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M. Hantel

Authors

Brasseur, G., Cramer, W., Ehrendorfer, M., Emmons, L., Erhard, M.,
Gerten, D., Gouretski, V., Granier, C., Haberlandt, U., Haimberger, L.,
Hantel, M., Hense, A., Huybrechts, P., Jaenicke, R., Koltermann, K.P.,
Kottek, M., Meincke, J., Miller, H., Ohmura, A., Raschke, E., Rubel, F.,
Rudolf, B., Schönwiese, C.-D., Stubenrauch, C.

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Preface

The key selection criteria of this handbook were discussed between the authors and the editorial team of Springer during a 3-day workshop in Vienna in September 2001. The workshop was organized jointly by the *University of Vienna* and the *Austrian Academy of Sciences*; it was funded by the Academy and by the *Federal Ministry for Education, Science and Culture*. Authors and publisher agreed that the book should comprise a set of all relevant climate budget quantities in a maximally standardised form mandatory for all climate subsystems. The format of the edition should be a one-volume printed book plus a DVD. The DVD should carry the data, all original articles in un-abbreviated form, specifically all figures in original colours, plus additional material like animations of the most important climate parameters and selected non-standard quantities.

A first draft version of book and DVD was circulated between authors, editor and publisher in December 2002 for internal review and for the purpose of overall balancing. A second draft has been available through internet since December 2003 for the same purpose and has been widely used by the community of authors.

The global climate system is represented in this book by arranging the data around the budget principle. This principle is basic for the entire climate system. A correct budget alone explains nothing. However, an advanced dynamic theory with an incorrect budget is of no use either. Thus budget climatology is the indispensable minimum upon which any deeper understanding of the system must rest. What we hope to demonstrate with this collection is that budgeting is not only a useful principle but also that “budget-thinking” has practically become state of the art in modern quantitative climatology.

The acknowledgements of the editor go to all persons who, next to the distinguished international authors of the various chapters, have made this edition possible, most notably: to the former and present chairpersons of the Clean Air Commission of the *Austrian Academy of Sciences*, Prof. Dr. Othmar Preining and Prof. Dr. Annemarie Popp; to the team from Springer-Verlag: Prof. Dr. Werner Martienssen (Editor in Chief of Landolt-Börnstein), Dr. Rainer Poerschke (Editorial Director Landolt-Börnstein), and Dr. Christian Meier (Editorial Office Landolt-Börnstein); and finally to my colleagues Dr. Leopold Haimberger, Mag. Markus Kottek and Dipl.-Hydr. Corinna Huhle who in innumerable ways have helped to transform chaotic ideas into coherent arguments, fine coloured pictures and eventually into printed text.

19 March 2005

Michael Hantel (Volume Editor), University of Vienna

Editor:

Hantel, M.

Institute for Meteorology and Geophysics (IMGW)
University of Vienna, UZA II
Pharmaziezentrum (2G 507)
Althanstraße 14
A-1090 Wien
Austria

Authors:

Brasseur, G.

Max Planck Institute for Meteorology
Bundesstraße 55
D-20146 Hamburg
Germany

Cramer, W.

Dept. Global Change and Natural Systems
Potsdam Institute for Climate Impact Research
Telegrafenberg A31
P.O. Box 60 12 03
D-14412 Potsdam
Germany

Ehrendorfer, M.

Institute for Meteorology and Geophysics
University of Innsbruck
Innrain 52
A-6020 Innsbruck
Austria

Emmons, L.

National Center for Atmospheric Research
Atmospheric Chemistry Division
PO Box 3000
Boulder, CO 80307
USA

Erhard, M.

Institute for Meteorology and Climate Research (IMK-IFU)
Forschungszentrum Karlsruhe GmbH
Kreuzackbahnstr. 19
D-82467 Garmisch-Partenkirchen
Germany

Gerten, D.

Dept. Global Change and Natural Systems
Potsdam-Institute for Climate Impact Research
Telegrafenberg C4
P.O. Box 60 12 03
D-14412 Potsdam
Germany

Gouretski, V.

Centre for Marine and Climate Research
Institute for Marine Research
University of Hamburg
Bundesstraße 53
D-20146 Hamburg
Germany

Granier, C.

Service d'Aeronomie
Universite Paris 6
Boite 102, Tour 15-14
F-75252 Paris Cedex 05
France

Haberlandt, U.

Institute of Water Ressources Management, Hydrology and Agricultural Hydraulic Engineering
University of Hannover
Appelstr. 9A
D-30167 Hannover
Germany

Haimberger, L.

Institute for Meteorology and Geophysics (IMGW)
University of Vienna, UZA II
Pharmaziezentrum (2G 507)
Althanstraße 14
A-1090 Wien
Austria

Hantel, M.

Institute for Meteorology and Geophysics (IMGW)
University of Vienna, UZA II
Pharmaziezentrum (2G 507)
Althanstraße 14
A-1090 Wien
Austria

Hense, A.

Meteorologisches Institut
Universität Bonn
Auf dem Hügel 20
D-53121 Bonn
Germany

Huybrechts, P.

Alfred-Wegener-Institut für Polar- und Meeresforschung
Postfach 120161
D-27515 Bremerhaven
Germany

Jaenicke, R.

Institut für Physik der Atmosphäre
Fachbereich Physik, Mathematik und Informatik
Johannes Gutenberg-Universität Mainz
Becherweg 21
D-55099 Mainz
Germany

Koltermann, K.P.

Bundesamt für Seeschifffahrt und Hydrographie (BSH)
Bernhard-Nocht-Str. 78
20359 Hamburg
Germany

Kottek, M.

Working Group Biometeorology
Institute of Medical Physics and Biostatistics
University of Veterinary Medicine Vienna
Veterinärplatz 1
A-1210 Vienna
Austria

Meincke, J.

Centre for Marine and Climate Research
Institute for Marine Research
University of Hamburg
Bundesstraße 53
D-20146 Hamburg
Germany

Miller, H.

Alfred-Wegener-Institut für Polar- und Meeresforschung
Am Alten Hafen 26
D-27568 Bremerhaven
Germany

Ohmura, A.

Geographisches Institut ETH
Universität Zürich Irchel
Winterthurerstrasse 190
CH-8057 Zürich
Switzerland

Raschke, E.

Lehmsalweg 14
D-27383 Scheeßel
Germany

Rubel, F.

Working Group Biometeorology
Institute of Medical Physics and Biostatistics
University of Veterinary Medicine Vienna
Veterinärplatz 1
A-1210 Vienna
Austria

Rudolf, B.

Deutscher Wetterdienst
P.O. Box 10 04 65
D-63004 Offenbach am Main
Germany

Schönwiese, C.-D.

Institut für Atmosphäre und Umwelt
J.W. Goethe Universität
Postfach 11 19 32
D-60054 Frankfurt a.M.
Germany

Stubenrauch, C.

Laboratoire de Meteorologie Dynamique (LMD)
Ecole Polytechnique
F-91128 Palaiseau cedex
France

Landolt-Börnstein**Editorial Office**

Gagernstr. 8, D-64283 Darmstadt, Germany
fax: +49 (6151) 171760
e-mail: lb@springer-sbm.com

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11 Global Precipitation

11.1 Introduction

Global precipitation is an issue that can be regarded from various perspectives. The leading point of this contribution is to focus on precipitation as a component of the global energy and water cycle. In particular this chapter provides information about the observational techniques, which are the basis of the gridded global precipitation data sets being delivered on DVD complementary to this book.

Precipitation can be observed by different measurement techniques. The most important of these are the classical in situ techniques (i.e., the conventional precipitation gauges operated in national networks) and the remote sensing techniques (i.e., the earth-based radar networks and the satellite-based instruments). Other data sources, not discussed here, include indirect techniques like the proxy approach; for example, present weather classifications and more qualitative historic documentary records, such as wet day counts. The various existing observation techniques have specific advantages and deficiencies. While surface networks of both gauges and radar have a generally higher accuracy, only precipitation estimates from multiple satellites provide a full global view. Therefore, recent global precipitation maps are based on merged gauge and satellite products.

After a short review of the historical development in mapping global precipitation, the role of precipitation in the water and energy cycle is discussed in the introductory sections 11.1.1 and 11.1.2. Further, the commonly used units and their conversions are given. The following sections 11.2 to 11.5 explain the different observational techniques, i.e. conventional gauge networks, precipitation radar and satellite-based instruments, with respect of the limitations and associated measurement errors. Uncertainties in global precipitation analysis become visible by comparing zonal profiles of different observation-based data sets.

The gridded precipitation data set visualised in the chart section of this book is derived from the monthly analyses of the Global Precipitation Climatology Project (GPCP), called GPCP Satellite-Gauge Combination Version 2 or short GPCP-V2 [03Adl]. The original data set provides monthly area-mean precipitation on a resolution of 2.5° latitude/longitude. There is currently no global precipitation data set of higher resolution available for the joint observation period 1991-1995. For compatibility with the data sets provided on the attached DVD, the GPCP-V2 data have been downscaled by interpolation to 1° grid boxes. Over land areas, however, there exists a high-resolution precipitation product for the period 1991-1995. This GPCC Full Data Product (further called „GPCC-Full“), being described in section 11.2, has been selected for reference for land surface precipitation. It is made available via DVD on the joint grid with a resolution of 1°.

Based on the maps presented in this contribution and in its annex on DVD, the global scale spatial and temporal distribution of precipitation is discussed in section 11.6, also covering the association of precipitation anomalies and El Niño - Southern Oscillation. Finally, a glimpse at the change of precipitation during the 20th century is given (11.7) followed by some closing remarks (11.8).

11.1.1 Review of global mean precipitation climatologies

Precipitation is one of the most frequently investigated climate quantities. Nevertheless, even today it is not a simple task to determine the exact value of global mean precipitation. While for example temperature is a state quantity, whose global value is relatively well known, precipitation is a highly variable flux quantity and its global values comprise big uncertainties. Tab. 11.1 depicts the historical milestones in the estimation of global precipitation maps and numbers. One of the first world-wide precipitation maps has been compiled at the beginning of the 20th century by Brückner (references see [95Rud]). It needed about 50 years until Möller published his seasonal precipitation maps for the globe.

Further 25 years later, as a milestone, Jaeger published his global monthly precipitation maps. Although Jaeger compiled his precipitation maps still by hand, he was the first to provide numerical gridded precipitation values. For that reason his precipitation climatology was also widely used for a long time. Further 10 years later [90Leg] evaluated climatic long-term mean data from world-wide 25,000 rain gauge stations. Using this data set they compiled the first objectively analysed global precipitation climatology based on bias-corrected rain gauge measurements. So far, all global precipitation estimates represented long-term climatic conditions only. With the establishment of the Global Precipitation Climatology Project (GPCP) by the World Climate Research Programme (WCRP) the era of time series of global gridded precipitation estimates began. In 1993 the GPCP delivered the first 24 months of digital global monthly precipitation maps using gridded gauge data for the land-surface and various satellite-based estimates for the oceans.

Table 11.1 Comparison of global, land and ocean annual mean precipitation (an extended selection from [95Rud]) in units mm/day. Note that only values calculated by Legates [90Leg] and from the GPCP-V2 data set [03Adl] have been corrected for systematic measurement errors.

Author	period	resolution	global	land	ocean
Brückner (1905)	long-term	mean annual	2.58	2.25	2.68
Meinardus (1934)	long-term	mean annual	2.75	1.82	3.13
Möller (1951)	long-term	mean seasonal	2.28	1.82	2.46
Budyko (1970)	long-term	mean seasonal	2.79	1.97	3.13
Baumgartner & Reichel (1975)	long-term	mean seasonal	2.67	2.04	2.92
Jaeger (1976)	1931 - 1960	mean monthly	2.74	2.07	3.01
UNESCO (1978)	1931 - 1960	mean annual	3.10	2.19	3.48
Legates & Willmott (1990)	long-term	mean monthly	3.12	2.32	3.50
GPCP-V2 (Adler et al. 2003)	1979 - 2001	monthly time-series	2.61	2.09	2.84

One widely used reference for the annual global mean precipitation P is 1000 mm/yr (in Table 11.1 consistently given as $P=2.74$ mm/d) presented by [76Jae]. This number is correspondent to the energy flux of about 80 W/m^2 , which represents the global latent heat transfer from the atmosphere to the earth's surface by release of sensible energy from condensation in the clouds and consumption by evaporation of the fallen rain at the surface. The global latent heat flux has been quantified as the residual from the other observed components of the energy cycle. [76Jae] used this number to scale his gridded global precipitation data set: monthly precipitation over land was given by quantitative climatic observations and maps; over ocean, however, only precipitation intensity frequency distributions were available from ship weather observations and have been used to map the spatial structure and seasonal variation. Eventually, Jaeger's global annual precipitation total was fitted by the energy budget.

Today, GPCP-V2 precipitation climatology comprises 25 years (1979-2003) of global monthly data fields, based on observations only by using a new technique to combine various satellite products and gauge data ([95Huf], [03Adl]). The monthly gridded precipitation estimates are calculated operationally in near real-time. The gauge observations from roughly 7,000 meteorological observing stations are analyzed by the GPCC, the Global Precipitation Climatology Centre [01Rud]. The numbers given in Table 11.1 for GPCP-V2 average global, land and ocean precipitation have been taken from the original publication of [03Adl]. For period considered in this book (1991-1995), global mean precipitation is calculated to 2.59 mm/d using the 1° gridded data being derived from the original 2.5° resolution of GPCP-V2.

World-wide highest locally observed precipitation

Precipitation is highly variable, it occurs in spatially and temporally limited events with very large gradients. From these reasons, quantitative assessment of area averaged precipitation fluxes and statistical analysis of precipitation temporal variability are difficult tasks. The range of measured values covers four orders of magnitude. Extremes are 100 times larger than mean values, e.g. global annual average of 2.7 mm per day versus the largest observed daily precipitation 1825 mm. For illustration world-wide observed highest precipitation depths are compiled in Table 11.2.

Table 11.2 World-wide observed highest precipitation depths (“world records”) [mm] for various observation time intervals and the corresponding average daily precipitation [mm/d] with date and location of observation [95Rud].

Time interval	Precipitation depth [mm]	Precipitation [mm/d]	Date/period of observation	Location of observation
1 minute	38	54,720	26 November 1970	Barot, Guadeloupe
3 minutes	63	30,240	29 November 1911	Porto Bello, Panama
8 minutes	126	22,680	25 May 1920	Füssen, Germany
20 minutes	206	14,832	07 July 1889	Curtea-de-Arges, Romania
1 hour	401	9,619	03 July 1975	Shangdi, China
6 hours	840	3,355	01 August 1975	Muduoca-idang, China
24 hours	1,825	1,825	15-16 March 1952	Foc Foc, La Reunion
5 days	4,301	860	23-27 January 1980	Commerson, La Reunion
10 days	6,028	603	18-27 January 1980	Commerson, La Reunion
31 days	9,300	300	01-31 July 1861	Cherrapunji, India
1 year	26,461	73	Aug 1860 - July 1861	Cherrapunji, India

11.1.2 Precipitation as a component of the global water and energy cycle

Observed data about surface precipitation resulting from rainfall and snowfall are necessary for assessment of global water resources and for understanding of the interaction between the water and energy cycle as well as for the assessment of climate impact on vegetation and all ecosystems. To promote this research fields, the WCRP established the Global Water and Energy Cycle Experiment (GEWEX), a long-term major international project. GEWEX contributes to the knowledge about global precipitation, which is crucial for the assessment of climate change and of the impact on nature, environment and human society. Questions concern the climate change impact on vegetation, desertification, duration of droughts, shift of climate zones, water resources, river runoff, floods, intensity and duration of extreme events. Fig. 11.1 depicts our understanding of the global water cycle. The four major water reservoirs are the oceans ($1,400,000,000 \text{ km}^3$), the water stored in inland and ice ($59,000,000 \text{ km}^3$) as well as the marine ($11,000 \text{ km}^3$) and terrestrial ($4,500 \text{ km}^3$) atmosphere. The main fluxes between these reservoirs or states are the vertical fluxes by precipitation P and evaporation E , and the horizontal moisture fluxes Q and surface water runoff R . While R generally points from land to ocean, moisture fluxes occur in both directions. But if we assume that water vapour storage in the atmosphere and water storage at land (rivers, lakes, surface snow and ice cover) is constant on average or the change can be neglected, net precipitation ($P-E$) over land is balanced by net evaporation ($E-P$) over ocean, and runoff is compensated by net atmospheric moisture fluxes.

The observed precipitation is of particular interest since it is the only in situ measured quantity of the water cycle. This is true at least for the land areas, whereas over the oceans precipitation is indirectly estimated from various satellite measurements. For the global water budget this implies that the individual climate compartments could not be estimated independently. Therefore, closing the atmospheric water budget, the moisture flux convergence can be taken from model runs [02Roa] or analysed radiosonde observations to calculate the evaporation as a residual, whereas in hydrology global climatological fields of precipitation and surface runoff [99Fek] are generally used to estimate evaporation.

Even if the key parameter, the global precipitation, is the same in the atmospheric and hydrologic budget respectively, a difference occurs. This difference (imbalance) is a measure of the accumulated uncertainties in the independently estimated compartments of the global annual water budget. It is of the order of 0.2 mm/d or in energy flux units about 5 W/m^2 (for conversion see section 11.1.3). Although 0.2 mm/d does not seem to be much, it is more than twice the precipitation trend calculated for the last 100 years (section 11.7). As the budgets presented here are restricted to observations, the monthly data sets generated by the Global Precipitation Climatology Project (GPCP) and the long-term climatology generated by the Global Runoff Data Centre (GRDC) are used to calculate the parameters for land areas: Precipitation $P = 2.09 \text{ mm/d}$ ($113,000 \text{ km}^3/\text{yr}$), runoff $R = 0.76 \text{ mm/d}$ ($41,000 \text{ km}^3/\text{yr}$) and evaporation $E = P - R = 1.33 \text{ mm/d}$ ($72,000 \text{ km}^3/\text{yr}$). For the ocean areas as well as globally the only observable quantity is precipitation. From the GPCP data set values of $P = 2.84 \text{ mm/d}$ ($374,000 \text{ km}^3/\text{yr}$) for ocean and $P = 2.61 \text{ mm/d}$ ($487,000 \text{ km}^3/\text{yr}$) for total precipitation have been calculated.

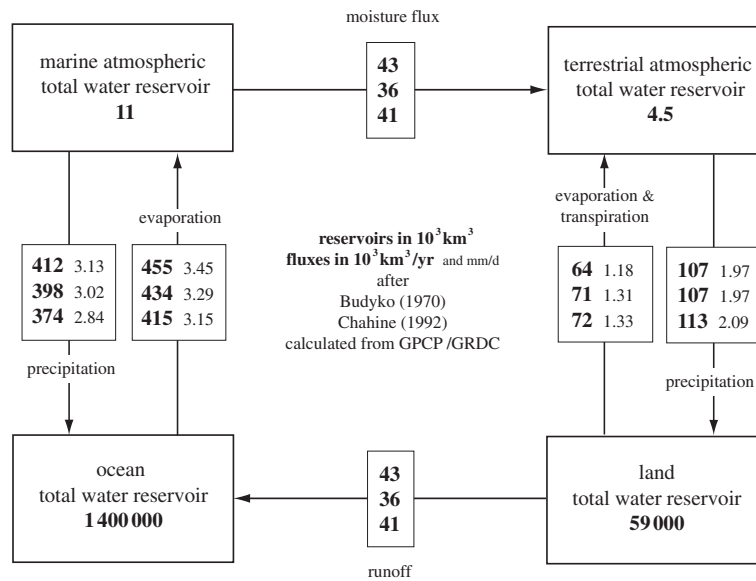


Fig. 11.1 Water reservoirs and fluxes in the global hydrological cycle.

These and resultant values are depicted in Fig. 11.1. Note that the values given in Tab. 11.1 are consistent with Fig. 11.1; units mm/d are converted to the given mass fluxes by multiplying with the covering land area ($148,700,000 \text{ km}^2$) or ocean area ($361,300,000 \text{ km}^2$) and the number of days (365) respectively (see section 11.1.3).

Another important climate parameter is the mean residence time of water in the atmosphere and oceans. The total yearly precipitation divided by atmospheric storage indicates that the atmosphere recycles its entire water content 30 times per year, giving water vapour a mean residence time in the atmosphere of about 12 days. In contrast, the mean residence time of a water molecule in the oceans as a whole is over 3,000 years, but it is not the same at all ocean depths. In the surface layers, it is only a few days or weeks, increasing to centuries and longer for the deep ocean levels. Generally, there exists a fast and a slow climate regime. The fast regime, consisting of the atmosphere, upper ocean layers and land surface, determines the amplitude and regional patterns of climate change. The slow regime, consisting of the bulk of the ocean, land glaciers and ice caps, modulates the transient response of the climate system and introduces considerable delay. The fast component of the hydrological cycle has a critical role in predicting climate change and is the primary focus of GEWEX. The exchange of water among the reservoirs shown in Fig. 11.1 occurs through atmospheric moisture flux, precipitation, runoff and evaporation. The driver for this exchange is the differential heating by the sun which varies with latitude. The exchange pathways are controlled by surface properties as well as atmospheric and ocean circulation. Thus, water and energy cycle in the climate system are linked by many processes. When an energy imbalance occurs in the climate system, the atmosphere-surface system reacts to re-establish the balance. In the atmosphere, balance is most efficiently re-established by means of transport of latent heat through evaporation and condensation. A comprehensive description of the energy cycle is given in chapter 9 and 10.

11.1.3 Definition of measured quantities and commonly used terms and units

Physically, precipitation is a mass flux (unit $\text{kg m}^{-2} \text{ s}^{-1}$). In meteorology, climatology, agriculture and hydrology the variable precipitation is frequently defined as precipitation depth per observation time interval. Similar notations used in various disciplines are e.g. precipitation intensity, precipitation amount, precipitation rate or rain rate (for definitions see [04Ros]). Typical precipitation is given in units of e.g. millimetres per minute, hour, day, month, season or year. Precipitation depth in millimetres describes the water supply in litres per 1 square metre horizontal surface. Historically, precipitation has been measured using a simple bucket: The increase of the water level in the bucket in millimetres exactly corresponds to

the water supply during a given time interval. The term precipitation intensity is mostly used for short time intervals of one hour or less, especially if series of data are discussed with regard to the temporal or spatial structure. In the field of modelling and remote sensing the term precipitation rate is understood as a mass flux of liquid water falling out of a grid box. Furthermore, precipitation total is used, e.g. if the total precipitation for a time interval (e.g. one month) has been summed up from individual observations for subintervals (e.g. days). For this book the commonly used precipitation unit mm/d (millimetres per day) has been chosen in order to provide comparable data sets, a unit, which can easily be related to the water mass flux and the corresponding energy.

Quantity:	Precipitation
Unit:	Millimetres per day [mm/d]

Most of precipitation results from rain(fall), snow(fall), sleet, fallen ice crystals and hail etc or mixed from those, and this fallen precipitation is traditionally measured at surface-based meteorological stations using precipitation gauges (special buckets). Additionally, precipitation is caused either by deposit or interception from drifting clouds or fog by vegetation. Water fluxes towards the surface are also caused by condensation of atmospheric water vapour at the ground (dew) or by sublimation (rime and hoar-frost). It is not trivial to directly measure deposited precipitation. Even if its contribution to the global water budget equation is very small, both, interception and dew may regionally be an important water source, e.g. for desert vegetation or forests in high latitudes.

Conversion of precipitation units

With the approximation 1 litre = 1 kg of water we easily find the relation:

Precipitation of **1 mm/d** = **1 l m⁻² d⁻¹** corresponds to a mass flux (per area unit) of **1 kg m⁻² d⁻¹**.

The relationship between annual, monthly and daily precipitations is:

1000 mm/yr $\approx$ **83.3 mm/mon** $\approx$ **2.74 mm/d**

Precipitation contributes to the global energy cycle by the vertical flux of latent heat caused by condensation in the atmosphere (energy release) and evaporation at the surface (consumption of energy):

The precipitation mass flux of **2.74 kg m⁻² d⁻¹** corresponds to the energy flux of **79.3 W/m²**.

11.2 In situ observation techniques for precipitation

Precipitation gauges are operating in meteorological, hydrological and climate observation networks in nearly all countries of the world. The World Meteorological Organisation (WMO) estimated that world-wide more than 400,000 gauge stations are operated [03WMO]. The international data exchange, however, is limited for various reasons by the data owners. Data from about 7,000 meteorological (synoptic) stations are operationally exchanged for the purpose of weather forecasts. For climate applications the most extensive data archive has been collected by the GPCC, comprising gauge-observed monthly precipitation depths from up to 40,000 stations (Fig. 11.2). Unfortunately there exists no international unique precipitation gauge and hence this huge data archive consists of measurements from a few dozen of gauge types with different accuracy. Thus it is important to have background information on the national standard rain gauges.

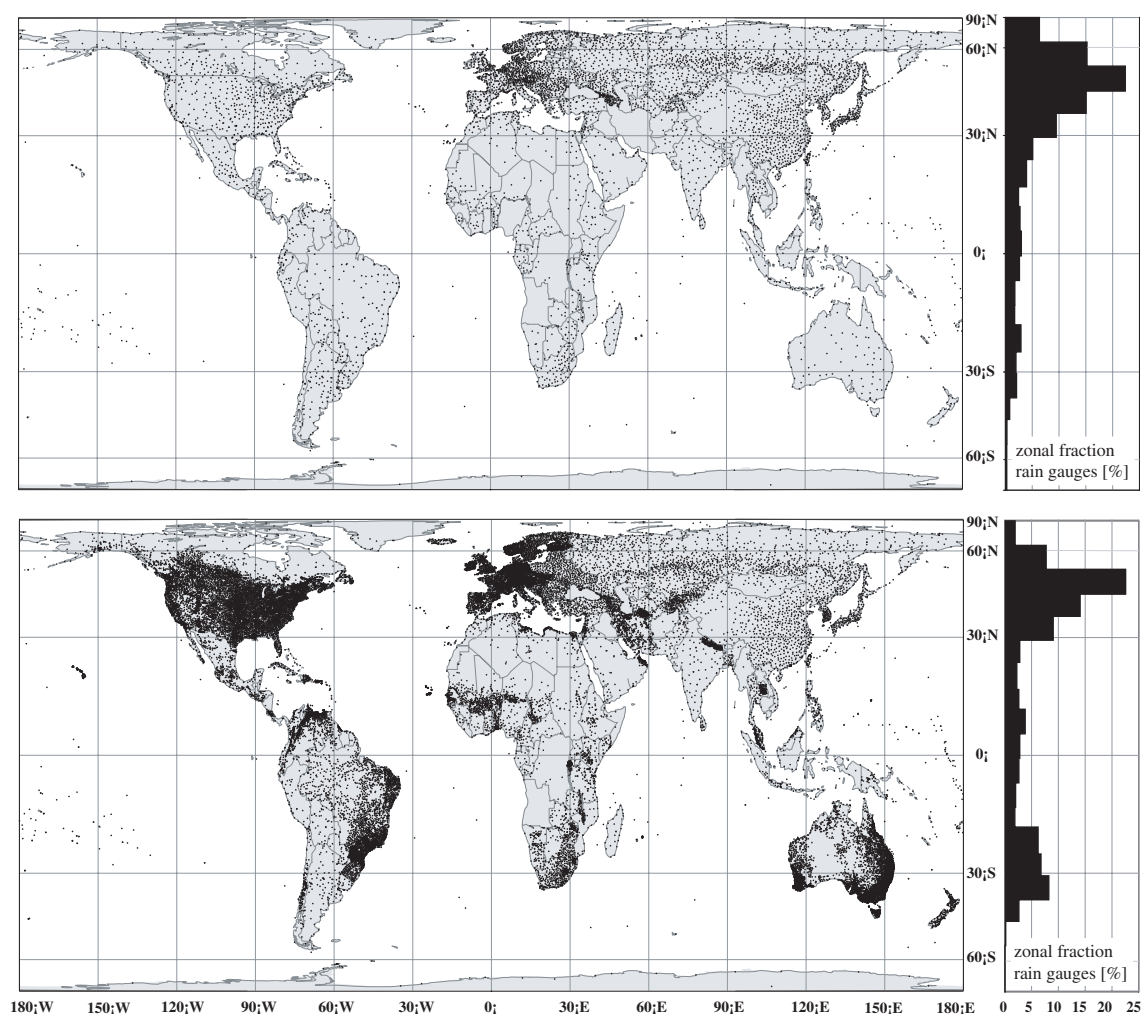


Fig. 11.2 Distribution of about 7,000 stations with precipitation measurements available operationally via the Global Telecommunication Network, GTS (upper panel) and up to 40,000 stations collected by the GPCC (lower panel). The histograms of the zonal fraction of stations depict the non-uniform distribution with more than 60% of the precipitation gauges between 30°N and 60°N in both data sets.

A precipitation gauge widely used around the world is the Hellmann gauge. This non-recording gauge for both rain and snow measurements is the standard gauge in 30 countries, such as the Central European countries Austria, Germany, Hungary and Poland. In Russia and all countries of the former USSR the Tretjakov precipitation gauge has been the national standard. One of the most effective gauges for solid precipitation measurements is the Canadian Nipher snow gauge. Detailed descriptions on the different types of precipitation gauges operated in the past by the national weather services have been presented by [89Sev]. For details on design and function of the most common precipitation gauges see e.g. [88Sum].

Typically, precipitation gauges consist of a funnel (collector) and a container to store the collected water. In high geographical latitudes or mountainous regions, where snow precipitations are frequent, the gauges are additionally equipped with a heating system to melt the snow and/or a wind shield to reduce the aerodynamic measurement errors as described in the following paragraphs.

Traditionally, the collected water is registered on a daily basis by a professional or volunteer observer. At certain stations, the gauges are equipped with an automatic recording system. Until the 1980s, only mechanical systems were used. Tables or paper scripts have been sent to the network operators for further use or digitisation. Intense quality control of the recorded data is an important issue [01Rud]. Beginning with 1980, the number of automatic gauges equipped with electronic recording and data transmission

facilities is rapidly increasing. The advantages of the automatic gauges are the real-time availability of digital data and the high temporal resolution (precipitation rates by minute). The disadvantage is the – in many cases – lower accuracy of measuring of climatic precipitation amounts due to larger systematic measuring errors.

While precipitation data resulting from numerical models or remote-sensing by weather radars and satellites generally represent area-averages on grid boxes gauge measurements are purely local. Therefore, gauge-observed data need to be transferred to corresponding grid boxes in order to compare or merge the data supplied by the different techniques. Commonly, the gauge data are transferred to maps or gridded data sets by manual (history) or objective analysis (state of the art). The accuracy of the resulting area-means depends on the density of observation, i.e. on the number of stations in the data base. In large parts, the total analysis error consists of the sampling error. The following two sections describe first the systematic gauge measuring error and secondly the interpolation of gauge data and its sampling error.

11.2.1 The systematic gauge measurement error

Although the analysis of precipitation gauge data is the ultimate method to determine the surface ground truth, the gauge measurements include a series of errors leading as a rule to an underestimation of the true precipitation. The main components of this systematic measurement error are losses due to wind field deformation above the gauge orifice (2-10% for liquid and 10-50% for solid precipitation), losses from wetting on internal walls of the collector and in the container (2-10%) and losses due to evaporation from the container (0-4%). Other sources of error are splash-in and splash-out as well as blowing and drifting snow. Except for the latter, it is possible to correct precipitation gauge measurements for systematic measurement errors [86Sev].

Operational correction procedures apply pre-defined correction functions providing the catch ratio (CR) or the correction factor (CF) of a specific gauge type with respect of relevant meteorological conditions (precipitation type, wind speed, air temperature) during the observed precipitation event. The correction functions are determined by comparisons of national gauges with international reference gauges [98Goo]. The catch ratio is defined by the relation of measured and reference precipitation ($CR = P_m/P_r$) and is related to the correction factor by $CR = 1/CF$.

Fig. 11.3, left, shows the catch ratio of dry snow for the Hellmann, the Tretjakov and the Nipher precipitation gauge as function of wind speed. As a result of the deformation of the wind fields above the gauge orifice the catch ratio of snow flakes decreases with increasing wind speed. For rainfall, the aerodynamic error is smaller but depends on the drop size distribution. Fig. 11.3, right, depicts that the CF is much higher for solid than for liquid precipitation. Precipitation gauges equipped with a wind shield are able to reduce the wind-induced error.

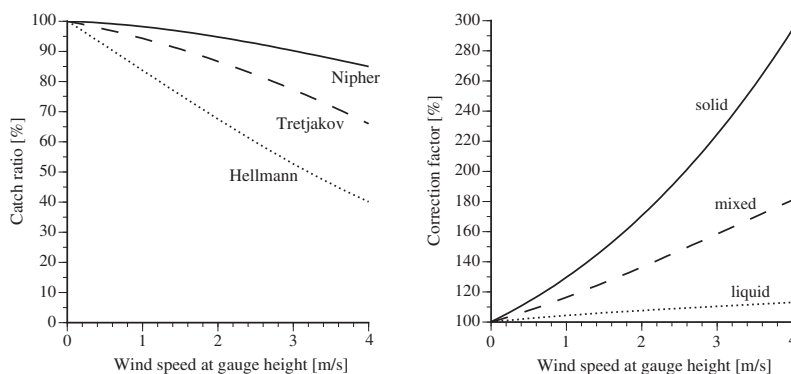


Fig. 11.3 Common depictions of the systematic measuring error: Typical functions of catch ratio of dry snow vs. wind speed for selected gauges (left) and correction factors for the unshielded Hellmann gauge vs. wind speed for different precipitation types (right), both after [98Goo].

Basis for assessment of the systematic gauge errors and development of correction functions are instrument comparison studies. Two types of reference gauges have been used in the WMO Precipitation Measurement Programme, the Double Fence International Reference (DFIR) gauge and the ground level pit gauge [98Goo]. These reference gauges are operated in a research mode at several sites, e.g. at high

latitudes in Canada, Russia, Alaska, but also in Switzerland, Croatia and Germany. At these sites, observations from various standard gauges are compared to reference measurements with respect to simultaneously observed meteorological conditions, i.e. air temperature, humidity, radiation, wind, and precipitation type. Generally, the aerodynamic correction factor of a specific gauge depends on the wind speed, the size of rain drops and the crystal structure of snow flakes. The total *CF* considers additionally the much smaller losses due to evaporation and wetting.

So far two correction procedures have been applied to global data sets. The first application is based on the long-term mean monthly correction factors (climatological corrections) described by Legates and Willmott [90Leg] and operationally applied to the GPCP data sets [01Rud]. The second, more realistic but not yet operational method, applies on-event calculated *CF*s to daily precipitation data transmitted via GTS ([99Rub] and [01Ung]). Fig. 11.4, for example, depicts the annual cycle of both, the climatological and the on-event *CF*s for the GEWEX regional experiments. These comprise the Baltic Sea Experiment (BALTEX, longitude/latitude = 9°E to 35°E / 50°N to 71°N), the GEWEX Continental-Scale International Project (GCIP, 115°W to 70°W / 29°N to 50°N), the GEWEX Asian Monsoon Experiment (GAME, 95°E to 122°E / 5°N to 35°N), the Large-Scale Biosphere-Atmosphere Experiment in Amazonian Basin (LBA, 78°W to 33°W / 20°S to 5°N) and the Mackenzie GEWEX Study (MAGS, not considered here). The corrections for BALTEX and GCIP rain gauges during the winter months are about 20-60 % (corresponding to the regional average snowfall fraction), while liquid precipitation measurements have been corrected by less than 10%. The corrections are significantly lower in the tropical regions of GAME (5-10%) and LBA (3-5%).

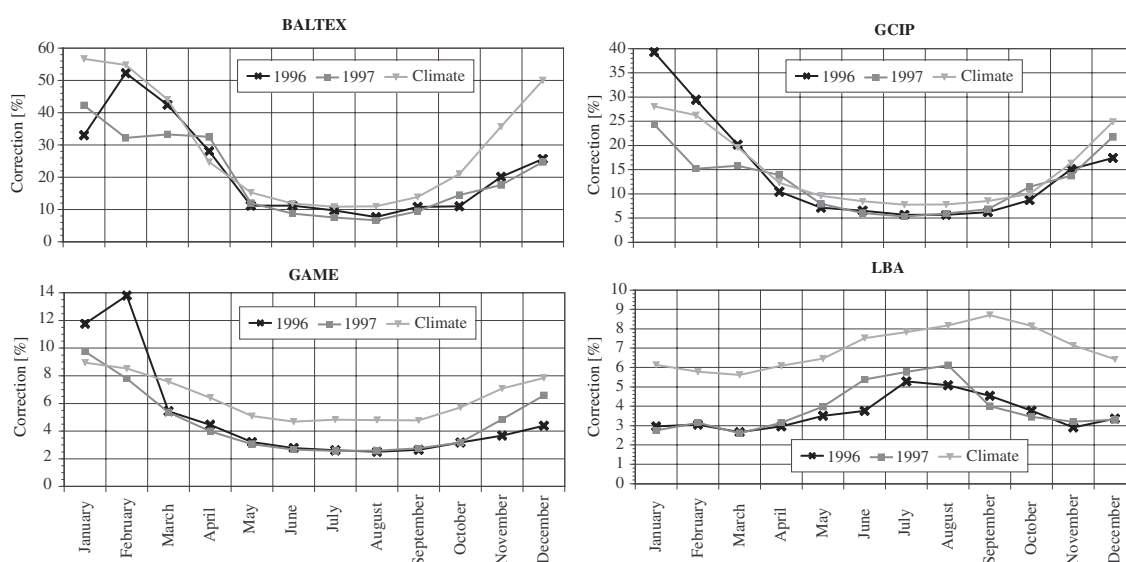


Fig. 11.4 Relative correction, *CF*-100, averaged over the GEWEX model domains BALTEX, GCIP, GAME and LBA. The *CF*s for 1996 and 1997 are based on the on-event correction model applied to daily precipitation measurements [01Ung]. The climatological *CF*s have been calculated by Legates and Willmott [90Leg].

The systematic error of Arctic precipitation measurements has been investigated by Førland and Hanssen-Bauer [00Før]. They found that the true precipitation in the Arctic is more than 50% higher than the measured value, due to the substantial under-catch of precipitation gauges during solid precipitation, frequent light rainfall events or windy conditions.

11.2.2 The calculation of areal mean precipitation and sampling error

Precipitation fields are not continuous in space and time. In order to create maps or gridded data sets, the gauge measurements have to be interpolated onto a regular grid. For global climate analysis, a system of grid points or boxes of equidistant geographical latitude and longitude is commonly used.

For the spatial analysis of irregularly distributed precipitation data, many methods have been proposed and applied to rainfall fields. One of the earliest methods applied in hydrology is based on so-called Thiessen polygons [11Thi]. In this method the irregularly distributed stations are assigned weights according to the area proportion they represent. The vertices of the polygon are constructed by the centres of the connecting lines of the station to its neighbour stations. Interpolation methods frequently used are based on the inverse distance weighting scheme (e.g. 64Bar, 59Cre). Here all stations located within a given radius are assigned weights according to their distance from the central point of a grid-box. Empirical methods complement the inverse distance weighting by directional grouping of stations [84She], by exclusion of stations if located in the shadow of nearer stations or by other empirical relations with respect of orography [94Dal]. Statistical interpolation methods apply variograms [51Kri] or spatial correlation functions [87Thi] instead of empirical distance weighting functions. Moreover, they consider also the spatial distribution of the stations to estimate a least square fit. These methods are optimal in a statistical sense and known as “kriging” or optimum interpolation. For applications of statistical interpolation methods to areal precipitation estimation see e.g. [01Rub1].

In order to numerically analyse the spatial distribution of precipitation, the observed data from the irregularly distributed stations are interpolated to the grid points of a geographic regular network. If one deals with area-related mean precipitation, e.g. river basins, country terrain or large-scale grid boxes, the area-mean can be calculated from the grid points included in the considered area.

The accuracy of gridded precipitation data depends most of all on the relation of the data density to the variability in the spatial distribution ([85WMO], [94Rud]). In other words, the sampling error of the analysis increases with decreasing station density, decreasing size of the grid box (area) and decreasing spatial correlation of precipitation measurements (decorrelation distance). The latter depends on the precipitation variability caused by the processes typically for specific climate regions and seasons as well as on the accumulation period (e.g. daily, weekly, monthly). In general, the correlation of observations from neighboured stations decreases with the station distance. Objective statistical methods are applicable best for dense networks which achieve on average correlation coefficients of not less than 0.5. The spatial variability of precipitation is rather large: Even for monthly precipitation totals the correlation coefficient falls below 0.5 within distances of 50 to 100 km [95Rud]. Therefore, for larger inter-station distances typical for global data sets, the application of a statistical method (kriging or optimum interpolation) is no advantage versus the use of empirical methods [89Bus].

One exemplary study on the sampling error depicts the influence of the number of stations per grid-box, the accumulation period (daily, weekly, monthly) and the seasonal variability (summer for dominance of convective rainfall, winter for more stratiform precipitation). The data used have been observed in Texas, and the investigation area of 56,000 km² approximately corresponds to an area of a grid box of 2.5° by 2.5° latitude/longitude in the mid latitudes. The results listed in Table 11.3 indicate that – for example – data from 10 stations (winter season) up to 16 stations (summer season) are required in order to calculate the box-mean of monthly precipitation with an accuracy of at least 10%.

The GPCC has calculated the sampling error of monthly precipitation as a function of the number of stations for different climatic zones by using data from very dense gauge networks of Australia, Canada, Finland, Germany, North and South USA [95Rud]. Based on statistical evaluation of the sampling errors compared to the regional variability of monthly precipitation, the following functional relationship between the relative sampling error (*RSE*), the relative standard deviation (*RSD*) of precipitation observed in the considered region and the number of gauges (*N*) has been applied [94Rud]:

$$RSE = c + a RSD N^{-b}$$

The constants have been calculated by regression analyses to $a = 0.865$, $b = 0.555$ and $c = 0.370$ (applicable to monthly precipitation).

Table 11.3 Empirically estimated sampling errors for daily, weekly and monthly precipitation totals in summer (JJA) and winter season (DJF) as function of the number of gauges in the sampling area of 56,000 km² after [85WMO]. Units in %.

Number of gauges per grid area		4	6	8	10	12	14	16	18	20	22	24
<u>Summer</u> (Texas)	daily	76	58	50	45	41	38	35	33	31	29	27
	weekly	44	33	26	24	21	18	17	15	14	13	12
	monthly	34	24	19	16	14	12	10	9	7	6	5
<u>Winter</u> (Texas)	daily	46	36	31	28	26	24	23	21	20	19	18
	weekly	24	21	17	15	13	12	10	9	7	6	5
	monthly	17	13	11	9	7	6	5	4	4	3	3

In recent years, various gridded data sets for the global land-surface precipitation became available. Two climatologies covering the entire 20th century by time-series of monthly precipitation have been published: New et al. (2001) used the collection of historical climate data of the Climate Research Unit, University of East Anglia in Norwich, UK (CRU), and the data set of [02Che] is based on the so-called Global Historical Climatology Network of the National Climate Data Center in Asheville, USA (GHCN). There exists another global climate data collection which has been compiled by the United Nations Food and Agricultural Organisation in Rome, Italy (FAO). So far, a gridded precipitation product derived from this data set has not yet been published. The Global Precipitation Climatology Centre (GPCC), operated by the German Weather Service (Deutscher Wetterdienst) in Offenbach, provides two different gridded data sets. The first is the so-called GPCC Monitoring Product (GPCC-Mon, 1986 to present), based on real-time available observations from 6,000-7,000 stations; the second is the GPCC Full Data Product (GPCC-Full, 1951 to present) including a larger number of stations (about 40,000 for 1986-1989, decreasing to about 20,000 for 2000). The additional data in GPCC-Full, provided by 173 countries, are delivered with a large time-delay [01Rud]. Table 11.4 presents the annual data coverage for the data bases in the period 1991 to 1995.

Table 11.4 Total period covered by data, rounded maximum number of stations for the best covered year in the time-series, and number of stations with monthly precipitation data for the individual years of the period 1991 to 1995 for the historical data sets of CRU, FAO and GHCN versus the recent data collections GPCC-Mon and GPCC-Full.

Data set	total period	maximum/ best year	1991	1992	1993	1994	1995
CRU	1700-2000	9,300/1970	3,941	3,759	3,063	2,777	1,348
FAO	1800-2000	10,700/1970	5,597	4,920	4,294	3,397	3,241
GHCN	1800-2000	14,700/1970	5,056	2,883	2,641	2,088	1,748
GPCC-Mon	1986-present	6,900/2001	5,963	5,653	5,968	6,002	5,755
GPCC-Full	1986-2000	37,500/1987	35,985	33,503	32,191	29,644	28,453

With respect of the observational data base (cf. Figure 11.2) and the resulting sampling error, the GPCC products are available in different spatial resolutions: 2.5° and 1° for the near real-time monitoring analysis and 2.5°, 1° and 0.5° for the Full Data Product [01Rud]. The user should consider the relation of the data base's number of stations and the spatial resolution with regard to the sampling error. The land-surface without Antarctica consists of about 3,000 boxes of 2.5° grid size, 20,000 boxes of 1° grid size, and 80,000 boxes of 0.5° grid size. As interpolation method SPHEREMAP is used, which is based on Shepard's interpolation scheme [85Wil]. The sampling error of the GPCC-Full is typically 3-15% for dense gauged areas (more than 10 gauges per 2.5° grid-box) and 15-100% for sparse gauged regions (less than 3 gauges).

The mean annual precipitation 1991 to 1995 depicted in Fig. 11.5 has been accumulated from the monthly fields of GPCC-Full. The annual precipitation values over land areas range from nearly 0 mm/d in the driest deserts of the world (e.g. Sahara in North Africa, Najd in Saudi Arabia, Atacama in Chile or Namib in Namibia), 0.2 mm/d in the Central Antarctic to more than 20 mm/d in the tropical rain forests. Typical precipitation values in the mid-latitudes of the Northern Hemisphere are 1 to 3 mm/d.

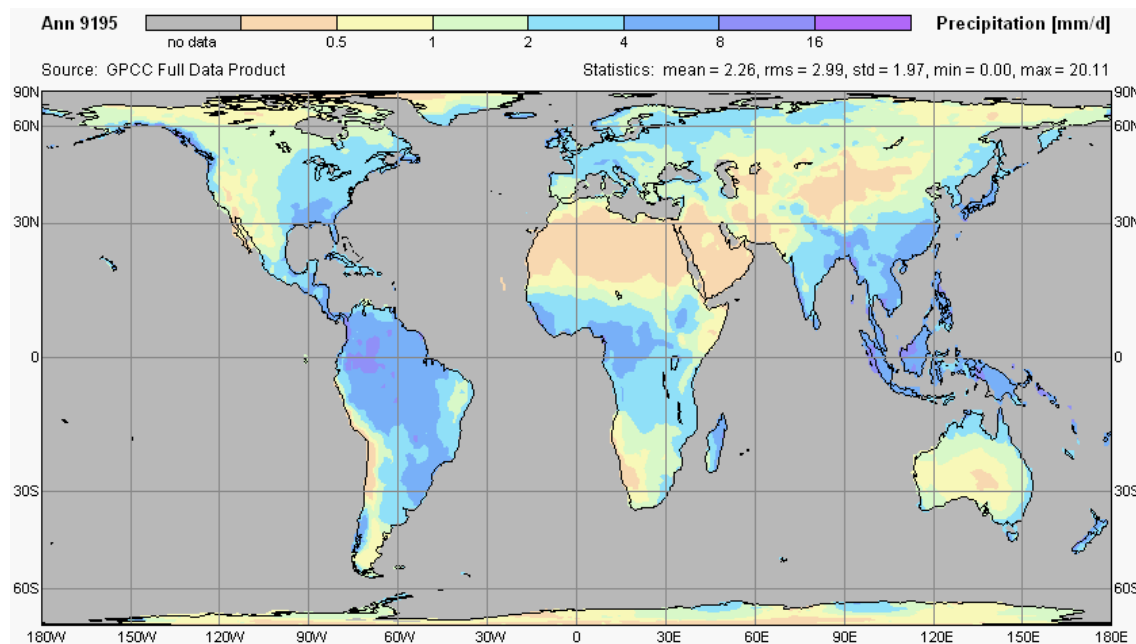


Fig. 11.5 Mean annual land precipitation from GPCC-Full for the period 1991-1995.

A comparison of GPCC-Full (Fig. 11.5) with the satellite-gauge combination GPCP-V2 (Fig. 17.121) shows differences on regional scale. This has two reasons. Firstly, the original resolution of the GPCP-V2 product is 2.5° resulting in a much smoother field without the extremes depicted in the 1° grid of GPCC-Full. Secondly, the GPCP-V2 product includes gauge observations from only 6,000 stations. With respect of the data base compared to other gauge-based products (c.f. Table 11.4), it is highly recommended to choose GPCC's Full Data gauge-based analyses in the optional 1° resolution which is the best compromise of sampling rate and spatial resolution, especially for the period 1991-1995 and in general for continental or regional studies.

11.3 Ground-based remote sensing: Precipitation radar networks

Quantitative precipitation estimates from ground-based weather radar networks associated with precipitation climatology are of increasing relevance. Early precipitation observations with radar have been made in the years 1940/41 while radar technology was developed during World War II in the United Kingdom [90Atl]. After computer power and telecommunication networks became available in the 1990s the first radar sites have been integrated to national networks. Today the entire region of both the European Union and the United States of America are covered by weather radar networks. While the United States operate the Next Generation Doppler Weather Radar, NEXRAD [00Ser], each of the European countries operates its own radar network [90Col]. Additionally, some of the national radar networks contribute to international networks, e.g. the Central European radar network (CERAD, see Fig. 11.6) or the Baltic radar network (BALTRAD).

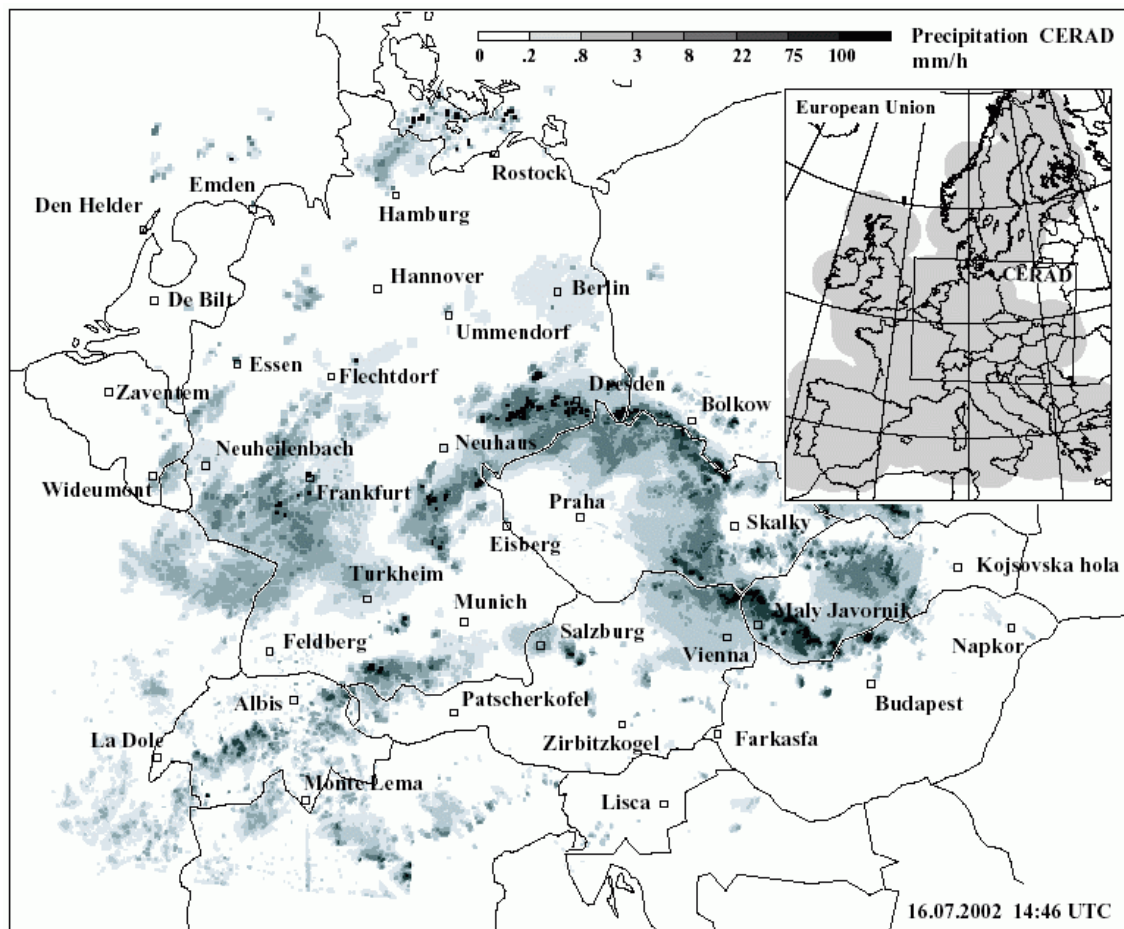


Fig. 11.6 Central European Radar network (CERAD) consisting of 38 single weather radar sites in Austria, Belgium, Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia, Switzerland and The Netherlands. CERAD provides half hourly precipitation fields with 4×4 km spatial resolution. The European Union and forthcoming member states operate a total number of 134 weather radar sites as depicted in the upper right corner scheme.

Operational rainfall products from weather radar networks provide areal precipitation accumulated between 10 min (BALTRAD) and 1 h (NEXRAD) with a spatial resolution of 2-4 km. Thus, these radar products have a significantly higher spatio-temporal resolution than precipitation fields analysed from gauges or satellites, but don't cover the entire globe. Similar to precipitation products derived from gauge networks radar products are basically restricted to land areas. An advantage of precipitation estimated by radar is that semi-enclosed seas may be covered, e.g. the Baltic Sea is completely covered by BALTRAD [01Rut]. The only possibility to observe precipitation over the world oceans however is by means of satellites (see section 11.4).

Limitations of quantitative precipitation observation by radar

Radar images have been traditionally interpreted by a forecaster, who applies his expert knowledge for quantitative conclusions on precipitation events such as the movement of convective cells. The generation of climatologic data sets on continental or global scales however, demands an automatic data processing including the handling of typical radar errors. So far the problem of an automatic reduction of the various radar errors has not been solved adequately. Problems associated with radar characteristics are for example spurious echoes (non-meteorological echoes from ships, aircraft, birds and insects, or reflections caused by the technique of the radar equipment), anomalous propagation (increase in ground clutter observation due to the refraction of the radar beam within an inversion layer), shielding of precipitation by mountains (for radar sites in the European Alps typically less than 50% of all pulse volumes are

completely visible), and growth or evaporation of precipitation below the beam (e.g. evaporation in the dry air below the level of the beam lead to an overestimation of the rainfall rate).

Furthermore, precipitation fields derived from radar networks are not homogenous. Attenuation of the radar beam by atmospheric gases and precipitation itself as well as differences in the radar equipment produce jumps in the precipitation amounts at the boundaries of measurements from single radar sites. Therefore, precipitation fields observed by radar networks necessarily have to be calibrated with ground truth data from precipitation gauge networks.

11.4 Space-borne remote sensing: Satellite observations of precipitation

Dense ground-based measurements as needed to calculate areal precipitation climatologies are limited to well-developed countries and regions. This limitation makes satellite remote sensing of precipitation indispensable, especially over the vast oceanic regions. Global precipitation estimates from satellite observations are available since the late 1970s and are based on the radiative intensities emitted or reflected by cloud and precipitating hydrometeors. It is distinguished between radiometer measurements with visible, infrared and microwave wavelengths.

Two different satellite systems are available for precipitation observation from space: first the meteorological geostationary satellites located in 36,000 km altitude (similar to the telecommunication satellites), and second the low level polar orbiting satellites of the former US Defence Meteorological Satellite Program (DMSP). They carry principally different instruments and complement each other by their specific advantages.

The system of five geostationary satellites (METEOSAT positioned at 0° longitude, GOES-East at 75°W, GOES-West at 135°W, GMS at 140°E and a second METEOSAT at 63°E) deliver a full area-coverage of infrared radiation observations of a high spatial (8 km) and temporal (30 min) resolution in the belt between 65°S and 65°N. As described in the next section, precipitation can empirically be estimated from infrared images in the belt 40°S and 40°N with some reservations.

The polar orbiting DMSP satellites carry the Special Sensor Microwave / Imager (SSM/I), providing passive radiation measurements in seven channels, 19.35 GHz h and v, 22.235 GHz v, 37.0 GHz h and v, and 85.5 GHz h and v (h = horizontal and v = vertical polarisation). SSM/I data are available since July 1987. Physical interaction with precipitation generation, which is more direct than the rainfall-infrared relation, is especially given in the channels of 19.35 GHz and 85.5 GHz. However, the spatial and temporal resolution of SSM/I is much lower with a pixel size of 69 km by 43 km for 19.35 GHz and 15 km by 13 km for 85.5 GHz [87Hol].

In recent years another more direct observation technique has been developed [98Kum]: The first satellite equipped with an active precipitation sensor (radar) has been launched in 1997 by the Tropical Rainfall Measuring Mission (TRMM). This satellite is also the first one being specially developed for precipitation observation and carries an advanced passive microwave imager (TMI) providing two more channels for 10 GHz with both horizontal and vertical polarisation. The microwave observations cover the tropical belt from 30°S to 30°N on a 3-hourly basis. The TRMM radar observes one individual surface segment only every 22 days, but delivers along its path vertical liquid water content profiles. The TRMM radar observation is used for calibration of the passive microwave based precipitation algorithms.

11.4.1 Determination of precipitation from observed infrared radiation data

The underlying principle for sensing precipitation by visible reflectivity is that reflectivity increases with cloud optical depth, which is approximately proportional to vertically integrated liquid water. Generally, clouds with higher values of liquid water are more reflective and are also more likely to be associated with precipitation. Due to the dependence on sunlight, the major shortcoming of visible measurements is the limitation to daylight hours.

For infrared wavelengths, the radiative intensity is usually expressed in terms of brightness temperature. It matches the measured intensity to Planck's blackbody function. The physical basis of infrared brightness temperature measurements related to precipitation is that cloud droplets are very absorptive in the thermal infrared spectrum. As a consequence, the cloud top may be viewed as the surface of a blackbody having the same temperature as the surrounding air. Therefore, cold infrared

brightness temperature is associated with the radiation source located in a higher atmospheric level, e.g. the existence of a precipitating deep convective system (Fig. 11.7 on the left).

Satellite retrieval techniques based on visible and infrared measurements are mainly based on statistical regression functions of surface observed precipitation (ground truth) against satellite observed radiation. This type of approach has mostly been applied to broadband outgoing long-wave radiation (OLR) observations from low-orbit satellites. Some of such techniques also consider rain types and storm development stages. Within the GPCP a technique known as GOES precipitation index (GPI) has been applied to the infrared measurements from geostationary satellites. The GPI relates the rain rate to area proportion covered by cold cloud tops, i.e. for a grid box the fraction of pixels with a brightness temperature lower than a given threshold, [79Ark] and [87Ark]. This method is applicable in the tropics only, where precipitation mostly is caused by large convective cloud systems. In the mid or high latitudes precipitation is often related to relative warm clouds while cold clouds frequently occur as cirrus not producing any rain or snowfall.

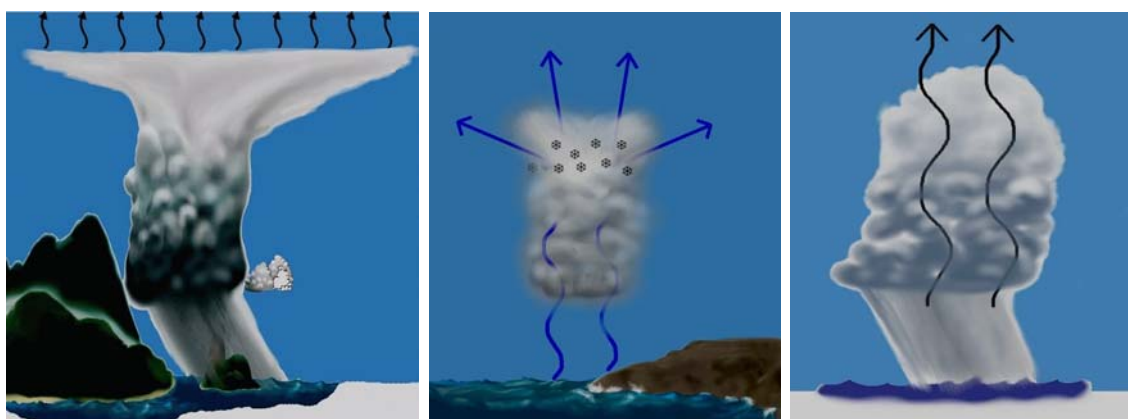


Fig. 11.7 Relationship between precipitating clouds and radiation. Left: Infrared brightness temperature from cold cloud tops is low compared to warm ground surface. Centre: Cloud droplets emit 19.35 GHz radiations rather than the ocean surface (not applicable over land). Right: 85.5 GHz radiation emitted by the surface is scattered by ice crystals in precipitating clouds.

11.4.2 Determination of precipitation from observed microwave radiation data

Microwave radiometers are passive sensors operating on low-orbit satellites. Microwave radiation can, opposite to visible and infrared radiation, penetrate through cloud and precipitation layers. Estimation of precipitation is based on emission or scattering of microwave radiation by water drops and ice particles in the atmosphere (Fig. 11.7). Microwave-based techniques rely on radiative transfer models or empirically derived algorithms.

The most physical approach is based on the emission of microwave radiation by water droplets of rain clouds. This emission can be measured from space in the channels 19.35 GHz and, weaker, 22.235 GHz (Fig. 11.7 on the right). Since the absorption by atmospheric water vapour is stronger in 22 GHz, the water vapour influence can be assessed by comparison of both channel measurements. Emission based techniques are limited to the application over ocean (the emissivity of oceanic water is lower than the emissivity of cloud drops). The high land surface emission spoils the evaluation of the drop signal.

Scattering-based techniques however, primarily operating with frequencies higher than 80 GHz, can be applied over both ocean and land surfaces. On the other hand they are less directly related to precipitation (Fig. 11.7 in the centre). Physical principle of scatter-based techniques is the scattering of 85 GHz radiation disseminated from the Earth's surface (both land and ocean) by ice particles in the atmosphere contributing to the physical process of precipitation generation (Fig. 11.7 in the centre). Thus the scatter signal is closely related to the precipitation rate. Scattering-based techniques fail to work for rain associated with shallow cloud-layers, because of lack of ice scattering. Emission-based techniques may fail sometimes as well. For example precipitation from deep cloud-layers cannot be determined

correctly because brightness temperature saturates. To overcome these shortcomings, combined emission and scattering-based algorithms have been developed.

Geographically the application of SSM/I is limited to latitudes up to about 70° in summer and about 55° in winter, due to the disturbance of the precipitation signal by surface snow or ice cover. A suitable basis for empirical precipitation estimation in high latitudes is the application of vertical water vapour profiles derived from TOVS observations (TIROS Operational Vertical Sounder, TIROS: Television and Infrared Observation Satellite; [97Sus]).

SSM/I-based methods are mostly realised by empirical or statistical single-channel signal relations to precipitation as the techniques of [97Fer] or [91Wil]. More realistic but very time-consuming in application are numerical models which simulate the cloud dynamics, the precipitation generation processes and the radiation transfer on a physical basis ([94Kum], [94Sim]). An empirical multi-channel model, for example, has been published by [93Bau]. All of these techniques include components, which require calibration or validation with ground truth data from in situ gauge measurements.

Two more satellite-based precipitation products, which are not considered in the comparison presented here, need to be mentioned: The Microwave Sensor Unit (MSU) carried by NOAA polar orbiting satellites provide microwave observations in three channels between 50 GHz and 55 GHz. The brightness temperatures have been related to oceanic precipitation on a monthly basis, using measurements from coastal and island stations [93Spe]. The results are very coarse. They are used, however, as a substitute for the period before SSM/I became available (January 1979 until June 1987).

Infrared GPI data have been archived since 1986. For earlier years from 1979 onwards, precipitation is estimated by application of a regression analysis versus outgoing longwave radiation observations [98Xie].

11.4.3 Comparison of various satellite-based precipitation estimates

The comparison of zonal means (Table 11.5) depicts that the satellite-based precipitation estimates differ substantially even for large-scale averages. Regionally, the products vary in a wider range than given in the summary of Table 11.5. The following paragraphs present some comments on the individual products, in order to rate the differences and their suitability:

- The IR-based Precipitation Index GPI overestimates rainfall averaged over the total tropical land surface. However, there are some regions, mainly the east coast of the continents, where GPI precipitation is too low compared to in situ observations [96Rud]. In the tropics, the GPI indicates too high precipitation compared with SSM/I emission over ocean and in particular with GPCC-Full over land. The reason is that some precipitation being generated in the cloud does not reach the ground.
- Although the emission-based techniques deliver the best precipitation estimates over ocean, the measured 19 GHz radiation can be contaminated by drifting sea ice. Precipitation from individual convective clouds or scattered groups of them may not be visible in the measured radiation [03Kle], if they cover a small fraction only of the beam cross cut.
- The precipitation signal in the 85 GHz observations is disturbed by snow or ice cover of the land surface. From this, precipitation cannot be estimated in the high latitudes depending on the snow and ice coverage. Therefore, in the SSM/I 85 GHz precipitation annual zonal results (Tab. 11.5) mainly winter observations are missing in the latitude belt 50° to 70°. So these results are not comparable to the other complete products in this belt. This 85 GHz channel delivers the only SSM/I-based precipitation estimates over land which are, however, less reliable in higher latitudes and not useable in the polar regions. Over ocean, SSM/I 85 GHz delivers less precipitation than the preferable 19 GHz emission-based technique.
- The TIROS Operational Vertical Sounder (TOVS) is operated on polar orbiting NIMBUS satellites and delivers vertical profiles of temperature, humidity and liquid water content [97Sus]. The empirical relation to precipitation has been fitted to higher level estimates, in particular to SSM/I results, and are the only available source for the high latitudes.
- The precipitation estimates from HOAPS (Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data, [02Jos]) are based on combination emission and scatter effects and use of all SSM/I channels. However, the data set version 1, being available so far, shows some inhomogeneities, due to

the temporal failure of one of the channels. A revised version 2 is expected to be published soon and will be a significant contribution to future precipitation estimates.

- The so-called GPCP multi-satellite product is compiled from following sources: for the tropics, GPI infrared based precipitation deliver the highest temporal and spatial resolution, but the precipitation level is adjusted to SSM/I-based estimates. For mid latitudes SSM/I-based products are used, 19 GHz over ocean and 85 GHz over land surface. TOVS-based estimates supply data for the high latitudes.

Table 11.5 Zonal distribution of mean annual precipitation from various satellite-based estimates over land-surface (Infrared GPI, SSM/I 85 GHz, TOVS and GPCP multisat) and over oceans (Infrared GPI, SSM/I 85 GHz, SSM/I 19 GHz, HOAPS V1, TOVS and GPCP multisat), for the period 1991-1995. GPCC-Full serves as ground truth over land-surfaces. Numbers in brackets indicate that they do not represent the full area of the latitude belt. Units in mm/d.

	latitude	Infrared GPI	Scatter SSM/I 85	Emission SSM/I 19	HOAPS V1 SSM/I 19-85	TOVS	GPCP multisat	GPCC-Full in situ ref.
a) Land	90° to 70°	—	—	—	—	0.48	0.68	0.85
	70° to 50°	—	(2.26)	—	—	1.28	1.30	1.86
	50° to 30°	(3.51)	1.34	—	—	1.39	1.28	1.81
	30° to 10°	2.41	1.75	—	—	1.92	1.59	2.11
	10° to -10°	6.08	5.46	—	—	4.48	4.76	4.89
	-10° to -30°	2.93	2.74	—	—	1.77	2.37	2.55
	-30° to -50°	(2.64)	1.82	—	—	1.51	1.81	2.45
	-50° to -70°	—	(1.25)	—	—	1.09	1.26	1.93
b) Ocean	-70° to -90°	—	—	—	—	0.37	0.51	—
	90° to 70°	—	—	—	1.65	0.53	0.73	—
	70° to 50°	—	(1.52)	2.32)	2.22	3.42	3.00	—
	50° to 30°	(3.00)	2.56	3.54	2.57	3.47	3.36	—
	30° to 10°	2.58	2.20	2.41	2.06	2.54	2.34	—
	10° to -10°	4.77	4.15	4.44	3.57	4.13	4.16	—
	-10° to -30°	1.82	1.87	2.19	1.81	1.85	2.07	—
	-30° to -50°	(2.70)	1.90	2.57	1.86	2.91	2.79	—
	-50° to -70°	—	(0.73)	(1.65)	1.31	2.78	2.58	—
	-70° to -90°	—	—	—	—	0.79	1.10	—

11.5 Combination of satellite and in situ measured precipitation data

In order to combine various satellite and gauge data two tasks have to be finished: (a) the selection of primary satellite and gauge products out of all available versions, and (b) the definition of the merging technique itself. Especially for global precipitation climatology, complicating conditions are given by frequent changes of instruments and analysis techniques following the fast technical development. Limitations are given by the availability of basic satellite data from earlier years. Infrared observations have not been archived in full spatial and temporal resolution from the beginning due to limited storage capacity.

The choice of the primary components for merging is based on comparison studies for the variety of satellite precipitation estimates. For reference, ground truth data have been achieved from dense surface-based gauge networks, complemented by radar observations. The evaluation and decision respects not only the general statistical errors, but distinguishes regional conditions and the availability of the basic observational data. Within the framework of GPCP an Algorithm Intercomparison Programme has been performed with three regional projects for Japan, Western Europe and the tropical Pacific [94Ark], additionally an international Precipitation Intercomparison Programme delivered results independently from GPCP ([94Bar], [01Adl]).

The global precipitation maps and gridded data sets published within this book are based on the GPCP Satellite-Gauge Combined Data Set Version 2 (GPCP-V2, [03Adl]). The combination method has been developed jointly by the participants of the Global Precipitation Climatology Project ([97Huf]; [03Adl]).

This data set supplies global fields of monthly precipitation means on 2.5° grid boxes for the period January 1979 to near present. The general approach with GPCP's method is to combine the precipitation information available from each source into a final merged product, taking advantage of the strengths of

each data type and removing biases based on hierarchical relations in the stepwise approach. With respect of its lower value, the SSM/I-85 GHz scatter product is not included in GPCP-V2 over ocean.

The multi-satellite product described above is combined with GPCC's near real-time Monitoring Product (GPCC-Mon, cf. 11.2.2) in two steps: First it is adjusted to bias corrected gauge-based results from selected grid boxes being well-covered by gauges ("anchor points"). In the second step the adjusted multi-satellite product is merged with complete gauge-based gridded precipitation fields using weights representing the sampling error estimates for each of the two products.

Another widely used global monthly precipitation product is CMAP (Climate Prediction Center Merged Analysis of Precipitation [97Xie]). It is also widely used. It also includes GPCC-Mon as ground truth. The composition of the satellite component and the merging technique is different from GPCP-V2 in some details as the results are (more about this in section 11.6.2).

Since October 1996, GPCP provides a new daily precipitation product with 1° spatial resolution, called "GPCP-1DD" [01Huf]. For this reason it cannot be used for this book's joint observation period 1991-1995. The global fields of GPCP-1DD include SSM/I-based estimates from an advanced technique (GPROF, [94Kum]), 3-hourly infrared observations and TOVS data. The GPCP-1DD precipitation estimates are adjusted on a monthly basis to GPCP-V2, and comprise by this gauge observations. The GPCP-1DD has been validated over Central Europe by [01Rub2] and [02Rub]. Its major advantage is the original 1° spatial resolution. It performs well on average, but the daily results scatter considerably compared to high-resolution daily gauge-based analyses.

11.6 Spatial structure of global precipitation

The general spatial structure of the global precipitation is depicted in the chart section of this book (Chapter 17), complemented by numerous additional maps in the Annexes of this chapter on DVD. The GPCP-V2 product [03Adl] has been adopted for both the printed as well as the digital version of the maps. The digital data archive contains of GPCP-V2 in its downscaled version (1° by 1°) as a numerical gridded data sets as well as a series of maps in movie format. The GPCP-V2 product is accessible in its original resolution (2.5° by 2.5° latitude/longitude) for all months from January 1979 to present time from the World Data Centre A for Meteorology [04WDC].

Complementary data sets on DVD are monthly precipitation fields on 1° grid boxes for the global land surface (continents) from GPCC-Full based on about 30,000 gauge stations and for the oceans from the HOAPS V1 satellite-based precipitation estimates.

Additional maps are presented in the Annexes in pdf-format which can easily be printed. Annex 11-A1 includes annual and seasonal maps of precipitation and variance of precipitation for both periods 1991-1995 and 1981-2000, complemented by maps of the stochastic estimation error for two individual sample months. The arrangement of the maps supports a visual comparison of the spatial distribution for the two periods 1991-1995 and 1981-2000. In Annex 11-A2 a comparison of annual and seasonal precipitation maps derived from GPCC and HOAPS is presented. The maximum values from the original 1° data sets (GPCC and HOAPS) are higher compared to GPCP-V2 (of original 2.5° resolution) due to the smoothing of the field by averaging on coarser grid boxes. Additional annual precipitation and anomaly fields for El Niño and La Niña years are presented in Annex 11-A3.

11.6.1 Variability of annual and seasonal precipitation on global scale

The annual precipitation maps of both periods (Annex 11-A1) show similar spatial structures. The difference field of both maps, however, uncovers a spatial shift of the precipitation zones in the tropical pacific: compared to the 20 years period, 1991-1995 precipitation is higher in the north and lower in the south of the equator. This is a result of the two strong El Niño events in 1982/83 and 1997/98 included in the longer but not in the shorter period.

The annual and seasonal precipitation variance is calculated from the standard deviations of all GPCP-V2 monthly precipitation fields of the considered periods 1981-2000 and 1991-1995. The period 1981-2000 is preferable, because it comprises a larger number of months (60 months per season versus only 15

months for 1991-1995) in order to calculate a seasonal variance. The global means of the individual seasonal variances are in the range from 0.73 - 0.84 mm/d, while the mean annual variance is considerably larger with 1.61 mm/d. The reason for this is the movement of the Inter-Tropical Convergence Zone (ITCZ) during the annual cycle, which causes a very high temporal variance at a fixed location. Figure 11.8 shows the global distribution of the seasonal precipitation variance for June-July-August (JJA) of the period 1981-2000.

One special feature of the GPCP-V2 product is that each monthly gridded precipitation field is complemented by calculated stochastic estimation errors on the same grid. An example is given in Figure 11.9. The relation of the variance of the precipitation field and the estimation error is a measure for the suitability of the product to represent realistic temporal structures. A comparison of Figure 11.8 (JJA variance) and Figure 11.9 (July error) shows high variances and lower errors in the tropics but low variances and high errors in the high latitudes.

While the globally averaged error of 0.83 mm/d for July 1995 exceeds the corresponding mean temporal variance of 0.78 mm/d for the JJA seasons, the spatial maximum error is only 3.13 mm/d which is much smaller than the maximum variance of 5.71 mm/d. Table 11.6 summarises the overall statistical characteristics of 20 years mean precipitation and precipitation variance for the JJA and DJF seasons versus the stochastic estimation error for July and January 1995. The stochastic estimation error represents a combination of the sampling error of the gauge product, and the general and sampling errors of the satellite-based products included in GPCP-V2 [95Huf]. The error shows a very similar behaviour for both seasons. Again, the error has been estimated for each individual month and shows a very similar statistical behaviour for the two selected samples. It is important to note, that the stochastic estimation error is of the same order as the seasonal variability.

Seasonal or annual means have not been calculated. The variability for the year is larger than the variability for the individual seasons because the year includes the annual cycle. The annual cycle of precipitation is not discussed in this paper, because it is mostly characterised by specific regional conditions as monsoon systems combined with orographical effects, land-sea interactions and many other processes. In the tropics it is caused by the spatial shift of the ITCZ accompanied by high precipitation.

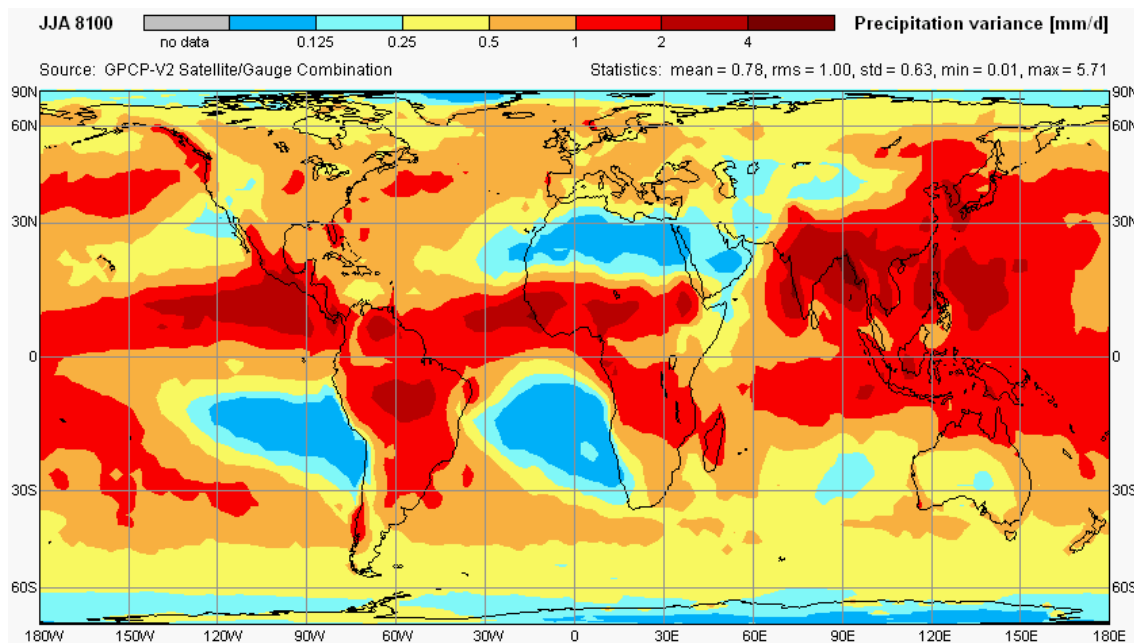


Fig. 11.8 Variance of GPCP-V2 monthly precipitation for the season June-July-August (JJA) in the period 1981-2000.

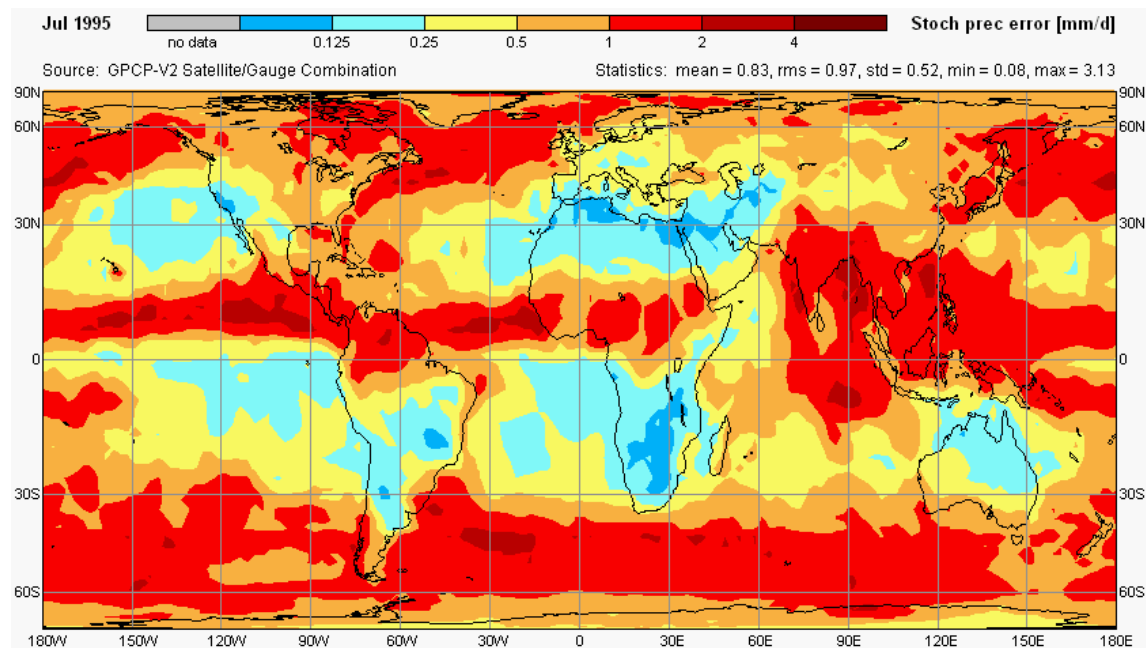


Fig. 11.9 Stochastic estimation error of GPCP-V2 monthly precipitation product for July 1995.

Table 11.6 Statistics (global mean, RMS difference, standard deviation, minimum and maximum) for selected GPCP-V2 fields: Mean precipitation and precipitation variance for the seasons JJA (northern summer, c.f. Fig. 11.8) and DJF (northern winter) as well as for the year (period 1981-2000), versus the stochastic estimation error for July 1995 (c.f. Fig. 11.9) and January 1995, respectively.

		global mean	RMS difference	Standard deviation	Minimum	Maximum
JJA 1981-2000	Precipitation	2.62	3.47	2.28	0.00	16.33
JJA 1981-2000	Variance	0.78	1.00	0.63	0.01	5.71
July 1995	Error	0.83	0.97	0.52	0.08	3.13
DJF 1981-2000	Precipitation	2.61	3.40	2.18	0.01	12.17
DJF 1981-2000	Variance	0.84	1.07	0.65	0.02	4.31
January 1995	Error	0.81	0.98	0.55	0.08	3.03
Annual 1981-2000	Precipitation	2.61	3.15	1.77	0.02	9.84
Annual 1981-2000	Variance	1.61	1.96	1.12	0.03	7.16

11.6.2 Zonal profiles

In order to prove the agreement between the different global precipitation estimates, zonal averages are compared in Table 11.7 for the two satellite-gauge combined products GPCP-V2 and CMAP as well as for ERA-40 model results, all for the period 1991-1995. As a reference GPCC-Full depicts our best knowledge of precipitation ground truth over the Earth's land areas. The overview is complemented by the two global long-term climatologies of [76Jae] and [90Leg].

Both combined products show zonal mean differences up to rounded 20%. CMAP shows higher precipitation over tropical ocean. This results from the adjustment of the satellite-based estimates for the entire tropical ocean using gauge measurements from atoll islands. GPCP has not done so, for these islands only represent a smaller area. These differences can be explained by the different analysis techniques applied. The observational products are still in the same range of agreement if the gauge analysis and the two climatologies are included in the comparison. However, the ERA-40 results (accumulated daily forecasts) show much larger deviations from observational products, in particular in

the tropical latitude belt. GPCP-V2 delivers higher precipitation for the latitude belt from 30° to 70°. Over land one reason is that CMAP does not include gauge corrections (c.f. section 11.2.1). Over ocean, CMAP includes both 19 GHz and 85 GHz data while GPCP-V2 only accepts the 19 GHz results which are assessed to be of higher quality (c.f. Table 11.5). The full global means of CMAP and GPCP-V2 are nearly identical. However, over land GPCC-Full, based on controlled and bias corrected gauge data, indicate precipitation being higher than both CMAP and GPCP-V2 for all latitude belts. The climatologies of [76Jae] and Legates and Willmott [90Leg] represent observations from the period of 1931-1960. The quality of the basic data is difficult to assess.

In general, the scattering of the observational products may represent the uncertainty in global precipitation estimation. The differences indicate that further research is needed in order to obtain a higher reliability and accuracy.

11.6.3 Anomalies of global precipitation (ENSO)

El Niño - Southern Oscillation (ENSO) considerably accounts for the inter-annual variability in global and hemispheric precipitation. ENSO explains about 38% of the inter-annual variance in globally averaged land precipitation and about 8% of the variability of global precipitation [01New]. It involves major shifts in both atmospheric pressure patterns and sea surface temperatures over large parts of the tropical Pacific and occurs every 2-7 years. Fig. 11.10 shows the seasonal global distribution of precipitation anomalies during the strong warm ENSO event 1997/98 (December to February).

Table 11.7 Zonal distribution of mean annual precipitation for the Earth's land-surface (a), the oceans (b) and the total globe (c) as calculated from GPCP-V2, CMAP and ERA-40 (period 1991-1995) and from two climatologies based on long-term means ([76Jae]; [90Leg]). GPCC-Full serves as ground truth over land-surfaces. Units in mm/d.

	latitude	GPCP-V2 sat-gauge	CMAP sat-gauge	ERA-40 model	GPCC-Full in situ reference	Jaeger climatology	Legates climatology
a) Land	90° to 70°	0.72	0.57	0.85	0.85	0.59	0.75
	70° to 50°	1.68	1.37	1.53	1.86	1.36	1.56
	50° to 30°	1.57	1.39	1.43	1.81	1.59	1.66
	30° to 10°	1.75	1.66	1.92	2.11	2.09	2.05
	10° to -10°	4.53	4.51	6.30	4.89	4.97	5.29
	-10° to -30°	2.23	2.14	2.38	2.55	2.51	2.53
	-30° to -50°	1.92	1.82	1.85	2.45	2.10	2.06
	-50° to -70°	1.24	0.92	1.49	1.93	1.54	2.97
	-70° to -90°	0.52	0.47	0.41	—	0.42	1.43
b) Ocean	90° to 70°	0.74	0.79	1.03		0.59	0.76
	70° to 50°	3.06	2.26	2.73		2.50	3.00
	50° to 30°	3.41	3.18	3.24		2.65	3.37
	30° to 10°	2.39	2.86	3.73		2.68	3.02
	10° to -10°	4.20	5.18	7.36		4.45	5.58
	-10° to -30°	2.10	2.41	2.75		2.37	3.23
	-30° to -50°	2.80	2.63	2.64		2.90	2.95
	-50° to -70°	2.58	1.91	2.44		2.46	2.96
	-70° to -90°	1.11	1.13	1.24		0.87	1.68
c) total	90° to 70°	0.73	0.71	0.97		0.59	0.75
	70° to 50°	2.11	1.65	1.91		1.72	2.02
	50° to 30°	2.47	2.28	2.32		2.11	2.50
	30° to 10°	2.17	2.44	3.11		2.47	2.68
	10° to -10°	4.29	5.01	7.09		4.58	5.51
	-10° to -30°	2.13	2.35	2.66		2.41	3.06
	-30° to -50°	2.72	2.56	2.57		2.83	2.88
	-50° to -70°	2.50	1.86	2.38		2.41	2.96
	-70° to -90°	0.67	0.64	0.62		0.54	1.50

Fig. 11.11 compares the Southern Oscillation Index (SOI) with time-series of monthly precipitation anomaly for selected regions. During all of the recent events in 1982/83, 1986/87, 1991/92 and 1997/98, precipitation is clearly higher than normal over the tropical Pacific and Northern Peru and lower than normal over the Indonesian “maritime continent” and the surrounding oceans. The precipitation signal is very strong for the two events with a longer lasting low and strong negative SOI (minimum lower than -3) with very high precipitation in the regions tropical Pacific and coast to western Andes of Peru, but also high precipitation for Argentina and Kenya. The Indonesian area drought also occurs during all the El Niño events. La Niña events are defined by positive SOI, which is also visible in precipitation by high values over Indonesia. A longitude/time cross section of tropical precipitation is additionally presented in Annex 11-A3.

All El Niño events had a major global impact. The 1982/83 event for example was associated with droughts in Australia, the Sub-Saharan Africa, Brazil and Central America (El Niño dry regimes). Typically, while in these regions El Niño causes droughts and bush fires, in other regions it causes floods which often trigger epidemics (El Niño wet regimes). In this context recent developments on El Niño-precipitation relationships [03Cur] as well as ENSO forecasts are of major importance in assisting the prediction of Malaria outbreaks.

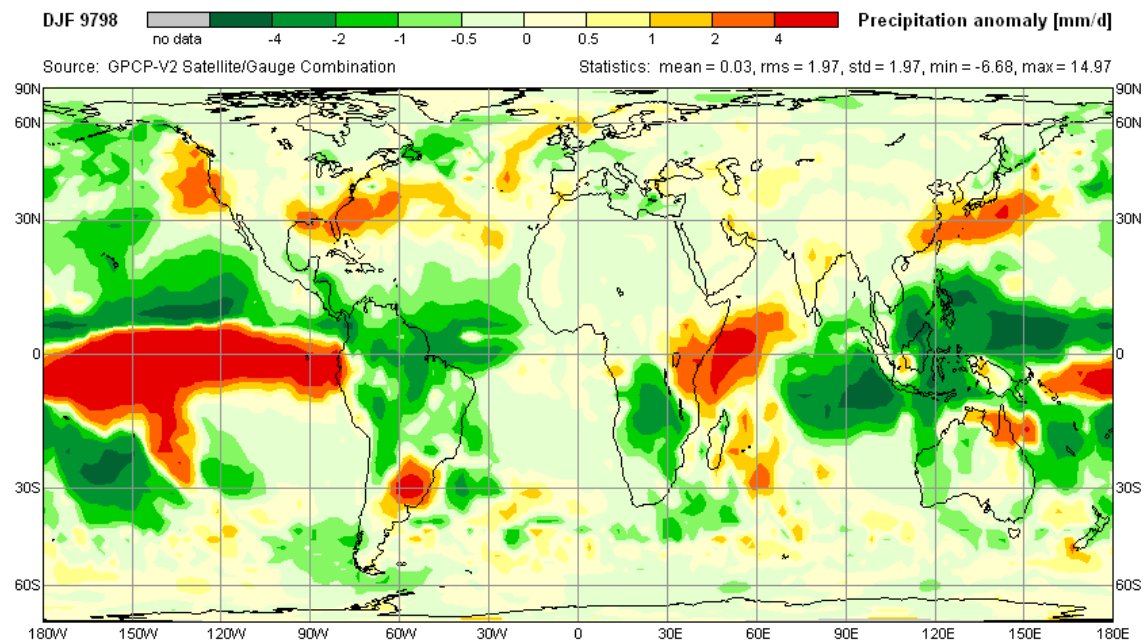


Fig. 11.10 Seasonal precipitation anomalies in mm/d for DJF 1997/98.

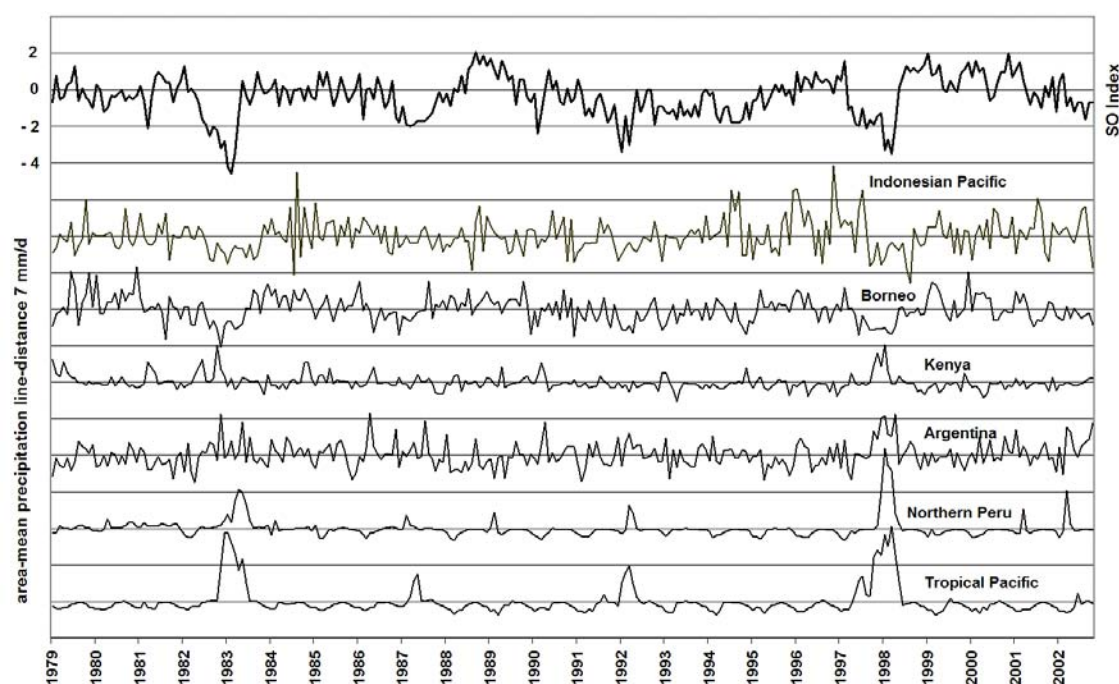


Fig. 11.11 Time series of the Southern Oscillation Index (SOI) and monthly precipitation anomalies for selected regions of the period 1980-2000. For each series of precipitation anomalies the base-line as well as the +7 mm/d and -7 mm/d line is given.

11.7 Global climate change and precipitation

Following the recent TA Report of the International Panel on Climate Change [01IPC], increasing global surface temperatures are very likely to lead to changes in precipitation and atmospheric moisture, due to changes in atmospheric circulation, a more active hydrological cycle, and increase in the water holding capacity throughout the atmosphere. However, the calculation of changes in global precipitation is a big challenge. According to the various limitations associated with precipitation measurements discussed in the sections 11.2 to 11.6 (different instruments and measuring techniques with high systematic measurement errors, sparse gauged areas, no sufficiently long satellite-based records and therefore no observations before 1979 over oceans) only for parts of the globe significant trends of precipitation may be estimated. Fig. 11.12 depicts the recent knowledge on the annual precipitation trend in the 20th century [01IPC]. The trends have been calculated for $5^\circ \times 5^\circ$ grid cells using rain gauge measurements of the period 1900 to 1999 that have been corrected for systematic errors. However, the global warming causes an increasing fraction of precipitation falling in liquid instead of solid phase which has not been considered by the correction procedure. The increase of the precipitation in the Northern Hemisphere is therefore likely to be lower by some percent than indicated in Fig. 11.12. A discussion on this topic focusing on Arctic trend analysis is given by Førland and Hanssen-Bauer [00Før].

Precipitation was increasing mostly in mid- and high latitudes in the Northern Hemisphere, but these increases vary spatially. For example, precipitation over the United States and Northern Europe has increased by 5-10%, whereas it decreases by the same amount over Southern Europe and the Mediterranean. A decreasing trend was also observed for the sub-tropics and tropics of the Northern Hemisphere (with marginal statistical significance) as well as for West Africa and the Sahara, where aridity continues since the 1960s. In Asia, the most remarkable feature of the global precipitation trend is an increase of the Monsoon rainfall in India by about 15%. On the Southern Hemisphere, annual total precipitation has increased over wide areas of Australia resulting in a significant increase of precipitation of about 10%. A similar increase has been analysed for Argentina, whereas at the Pacific Coast of South

America annual precipitation decreases. No trends have been analysed for the Amazonian region. Currently it is not possible to specify a global precipitation trend. For global land precipitation, however, about 2% increase since the beginning of the 20th century has been estimated by Hulme et al. [98Hul] and [01New].

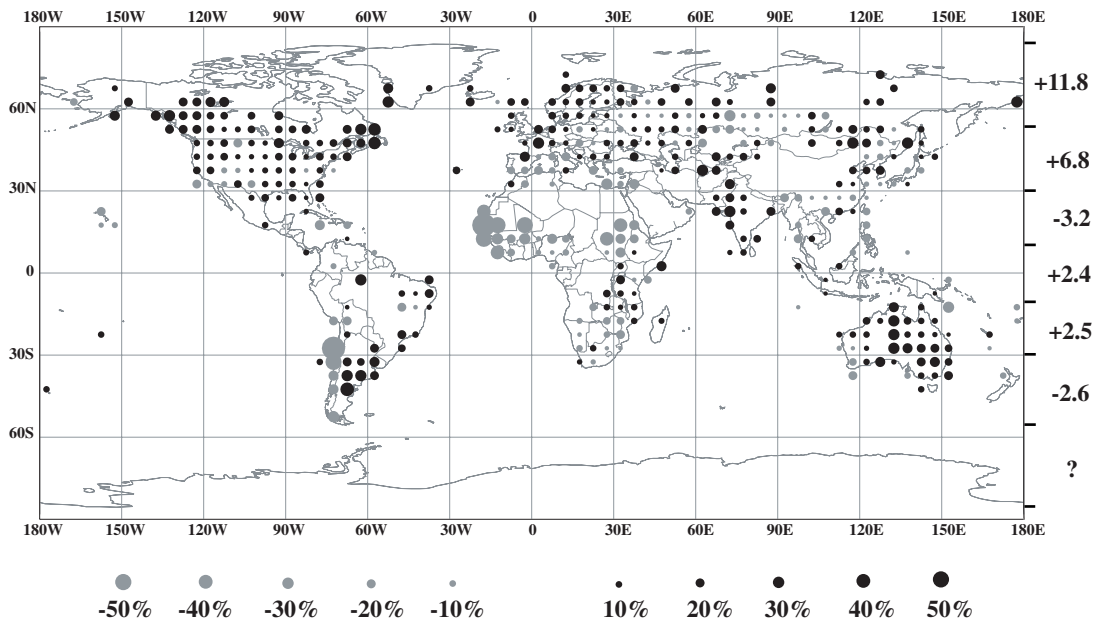


Fig. 11.12 Trend in annual precipitation in the 20th century after [01IPC]. Units in percent/century. Average significant trends (5% level) within 4 latitude bands are given as: +11.8% (85°N to 55°N), +6.8% (55°N to 30°N), -3.2% (30°N to 10°N) and +2.4% (10°N to 10°S). Note that the trends of +2.5% (10°S to 30°S) and -2.6% (30°S to 55°S) are not significant. No long-term observations are available for the Antarctic region.

11.8 Final remarks

During the last 20 years, a significant progress has been made in estimation of global precipitation. However, so far neither climate models nor observations can deliver digital global precipitation data with accuracy and spatial and temporal resolution as is required for hydrological and climate impact studies. The numbers for global precipitation given in this book are not the final numbers. They represent the best possible observation-based estimate which is available today. They may differ from numbers provided by other authors, e.g. from residuum values of atmospheric energy budgets. Users of gridded global precipitation data sets are recommended to consider the accuracy of the product used and pay attention to corresponding information as station density or analysis error estimates, if it is provided with the data.

The development of satellite-based observation techniques is still going on. A new improved version 2 of HOAPS just recently became available. The Global Precipitation Mission (GPM) is in its planning phase. Based on the experience from TRMM, two polar-orbiting radar satellites are scheduled. Six complementary satellites carrying advanced passive microwave scanners are planned in order to cover the diurnal cycle by totally eight global microwave images. Simultaneously, the collection of in situ observed precipitation data will be enhanced and the regional coverage by ground based radar networks will be improved as well.

Although in recent years visible progress took place in analysing global precipitation fields, it is even at present not possible to give a statement on realistic global precipitation trends. Firstly, the high spatial/temporal variability as well as the chaotic nature of the precipitation process itself makes it difficult to estimate a global trend. Secondly, measurement errors of operational gauges as well as interpolation and sampling errors of areal precipitation estimates lead to uncertainties in global precipitation fields that are of the order of the climate trend itself. Nevertheless, for the land areas

regional precipitation trends have been estimated from gauge observations as presented in Fig. 11.12 and by Schönwiese in chapter 15.

Climatological aspects to be investigated comprise the change of the precipitation variability, trend of the frequency and level of extreme precipitation events, all with respect of homogeneity and representativeness of the observed data. Related studies are currently worked out in the framework of CLIVAR supported by national (e.g. DEKLIM in Germany) and European programmes (EuroCLIVAR). In order to fulfil the researcher's request for long time-series of gridded precipitation data sets, the GPCC is going on to merge the historical data collections of CRU, FAO and GHCN with its own data collection from the recent years.

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<http://www.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html>

Overview of Annexes to Chapter 11

Annex 11-A1: Spatio-temporal distribution of global precipitation

This Annex includes additional global precipitation maps derived from the GPCP Version 2 Satellite-Gauge Combination (short: GPCP-V2). In particular, coloured maps of mean precipitation and of the variance of monthly precipitation are presented with a comparison of the two periods 1991-1995 (the common period of this book) and 1981-2000 (the longest multi-decade period being available from GPCP-V2 so far). Additionally, maps for the total stochastic error of the GPCP-V2 product are shown for two sample months. The Annex is complemented by maps showing the differences between GPCP-V2 versus CMAP and versus ERA-40.

Annex 11-A2: Complementary global precipitation products for the period 1991-1995

This Annex presents complementary gridded data sets, i.e. global terrestrial and oceanic precipitation maps for period 1991-1995. The terrestrial precipitation maps are derived from GPCC's Full Data Product (GPCC-Full), an analysis based on monthly precipitation observed at about 30,000 meteorological stations. The oceanic precipitation maps are provided by the HOAPS Version 1 Data Set (Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data, short: HOAPS V1) being based on SSM/I satellite observations. Both products are originally available on 1° latitude by 1° longitude spatial resolution.

Annex 11-A3: ENSO precipitation and anomalies

Complementary to section 11.6.3, the maps and diagrams of this Annex illustrate the global distribution of precipitation anomalies related to El Niño – Southern Oscillation (ENSO).

Annex 11-A1: Spatio-temporal distribution of global precipitation

This annex presents additional global maps derived from GPCP Satellite-Gauge Combination Version 2 Data Set (short: GPCP-V2). In particular it includes maps of mean precipitation as well as of the variance of monthly precipitation for the two different periods 1991-1995 (the common period of this book) and 1981-2000 (the longest multi-decade period being available from GPCP-V2) and in addition difference maps for the two periods. For comparison, two sample maps are given for the total stochastic error [mm/d] of estimation of monthly precipitation of the GPCP-V2 product.

Important note: The spatial resolution of the original GPCP Version 2 is 2.5° latitude by 2.5° longitude. For compatibility of all gridded data sets provided with this book, the GPCP Version 2 product has been down-scaled by interpolation to 1° latitude by 1° longitude grid boxes. Currently there is no satellite-gauge combined analysis of higher resolution available for the periods considered in this edition.

The annex is complemented by a comparison of GPCP-V2 versus two other global gridded data sets, CMAP and ERA-40.

List of content

For each page: mean value 1991-1995 on top; mean value 1981-2000 in centre; difference at bottom:

- 11.A1_01 GPCP-V2 mean annual precipitation [mm/d]
- 11.A1_02 GPCP-V2 mean DJF precipitation [mm/d]
- 11.A1_03 GPCP-V2 mean MAM precipitation [mm/d]
- 11.A1_04 GPCP-V2 mean JJA precipitation [mm/d]
- 11.A1_05 GPCP-V2 mean SON precipitation [mm/d]

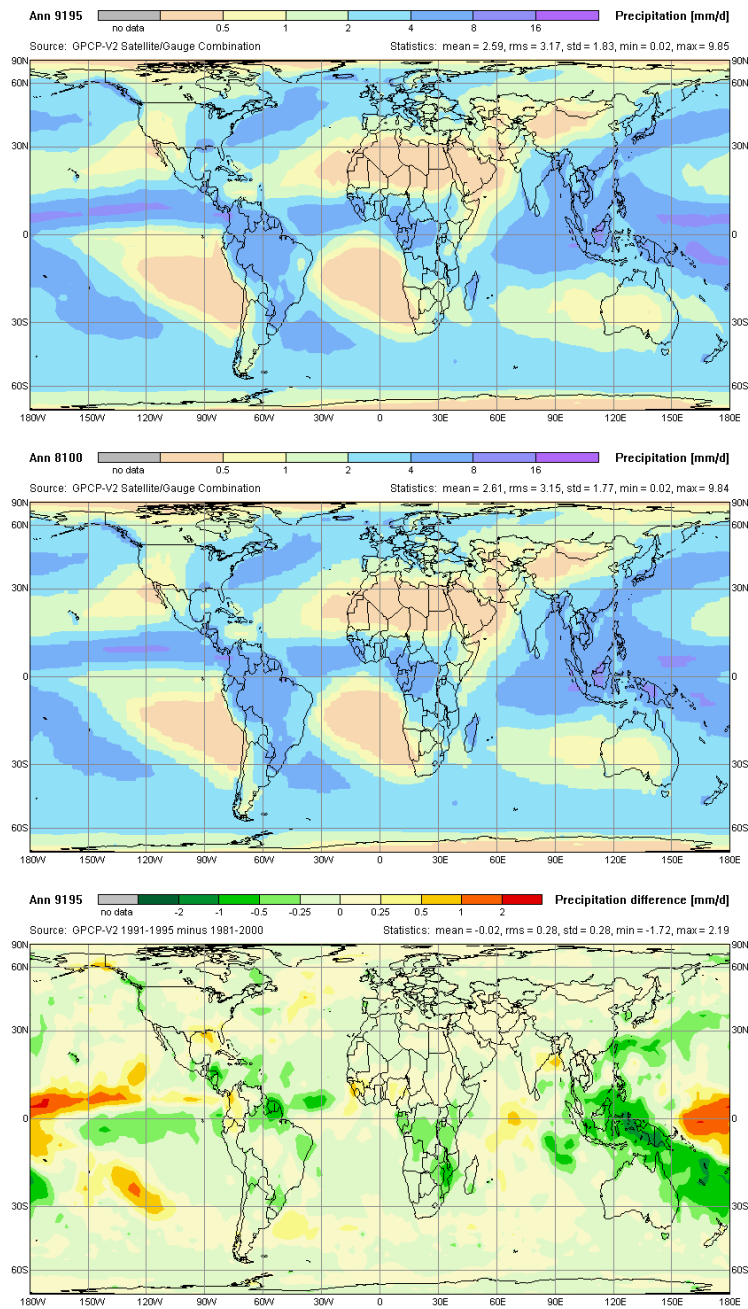
- 11.A1_06 GPCP-V2 mean annual variance of monthly precipitation [mm/d]
- 11.A1_07 GPCP-V2 mean DJF variance of monthly precipitation [mm/d]
- 11.A1_08 GPCP-V2 mean MAM variance of monthly precipitation [mm/d]
- 11.A1_09 GPCP-V2 mean JJA variance of monthly precipitation [mm/d]
- 11.A1_10 GPCP-V2 mean SON variance of monthly precipitation [mm/d]

- 11.A1_11 GPCP-V2 global distribution of the total stochastic error [mm/d] for two sample months
(on top: January 1995, at bottom: July 1995)

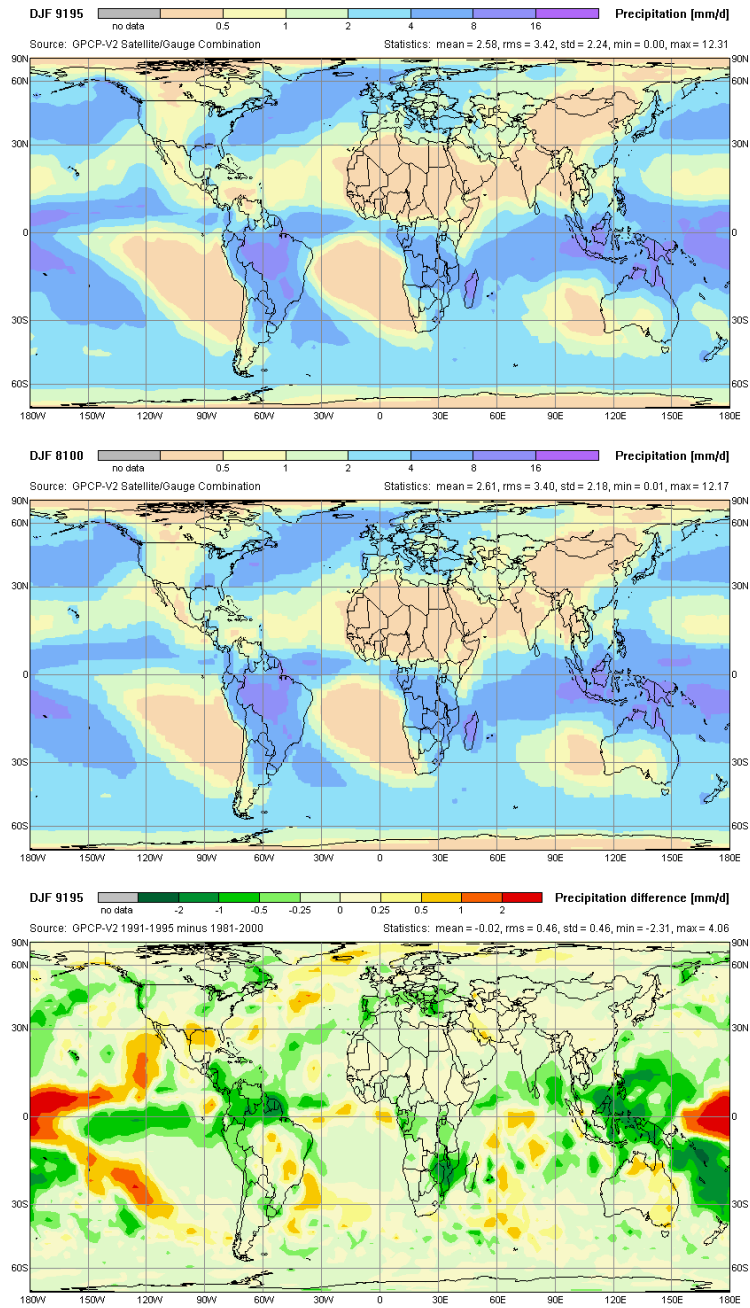
- 11.A1_12 Ratio of the July 1995 stochastic error (11.A1_11b) and the JJA 1981-2000 variance
(11.A1_09) [%]

- 11.A1_13a CMAP mean annual precipitation 1991-1995 [mm/d]
- 11.A1_13b Difference CMAP minus GPCP-V2 mean annual precipitation 1991-1995 [mm/d]
- 11.A1_14a ERA-40 mean annual precipitation 1991-1995 [mm/d]
- 11.A1_14b Difference ERA-40 minus GPCP-V2 mean annual precipitation 1991-95 [mm/d]

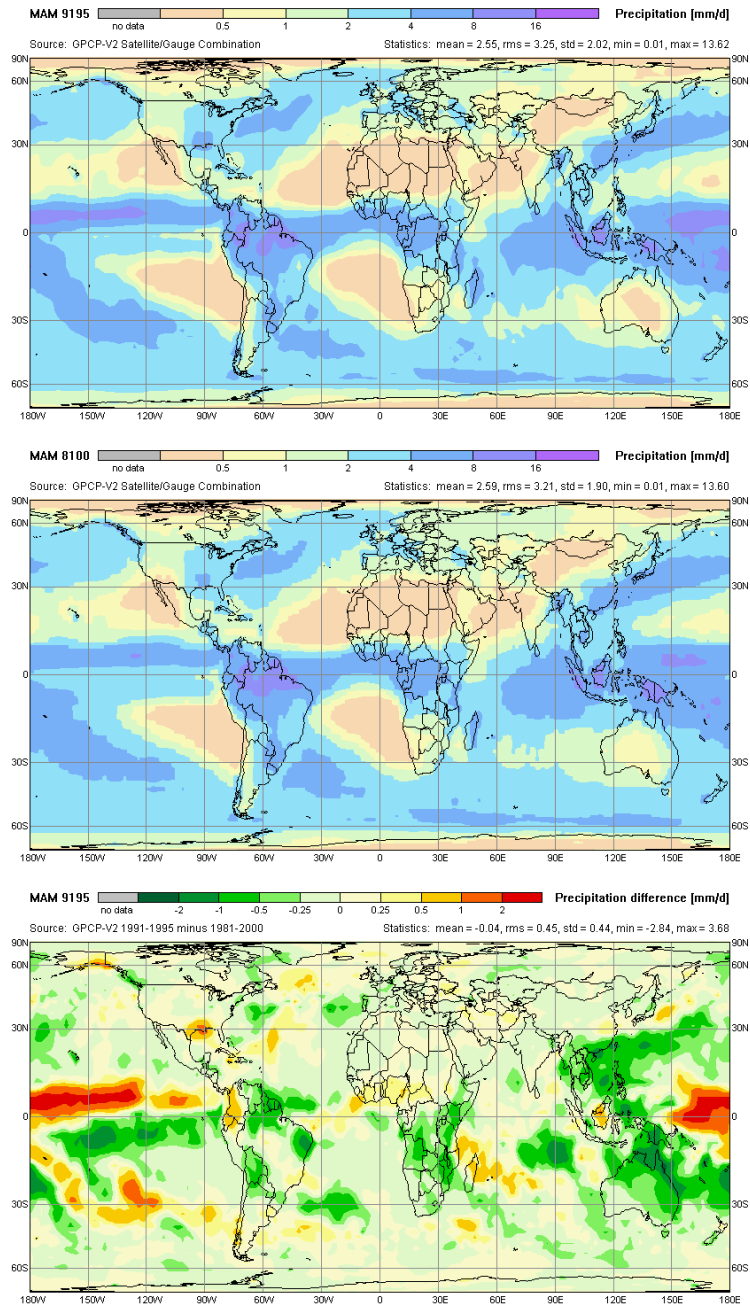
11.A1_01 GPCP-V2 mean annual precipitation [mm/d]



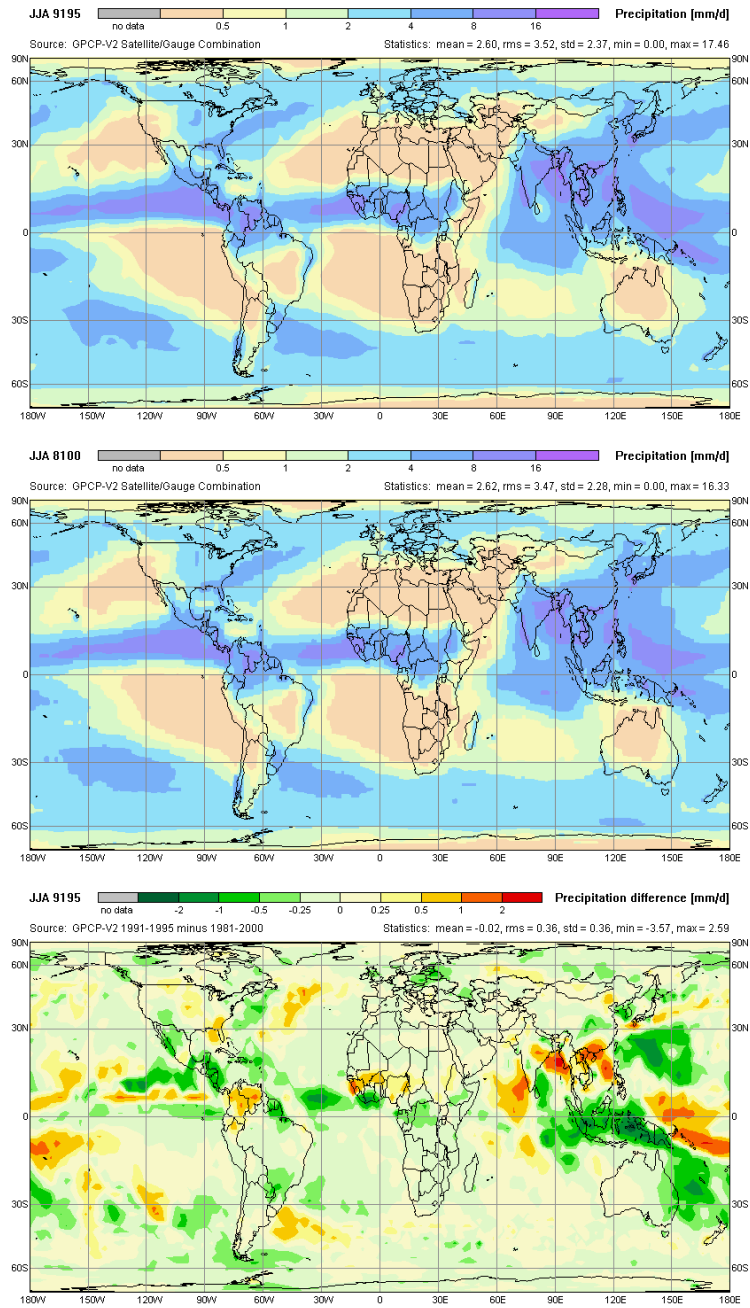
11.A1_02 GPCP-V2 mean DJF precipitation [mm/d]



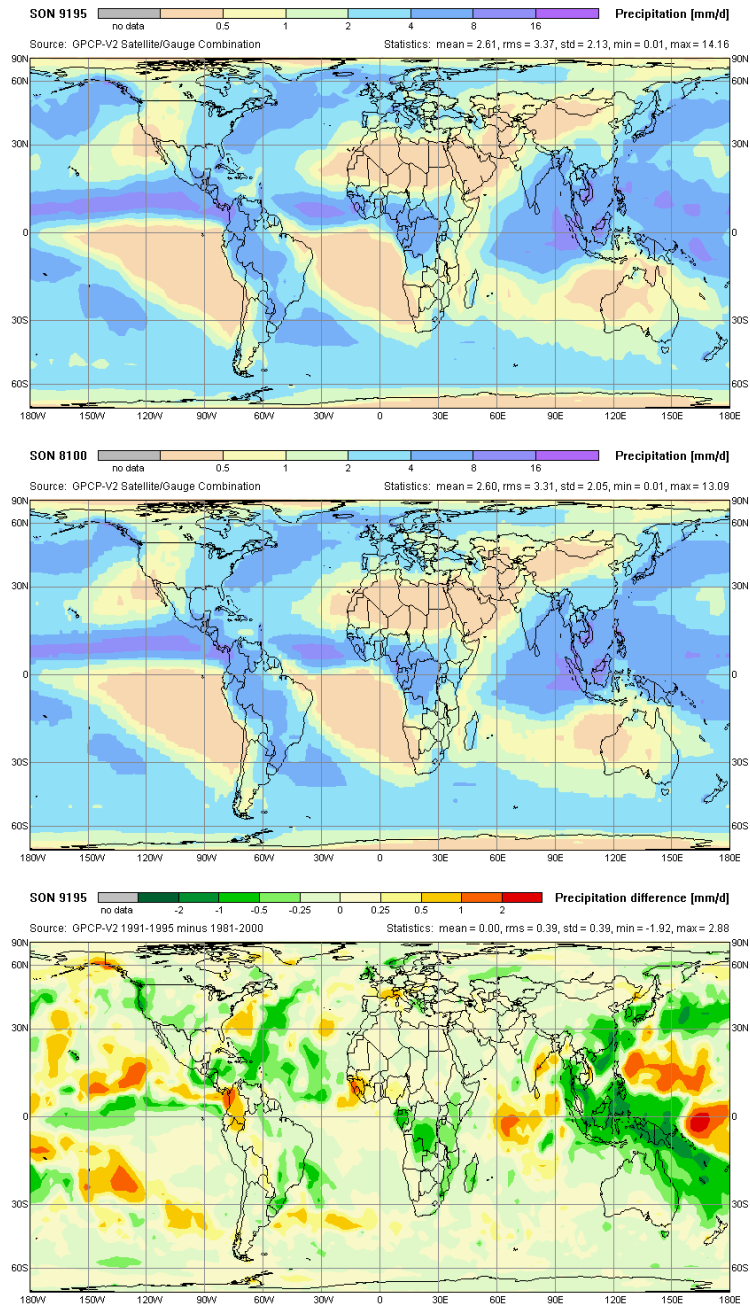
11.A1_03 GPCP-V2 mean MAM precipitation [mm/d]



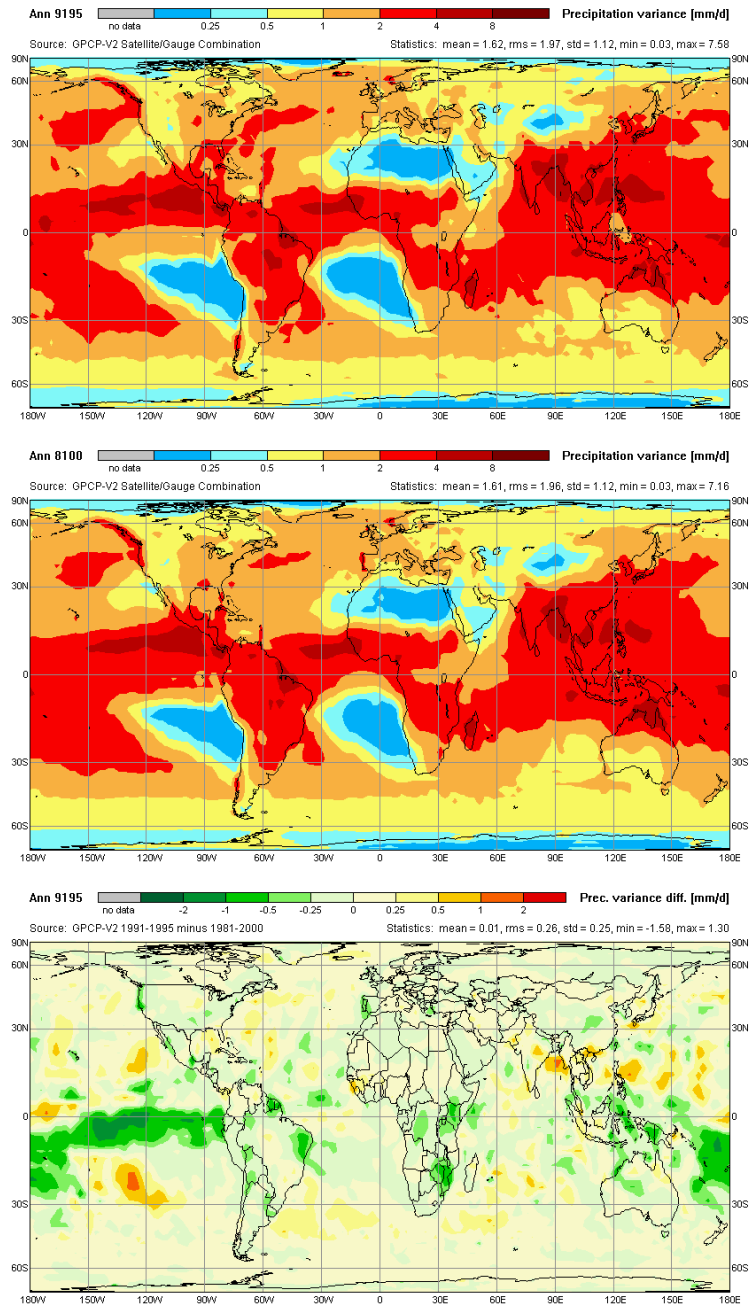
11.A1_04 GPCP-V2 mean JJA precipitation [mm/d]



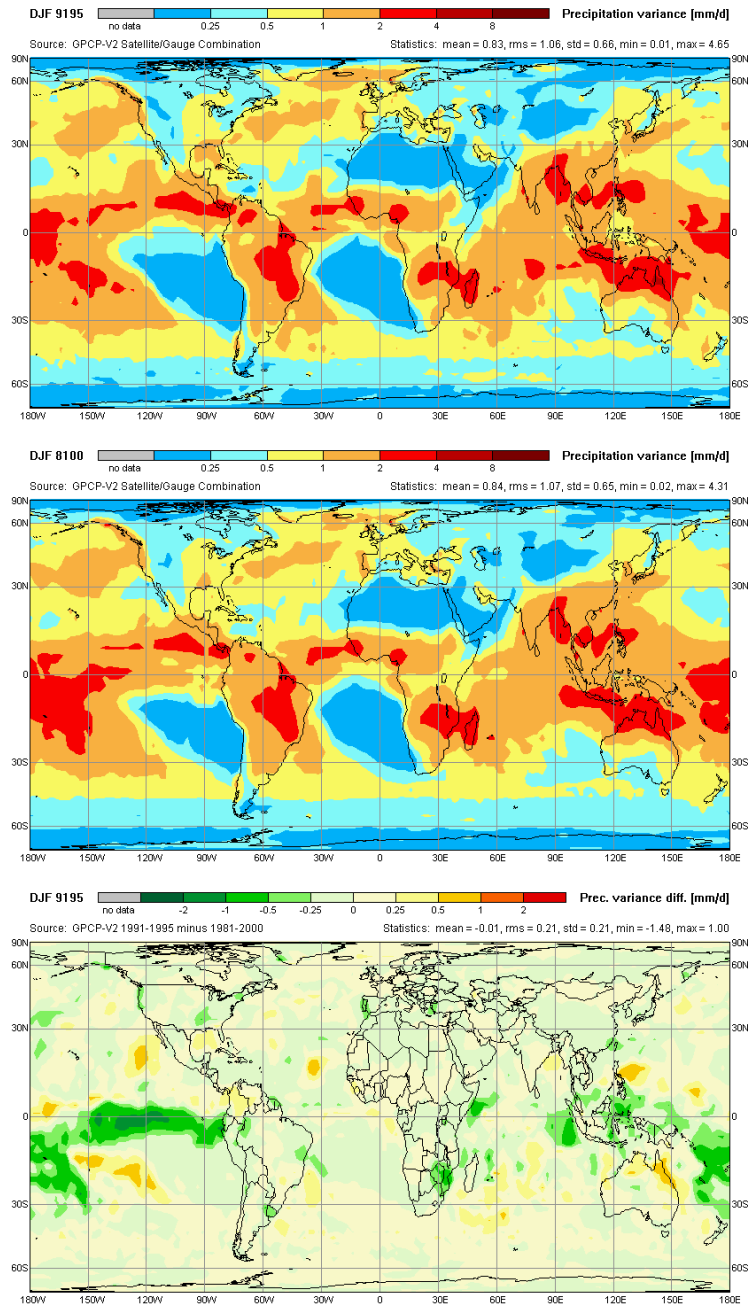
11.A1_05 GPCP-V2 mean SON precipitation [mm/d]



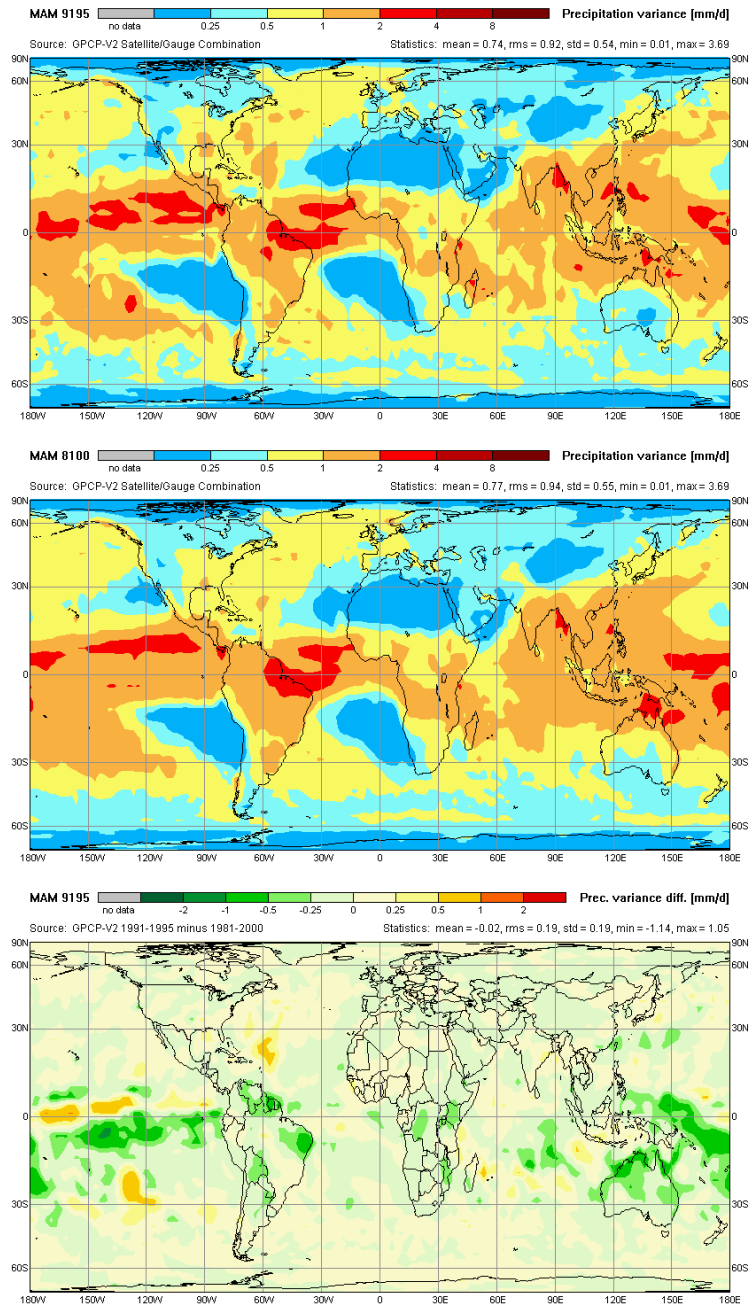
11.A1_06 GPCP-V2 mean annual variance of monthly precipitation [mm/d]



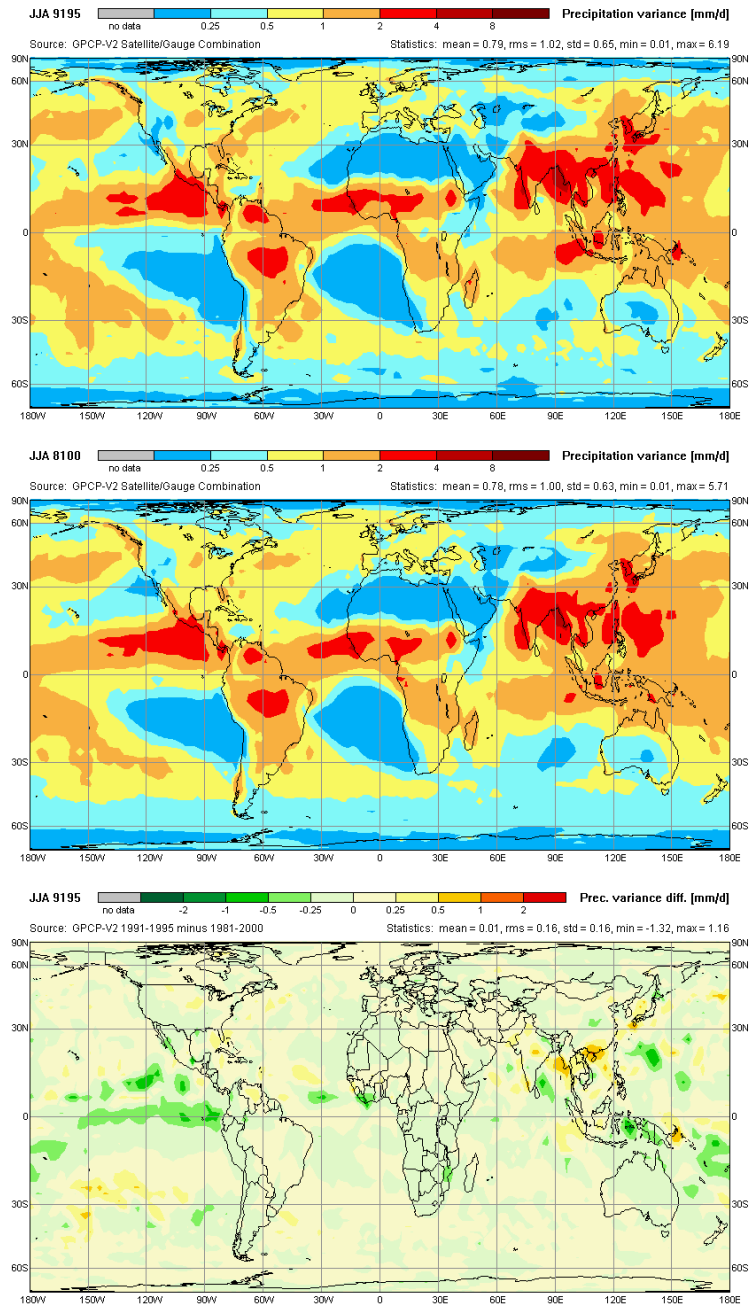
11.A1_07 GPCP-V2 mean DJF variance of monthly precipitation [mm/d]



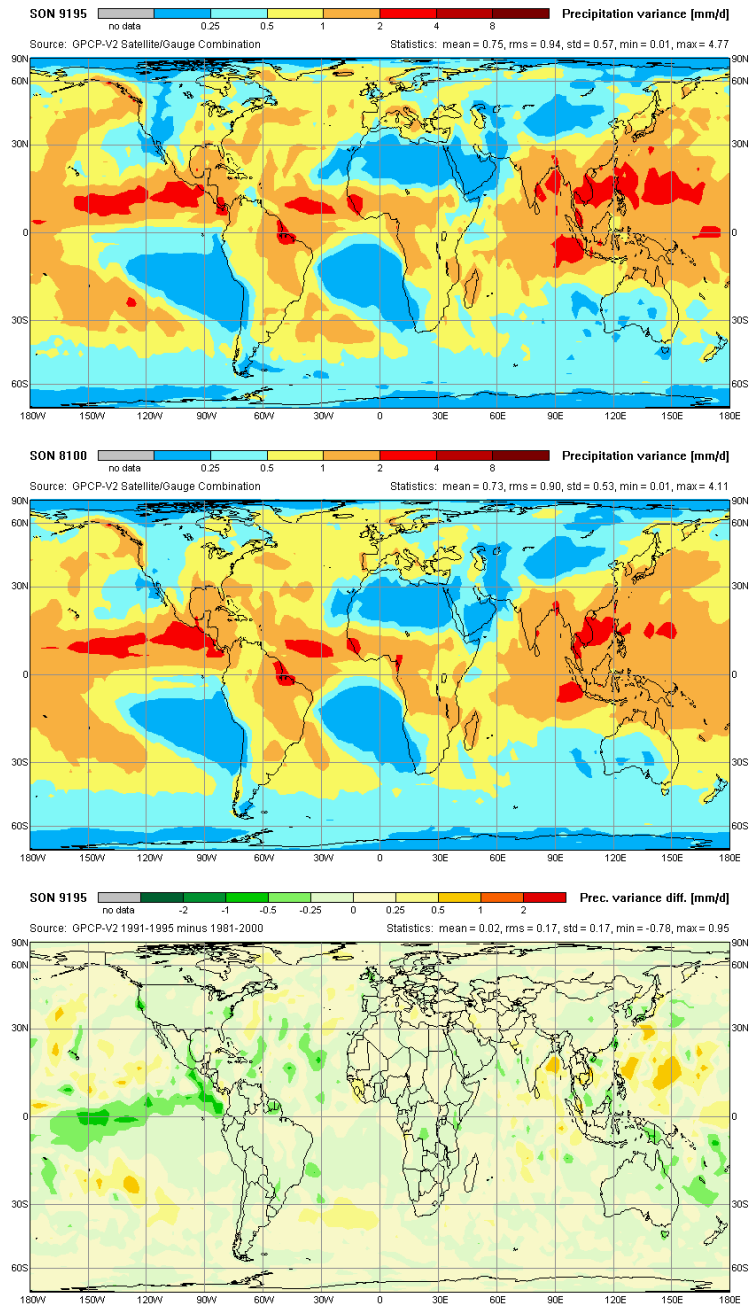
11.A1_08 GPCP-V2 mean MAN variance of monthly precipitation [mm/d]



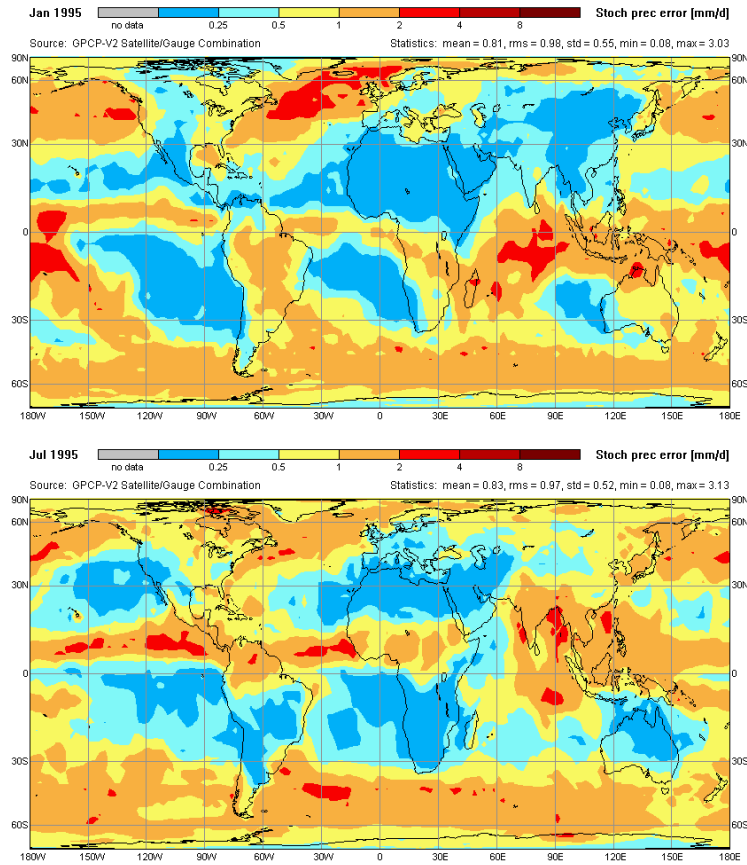
11.A1_09 GPCP-V2 mean JJA variance of monthly precipitation [mm/d]



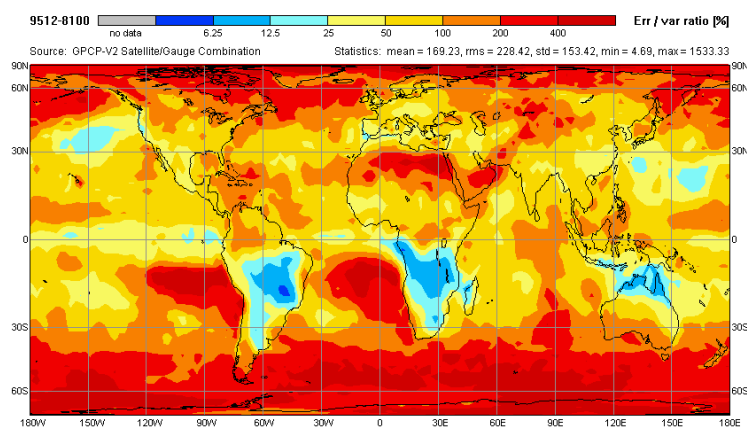
11.A1_10 GPCP-V2 mean SON variance of monthly precipitation [mm/d]

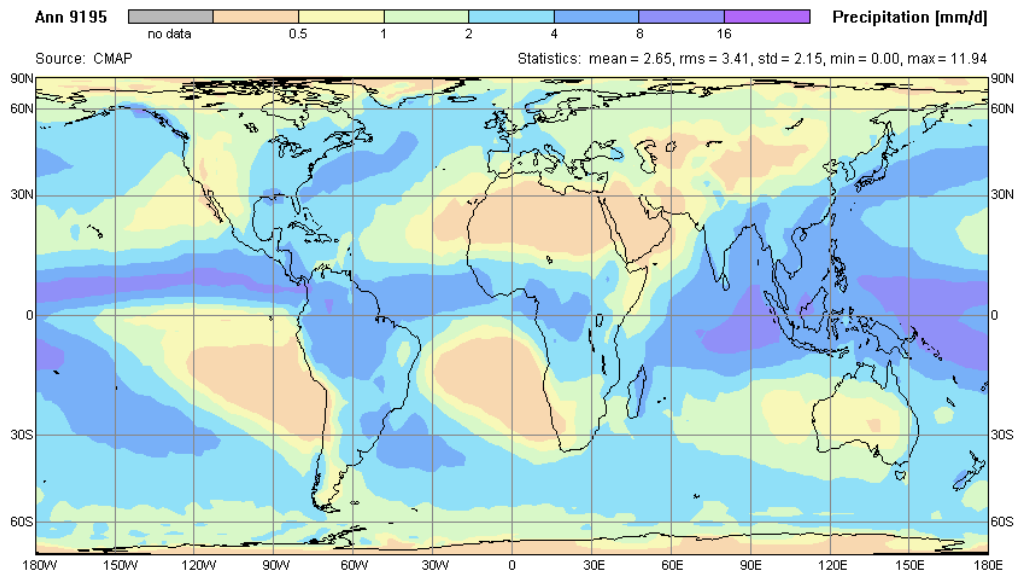
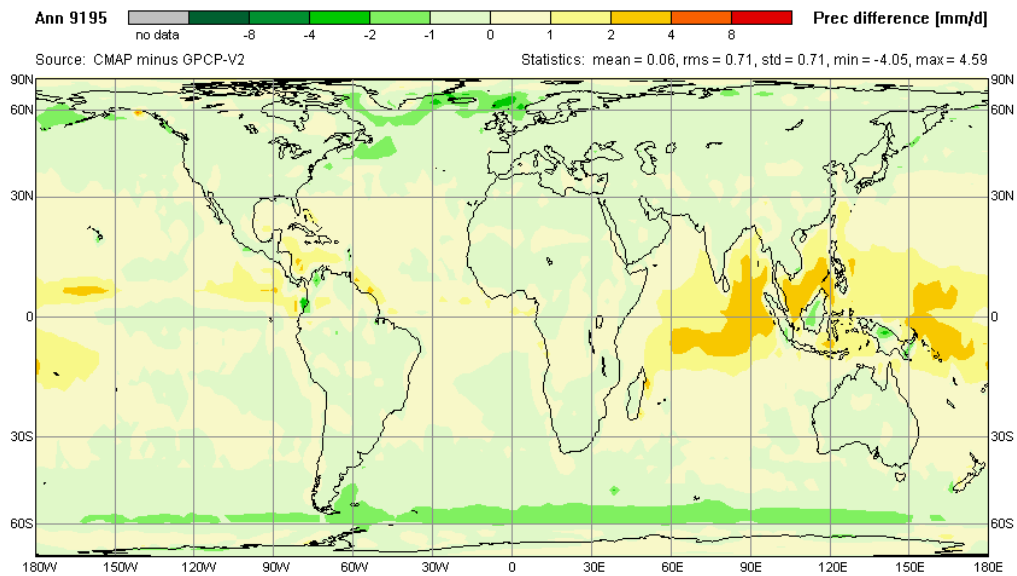


11.A1_11 GPCP-V2 global distribution of total stochastic error [mm/d] for two sample months (January 1995 and July 1995)

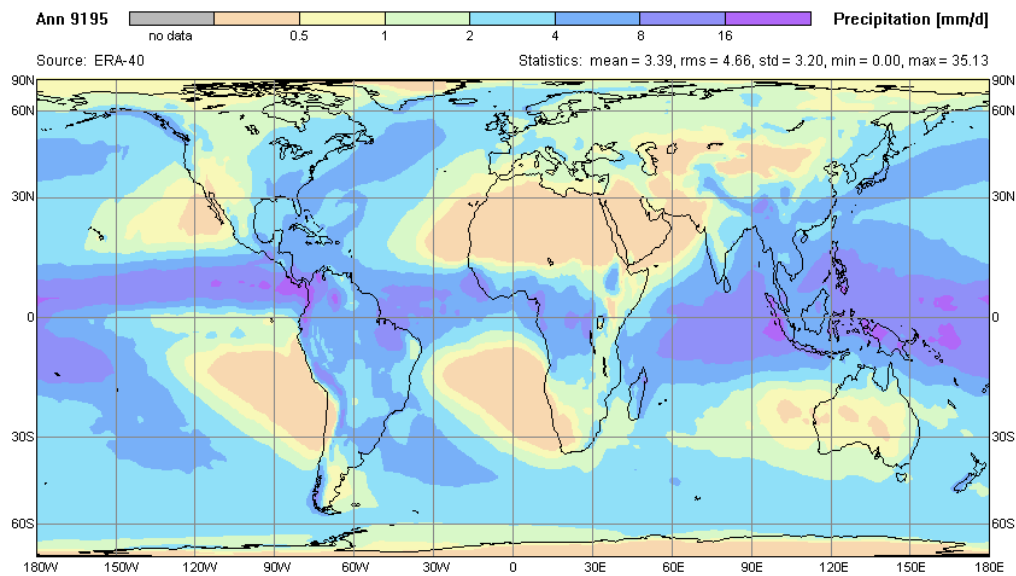


11.A1_12 Ratio of the July 1995 stochastic error and the JJA 1981-2000 variance [%]

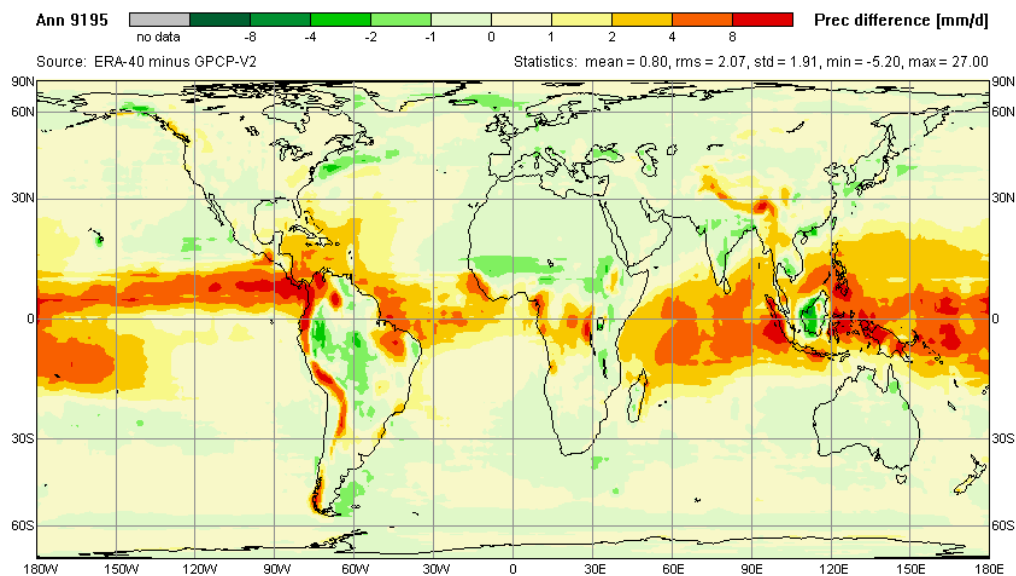


11.A1_13a CMAP mean annual precipitation 1991-1995 [mm/d]**11.A1_13b Difference CMAP minus GPCP-V2 mean annual precipitation 1991-1995 [mm/d]**

11.A1_14a ERA-40 mean annual precipitation 1991-1995 [mm/d]



11.A1_14b Difference ERA-40 minus GPCP-V2 mean annual precipitation 1991-95 [mm/d],



Annex 11-A2: Complementary global precipitation products for the period 1991-1995

This annex presents global terrestrial and oceanic precipitation maps for period 1991-1995. The terrestrial precipitation maps are derived from GPCC's Full Data Product (short: GPCC-Full), an analysis based on monthly precipitation observed at about 30,000 meteorological stations. The oceanic precipitation maps are provided by the HOAPS Version 1 Data Set (Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data, short: HOAPS V1) being based on SSM/I satellite observations. Both products are originally available on 1° latitude by 1° longitude spatial resolution. Users of these data sets should be aware that GPCC-Full will be stepwise replaced after additional gauge observations become available, and that a new corrected version 2 of HOAPS is expected to be published soon.

A comparison of the maps from GPCC-Full (land) and HOAPS V1 (ocean) against the GPCP-V2 global maps (Annex 11-A1) will show considerable differences, resulting from two overlapping causes, which are first the different data bases and second the different spatial resolutions. In particular the latter one is responsible for that regional maximum precipitation visible in the 1°-products is not depicted by GPCP-V2, for which the original version provides only 2.5° grid box area-mean precipitation values.

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- 11.A2_01b HOAPS V1 satellite-based annual precipitation for the global ocean [mm/d]

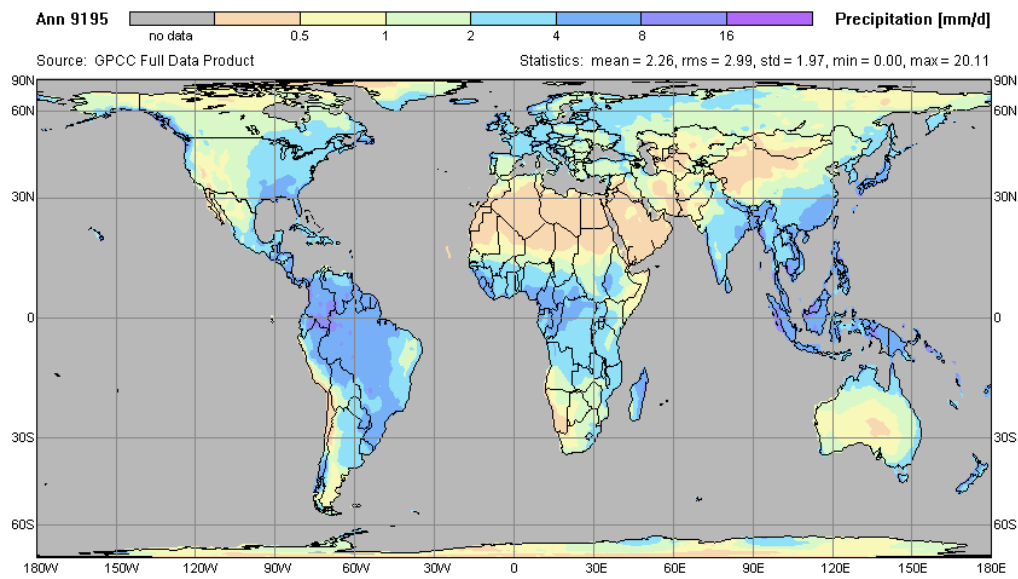
- 11.A2_02a GPCC-Full DJF precipitation for the global land-surface [mm/d]
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- 11.A2_03a GPCC-Full MAM precipitation for the global land-surface [mm/d]
- 11.A2_03b HOAPS V1 satellite-based MAM precipitation for the global ocean [mm/d]

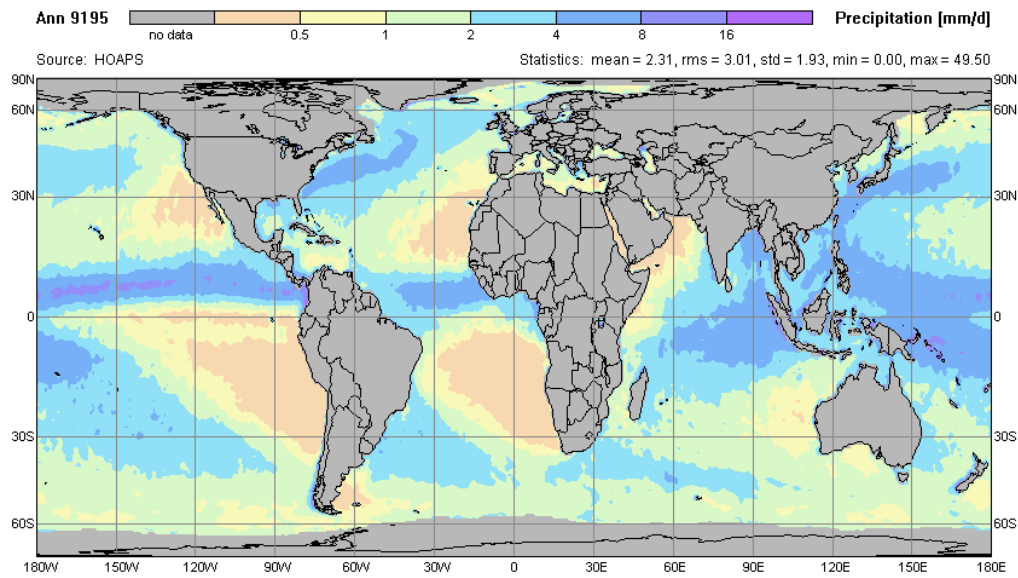
- 11.A2_04a GPCC-Full JJA precipitation for the global land-surface [mm/d]
- 11.A2_04b HOAPS V1 satellite-based JJA precipitation for the global ocean [mm/d]

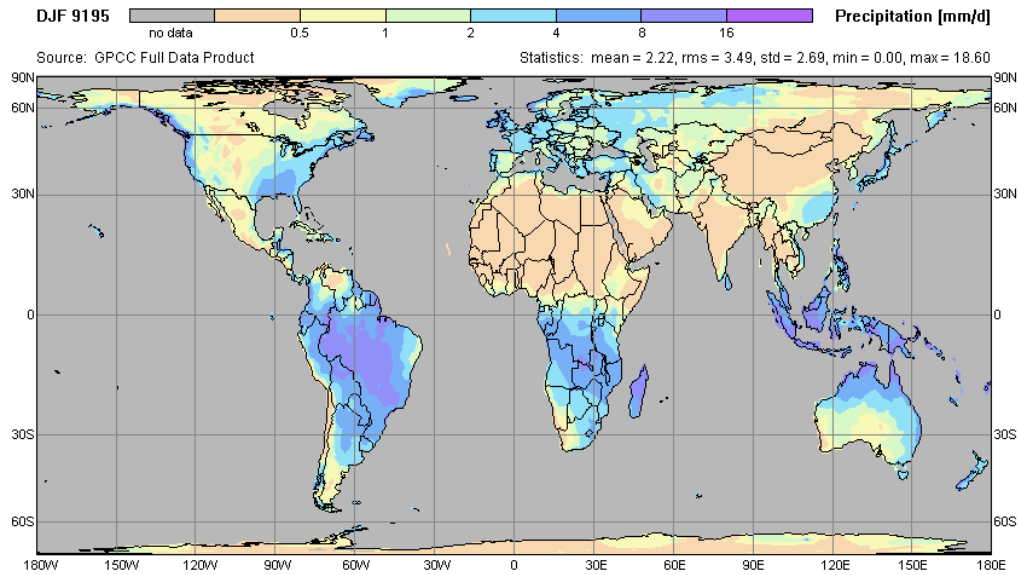
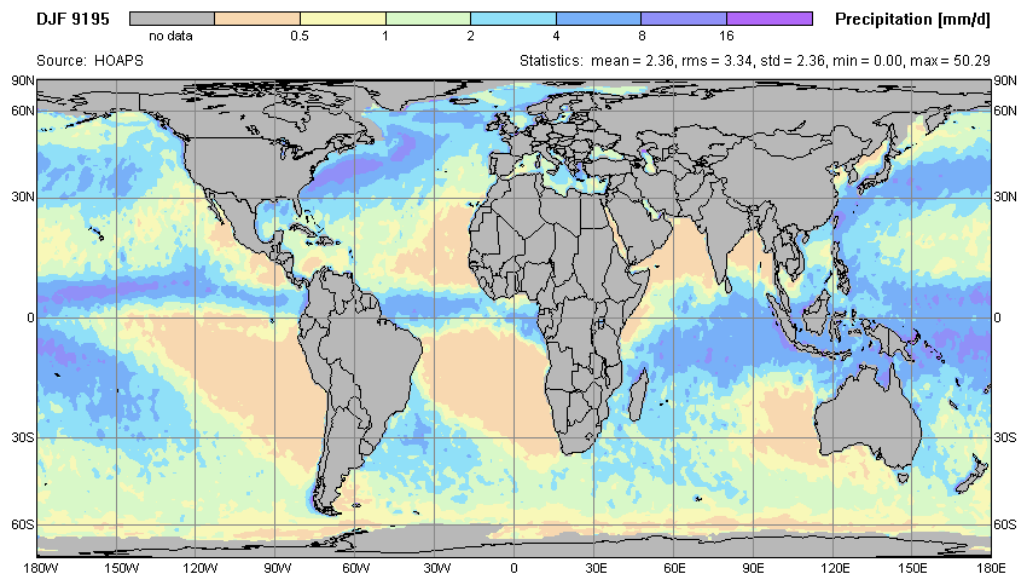
- 11.A2_05a GPCC-Full SON precipitation for the global land-surface [mm/d]
- 11.A2_05b HOAPS V1 satellite-based SON precipitation for the global ocean [mm/d]

11.A2_01a GPCC-Full annual precipitation for the global land surface [mm/d]

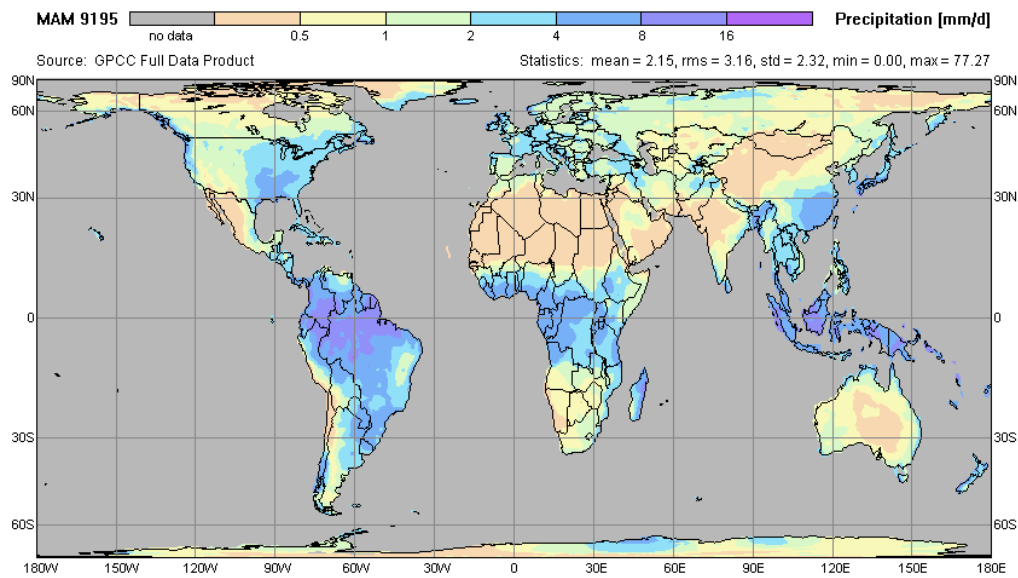


11.A2_01b HOAPS V1 satellite-based annual precipitation for the global ocean [mm/d]

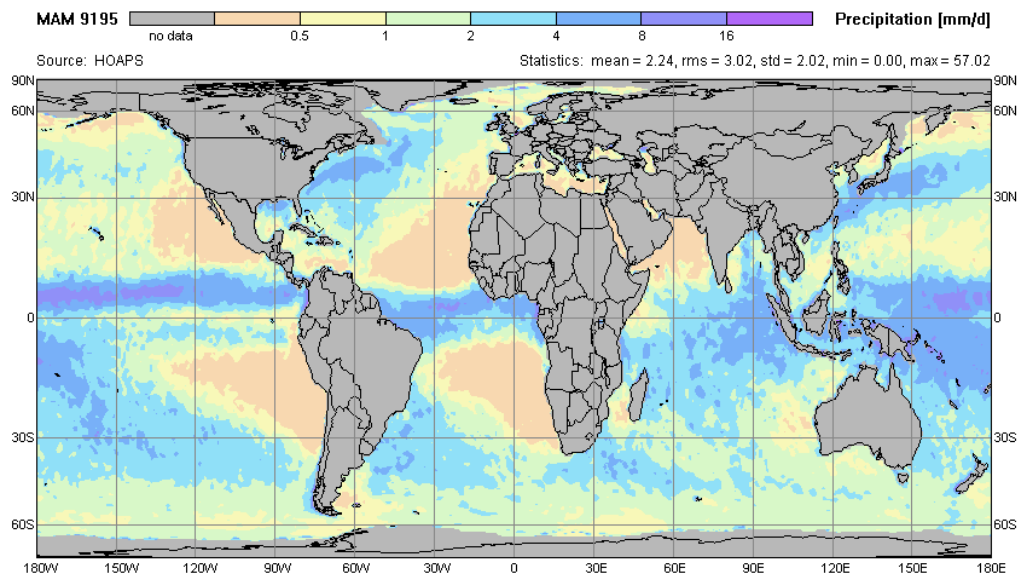


11.A2_02a GPCC-Full DJF precipitation for the global land surface [mm/d]**11.A2_02b HOAPS V1 satellite-based DJF precipitation for the global ocean [mm/d]**

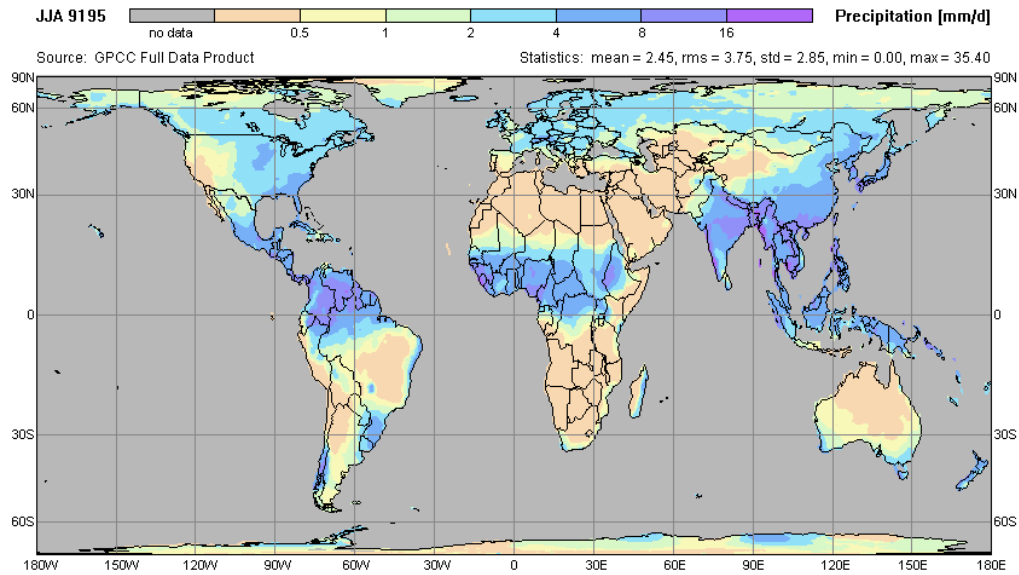
11.A2_03a GPCC-Full MAM precipitation for the global land surface [mm/d]



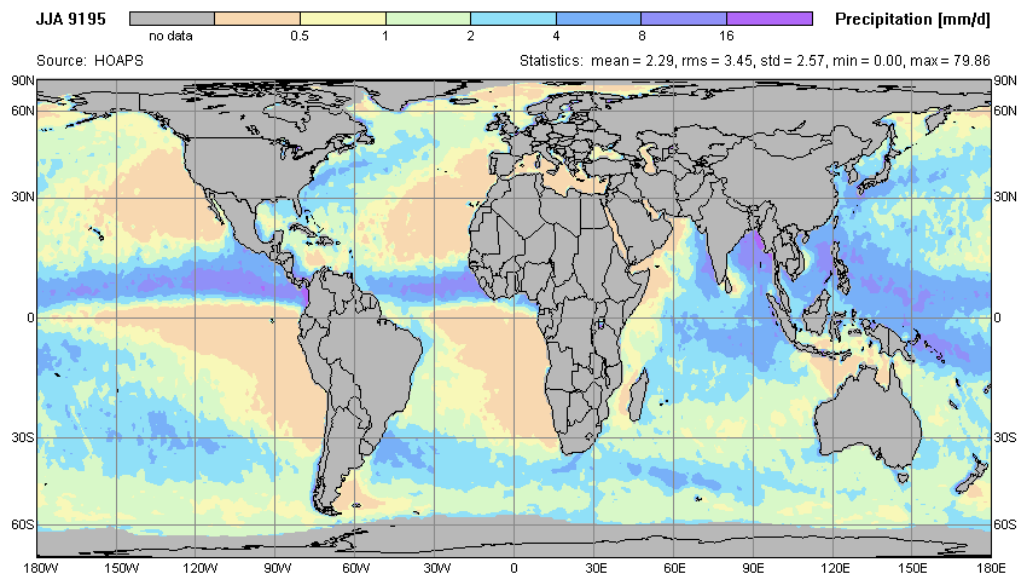
11.A2_03b HOAPS V1 satellite-based MAM precipitation for the global ocean [mm/d]



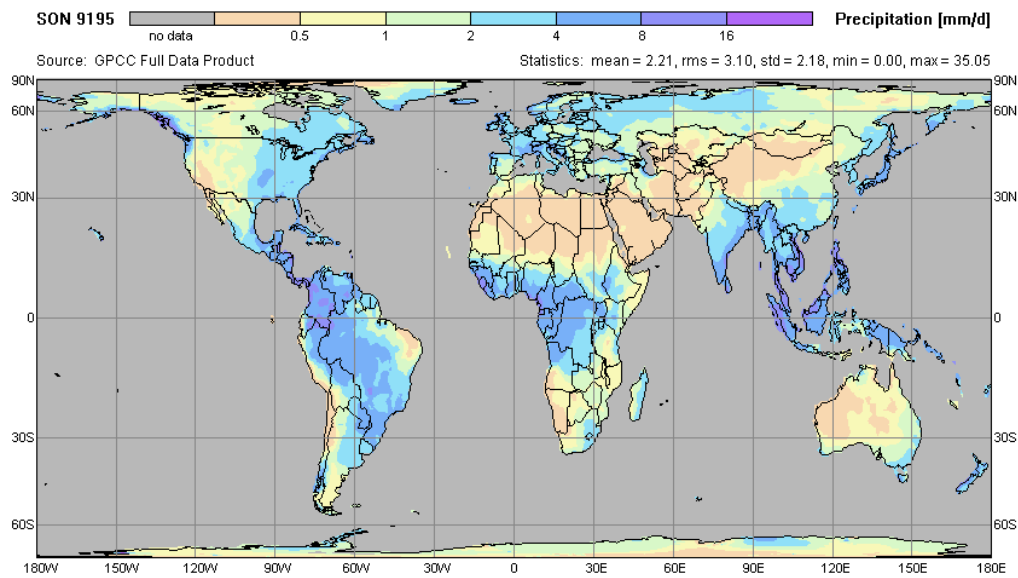
11.A2_04a GPCC-Full JJA precipitation for the global land surface [mm/d]



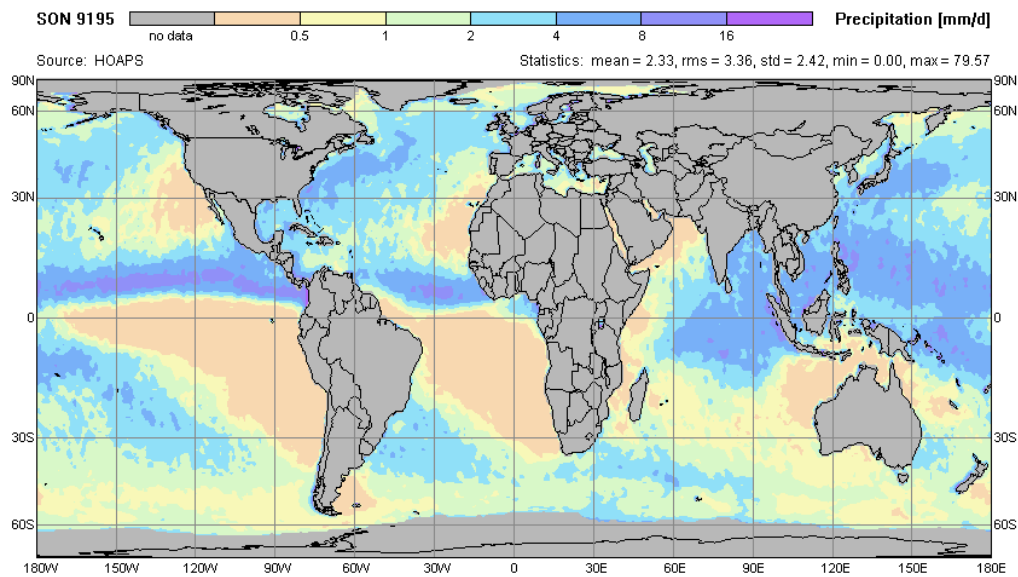
11.A2_04b HOAPS V1 satellite-based JJA precipitation for the global ocean [mm/d]



11.A2_05a GPCC-Full SON precipitation for the global land surface [mm/d]



11.A2_05b HOAPS V1 satellite-based SON precipitation for the global ocean [mm/d]



Annex 11-A3: ENSO Precipitation and Anomalies

The maps of this Annex illustrate the global distribution of precipitation related to the El Niño – Southern Oscillation (ENSO).

The Hovmoeller diagram shows the temporal variability and clearly depicts the warm ENSO signal with high precipitation over the south-equatorial Pacific Ocean reaching to the South-American west coast (Ecuador and Peru) as well as the dry zone in Indonesian region during the El Niño events 1982/83, 1986/87, 1991/92 and 1987/98.

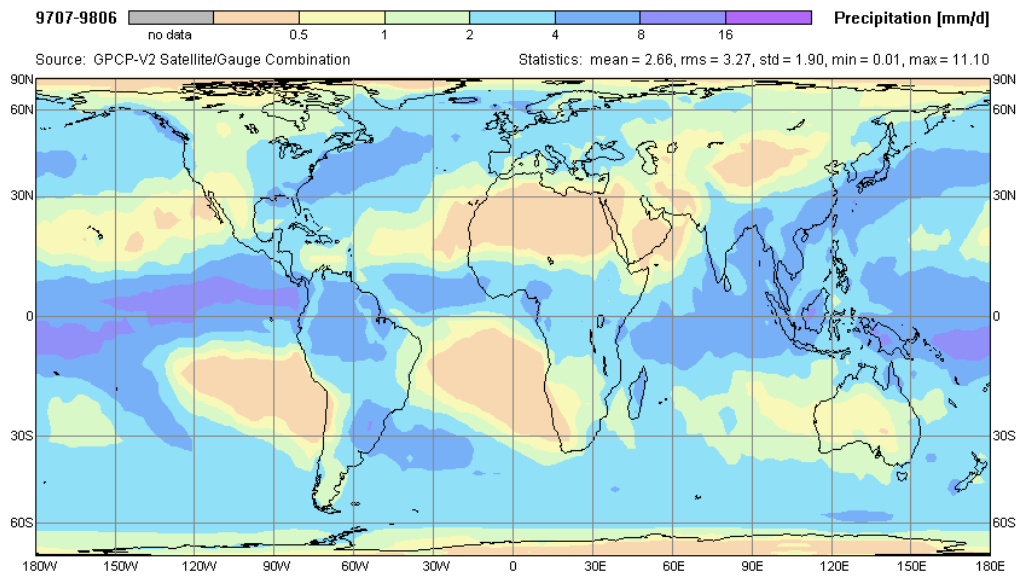
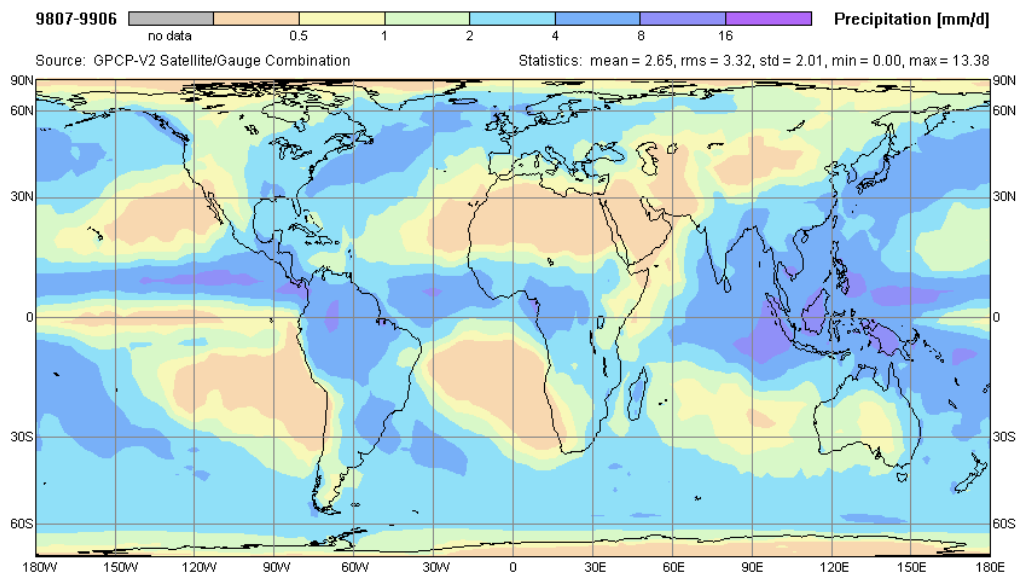
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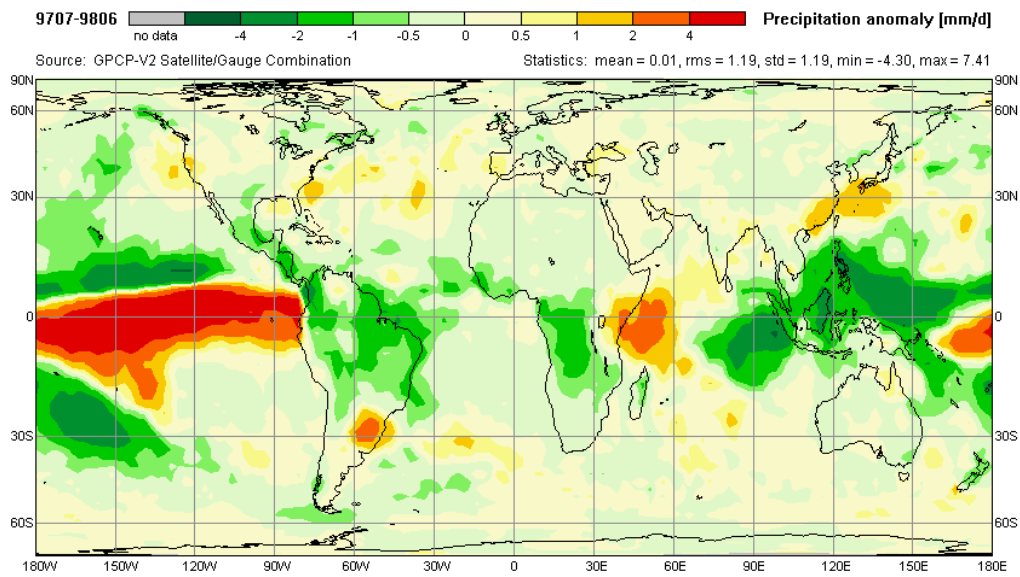
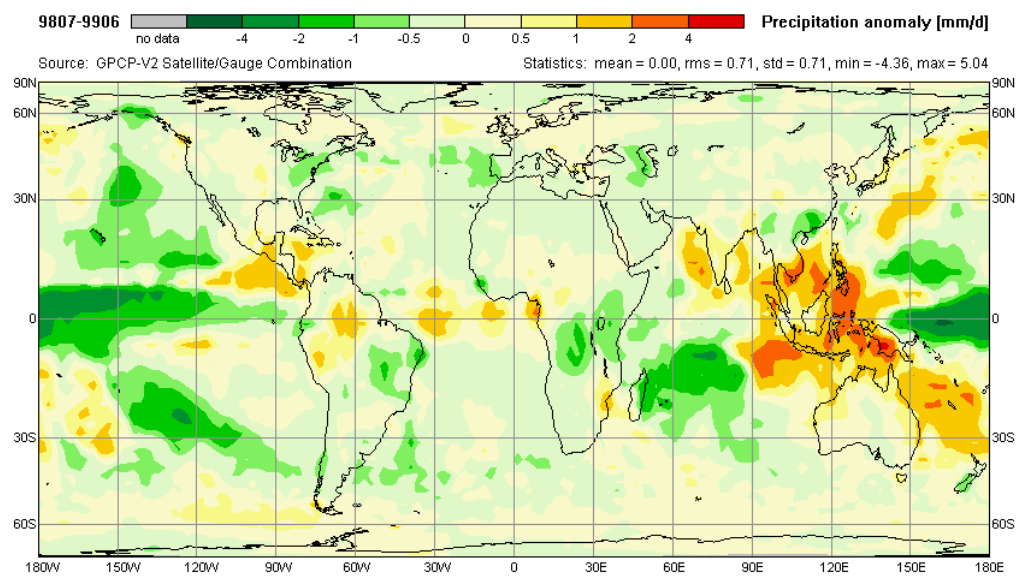
- 11.A3_01a GPCP-V2 Precipitation [mm/d] for the El Niño Year July 1997 – June 1998
- 11.A3_01b GPCP-V2 Precipitation [mm/d] for the La Niña Year July 1998 – June 1999

- 11.A3_02a GPCP-V2 Precipitation Anomaly [mm/d] for the El Niño Year July 1997 – June 1998
- 11.A3_02b GPCP-V2 Precipitation Anomaly [mm/d] for the La Niña Year July 1998 – June 1999

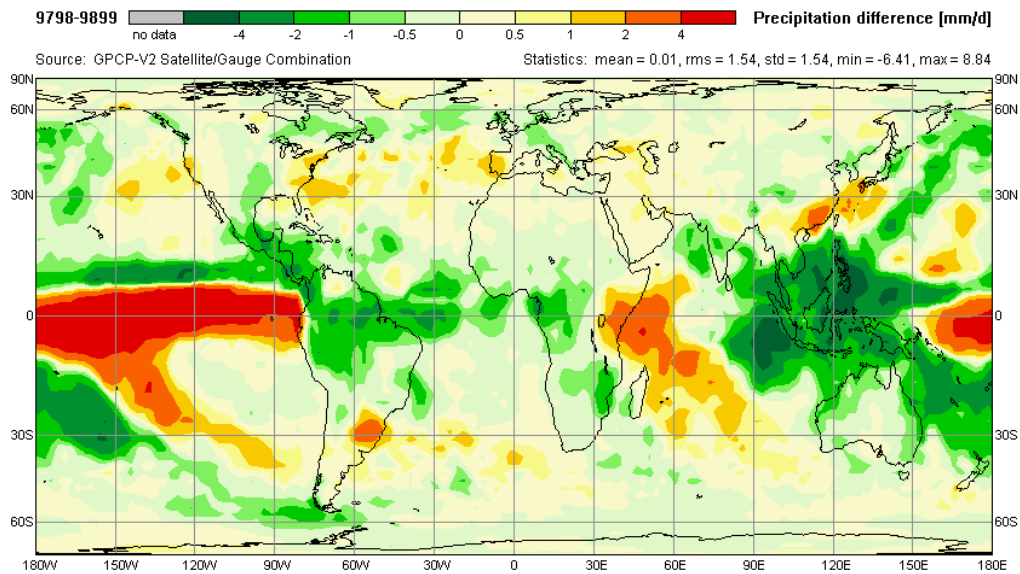
- 11.A3_03a GPCP-V2 Precipitation Difference [mm/d] for the El Niño Year July 1997 – June 1998
minus La Niña Year July 1998 – June 1999
- 11.A3_03b Comparison of regional mean precipitation time-series showing the ENSO signal
(coloured version of Figure 11.10 from the book chapter 11)

- 11.A3_04 Time/longitude Hovmoeller diagram for the latitude belt 0° - 5°S
for GPCP-V2 monthly precipitation [mm/mon]

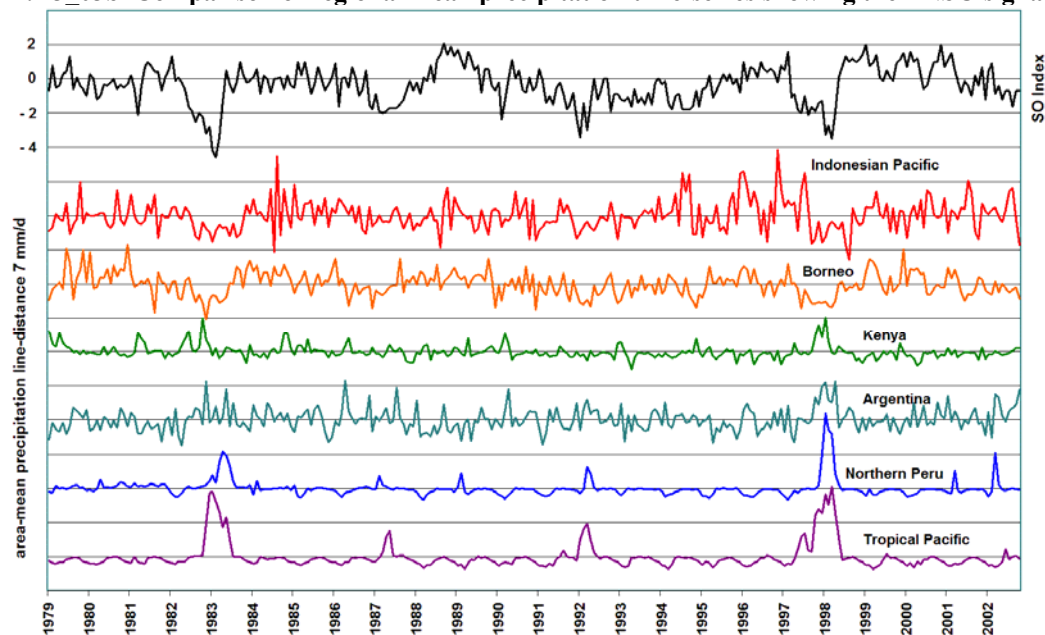
11.A3_01a GPCP-V2 Precipitation [mm/d] for the El Niño Year July 1997 – June 1998**11.A3_01b GPCP-V2 Precipitation [mm/d] for the La Niña Year July 1998 – June 1999**

11.A3_02a GPCP-V2 Precipitation Anomaly [mm/d] for the El Niño Year July 1997 - June 1998**11.A3_02b GPCP-V2 Precipitation Anomaly [mm/d] for the La Niña Year July 1998 – June 1999**

11.A3_03 GPCP-V2 Precipitation Difference [mm/d] for the El Niño Year July 1997 – June 1998 minus La Niña Year July 1998 – June 1999



11.A3_03b Comparison of regional mean precipitation time-series showing the ENSO signal



11.A3_04 Time/longitude Hovmoeller diagram for the latitude belt 0° - 5°S for GPCP-V2 monthly precipitation [mm/mon]