

1.5 Distribution and transport of water in the atmosphere

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SUMMARY: *The atmosphere contains only about 0.001 % of the water available on our planet. Despite this small amount its horizontal and vertical distribution plays a key role in the global water cycle and the Earth's climate. The atmosphere has direct connections to most of the other reservoirs and steers the redistribution of water between them with an average turnover time of about 10 days. Evaporation over the oceans exceeds precipitation and over land evapotranspiration amounts only to 2/3 of the precipitation reaching the ground. Consequently, there is a net flux of water from the oceans towards the continents, of course via the atmosphere, which has the largest overall volume of fluxes. Water is present in the atmosphere as solid, liquid, or gas. Water vapour is the most important greenhouse gas in the atmosphere and, in addition, changes of water phase and cloud-radiation interaction contribute strongly to the global energy cycle. Water is also a physically and chemically integral part of other biogeochemical cycles. Although there have been large efforts and improvements in recent years, uncertainties in quantifying the components of the atmospheric water cycle still exist. Observational capabilities on the global scale are not satisfactory at present, but the advent of new satellites devoted to the global observation of precipitation and cloud systems along with dedicated modelling projects certainly will improve the situation.*

Although the atmosphere contains only 0.001% of the available water on our planet, this compartment of the global water cycle has a particular significance.

The atmosphere is in direct contact to all other reservoirs of the water cycle, with the exception of the groundwater. Therefore, the atmosphere plays a central role in the redistribution of water.

Driven by solar radiation, that for a large extent is used for evaporation, there is a perpetual exchange of water between the atmosphere, the oceans, and the land surface. About 90% of the water in the atmosphere emanates from the oceans, lakes and other open waterbodies. Via atmospheric transport and relevant transfer processes a part of the water which evaporated over the oceans reaches the land areas, where it may precipitate and support the existence of life. In addition, weather and climate of a region is significantly influenced by water vapour, clouds and precipitation. Water vapour absorbs and emits strongly in the infrared part of the electromagnetic spectrum. It is the most important greenhouse gas in the atmosphere; it accounts for about 60% of the natural greenhouse effect. Clouds, which backscatter radiation in the visible spectral range and absorb in the infrared, cover large areas of the sky and thereby modify, in a dominant way, the radiation balance and thus climate. Water is also important because it occurs in its three phases in the atmosphere: ice, liquid and gas. During phase changes considerable amounts of energy are bounded or released, and this plays an important role in the local energy budget, thus influencing atmospheric dynamics. The related latent heat flux amounts to about 80 W/m² on global average for a mean insolation of 342 W/m².

Water in the atmosphere is also in physical (clouds, precipitation) as in chemical respect integral part of biogeochemical cycles, which themselves are important components of the climate system. By the processes of rainout and washout of pollutants (gases and aerosol particles) the water cycle contributes crucially to the self-cleansing of the atmosphere.

Knowledge of the atmospheric aspects of the water cycle is also a fundamental basis for hydrological research in support of water authorities, which deal with the availability of drinking water on one side and flooding risks on the other.

To provide profound knowledge on processes controlling the atmospheric water cycle is a great challenge for atmospheric sciences. As major components of the atmospheric branch of the hydrological cycle, in addition to atmospheric storage, the water fluxes connected to precipitation and evaporation are to be determined to an acceptable accuracy. The change of global or regional climate, as anticipated nowadays, is certainly accompanied by a change in components of the water cycle. Due to the lack of reliable data for oceanic precipitation and surface evaporation our quantitative knowledge of atmospheric water storage and water fluxes and their temporal behaviour is still fairly limited.

The water budget of the atmosphere

The atmospheric water budget can be described by the equation (e.g. PEIXOTO & OORT 1992)

$$\partial W/\partial t + \partial W_c/\partial t = -\text{div}_h \mathbf{Q} - \text{div}_h \mathbf{Q}_c + (E-P) \quad (1)$$

here:

W is the water vapour content of a vertical column, which extends from the ground to the top of the atmosphere (this quantity is known as precipitable water),

W_c respectively denotes the column storage of liquid water and ice,

Q is the vertically integrated two-dimensional water vapour flux,

Q_c is the vertically integrated two-dimensional water flux in the liquid and solid phases.

E denotes evaporation and

P is the precipitation.

Generally, the water content in the liquid and solid phases and the related fluxes in the atmosphere are small

($\partial W_c/\partial t \ll \partial W/\partial t$ and $Q_c \ll Q$), often the water budget is approximated by the following simplified equation

$$\partial W/\partial t = -\text{div}_h \mathbf{Q} + (E - P), \quad (2)$$

which is schematically illustrated in *Fig. 1.5.1*. The excess of evaporated water compared to precipitation is balanced by the local rate of water vapour storage and by the horizontal transport of water vapour into and out of the considered column. By spatial averaging the atmospheric water budget can be derived for selected regions (e.g. for the purpose of water budget studies for river catchments).

The first overview requires the consideration of global averages of the water budget components which, for this purpose, should be divided into those representing the oceans and those for the continental areas (see Chapter 1.3). The scheme in *Fig 1.5.2* provides the parts of the global water fluxes through the marine and terrestrial atmosphere as well as the respective water storage. The numbers given in *Fig. 1.5.2* are those published by OKI (1999), within the expected error margins they correspond to those of e.g. CHAHINE (1992), TRENBERTH & GUILLEMOT (1998) and TRENBERTH et al. (2006); see also Chapter 1.3. The given equation (2) can only lead to reliable results if input data is of adequate quality (OKI 1999). Large errors are to be expected in the determination of $\text{div}_h \mathbf{Q}$. By combining all data sources, it is now possible to approximate the global water cycle on an annual mean. Quite large errors are still to be expected if water budgets for smaller spatial scales (regional and smaller) are to be obtained or if the averaging time is less than a year (ROADS 2002).

Although the given values are still not totally certain, it can be deduced from *Fig 1.5.2*, that, on average, over the oceans evaporation considerably exceeds precipitation (see Chapter 1.3). The opposite is true over the land areas, where precipitation amount is much larger than evaporation. Therefore, on average, there is a net transport of water from the oceans towards the land. Based on OKI's (1999) data, this amounts to about 9.3% of the water which evaporates

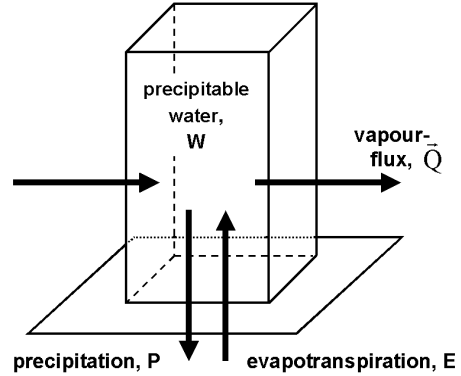


Fig. 1.5-1: Schematic of the terms of a simplified water balance in an atmospheric column.

over the oceans. In other words, almost 35% of the precipitation reaching the land surfaces was originally evaporated over the oceans and subsequently transported by the large scale wind systems towards the continents.

The mean residence time of water in a reservoir can be estimated from the ratio of the mass in the reservoir to the flux of water out of the reservoir. For the atmosphere this estimation leads to a value of about 10 days as a mean residence time. In other words, the atmosphere exchanges its water about 36 times per year and therefore it is the reservoir of the water cycle with the largest rates of exchange.

The fluxes in *Fig. 1.5.2* are given in units of km^3/year . Weighting those values with the appropriate areas allows the presentation of mean annual column heights of precipitation and evaporation, respectively. The global average of the annual precipitation column height as well as that of the evaporation column height amounts to almost 1 metre. Over the oceans the mean annual precipitation sums up to about 1157 mm and the mean annual evaporation to about 1275 mm. The respective heights for the land areas are 669 mm for precipitation and 436 mm for evaporation. Thus the mean evaporation height is roughly three times as high

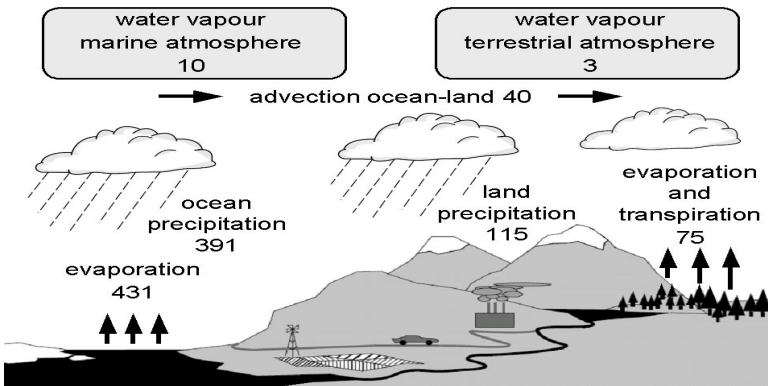


Fig. 1.5-2: Schematic of the atmospheric branch of the water cycle. Storage (in boxes) is given in 10^{15} kg and fluxes in 10^{15} kg/year. Considering a liquid water density of 10^3 kg/m^3 , 10^{15} kg correspond to 10^3 km^3 (data from OKI 1999).

over the oceans compared to the land areas. The evaporation ratio E/P for land amounts to 0.65, which means that on average only about 2/3 of the precipitation reaching the land surfaces evaporates there again. ROADS (2002) presents precipitation and evaporation data including some error estimates for nine representative climate regions distributed over the globe. Estimates of average annual precipitation and evaporation for the different continents based on data tabled in PEIXOTO & OORT (1992) are provided by PAGANO & SOROOSHIAN (2006). As can be expected, considerable differences exist on the continental scale, which range from extremely low values for Antarctica (P: 169 mm, E: 28 mm) to the highest values found for South America (P: 1564 mm, E: 946). As an example for the mid-latitudes of the Northern hemisphere the German Weather Service reports for Germany an average annual precipitation column height of 779 mm for the time period from 1961 to 1990 and a respective evaporation column height of 481 mm.

Water vapour

Water vapour, which accounts only for roughly 0.25% of the mass of the atmosphere, is a highly variable constituent in space and time. The inhomogeneous water vapour distribution is pronounced along the vertical co-ordinate, its concentration decreases drastically with the height above the surface. But also near the ground the concentrations vary by more than three orders of magnitude from 10 parts per million by volume in the coldest regions of the Earth's atmosphere up to as much as 5% by volume in the warmest regions. The latter value is only reached in very hot and humid air masses in the tropics. The tropical atmosphere contains more than three times as much water in comparison to the extratropical atmosphere. Expressed as specific humidity (mass of water vapour in g per 1 kg of humid air), the values near the ground vary between 18 to 19 g/kg in the tropics and 1 g/kg in the polar regions. The large scale distribution pattern of water vapour principally follows that of the temperature. Since the equilibrium vapour pressure strongly increases with temperature (Clausius-Clapeyron-equation), warm air masses can contain many more water molecules compared to colder ones before saturation (equilibrium vapour pressure) is reached. The region with highest humidity on Earth is therefore located over the Western Equatorial Pacific, the area with the highest observed sea surface temperatures. But there are also exceptions to the temperature related

distribution of water vapour. Over the larger scale deserts the water vapour concentration in air is extremely low despite high temperatures, mainly due to large scale sinking motions over these parts of the continents.

If the total water vapour content of the atmosphere would condense, precipitate and stay homogeneously distributed at the surface, a column with a height of about 25 mm would result. Fig. 1.5.3 shows the global distribution of precipitable water based on a multi-year averaging period. The continuous decrease, with only a few exceptions, of the atmospheric water content from equatorial latitudes with about 50 mm towards the poles with typical values around 5 mm is obvious. The exceptions from zonal symmetry are associated with the geographical location of the large mountain ranges along the coasts of the continents. In general, the precipitable water is higher over the oceans than over the continents. For several scientific assessments the fields of relative humidity (ratio of the actual to the equilibrium water vapour pressure) are of interest. A related climatology can be found in PEIXOTO & OORT (1996).

The mean values for a period of ten years as shown in Fig. 1.5.3, may lead to the impression that the global humidity field behaves smoothly. This is only true if a multi-year averaging is used. The inspection of humidity distributions on a daily basis reveals a significantly more complex pattern, which is related to the position of cyclones and the actual wind fields. In a temporal sense, in general, the water vapour distribution changes with seasonal changes in temperature, which are more pronounced in the Northern hemisphere than in the Southern hemisphere. Of course, the temporal variability is closely related to special events in the atmospheric circulation, such as monsoons and ENSO (El Niño Southern Oscillation). Variability within a year is primarily due to monsoon events, while year-to-year variability is attributable to ENSO. In general, interannual variability is less pronounced compared to interseasonal variability (AMENU & KUMAR 2005). A characteristic of the ongoing global climate change is the tendency toward an increase in tropospheric water vapour (HELD & SODEN 2000), which accompanies an increase in global mean temperature and an increase in sea surface temperature. Feedbacks due to changes in atmospheric water vapour amplify the climate system's response to virtually all climate forcings. However, there is a lack of reliable measurements for larger time periods on global scale to support this statement in a quantitative manner. Data for the last three to four decades of the

Pressure range [hPa]	Altitude band [km]	Northern hemisphere [mm]	Southern hemisphere [mm]	Global [mm]
500–300	5.5–9	1.5	1.4	1.5
700–500	3–5.5	5.0	4.2	4.6
ground–700	0–3	19.4	18.4	18.9

Table 1.5.1: Water vapour column content in mm for different altitude bands in the troposphere. The values are hemispheric resp. global averages for time period 1988–1992 (after RANDEL et al. 1996).

twentieth century indicate an increase of the water vapour content for the lower troposphere of the Northern hemisphere (ROSS & ELLIOT 2001).

The non-uniform distribution of water vapour in the atmosphere is even more pronounced in the vertical direction. Here, the generally decreasing temperature with altitude in the troposphere is the crucial factor. The water vapour concentration varies over four orders of magnitude, ranging from one to a few percent by volume near the ground, to a few parts per million (ppm) by volume in the stratosphere. Almost half of the atmospheric water vapour is found below an altitude of 1.5 km. Less than 5% occurs above 5 km and less than 1% in the stratosphere above approximately 12 km (SEIDEL 2002). *Table 1.5.1* provides the water vapour content for different height bands of the troposphere.

Although of minor importance on an amount basis, the water vapour in the upper troposphere/lower stratosphere region (UTLS) needs to be considered (reported values of the water vapour content of the lower stratosphere are typically in the range of 3–7 ppm). Beside its importance for the radiation budget, water vapour plays a key role in the chemistry of this sensitive part of the atmosphere. There is strong evidence for a considerable increase of the water vapour concentration in the lower stratosphere (KLEY et al. 2000).

The distribution and transport of water vapour above the planetary boundary layer (above 1–2 km) is closely linked to the general circulation of the atmosphere. A thorough discussion of the zonal and meridional transports can be found in PEIXOTO & OORT (1992). The upward vertical transport in the equatorial regions is coupled to the ascending branches of the Hadley cells (see Chapter 1.2 in LOZÁN et al. 2001). In the mid-latitudes and higher latitudes this transport is connected to extratropical cyclones. On the regional and local scale the most effective transport of water vapour takes place via convection.

Water vapour enters the atmosphere by evaporation. During this process liquid water or ice at the surface is transferred to the gaseous phase. As can be seen in *Fig. 1.5.2*, evaporation over the oceans is the dominant source

for the atmospheric water budget. The rate of evaporation depends on several factors, for example, among others, the local energy budget, the availability of water, the actual vapour pressure, the turbulent exchange of air near the surface, the surface structure, as well as the natural cover. Strictly, the term evaporation is used only for the phase change over open water surfaces. This includes the water on the surface of vegetation (intercepted water). Plants also give off water vapour to the atmosphere through their leaves or needles (90% through their stomata), this process is called transpiration. The rate of transpiration depends beside on meteorological parameters (solar radiation, humidity, temperature, wind) strongly on the type of plant, the habitat, the season and on soil parameters. Evaporation from the surface and transpiration are not easy to distinguish above vegetated surfaces, therefore, often the expression evapotranspiration is used for the sum of land surface evaporation, interception, evaporation and transpiration. Furthermore, the term potential evaporation is used in contrast to the actual evapotranspiration to denote the amount of water that could be evaporated and transpired if there was sufficient water available. For many land areas, because of an insufficient water supply, the actual evapotranspiration is far below the potential one. Of the 30-years average of 481 mm for evaporation over Germany (previously mentioned), according to the German Weather Service, 328 mm are due to transpiration, 72 mm from evaporation of intercepted water and 42 mm evaporated at the surface. But on global scale 90% of atmospheric water comes from evaporation, while the remaining 10% is from transpiration.

Clouds

Clouds can be seen as the connecting link between water vapour on one side and precipitation on the other. Precipitation is exclusively produced by clouds, but it also has to be mentioned, that not all clouds lead to precipitation. Clouds are the visible evidence for the existence of the liquid or solid phase of water in the atmosphere. Although clouds on average cover more than 60% of the Earth's

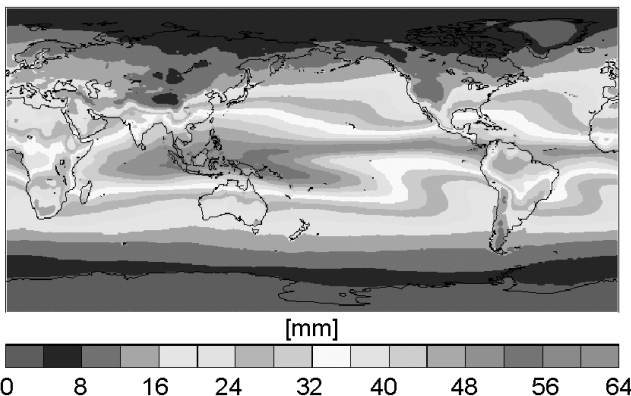


Fig. 1.5-3: The global distribution of total atmospheric water vapour above the Earth's surface (precipitable water). The given values are averages for the period 1988–1997 and include data from both satellite and radiosonde observations (after SEIDEL 2002).

surface, the amount of water they contain is comparatively small. It accounts for only 0.25–0.3% of the total water in the atmosphere. Despite this relatively small amount of water, clouds play a crucial role in the global water cycle. The microphysical processes in clouds eventually form large cloud particles, which may start falling as rain, snow or graupel. Precipitation is an effective path to bring water from the atmosphere back to the oceans or land surfaces. Beside this vital role, clouds contribute to the vertical and horizontal redistribution of water vapour in the atmosphere. As a result of their significance in the radiation and energy budget of the Earth (QUANTE 2004), in many regions of the globe clouds determine the rates of evaporation and influence regional and local circulation systems through the release of latent heat or heating- and cooling rates associated with radiative processes.

Substantial requirement for the effective formation of clouds are the water vapour saturation of the environment and the existence of suited cloud condensation nuclei (CCN) and ice nuclei (IN), respectively. Water vapour saturation can be reached in several ways. In the majority of cases of cloud formation, saturation is the result of lifting of air masses with subsequent (adiabatic) cooling. Corresponding vertical motions are mainly due to thermal convection (cumulus, cumulonimbus), active and passive lifting in connection with movements of frontal systems (cirrostratus, altostratus, nimbostratus), and forced lifting by mountain ranges (orographic lifting). Microphysical processes during cloud formation and evolution are numerous and complex (see e.g. PRUPPACHER & KLETT, 1997). Here, in addition, aerosol physics and chemical aspects play an important role. Thorough knowledge of the microphysics of clouds is crucial for understanding the formation of precipitation.

Many different types of clouds exist and detailed classification schemes have been developed, but will not be presented here. In general, clouds are classified as high-level, mid-level, and low-level clouds (stratiform clouds) and as clouds with large vertical extent (convective clouds). According to the phase of the cloud particles liquid water-, ice water-, and mixed phase clouds can be distinguished. Often a distinction between precipitating and non-precipitating clouds is also made. Global average amounts for different cloud types according to surface observation climatologies (WARREN & HAHN 2002) are shown in Table 1.5.2. The most common types are stratocumulus, altocumulus and cirriform clouds, the dominance of low-level stratus and stratocumulus over large areas of the oceans is obvious in the data. The annual average total cloud cover from surface observations (1982–1991) is 64% (54% over land and 68% over the oceans) (WARREN & HAHN 2002). The annual total cloud amount from the International Satellite Cloud Climatology Project (ISCCP)

considering data from 1986 to 1993 is 68% (58% over land and 72% over oceans) (ROSSOW & SCHIFFER 1999).

The liquid water content or ice water content of clouds is highly variable. Typical values are (range in brackets): marine stratocumulus 0.4 g/m³ (0.1–0.6 g/m³), continental stratocumulus 0.3 g/m³ (0.03–0.45 g/m³); cumulus 1 g/m³ (0.5–2.5 g/m³), cumulus congestus und cumulonimbus up to 4 g/m³; cirrus 0.02 g/m³ (0.0001–0.3 g/m³).

The global distribution of cloud amount as annual average for the time period 1983–1997 is shown in Fig. 1.5.4. As can be expected, the cloud cover is continuously high in the equatorial belt due to strong convection along the Inter Tropical Convergence Zone (ITCZ). High cloud amounts also occur in the regions of the extratropical storm tracks along the polar fronts in mid-latitudes (50–60°). Minima of cloudiness are observed in the zones of downward motion in the subtropics associated with the Hadley cells. Lowest values of cloud amount are found over the desert areas. A further examination of satellite cloud climatologies (figures not shown here) reveals in the tropics and subtropics the existence of low level, often quite homogeneous, stratocumulus fields at the western rims of the large continents over ocean areas, which are typically relatively cold. Largest coverage with high clouds is found in the tropics, many of these are sheared off the tops of deep cumulonimbus towers. Consistent global climatologies for cloud water content over land and ocean areas are currently not available and only rough estimates are possible. The preliminary evaluation of the ISCCP data (ROSSOW & SCHIFFER, 1999) with respect to cloud water content come to a global average cloud water path falling in the range of 60–80 g/m² (or 0.006–0.008 cm) (pers. communication W. Rossow).

Due to their tremendous influence on the solar and terrestrial radiation and the formation of precipitation, clouds are an important factor determining climate. The different types of clouds are embedded in the climate system by a multitude of dynamical, thermodynamical and related feedback processes. Substantial knowledge on changes in cloud properties over time periods of decades would lead to an improved understanding of their role in

Table 1.5.2: Cloud type amounts from surface observations; cloud overlap is possible (from WARREN & HAHN 2002).

Cloud type	Annual average amount [%]	
	Land	Ocean
Stratus	5	11
Stratocumulus	12	22
Cumulus	5	12
Cumulonimbus	4	4
Nimbostratus	5	6
Altostratus	4	} 22
Altocumulus	17	
Cirriform	22	13

current and future climate change. Unfortunately the data currently available is not sufficient to allow for reliable statements on changes in global cloud cover for longer periods back in time. I.e. large inadequacies exist in monitoring long-term changes in global cloudiness with surface and satellite observations (DAI et al. 2006). Changes in other cloud parameters are even more difficult to assess on a global scale. Nevertheless, for some larger regions there is evidence of an increase of cloud amount. The IPCC (HOUGHTON et al. 2001) reports an estimated increase of about 2% in cloud cover over land for the last one hundred years. This increase is in many regions significantly correlated with a change in the daily temperature range (maximum minus minimum temperature). For ocean areas only a few ship-based observation can be used for robust estimates on regional changes in cloudiness. Long-term upward trends in altostratus and nimbostratus clouds are found for the mid-latitude North Pacific and North Atlantic Oceans (PARUNGO et al. 1994). NORRIS (1999) found an increase in total sky cover of approximately 2%, and an increase of approximately 4% in low cloud cover over the oceans in his analyses of ship reports between 1952 and 1995. Surface observations have been analysed to document changes in cirrus clouds (MINNIS et al. 2004), and low-, mid-, and upper-level cloud cover (NORRIS 2005), and it is found that upper-level cloud cover may have declined by 1.5% (of sky cover) over global land from 1971 to 1996. High ice clouds in the tropics, which play a special role in controlling climate of that region, show an increase in cover of about 2% since 1978 (WYLIE et al. 2003). To assess the impact of these changes on climate is not an easy task. Relevant studies need to consider possible changes in cloud height and thickness, in cloud overlap, and in microphysical and radiative properties, which are, if at all, only rudimentarily known on global scale. Changes in radiative properties and the life time of clouds are closely coupled to the distribution of aerosols, which is also likely to be altered in a changing climate. All of these topics are presently subjects of intensive research.

Precipitation

Via precipitation, the water, which originally evaporated at ground level, is brought back from the atmosphere to the Earth's surface. Precipitation includes rain, snow, sleet, grauple, and hail. Although precipitation and its distribution in space and time is essential for life on Earth, the cloud processes leading to precipitation size particles are not known in full detail. The description of the relevant microphysics and related modelling activities are one of the major tasks of cloud physics. In the centre of interest are the growth processes, which eventually lead to particle sizes allowing for terminal velocities sufficient for the particles to reach the ground before they evaporate. In the case of water droplets, particles with radii larger than 0.1 mm are formally called rain drops. During the development of precipitation various macro- and microphysical processes are involved, which can not be treated here in detail (see e.g. PRUPPACHER & KLETT 1997). The size distribution and number concentration of cloud particles play an essential role during the formation process, as does the vertical wind component (updrafts). Also, the temperature at cloud level plays an important role, as it essentially determines the phase of cloud particles. In pure water clouds (warm rain process, Bowen-Ludlam-process) precipitation formation results from coalescence (merging of water droplets of typically different sizes after collision, which is favoured by differing relative fall velocities). In mixed phase clouds, consisting of supercooled liquid droplets and ice crystals, the Bergeron-Findeisen-process is the dominant way of precipitation formation. Ice crystals acquire water molecules from nearby supercooled water droplets. As these ice crystals gain mass they may begin to fall, acquiring more mass as coalescence occurs between the crystal and neighbouring water droplets. The resulting precipitation can reach the ground either in liquid or solid phase depending on the local atmospheric conditions. Precipitation from pure ice clouds is the result of ice crystal growth by sublimation of water vapour and by aggregation. The precipitation efficiency of clouds, on average, is in the

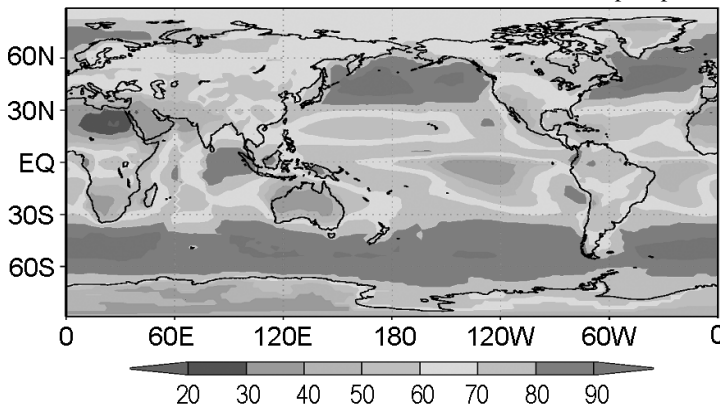


Fig. 1.6-4: Annual average cloud amount (1983–1997) in % from the International Satellite Cloud Climatology Project (ISCCP), which uses data from geostationary and polar-orbiting satellites (ROSSOW & SCHIFFER 1999).

order of 30%, thus only the minor part of the cloud water is transferred to precipitation. It should also be mentioned that a non negligible fraction of particles falling from clouds evaporate before they reach the surface.

In general, related to the external forces supporting the formation, precipitation is distinguished according to convective, stratiform (occurs as a consequence of slow ascent of air in warm fronts), and orographic precipitation. Stratiform compared to convective precipitation typically covers larger areas and has a much longer duration. Convective precipitation falls as showers, with rapidly changing intensity, which can be very high. It occurs briefly and only over smaller areas, as convective clouds have limited horizontal extent. Convective precipitation is most important in the tropics. Graupel and hail always indicate convection. In midlatitudes, convective precipitation is associated with cold fronts (often behind the front) and squall lines.

Although most precipitation falls over the oceans, precipitation reaching the land surfaces is of crucial importance for life on Earth. On long-term average 2/3 of the water precipitated over land returns back to the atmosphere via evapotranspiration, the rest contributes to the surface runoff or eventually reaches the groundwater. The distribution pattern of precipitation shows tremendous spatial variation, that is caused by or largely attributable to the general circulation, the temperature distribution, the non-uniform land-ocean distribution, and orographical conditions. The high spatial and temporal variability of precipitation has a large impact on vegetation, droughts, and flooding. Fig. 1.5.5 shows the global distribution of annual means of precipitation expressed in mm per day. The global and also the regional distribution of precipitation occurrence has a similarity with the distribution of cloudiness; but this is not necessarily true for the amount of precipitation. Generally, the annual mean of precipitation amount decreases from the equator towards the poles. But larger inhomogeneities exist in this averaged distribution, explained by the aspects mentioned above. About 2/3 of

global precipitation occurs in the latitude band between 30°N and 30°S. Most intensive belts of precipitation are connected to the pronounced convection in the Inner-Tropical Convergence Zone (ITCZ) and the Southern Pacific Convergence Zone (SPCZ). Here a persistent precipitation amount of more than 2,000 mm per year can be found, in some regions the value of 3,000 mm per year is exceeded (i.e. the equatorial regions of South America, Africa, and Indonesia). A secondary maximum in precipitation amount in both hemispheres occurs over the midlatitudes along the tracks of the extratropical cyclones, where considerable precipitation is produced by their frontal systems.

Extremely dry areas can be found in the subtropical regions that are under the influence of large, almost permanent, anticyclones. Huge parts of the subtropical continents, such as Africa and Australia, are covered by deserts, where precipitation is very low. Over the polar regions the water vapour content of the atmosphere is extremely low and accordingly the amounts of precipitation are typically very low with annual amounts less than 200 mm per year.

The global average annual precipitation amount, as already mentioned further above, is about 990 mm per year. The world record in annual precipitation amount is reported for Cherrapunji (India, Khasia mountains), where 26,461 mm/year were recorded from August 1860 to July 1861. On the other hand, there are areas that do not receive any precipitation, sometimes for many consecutive years, e.g. the region Assuan in Egypt received almost no rain over the course of 20 years between 1901 to 1920.

In many regions around the Earth the temporal variations in precipitation activity are noticeable. Beside pronounced daily cycles there are strong seasonal cycles, as well as non-periodical variability. A prominent seasonal phenomenon is the tropical rain falls which are associated with the monsoon circulation. Remarkable non-periodical deviations from longer term means of precipitation amount can be observed in regions that are influenced by El-Niño-Southern Oscillation (ENSO).

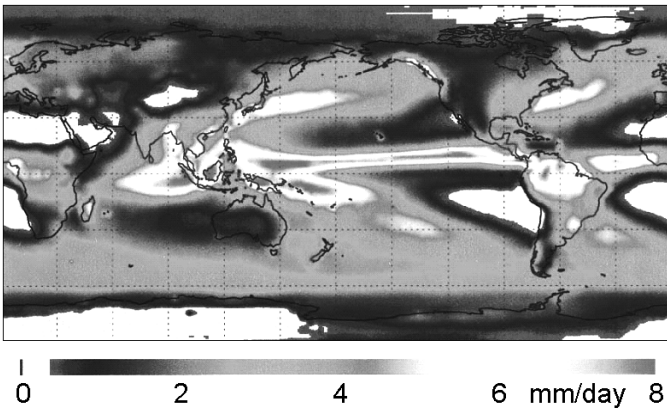


Fig. 1.5-5: Annual mean precipitation in mm/day. The data is representative for the 23 year period from 1979 to 2001 and is based on a merged analysis that incorporates precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data, and surface rain gauge observations (ADLER et al. 2003).

The spatial variability of precipitation is most notably pronounced on small scales (i.e. strong shower activity). These extreme events are of foremost interest for water and traffic authorities as well as for the agricultural sector.

A part of the precipitation on regional scales comes from precipitation recycling (ELTAHIR & BRAS 1996). Precipitation recycling denotes that part of the precipitation in a region, which originates from water evaporated in that region (the contribution of local evaporation to local precipitation); the other part is formed from water vapour advected into the area. Any study on precipitation recycling concerns how the atmospheric branch of the water cycle works, namely, what happens to water vapour molecules after they evaporate from the surface, and where will they precipitate? In general it can be stated that the part of the precipitation from regionally evaporated water gets lower when the considered region is smaller. The recycling ratio varies strongly between winter and summer. In summer the importance of horizontal transport of water vapour declines. According to TRENBERTH (1999) the contribution by precipitation recycling on the 500 km scale accounts for about 10% on global average; on the 1,000 km scale this value is about 20%. The latter value means that on average 80% of the humidity, which contributes to the precipitation, comes from distant regions. The associated atmospheric transport covers distances of more than 1,000 km. Quantitative descriptions of regional water cycles need, of course, to consider the local conditions. However, the results of TRENBERTH (1999) underline the importance of long-distance transport of water vapour for the global distribution of precipitation.

In connection with the increase of global temperature over the last decades and the increase in water vapour concentration in the lower troposphere, as observed for the Northern hemisphere, the question arises as to, whether an associated change in precipitation occurs. The IPCC report (HOUGHTON et al. 2001) states with high confidence an increase of precipitation on the order of 5–10% since 1900 for the mid-latitudes and higher latitudes of the Northern hemisphere. This increase is most likely attributable to strong or even extreme events (TRENBERTH et al. 2003).

Some final remarks

The tremendous importance of water in the atmosphere for the global water cycle and the climate of the Earth is still confronted with considerable uncertainties in the quantification of the various storage and flux components and their variability and changes in the branches of the atmospheric water cycle. Our quantitative knowledge of these components is still fairly limited because of a lack of reliable data, which is due to deficiencies in global coverage of high-quality measuring systems for the acquisition of precipitation, water vapour and cloud parameter fields

(TRENBERTH et al. 2006). These fields would be needed to form a basis for the construction of consistent climatological data series and for modelling studies concerning the water exchange between the reservoirs. For an improvement of weather forecast and climate simulation studies in connection with global change an enhanced knowledge of the frequency, duration, and intensity of precipitation on global and regional scale is needed.

A few programmes do exist which are devoted to an improvement of the understanding of the global water cycle. The programmes are also intensely concerned with its atmospheric branch. One of the more comprehensive activities is the Global Energy and Water Cycle Experiment (GEWEX), a core project of the World Climate Research Programme (WCRP). GEWEX, an integrated program of research, observations and science activities, began in 1988 and is currently in its second phase (see www.gewex.org). Its strategy is to combine results of observations and modelling of the water and energy cycle for the atmosphere, the land surfaces and the upper ocean layers. The ultimate goal of GEWEX is the improved prediction of global and regional climate change. As central activities, the continental scale experiments should be mentioned. These concentrate on the development of the best available water and energy budgets for selected regions of the globe. Quite a few of the sub projects within GEWEX are ultimately devoted to the atmospheric branch of the water cycle.

Based on all currently ongoing research activities, an improvement of the quantitative determination of the components of the atmospheric water cycle might be expected in near future. An improvement of the parameterised physics and the horizontal as well as the vertical resolution of the models, which are used for four dimensional data assimilation projects (4D-VAR), will have a substantial impact on further development in this field. Extended studies on these aspects are currently under way at several operational or research centres such as the European Centre for Medium-Range Weather Forecasts (ECMWF) or the US-National Center for Atmospheric Research (NCAR).

The extension of the global observing system within the upcoming years will specifically enhance the progress in the quantitative determination of precipitation over the ocean areas and knowledge of vertical profiles of cloud water and cloud ice content. Here a combination of satellite based active remote sensing with passive sensors is a key to advancement. Extended ground based networks of Doppler radar systems, wind profilers, water vapour lidars in conjunction with improved radiosondes (with respect to water vapour measurements) will permit further comprehensive and improved studies of the water budget for subsystems on continental scale, creating a sound basis for the evaluation of models used for regional and global predictions of the atmospheric water cycle in a changing climate.