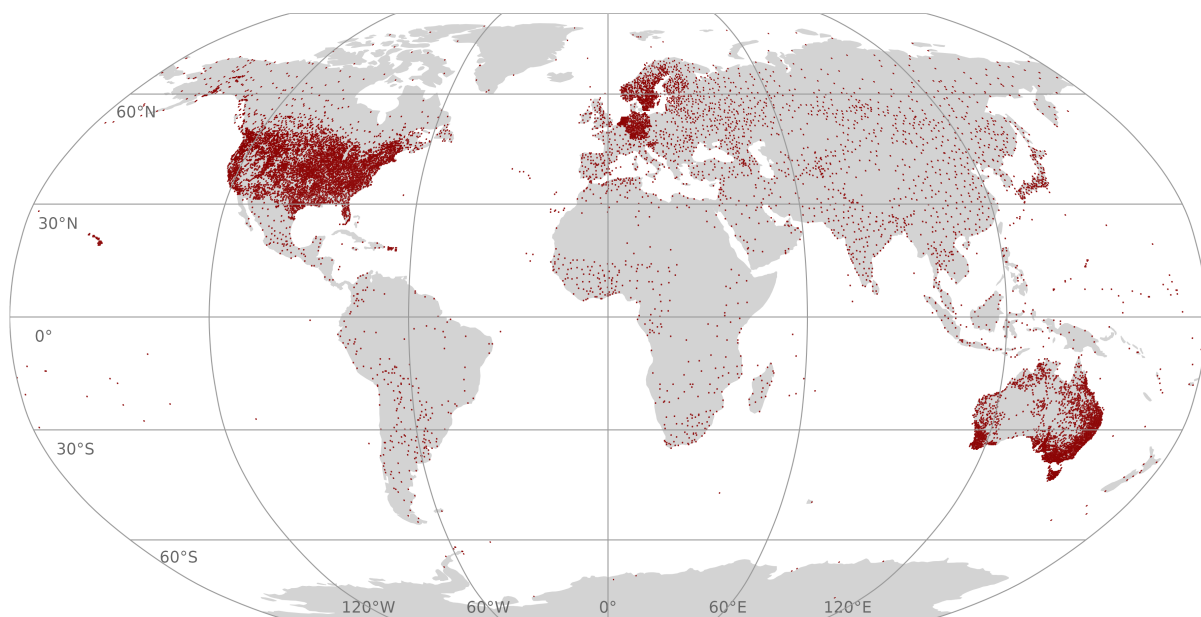


Figure S11. Operational GHCN stations during 2000-2019.

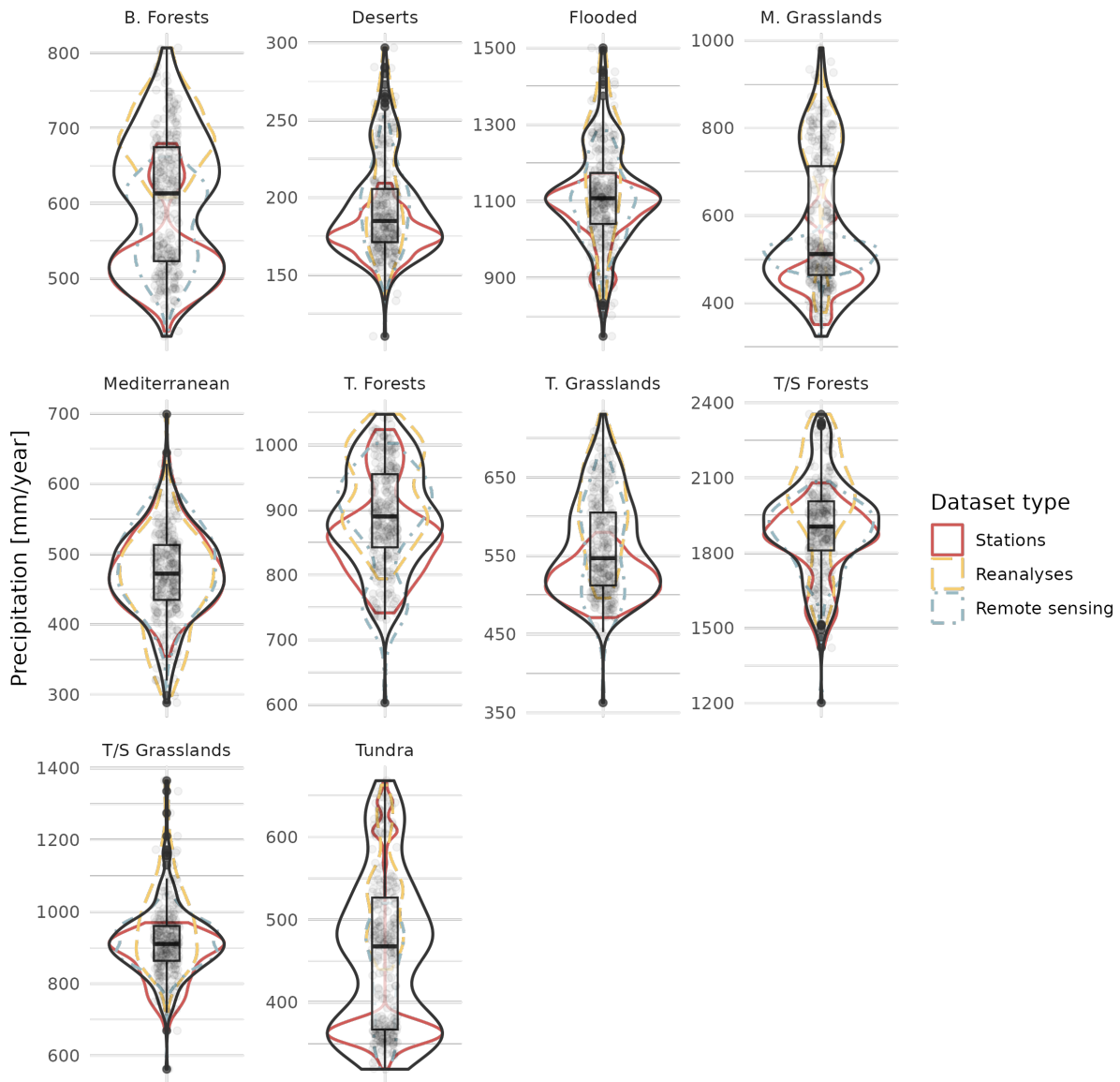


Figure S12. Mean annual precipitation of all datasets for each biomes and data set type. The black line and the box plot correspond to all three sources. Points represent annual values from individual data sets.

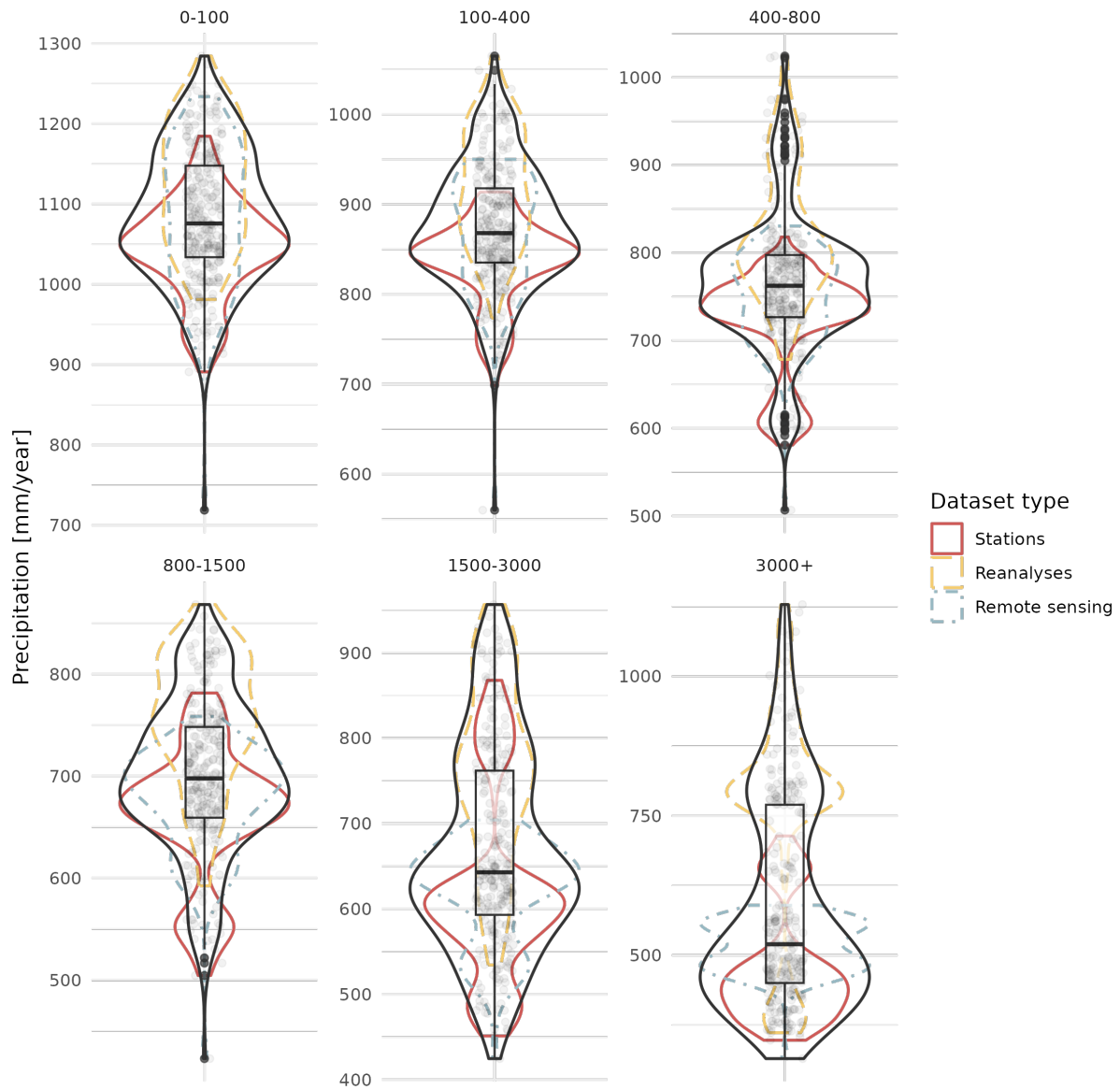


Figure S13. Mean annual precipitation of all datasets for each elevation zone and data set type. The black line and the box plot correspond to all three sources. Points represent annual values from individual data sets.

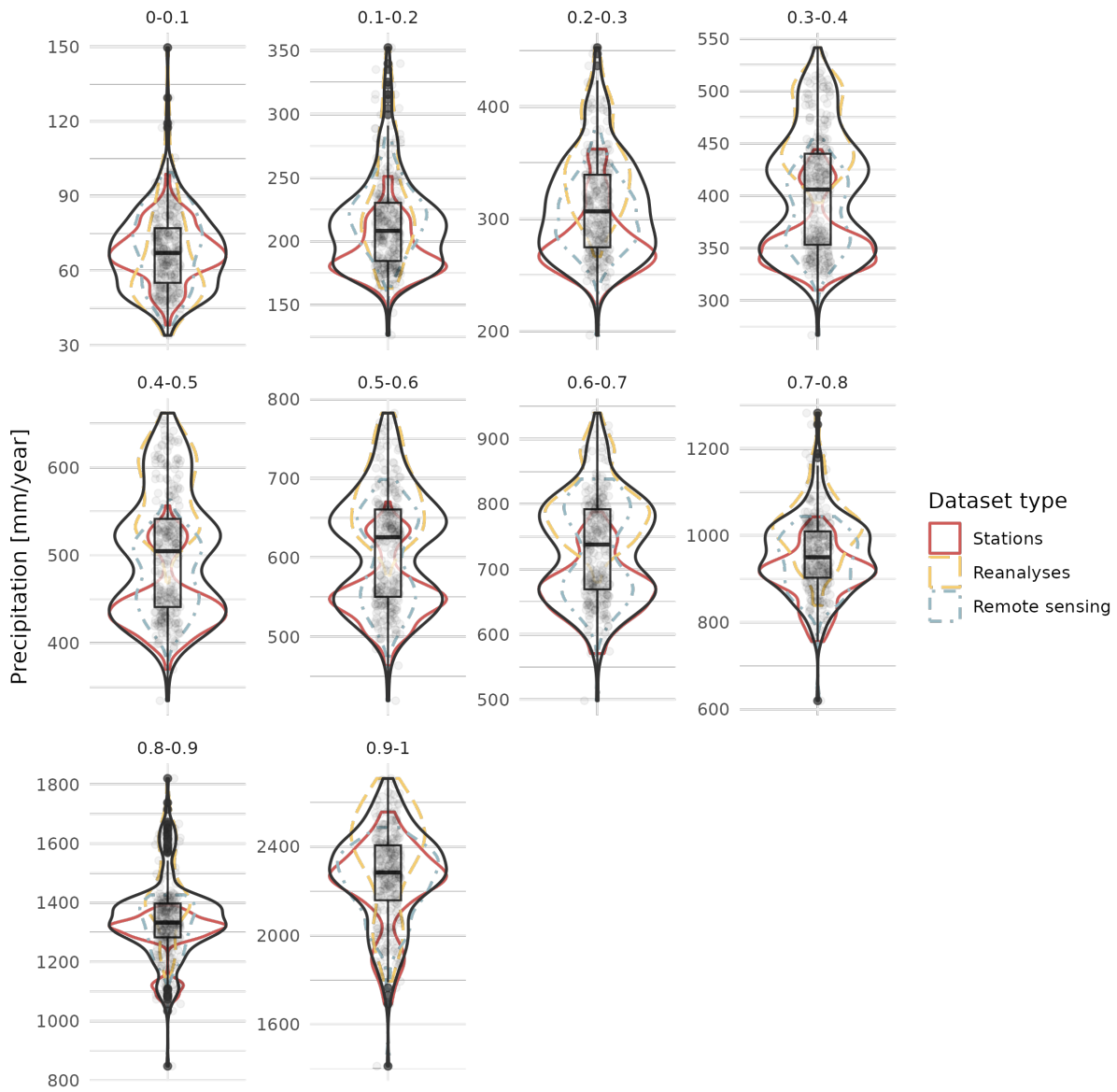


Figure S14. Mean annual precipitation of all datasets for each precipitation intensity class and data set type. The black line and the box plot correspond to all three sources. Points represent annual precipitation values from individual data sets.

Table S1. Data description as of last access (January, 2023)

Name	Source	Period	Resolution	Reference
CHIRPS 2.0	https://11nq.com/baMSc	1981-2022	0.05°	Funk et al. (2015)
CMAP	https://acesse.dev/VY1g9	1979-2022	2.5°	Xie and Arkin (1997)
CMORPH CDR	https://encr.pw/I02sr	1998-2021	0.25°	Joyce et al. (2004)
CPC-Global	https://11nq.com/gj1qY	1979-2022	0.5°	Xie et al. (2010b)
CRU-TS 4.06	https://encr.pw/HJuPy	1901-2021	0.5°	Harris et al. (2020)
EM-EARTH	https://acesse.dev/PZolS	1950-2019	0.1°	Tang et al. (2022)
ERA5	https://acesse.dev/3QApW	1959-2022	0.25°	Hersbach et al. (2020)
GPCC 2020	https://11nq.com/BGYS0	1891-2019	0.25°	Schneider et al. (2011)
GPCP CDR 2.3	https://encr.pw/uB2dQ	1979-2022	0.5°	Adler et al. (2018)
GPM-IMERG 06 Final	https://acesse.dev/f0LYS	2000-2021	0.1°	Huffman et al. (2019)
JRA55	https://encr.pw/PLInx	1958-2022	1.25°	JMA, Japan (2013)
MERRA2	https://acesse.dev/L6gA8	1980-2022	$0.5 \times 0.625^\circ$	Bosilovich et al. (2016)
MSWEP 2.8	https://11nq.com/5QEP5	1979-2022	0.1°	Beck et al. (2019)
NCEP/NCAR R1	https://11nq.com/S24kp	1948-2022	1.875°	Kalnay et al. (1996)
NCEP/DOE R2	https://11nq.com/7xCYL	1979-2022	1.875°	Kanamitsu et al. (2002)
PERSIANN-CDR	https://acesse.dev/kioaF	1983-2022	0.25°	Ashouri et al. (2015)
PREC/L	https://11nq.com/sx5JZ	1948-2022	0.5°	Chen et al. (2002)

Table S2. Ensemble standard deviation of annual precipitation.

Source	Tropical	Arid	Temperate	Continental	Polar	Global
All	3 992	1 515	1 827	2 519	966	9 445
Stations	4 149	285	1 648	1 934	1 416	8 285
Reanalyses	5 139	2 211	1 842	787	443	8 044
Remote Sensing	2 438	1 018	1 700	2 015	319	7 488

Table S3. Climatic partition of precipitation volume (km3/year) for datasets with global coverage.

Dataset	Tropical	Arid	Temperate	Continental	Polar	Global
CMAp	47 630	11 269	20 436	16 819	3 807	100 425
CPC	42 226	10 131	20 219	16 512	3 102	92 653
CRU-TS	52 051	10 780	22 737	18 252	3 750	108 221
EM-EARTH	51 497	10 536	24 828	21 447	6 608	115 501
ERA5	53 587	10 765	26 222	22 013	5 421	118 561
GPCC	51 528	10 603	23 016	17 742	3 485	106 994
GPCP	52 165	12 869	23 721	21 149	4 342	114 779
GPM-IMERG	52 448	11 881	24 117	20 824	3 687	116 923
JRA55	53 106	15 031	24 538	23 156	5 440	121 827
MERRA2	45 543	10 968	21 286	21 631	4 370	105 560
MSWEP	51 000	10 240	22 855	18 739	4 232	107 599
NCEP/DOE	57 402	15 052	25 113	23 433	5 083	126 613
NCEP/NCAR	58 703	11 333	23 976	23 055	4 868	122 466
PREC/L	50 680	10 865	22 384	17 035	3 618	105 232

Table S4. Partition of mean precipitation over land cover types in thousand km³ per year (mm in parentheses).

Type	Stations	Reanalyses	Remote sensing	All
Forests	45 640 (1 401)	49 862 (1 530)	46 500 (1 427)	47 394 (1 454)
Savannas	18 364 (1 023)	20 779 (1 157)	19 213 (1 070)	19 469 (1 084)
Croplands	17 490 (901)	19 378 (998)	18 321 (944)	18 402 (948)
Shrublands	11 418 (395)	14 341 (497)	12 009 (416)	12 631 (437)
Water	4 842 (929)	5 350 (991)	5 075 (934)	5 090 (952)
Grasslands	4 677 (486)	5 870 (610)	4 978 (517)	5 189 (539)
Barren	1 714 (95)	1 921 (107)	1 847 (102)	1 826 (101)
Snow/Ice	1 283 (521)	1 109 (549)	1 004 (521)	1 141 (531)
Other	107 (925)	110 (926)	107 (935)	108 (928)

Table S5. Partition of mean precipitation over biomes in thousand km³ per year (mm in parentheses).

Category	Stations	Reanalyses	Remote sensing	All
T/S Forests	43 951 (1 834)	47 799 (1 994)	44 752 (1 867)	45 554 (1 901)
T/S Grasslands	18 538 (870)	20 551 (965)	19 420 (912)	19 509 (916)
T. Forests	14 024 (865)	15 084 (930)	14 189 (875)	14 450 (891)
B. Forests	8 219 (535)	10 650 (693)	8 760 (570)	9 241 (602)
T. Grasslands	5 469 (519)	6 392 (607)	5 879 (558)	5 915 (562)
Deserts	4 597 (175)	5 416 (208)	5 047 (192)	5 018 (192)
Tundra	3 405 (413)	4 342 (530)	3 533 (433)	3 776 (460)
M. Grasslands	2 313 (477)	3 464 (714)	2 464 (508)	2 767 (570)
Mediterranean	1 572 (480)	1 495 (456)	1 587 (484)	1 549 (473)
Flooded	1 538 (1 056)	1 714 (1 177)	1 595 (1 095)	1 617 (1 111)

Table S6. Partition of mean precipitation over elevation zones in thousand km³ per year (mm in parentheses).

Zone	Stations	Reanalyses	Remote sensing	All
0-100	20 675 (1 044)	22 502 (1 126)	21 627 (1 081)	21 599 (1 084)
100-400	41 056 (834)	45 246 (920)	42 638 (866)	43 005 (874)
400-800	21 378 (721)	24 159 (820)	22 137 (747)	22 588 (764)
800-1500	14 512 (661)	16 513 (755)	14 774 (675)	15 302 (699)
1500-3000	5 966 (618)	7 213 (762)	5 787 (618)	6 360 (670)
3000+	1 948 (477)	3 087 (758)	2 091 (515)	2 396 (588)

Table S7. Partition of mean precipitation over precipitation intensity classes in thousand km³ per year (mm in parentheses).

Quantile	Stations	Reanalyses	Remote sensing	All
0-0.1	1 089 (68)	1 059 (67)	1 113 (69)	1 085 (68)
0.1-0.2	2 095 (192)	2 506 (231)	2 362 (219)	2 318 (213)
0.2-0.3	3 010 (281)	3 714 (347)	3 238 (304)	3 327 (311)
0.3-0.4	3 932 (360)	5 042 (462)	4 185 (383)	4 401 (403)
0.4-0.5	5 225 (449)	6 671 (574)	5 523 (476)	5 826 (501)
0.5-0.6	6 569 (557)	7 975 (677)	7 038 (597)	7 205 (612)
0.6-0.7	8 183 (672)	9 695 (797)	8 842 (727)	8 911 (732)
0.7-0.8	13 718 (906)	15 386 (1 017)	14 191 (937)	14 449 (955)
0.8-0.9	21 566 (1 278)	24 100 (1 428)	22 185 (1 314)	22 648 (1 342)
0.9-1	40 148 (2 215)	42 571 (2 346)	40 376 (2 225)	41 079 (2 265)