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Cloud-controlling Factors of Cirrus

Bernd Kärcher[1] and Peter Spichtinger[2]

[1]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
[2]ETH Zurich, Institute for Atmosheric and Climate Science, Zurich, Switzerland

Abstract

Factors controlling cirrus clouds comprise small- and large-scale atmospheric dynamics, ice nucleation behavior of natural and anthropogenic particles, and interaction with terrestrial and solar radiation. Current understanding of these factors is summarized. Key uncertainties in this active area of research are addressed, and future developments aimed at reducing these uncertainties are outlined.

Introduction

Various definitions of cirrus clouds exist in the scientific literature (Lynch et al. 2002). In this chapter, we define cirrus as clouds that primarily inhabit the global upper troposphere and tropopause region and which lack a liquid water phase; that is, they are entirely composed of ice crystals. This is equivalent to a temperature criterion constraining the ice formation process, as liquid water droplets freeze spontaneously below ~235 K, depending on their size. Upper tropospheric cirrus ice crystals may subsequently sediment and populate lower atmospheric regions, which we assume to be cloud-free to avoid overlap with other (e.g., mixed-phase) cloud types. Consequently, to form and persist, cirrus require relative humidities over ice (RHI) that exceed 100%; hence cirrus develop predominantly in ice-supersaturated regions. Low-level ice clouds and ice fogs of the Arctic and Antarctic (including Diamond Dust) are not considered cirrus. In addition, high-latitude ice clouds appear well within the lower stratosphere during the polar winter, and these are known as type II polar stratospheric clouds.

The water budget in the climatically sensitive region of the upper troposphere and the radiation balance at the top of the atmosphere are greatly influenced by the amount of condensate in the form of ice and its vertical distribution. Cirrus cloud coverage is substantial according to satellite climatologies (Wang et al. 1996; Rossow and Schiffer 1999) and affects the atmosphere and climate globally, because cirrus trap longwave radiation effectively and can be strong reflectors of incident solar radiation (Stephens et al. 1990).

In addition to their climatic relevance, cirrus clouds are unique among the Earth's plethora of cloud types for two reasons. First, the prevalence of rather high ice nucleation thresholds (tens of percent supersaturation with respect to ice) and long growth and sublimation timescales (owing to the low-temperature environment) result in regions of persistent supersaturation inside and outside of cirrus, as well as a lack of a clear distinction between primary ice (nucleating and growing by vapor diffusion) and secondary (aggregating and precipitating) ice. Second, because ice crystals may survive substantial subsaturations, the transition between clear and cloudy air is rather continuous; this contrasts with other liquid-phase clouds, where cloud and water-saturated regions are almost identical. Sedimentation of ice crystals constitutes an important factor in determining cirrus morphology and development. Finally, cirrus evolve often in a rather stable thermodynamic environment, contrary to most other tropospheric clouds types.

Most of the uncertainty surrounding climate change prediction using general circulation models (GCMs) arises from interactions and feedbacks between dynamic, microphysical, and radiative processes affecting cirrus (Zhang et al. 2005). Model climates are sensitive to even small changes in cirrus coverage (Lohmann and Kärcher 2002) or ice microphysics (see Jakob in Lynch et al. 2002). Optically thin cirrus in the tropical tropopause layer dehydrate the air entering the stratosphere, affecting water vapor and hence ozone concentrations there (Holton and Gettelman 2001). As cirrus ice crystals might scavenge fine aerosol particles and soluble trace gases, ice crystal sedimentation may lead to a vertical redistribution of these substances. Cirrus particles trap or adsorb chemically active trace gases, such as nitric acid (Kärcher and Voigt 2006), and initiate heterogeneous halogen chemistry (Thornton et al. 2007), both of which affect ozone. Settling ice crystals trigger glaciation of warm clouds (e.g., altocumulus), changing their precipitation efficiency by producing deep ice-cloud layers and modulating the hydrological cycle (Herzegh and Hobbs 1980).

It is difficult to define cirrus based on atmospheric measurements. Lidar instruments are capable of detecting cirrus with optical depths as low as 10^{-4} at wavelengths in the visible part of the radiation spectrum, whereas many satellite sensors require visible optical depths of ~0.1 for cirrus to be detected via their forcing in the terrestrial spectrum. Usually, optical spectrometers have acceptable sampling statistics only when measuring ice particle concentrations *in situ* above ~0.1 cm^{-3}, although counterflow virtual impactors can be designed to detect concentrations as low as 0.005 cm^{-3}. The size range 1–10 μm may be populated with both haze droplets and small ice crystals and is particularly difficult to study experimentally (Kärcher and Solomon 1999).

Meteorology textbooks present a host of cirrus cloud types based primarily on their visual appearance. Here, we adopt a simpler categorization by covering the basic types of stratiform cirrus: cirrus formed *in situ* by ice nucleation processes; anvil cirrus arising from deep convective outflow (cumulonimbus clouds); and contrail cirrus that result from jet aircraft operations. *In-situ* cirrus, in which ice nucleates both on supercooled liquid aerosol particles and a special class of heterogeneous ice nuclei (IN), are ubiquitous at all latitudes. Anvil cirrus are widespread in the tropics; along with upper level *in-situ* cirrus, they affect climate most strongly. Contrail cirrus are the only single, purely anthropogenic cloud type that affect midlatitude radiative forcing on regional scales, and are arguably the most obvious human influence on the Earth's climate. They have been invoked to explain a sudden increase in high cloud cover in the U.S.A. at the beginning of the jet era (Liou et al. 1990). Anvil and contrail cirrus have distinct sources that are not primarily connected to *in-situ* ice nucleation processes. The special class of frontal cirrus (cirrostratus) may exhibit features that are characteristic of both anvil and *in-situ* cirrus. For instance, ice condensate can be lofted up in mixed-phase frontal clouds or it may nucleate on aerosol particles in upper cloud levels.

We begin by summarizing the current understanding of cloud-controlling factors of cirrus. We will not provide a complete review, as virtually all aspects of cirrus have been treated elsewhere (Lynch et al. 2002). Instead, our goal here is to supplement the existing body of knowledge with more recent work appropriate to the goals of this Forum. We will focus on what is less well known about cirrus and outline directions for future research to consider.

Current Understanding

Dynamic Controls

The regional appearance of contrail clusters without natural cirrus cloudiness and the large horizontal extent of tropical anvils imply that the upper troposphere is often supersaturated with respect to ice. Three cooling mechanisms control cirrus formation and development by increasing the relative humidity past ice saturation: (a) adiabatic vertical air motions acting on a wide range of spatial and temporal scales; (b) turbulent mixing of air parcels caused by dynamic instabilities or wind shear; and (c) diabatic effects arising from longwave heating or shortwave cooling. The latter two mechanisms evolve on timescales that are probably too long to cause cloud formation, but which affect the life cycle of cirrus after formation. Once cirrus has formed, diabatic processes may couple back to internal cloud dynamics.

Adiabatic vertical air motion is caused by a range of gravity waves spanning spatial and temporal scales from 1–1000 km and from Brunt-Väisälä periods to seasonal timescales, respectively. As is true for all clouds, cirrus represent a multiscale system; motions and processes that transpire on different scales interfere with each other. To estimate the consequences for cirrus evolution, it is imperative that we have an accurate prediction of air temperature changes (cooling rates, $\omega = |dT/dt|$) and corresponding changes in RHI. Variability in water vapor caused by advective or diffusive transport is another factor affecting cirrus, but it is considered of secondary importance for cirrus formation (Kärcher and Ström 2003). This is different to lower tropospheric clouds, where fluctuations of total water appear to be more important than temperature variability (Tompkins 2003).

Aircraft measurements suggest typical horizontal extensions of ice-supersaturated regions of ~150 km in the midlatitude upper troposphere (occasionally few 1000 km) (Gierens and Spichtinger 2000). Ice supersaturation occurs in vertical layers 0.6–1.4 km (occasionally 3–5 km) thick at mid- and high latitudes (Downing and Radke 1990; Spichtinger et al. 2003a; Treffeisen et al. 2007), but the variability in layer thicknesses is large. Ice-supersaturated regions are colder and/or moister than the surrounding air masses (Spichtinger et al. 2003b). Regions of ice supersaturation coincide with areas where the mean RHI as well as its variability is high (Gettelman et al. 2006a). For instance, an ice-supersaturated region extending 1000–2000 km horizontally and up to 3 km vertically and lasting for more than 24 h was observed to form near the outflow region of a warm conveyor belt (Spichtinger et al. 2005b).

Cirrus clouds coexist with regions where RHI > 100%. This is obvious when comparing regions with a high frequency of supersaturation with the spatial distribution of cirrus, both exhibiting similar patterns. Sometimes cirrus develop fallstreaks (*virga*) that may have a larger vertical extent than the associated supersaturated layers, because large sedimenting ice crystals may survive in subsaturated air for a long time (Pruppacher and Klett 1997). The similarity between large-scale patterns of high relative humidity and cirrus occurrence implies that synoptic cold pools define the overall thermodynamic conditions in which *in-situ* cirrus formation and evolution takes place (Newell et al. 1996). Connections between radiatively important microphysical properties of optically thin cirrus and atmospheric humidity, large-scale updraft velocity, and other meteorological parameters have been illuminated by satellite retrievals (Stubenrauch et al. 2004).

Observed cirrus properties cannot, however, be reproduced in simulations in which ice formation is forced only with synoptic cooling rates ($\omega \approx 1$ K/h) (Kärcher and Ström 2003). Instead, cirrus cloud microphysical properties are controlled to a large part by mesoscale variability in ω (Ström et al. 1997; Haag and Kärcher 2004). Mesoscale (1–100 km) temperature fluctuations arise from mesoscale gravity waves; these waves could be excited by convection (Bretherton and Smolarkiewicz 1989), stratified flows over orography

(Smith 1979), geostrophic adjustment (Plougonven et al. 2003), or baroclinic instability (Wang and Zhang 2007). Evidence for the generation of cirrus by Kelvin-Helmholtz wave breaking and internal gravity waves is available (Marsham and Dobbie 2005; Spichtinger et al. 2005a). Cirrus occur more frequently over mountainous regions (Dean et al. 2005). Away from these source areas, a persistent background of such fluctuations driven by high-frequency gravity waves is observed at all latitudes and seasons in cirrus levels (Gary 2006), typically leading to mean $\omega \approx 10$ K/h. Turbulence is associated with all kinds of these waves.

Anvil and contrail cirrus have dynamic origins that differ from cirrus formed *in situ*. Convective anvil cirrus materialize through detrainment of frozen (or rapidly freezing liquid) condensate from deep cumulus updrafts. Anvils develop into stratiform cirrus in favorable conditions, becoming a significant source of upper tropospheric cloud ice at midlatitudes (Tiedtke 1993). The initial ice crystal number density and mass are largely determined by the evolution of the freezing drop size distribution during upward transport (in turn linked to the updraft speed) and by the rate of entrainment of drier ambient air. Given the variability in tropical storm sizes (~100–1000 km) and intensities of mesoscale convective systems, anvils exhibit a wide range of optical properties and lifetimes (see DelGenio in Lynch et al. 2002). The regions with the highest frequencies of deep convection are collocated with regions where thin tropical tropopause cirrus is prevalent (Dessler et al. 2006). Large updraft speeds in the tops of overshooting convective plumes enable the freezing of entrained liquid particles and lead to the formation of thin cirrus well above the main convective detrainment level that contain copious small (radius ~10 μm) ice crystals (Jensen and Ackerman 2006). As mentioned above, ice in frontal cirrus may either form *in situ* (in upper levels) or originate from the upward transport of frozen condensate.

Atmospheric conditions enabling the formation of jet contrails can be derived by analyzing the bulk moisture and heat budgets in cooling aircraft plumes. Plume cooling is brought about by rapid (~0.1 s) isobaric mixing of an initially free, hot turbulent jet with colder ambient air, leading to transient water-supersaturated states. The maximum temperature and minimum relative humidity at which contrails form are determined by ambient temperature, pressure and RHI, specific heat of jet fuel combustion, emission index of water vapor, and the overall aircraft propulsion efficiency (Schumann 1996). Thus contrail formation is easier to predict than *in-situ* cirrus formation, because contrail occurrence is related to local temperature, not to ω. While contrail formation occurs along airplane flight paths, the development of the initially line-shaped clouds into persistent, extended contrail cirrus decks is controlled by weather patterns and the multiscale dynamic processes determining atmospheric ice supersaturation.

Turbulence is often found near the tropopause (Worthington 1999) and is thus an essential component for the evolution of all three types of cirrus clouds.

Turbulence in cirrus is linked to both the dynamic state of the background flow (mainly atmospheric stability) and the microphysical and radiative processes that occur within clouds (see Quante and Starr in Lynch et al. 2002). The complex spatial structure of cirrus results from interactions between localized turbulence, diabatic heating, vertical mixing, and particle sedimentation (Jensen et al. 1998; Whiteway et al. 2004).

Aerosol Effects

Aerosol particles serve as precursors to ice crystals in cirrus clouds that form *in situ*. Homogeneous freezing of liquid particles and heterogeneous ice nucleation at solid surfaces of mixed-phase or insoluble particles contribute to a variable proportion to ice initiation in cirrus. Secondary ice multiplication (i.e., rime splintering, fragmentation during evaporation, or collisions between crystals) is important for the glaciation of supercooled water clouds and is much less relevant in understanding ice formation in cirrus (Cantrell and Heymsfield 2005). Direct ice nucleation from aerosol particles is not the primary determinant for the ice content in anvil and contrail cirrus, but may contribute to their ice budgets at some point during their life cycle.

In cirrus levels, supercooled aqueous particles contain mainly dissolved sulfuric acid (H_2SO_4) and organics (Murphy et al. 1998) and perhaps ammonium, although this is difficult to detect *in situ*. A laboratory analysis of 18 different aqueous solutions (including salts and organics) in the form of emulsion drops (radii ~1–10 μm) provided unequivocal evidence that their equilibrium freezing temperatures are independent of the chemical nature of the solutes (Koop 2004). Critical relative humidities describing the onset of homogeneous freezing have been inferred as a function of temperature and have been used widely in models. Soluble organics tend to lower the freezing rates relative to pure aqueous H_2SO_4 owing to their lower hygroscopicity and possibly a reduced accommodation coefficient of water molecules; both result in less water uptake (Kärcher and Koop 2005) and cause organic-rich particles to remain preferentially unfrozen (Cziczo et al. 2004a). Independent measurements in an aerosol chamber as well as in the field have confirmed the critical RHI (~150–170%) (Möhler et al. 2003; Haag et al. 2003; Hoyle et al. 2005), also for ammonium sulfate particles, which have been controversially discussed (Abbatt et al. 2006).

The temporal development of RHI in an adiabatically rising air parcel is controlled by cooling of air (increasing RHI) and depositional growth of ice particles (reducing RHI) that nucleate once the homogeneous freezing threshold is passed. The total number of ice crystals forming in such a cooling event and their initial size is determined by the nucleation, τ_n, and growth, τ_g, timescales (Kärcher and Lohmann 2002). The former is inversely proportional to ω and depends on fundamental properties of the nucleation rate coefficient; the latter is inversely proportional to the ice saturation vapor pressure. If $\tau_n > \tau_g$, initial growth is faster than freezing, and the ice crystals lose their memory about their initial size. In this fast growth regime, realized over much of the midlatitudes, the number of ice crystals formed is very insensitive to details of the freezing aerosol size distribution but rises as $\omega^{3/2}$, rendering the exact knowledge of the cooling rate very important. This is contrary to the activation of cloud condensation nuclei in warm clouds, where the dependence of cloud drop number density on ω is weaker. Background mesoscale temperature fluctuations in conjunction with homogeneous freezing are capable of explaining the high number densities (~0.1–10 cm^{-3}) of small ice crystals routinely measured in cirrus forming *in situ* at all latitudes (Kärcher and Ström 2003; Jensen and Pfister 2004; Hoyle et al. 2005).

At low temperatures, changes in liquid particle number and size can cause a relatively weak indirect effect on total ice crystal concentration (changes of either sign within a factor of ~2) (Kärcher and Lohmann 2002). According to climate model simulations that include homogeneous freezing and tuned subgrid-scale components of the vertical wind speed, the eruption of Mt. Pinatubo caused no significant effect on cirrus radiative forcing consistent with ISCCP data analyses; however, a noticeable radiative impact of cirrus changes, after very intense volcanic eruptions, cannot be ruled out (Lohmann et al. 2003). Changes in ice crystal properties brought about by enhanced SO_2 emissions in China and Southeast Asia and subsequent enhanced aerosol nucleation may impact future stratospheric humidity by lifting more ice crystals of smaller size into the tropical lower stratosphere (Notholt et al. 2005). More significant aerosol indirect effects are possible if efficient IN and liquid particles compete during cirrus formation (DeMott et al. 1997).

Heterogeneous ice nucleation involves several distinct modes of action (nucleation modes) and requires particles that exhibit particular surface features supporting ice formation (see DeMott in Lynch et al. 2002). In cirrus levels, the predominant nucleation modes are immersion freezing and perhaps deposition nucleation. Immersion nuclei are enclosed within a liquid particle and their surfaces trigger ice formation in the surrounding liquid; deposition nuclei have dry surfaces at which ice nucleates directly from the vapor phase. Immersion nuclei are likely abundant and constitute a subset of the insoluble particle fraction. Efficient deposition nuclei that derive from the Earth's surface are probably rare in the upper troposphere, because they act most likely as cloud nuclei and are removed from the atmosphere before they reach cirrus levels. Surface crystallization of supercooled water has been proposed as a process competing with bulk homogeneous freezing (Tabazadeh et al. 2002); however, its relevance for ice nucleation from aerosol particles in cirrus conditions has not been demonstrated. Ice nuclei relevant to cirrus formation include mineral dust, crystallized salts in mixed-phase particles, and perhaps black carbon soot and sea salt. For a given IN type, chemical composition and size are important factors in the determination of IN activity. Preactivation may occur when a particle once formed ice, experiences subsaturation, and later forms ice at lower RHI than the unactivated particle in otherwise similar conditions.

Although soluble sulfates and organics dominate, at times, the composition of free tropospheric particles at northern latitudes, the fraction of IN is typically enriched in mineral dust and fly ash, metallic components, and, to a much smaller degree, carbon, potassium, and other trace species (DeMott et al. 2003). Convective storms have the potential to transport gases and particles, including sea salt or mineral dust, from the boundary layer up to the upper troposphere (Cziczo et al. 2004b). It is unlikely, however, that significant amounts of very potent IN deriving from surface sources, such as pollen (Diehl et al. 2001) or Saharan dust (Sassen et al. 2003), are able to reach frequently cirrus levels away from deep convection. Most of those ice precursors are likely to be removed by precipitation scavenging in the lower troposphere. In terms of the efficiency of black carbon (soot) particles for cirrus ice formation, available laboratory and field information is inconclusive (Kärcher et al. 2007).

At a given cooling rate, deposition of water vapor on ice crystals formed from IN at low supersaturations reduces or halts the increase in RHI in a rising air parcel, leading to fewer homogeneously frozen particles relative to pure homogeneous cloud formation. Hence, adding IN to a liquid particle population reduces the total number of nucleated ice crystals. This mechanism was coined the "negative Twomey effect" (Kärcher and Lohmann 2003) in association with the traditional Twomey effect in warm clouds, where the addition of cloud condensation nuclei enhances the cloud droplet number density. The negative Twomey effect can lead to reductions of the total ice crystal concentration by up to a factor of 10. According to model simulations, it causes lower cirrus albedo as a result of increased effective radii and decreased ice water contents, as well as nonlinear changes in cirrus occurrence, optical extinction, and subvisible cloud fraction (Haag and Kärcher 2004). The exact magnitude of these changes depends on the ratio between the cooling rate and rate of increase in ice mass attributable to water uptake on heterogeneously nucleated ice particles. If sufficient IN are available and the cooling rates are slow enough to activate only a fraction of these IN (and none homogeneously), more ice crystals can form, compared to a case without IN, but this effect is much weaker than the negative Twomey effect (Kärcher et al. 2006).

One satellite case study of polluted aerosol and ice cloud properties over the Indian Ocean lends support for the existence of the negative Twomey effect in the upper troposphere (Chylek et al. 2006). Extensive lidar studies in the same region, however, yield inconclusive results (Seifert et al. 2007). *In-situ* measurements provide direct evidence for an impact on cirrus via heterogeneous nucleation (Haag et al. 2003; DeMott et al. 2003), suggesting background IN concentrations of ~10–30 l^{-1} at northern midlatitudes. In the majority of cases, the presence of IN did not prevent homogeneous freezing from occurring, but presumably modified cirrus properties. However, observed differences in cirrus properties cannot easily be traced back to IN (Gayet et al. 2004), partly because of the difficulty of separating aerosol effects from effects caused by variability in dynamic forcing.

Observations of the response of deep convective clouds to aerosol particles and soluble trace gases, in general, and to anvil properties, in particular, are very rare (Cziczo et al. 2004b). Only a limited number of numerical studies have addressed this issue using models that couple transport and entrainment in deep convection with detailed cloud microphysics. To describe anvil cirrus properly, the entire cloud evolution must be known, including warm and mixed-phase precipitation and dynamic-microphysical-radiative feedbacks. In general, ice phase processes respond very sensitively to even small changes in the cloud environment (e.g., continental vs. maritime, thermal stability, moisture vertical profile), assume aerosol properties, and represent multiple pathways that tie liquid and ice phase processes together. As a result, local concentrations of ice particles and IN are only poorly correlated.

Some numerical studies of continental deep convection suggest the production of more but smaller anvil ice crystals with increasing aerosol input, either from surface sources or through entrainment of mid-tropospheric particles (Khain et al. 2004; Fridlind et al. 2004). By contrast, Cui et al. (2006) report the opposite behavior and point to differences in convective strength (whether or not cloud tops reach homogeneous freezing levels) and in assumed ranges of aerosol concentrations as possible explanations. In model studies of intense tropical thunderstorms, Connolly et al. (2006) suggest a strong influence of aerosols via the ice phase on cloud microphysics and dynamics; other studies hint at IN not acting as key players in determining anvil cirrus radiative effects (Carrió et al. 2007). Regardless, ice processes responsible for driving the response of cloud evolution to aerosol in such simulations are highly uncertain, and measurements of small ice crystals in deep convective clouds, which many numerical studies use as a guide, are fraught with uncertainties.

Jet engines produce copious plume particles that serve as contrail IN (Kärcher 1999): soot particles formed during fuel combustion, ultrafine particles composed of H_2SO_4, and organics formed in the plume mainly on emitted chemiions (charged molecular clusters) before ice saturation is reached. Available observations are consistent with activation of $\sim 10^4$–10^5 cm^{-3} of plume aerosols into small (some 0.1 μm) water droplets that freeze immediately. A surplus of plume particles and the strong dynamic control of contrail formation driven by large plume cooling rates ($\sim$1000 K s^{-1}) cause the properties of nascent contrails to be rather insensitive to details of the ice nucleation process.

Radiative Effects

Cirrus clouds have a varying effect on the radiation budget (Stephens and Webster 1981). Optical properties of ice crystals are determined by the refractive index of bulk ice as well as crystal size, shape, and orientation relative to incident light. Shape and orientation render the determination of radiative forcing by cirrus significantly more complicated than that of warm clouds composed of spherical water droplets. For sufficiently low optical depth, absorption of infrared radiation and re-emission at colder temperatures dominates scattering of solar radiation, in which case cirrus warm. As optical depth becomes larger, the solar albedo effect increases, leading to a net cooling. The albedo increase is larger for smaller effective ice crystal radii. This picture does not change significantly when supersaturation is allowed inside thin midlatitude cirrus (Fusina et al. 2007). The radiative response of cirrus is further influenced by their coverage, altitude and thickness, spatial inhomogeneity, and numerous other factors, including ice crystal size distribution, solar zenith angle, surface albedo, and presence of clouds and water vapor column.

Thin cirrus cool the surface and exert a net warming within and at the top of the atmosphere; optically thick ice clouds still warm the atmosphere on the whole but cool the surface and the upper atmosphere (Chen et al. 2000). Generally, the net radiative forcing by cirrus results from a difference of two large numbers and is therefore difficult to measure or calculate accurately. Hence, the transition between net heating and net cooling in a cirrus cloud layer is difficult to predict. This problem is aggravated by the fact that the spatial structure on the cloud scale can significantly affect the cirrus radiative response attributable to 3-D effects (horizontal photon transport) (Zhong et al. 2008).

Whereas *in-situ* cirrus visible optical depths rarely exceed ~5 (thin, high cloud according to the ISCCP classification), those values range from ~10–50 for anvil cirrus. Line-shaped contrails have mean optical depths ~0.1–0.5, similar to thin cirrus. Detailed numerical studies revealed that radiation can have dramatic effects on cirrus causing significant differences in cloud inhomogeneity and lifetime compared to studies ignoring radiative effects (Dobbie and Jonas 2001). Solar radiation was found to be important in layers with optical depth in the range of 1–2, whereas infrared radiation was more important in thicker layers (> 2). Thin cirrus with optical depth < 1were found to be only marginally affected by radiation. Depending on the initial cloud layer stability, radiation interactions can produce a more vigorous dynamic evolution, including cellular enhancements at the scale of the layer thickness, and can increase ice water path and lifetime. Anvil cirrus or midlatitude cirrus layers in summer (over warm surfaces) can be maintained through turbulence generated by radiative heating of lower cloud parts (see Quante and Starr in Lynch et al. 2002). Buoyancy lifts and cools the cloud layer and serves to maintain it against the dissipating effects of heating (Köhler 1999). Radiative cooling at cloud tops may create supersaturations high enough to initiate ice nucleation. Similar radiative stabilization may also operate in some contrail cirrus evolving in supersaturated air according to numerical simulations (Jensen et al. 1998).

Cirrus clouds are strong absorbers in the infrared spectral region; hence, from brightness temperature differences, they can be detected day and night using remote-sensing techniques. Remote sensing works well over the ocean because the signal to noise ratio is large enough to determine high clouds relatively accurately. Over land, detection is more difficult and uncertainties are higher. Often, various remote-sensing methods differ in quantitative results about cloud frequencies of occurrence or cloud amount and properties, depending on the type of observation (e.g., nadir vs. limb sounding) and underlying retrieval methods (Stephens and Kummerow 2007). High frequencies of occurrence are found in the tropics over Amazonia, central Africa, and the Indonesian warm pool (Rossow and Schiffer 1999). The Intertropical Convergence Zone (ITCZ) is also characterized by high cirrus cloud amounts. Storm tracks mark high probabilities to find cirrus in extratropical latitudes.

Life Cycle

Remote sensing has been applied to study the life cycle of clouds or cloud systems in a few cases, and only little is known in this respect about cirrus. Tropical convection or midlatitude synoptic weather systems in combination with radiative effects are presumably responsible for seasonal and diurnal variability in the amount of cirrus. Satellite measurements have revealed pronounced diurnal cycles of cirrus over land (maximum occurrence during the late afternoon), in particular in the tropics and at midlatitudes in summer (Wylie and Woolf 2002). The single maximum indicates the building of convective systems and the spreading of anvils from them. Diurnal cycles have been found to be small or absent during winter over the continental U.S.A. In the western tropical Atlantic ITCZ, dual maxima (morning and late afternoon) have been found, the causes of which are not well understood. Observed seasonal variations in the tropics and subtropics are tied to cycles of convective activity and movement of the ITCZ (Stubenrauch et al. 2006). The seasonal cycle in cirrus occurrence at midlatitudes is weaker and more closely linked to synoptic-scale dynamics. Here, the highest probability of occurrence occurs in spring and autumn, whereas the lowest probability occurs in summer, and is more pronounced over the ocean than over land.

Estimating the life cycle of cirrus clouds from satellite data is possible, but difficult. Safer conclusions can be reached by employing modeling tools in support of the remote sensing, such as Lagrangian trajectory calculations (Luo and Rossow 2004). The outflow of convective systems is first transformed into cirrostratus and subsequently into thin cirrus. The timescales of these processes have been estimated as ~6–12 h for the transition to cirrostratus and ~1 d for the transition to thin cirrus. The cirrus amount has an e-folding time of ~5 d; the mean lifetime of the convectively driven cirrus is ~10 h. A comparable study addressing the life cycle of midlatitude cirrus does not exist.

Virtually nothing is known about the life cycle of contrail cirrus, which is essential for an assessment of the aviation climate impact. Available *in-situ* information is scarce and covers only contrail ages up to ~30–60 min, occasionally longer when tracking individual contrails in remotely sensed data. These measurements do not allow representative statistics. The contrail life cycle is not yet represented in global models.

Key Uncertainties

Supersaturation

The SPARC Water Vapor Assessment Report (Kley et al. 2000) discussed different techniques to measure water vapor and relative humidity in the atmosphere (balloon-borne sondes, aircraft instruments, remote sensing). Systematic and sometimes significant differences in measured RHI values have been found by comparing various instruments, particularly in low-pressure and low-temperature conditions. Satellite observations are employed to infer relative humidity without having been designed to measure RHI (Spichtinger et al. 2003b; Gettelman et al. 2006b), so these measurements are very uncertain. More comparisons between different *in-situ* instruments have been carried out in a number of recent field campaigns. At temperatures above ~210 K, different *in-situ* techniques yield similar RHI values, although uncertainty ranges are still substantial (~5–10% standard deviation in absolute terms). Discrepancies are large and unresolved at lower temperatures (Peter et al. 2006). Some data taken in extremely cold tropical conditions (180–185 K) suggest differences in measured water vapor mixing ratios by a factor of two, yielding RHI-values much above the thresholds for homogeneous ice formation (Jensen et al. 2005).

Current models employed to simulate the deposition of H_2O molecules on ice surfaces rely on very simple concepts of bulk diffusional growth of ice particles with idealized shapes (e.g., spheroids). Surface effects that may limit water uptake are lumped into a bulk deposition coefficient, α, for H_2O molecules, impinging on a homogeneous ice surface, and the rate of uptake is proportional to the supersaturation (i.e., the H_2O saturation vapor pressure over ice). Model simulations using the saturation vapor pressure of hexagonal ice and $\alpha = 0.1$–1 appear to be consistent with observations of homogeneous freezing (Möhler et al. 2003; Haag et al. 2003) and cirrus formation in the field (Kärcher and Ström 2003; Hoyle et al. 2005) above ~210 K. In colder conditions, the situation reverses. Cubic ice with a larger vapor pressure may nucleate, depending on particle composition (Murray and Bertram 2007), before it transforms into hexagonal ice on the timescale of hours (Murphy 2003). The deposition coefficient may decrease with decreasing temperature or increasing supersaturation (Wood et al. 2001), in some cases perhaps by blockage of active H_2O adsorption sites via co-adsorbed HNO_3, which stabilizes in the form of the nitric acid trihydrate (step pinning) (Gao et al. 2004). Growth laws, which ignore physical processes that determine the nucleation of growth steps on realistic ice crystal facets, may no longer be applicable at low temperatures, low pressures, and small ice crystal sizes. The mobility of H_2O molecules in supercooled liquid particles may decrease at very low temperatures because of an increased viscosity of the solution, suppressing ice germ formation. All of these issues retard ice formation and may explain, at least qualitatively, observations of ice supersaturations above the currently expected homogeneous freezing levels. Water activity of liquid aerosol particles needs to be known to compute homogeneous freezing nucleation rate coefficients (Koop 2004). In turn, activity depends on the vapor pressure of supercooled liquid water, for which available expressions contain large uncertainties up to some tens of percent at temperatures well below the spontaneous freezing point of pure water (Murphy and Koop 2005). Detailed studies addressing these issues are urgently required.

Vertical Velocities

Owing to the strong dynamic control of cirrus formation, measuring and predicting vertical velocities over a range of spatial scales is of paramount importance for the simulation of cirrus clouds. The mesoscale appears to be especially relevant to ice nucleation in cirrus (Kärcher and Ström 2003). However, mesoscale processes (horizontal scales of several 10 km) are neither captured by cloud-resolving models (~100 m) nor by global models (~100 km) and must therefore be prescribed or parameterized. (Below, we return to this issue in the context of new developments regarding cloud-system-resolving models.) For instance, a subgrid-scale component of the vertical velocity tuned in proportion to the turbulent kinetic energy is used to drive the homogeneous nucleation parameterization in the climate model ECHAM (Lohmann and Kärcher 2002).

In many general circulation models (GCMs), parameterizations for the gravity wave drag of mountain waves are used for a better representation of the stratospheric circulation (Lott and Miller 1997; Scinocca and McFarlane 2000). Attempts to use such parameterizations for the representation of orographic cirrus in GCMs have been reported only recently (Dean et al. 2007; Joos et al. 2008). A consistent approach to parameterize vertical velocity (i.e., temperature changes) and water vapor fluctuations from gravity waves and other sources for use in GCM cloud microphysical schemes has not yet been developed.

To make matters worse, vertical wind speeds are notoriously difficult to measure *in situ*. Evaluation of aircraft probes determining vertical velocities contain large biases (10–30 cm s^{-1}) when evaluated along short flight segments (Bögel and Baumann 1991). Statistics of such data comprising many flight hours are more reliable but do not yield local information on cooling rates. Cooling rates inferred from measured air parcel displacements relative to isentropic trajectories using the microwave temperature profiler are relatively accurate. The statistic of such mesoscale temperature fluctuations provided by Gary (2006) covers large portions of the northern hemisphere, lower stratosphere, and tropopause region but does not contain signals arising from lee waves.

Ice Particle Measurements

Measurements of particle concentrations with optical particle spectrometers that have shrouds or inlets (e.g., the FSSP and the CAS) could be affected by shattering of large ice crystals (Gardiner and Hallett 1985; Field et al. 2006; McFarquhar et al. 2007). Shattering leads to unreasonably large ice particle number concentrations and to artificial broadening of inferred size distributions. This is highly relevant, as small ice crystals have been estimated to dominate cirrus optical extinction. Shattering seems to be a serious issue for several cloud probes in the presence of a sufficient (yet relatively small) number of large (> 100 μm) ice crystals. Quantifying the effects of shattering in previous field measurements requires careful analyses. Measurements in anvil cirrus appear to be particularly prone to errors. A recent study suggests that conclusions from some previous studies of the radiative effect of small ice particles require reevaluation (Heymsfield 2007).

Accurate determination of ice crystal shape is very important for the calculation of parameters crucially affecting the overall radiative effects of cirrus. These parameters include ice particle density, surface areas, and effective (optically active) radius. Although cloud imaging probes can be used to infer ice crystal habits with reasonable accuracy (Lawson et al. 2006), measuring habits of small (< 50 μm) ice particles is still challenging (Baumgardner et al. 2005). Determination of crystal habit is a prerequisite to the accurate determination of optical properties and terminal fall speeds of large ice particles. Using a static diffusion chamber, laboratory studies have provided a classification of ice crystal habits, among other properties, at ice supersaturations and air pressures comparable to those in the atmosphere in the temperature range 203–253 K (Bailey and Hallett 2004). Columnar shapes appear to be prevalent below 233 K. With increasing supersaturation and decreasing temperature, bullet rosettes, needles, and plates appear with higher frequencies. These findings are largely consistent with field observations. Differences in shapes bring about changes in growth rates of up to ± 50% under identical growth conditions. The shape-dependence of mass growth rates affects the competition for available condensate and is often not adequately considered in models.

In the laboratory studies, temperature appears to be the primary factor controlling ice crystal habits, followed by supersaturation and pressure (via H_2O diffusivity) as secondary factors. However, sedimentation, updrafts within cloud, and inhomogeneities in temperature and RHI fields might at times result in a poor correlation between habits and temperatures observed in real cirrus clouds (Field and Heymsfield 2003). A spread in ice nucleation thresholds further adds to the complex spatial distribution of ice crystal habits detected *in situ*. Therefore, field measurements are difficult to interpret without the help of models for which the laboratory findings provide a useful guide.

Ice Initiation and Growth

A great number of atmospheric measurements of high relative humidities close to the homogeneous ice nucleation limits, the prevalence of mesoscale temperature fluctuations generating high local cooling rates, reliable laboratory measurements of homogeneous freezing rate coefficients (enabling sound representation of ice formation in models), and the frequent observation of numerous small ice particles strongly suggest that homogeneous freezing is a ubiquitous pathway for cirrus formation (DeMott et al. 2003; Haag et al. 2003; Law et al. 2005). The predominance of homogeneous freezing does not rule out possible effects of IN on cirrus properties, as IN number concentrations appear to be low enough to modify cirrus properties instead of frequently preventing homogeneous freezing from occurring. However, geographical distribution, size distribution and chemical composition, and ice nucleation modes of IN at cirrus levels are not well known. Although it may constitute an insignificant portion of the total aerosol, IN may exert a significant control on the microphysical structure of cirrus. Since the competition between liquid particles and IN for available water during nucleation depends sensitively on vertical air motion variability, uncertainties in the latter have strong impacts on predicted indirect IN effects on cirrus.

Mineral dust particles can act as efficient IN over a wide range of temperature conditions. In the accumulation mode size range, they may survive lower tropospheric cloud processing and reach the upper troposphere. Presumably, those residual dust particles might exhibit specific seasonal and geographical patterns, owing to the variable source strength (dust storms), which have not yet been systematically explored. There is mixed evidence for their ice nucleation behavior at mid-tropospheric temperatures (Sassen et al. 2003; Ansmann et al. 2008). While being transported to cirrus altitudes, their ice-nucleating ability may further change because of ongoing chemical processing and coagulation with background particles. Using surrogates of dust, laboratory studies have shown that the IN activity may decrease with decreasing size (in the range 50–200 nm), depending on the chemical nature of a surface coating (Archeluta et al. 2005; Knopf and Koop 2006). Onset RHI values of ice nucleation span ranges from near ice saturation up to values required for liquid particle freezing.

Ice formation by soot particles remains very poorly understood (Kärcher et al. 2007). Some soot particles act as IN, as they have been found as residuals in ice crystals formed on upper tropospheric aerosol samples (Chen et al. 1998). The ice nucleation behavior of soot particles in various nucleation modes seems to depend very sensitively on size and surface characteristics, supersaturation, and temperature. As for mineral dust, ice nucleation often occurs over a range of RHI, which can be attributed to individual particle characteristics in the samples. Many laboratory studies have not quantified the nucleation properties on a single particle basis, rendering interpretation of those results difficult. Further, atmospheric aging processes are not well quantified, and associated uncertainties propagate directly into global model predictions of upper tropospheric soot abundance (Hendricks et al. 2004). Thus, studies have often used soot samples of unknown relevance to atmospheric soot.

Heterogeneous effects on ice nucleation may also occur in partially soluble particles in which crystalline inorganic or organic phases (in particular oxalic acid) can form (Zobrist et al. 2006; Abbatt et al. 2006). Ice formation in mixed-phase particles may compete with deliquescence of crystalline solids at low supersaturations, bringing about more complicated pathways to cirrus formation than by fully insoluble IN alone (Colberg et al. 2003). Such effects have not yet been detected *in situ*.

Once ice crystals evaporate and release insoluble core particles upon which they have nucleated, it is possible that the cores facilitate ice formation in a subsequent nucleation event by lowering the nucleation threshold to form ice again (preactivation). This mechanism is poorly understood experimentally and theoretically. Preactivation has been identified as being potentially important for dust (Knopf and Koop 2006). The IN behavior of soot particles may change once they are released from evaporating ice particles, because they may change their size and shape (i.e., they fractionate into smaller pieces or aggregate into larger clusters). Short-lived or persistent contrails may act as preactivating agents for exhaust soot particles.

Even if the nucleation puzzle was solved and the evolution of ice crystal habits as a function of ambient conditions were known, incomplete knowledge about the physical nature of ice surface kinetics strongly limits atmospheric applications (Wood et al. 2001). Once H_2O molecules impinge onto flat facets (terraces) at the ice surface, through diffusion from the gas phase, they migrate toward ledges (growth sites) and may become incorporated into the lattice with a certain probability before desorption. Ice growth is promoted either by screw dislocations (a continuous ledge source) at low local supersaturation, or by two-dimensional nucleation (at local ledge sources) requiring higher local supersaturation. The number and spacing of ledges in turn are functions of the ambient supersaturation and crystal-specific features. Models capable of predicting ledge properties for cirrus ice crystals are not available.

Indirect Aerosol Effects

Most previous cloud-resolving simulations (e.g., those performed in the working group 2 of GEWEX, which focused on cirrus cloud processes) did not study aerosol effects in cirrus in detail. Instead, parameterizations of IN activity originally developed for mixed-phase cloud conditions have been employed and extrapolated to lower temperatures; sometimes studies did not include homogeneous freezing from supercooled aerosols and mostly neglected small-scale dynamic variability. Details of how IN could modify cirrus properties and frequency of occurrence in realistic dynamic conditions and with aerosol forcing supported by observations were first suggested by near-global, domain-filling trajectory simulations of midlatitude cirrus, using a parcel model with parameterized ice particle sedimentation (Haag and Kärcher 2004). More recently, the negative Twomey effect has been studied in large-eddy simulations (LES) on the cloud scale (Spichtinger and Gierens 2008a). These simulations indicate that under some conditions, the initial macroscale evolution of cirrus may be markedly affected by IN, while overall radiative properties are still dominated by liquid particle freezing. Cirrus formation and ice particle sedimentation are found to feed back to the aerosol distribution by nucleation scavenging and vertical redistribution. Large ice crystals may survive substantial distances when falling through subsaturated air. When interacting with liquid water clouds, they initiate the Bergeron–Findeisen process and change precipitation rates.

Because of the wide range of dynamic, thermodynamic, and aerosol-related parameters, indirect aerosol effects on cirrus cannot be properly quantified, and final conclusions on the importance of IN for cirrus radiative forcing cannot yet be provided. Modification of lower-level clouds by cirrus has not been studied in detail.

Radiative Forcing

Radiative transfer simulations with prescribed cirrus microphysical properties have illustrated the fact that for a given ice water path, the net cloud forcing is basically determined by the effective ice crystal radius. Decreasing the latter causes the instantaneous radiative forcing to change sign from warming to cooling. High numbers of small ice crystals are especially prevalent in young contrail cirrus and some anvil cirrus. The effective radius at which the transition to cooling occurs depends strongly on the assumed ice crystal habit (Zhang et al. 1999). The crucial impact of habit on cloud solar and thermal infrared radiative response has also been demonstrated in field measurements (Wendisch et al. 2005, 2007). In addition, ice particle habits affect the remote sensing of cirrus. Much uncertainty is introduced in these issues as a result of the poor understanding of the factors controlling ice particle shapes.

Cirrus radiative forcing is known to depend on horizontal inhomogeneity on scales unresolved by global models (< 100 km) (Fu et al. 2000; Carlin et al. 2002), affecting the mean climate state. Including effects of spatial inhomogeneity in global model simulations may change radiative forcings by tens of W m^{-2} (Gu and Liou 2006). For experimental investigations of the impact of these inhomogeneities, new measurement techniques have been developed that combine nadir observations and in-cloud radiation measurements (Schmidt et al. 2007), besides lidar instruments.

Cirrus radiative forcing is also very sensitive to the vertical inhomogeneity (i.e., the vertical distribution of cloud ice on scales of a few 100 m). Small ice modes originate from homogeneous freezing and are predominantly observed in upper cloud layers, where supersaturation levels are highest (Miloshevich and Heymsfield 1997). Large ice modes are typically observed in lower cloud regions and are fed by sedimenting and aggregating ice crystals. Although understanding of ice particle aggregation as an isolated process has advanced (Field and Heymsfield 2003; Westbrook et al. 2004), a rigorous treatment of factors affecting aggregation in the presence of diffusional growth, sedimentation, and small-scale turbulence has not been performed and dedicated observations are rare (Westbrook et al. 2007). Early heterogeneous nucleation of few IN may also contribute to large ice modes. Interaction of turbulence, nucleation, and growth may lead to a more complex layering of ice crystal sizes according to an LES model (Spichtinger and Gierens 2008b). Tails at low values of probability distribution functions (PDFs) of ice water content (Haag and Kärcher 2004) and optical depth (Immler and Schrems 2002) may well be affected by sedimentation and aggregation processes, as well as by IN and by low cooling rates. The impact of sedimentation has been highlighted by Jakob (in Lynch et al. 2002) using a numerical weather prediction model. He showed that cirrus radiative forcing may be subject to changes of some 10 W m^{-2} given uncertainties in ice particle terminal fall velocities in the range 0.1–2 m s^{-1}.

The understanding of the global net radiative response of various cirrus cloud types is still uncertain. There are crucial uncertainties concerning the extinction component attributable to small ice particles and the host of factors controlling anvil microphysical properties in mesoscale convective systems, among other issues. In addition, the annual and global mean picture of cirrus cloud radiative forcing derived from the ISCCP D2 data contains substantial simplifications in treating the vertical layering of cloud, the radiative transfer in cirrus, and in assumptions about nighttime radiative fluxes (Chen et al. 2000).

Cirrus Representation in GCMs

In the ECMWF-integrated forecast system, a simple method of representing ice supersaturation before cirrus formation via homogeneous freezing has been implemented into the operational scheme, which uses a prognostic cloud fraction variable (Tompkins et al. 2007). This step has led to a significant improvement of the relative humidity fields at the tropopause, and to corresponding increases of the net incoming solar and outgoing longwave radiation of ~2 W m^{-2} that almost cancel each other globally. The updated scheme still relies, however, on bulk mass microphysics with a temperature-dependent water/ice phase partitioning and uses saturation adjustment after cirrus formation (i.e., it does not allow in-cloud supersaturation to occur).

A different approach has been taken in the ECHAM climate model. An improved prognostic two-moment (ice particle number and mass) microphysics package is currently being implemented that parameterizes homogeneous freezing in competition with heterogeneous ice nucleation on the subgrid scale; cloud ice derived from different aerosol sources (liquid and IN) are tracked separately for the first time in a GCM framework (Kärcher et al. 2006). This enhanced microphysical complexity allows more interactions between dynamics and aerosols during cirrus formation to be studied on a global scale. However, the cloud fraction is still diagnosed based on resolved relative humidity and predicts an overcast grid box already at saturation. Thus, it cannot handle the supersaturation now allowed in cirrus conditions. This basic inconsistency is also present in alternative approaches to represent ice supersaturation and aerosol–ice interactions in GCMs with diagnostic cloud fraction (Gettelman and Kinnison 2007; Liu et al. 2007).

A central assumption common to virtually all GCM cloud schemes is that cloud particles form as soon as saturated conditions are surpassed. Likewise, cloud particles are not allowed to exist in subsaturated conditions. These are fair assumptions for low-level tropospheric clouds that form and exist close to water saturation. Hence, statistical cloud schemes based on PDFs of total water (and perhaps other variables) allow the cloud fraction and cloud water content to be diagnosed, once the moments of the underlying PDFs are known. These central assumptions do not hold in the case of pure ice clouds, indicating that current parameterization concepts need to be fundamentally modified (Kärcher and Burkhardt 2008), in particular the use of cloud schemes that diagnose cloud fraction based on resolved relative humidity. Ultimately, GCM parameterizations that provide a consistent description between cloud fraction, ice supersaturation, and ice nucleation form a sound basis for subgrid parameterizations of cirrus cloud inhomogeneity and overlap.

Validation of GCMs

When evaluating the water budget in climate models, the emphasis is usually on warm clouds. Comprehensive efforts to validate GCM predictions of ice water content, effective ice crystal sizes, and other crucial cirrus properties have not yet been reported. Current GCM results cannot be accurately constrained by available satellite data (Zhang et al. 2005). However, the microphysics of ice clouds is often used for tuning the models (see Jakob in Lynch et al. 2002), particularly sedimentation rates that control simulated ice water content. Consequently, there are indications that optical properties of natural cirrus are not represented well, at least in some climate models (Lohmann et al. 2007). Accurate global model validation is seriously complicated by lack of climatologically representative data (e.g., from airborne measurements), uncertainties in defining what has actually been detected (e.g., detection efficiencies of cloud in remote sensing), and uncertainties in measurements (e.g., frequencies and absolute values of supersaturation). Few concepts exist to describe systematic strategies for a process-oriented validation of GCMs (Eyring et al. 2005).

Therefore, the proper validation of ice microphysical processes and simulated cirrus properties remains an elusive goal.

Climate Change

Climate change may bring about changes in the global distribution of temperature, relative humidity, and cooling rates attributable to greenhouse gas emissions. The distribution and efficacy of ice-nucleating aerosols may also change. These changes could significantly modify cirrus properties (Kärcher and Ström 2003). Any effort to ascribe cause to changes or trends of cirrus cloud properties requires a careful evaluation of the underlying processes.

While the atmosphere can hold more moisture at higher temperatures, it is likely that relative humidity remains largely unaffected (Held and Soden 2000), but possible changes in upper tropospheric relative humidity cannot be excluded. The tropopause height rises as a result of tropospheric warming and simultaneous stratospheric cooling (Santer et al. 2003). Peak clear-sky supersaturations and cirrus cloud tops occur frequently, very close to the tropopause. A change in the vertical extension of the troposphere may imply a change in the vertical distribution of relative humidity and hence modify cirrus occurrence and properties. If cirrus form at warmer/colder temperatures (i.e., different distances relative to the future tropopause height), then the number of ice crystals will decrease/increase (Kärcher and Lohmann 2002) and affect the radiative response of cirrus (Fusina et al. 2007).

Changes in the meridional temperature gradient affect the atmospheric circulation. In a warmer climate, storm tracks might be shifted toward higher latitudes, and midlatitude weather systems might become weaker (Yin 2005; Bengtsson et al. 2006). This may cause changes in mesoscale variability in vertical velocities, which have been identified as the key controlling factors of cirrus formation, besides temperature. Finally, properties of IN from natural and anthropogenic sources might continue to change (Bigg 1990). The indirect aerosol effect and changes in dynamic forcing patterns may alter cirrus cloud properties by similar amounts (Haag and Kärcher 2004). Thus, differentiating between natural and anthropogenic causes of possible cirrus changes represents a great challenge.

It is difficult to predict if and how properties of anvil cirrus might change in the future. It seems plausible, however, that the frequency of occurrence of anvils changes in proportion to the number of deep convective events in the tropics. As air traffic continues to grow at a substantial rate and the atmosphere is not saturated with respect to contrail occurrence, contrail cirrus will be a more frequent phenomenon in decades to come. A larger occurrence of contrail cirrus might tap more condensable ambient water by growth and sedimentation. This may cause the atmosphere not to reach, or to reach later, the thresholds for formation of natural cirrus. As for *in-situ* cirrus, the behavior of anvil and contrail cirrus in a future climate cannot be predicted with confidence unless the processes controlling their formation and evolution are understood. This includes the development of a predictive capability for feedbacks between microphysics, radiation, and dynamics across various spatial and temporal scales, including potential experimental clarification.

The Way Ahead

Measurement Techniques

The design of airborne measurements that have the potential to unravel the relative roles of homogeneous freezing and heterogeneous ice nucleation (i.e., the indirect effect of IN on cirrus clouds) is very challenging. An atmospheric closure experiment would require a combination of at least high-resolution measurements of aerosol composition and ice nucleation activity, vertical air motion, relative humidity, and cirrus ice particle size distribution in the range 1–1000 μm. Cloud ice properties could be predicted directly from dynamic and aerosol information, ideally in combination with numerical modeling.

Phase-dependent particle sampling in conjunction with particle spectrometers has recently improved our capabilities of cold cloud analyses (Mertes et al. 2007). Progress has recently been made to reduce uncertainties attributable to shattering; the conditions in which contributions from small particles are significant have been identified and methods have been proposed to correct available data (Field et al. 2006; Heymsfield 2007). The use of different measurement techniques on the same measuring platform leads to a better estimate of the impact of shattering (Gayet et al. 2006). Wind tunnel studies could also be helpful to characterize the influence of shattering or to design inlets with reduced impact. A better knowledge of ice particle size distributions in combination with habit distributions will enable improved cirrus cloud radiation modules for use in GCMs to be developed.

There is an urgent need for improved real-time *in-situ* measurement capabilities of ice nucleation from upper tropospheric particles (Stetzer et al. 2007). Chemical composition of IN is best measured in conjunction with mass spectrometry (Cziczo et al. 2004a). Fast IN sensors for cirrus applications are becoming available, as revealed by a recent workshop[1] on ice nucleation measuring systems. New ways of combining different instruments should be fully exploited, for example, through the combination of counterflow virtual impactors, continuous flow diffusion chambers and aerosol mass spectrometry (Cziczo et al. 2003).

Laboratory experiments are well suited to develop and test airborne instrumentation, but may also be employed to study inherent differences in methods for measuring particles and humidity in the atmosphere and in the

1 http://lamar.colostate.edu/~pdemott/IN/INWorkshop 2007.htm/

laboratory. Laboratory-based studies should be performed to examine details of fundamental processes of ice formation (e.g., what makes certain particles better IN than others). In this regard, direct sampling of particles of atmospheric relevance would be most fruitful, as techniques for generating aerosol particles that closely resemble their atmospheric counterparts are limited. Finally, evolutionary studies under controlled initial conditions and thermodynamic histories enable the detailed investigation of processes related to ice formation and growth and ice crystal optical properties.

High-quality fields of relative humidity require very accurate measurements of temperature and water vapor mixing ratio. The current suite of satellite sensors is not fully adequate to study supersaturation in the upper troposphere, despite the valuable insights gained from recent evaluations of microwave limb sounder (MLS) and AIRS measurements. Higher resolution—both vertically and horizontally—and better cloud clearing are required for these observations. This heightens the current role of *in-situ* measurements. The scientific community is making headway in understanding pending discrepancies between various *in-situ* measurement techniques that often rely heavily on extensive laboratory calibrations (Peter et al. 2008). Dedicated campaigns aimed at an intercomparison of different measurement techniques and improved theoretical concepts of small ice crystal growth at low temperatures and pressures will support these efforts. Radiosondes underestimate upper tropospheric relative humidity even when corrections are applied that enable the detection of supersaturation (Spichtinger et al. 2003a). Recent developments of low-cost yet accurate frost-point hygrometers (Verver et al. 2006) could improve routine measurements of ice supersaturation in cirrus conditions. The value of radiosonde measurements can be increased by including information about clouds, e.g., by modifying aerosol backscatter-sondes. This would also yield more information on the vertical structure of cirrus clouds on a routine basis.

An improved estimate of vertical air motion variability is necessary to detect any aerosol impact on cirrus properties. As a prerequisite to drive physically based cirrus parameterizations, it is important to obtain cloud-scale vertical velocity PDFs (Kärcher and Lohmann 2002). In a GCM framework, those might be derived from gravity wave drag parameterizations, and be validated with MTF data and a systematic evaluation using advanced LES cirrus models. Mesoscale gravity wave structure could also be explored using high-resolution GPS retrievals of upper tropospheric temperatures.

The potential of new airborne instrumentation can be fully exploited by means of two new research aircraft, HALO[2] (in Germany) and HIAPER[3] (in the U.S.A.), which have altitude, range, and endurance capabilities well suited to perform critical atmospheric research. The research communities have made great efforts to transform business jets, which serve as host aircraft,

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[2] http://www.halo.dlr.de

[3] http://www.hiaper.ucar.edu

into cutting-edge observational platforms, which will operate mainly in the upper troposphere and lower stratosphere region, probing horizontal scales ~0.1–1000 km. Both HIAPER and HALO will deploy comprehensive sets of instrumentation for a wide variety of scientific applications, including research into cirrus clouds and their radiative and chemical effects, to meeting most of the research needs discussed here over the next decades.

After the first flights of a backscatter lidar (LITE, in 1996) and a precipitation radar (TRMM, in 1997) in space, a new era of satellite observations has emerged with the completion, in 2006, of the NASA/CNES A-Train (afternoon) constellation of five low orbit satellites flying in formation. The CALIPSO lidar and the CloudSat cloud-profiling radar provide unprecedented global surveys of cloud properties and high-resolution vertical profiles (at resolutions below ~100 m for lidar and ~500 m for radar) with spatial and temporal coverage needed to evaluate parameterizations of clouds and cloud-related processes in global models (Chepfer et al. 2008). Besides advancing our understanding of moist (especially convective) processes in the climate system, ice clouds and upper tropospheric humidity may become a strong focus of research using these tools. However, it is also clear that much remains to be done to render data from these new sources useful for the development of GCMs (Sassen and Wang 2008).

Modeling Techniques

The use of bulk microphysics in cirrus cloud-resolving models has a long tradition (Starr and Cox 1985). Most existing schemes only prognose the cloud ice mass and are therefore computationally efficient enough to be included in a multidimensional model framework (in particular, in LES models). However, surprisingly few three-dimensional LES simulations of cirrus have been reported to date. LES models and GCMs have included, only recently, two-moment schemes (based on ice particle mass and number concentrations), but only very few of them allow for coupling with a detailed aerosol model for an advanced treatment of ice nucleation. Such schemes remain very valuable in either simulating case studies based on observations or in conducting sensitivity studies in terms of the wide range of parameters that control cirrus formation and evolution (Spichtinger and Gierens 2008b). In one- or two-moment schemes, microphysical processes and radiative properties must be heavily parameterized as a function of ice water content (and ice particle number density). To arrive at more realistic simulations that enable a better control of underlying processes, more size-resolved aerosol and ice microphysics modules in cirrus-resolving models are required (Jensen et al. 1994).

An alternative approach is currently being developed at DLR-IPA, in which the EULAG LES model[4] is coupled with a sophisticated aerosol–ice–radiation

[4] http://www.mmm.ucar.edu/eulag

package to obtain a benchmark LES cirrus model. This package tracks liquid background particles and a number of IN types on a moving size grid and computes ice nucleation rates for each aerosol particle type and size. Ice particle growth, sedimentation, aggregation, light absorption, trace gas uptake, evaporation, and particle core return are simulated using a Lagrangian tracking method for a large number of simulation particles (clusters carrying a number of real ice crystals). The detailed location and history of individual ice particle clusters (i.e., nucleation core, supersaturation) and physical properties (i.e., shape, vapor pressure) can be tracked as a function of time. Such simulations may have the potential to set new standards for analyzing field observations and improving GCM parameterizations.

The use of new concepts for multiscale modeling of atmospheric flows for detailed cirrus studies appears to be a promising research avenue. Adaptive grid methods, new closure models for turbulence, modified approaches for nudging and nesting, as well as the prescription of spatially and/or temporally variable environmental conditions could be introduced in cloud modeling efforts. Such concepts are being developed and applied to cirrus within the priority program Multiscale Modeling in Fluid Dynamics and Meteorology[5] funded by the German Research Foundation. Until a better understanding of ice crystal growth has emerged from new theories or models that combine faceted crystal growth with shape and surface kinetic effects, process modeling must rely on the simplified concepts of diffusional growth in which these effects are treated empirically by parameters such as deposition coefficients and capacitance factors.

Another new development concerns the design of 1–5 km scale-resolving models, commonly referred to as cloud system-resolving or cloud ensemble models (Tompkins and Craig 1998; Grabowski and Moncrieff 2001). Those can be run over wide domains (1000 km to global) and allow interactions of individual clouds with the large-scale circulation to be studied. They have not yet been applied to study cirrus in detail. As mentioned before, ice nucleation in cirrus and the temperature fluctuations that drive the formation process are linked to the mesoscale (1–100 km). On similar scales, inhomogeneities in the three-dimensional structure of cirrus have been found to be important for determining their radiative effects, including cloud overlap issues (Hogan and Kew 2005). Therefore, attempts to employ cloud system-resolving models to study the interactive chain of dynamic forcing, ice nucleation, and radiation appear to be very promising. As a first step, existing parameterization schemes for homogeneous ice nucleation and initial growth (Kärcher and Lohmann 2002) could be directly applied in such models to facilitate the improvement of their cirrus microphysics. Within this context, the use of very high-resolution numerical weather prediction models would also be helpful.

5 http://emm.mi.fu-berlin.de/DFG-MetStroem/

Despite recent progress, cirrus clouds are still insufficiently represented in global models. A number of GCMs have been coupled to sophisticated aerosol modules (Jacobson 2001; Adams and Seinfeld 2002; Stier et al. 2005; Lauer et al. 2005), but the coupling of these modules to the GCM cloud schemes, and to cirrus schemes in particular, is in its infancy. The introduction of separate prognostic ice variables and a physically based parameterization of cirrus formation enable the simulation of ice supersaturation on the resolved scales (Lohmann and Kärcher 2002). Realistic dynamic forcing of ice nucleation requires the inclusion of temperature fluctuations induced by gravity waves from orography (Dean et al. 2007; Joos et al. 2008) and other sources. On the one hand, aerosol modules should allow the prediction of background aerosols and IN and need to be coupled to suitable ice nucleation parameterizations that allow for competition between different ice-nucleating particle types (Kärcher et al. 2006; Liu et al. 2007). On the other, the cirrus cloud schemes should enable the prediction of a number of ice tracers for each type of ice-forming aerosols, and the GCM radiation modules ideally make use of this information to compute the radiative responses of the individual ice types. This includes predictions of accurate ice crystal size information. Efforts are underway to arrive at a consistent description of cirrus cloud fraction, dynamic forcing, ice microphysics, and ice supersaturation in GCMs (Kärcher and Burkhardt 2008). Recent progress in representing contrail cirrus as a distinct cirrus cloud type, with coverage and optical properties different from natural cirrus, provides valuable guidance (Burkhardt et al. 2008).

Concluding Remark

Cirrus cloud research is intimately connected with important societal issues, such as climate change, weather prediction, and aircraft operations. The direct impact of cirrus clouds on climate is based on their substantial radiative effects. The partial control of stratospheric water vapor concentrations and the possible impact on tropospheric ozone chemistry provide further examples of how cirrus cloud physics is closely tied to climate change issues. Improved weather prediction, as a result of advanced representation of cirrus in forecast models, may prove very valuable in furthering the quality of medium-range forecasts. To allow sustainable growth of aviation, it is imperative for the climate impact of contrail cirrus clouds to be known accurately so that appropriate mitigation strategies can be developed.

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