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The role of clouds in the climate system

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Abstract. Clouds are important for global climate since they have a strong impact on solar and terrestrial radiation as well as on the formation of precipitation. The different types of clouds in the atmosphere are linked to the climate system by a multitude of dynamical and thermodynamical processes including numerous feedback mechanisms. In present-day climate, on average, clouds cool our planet, the net cloud radiative forcing at the top of the atmosphere is about –20 Wm^{-2}. One of the most interesting questions concerning clouds is: how will they respond to a change in climate? A slight change in cloud amount or a shift in the vertical distribution of clouds might have a considerable impact on the energy budget of the Earth. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states clearly that cloud processes and related feedbacks are among the physical processes leading to large uncertainties in the prediction of future climate. The main reason for this is that many microphysical and dynamical processes controlling the life cycle and radiative properties of clouds are not adequately implemented in global climate models. The interaction of aerosols and clouds and the resulting radiative forcing (indirect and semi-direct aerosol effect) is one of the major fields of active cloud research at present. This chapter introduces various aspects of the cloud-climate relation and summarizes the discussions of topics currently under scientific debate.

1. INTRODUCTION

Clouds are an integral component of the earth system. At any given time clouds cover between 60% and 70% of the globe. They strongly interact with climate by regulating the temperature and moisture structure of the atmosphere. Thus, clouds need to be considered in studies addressing issues of the climate system and possible climate changes, i.e. the prediction of future climate in response to anthropogenic release of greenhouse gases and aerosols. Nevertheless, many aspects of the cloud-climate relation are not fully understood or can not be adequately quantified or modelled. The Intergovernmental Panel on Climatic Change (IPCC) points to clouds and related feedbacks as one of the main uncertainties in the prediction of future climate [1].

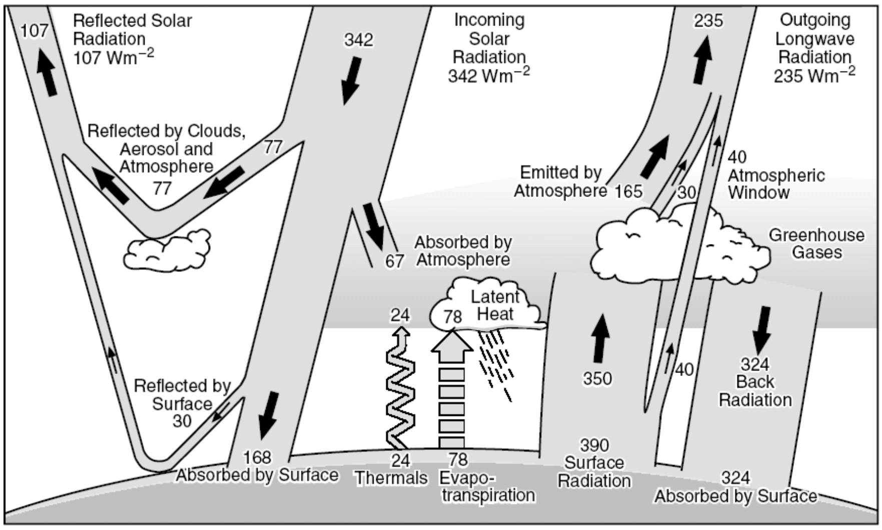

Figure 1. The Earth's radiation balance. Clouds reflect and absorb solar radiation, they absorb and emit infrared radiation, and during their formation they release latent heat (from Kiehl and Trenberth [7]).

Clouds influence climate by scattering sunlight back to space and toward the Earth's surface, by absorbing infrared radiation and emitting it toward the surface or toward space, by releasing latent heat of condensation, by transporting heat, moisture and atmospheric trace constituents over large distances, and by precipitating water to the surface [2-5]. All of the associated processes depend on cloud microphysics [6], itself being linked to radiation and atmospheric and cloud dynamics (turbulence) by complex interactions. In turn, climate influences clouds by setting the conditions that affect cloud formation, their horizontal and vertical distribution, their composition and their radiative and hydrological properties.

The balance between incoming solar radiation and outgoing infrared radiation ultimately determines the Earth´s climate. The average energy fluxes for the present day climate according to Kiehl and Trenberth [7] are presented in Figure 1. Since clouds play a major role in determining the net radiation balance, any change in cloud coverage and their optical properties leads to a modification of the climate state.

Clouds play a key role in the atmospheric branch of the hydrological cycle, which is intimately linked to the climate system. They are involved in transporting water evaporated over the oceans to the continents, where for its release the formation of precipitation within clouds is the important factor. As the numbers in Figure 2 indicate, evaporation over the ocean exceeds precipitation and over land evapotranspiration amounts to only two thirds 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 and involving cloud processes. Beside the associated changes in the water vapour distribution the effects of precipitation on soil moisture and vegetation have a propound influence on climate. The data provided in Figure 2 are taken from Oki [8] and correspond within the error margins to those presented by Chahine [5] and Trenberth and Guillemot [9].

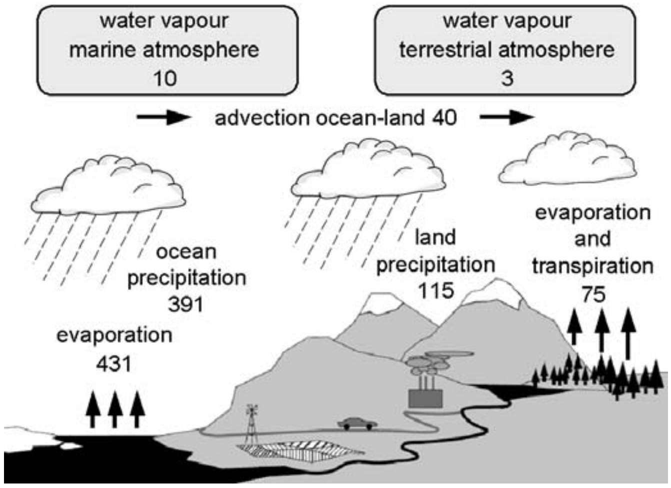

Figure 2. Schematic diagram of various fluxes and reservoirs within the atmospheric branch of the water cycle with their yearly average magnitudes (data from Oki [8]). The water vapour reservoirs (in boxes) are given in 10^{15} kg and the fluxes in 10^{15} kg year^{-1}.

Clouds affect significantly the vertical transport in the atmosphere. Updrafts and downdrafts associated with convection and clouds determine in a major way the vertical redistribution of trace species. Clouds scavenge gaseous and particulate materials and eventually return them via precipitation to the surface (wet deposition) [10]. They provide a medium for aqueous-phase chemical reactions and production of secondary species. The presence of clouds influences photochemical processes by modifying the amount of ultraviolet radiation [11,12], and thus photodissociation rates of trace gases [13]. Tropospheric chemistry is strongly influenced by these processes and hence is the chemistry-climate relation.

This overview concentrates on the effects of the cloud-radiation interaction in the climate system. The complex cloud-chemistry-climate topic deserve its own review, for a summary of the involved scientific challenges see e.g., [14].

2. CLOUD TYPES AND SOME TYPICAL PROPERTIES

2.1 Cloud classification

What is a cloud? According to the World Meteorological Organization (WMO), a cloud is an aggregate of minute, suspended particles of water or ice, or both, above the Earth´s surface that are in sufficient concentrations to be visible. The modern term ‘cloud’ needs also to include those aggregations of cloud particles, which are invisible to the human eye, i.e. subvisual cirrus in view of their potential impact on climate [15]. Many different types of clouds exist and detailed classification schemes have been developed. A comprehensive cloud classification including genera and species is provided by the WMO [16,17]. In Table 1 only some general classification is given, it focuses on clouds which have a profound influence on the energy budget and water cycle.

Table 1. Principle cloud types, simplified classification based on [10] and [16].

Height level	Name	Typical composition	Appearance	Base height [km]
high clouds	Cirrus (Ci)	pure ice crystals	detached clouds in the form of white, delicate filaments or patches or narrow bands	7 – 16
	Cirrostratus (Cs]	mainly ice crystals	Transparent, layered cloud veil of fibrous or smooth appearance	7 – 16
	Cirrocumulus (Cc)	almost exclusively ice crystals	composed of very small elements in the form of grains or ripples	7 – 16
mid-level clouds	Altostratus (As)	almost invariably water droplets, ice crystals at very low temperatures	uniform whitish or grey sheet or layer	2 – 7
	Altocumulus (Ac)	almost invariably composed of water droplets, ice crystals at very low temperatures	white or grey puffs or waves in patches or layers	2 – 7
low-level clouds	Stratus (St)	water droplets	grey layer with a fairly uniform base	0 – 2
	Stratocumulus (Sc)	water droplets	layer of merged puffs or large rolls	0 – 2
	Nimbostratus (Ns)	water droplets, ice crystals possible	uniform dark grey layer from which precipitation is falling	0 – 4
clouds with vertical development	Cumulus (Cu)	water droplets	detached heaps or puffs with sharp contours and flat bases, moderate vertical extent	0 - 3
	Cumulonimbus (Cb)	water droplets and ice crystals	cloud towers with large vertical extent and smooth or flattened tops, which often spread out in the shape of an anvil	0 - 3

The classification of clouds can be based on their altitude within the atmosphere (*low, mid-level, and high clouds*), their phase (*liquid, ice, or mixed*) or their manifestation. Cumulus and cumulonimbus clouds are called *convective clouds* because of the central role of convective updrafts in their development and structure. They usually show a relative large vertical extend compared to their horizontal dimension. In contrast to convective clouds, *stratiform clouds,* like *stratus, stratocumulus, cirrostratus*, and *cirrocumulus*, have a more layered appearance, they usually span much larger areas than convective clouds and thus account for most of the global cloud cover. Some cumulus clouds can be very deep and extend to the tropopause, where they generally spread out and form large cirrus anvils. Often also a distinction between *precipitating* and *non-precipitating clouds* is made.

2.2 Cloud properties

Clouds are composed of hydrometeors which differ in phase, size and shape. The basic hydrometeors in the atmosphere are water droplets, ice crystals, rain drops, graupel, hail and snow flakes. Where water droplets and ice crystals are cloud particles, the latter four hydrometeor types are called precipitation particles. Depending mainly on the vertical temperature profile, the different hydrometeors can be present in all clouds in a more or less distinct number concentration. Pure water clouds are observed at temperatures above 5°C and pure ice clouds below –40°C, in the broad temperature range of –5 to –40°C mixed phase clouds can be present. The particles in clouds occur in a range of sizes leading to characteristic size distributions. Typical shapes of droplet distributions for different types of water clouds are shown in Figure 3, some cloud types contain mainly small droplets while others show a broad range of droplet sizes. The integral over the masses of the single particles within a cloud defines its liquid water content (LWC) or ice water content (IWC). *In situ* measurements of particles often provide an estimate of the size of the hydrometeors instead of the mass. For irregular shaped particles the determination of the cloud water content is difficult due to uncertain size-mass relations. Especially ice crystals in clouds can be found in large number of different shapes (e.g., column, plates, stellars, bullet rosettes, aggregates etc.). Some typical values for microphysical properties for different types of clouds are summarised in Table 2. The provided values are based on direct measurements from airborne platforms. The wide ranges of values for the parameters are partly due to inhomogeneities within the encountered clouds, but they also reflect the variability in the natural occurrence of the different cloud types.

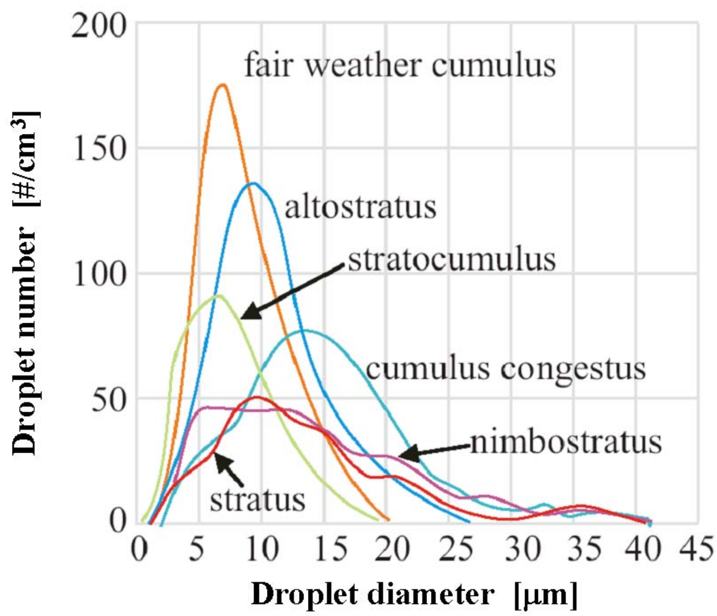

Figure 3. Typical droplet size spectra for different types of water clouds (from H. Verlinde).

Table 2. Typical microphysical properties for different cloud types compiled from [18-23].

Parameter	Typical Value	Typical Range
Marine stratocumulus (cloud top region)		
Particle concentration	150 cm^{-3}	45 to 300 cm^{-3}
Drop size ∅	20 µm	4 to 25 µm
Liquid water content (LWC)	0.4 gm^{-3}	0.1 to 0.6 gm^{-3}
Continental stratocumulus (cloud top region)		
Particle concentration	250 cm^{-3}	40 to 500 cm^{-3}
Drop size ∅	10 µm	4 to 18 µm
Liquid water content	0.3 gm^{-3}	0.03 to 0.45 gm^{-3}
Continental cumulus		
Liquid water content	1.0 gm^{-3}	0.5 to 2.5 gm^{-3}
Altocumulus, -stratus		
Particle concentration	100 cm^{-3}	30 to 1000 cm^{-3}
Drop size ∅	8 µm	4 to 20 µm
Water content	0.03 gm^{-3}	0.01 to 0.75 gm^{-3}
Cirrus		
Particle concentration	30 l^{-1}	10^{-4} to 10^{4} l^{-1}
Crystal size (length)	250 µm	1 to 4000 µm
Ice water content (IWC)	0.02 gm^{-3}	10^{-4} to 0.3 gm^{-3}

For detailed studies of radiative transfer through the cloudy atmosphere, a fundamental aspect of the cloud-climate relation, the radiative properties (albedo, emittance, absorptance, optical depth) of clouds need to be known. In principle these properties can be inferred from the number concentrations, sizes and shapes of the cloud particles, but in general for most clouds this information is not available even in crude approximation. In addition, the complex three-dimensional structure of clouds complicates radiative transfer studies. The frequently applied plane-parallel assumption in radiation calculations is certainly not correct even for large-scale energy budget studies [24]. However, some cloud types (e.g., marine stratus) can be approximated by the plane parallel assumption. For an overview on radiative properties of clouds see e.g., Liou [25].

3. FORMATION AND DEVELOPMENT OF CLOUDS

3.1 General aspects

In order to fully appreciate the many ways clouds are linked to climate processes, it is useful to briefly summarize the main aspects of their formation. The factors of prime importance in cloud physics are the air motion, available water vapour, and the number and composition of particles serving as cloud condensation nuclei or ice nuclei. Most clouds are formed by the lifting of moist air which cools adiabatically by expansion under falling pressure. Eventually, relative humidity approaches saturation and condensation becomes possible. The height where this condition is reached is called lifting condensation level. There are several ways how the necessary lifting of air masses can be achieved. Local ascent of warm, buoyant air parcels in a conditionally unstable environment leads to convective clouds. The associated updraft velocities are a few meters per second, but in large convective cloud systems also several tens of meters per second can be reached. Cloud lifetimes range from minutes to hours. Forced lifting by e.g., frontal movements leads to stratiform clouds. Here, the updraft velocities are much lower, typical values are in the range of a few centimetres per second to ten centimetres per second. The lifetime of these clouds typically range between hours and tens of hours. Air masses passing hills or mountains experience a forced lifting, if clouds are formed in this way they are called orographic clouds. The spatial and temporal distribution of surface heating and the paths of large scale weather systems determine the type of clouds occurring in a region. A detailed discussion of the role of atmospheric motions in the formation of the different cloud types can be found in the monograph by Houze [26].

3.2 Nucleation

Among the many facets of cloud physics the nucleation process plays an essential role.

3.2.1 Warm clouds

Cloud droplet formation in warm clouds without supporting particles (homogeneous nucleation) is extremely unlikely, it needs an enormous supersaturation. Certain energy barriers to growth need to be overstepped by a droplet embryo. For example the formation of a small droplet of 1.73 nm consisting of 730 molecules by random collisions of water molecules requires a supersaturation of about 2 (200% relative humidity). Almost all of the cloud droplets in the atmosphere have their origin in a so called heterogeneous nucleation process, which involves atmospheric particles. A subset of aerosol particles that are large enough and soluble enough to initiate cloud droplet growth is called cloud condensation nuclei (CCN). Typically CCNs consist of sulfates, sea salts, organic materials, black carbon, and minerals, in varying proportions, according to their regional sources. Depending on their size, their chemical composition and the ambient relative humidity aerosol particles can take up a certain amount of water molecules. But not all aerosols which take up water will grow into cloud droplets, only those passing a critical radius are able to grow and form a cloud droplet. These aerosols are said to be activated. Their basic growth behaviour is described by the so called Köhler theory (e.g., [27,28]), the according Köhler equation can be written as:

$$\frac{e_{sr}}{e_{s\infty}} = \left(1+\frac{a}{r}\right)\left(1-\frac{b}{r^3}\right) \approx 1+\frac{a}{r} - \frac{b}{r^3} \tag{1}$$

$$\text{where } a=\frac{2\sigma_{lv}}{n_l k_B T} \quad \text{and} \quad b=\frac{3\, i\, m_s\, M_w}{4\pi\rho_l M_s} \tag{2}$$

with e_{sr}: water vapour pressure at actual radius; $e_{s\infty}$: saturation vapour pressure for flat surface; r: particle radius; σ_{lv}: surface tension liquid-vapour; n_l: number of water molecules per unit volume of liquid; k_B: Boltzmann constant; T: tempeature; M_w: molecular weight of water; M_s: molecular weight of solute; m_s: mass of solute; i: number of ions into which each molecule dissociates; ρ_l: density of water.

Equation 1 describes the cloud droplet activation and expresses the two effects that determine the vapour pressure over an aqueous solution droplet - the opposing effects of curvature (*Kelvin effect*), which increases the equilibrium vapour pressure, and solute (*Raoult effect*), which lowers the equilibrium vapour pressure. The maximum of (1) defines the critical radius and the critical saturation. For a pure water droplet there is no solute effect and the curvature effect leads to a higher vapour pressure compared to a flat interface. The vapour pressure of a solution droplet can be higher or lower than the flat interface value depending on the relative importance of the solution term to the curvature term. In cloud physics a particle is not considered a cloud droplet unless its radius exceeds the critical radius. Due to the solution effect a droplet can be in an equilibrium state in a subsaturated environment. If the environmental satura-

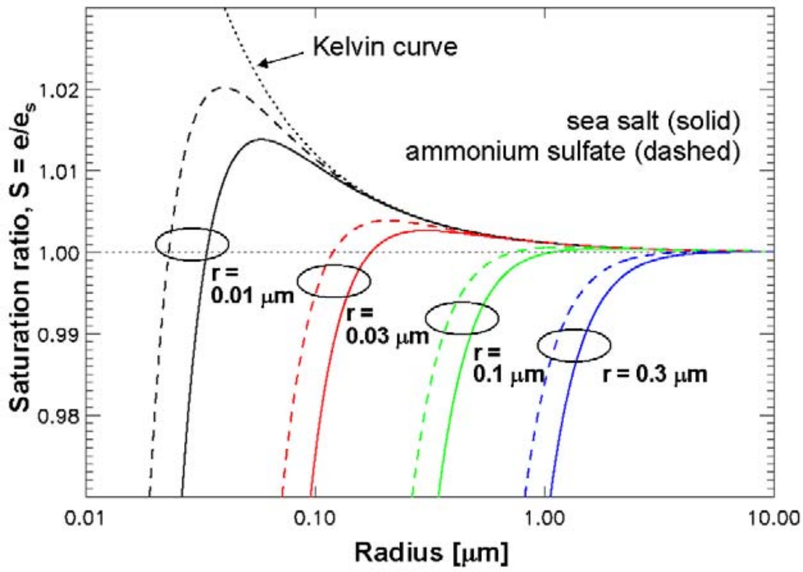

Figure 4. Equilibrium saturation ratio of solution droplets formed on sea salt or on ammonium sulfate particles for different dry radii between 0.01 μm and 0.3 μm (figure based on calculations by U. Lohmann).

tion is larger than the critical saturation the particle is called activated. It starts growing and eventually becomes a cloud droplet. In Figure 4 the Köhler curves for NaCl (sea salt) and $(NH_4)_2SO_4$ (ammonium sulfate) are shown for different dry radii.

The affinity of atmospheric particles for water, as seen in (1), is a key parameter in the formation of cloud droplets. The classical nucleation theory, as sketched above, is based on the assumption that the active fraction with respect to hygroscopic growth is composed of inorganic salt particles and that the particles are in thermodynamic equilibrium until the point of spontaneous growth. Therefore for the cloud forming process it is of importance whether the atmospheric aerosols are composed of more hygroscopic, neutral or hydrophobic material. Recent studies report that actual CCN may have a wide range of solubility from hygroscopic to only slightly soluble. There is clear evidence that a large fraction (between 20 and 60%) of organic material, an ubiquitous compound of atmospheric particles, is water soluble and therefore can serve as cloud condensation nuclei [29-34]. In addition to the partially soluble organic compounds it has recently been established that soluble gases (such as HNO_3 or NH_3) [35] and the depression of surface tensions by organic substances [36] also influence the formation of cloud droplets in a manner not accounted for by the Köhler theory. Laaksonen et al. [35] provide a more complete multiphase-multicomponent theory and present a modification of the Köhler equation to include soluble trace gases and slightly soluble substances. The simultaneous condensation of the strongly hygroscopic gaseous substances and water vapour on a CCN can depress the water vapour pressure significantly. The result of this is a shift towards smaller activated particles at a given relative humidity. A change of surface tension by organic solutes may also lead to an increase in the droplet population [36]. This way chemical phenomena affect the radiative (optical) properties of clouds and a link between pollution (gases and particles), clouds and climate is marked. But there are still uncertainties concerning the sensitivity of cloud droplet number concentration to the chemical effects, which is strongly dependent on the actual environmental situation [37,38]. An updated discussion of the efficiency of cloud droplet formation on organic aerosols based on new laboratory results is given in [39]. The quantification of the chemical influence on cloud activation on the large scale currently lacks the availability of global data, but first estimates underline the climatological significance [40].

In polluted regions the supply of activated CCNs can lead to droplet concentrations on the order of 1000 cm^{-3}, while in remote areas typical droplet concentrations are around 10-100 cm^{-3}. About 75% of the aerosol mass in the atmosphere, from which only a subset acts as CCN, is accounted for by primary processes (20% wind generated dust, 40% sea spray, 10% biomass burning and 5% industrial processes), the other 25% are from secondary sources that involve gas-to-particle conversion. A comprehensive overview on aerosol sources is provided in chapter 5 of [1]. The regional concentration of aerosols is controlled by coagulation, condensation, scavenging, washout, sedimentation, dispersion, mixing and advection. There are several ways the atmospheric particle load and their regional and global distribution depend on climate. E.g., the entrance of dust and sea salt into the atmosphere is strongly dependent on wind speed, which is coupled to the regional temperature distribution. The removal of aerosols from the atmosphere by washout depends on the distribution of clouds and precipitation.

Once particles are formed in a cloud they can grow by condensation and/or by collection (collision and coalescence) of the drops. The droplet growth equation, which describes the change of the droplet radius as a function of supersaturation, shows that larger drops take longer to grow and condensation growth practically stops around 20 μm, here collection becomes the dominant growth mechanism [41]. Growth by collection of particles is sensitive to the initial size distribution (terminal velocities) and to cloud dynamics [26], the existence of a few larger particles accelerates the particle spectrum broadening. Precipitation size particles (> 100 μm) in water clouds can only grow via collection. Clouds dissipate by evaporation or by precipitation. The life cycle of the clouds, which determines how long their radiative properties are acting in the climate system, for many clouds depends very much on their initial formation (nucleation).

3.2.2 Cold clouds

Ice nucleation and growth is even more complicated than droplet nucleation. Here only the main aspects are sketched, more details of the physics involved in ice nucleation are given by [27,42-44]. Direct nucleation from vapour (*homogeneous deposition*) is only possible at very low temperatures and extremely high supersaturations. It never happens in the atmosphere [43]. Ice particles may arise from freezing of supercooled cloud droplets (*freezing nucleation*). The supercooled state of water can persist to temperatures as low as –40°C, the temperature below which homogeneous freezing will occur. Most commonly first ice particles are formed when the temperature is in the –10°C to –15°C range and ice formation appears to become facilitated by certain aerosol particles called ice nuclei (IN). In general, INs have different properties than CCNs. INs acting as freezing nuclei may exhibit three basic modes of action: *condensation-freezing*, *contact-freezing*, and *immersion-freezing.* In some cases INs catalyse ice formation by acting as molecular templates for the crystal lattice, on which water vapour is directly deposited (*deposition nucleation*). Ice nuclei are thought to be largely composed of minerals (dust), but also biogenic material is considered to act as efficient IN [45-48]. Anthropogenic processes appear to increase the concentration of IN under some circumstances but they also can decrease it under others [6]. It is possible that adsorption of atmospheric constituents, such as sulfates and aliphatic alcohols, can either activate or deactivate certain classes of atmospheric aerosols, rendering them more or less efficient as IN [42]. Some ice particles owe their existence to other prior existing ice particles via several mechanisms (*secondary ice formation*) [41]. Crystals grow by *vapour deposition*, *riming* and *aggregation*. Dynamical processes in ice clouds provide an important coupling between cirrus cloud microphysical and radiative processes; the interaction of turbulence, radiation and microphysics controls crystal growth, shape and size spectra [49-51].

3.3 Cloud dissipation and change in properties

Particles may leave a cloud by evaporation or via the precipitation process. In warm clouds some 1 million small droplets must collide and coalesce to make a rain drop large enough to be able to fall to the ground. Much of the precipitation begins in the ice phase, although the particles can melt before they reach the ground [41]. The life time of clouds is considerably shortened when effective precipitation mechanisms are active. To establish the links between the global distribution of clouds and the amount of precipitation in a quantitative manner is one of the great challenges of cloud physics [52].

The number of available aerosols, and their chemical composition will determine the microphysical properties of clouds. A change (number, size, chemical composition) in the aerosol load of the atmosphere is likely to change the microphysical properties and consequently the radiative properties of clouds. Baker [6] provides a comprehensive review of possible influences of cloud microphysics on climate. See also section 6 on the indirect aerosol effect.

4. GLOBAL OCCURRENCE OF CLOUDS

The overall influence clouds have on climate depends on how (where and when) clouds of different types are distributed over the Earth. The most important properties which effect radiation and precipitation are beside microphysical characteristics and radiative properties the cloud height, thickness and horizontal extent. The climatic effects of clouds further depend on their geographical location, the albedo and temperature of the underlying surface and the season and the time of the day they occur. Since often several layers of clouds are present in a vertical column, cloud overlap is an important parameter to be considered in cloud–climate studies.

Cloud climatologies based on surface or satellite observations provide some of this information on the global scale as it is needed for climate studies [53,54].

Global average amounts for different cloud types according to surface observation climatologies [54] are shown in Table 3. 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) [54]. 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) [53].

Table 3. Cloud type amounts from surface observations; cloud overlap is possible (from [54]).

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

The global distribution of cloud amount as based on ISCCP results is shown in Figure 5. As expected the cloud cover is continuously high in the equatorial belt due to strong convection along 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 the ISCCP data (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 large cumulonimbus towers. Consistent global climatologies for cloud water content or effective particle size over land and ocean areas are currently not available.

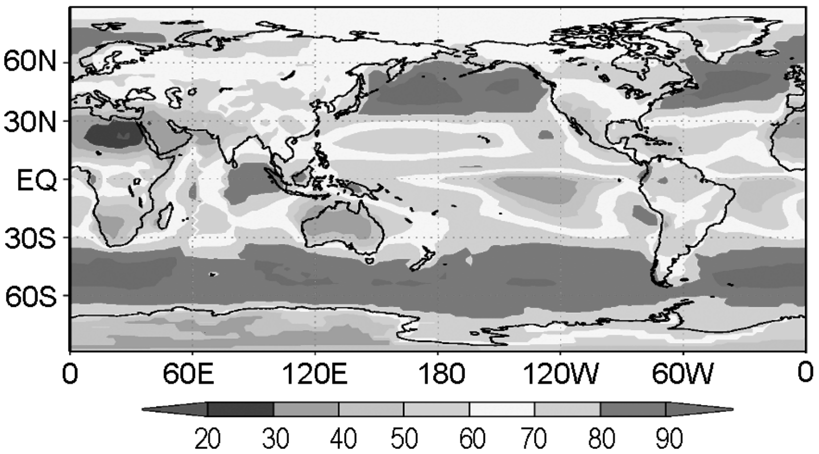

Figure 5. Annual average cloud amount (1983-1997) in % from the International Satellite Cloud Climatology Project [53].

5. CLOUD FORCING

5.1 Definition

Sufficient information on the microphysical and radiative properties of clouds in space and time for the evaluation of the effects that clouds have on the Earth's climate is not available on the global scale and for longer time periods. Therefore it is common to use the concept of *cloud radiative forcing* (CRF) to assess the radiative effects of clouds. The term *cloud forcing* was first introduced by Charlock and Ramanathan [55]. CRF is the amount by which the presence of clouds alters the top-of-the-atmosphere (TOA) energy budget. It is determined by the difference between the cloud-free radiation budget climatology and the average one over all scene types [55-58]. Both, models and satellite observations have been used to investigate cloud forcing.

The net radiation at the top of the atmosphere, R, is the difference between absorbed solar (shortwave) radiation and emitted terrestrial (longwave) radiation:

$$R = S\,(1-\alpha) - F = Q - F \quad (3)$$

S is the insolation, α is the planetary albedo, F is the outgoing longwave radiation, and Q is the absorbed solar radiation. The net cloud radiative forcing (NCF) is thus defined as:

$$NCF = R - R_{clear} \quad (4)$$

The net cloud radiative forcing can be split into a shortwave forcing (SWCF) and a longwave forcing (LWCF):

$$NCF = SWCF + LWCF = (Q - Q_{clear}) - (F - F_{clear}) \quad (5)$$

Because clouds reflect more than clear skies, SWCF < 0, they reduce the energy into the earth-atmosphere system. This factor is referred to as the 'albedo' or 'cooling effect'. Clouds are opaque to infrared radiation and generally emit at temperatures colder than the temperature associated with the emission from the clear sky, LWCF > 0. This is the cloud 'greenhouse' or 'warming effect'. The net of the two competing effects is a delicate balance, that depends on height, thickness, amount of clouds and number concentration, size, phase and shape of cloud particles.

5.2 Observations of CRF

Results from the Earth Radiation Budget Experiment (ERBE) [56] presented in Table 4 show that clouds approximately double the albedo of the Earth from an estimated clear sky value of 0.15 to its average of 0.3. The associated SWCF amounts to –49 Wm^{-2} as a global average. Thus, about 50 Wm^{-2} is reflected by clouds that would not be reflected by the cloud-free planet. LWCF estimated by ERBE is approximately 32 Wm^{-2}. Therefore, the net effect of the cloud population for the years 1985 to 1989 on the global energy balance adds up to –17 Wm^{-2}. Estimates of cloud forcing based on ISCCP data [53] for the years 1991 to 1995 come to slightly different values [59], especially for the LWCF, the reported net cloud forcing is about –24 Wm^{-2} (LWCF: +25 Wm^{-2}, SWCF: -50 Wm^{-2}). But the general result of the two assessments stays the same, that overall at present clouds cool our planet.

Table 4. Estimates of the effects of clouds on the radiation budget of the Earth at the top of the atmosphere. Annual global averages for the years 1985 to 1989 obtained from the Earth Radiation Budget Experiment (ERBE) are provided (after [56]).

Quantities at top of the atmosphere (TOA)	Global mean	Clear sky	Effect of clouds
Outgoing terrestrial radiation	-234 Wm^{-2}	-266 Wm^{-2}	**+32 Wm^{-2}**
Absorbed solar radiation	239 Wm^{-2}	288 Wm^{-2}	**-49 Wm^{-2}**
Net radiation	+5 Wm^{-2}	+22 Wm^{-2}	**-17 Wm^{-2}**
Albedo	30%	15%	**+15%**

The global distribution of the cloud forcing is not homogeneous, there are substantial regional differences and seasonal variations. The longwave cloud forcing is largest where high-level clouds are present, such as in regions of tropical convection and mid-latitude storm tracks. Largest values attained are about 70 to 80 Wm^{-2}. SWCF is also maximum in areas with active convection, but low stratus/stratocumulus regions in the tropics and at high latitudes are of equal or even greater importance. The effects of clouds on the shortwave radiation is strongly modulated by the incoming solar radiation. Maxium reductions in absorbed solar radiation are of the order of 120 Wm^{-2} and found over ocean areas in high latitudes in the summer hemisphere. The net cloud forcing is almost everywhere negative. In the tropics the large values of SWCF and LWCF cancel each other almost, leading to a small net forcing. NCF is largest over the tropical stratus/stratocumulus regions and over mid-latitude and high latitude ocean areas. The uneven distribution of net cloud forcing over the globe can be seen in Figure 6, which presents annual averages for the years 1991 to 1995. Zonal averages of NCF (Figure 7) underline the importance of mid- and high latitude clouds in the radiation budget at the top of the atmosphere. While SWCF and LWCF show quite a variability, the net cloud forcing between 35°S and 35°N is relatively small, on average about -15 Wm^{-2}. Since clouds reduce the net radiation more in high latitudes than in the equatorial region, in the annual mean they slightly increase the required equator-to-pole energy transport [58]. Clouds partition their radiative effects between the atmosphere and the surface. In the atmosphere cloud radiative forcing has a profound influence on local and regional circulations. The quantification of this influence lacks global observational information on cloud heights and thickness. Planned satellite projects including active instruments (radar, lidar) in their payload will improve this situation in the near future [60].

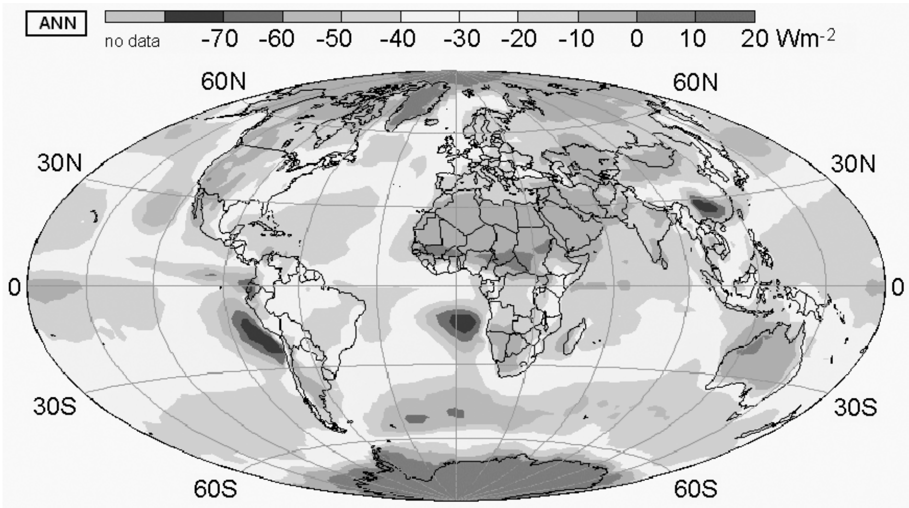

Figure 6. Annual average net cloud forcing (1991-1995) based on data of the International Satellite Cloud Climatology Project (from [59]).

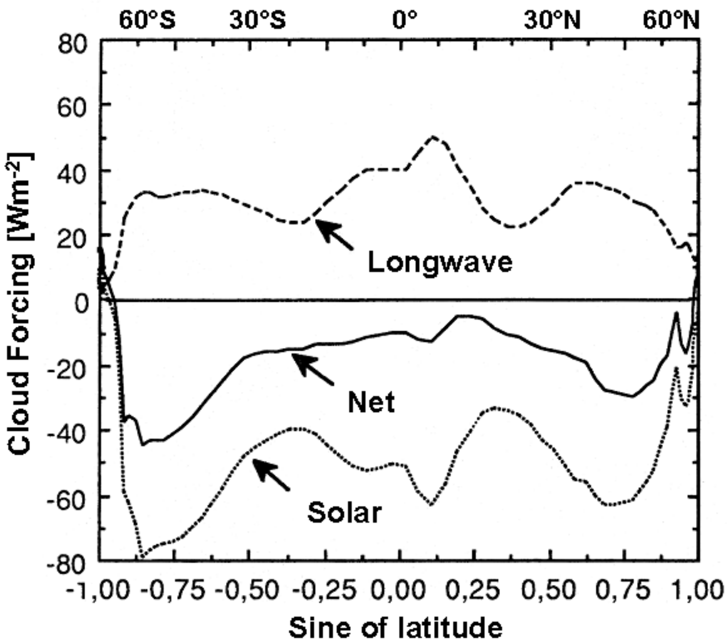

Figure 7. Zonal averages of annual mean cloud forcing components (from [58]).

Considering cloud types it can roughly be said that for low clouds the shortwave effect (cooling) and for high clouds the longwave effect (warming) dominates. Although the net CRF seems fairly modest, compared to a direct forcing by a possible doubling of the atmospheric carbon dioxide concentration of about 4 Wm^{-2} [1] the CRF components and their sum are large. A moderate shift in cloud properties, amount, or distribution can have comparable effects as a doubling of CO_2. Just to illustrate one aspect by a simple estimation (no multiple-layers, no 3D effects), a change in net radiation of -4 Wm^{-2} can be achieved by increasing the cloudy-sky albedo by 0.02 (or 5%) from 0.4 (current value, using a fractional cloud cover of 0.6) to 0.42, everything else kept constant.

As stated above, the effects of clouds on longwave and shortwave radiation are largely reciprocal producing a much smaller net effect. Any process that affects one of the components without a reciprocal change in the other has a great potential for altering the earth radiation budget and thus climate.

6. INDIRECT AEROSOL EFFECT

Among the interactions of clouds with their environment the *cloud-aerosol interaction* is increasingly recognized as a key factor controlling their radiative properties, life time, and the precipitation regime on local, meso- and global scales. Aerosols have an impact on the radiation budget of the Earth because they scatter and absorb solar and infrared radiation in the atmosphere, this is the direct aerosol effect [61,62]. Since the microphysical properties of clouds are closely regulated by the condensation or ice nuclei concentration and composition, the reflectivities of clouds may be sensitive to atmospheric aerosol concentrations. The aerosol concentration and its composition locally and regionally vary due to anthropogenic activities or natural changes and affect cloud albedo and thus climate more or less substantially. The influence of aerosols on cloud microphysical and radiative properties (indirect aerosol effect) and the associated climate forcing is an area of active research. Here only a brief outline of the topic can be given, for a more detailed summary of the current knowledge on observational evidence and model studies concerning the aerosol-cloud-climate relation see [1,62-65]

The possible climatic influence of aerosols through the mechanism of an increase in the cloud droplet number concentration and a resultant enhancement of cloud albedo and associated cooling of the planet was brought into attention by Twomey in the 1970s [66-68]. In Twomey´s model with a given cloud thickness and a fixed cloud liquid water content the increase in droplet concentration lead to a decrease in droplet size [68]. This effect is referred to as the *first indirect aerosol effect, albedo effect* or *Twomey effect*. The reduction of cloud droplet size affects the precipitation efficiency of the clouds, tending to inhibiting the development of precipitation and resulting in more persistent clouds and an associated additional cooling influence [69]. The latter effect is termed as *second indirect aerosol effect* or *cloud lifetime effect*. In addition the geometrical cloud thickness may also be altered under certain conditions [70]. Just recently another indirect aerosol effect has been postulated, which is connected to the width of the cloud droplet size distribution. A broadening of the droplet size spectrum in polluted air would result in a reduced cloud albedo and lead to an indirect warming effect [71].

Beside the mentioned indirect effects of aerosols on clouds and potentially on climate, there is a more direct effect of aerosols, which might also alter cloud appearance or cover. Aerosols mainly consist of non-absorbing material as sulphates, nitrates and organic carbon (OC), e.g., [72]. These aerosols partly scatter solar radiation back to space, thus leading to a cooling of the climate system. But aerosols can also contain absorbing material, i.e. black carbon (BC) from burning of biomass and fossil fuel. This absorption leads to a warming, which partly might offset the cooling due to the scattering effect [1]. Through heating of the air and a reduction in relative humidity aerosol absorption may decrease the low-cloud cover and the cooling associated with it [63]. The solar radiation absorbed by the surface decreases with increasing aerosol absorption, a related increase in static stability near the ground could reduce convective activity and lead to lower surface moisture fluxes [63,73]. Less moisture and less convective activity is likely to reduce the probability of cloud formation. The reduction in cloud cover associated with warming through absorbing aerosols is termed the semi-direct effect, it would amplify the direct warming influence of absorbing aerosols [74]. The magnitude of the semi-direct effect is probably strongly dependent on the vertical profile of absorbing aerosols, in the case of marine stratocumulus it is essential, whether the main aerosol layer is located within or above the boundary layer [75]. Several aspects which might further complicate the BC effects on clouds are related to changes in cloud microphysics by radiative heating, i.e. if black carbon is included within CCN populations, are discussed in [37]. If black carbon is included in cloud droplets, the heat released can increase the droplet temperature enough to affect the droplet equilibrium.

The aerosol effects in the climate system involving water clouds are sketched in the schematic in Figure 8. Certain aerosols act as ice nuclei and therefore influence the formation and albedo of cold clouds, this opens the possibility of an indirect effect on ice clouds by anthropogenic aerosol emissions. Insoluble anthropogenic aerosols may change the microphysics of cirrus clouds contact freezing [76,77]. At present, such effects are not quantified sufficiently on the global scale.

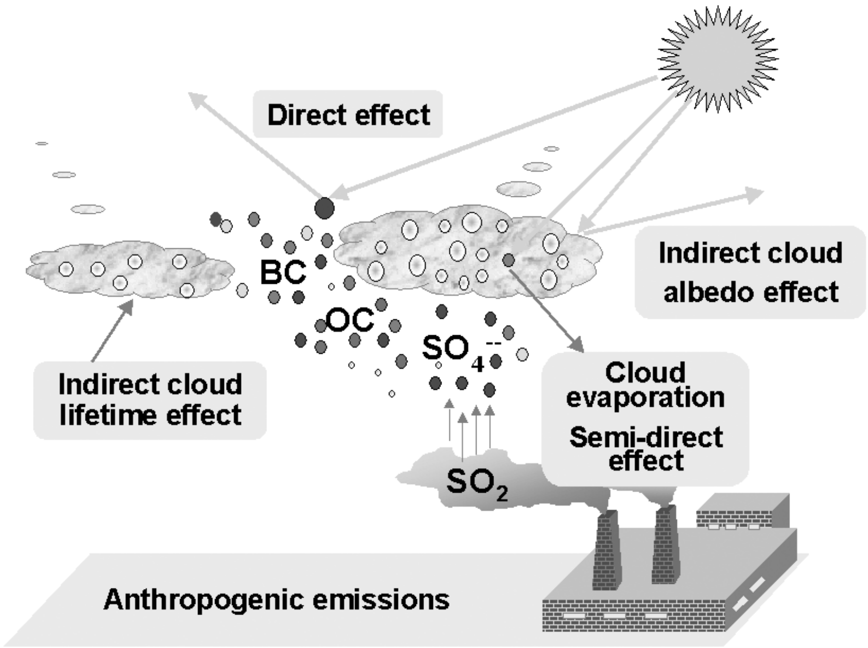

Figure 8. Schematic of the aerosol effects in the climate system. The aerosol indirect effects and the semi-direct effect force climate via clouds (figure from U. Lohmann).

The impact of the indirect and semi-direct aerosol effects could be enhanced by feedback loops. A plausible *aerosol-precipitation feedback* mechanism could work as follows: less precipitation removes less aerosols and leads to drier surfaces, which allow for more dust to be blown up and for more smoke from natural fires. All these effects and feedbacks related to cloud-aerosol interaction need to be considered in reliable assessments of future climate, although currently large uncertainties exist concerning their quantification [63].

Several field, satellite and modelling studies have attempted to identify and quantify the different aspects involved in indirect and semi-direct aerosol forcing. To date, there are no conclusive observations showing the entire chain of processes of the aerosol indirect effect from enhanced aerosol concentrations to enhanced cloud albedo on a scale large enough to influence significantly the Earth´s radiation budget [62]. But there are numerous observational studies, which could assess the aerosol indirect effect on the local to regional scale. The observational evidence includes measurements of an anthropogenic influence on CCN concentrations and enhanced cloud droplet number concentrations. The increase in cloud droplet concentration and reduction in their size by an enhancement of the anthropogenic aerosol concentration seems to be well established and could be demonstrated by several in situ aircraft observational studies; Figure 9 illustrates this increase in drop concentration. Here, also the so-called ship track phenomenon should be mentioned. Effluents of ship-stacks lead to a modification of cloud microphysical properties and an increase in cloud albedo, if the plume enters marine boundary layer clouds, as it can be well observed by direct measurements and from satellites [e.g., 78-81]. The effect of aerosols on cloud life time and precipitation efficiency seems to be currently difficult to quantify on a the global scale from available satellite observations [64]. Locally, a suppression of precipitation in clouds by high aerosol concentrations from biomass burning or industrial emissions could be deduced from a combination of active and passive satellite observations [82,83].

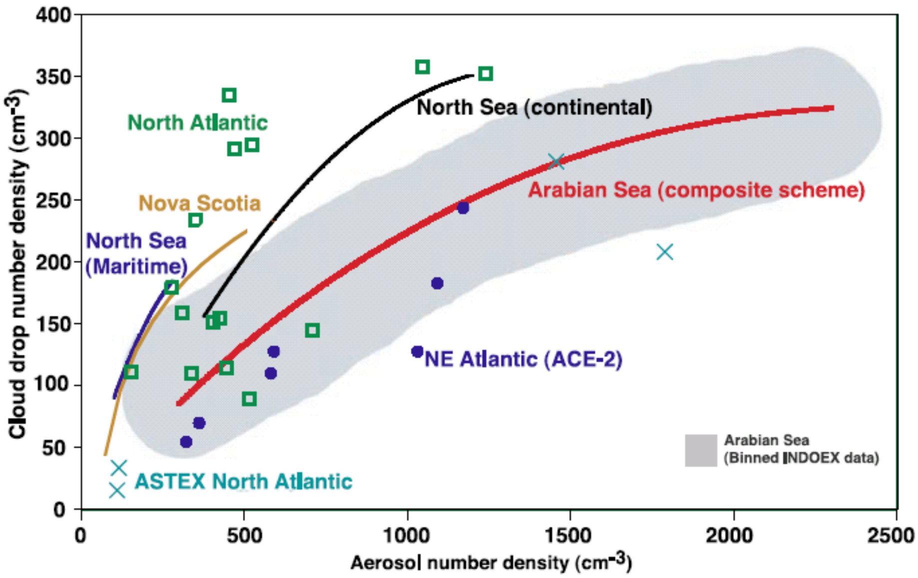

Figure 9. Aircraft data gathered over several regions of the Earth illustrating the increase of cloud droplet number concentration with the aerosol number concentration (from [63]).

The results of most observational and modelling studies concerning the indirect and semi-direct aerosol effect are summarized in [1,62,64,65]. Convincing observational evidence of the effect of smoke aerosols to inhibit cloud formation is given by Koren et al. [84].

To underline the importance of the indirect aerosol effect on climate it is helpful to compare the radiative forcing assigned to this effect (according to current understanding) against that of the greenhouse gases. The 2001 assessment of the IPCC [1] provides estimates of the magnitudes and uncertainties of the different radiative forcings from pre-industrial times (1750) to present (2000). These estimates are plotted in Figure 10. With the range of –2 Wm^{-2} (cooling) the indirect aerosol effect has the potential to be key contributor to radiative forcing. The radiative forcing of well mixed greenhouse gases amounts to 2.45 Wm^{-2} for the considered time span. Because of the existing uncertainties associated with the quantification of the aerosol indirect effect, only an uncertainty range and not a best estimate is given in Figure 10. Indirect forcing uncertainties arise because aerosol-cloud interactions are complex, many aspects are unknown or poorly understood. Climate models are used for a global assessment of the indirect forcing. Aerosol-cloud interactions take place at smaller spatial scales than climate models can resolve, and must be parameterized. In most models, if at all, only a few of the involved processes are implemented in the physical parameterizations; so climate models provide limited information about clouds and aerosols. The central problem of the indirect effect therefore is to determine the relationship between aerosol and cloud radiative properties, using the limited information available by climate models. Certainly, the uncertainties in connection with the indirect aerosol effects have to be reduced, before quantitative statements concerning the role of clouds (cooling vrs. warming effect) in climate change can be made.

7. CLOUDS AND GLOBAL CLIMATE CHANGE

7.1 Observed changes in cloudiness

For the assessment of the role of clouds in present-day climate change information on variations in total cloud amount for different cloud types (over several decades back in time) would be very helpful. Unfortunately not many studies exist addressing this issue in a systematic way. No clear and conclusive picture evolves from the few available analyses of longer term changes in regional cloudiness. Estimates of variations in cloud amount based on satellite data date only back to the mid-eighties [53].

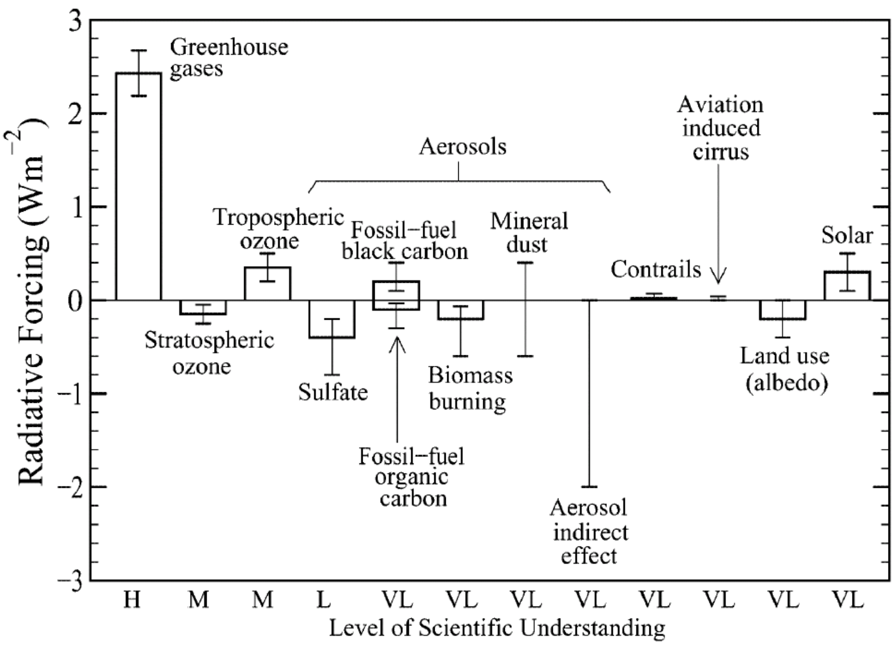

Figure 10. Global annual-mean radiative forcing, from 1750 to 2000, due to several agents. Estimated magnitudes are shown as rectangular bars, uncertainties are given by the vertical lines. Indicated level of scientific understanding: high (H), medium (M), low (L), very low (VL) (from [85]).

Some researchers examined cloud cover changes over the former USSR (FSU), these studies show an increase in cloudiness, which is significantly negatively correlated with changes in the diurnal temperature at the surface [86-88]. Similar observations have been made for the United States [89] and northern Europe [90]. Over the FSU during the past several decades a decrease in low-level cloud cover was offset by an increase in cumulus and cirrus clouds [88]. For large parts of China decreasing trends in cloud cover (1 to 2 % cover/decade) have been reported for the years from 1951 to 1994, this holds for daytime and night-time observations [91,92]. For the tropics and sub-tropics no similar statements can be made concerning longer term changes in cloud amounts.

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 reported for the mid-latitude North Pacific and North Atlantic Oceans [93]. For the years from 1952 to 1995 an increase in total sky cover of about 2% and an increase of about 4% in low cloud cover is found [94]. The latter trends are equally large in the southern and northern hemisphere, this makes an attribution to increased anthropogenic aerosol emissions improbable.

There are only a few analyses of amounts of various cloud types over the tropics. Trends in tropical cloud cover (20 N to 20 S) have been monitored with multi-spectral observations from the eleven polar orbiting HIRS (High resolution Infrared Radiation Sounder) since 1978 [95]. While total cloud cover remained relatively steady over the 23 years, high cloud cover has a modest increase in the second decade over the first decade (about 2%). However, it can not be ruled out at present that orbit drift of some sensors and instrument differences are part of this trend. A comparison of the HIRS data with ISCCP results [53] finds more clouds and more high clouds in the HIRS than in the ISCCP analysis. In addition, ISCCP shows a noticeable decrease in all and high cloud cover over the tropics from 1983 to 1999.

The relation of the increase in cloud cover over many land areas of a few percent over the last century to changes in the diurnal temperature range might be a link to climate change. Differentiated statements on the cloud-climate change relation for the last century lack more complete observations of the global cloud fields including microphysical parameters and vertical cloud layer distributions (cloud overlap). Upcoming satellite missions with combinations of passive and active instruments suited for cloud profiling might improve this situation for the future.

7.2 Clouds in Climate Models

General circulation models (GCMs) are currently the only tools for studies of future climate change that allow for the account of a complex set of climate processes. The Third Assessment Report (TAR) published by the Intergovernmental Panel on Climate Change (IPCC) in 2001 [1] stated, that the Earth will warm by between 1.4°C and 5.8°C by the end of the twenty-first century. These estimates are based on modelling studies with global atmospheric circulation models in their centre. Mainly two factors are responsible for the wide range of estimated future global temperatures: these are the uncertainty over the demographic, technological and ecological development of our society with its effect on energy consumption and greenhouse-gas emissions and the uncertainty in the understanding of the physical processes involved and the ability to model them in GCMs. Cloud processes and related feedbacks are explicitly mentioned in [1] among the physical processes leading to large uncertainties, a fact that is confirmed by a recent quantification study of modelling uncertainties published by Murphy et al. [96].

One of the most interesting questions concerning clouds is: how will they respond to a change in climate, which might be induced by an enhanced greenhouse effect, changes in the solar constant, or changes in the Earth´s surface reflectivity? Here, the question of possible cloud feedback mechanisms comes up. As noted before, the effects that clouds have on the radiation field depend on cloud amount, cloud water content, and the microphysical properties of clouds, as well as their vertical distribution and overlap. The complex dependencies of the listed quantities on changes in atmospheric temperature and moisture profiles and the fact that clouds can either cool or warm the earth system make it difficult to use simple physical arguments for the assessment of expected cloud feedbacks on climate. Only very detailed models of the climate system could help advancing the cloud feedback topic in a quantitative manner.

Representing clouds in GCMs is challenging, because for these models clouds are typically subgrid-scale entities (horizontally especially for convective clouds and often vertically for stratocumulus and cirrus). Small- and mesoscale motions which underlie the evolution of clouds and cloud systems are simply not resolved as are the interactive processes, which contribute to cloud-radiation interaction, like microphysical processes controlling the growth and phase of the various hydrometeors. The direct treatment of cloud related processes in climate models is incomplete. The models must rely on parameterisations of cloud processes, which are a weak point, because they typically involve idealizations that are only approximately valid, i.e. for the scale they are employed on.

The way clouds are represented in GCMs have a large influence on the overall results of climate studies. This is illustrated by an example: in a CO_2–doubling experiment with the Hadley Center (UK Met Office) general circulation model Senior and Mitchell [97] could show the impact of including prognostic cloud water and interactive cloud radiative properties into the model. The average global temperature change using a relative humidity-threshold scheme for cloud formation and non-interactive radiative properties for clouds was determined to be 5.4°C, while the new scheme lead to an average global temperature change of 1.9°C for CO_2-doubling.

Several studies have addressed the response of cloudiness in GCMs to prescribed climate perturbations. In a comparison of 19 models forced with 2 K sea surface temperature anomalies (fixed sea ice and snow), Cess et al. [98] show considerable disparity between the models in both magnitude and sign of the cloud feedback. An updated comparison [99] shows some convergence between the models concerning the net cloud radiative forcing, but by separating in longwave forcing and shortwave forcing still considerable differences between models are found. By comparing the change in the top of the atmosphere cloud radiative forcing (CRF) for 10 up-to-date climate models in a CO_2-doubling experiment considerable deviations of this parameter between the models was found [100] (Figure 11). The discrepancy in the simulated CRF changes is large, in sign and magnitude, for longwave and shortwave as well as for net cloud radiative forcing. The disagreement between the models points toward a large uncertainty in cloud related model climate sensitivity and casts some doubts in the model´s ability to realistically handle cloud-feedback processes. Many aspects concerning cloud-feedback processes and their representation in current GCMs are discussed in chapter 7 of [1].

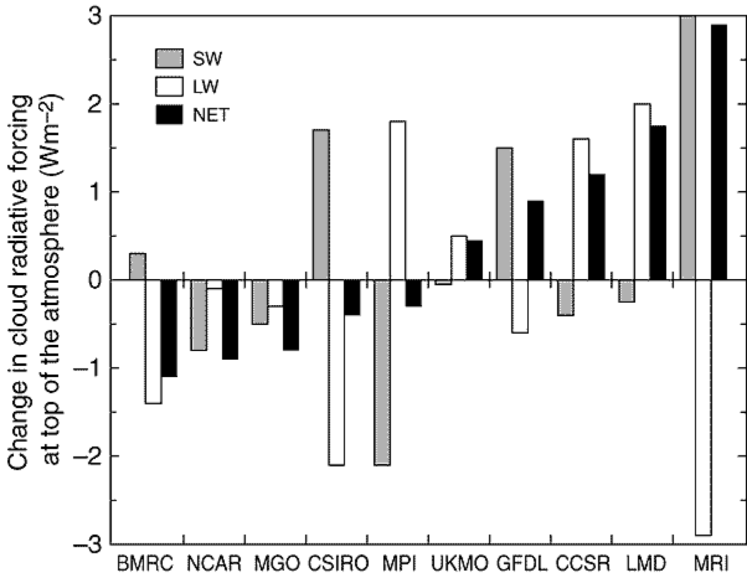

Figure 11. Comparison of changes in cloud radiative forcing at the top of the atmosphere associated with a CO_2-doubling experiment with 10 leading climate models [100].

Anthropogenic impacts on clouds, as the indirect aerosol effects and the semi-direct aerosol effect (section 6), need detailed considerations of cloud dynamics and its coupling to cloud microphysics. Tackling the climate sensitivity to these important forcings using current parameterisations of cloud dynamics and microphysics will lead to results with very low confidence. Only some of the GCMs use more sophisticated parameterisation schemes (e.g., [101]), but in general advancement in the cloud parameterisation problem has been very slow. A way out of this dilemma could be the so-called *superparameterisations*, which are advocated by recent conceptual papers [102,103]. The suggested method is to run cloud resolving models (in 2-d version) inside global circulation models to avoid simple parameterisations. At present, a limiting factor for this approach are the computationally very expensive model runs. Although there has been progress in their physical representation in the models, for a while clouds seem to remain a dominant source of uncertainty in climate prediction.

7.3 Topics currently under discussion

Here, some cloud related aspects, which are currently under scientific discussion within the ongoing debate on global warming, are summarised. A comprehensive review of the topics is beyond the scope of this overview. Relevant references are provided, which can serve as a starting point for a profound study of the issues.

7.3.1 Cloud absorption anomaly

Recently, several studies [104-106] suggest that clouds may enhance the global mean atmospheric absorption, while radiation schemes used in general circulation models (GCMs) indicated that clouds have little effect on globally averaged atmospheric solar absorption (e.g., [103]). The hypothesis is: satellite and *in-situ* data indicate that clouds absorb about 3 times (25 to 35 Wm^{-2}) as much solar radiation as theory and models (radiative transfer models, RTMs) predict. The magnitude of this discrepancy between models and observations and its explanation are, however, a subject of much debate and uncertainty (e.g., [108-115]). Conventional knowledge states that clouds, on average, have a small influence on total atmospheric absorption. Thus the proposed missing absorption of solar radiation by clouds was termed cloud absorption anomaly (CAA). If GCMs would be off by such an amount (~30 Wm^{-2}), the simulations of future climate change would be more in question.

References and discussions about the underlying observational data and their interpretation can be found in [116,117]. Doubts have been cast on the quality of data and analysis methods used in some of the early studies supporting CAA [115,118,119]. Several studies point toward other explanations of the missing atmospheric absorption in some models beside anomalous cloud absorption. These include effects of inhomogeneous clouds (3-D effect, non-uniform clouds compared with uniform clouds in GCMs) [120], water vapour continuum absorption [121,122] and possible exotic absorbers like water vapour dimers [123].

New observations concerning CAA report only 10% difference to models. Hansen et al. [113] found no evidence for a 30 Wm^{-2} 'radiation mystery', when comparing their climate model output with observations. New studies using radiative transfer models (RTMs) show an agreement with observations to within 10% under cloudy conditions [e.g., 124]. Accounting for heterogeneity of surface albedo was one of the issues to reduce some of the differences [115]. Li et al. [115] point out that there are more sophisticated RTMs in use than those implemented in GCMs. Nevertheless, atmospheric absorption in some GCMs has increased in recent years, chiefly due to enhanced absorption by aerosols and gases, but not by clouds [115].

The discussion on CAA is ongoing, but the evidence for a strong cloud absorption anomaly has become much weaker over the years. A comprehensive up-to-date overview on CAA is included in [125].

7.3.2 "Adaptiv Iris"

The tropics are an important region in the climate system. Here, large amounts of energy are exchanged between the surface (ocean) and the atmosphere. Therefore, getting the climate processes for the tropics right in GCMs is fundamental for using them as reliable tools for global climate change studies.

Lindzen et al. [126] used upper-level cloudiness and sea-surface temperature (SST) data from the eastern part of the western Pacific (Japanese Geostationary Meteorological Satellite-5) to develop a negative feedback concept which suggests that "the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." In short: as tropical SST increases, the anvil cloudiness decreases. Since these anvils mainly have a warming effect (large LWCF), this represents a strong negative feedback and counters global warming. Lindzen et al. [126] state that existing GCMs lack such a negative cloud/moist areal feedback.

The findings underlying the negative-feedback proposed by Lindzen et al. [126] were challenged by other groups. Lin et al. [127] used measurements from the Clouds and Earth's Radiant Energy System (CERES) sensor and got significantly different results from those reported by Lindzen et al. [126]. It was found that clouds in the tropics do change in response to warmer sea surface temperatures, but that the cloud changes serve to slightly enhance warming at the surface. Specifically, whereas the Lindzen et al. experiment predicts that cirrus clouds change in extent to reduce warming at the surface by anywhere from 0.45°C to 1.1°C [126], the Lin et al. experiment predicts that changes in the tropical clouds will help warm the surface by anywhere from 0.05°C to 0.1°C [127].

Hartmann and Michelsen [128] analysed spatial patterns of anomalous cloudiness and winds associated with the negative correlation between cloud-weighted SST and high-cloud fraction. They point out that the correlation noted by Lindzen et al. [126] results from variations in subtropical clouds that are not physically connected to deep convection near the equator, and that it is thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases.". A discussion concerning the statistical significance of some of the correlations underlying the conclusions in Lindzen et al. [126] can be found in Harrison [129] and Bell et al. [130].

Fu et al. [131] argue that the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive. The authors further claim that low clouds and water vapour were not correctly treated in the study by Lindzen et al. [126]. The clouds in question have a much higher albedo than assumed in [126], with the result that the negative feedback in their assessment would be too strong. In a reply to Fu et al. [131] Chou et al. [132] agree that Lindzen et al. [126] may have overestimated the iris effect to some extent, though hardly by as much as that suggested by Fu et al. [131].

7.3.3 Cosmic rays and clouds

There has been much controversy about changes in sun related parameters and their influence on climate change in the last century. A relatively new assessment relates the Galactic Cosmic Ray (GCR) flux reaching the Earth, which varies inversely with solar activity, to changes in cloud cover. In 1997 Svensmark and Friis-Christensen [133] suggested a modulation of the Earth´s total cloud cover by variations in the GCR flux, the results were updated by Svensmark in 1998 [134]. The main conclusion was that the amount of clouds on Earth varies in phase with the GCR flux. The GCR flux varies inversely with the 11-year solar cycle, see also [135]. Kernthaler et al. [136], who studied the relationship of different cloud types and GCR flux, could not find a clear link. The hypothesis was subsequently modified to a connection between GCR flux and low cloud cover by Marsh and Svensmark [137]. Since low clouds have on average a cooling effect in the climate system, this relation is of importance in the debate, to which extent anthropogenic emissions of greenhouse gases and/or natural reasons are to be made responsible for the observed global warming. It was suggested that a decrease in the GCR flux over the 20th century (by 50% over the last 1000 years) had resulted in a decrease of low cloud cover by more than 8%, with the potential to explain a significant fraction of observed global warming during that time period. To establish a link to clouds, there is a need to explain the GCR influence on aerosol formation. The hypothesis is that galactic cosmic rays produce cloud condensation nuclei through ionisation in the atmosphere [138]. The proposed physics consider the influence of ions on microphysical processes: ultrafine condensation nuclei (UCN) lead to a lower nucleation barrier and the nucleation can take place at lower ambient water vapour concentrations. Relevant ion-aerosol-cloud processes are reviewed by Harrison and Carslaw [139]. The suggested GCR-cloud connection has been subject of controversy. It was especially pointed out that there is no evidence that cosmic rays significantly affect CCN concentrations in nature, but current knowledge of aerosol formation in the atmosphere is insufficient and firm conclusion can not be drawn at present [140,141]. Richardson et al. [142] could not confirm significant trends in GCR flux over the last 50 years, for which the correlation between cloud and GCR flux was claimed.

Furthermore, the correlations between cosmic rays and cloud cover disappear as new satellite data come in [143,144], ISCCP cloud amount data is now available for a period of 18-years (1983-2001), Figure 12. Additional discussion of the cosmic ray topic including the attribution of the observed cloud cover changes to different reasons can be found in [145-147].

In an updated analysis of their statistical assessment [143] of the connection between solar activity, clouds and climate Kristjánsson et al. [148] conclude, that when global averaged low cloud cover is considered, consistently higher correlations (but opposite sign) are found between low cloud cover varia-

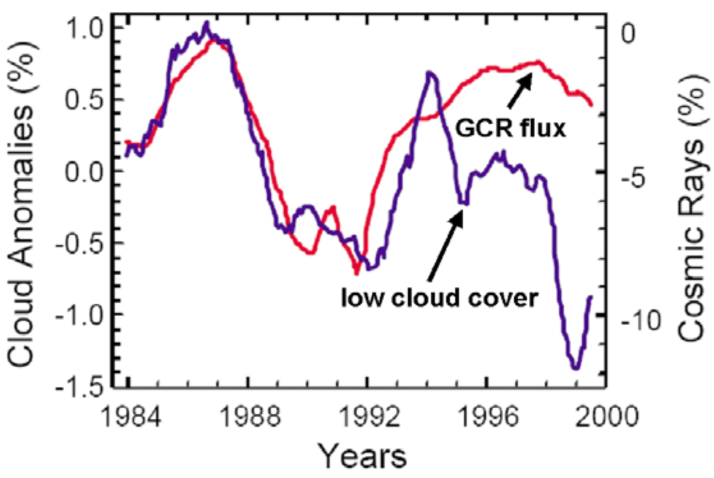

Figure 12. Change in low cloud cover and galactic cosmic ray flux for the years 1984 to 2000. The figure is taken from [144] and contains a smoothed version of the data presented in [143]. The correlation reported in [137] stops at about 1995.

ions and solar irradiance variations than between variations in cosmic flux and low cloud cover. The observed variations in marine low cloud cover are not inconsistent with a modulation by variations in solar irradiance causing changes in lower tropospheric stability (which influences moisture fluxes and convective activity). Kristjánsson et al. [148] point out that still many details are missing for a complete analysis, but a cosmic ray modulation of the low cloud cover seems less likely, although it can not be ruled out.

8. CONCLUSIONS

Clouds play a key role in the climate system. They strongly modulate the energy budget of the Earth and are an important factor in the global water cycle. Furthermore, clouds affect significantly the vertical transport in the atmosphere and determine in a major way the redistribution of trace gases and the deposition of aerosols via precipitation. In present-day climate, on average, clouds cool our planet, the net cloud radiative forcing at the top of the atmosphere is about –20 Wm^{-2}. Any change in cloud amount, cloud properties or shift in the vertical distribution of clouds can lead to considerable changes in the global energy budget and thus affect climate. Unfortunately, many facets of the interaction of cloud microphysics, dynamics and radiation, which determines the cloud properties and their life cycle, are not fully understood. Current research concerning cloud physics and climate concentrates on the cloud-aerosol interaction. With upcoming new satellite missions, some progress is to be expected in the observation of the global three-dimensional cloud distribution and key microphysical parameters.

A large fraction of the uncertainties in the prediction of future climate is due to the representation of clouds and cloud feedbacks in general circulation models. Many of the important processes involved in cloud evolution take place on scales, which are not resolved by the models and therefore need to be parameterised. But the simple parameterisations used in the models involve idealisations that are only approximately valid, progress on the cloud parameterisation problem has been very slow. A way out of this dilemma could be the so-called *superparameterisation*. The suggested method is to run cloud resolving models (in 2-d version) inside global circulation models to avoid simple parameterisations. At present, a limiting factor for this approach are the computationally very expensive model runs. It has also to be stated that the complex *cloud-climate-chemistry* relation is not fully addressed in present day climate models.

Some areas of controversy in the ongoing climate change debate are related to the cloud-climate question. The most prominent among the scientifically discussed aspects are the *anomalous absorption* of solar radiation, whether the Earth has an *adaptive iris* in the tropics, and whether *cosmic rays* influence cloudiness. It seems that the cloud-climate relation will continue to stay in the centre of interest for quite a while.

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