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Water in the Earth's atmosphere

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Abstract. Water is the key to our existence on this planet and it is involved in nearly all biological, geological, and chemical processes. Life on Earth depends very much on the remarkable properties of water. The availability of freshwater is for many regions one of the key concerns in connection with global climate change. 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. Progress is urgently needed to adequately contribute to the answer of one of the central questions in the context of global warming: Is the hydrological cycle accelerating?

1. INTRODUCTION

Water is an extraordinary substance, due to its in many respects unusual behaviour it is irreplaceable in a multitude of natural and engineering processes. Water enters into the operation of the climate system in a remarkable variety of ways [1]. 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 ground water. 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 oceans, the atmosphere 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 [2]. 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 [3-7]. 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/m^2 on global average for a mean insulation of 342 W/m^2 [8].

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 [9-11]. Tropospheric chemistry is largely influenced by clouds [12-16]. By the processes of rainout and washout of pollutants (gases and aerosols) the water cycle contributes crucially to the self-cleansing of the atmosphere. Back on earth precipitated water is a powerful geologic force shaping and altering the landscape by weathering [17] and erosion [18,19], partly because of its acidity and partly because water expansion during freezing.

In the stratosphere water in its solid phase as constituent of polar stratospheric clouds (PSCs) plays a critical role in heterogeneous chlorine chemistry and, thus, in Antarctic/Arctic ozone depletion [20,21].

Knowledge of the atmospheric aspects of the water cycle is also a fundamental basis for hydrological research in support of the operational water management community and policymakers, which deal with the availability of drinking water on one side and flooding risks on the other [22-25].

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. Progress is definitely needed, since one of the central questions in the context of future global warming is: to what extent will the hydrological cycle accelerate? In this overview the main topics around water in the Earth's atmosphere are covered, several references are included, which could serve as a starting point for more detailed assessments.

2. WATER

Water is the only chemical compound on this planet that occurs naturally in all three physical states: solid, liquid and vapour. It existed long before any form of life evolved, but, since life developed, its properties came to exert a controlling influence over many biochemical and physiological processes that make our life possible [26]. It is because of this close connection to life that many missions to other planets concentrate on the detection of water. Here, we start with a few general remarks on water, since in atmospheric sciences, it is not widely perceived, that there are still basic questions to be answered concerning the physical details of one of its most important substances. The water molecule as well as local molecular structures have been, and still are, the subject of intensive theoretical and experimental study.

Water exhibits an impressive array of anomalies in its physical properties, among these are the well-known expansion when it freezes at normal pressure and the presence of a liquid-phase density maximum at +4°C. Compared to "similar" substances water has a high melting point, high boiling point and a high critical point. Other features are the high specific heat capacity and surface tension of liquid water. Additionally, the temperature dependence of its compressibility, heat capacity and thermal expansion coefficient show an unusual progression. All these anomalies have important consequences which make up for the special role water plays in the atmosphere. E.g. evaporation, latent heat fluxes, saturation pressures, cloud droplet and precipitation formation, as well as supercooling would all look much different without these peculiar properties.

Water seems, at first sight, to be a very simple V-shaped molecule, consisting of just two (light) hydrogen atoms attached to an (relatively heavy) oxygen atom by strong covalent bonds. There are very few molecules that are smaller or lighter. The approximately 16-fold difference in mass gives rise to its ease of rotation and the significant relative movements of the hydrogen nuclei. The principal vibrations and rotations are at frequencies in the terrestrial radiation spectrum, they make water vapour to be the most important greenhouse gas on Earth. These frequencies are modified in the condensed states, where intermolecular effects become important. Ultimately, the detailed interaction of a water molecule with its

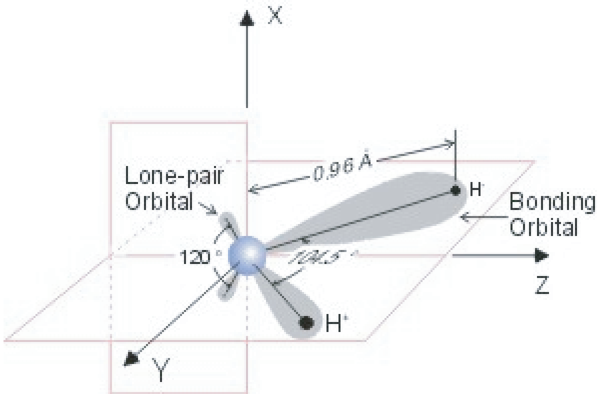

Figure 1. Geometry of a free H_2O molecule in equilibrium.

neighbours, also called "water structure", is of key importance for understanding the unique properties of aqueous systems on the macroscopic scale.

An isolated H_2O molecule is sketched in figure 1, the equilibrium geometry shows an O-H bond length of 0.957 Å, and the H-O-H angle is 104.52°. It is of crucial importance for the properties of water and ice that the molecule is bent. The bent form results in a dipole moment and determines the ways the molecules fit together. The water molecule contains ten electrons, two from the hydrogen atom. Because of the presence of the hydrogen nuclei the electronic charge is not distributed symmetrically around the oxygen nucleus, it is drawn towards the hydrogen nuclei with the consequence of a dipole moment.

The polarity of each water molecule results in a weak attraction between it and other water molecules. Linus Pauling [27] called the favourable attraction between two water molecules a hydrogen bond. Each water molecule can simultaneously participate in four such bonds, sharing its two hydrogen atoms with two neighbouring water molecules and sharing two other hydrogen atoms associated with two other neighbours. Only 5% of the total energy is in the hydrogen bond, which still is about 17 times stronger than typical bonds between molecules in liquid phase. Ice is a tetrahedral ordered array of such hydrogen bonded water molecules, resulting in a network of tetrahedrons. Liquid water is a disordered network of such bonded waters. Considerable revision has occurred to details of how the liquid is geometrically organized by hydrogen bonding, and the earlier views that water should be seen as modified versions of ice had to be modified. Although the hydrogen atoms are often shown along lines connecting the oxygen atoms, this is now thought unlikely even in ice, with non-linearity, distances and variance; all increasing with temperature [28]. In liquid water, the lifetime of a hydrogen bond is in the femtosecond to picosecond order, and it is broken in the course of translational and rotational motions [29]. It has proven difficult to transform this insight into a quantitatively accurate molecular theory of liquid water. A detailed description of the hydrogen bond network in liquid water is the key to understanding its unusual properties.

The present consensus seems to be that liquid water is a macroscopic network of molecules connected by frequent but transient hydrogen bonds, which allow unbonded neighbours to occur in numbers that vary with temperature and pressure. Anomalous properties of water arise from the competition between relatively bulky ways of connecting molecules into local patterns characterized by strong bonds and nearly tetrahedral angles and more compact arrangements characterized by more strain and bond breakage.

The most recent discussion on the molecular structure of liquid water is about, whether it consists mainly of structures with two strong hydrogen bonds (with the possibility that water molecules form chains or closed rings), in contrast to the commonly accepted semi-tetrahedral structure close to the four bonds found in the tetrahedral structure of ice [30-33]. These details are important for a better understanding of the exceptional properties of liquid water, and at the end for a clearer answer to why water is essential for life including the many processes determining climate.

As already mentioned, in ice H_2O molecules arrange in a tetrahedral hydrogen bonding with little distortion. Currently there are 15 different solid phases of water known, the most common one under atmospheric pressure and temperature conditions is the Ih phase, the normal hexagonal crystalline ice. So, virtually all ice in the Earth's atmosphere is ice Ih with the exception of only a small amount of ice Ic (cubic ice, formed at low temperatures, 130 –150 K, and stable to 200 K). Under high pressure other phases of ice exist, the tetrahedral hydrogen-bonding is still the preference, but some bending and deviations from linearity occur, since a higher packing density is sought for [34]. Ice in the atmosphere under real world conditions appears in many different crystal shapes [35], many of them with different types of impurities [36].

There are several general references on liquid water [26, 34, 37-43], while only a few more general texts on ice can be recommended [44-46]. An excellent and well kept source of information on liquid water is the internet site "www.lsbu.ac.uk/water/index.html" compiled by M. F. Chaplin from London South Bank University. The books by Ball [47] and Kandel [48] should also be mentioned, which set water into a broader perspective, they tell the story of water from the big bang through the rise of civilization to present.

The phase water occurs in depends on the temperature and pressure it is exposed to. At the normal range of atmospheric pressures and temperatures on Earth water can exist in all its three basic states, as is evident from its phase diagram in Figure 2, which shows the phase transition curves as function of temperature and partial pressure (see [49]). The Earth trajectory in figure 2 driven by an increasing water vapour greenhouse effect intercepts the water phase curves in the vicinity of the triple point of water (273.16 K), allowing the formation of a complex hydrological cycle. The curve for Venus, in contrast, because of a start with a considerably warmer primitive surface temperature does not intercept any of the water phase transitions at all, water stays as a gas. The state curve for Mars starts at a relatively low temperature (∼240 K; not shown here) and rapidly intercepts the vapour-ice phase transition. Martian

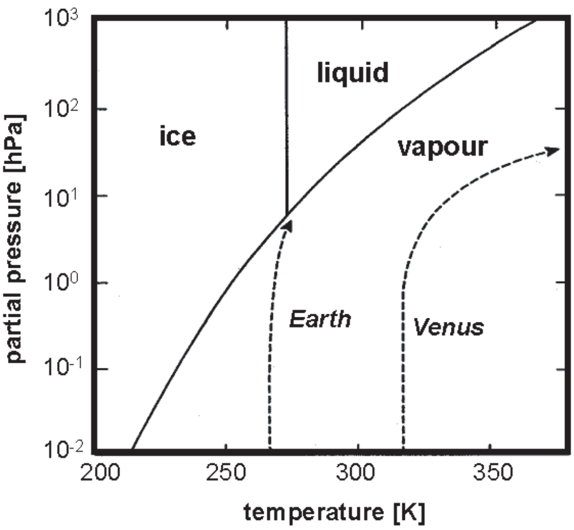

Figure 2. Phase diagram of water illustrating the possible occurrence of the three states of water for the range of temperatures observed at the Earth's surface and in the lower atmosphere (∼190K to 325 K and 0 to 50 hPa partial pressure range at the surface).

water occurs in relatively small concentrations but can exist either as gas or as ice. In the upcoming sections the water on Earth will be the subject.

3. THE GLOBAL HYDROLOGICAL CYCLE

Water is present in all compartments of the Earth's system which determine the climate of our planet. Appoximately 71% of the Earth's surface is covered with salty water in the oceans. Some parts of the continents are covered by fresh water (in lakes and rivers) and solid water (as ice or snow). Some water is existent in vegetation and in the atmosphere. Several studies deal with a quantitative description of the available water and its movement (e.g. [50-52]), a comprehensive review of freshwater resources can be found in [53-55]. Table 1 provides estimates of the water distribution, beside the volume and its share of the total water also the share of fresh water is given, which for obvious reasons is of special interest for mankind. It can be seen that only less than 3% of the Earth's available fresh water occurs in lakes and streams. So the exchange between the reservoirs is of vital importance for life.

Table 1. Distribution of Water on Earth (from [50]).

			Share of world reserves (%)	
Form of water	*Area covered* ($1000\,km^2$)	*Volume* ($1000\,km^3$)	*of total water reserves*	*of reserves of fresh water*
World ocean	361,300	1,338,000	96.5	-
Total groundwater(1)	134,800	23,400	1.7	-
Fresh ground water	134,800	10,530	0.76	30.1
Soil moisture	82,000	16.5	0.001	0.05
Glaciers and permanent snow cover	16,000	24,000	1.74	68.7
Antarctica	14,000	22,000	1.56	61.7
Greenland	1,800	2,300	0.17	6.68
Arctic islands	230	83.5	0.006	0.24
Mountainous areas	220	40.6	0.003	0.12
Ground ice in zones of permafrost strata	21,000	300	0.022	0.86
Water reserves in				
Lakes	2,000	180	0.013	-
Fresh water	1,240	91	0.007	0.26
Salt water	820	85.4	0.006	-
Marsh water	2,700	11.47	0.0008	0.03
Water in rivers	148,800	2.12	0.0002	0.006
Biological water	510,000	1.12	0.0001	0.003
Atmospheric water	510,000	12.9	0.001	0.04
Total water reserves(2)	**510,000**	**1,390,000**	**100**	-
Fresh water(2)	148,800	35,000	2.35	100

(1) Not including ground-water reserves in Antarctica.
(2) Deviations are due to rounding.

The hydrological cycle is the perpetual movement of water throughout the various components of the Earth's climate system. Although it is a continuum, its description usually begins with the evaporation of water from the ocean driven mainly by solar radiation. Under the influence of certain changes in temperature and/or pressure in the atmosphere, the moisture might condense and eventually return to the Earth in form of rain, hail, sleet or snow. Some of the water that precipitates over land does not evaporate again and enters lakes or rivers or infiltrates into the soil and contributes to the ground water. The water is brought back to the oceans mainly by rivers and ground water flow. It are these streams in addition to the precipitation over the oceans, which close the water cycle. A sketch of the various fluxes within the water cycle is presented in figure 3. It has to be mentioned that the hydrological cycle

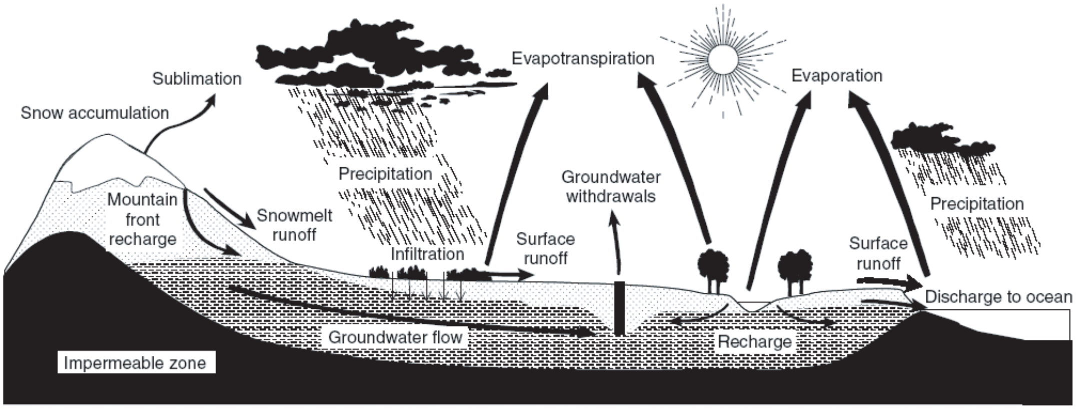

Figure 3. Schematic diagram of the various fluxes within the hydrological cycle (figure provided by T.C. Pagano).

is characterized by its variability in space and time, the time scales among the different reservoirs vary considerably, the atmosphere having the fastest overturning times (see below). Quite a large amount of water is stored for long times in the antartic and arctic ice sheets.

The water cycle is intricately intertwined with many other global and regional environmental cycles [10], most prominently the global energy cycle ([56, 57]. Additional information on the overall global water cycle can be found in e.g. [1, 49, 52, 58, 59].

4. THE WATER BUDGET OF THE ATMOSPHERE

The atmospheric water budget can be described by the equation (e.g. [51])

$$\partial W/\partial t + \partial W_c/\partial t = -\mathrm{div}_h \mathbf{Q} - \mathrm{div}_h \mathbf{Q_c} + (E - P) \tag{1}$$

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.
- $\mathbf{Q}$ is the vertically integrated two-dimensional water vapour flux.
- $\mathbf{Q}_c$ is the vertically integrated two-dimensional water flux in the liquid and solid phases.
- E denotes evaporation and
- P is the precipitation.
- h subscript stands for horizontal

Generally, the water content in the liquid and solid phases and the related fluxes in the atmosphere are small ($\partial W_c/\partial t << \partial W/\partial t$ and $\mathbf{Q_c}, << \mathbf{Q}$), often the water budget is approximated by the following simplified equation

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

which is schematically illustrated in figure 4. 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

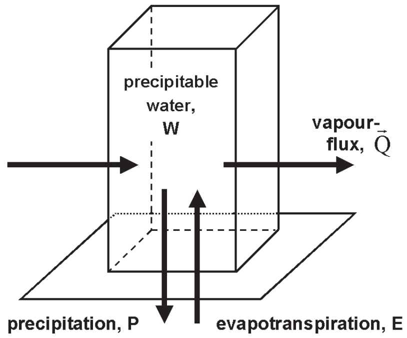

Figure 4. Schematic of the terms of a simplified water balance in an atmospheric column.

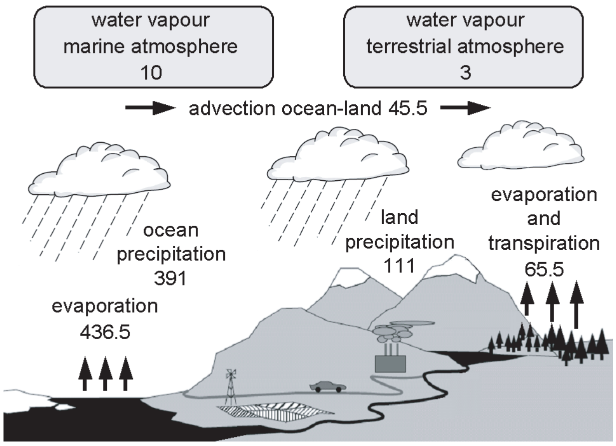

Figure 5. Schematic of the atmospheric branch of the water cycle. Storage (in boxes) is given in 10^{15} kg and fluxes in 10^{15} kg/a. Considering a liquid water density of 10^3 kg m^{-3}: 10^{15} kg correspond to 10^3 km^3 (data from [55]).

continental areas. The scheme in figure 5 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 figure 5 are those published by Oki and Kanae [55], within the expected error margins they are roughly comparable to those in [52, 58, 60-62]; Table 2 compares hydrological fluxes in the atmosphere as published by different authors.

Table 2. Global hydrological fluxes in the atmosphere.

	Chahine [58] [10^{15} kg/a]	Shiklomanov [61] [10^{15} kg/a]	Oki [52] [10^{15} kg/a]	Oki and Kanae [55] [10^{15} kg/a]	Trenberth et al. [62] [10^{15} kg/a]
Evaporation over oceans	434	503	431	436.5	433
Precipitation over oceans	398	458	391	391	399
Evapotranspiration over land	71	74	75	65.5	69
Precipitation over land	107	119	115	111	103
Net flux ocean → land	36	45	40	45.5	34

The given equation (2) can only lead to reliable results if input data is of adequate quality [52]. 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 [63].

Although the given values are still not totally certain, it can be deduced from figure 5, that, on average, over the oceans evaporation considerably exceeds precipitation. 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 data [52], this amounts to about 9.3% of the water which evaporates 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 figure 5 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 meter. Over the oceans the mean annual precipitation according to Oki's data [52] 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 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 [63] 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 and Oort [51] are provided by Pagano and Sorooshian [59]. 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). The land-atmosphere interaction leads to high variability and seasonality in the governing processes. 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.

5. 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 coordinate, 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

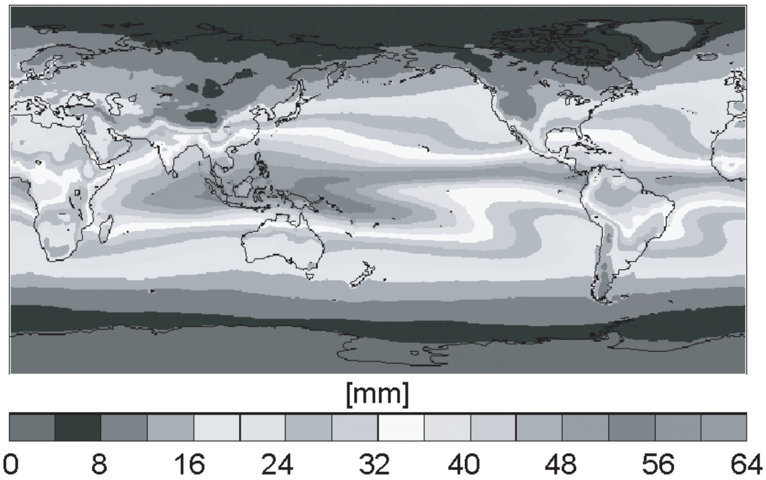

Figure 6. The global distribution of total atmospheric water vapour above the Earth's surface (precipitable water). The given values are averages for the period 1988-1997 and include data from both satellite and radiosonde observations (after [64]).

(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. Figure 6 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 [65]. A fairly short satellite based climatology of relative humidity in the upper troposphere is provided by Gettelman et al. [66]. Global surface data of relative humidity for the period from 1974 to 2004 is evaluated by Dai [67].

The mean values for a period of ten years as shown in figure 6, 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 cylones and the actual wind fields. The analysis of global weather data on winds (storms) and their water content revealed that there are major conduits in the atmospheric circulation system, which transport large amounts of water in narrow streams from the tropics through the midlatitudes toward higher latitudes [68, 69]. For these plumes the term "atmospheric rivers" has been coined. There are about three to five of these rivers in the sky in each hemisphere at any time, they contain 95% of meridional water vapor flux at 35° latitude, but in less than 10% of the zonal circumference. Not only do atmospheric rivers play a crucial role in the global water budget, under certain circumstances these events can also lead to heavy coastal rainfall and flooding [70]. In a temporal sense, in general, the water vapour distribution changes with seasonal changes in temperature, which

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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 Nino 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 [71]. A characteristic of the ongoing global climate change is the tendency toward an increase in tropospheric water vapour [2], which accompanies an increase in global mean temperature and an increase in sea surface temperature. 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 twentieth century indicate an increase of the water vapour content for the lower troposphere of the northern hemisphere [72].

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 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 [64]. Table 3 provides the water vapour content for different height bands of the troposphere.

Table 3. 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 [73]).

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

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. Changes in stratospheric water vapour could considerably modify the circulation of the extratropical troposphere [74]. There is strong evidence for a considerable increase of the water vapour concentration in the lower stratosphere. Continuous observations suggest that the stratospheric water vapour has increased by about 1% per year for a period of 20 years until the mid-1990s [75-77]. The trend may even have lasted longer, probably up to half a century [78].

The distribution and transport of water vapour above the planetary boundary layer is closely linked to the general circulation of the atmosphere. A thorough discussion of the zonal and meridional transports can be found in [51]. The upward vertical transport in the equatorial regions is coupled to the ascending branches of the Hadley cells. 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 figure 5, evaporation over the oceans is the dominant source for the atmospheric water budget. The rate of evaporation depends on several factor, for example on 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 evopotranspiration 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.

6. 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 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 [6, 7, 79], 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 [80-83]. 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. [84-86]). Here, in addition, aerosol physics and chemical aspects play an important role [87-89]. Thorough knowledge of the microphysics of clouds is crucial for understanding the formation of precipitation [81].

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 [90] are shown in table 4. 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) [90]. 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) [91].

Table 4. Cloud type amounts from surface observations; cloud overlap is possible (from [90]).

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

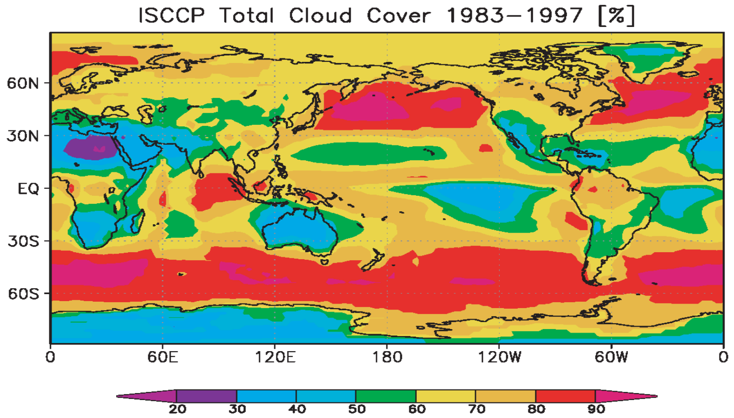

Figure 7. Annual average cloud amount (1983-1997) in % from the International Satellite Cloud Climatology Project (ISCCP), which uses data from geostationary and polar-orbiting satellites [91].

The liquid water content or ice water content of clouds is highly variable. Typical values are (range in brackets): marine stratocumulus 0.4 gm^{-3} (0.1 – 0.6 gm^{-3}), continental stratocumulus 0.3 gm^{-3} (0.03 – 0.45 gm^{-3}); cumulus 1 gm^{-3} (0.5 – 2.5 gm^{-3}), cumulus congestus und cumulonimbus up to 4 gm^{-3}; cirrus 0.02 gm^{-3} (0.0001-0.3 gm^{-3}).

The global distribution of cloud amount as annual average for the time period 1983 – 1997 is shown in figure 7. 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 [91] with respect to cloud water content come to a global average cloud water path falling in the range of 60 to 80 g/m^2 (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 [92-93]. Substantial knowledge on changes in cloud properties over time periods of decades would lead to an improved understanding of their role in 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 [94]. 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 [95] 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 observations 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 [96,97] 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 [98], and low-, mid-, and upper-level cloud cover [99], 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 [100]. 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.

7. 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. [81,84]). 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 [101]. 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 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.

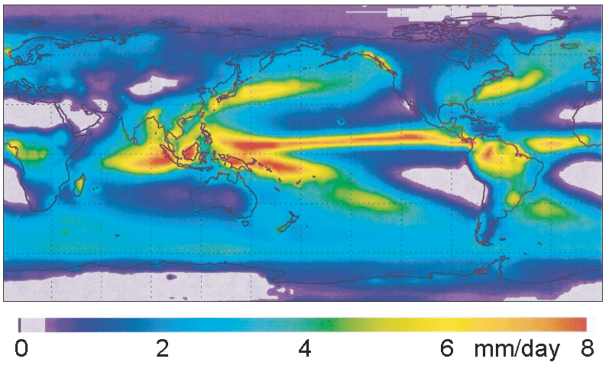

Figure 8. Annual mean precipitation in mm/day. The data is representative for the 23 year period from 1979 to 2001 and is based on a merged analysis that incorporates precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data, and surface rain gauge observations [103].

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 synoptic systems, i.e. warm fronts), and orographic precipitation. Stratiform compared to convective precipitation typically covers larger areas and has a much longer duration, it occurs typically with frontal systems [86,102]. 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 orographic conditions. The high spatial and temporal variability of precipitation has a large impact on vegetation, droughts, and flooding. Figure 8 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 ITCZ and the Southern Pacific Convergence Zone (SPCZ). Here a persistent precipitation amount of more than 2000 mm per year can be found, in some regions the value of 3000 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 fall which is associated with the monsoon circulation. Remarkable non-periodical deviations from longer term means of precipitation amounts can be observed in regions that are influenced by El-Nino-Southern Oscillation (ENSO).

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 [104]. 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 [105] the contribution by precipitation recycling on the 500 km scale accounts for about 10% on global average; on the 1000 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 1000 km (see figure 9). Quantitative descriptions of regional water cycles need, of course, to consider the local conditions. However, the results of Trenberth [105] 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

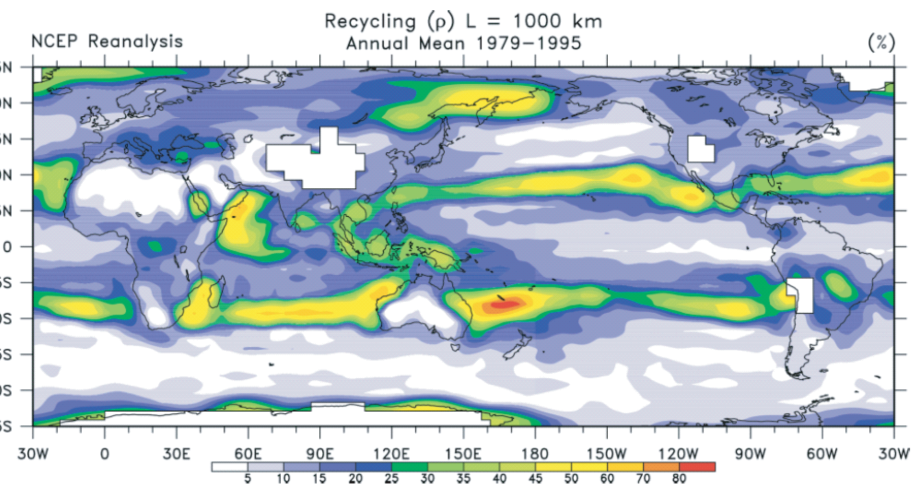

Figure 9. Estimate of the annual mean recycling ratio of the percentage precipitation coming from evaporation within a length scale of 1000 km (from [106]).

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arises, whether an associated change in precipitation occurs. The IPCC report [95] states with high confidence an increase of precipitation on the order of 5 to 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 [106].

8. ATMOSPHERIC WATER AND GLOBAL CHANGE

Amongst the highest priorities in Earth science and environmental policy issues confronting society are the potential changes in the Earth's water cycle due to climate change. Key questions are aiming on the availability of water on one hand and possible flood events on the other. Both topics a closely related to the development of the atmospheric water cycle in a warmer world. By now it is generally agreed upon that the Earth's climate will undergo changes in response to natural variability, including solar variability, and to increasing concentrations of greenhouse gases and aerosols. Furthermore, agreement is widespread that these changes may profoundly affect atmospheric water vapour concentrations, clouds, and precipitation patterns. For example, a warmer climate, directly leading to increased evaporation, may well accelerate the hydrologic cycle, resulting in an increase in the amount of moisture circulating through the atmosphere. Detecting changes is not an easy task given the natural variability of the climate system. Using estimates of natural variability in precipitation (P), evaporation (E), and discharge (R) in combination with model results for a global warming scenario Ziegler et al. [107] determined that data records having lengths on the order of 35 to 70 years are needed to detect significant changes in global terrestrial P, E, and R that might be caused by a warming-induced intensification in the global hydrological cycle. Longer records are generally needed to detect predicted changes in P, E, and R at the continental scale. Huntington [108] has compiled historical trends in hydrologic variables and reviews the current state of science, the paper concludes that although data are often incomplete in spatial and temporal sense the weight of evidence indicates an ongoing intensification of the water cycle.

Discussions of global climate change tend to focus on increasing surface temperature, but quite a few studies are addressing also the water cycle-climate change relation, although their number may not be adequate regarding its potential importance. Several of these research projects are based on predictions using global coupled climate models [109,110], and for a number of those extreme precipitation events [111,112] and their spatial distribution pattern [113] is of main interest. Many uncertainties remain, however concerning regional aspects, as illustrated by the inconsistent results given by current climate models regarding the 20$^{\text{th}}$ century [114] and the future distribution of precipitation. It should be mentioned that processes related to the water cycle, like evapotranspiration, cloud- and precipitation formation, are amongst the more uncertain ones represented in the models. These are especially important processes, since they are involved in feedback loops. Water vapour is found to provide the largest positive feedback in models (e.g. [115]), and the feedback from clouds is generally not consistent in between models [116]. Nevertheless, a combination of modelling and data analysis [117] as well as model sensitivity studies and ensemble evaluation might give first indications, whether the water cycle "shifts gear" [118].

Will global warming lead to more evaporation and hence to an increased water vapour content of the atmosphere? What do recent observations suggest? Studies based on radiosonde data from the end of the past century, which saw an increase of the mean temperature over land and over the oceans [95], revealed the presence of regional moistening trends for the lower troposphere since the mid-1970s [72,119]. Based on satellite measurements Trenberth et al. [120] observed increases in precipitable water over the global oceans since the mid-1980s. But caution is advised by Trenberth et al [120] for extracting information on trends in tropospheric water vapour from global reanalysis products, since they suffer from spurious variability and trends related to changing data quality and coverage. Satellite data presented in [121] supports column-integrated moistening trends for the years from mid-1980s. A most recently published evaluation of *in situ* surface air and dewpoint temperature data found very significantly increasing trends in global and Northern Hemispheric specific humidity [67]. For the period from 1974 to 2004 the global annual specific humidity increased by 0.06 g kg^{-1} $decade^{-1}$. Global changes in relative humidities are reported to be small for this time segment, mainly due to concurrently increasing temperatures.

While it seems to be established that evaporation over the ocean increases with increasing SST, as it can be inferred from HOAPS data [122] for 1988 to 2002 (Bakan personal communication, 2006), the situation over land is far from being settled [123]. Here, the interpretation of reported recent decreasing trends in pan-evaporation is a reason for controversy [123]. The expectation is that a warming would increase evaporation. Two proposals exist for an explanation of the so-called pan-evaporation paradox. Pan-evaporation (potential evaporation) may be indicative of increasing actual evapotranspiration because of cooler and more humid air is surrounding the pan [124,125]. A second explanation relates the decline in pan evaporation to those in diurnal temperature range and global solar radiation (possibly due to increased cloudiness and aerosol concentrations, e.g. [126], implying that actual evapotranspiration is also declining due to a reduced availability of energy at the surface [127,128]. Reduced wind speed near the surface due to changes of vegetation surrounding the observational sites may also to be considered. A more recent analysis by Wild et al. [129] of surface temperature and solar radiation records from the late 20th century based on 30 years of energy balance data including records from more than 2000 sites indicates that the observed intensification of the hydrological cycle outside the tropics was likely caused by the transfer of moist air from the oceans rather than from evaporation over land. These authors found no indications of increased radiative heating between 1960 and 1990, thus ruling out increased atmospheric moisture from land surface evaporation. A mechanism which might reduce evapotranspiration is a direct effect of an increase of atmospheric carbon dioxide (CO_2). Notably, elevated CO_2 concentrations induce stomata closure and therefore reduce transpiration [130]. The analysis by Gedney et al. [131] suggests that stomatal-closure effects are already having a direct influence on the water balance over land.

What do models forecast for the future water vapour content? All climate models predict that the concentration of water vapour in the troposphere will increase markedly in the future. In particular, they produce increases in water vapour concentrations that are comparable to those predicted by fixing relative humidity [2]. An evaluation of most recent runs of 20 coupled climate models performed for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (AR4) by Held and Soden [132] supports the finding of an increase of global mean column integrated water vapour with increasing global mean surface temperature which follows a Clausius-Clapeyron scaling (column integrated water vapour is dominated by the lower troposphere). One important aspect of the climate debate over the last 15 years centers around the humidity of the upper troposphere. Actually a negative feedback mechanism has been postulated [133]. As climate models predict that the concentration of water vapour in the UT might double by the end of the century, given the proposed increases of greenhouse gases, a clarification of UT-water vapour trends based on observations accompanied by modelling is desirable. The moistening is not easy to detect using conventional observing systems. The study by Soden et al. [121] uses multi-channel satellite measurements from 1988 to 2004 to detect distinct radiative signatures of UT-moistening in order to test one aspect of water vapour feedback. They could show that the observations were accurately captured by climate model simulations driven by observed SST, a clear evidence that GCMs are properly representing climate feedback from upper tropospheric water vapour. Their observed radiance record requires a global moistening of the UT in response to global warming that is equivalent to the assumption of constant relative humidity. The results of Soden et al. [121] eliminate one potential uncertainty within climate models, and lend further credence to model projections of future water vapour concentrations as those reported by Held and Soden [132].

What about precipitation in a warmer climate? The increased atmospheric moisture content associated with a warming might be expected to lead to increased global mean precipitation. However, precipitation is also strongly influenced by changes in the tropospheric energy budget and the atmospheric circulation, so spatio-temporal patterns of precipitation change are likely to be complex. The Third Assessment Report of Intergovernmental Panel on Climate Change [95] has reported various changes in regional precipitation, there was no simple overall pattern beside that the increase occurs predominately at higher latitudes. Global terrestrial annual mean precipitation showed a small upward trend over the 20th century of approximately 2.1 mm/decade (based on the Global Historic Climatology Network, GHCN, data; to be reported in the IPCC Fourth Assessment Report, AR4, in 2007). However, the record is characterised by large interdecadal variability, and global terrestrial annual mean precipitation based on the New et al. [134] record shows almost no trend since 1940. By use of an ensemble of global models simulating the 20th century, Bosilovich et al. [135] find an increasing trend in precipitation over ocean areas and a decreasing trend over land. The decreases over land are not uniform, however, with most decreases being over the tropics. The assessment of a modification of precipitation intensity is not so conclusive. One of the major problems in examining the climate record for changes in extremes is a lack of high-quality, long-term data [136].

What are the expected changes in precipitation in a future climate? As mentioned above, modelling precipitation without supporting data assimilation is not an easy task. In addition precipition is not characterized by an averaged amount, but frequency, intensity and spatial distribution are also of interest. In the sense that all models in use for AR4 as well as earlier studies show considerable changes for precipitation quantities related to an increase in global temperature [95,109,110] a robust result is available. The models all show an increase in global mean precipitation, but this forecast is far less consistent as the one for temperature projections when the percentage change of amount is considered. This is not surprising since a complex energy balance relationship is expected to be responsible for changes in the mean hydrologic cycle [117].

As an example for projected changes in mean precipitation, in figure 10 results from the ECHAM 5 model for the northern hemisphere winter months are displayed. The simulations followed the climate change scenario A1B of IPCC (amid-range positive radiative forcing scenario), here the difference of

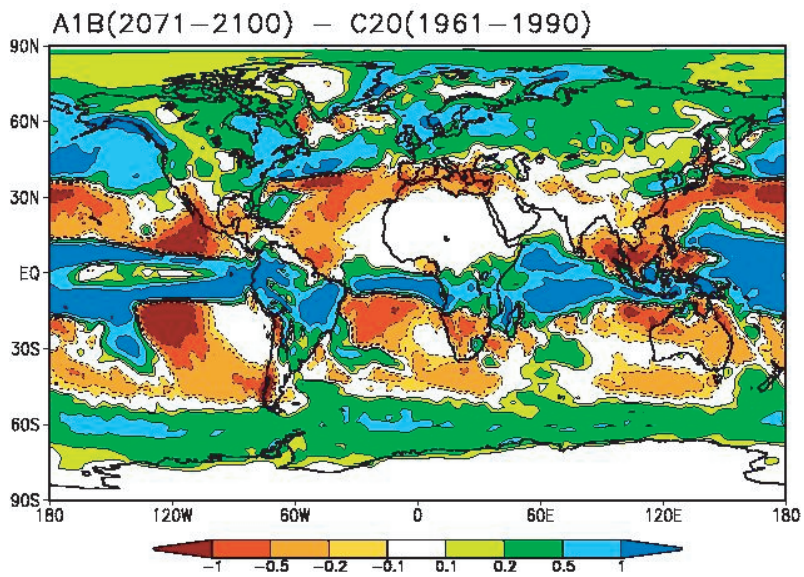

Figure 10. Geographical distribution of the simulated change in mean rates of precipitation for winter months (in mm/day) from the last 30 years of the 20th century to the last 30 years of the current century. Model calculations were made using the ECHAM 5 model under the IPCC A1B scenario (graph from E. Röckner).

30 year averages at the end of the 21st century and the end of the 20th century are shown. It can be seen that according to this simulation changes are to be expected everywhere on the globe, although with variable amount. The most pronounced increases in precipitation are found along the equatorial belt. Increases in precipitation are also forecasted for higher latitudes in both hemispheres, while less rain is expected to occur in the subtropical areas around 30° latitude. For the summer months (not shown here) the potentially drier regions cover large parts of Europe (E. Röckner, personal communication). Experiments conducted using a suite of regional climate models for Europe underline that a warming may regionally lead to strong changes in the hydrological cycle [137]. But the changes occur regionally as well as seasonally with varying intensity and sign and are strongly dependent on the model in use.

It has been widely projected that extremes in precipitation could increase more than the annual or seasonal mean. Since changes in precipitation extremes are postulated to be related to changes in atmospheric temperature [117], under warmer atmospheric conditions, increases in extreme precipitation events could be expected. It has been argued that the enhancement of extremes is principally caused by enhancement of atmospheric moisture content [138]. A general increase in the intensity of precipitation in a future warmer climate has been reported in e.g. [95,111,112,139,140]. Several extreme indices which relate to precipitation have been defined [141,142], the discussion around them can not be repeated here. But it is clear that increases of precipitation intensity do not have a uniform spatial distribution, the actual pattern is related to the relative importance of dynamical to thermodynamical processes, which itself is varying between different models [113,143]. Thermodynamical changes are due to changes in atmospheric water content, while dynamic changes are due to changes in atmospheric motion (circulation, advection, updrafts). In a multi-model evaluation Meehl et al. [113] found that in the tropics increases in water vapour associated with positive SST anomalies produce increased precipitation intensity over most land areas. In midlatitudes the pattern of precipitation increase is related only in part to increased water vapour content but also to changes in atmospheric circulation. Advective effects contribute to greatest precipitation intensity increases over large parts of North America, Northern Europe and other high-latitude regions. In a study using 6 climate models Emori and Brown [143] looked into the relative increase in precipitation mean and extremes. In contrast to earlier reported assessments (e.g. [95]), they found over most parts of mid- to high latitudes, that mean and extreme precipitation increase in comparable magnitude mainly due to a comparable thermodynamic increase. And the dynamic influence on the difference between mean and extreme precipitation plays a secondary role [143]. Barnett et al. [112] reported that the frequency of extremely wet days is likely to increase. They deduced from an ensemble of 53 model versions of the HadSM3 coupled general circulation model, that under $2 \times CO_2$ conditions the global- and ensemble average extremely wet days (according to their statistical definition) become twice as common.

But model results still should be considered only as indicative. Dai [114], examined the newest generation of 18 coupled climate models using available observations, one concluding statements is: “The results show that considerable improvements in precipitation simulations are still desirable for the latest generation of world’s coupled climate models”. In a similar assessment Sun et al. [144] specify: “Although the models examined here are able to simulate the land precipitation amount well, most of them are unable to reproduce the spatial patterns of the precipitation frequency and intensity”. So, caution is advised in too strictly interpreting the currently predicted patterns of precipitation intensity. But it is highly probable that regionally and locally severe changes of the atmospheric part of the hydrological cycle are to be expected, if global warming can not be mitigated by political and technological measures.

9. 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 [62]. 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 the 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; re-analysis; e.g. [145]) will have a substantial impact on further development in this field. Extended studies on theses aspects are currently under way at several operational or research centres such as the European Centre for Medium-Range Weather Forecasts (ECMWF) or the 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 like the recently launched CLOUDSAT [146] and CALIPSO Missions with passive sensors is a key to advancement. Extended ground based networks of Doppler radar systems, wind profilers, water vapour lidars in conjunction with radiosondes (improved with respect to water vapour measurements) will permit further comprehensive and advanced 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. Reliable regional predictions of future availability of fresh water are needed for the development of adaptation strategies in response to global warming. Authoritative advice at an early stage is highly desirable for the prevention of potential regional and international conflicts about water.

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