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3.1.2 The global precipitation pattern and its changes in the 20th century

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SUMMARY: *Air temperature and measurable falling precipitation are basic meteorological parameters to be used in both observational statistics and validation (such as calibration) of general circulation models. The preference of precipitation being a conservative element of climate may be explained by its relatively simple method of areal determination in contrast to more difficult estimates of the energy balance components, e.g. net radiation or turbulent fluxes of latent heat, which would be more suitable to check model output. The aim of this chapter – seen against the background of the total draft of this book – is to present problems and limits of precipitation determination and its temporal changes above continents and oceans.*

Together with air temperature we see measurable falling precipitation to be the second basic meteorological parameter, which is usually favoured for the validation (and calibration) of global climate simulation models. The charm of this conservative element of climate may be explained by the fact that it is relatively simple to derive area-related assessments, in contrast to the components of the energy balance, e.g. net radiation or the turbulent energy flux of latent heat. These components, on the one hand, are actually more suitable for this purpose, but on the other hand more difficult to determine. The aim of this chapter – within the overall concept of this book – is to address the problems and restrictions of the determination of precipitation and to give some information about the growing knowledge of the global precipitation behaviour in time and space above continents and oceans.

The determination of precipitation

We use three methodical complexes in climate research, considered here for the example of precipitation. These methods are supplementary and coupled together. In the middle of the 19th century, the period of instrumental observations began. First, local measurements by rain gauges dominated, later and today completed by means of areal distributions derived from radar and satellite techniques. For earlier time, we are able to use the manifold indirect reconstructions of paleoclimatology called proxy data. So, the interpretation of direct and indirect information available from various data archives leads to qualitative and quantitative precipitation characteristics (DOSTAL 2005, BÜRGER et al. 2006). Paleoclimatology, which is able to penetrate far into the past of the system Earth, provides only rough estimates for prehistoric time as well as the interpretation of written sources showing likewise a decreasing accuracy and increasing difficulties with growing distance from the present. However, the analysis of observations and proxy data is completed by means of numerical simulations of local, regional, and global distributions of precipitation based on the atmosphere, oceans and land surfaces processes. This concerns both the understanding of the past and future projections as well.

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Measurements over continents and oceans

It is reasonable, when estimating area totals of precipitation or regarding and analysing station-related precipitation time series, first to clarify the definition of precipitation. There is a difference between falling precipitation (liquid or solid), deposit precipitation (again liquid or solid), land-filled precipitation (snow cover) and dispersed precipitation, which is snow, already addressed in the category »falling«. Falling precipitation is typically collected by gauges at local observation sites above terrestrial surfaces (RUDOLF 1995). The water content in these collecting containers is then read in a measuring glass, recorded by means of strip chart recording float gauges, drop counting, tipping gauges or weighing balances. Thereby, snow may cause a problem, because it can be blown out of the gauge aperture removing itself from the quantitative determination. Snow collection is nearly impossible due to wind influences in the central polar regions, where snow falls all year round. In this situation, precipitation measurements are exchanged by reports of »snow drift days« and accumulation measurements of the snow cover. Fortunately, these areas – in comparison to the Earth's total surface area – are small and the amounts of snow are likewise small (approximately 50–100 mm per year, see *Fig. 3.1.2.-1*) due to low temperatures (far below the 0 °C level). So, they play no important role in the determination of the global precipitation balance (JAEGER 1976). On the other hand, higher air temperatures due to the anthropogenic greenhouse effect – regionally we may expect a temperature rise as large as 10 °C within the next 100 years – are leading to a higher water vapour pressure deficit above the ice shields. This could mean increased solid precipitation in these regions, causing a higher terrestrial water fixation which, in turn, may lead to a falling tendency of the global sea level (STERR 1998).

Deposited precipitation – dew or hoar frost – is also difficult to determine. This holds also for fog precipitation, which can grow up to considerable amounts in some (mountain) regions of the continents. The conventional determination of (falling) precipitation is a »point« measurement. Areal precipitation distributions, which are more appropriate for the character of precipitation, are nowadays the result of objective assessment methods. They are used for the construction of isohyetal maps (contour lines of precipitation) and for the calculation of grid point related data. It is necessary to mention in this context the outstanding work of the Global Precipitation Climatology Center (GPCC) in Offenbach, Germany, which is maintained by the German Weather Service (DWD) on commission of the World Meteorological Organisation (WMO) in Geneva. Its task is the collection of data material provided world-wide from different measurement methods and devices and the analysis of all these data (RUDOLF 1995). Problematical is the objective determination of area-related precipitation distributions in regions with sharp precipitation gradients in horizontal or vertical direction (high mountains). Results in this field of research, however, can be corrected using geographical knowledge and experience in observation.

The author presented in 1976 a »subjective« analysis of global precipitation patterns, covering the continents and the oceans as well (JAEGER 1976). The innovations in those days, which ensure the up-to-date use of the data set (ADLER et al. 2003, JAEGER et al. 2006) are the following:

- Use of data from the climatological normal period 1931–1960. Only very few gaps were closed using data from other reference periods.
- Construction of monthly maps and an annual map for the total area of the Earth including the annual cycle for the globe in total and for parts of it.
- Presentation of a data set of monthly grid point related totals in a 5°-grid point system completed by comparative calculations to be applied to climatic models (BOERS et al. 1992).

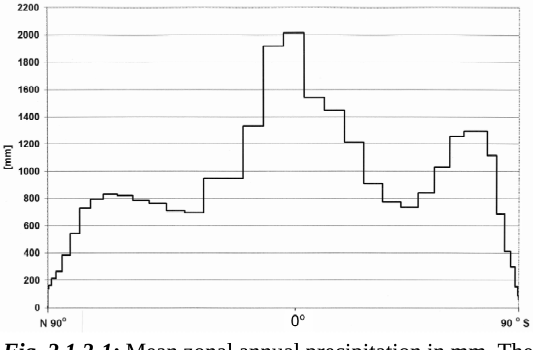


Fig. 3.1.2-1: Mean zonal annual precipitation in mm. The abscissa represents the real spatial share of the 5° latitudinal belts. 0° = equator (JAEGER 1976).

The total global precipitation budget has to involve the determination of oceanic precipitation as well. Conventional methods for this purpose are the analysis of diaries of ships (qualitatively) and the consideration of atlases (again quantitatively) based on observations from ships and measurements on islands (JAEGER 1976, LEGATES 1987). The unequal distribution of the maritime trade routes is a problem, preventing fair data quality over large oceanic areas with only small information from travelling ships. The extrapolation of island measurements to the surrounding water areas requires a high degree of special feeling and experience, because terrestrial areas are provoking convectional precipitation due to stronger surface heating which would not appear in the absence of land. Orographical effects on islands, too, may reduce the representativeness of the rain with respect to the surrounding oceanic water areas. This is why TAYLOR (1973) called his area-related rain analysis of the Pacific Ocean self-critically »An Atlas of Pacific Islands Rainfall«. Direct measurements of precipitation over sea is difficult and only possible in a poor coverage. After the removal of many weather ships operating at fixed co-ordinates which measured precipitation, too, we have more and more data from buoys, which are able to provide precipitation information in a acoustic or optical way. Also travelling ships may be used as carriers, where special gauges with additional vertical drop collection are used. The optical measuring principle needs an additional calibration procedure (GROSSKLAUS 1996). All in all, conventional oceanic precipitation determination remains to be a difficult task. Note, in addition, that oceanic areas are much larger than land areas.

Satellite based techniques

Today it is impossible to ignore the methods of determining hydrometeors by means of electromagnetic waves. Optical devices can detect precipitation like conventional gauges at specific places. The weakening of light beams enables raindrop or snowflake counting in connection with the determination of their sizes. Another ground-based method is the use of precipitation radars, now covering the whole of Western Europe. The radar echo is dependent on the diameter of the drops to the power of six. This makes it necessary to detect drop spectra by means of so-called distrometers (optical sensors working at specified stations) in order to be able to calibrate the radar picture information precisely.

The application of electromagnetism is now most important in case of satellite techniques. Thereby, the atmosphere is observed from some distance at high altitudes, called remote sensing. Here again, the GPCC in Offenbach plays a central role in collecting the information.

The complex and permanent observations from the different space platforms are analysed by the corresponding working groups and transmitted to GPCC in Offenbach where these products are processed further (ADLER et al. 2003). Meanwhile, in the context of the Global Precipitation Climatology Project (GPCP), GPCC has produced a »version 2« of a global precipitation data set based on all these recording techniques representative from 1986 up to today. The data are available from GPCC website http://gpcc.dwd.de. In the USA, NOAAs »World Data Center A« (NOAA = National Oceanic and Atmospheric Administration) provides products of precipitation measurements and analyses, too, via website http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.nasa.gov or http://precip.gsfc.nasa.gov.

Fig. 3.1.2-2 gives an impression of the complexity of the determination of precipitation by means of remote sensing and of the applied methods. It should be stressed that a reasonable determination of precipitation over the whole Earth still needs ground truth measurements.

The use of different ranges of the electromagnetic spectrum at different satellite platforms requires computation techniques restricted according to geographical latitudes which are indicators of both different precipitation formation processes and distinction between ocean and land.

Satellite derived infrared data (spectral range 10.5–12.5 mm) are used to determine the extension of convective cloud systems where the coverage of high cold clouds

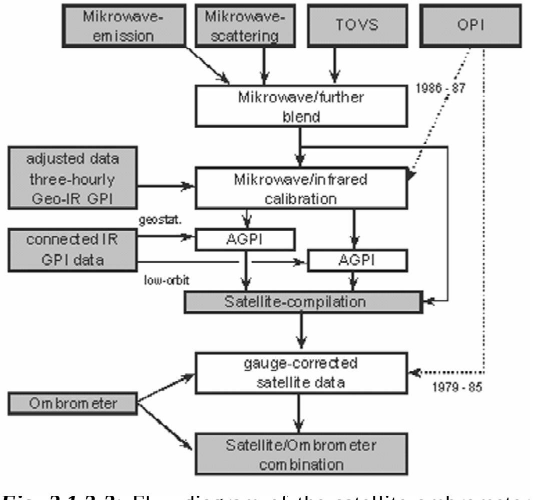


Fig. 3.1.2-2: Flux diagram of the satellite-ombrometer combination technique (version 2) of the global precipitation climatology project (after ADLER et al. 2003). TOVS: TIROS Operational Vertical Sounder-; OPI: precipitation index, based on long-wave radiation measurements of low orbit operating satellites (OLR: outgoing longwave radiation); Geo-IR: Infrared information of geostationary satellites; GPI: Geostationary Operational Environmental Satellite (GOES) precipitation index; AGPI: adjusted GPI, discrito geosynchronical and low orbit satellites.

(threshold value = 235 K) can be correlated with precipitation (ARKIN & MEISNER 1987). The reference value of 3 mm precipitation per hour, defined to create absolute values, was determined by empirical radar images and gauge measurements at research vessels during GATE (GARP Atlantic Tropical Experiment; GARP = Global Atmospheric Research Programme). GARP methods are meanwhile developed further to a technique which can be applied operationally in the tropical and extratropical area between 40° N and 40° S, both over oceans and land areas as well. RUDOLF (pers. comm. 2004), however, proposes to orientate this procedure to the seasonal variation of the ITCZ (inner tropical convergence zone). In his opinion the formally drawn 40° border to the temperate latitudes does include the appearance of cyclonal cirrus cloudiness. Its ice crystals have nothing to do with the formation of convective precipitation and, therefore, may lead to misinterpretations.

Precipitation estimates in the microwave range have been carried out since 1987 in the frequency channels 19, 22, 37, and 85 GHz by a polar orbiting satellite called »Special Sensor Microwave / Imager« (SSM/I). The emission of water clouds and raindrops is recorded separately, horizontally and vertically polarised (HOLLINGER et al. 1987). In the first instance, this way of microwave information was realised only over sea surfaces and converted to absolute precipitation values using algorithms which are developed on the basis of emission histograms (WILHEIT et al. 1991). The advantage of oceanic surfaces is that it is arithmetically more simple to handle background radiation there, in contrast to the patchwork of terrestrial agricultural and natural surfaces. *Fig. 3.1.2-3* shows an example in a 5°-grid dissolution for January 1989 (from RUDOLF 1995). The inclusion of solid Earth into microwave based precipitation determination is possible using the 85 GHz range scattering index described by FERRANO (1997). This scattering index is currently calibrated using precipitation rates from ground radar bases and enables a sensitivity of 1 mm/h (FERRARO & MARKS 1995). The loss of the 85 GHz channel in 1990 and 1991 was compensated by signal processing in the range of 37 GHz, unfortunately resulting in a reduction in sensibility of 5 mm/h.

Another remote sensing method for the determination of precipitation is possible by the TIROS satellite (Television and Infrared Observation Satellite) with its »Operational Vertical Sounder« (TOVS) (SUSSKIND et al. 1997). This system allows to determine precipitation rates on the basis of regressions of low levelled extended cloud fields with corresponding ombrometer data and parameters derived from satellite data, which are describing cloud volumes, the pressure at the upper cloud level, the degree of coverage of clouds (cloudiness), and the vertical profile of the humidity of the air.

All precipitation data – derived by remote sensing – are collected operationally in the GPCC in Offenbach and compiled likewise operationally to maps and data sets, e.g. monthly totals gridded with 2.5° dissolution. These products are available online. Thus, the evaluation of precipitation climatology products is possible. The reliable and precise description of the spatial and temporal patterns of global precipitation improves the climate diagnosis, which is addressed in this book. Moreover, tt is useful to enhance the accuracy of weather forecasts and simulations of the global climate.

Error analysis

The necessity to calibrate the above mentioned satellite based operational precipitation estimations even today by means of ombrometer measurements (e.g. ARKIN & MEISNER 1987) underlines the importance of ground based measurements. Consequently there is a necessity, too, to check the data sets in order to remove any errors. Clarity on precipitation characteristics in gauges, its systematic measurement errors, and its different margins for error removals in different time scales is required. SEVRUK (e.g. 1989) carried out intensive investigations of precipitation measurements in the 1980s. He was able to precise the dependencies of these ground-based measurements from instrumental and atmospheric influences. On the base of SEVRUKS work, LEGATES (1987) presented an equation of error analysis for values of monthly precipitation. It can be handled with meteorological information, which is available at measuring sites (cited after RUDOLF 1995):

$$P_{CO} = (1-s)\cdot k_r\cdot(P_g + DP_{wr} + DP_{er}) + s\cdot k_s\cdot(P_g + DP_{ws} + DP_{es})$$

with

P_{CO} = corrected mean monthly amount of precipitation,
P_g = measured mean monthly amount of precipitation,
s = snow fraction of the mean monthly total of precipitation,
k_r = correction factor, wind speed dependent, to be used in case of rain,
k_s = correction factor, wind speed dependent, to be used in case of snow,
DP_w = adhesion loss in case of rain (r) or snow (s), respectively
DP_e = evaporation loss in case of rain (r) or snow (s).

Air temperature and wind speed data can provide the required values for error correction estimates resulting in a corrected total mean of global annual precipitation of 1,138 mm, according to LEGATES (1987), in comparison to an uncorrected value of 1,027 mm. It is possible to mitigate the (strong) influence of the turbulent wind field around precipitation gauges by means of special shields reducing the influence of wind. This does not mean that other corrections are superfluous, but there is an outstanding improvement in comparison to unshielded measurements, for example in case of HELLMANN gauges widely used in Germany (MICHELSON 2004).

When carrying out precipitation measurements above the canopies of forests – so-called gross precipitation measurements – windshields around the gauges can be omitted because forest canopies provide enough roughness elements in the wind field favourable for precipitation measurements (JAEGER 1985). Unfortunately, such measurements are rare because of the high costs and they are not incorporated into the official precipitation measurement networks.

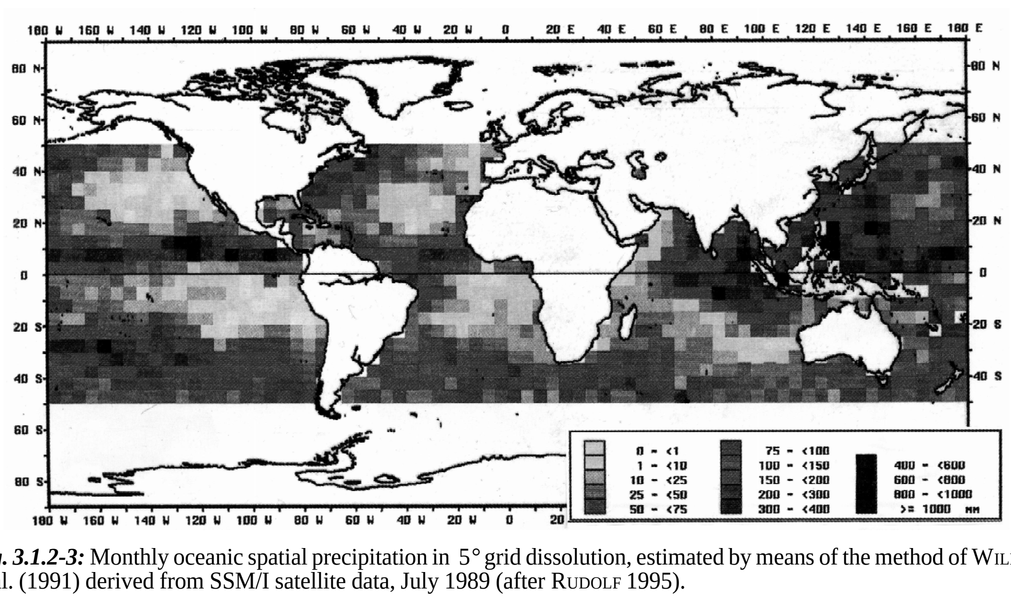


Fig. 3.1.2-3: Monthly oceanic spatial precipitation in 5° grid dissolution, estimated by means of the method of WILHEIT et al. (1991) derived from SSM/I satellite data, July 1989 (after RUDOLF 1995).

Simulation

Of course, precipitation is also simulated by climate models and used for model validation (GRASSL 2002). Such models have become an important tool of climate research. While weather forecast models concern the near future (some days), one aim of climate modelling is the reproduction of past, may be far away from today, where the results can be compared with data sets from different observational sources (direct measurements, proxy data, information from paleogeology). For the other aim, prediction of future climates, such simulation models are the only reasonable tool where even today the reliability and especially quantitative accuracy is restricted, in particular in case of regional climate change (see e.g.: ftp://ftp.zmaw.de/project/uba). However, the comparison of the climate model output with observational precipitation products as described above, from measurements on the ground matches with satellite data (www.gewex.com), is problematical because just these products are used to check and verify climate models.

Fig. 3.1.2-4 compares the simulation results of sixteen different GCMs (Global Circulation Models) (BOERS et al. 1992). Thereby, the object of consideration is the zonally averaged simulated precipitation in the summer of the northern hemisphere (June to August) in mm/day which is presented together with the observational precipitation climatology of JAEGER (1976). The unit mm/day is common in the community of modellers. It should be stressed, that the value of 1 mm/day means, in relation to the whole year, a value of 365 mm. This means, an apparently small change of one mm represents an annual value of some hundred mm. Correlation coefficients between gridded results of observations and corresponding model simulations amount to 0.6–0.8. However, the same holds for the comparison of observational precipitation data sets (HULME 1994).

The evaluation of global precipitation balances

The history of global precipitation climatology products is closely related to the attempts to determine the other components of the water balance. BRÜCKNER (1905) was the first who ventured to present numeric values of all these components, separated for continents and oceans (JAEGER et al. 2006). *Table 3.1.2-1* shows an overall view of this aspect based on the work of many authors. The related Figures reflect an improving data situation as well as improvements with respect to the quality of methods. The differences in *Fig. 3.1.2-5* are due to increasing spatial densities of the data used. Whereas precipitation on continents is nearly exclusively gauge based, energetic approaches and analyses of ship diaries of navies and commercial fleets are playing an important role over the oceans. Even oceanic salt concentrations can be used in the determination of marine water balance components. The last column of *Table 3.1.2-1* shows a considerable magnitude of global precipitation or evaporation value estimations, respectively, in the course of time. However, this magnitude may not be misinterpreted with regard to global climate change. The methodical basics are too different from estimate to estimate. Moreover, the different spatial density of the underlying data and inhomogeneity effects of the related time series cannot be neglected.

Regional distribution of precipitation

Fig. 3.1.2-6 presents a global map of the annual global distribution of precipitation on the basis of an observational data analysis with the normal period 1931 to 1960 as a reference (JAEGER 1976). This analysis is based on climatic atlases providing mean monthly precipitation totals of this period and the compilation of the related annual values.

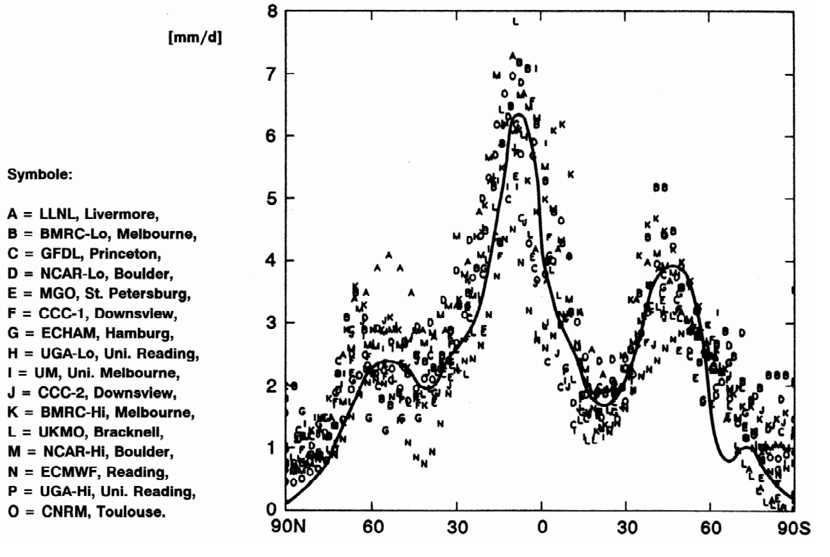
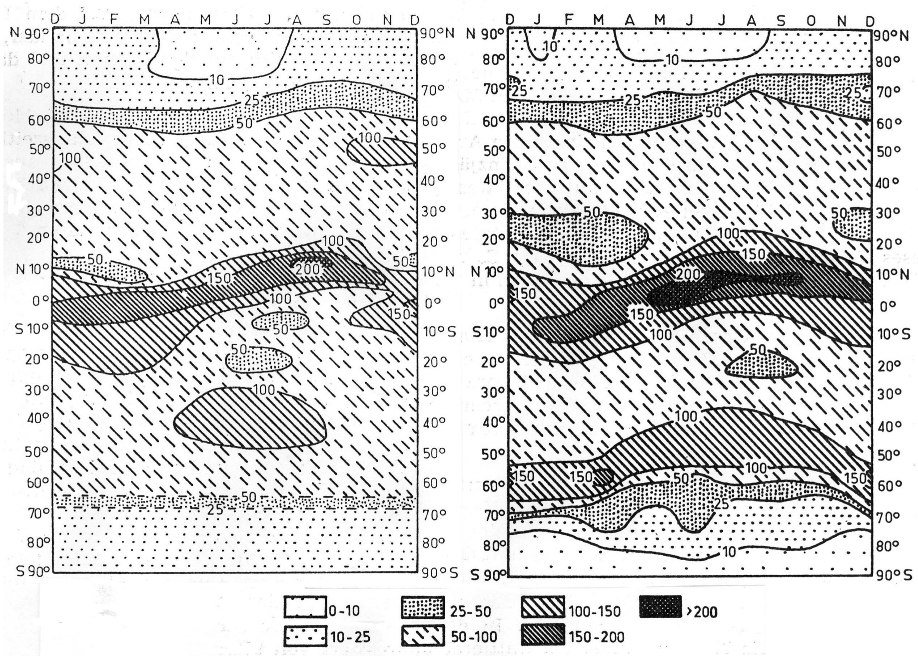


Fig. 3.1.2-4: Latitudinal (zonally averaged) north summer (June – August) precipitation in mm/day according to different GCMs. The letters represent the different institutions explained at the left margin of the graph. The solid line specifies the precipitation distribution after JAEGER (1976). From BOERS et al. (1992).

Table 3.1.2-1: Mean annual components of the water balance in mm for continents, oceans, and the whole Earth , compiled after sources from JAEGER (1976), KESSLER (1985), and RUDOLF (1995). N_L = terrestrial precipitation, V_L = terrestrial evaporation, A_L = continental discharge, N_M = precipitation over the oceans, V_M = evaporation from the sea, N_E = global precipitation, V_E = global evaporation.

Author	**Year**	N_L	V_L	A_L	N_M	V_M	$N_E = V_E$
Johnson	?			376			
Black	1864/81				1,019		
Reclus	1883			188			
Woeikof	1886	524	410	114			
Murray	1887	820	652	168			
Bezdek	1904	813					
Brückner	1905	820	652	168	994	1,064	940
Fritzsche	1906	753	544	208	978	1,064	910
Lütgens	1911					1,402	
Schmidt	1915	753	544	208	670	756	690
v. Kerner	1919				1,006		
Wüst	1922	753	504	249	740	842	743
Kaminski	1925	544	343	202	850	933	760
Ekhart	1930						970
Brooks/Hunt	1930	665			1,102		975
Cherubim	1931	753	504	249	925	1,028	880
Meinardus	1934	665	417	249	1,141	1,244	1,002
Halbfaß	1934	672	349	323	1,136	1,269	1,000
Wüst	1936	665	417	249	823	925	780
Mosby	1936					1,061	
Wundt	1938	665	417	249	958	1,061	880
Lvovitch	1945	719	477	242	1,141	1,241	1,020
Albrecht	1949						770
Möller	1951	665	417	249	≤ 897	≤ 1,000	≤ 832
Reichel	1952	672	470	202	873	956	810
Wüst	1954	672	491	181	897	972	830
Budyko	1955	672	444	228/255	1,025	1,130	930
Mosby	1957	686			907		842
Albrecht	1960	672	450	222	1,047	1,138	940
Budyko	1963	719	410	309/322	1,119	1,252	1,000
Marcinek	1964			242			
Mira Atlas	1964	726	484	242	1,141	1,241	1,020
Sellers	1965						1,004
Strahler	1965	679			828		784
Nace	1968	672	464	208	884	970	820
Keßler	1969	672	403	269	1,136	1,247	1,000
Lvovitch	1969	732	484	249	1,138	1,241	1,020
Mather	1970	712	464	249	1,058	1,161	955
Budyko	1970	719	430	289	1,141	1,260	1,020
Baumgartner & Reichel	1970	672	437	235	1,061	1,158	950
Marcinek	1973	670			1,035		931
Baumgartner & Reichel	1973	746			1,066		973
Schutz & Gates	1972/74						865
Manabe & Holloway	1974	972			1,077		1,041
Jaeger	1976	756			1,099		1,000
UNESCO	1978	800			1,270		1,130
WZN nach Shea	1986	801					
WZN nach Legates	1987	875			1,278		1,138
WZN nach Fiorino	1993	815			1,524		
GPCP Version 1	1993	756			1,141		1,012
WZN mit EZMW Daten	1994	916			1,393		1,217

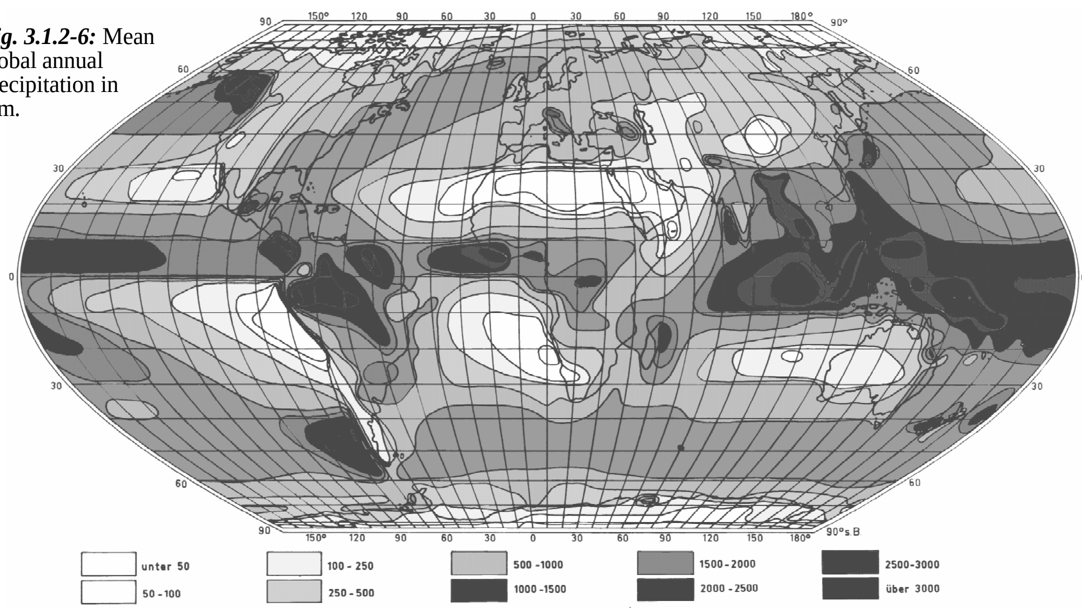
Fig. 3.1.2-5: Annual cycle of precipitation in mm at different latitudes of the Earth. Left after BROOKS & HUNT (1930), right after JAEGER (1976).



KESSLER (1968) estimated the mean annual global evapotranspiration to be 1,000 mm, which should be equal to the mean global value of precipitation. This is supported by further global energy balance estimates and further analyses of precipitation. In consequence, the marine monthly 5° grid point related values were increased by 6% in order to obtain a global annual value of 1,000 mm.

Fig. 3.1.2-7 specifies the mean annual latitudinal (zonally averaged) pattern of the global precipitation according to three different precipitation climatology products (ADLER et al. 2003). They all show small amounts of precipitation gain in the polar regions which is due to temperature controlled small water vapour saturation pressure resulting small amounts of precipitable water. Furthermore, they all show the two hemispheric secondary maxima in the temperate regions, the dry regions within the subtropical anticyclones and the absolute maximum of the inner tropics caused by the ITCZ. It is interesting to

Fig. 3.1.2-6: Mean global annual precipitation in mm.



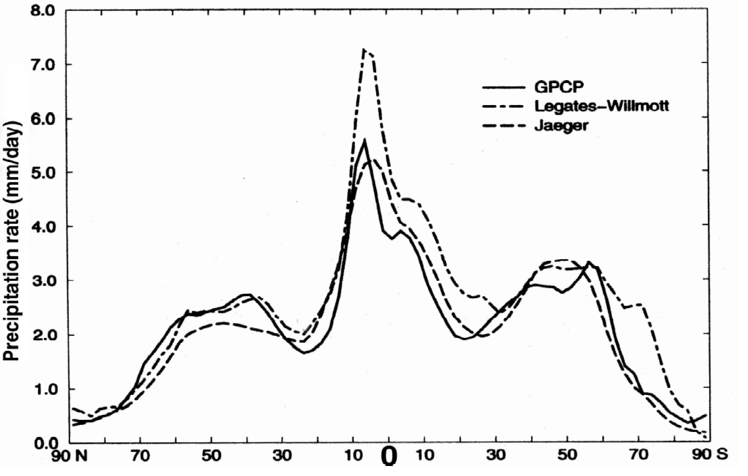


Fig. 3.1.2-7: Latitudinal (zonally averaged) mean precipitation in mm/day.
solid line: GPCP (Global Precipitation Climatology Project)
dashed–dotted line: precipitation after LEGATES & WILLMOTT (1990)
dashed line: precipitation after JAEGER (1976).

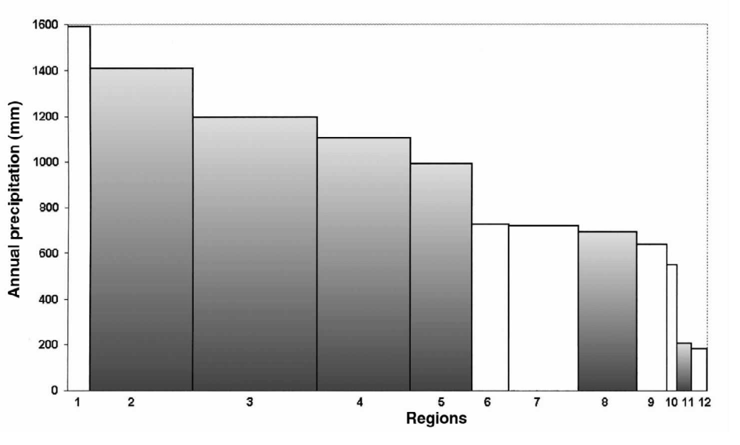


Fig. 3.1.2-8: Mean precipitation within twelve regions of the globe.
1: South America,
2: North Pacific,
3: South Pacific,
4: Indian Ocean,
5: North Atlantic,
6: Africa,
7: Eurasia,
8: South Atlantic,
9: North America,
10: Australia,
11: Arctic Sea,
12: Antarctica.
The x-axis sections are representing the areal expansions of the according regions, respectively.

emphasise the fact that the LEGATES & WILLMOTT (1990) data are showing a deviation of approximately 2 mm/day from the other estimations in the inner tropical belt. LEGATES & WILLMOTT carried out an intense error analysis to correct the precipitation data. However, their corrections in the tropical region may be somewhat too large. Note also the relatively large precipitation (snow accumulation) value of the GCPCestimation at the south pole.

Global and regional changes in precipitation patterns

In *Fig. 3.1.2-8* an analysis of precipitation within twelve different regions of the globe can be found. South America shows the highest average amount of precipitation with around 1,600 mm per year, followed by the oceanic region of the North Pacific. The spatial changes of precipitation during the last century is difficult to estimate. Actually, small scale trends and trends at individual sites are detectable, but the inhomogeneities in the data time series, changing spatial densities of observation networks and changes in methods of handling are leading to biases which hamper a reliable detection of global precipitation changes.

Concluding remarks

The WMO's definition of climate normal periods (CLINOs) was a step to try to separate climatological information (the signal) from the noise. The determination of the global change behaviour in precipitation would require comparable analyses related to other normal periods. Actually, meanwhile the GPCC produces hybridal products of high quality in global resolution of grid fields downscaled to 1° dissolution. However, because this information is available no longer than since 1979, reliable statements with respect to global change are not possible (ADLER et al. 2003). The climate model simulation tool – considered here with a critical view – yields a slight enhancement of precipitation over Europe in the future. However the strongest changes are found in those areas where also the models produce the largest systematically errors (JACOB 1998)♦