CLIMATE IMPACT OF CONTRAILS AND CONTRAIL CIRRUS

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EXECUTIVE SUMMARY

Generally, the climatic impact of air traffic (of which a substantial part may be due to contrails and contrail cirrus) today (year 2000) amounts to 2-8% of the global radiative forcing associated with climate change. Due to the projected increase in air traffic [ICAO, 2007] the relative importance of air traffic is going to increase drastically. In the long term it may well be, that the most serious threat to the continued growth of air travel is its impact on climate [Green, 2005]. In view of the societal relevance and economic importance of sustainable growth of global aviation, it would be appropriate that the climate science community received sufficient funding, allowing significant progress estimating climate impacts, in order to ensure that political decisions are based on increasingly sound scientific knowledge. Aircraft-induced cloudiness, which comprises contrail cirrus and modification of cirrus by aircraft exhaust soot emissions are the most uncertain component in aviation climate impact assessments [IPCC, 2007]. Since they may be the largest component in aviation radiative forcing aircraft-induced cloudiness and contrail cirrus in particular require a large research effort.

Contrails develop at lower relative humidity than natural cirrus and therefore can increase high cloudiness and change the radiation budget significantly in or near regions with high air traffic density. Several studies have inferred coverage due to line-shaped contrails in limited areas using satellite data. In situ measurements have been made analyzing young contrails regarding their ice water content, particle sizes and particle habit, some of which have not been fully mined. Radiative transfer models estimate the radiative forcing due to individual contrails. Current estimates of global contrail radiative forcing are based on climate model simulations using a simple parameterization for line-shaped contrail coverage and their ice water content.

From those studies we know that line-shaped contrail coverage in areas of high traffic density may be as large as a few percent. The optical properties of the probed contrails are distinct from natural cirrus with line-shaped contrails consisting of a larger number of smaller particles. The optical properties of isolated line-shaped contrails change the radiative balance in a way that they cause in the majority of situations warming of the atmosphere. Line-shaped contrails are estimated to cause a global radiative forcing of about 10 mW/m^2.

Contrary to the IPCC, we judge the state of science regarding contrail radiative forcing to be poor. Regional line-shaped contrail coverages have not been inferred from satellite data in a way that warrants intercomparability. Detection thresholds have not been properly estimated and discussed so that a comparison with model estimates is hampered. Available airborne measurements of contrails suffer from the poor detectability and characterization of size and habit of small ice crystals typical for contrails. Estimates of global line-shaped contrail coverage are all based on one single contrail parameterization approach using a climate model. Most of those studies use the same global model, the same tuning data set and the same assumptions about contrail ice microphysics and optical depth so that similar results are not surprising. There exists a pending dissent about contrail optical properties from Lidar measurements and satellite retrievals estimating larger mean optical depth than suggested by global models. Due to the problems using observational data for model validation the extent of the disagreement is not known. Radiative transfer simulations find only modest changes of contrail radiative forcing due to three-dimensional effects, the inclusion of the diurnal cycle of air traffic and other factors. However, even the most advanced radiative transfer studies have not yet incorporated best knowledge of key parameters such as contrail ice microphysics in order to place conclusive bounds on associated uncertainties.

Therefore, in a first step, we recommend that more independent studies and sensitivity experiments should be performed estimating the climate impact of line-shaped contrails so

that proper error bars of radiative forcing can be inferred. Better observational data together with the associated detection thresholds and efficiencies must be obtained that can be used for constraining contrail model parameterizations and model validation. A uniform data set estimating line-shaped contrail coverage from satellites globally is needed.

Without further progress in contrail modeling we will not be able to answer questions about the climate impact of future air traffic scenarios. Radiative forcing estimates due to contrails cannot be simply scaled with an increased air traffic since future air traffic is forecasted to increase mainly in the more humid subtropics of southeast and east Asia. Model estimates of radiative forcing are mainly describing the effect of contrails in the areas of strongest current air travel, the extratropics. Observational studies as well have been focusing on the mid latitudes. In the subtropics there is little observational evidence of the optical properties and radiative effects of contrails and it is not known how well current contrail parameterizations will perform in the tropics.

Until now not even an accepted (IPCC-level) best estimate of radiative forcing due to aircraft-induced cirrus changes exists and the state of knowledge is generally judged to be very low. Persistent contrails spreading into long-lived contrails cirrus decks covering substantial regional areas is observed at times, hence significant atmospheric effects can be expected. However, there is no robust estimate for the additional coverage due to contrail cirrus. The small- and synoptic-scale meteorological conditions supporting contrail cirrus development (including relative humidity and wind shear) appear to be highly variable. Therefore, no simple relationship exists between contrail age and linearity and detectability. The optical properties of contrail cirrus are not known and radiative forcing due to contrail cirrus has not been estimated. Therefore, current estimates of total aviation-induced radiative forcing likely lack an important contribution. Contrail cirrus may not only change the radiative balance due to an increase in cloud coverage or optical thickness of existing cirrus but also by modifying the upper tropospheric moisture budget and by replacing or changing natural cirrus, should the optical properties of contrail cirrus remain distinct from natural cirrus. Cirrus changes due to the emission of soot particles from aircraft jet engines are much less certain. The ice-nucleation behavior of fresh soot emissions is probably poor according to in situ data, but regional or large-scale effects on cirrus properties and coverage cannot be ruled out. Progress in this area requires a targeted field study demonstrating the ability of aging aircraft soot particles to form ice at lower relative humidities than ice nuclei from other sources or the ability to change particle size spectra in cirrus.

We propose introducing contrail cirrus as a new, purely anthropogenic ice cloud type and recommend studying the whole life cycle of contrails. On the one hand in situ and remote sensed observations of aged contrail cirrus are needed. On the other hand contrails should be treated in global models as an independent cloud class together with their associated ice water content. The formation of contrail cirrus from individual young contrails over a wide range of spatial scales requires a special model study. Also identification of aviation induced cloudiness in observations needs further studies.

Avoiding persistent contrail formation due to suitable operational (real time) changes in air traffic management may provide a clue for efficiently reducing the aviation climate impact due to persistent contrails on a short time scale. Weather forecast models may be used to predict areas in which contrails form and persist with similar limitations as climate models and would therefore benefit from the climate model research. This predictive capability is a prerequisite for the development of mitigation strategies.

INTRODUCTION AND BACKGROUND

Changes in cirrus cloudiness caused by contrails, contrail cirrus and soot particles together are denoted as aircraft-induced cloudiness (AIC) [Forster *et al.*, 2007]. Persistent contrails spread considerably during their life time and transform from line-shaped (or linear) into more irregularly formed contrail cirrus. Contrail cirrus is composed of irregularly-shaped ice crystals that, just like natural cirrus, reflect solar radiation and trap outgoing longwave radiation [Platt, 1981; Stephens and Webster, 1981]. Radiative effects of cirrus and contrails have been addressed in several review or overview articles [Liou, 1986; Graßl, 1990; Parungo, 1995; Fabian and Kärcher, 1997; Fahey *et al.*, 1999; Lee *et al.*, 2000; Schumann and Ström, 2001; Minnis, 2003; Schumann, 2002, 2005]. Observations reveal that young contrail ice crystals have smaller effective diameters than natural cirrus [Sassen, 1979; Betancor Gothe and Graßl, 1993; Gayet *et al.*, 1996; Petzold *et al.*, 1997; Lawson *et al.*, 1998; Heymsfield *et al.*, 1998; Poellot *et al.*, 1999; Schröder *et al.*, 2000; Febvre *et al.*, 2008]. Such comparatively small particle sizes render the radiative impact of contrails different from that of most natural cirrus clouds during at least part of the contrail life cycle. The contrail radiative effect is thought to be a net warming as longwave heating dominates over shortwave cooling owing to the relatively small visible optical thickness (< 0.5) of most contrails probed in field measurements [Duda and Spinhirne, 1996; Jäger *et al.*, 1998; Meyer *et al.*, 2002; Duda *et al.*, 2004; Minnis *et al.*, 2005; Palikonda *et al.*, 2005; Atlas *et al.*, 2006]. Additional cloudiness may also be induced by aviation due to the possible influence of aviation aerosol (mainly soot emissions) on cirrus clouds [Ström and Ohlsson, 1998; Hendricks *et al.*, 2005]. In the literature this effect was termed soot cirrus [Schumann, 2006].

Generally, the climatic impact of air traffic (of which a substantial part may be due to contrails and contrail cirrus) today (year 2000) amounts to 2-8% of the global radiative forcing associated with climate change. Since air traffic has been increasing on average by 5% per year since the 1990 (twice as fast as the global economy), emissions have been increasing, even though fuel consumption per passenger kilometer has been reduced significantly. Due to the projected increase in air traffic [ICAO, 2007] the relative importance of air traffic is going to increase drastically. Additionally, air traffic is concentrated in certain regions that experience much larger climate impact due to air traffic than the global mean. In the long term it may well be, that the most serious threat to the continued growth of air travel is its impact on climate [Green, 2005]. The planned introduction of emission trading schemes must be based on a solid scientific basis which is currently still lacking especially for non-CO_2 emissions [IPCC, 2007; Wuebbles and Ko, 2007]. The necessary scientific research would support the strategic planning of the Joint Planning and Development Office (JPDO) to develop the Next Generation Air Transportation System (NextGen) and the European vision 2020 of the Advisory Council for Aeronautics Research in Europe (ACARE), as well as informing the International Civil Aviation Organization (ICAO) through its Committee on Aviation Environmental Protection (CAEP) on how scientific knowledge may be used to improve assessments of environmental health and welfare impacts of aviation environmental policy. In view of the societal relevance and economic importance of sustainable growth of global aviation, it would be appropriate that the climate science community received sufficient funding, for supporting not only applied but also basic research allowing real progress estimating climate impacts, in order to ensure that political decisions are based on increasingly sound scientific knowledge.

Contrails are short-lived when forming in dry air. They are persistent and grow in terms of their horizontal coverage and ice water content whenever the air masses, in which they reside, stay saturated or supersaturated with respect to the ice phase [Brewer, 1946]. Ice-supersaturated regions and cirrus occurrences are closely tied to synoptic weather patterns [Detwiler and Pratt, 1984; Schumann, 1996; Kästner *et al.*, 1999; Spichtinger *et al.*, 2003a, 2005; Haag and Kärcher, 2004; Gettelman *et al.*, 2006; Carleton *et al.*, 2007] and mesoscale vertical air motion variability [Kärcher and Ström, 2003]. Typical thicknesses of ice-supersaturated layers are 500 m at middle and high latitudes [Spichtinger *et al.*, 2003b; Treffeisen *et al.*, 2007; Rädel and Shine, 2007a] limiting the vertical extent of contrail cirrus. Occasionally much deeper layers have been observed indicated by contrail fall streaks [Knollenberg, 1972; Konrad and Howard, 1974; Schumann, 1994; Atlas *et al.*, 2006]. Contrail outbreaks, which describe clusters of persistent contrails that spread in suitable weather conditions, indicate that ice supersaturated layers can be horizontally extended (at least up to 35,000 km^2) [Minnis *et al.*, 1998] and can last for many hours [Detwiler and Pratt, 1984; Mannstein *et al.*, 1999; DeGrand *et al.* 2000; Duda *et al.*, 2001, 2004, 2005]. Since the beginning of jet air traffic, it is known that contrail cirrus can appear without natural cirrus when atmospheric conditions do not support natural cloud formation, enhancing natural cloud coverage [e.g., Kuhn, 1970; Detwiler and Pratt, 1984; Schumann and Wendling, 1990]. Contrails or contrail clusters are also observed in conjunction with cirrus clouds depending on the synoptic situation [Sassen, 1997; Immler *et al.*, 2007]. Atmospheric feedbacks presumably exist between persistent contrails and natural cirrus, because they share the same condensable water vapor reservoir.

Until now only young or linear contrails have been subject to observational and theoretical analyses. Jet exhaust contrails form by condensation of the emitted water vapor mainly on co-emitted aerosol particles [Busen and Schumann, 1995; Gierens and Schumann, 1996; Schumann, 1996; Kärcher, 1996; Schröder *et al.*, 1998; Kärcher *et al.*, 1996, 1998; Schumann *et al.*, 1996; 2002]. Dynamical processes related to the decay of aircraft vortices determine the number and mass of contrail ice crystals that survive in ice-supersaturated air [Lewellen and Lewellen, 2001; Unterstrasser *et al.*, 2008]. The effective diameters of observed ice crystals in young contrails are initially ~1 µm and increase with contrail age [Sassen, 1979; Gayet *et al.*, 1996; Freudenthaler *et al.*, 1996; Strauss *et al.* 1997; Petzold *et al.*, 1997; Goodman *et al.*, 1998; Lawson *et al.*, 1998; Heymsfield *et al.*, 1998; Sassen and Hsueh, 1998; Poellot *et al.*, 1999; Schröder *et al.*, 2000; Del Guasta and Niranjan, 2001; Febvre *et al.*, 2008]. Individual contrails can persist for many hours with radiative processes affecting contrail longevity and growth [Kuhn, 1970; Knollenberg, 1972; Gierens, 1994]. Contrail cirrus are frequently observed to spread, inducing additional cirrus cloud coverage. This contrail cirrus can only to some extent be distinguished from natural cirrus using satellites by tracking. Microphysical properties of this aged and hence nonlinear contrail cirrus depends on the amount of water vapor available in the ambient air and less on the moisture input from the aircraft [Schumann, 2002]. In a sheared environment, the increase in horizontal coverage is dependent on the vertical extent of the contrail, which is in turn controlled by ice crystal sedimentation and hence vertical layering of supersaturation. The size of the ice crystals in contrail cirrus and their sedimentation properties may depend on the initial number of ice crystals formed in the young contrail [Schumann, 1996] and on the processing of the ice crystals in the wake vortices [Lewellen and Lewellen, 2001]. Otherwise, the temporal evolution of initially linear contrails into spreaded contrail cirrus [Reinking, 1968; Gierens, 1998; Minnis *et al.*, 1998; Schröder *et al.*, 2000; Atlas *et al.*, 2006] is controlled by atmospheric state variables and dynamical processes (e.g., relative humidity, temperature, vertical shear of the horizontal wind field perpendicular to the contrail axis, horizontal advection and diffusion, vertical air motion). Coverage due to nonlinear contrail cirrus has not been simulated yet. Attempts to estimate contrail cirrus coverage and optical depth from remote sensed data are considered very uncertain [Fahey *et al.*, 1999; Sausen *et al.*, 2005]. The number and size distribution of ice crystals in nonlinear contrail cirrus is not known. Remote sensing observations may miss linear contrails with a width lower than the pixel size. Aviation-induced cloudiness components, nonlinear contrail cirrus and soot cirrus are indistinguishable from background cirrus. So far, the IPCC has assigned a best estimate of radiative forcing to linear contrails only [Fahey *et al.*, 1999; Forster *et al.*, 2007].

Observational tools include Lidar and Radar instruments, satellite sensors and standard cloud physics instrumentation onboard high flying aircraft, but available measurements do not cover the full contrail cirrus life cycle [SSWP Key Theme 4]. Lidar and Radar have been used to conduct case studies of contrails or to develop local contrail statistics [Konrad and Howard, 1974; Kästner *et al.*, 1993; Freudenthaler *et al.*, 1996; Sassen, 1997; Jäger *et al.*, 1998; Uthe *et al.*, 1998; Sassen and Hsueh, 1998; Del Guasta and Niranjan, 2001; Sussmann and Gierens, 2001; Immler *et al.*, 2007]. Observational studies of regional contrail coverage have been reported, including visual inspection of satellite images and automated algorithms to identify linear objects in satellite scenes [Joseph *et al.*, 1975; Carleton and Lamb, 1986; Lee *et al.*, 1989; Schumann and Wendling, 1990; Bakan *et al.*, 1994, Mannstein *et al.*, 1999; Chen *et al.*, 2001; Meyer *et al.*, 2002, 2007; Minnis *et al.*, 2003, 2005; Palikonda *et al.*, 2005; Duda *et al.*, 2005; Stuefer *et al.*, 2005; Mannstein and Schumann, 2005]. For uniform detection of contrails during day and night, most studies used infrared satellite images which may detect preferably contrails effective in the infrared and may underestimate the fraction of contrails with high solar albedo. Time series composed of studies using different remote sensing instruments suffer from different false alarm rates and detection efficiencies. A global, homogeneous analysis of coverage and optical properties by linear contrails is still missing. Number and size of ice crystals and optical depth of non line-shaped contrail cirrus cannot be observed since they can generally not be distinguished from natural clouds. Therefore optical properties need to be modeled.

The restriction to polar orbiting satellites results in a temporal sampling of contrails that interferes with the daily pattern of air traffic. Any attempt to relate observed contrail cirrus coverage to air traffic has to rely on a precise knowledge of real air traffic movements. Such information is available only regionally. Available trend analyses are considered uncertain, because the aviation signal is difficult to isolate and the trends of natural cirrus cloud amounts may have many causes [Chagnon, 1981; Liou et al., 1990; Boucher, 1999; Zerefos *et al.*, 2003; Minnis *et al.*, 2004; Stubenrauch and Schumann, 2005; Stordal *et al.*, 2005; Travis *et al.*, 2007; Eleftheratos *et al.*, 2007]. Attempts to attribute observed cirrus trends to aviation cannot discriminate among contrail and soot effects and natural trends. Contrail and soot effects on cirrus therefore need to be analyzed separately using improved correlation analysis of observations or modeling tools. Observation-based studies have discussed the contrail effect on surface temperature and diurnal temperature range [Travis *et al.*, 2005; Ponater *et al.*, 2005; Hansen *et al.,* 2005].

Modeling approaches comprise microphysical process models [Kärcher *et al.*, 1995; Brown *et al.*, 1997; Kärcher, 1998; Yu and Turco, 1998], Large-Eddy simulations (LES) [Boin and Levkov, 1994; Gierens, 1996; Chlond, 1998; Jensen *et al.*, 1998a; Gierens and Jensen, 1999; Khvorostyanov and Sassen, 1998; Sussmann and Gierens, 1999, 2001; Chen and Lin, 2001; Lewellen and Lewellen, 2001; Ström and Gierens, 2002; Paoli *et al.*, 2004; Unterstrasser *et al.*,, 2008], radiative transfer calculations and radiative forcing estimates [Fortuin *et al.*, 1995; Strauss *et al.,* 1997; Schulz, 1998; Liou *et al.*, 1998; Minnis *et al.*, 1999; Meerkötter *et al.*, 1999; Myhre and Stordal, 2001; Chen *et al.*, 2001; Stuber *et al.*, 2006; Gounou and Hogan, 2007; Stuber and Forster, 2007; Rädel and Shine, 2007b] and global or regional modeling [Liou *et al.*, 1990; Rind *et al.*, 1996; Sausen *et al.*, 1998; Wang *et al.*, 2001; Duda *et al.*, 2005; Ponater *et al.*, 1996, 2002, 2005; Marquart *et al.*, 2003; Fichter *et al.*, 2005; Hansen *et al.*, 2005]. Process-based and LES models covered only contrail formation or early stages of the transformation into cirrus. Most radiation models use optical depth and ice water content in a parametric manner instead of representing realistic values and respective variability. However, the latter is important, as climate forcing is known to be strongly influenced by regional and seasonal forcing patterns. Only few attempts have been undertaken to investigate the global impact of linear contrails with climate models. Contrail modeling relies on the successful simulation of the large scale climate and is hampered by the limited information of observed [SSWP Key Theme 3] and simulated [Kärcher *et al.*, 2006; Tompkins *et al.*, 2007; Liu *et al.*, 2007; Gettelman and Kinnison, 2007] upper tropospheric supersaturation.

We propose to introduce contrail cirrus as a new, purely anthropogenic ice cloud type in global models for the following reasons. Contrail cirrus have distinct optical properties and interact with the moisture field and natural cirrus. Individual contrails have been tracked for long periods of time (as long as 17 hours) in satellite imagery [Minnis *et al.*, 1998], and this does not seem an upper limit of possible life times. Therefore they can be advected, spread and condense water causing considerable cloud coverage away from the source areas. Contrail cirrus can significantly change cirrus coverage in the vicinity of air traffic routes and alter radiative fluxes. The prospect of climate change and rapidly increasing demands for air transportation emphasizes the need to study contrail cirrus. To enable an environmentally sustainable development of air traffic in the future is a major motivation for research in this area, with strong links to research efforts aiming at understanding dynamical, microphysical and chemical processes in the upper troposphere and lower stratosphere region.

Section 2 reviews the current state of science, focusing on advancements since the 1999 IPCC report. Section 3 discusses limits of available methods and identifies research issues that urgently need improvement to enable scientific progress. Section 4 prioritizes outstanding issues. Section 5 provides recommendations to maximize science output. The SSWP closes with a summary in section 6 and a comprehensive list of references.

2. REVIEW

a. Current state of science

Thermodynamic conditions for contrail formation

Contrails were first observed in 1915, but it took more than 25 years to provide proper explanations. Early theories of contrail formation before 1940 (reviewed by Schumann [1996]) considered various details of mixing of the engine heat, moisture and particle emissions in the exhaust jet behind the engine with ambient air and various microphysical details of particles, and liquid or ice particle formation. It was therefore a major progress when Schmidt [1941], and later Appleman [1953], explained the formation of contrails purely thermodynamically without the need to consider details of jet mixing and particle microphysics. The only assumption needed is about whether contrail particles form at liquid water or ice saturation. Schmidt [1941] assumed contrail formation at ice saturation. Several other studies at the same time, as reviewed in Schumann [1996], see e.g. Brewer [1946], provided clear evidence that contrail formation requires liquid saturation. This has been confirmed in many follow-on studies [Schumann *et al.*, 1996; Jensen *et al.*, 1998b; Kärcher *et al.*, 1998; Schumann, 2000].

The thermodynamic theory assumes isobaric mixing of both specific heat (enthalpy) and water vapor concentration in the exhaust at equal rates after complete combustion with ambient air without other sources and losses (such as radiative heating). This approach ignores details of the initial split of exhaust energy in internal energy and kinetic energy in the exhaust jet [Schumann, 1996, 2000] and initial variations of the heat/moisture ratio between the core and bypass parts of the engine jets [Schumann *et al.*, 1997]. The thermodynamic theory also ignores details of initial visibility [Appleman, 1953]. All these issues impact the predicted threshold temperature below which contrails form by up to ~1 K only. However, it was found important to note that only part of the chemical fuel energy is converted to heat in the engine exhaust. A fraction η, corresponding to the overall propulsion efficiency is used to propel the aircraft against its drag. This fact was known in principal already to Schmidt [1941], but the explicit inclusion of the overall propulsion efficiency $\eta = F\ V/(m_F\ Q)$ as a function of aircraft speed V, fuel mass flow rate m_F and engine thrust F (or specific fuel consumption per thrust, SFC = m_F/F) was first identified in Busen and Schumann [1995] and explained in detail by Schumann [1996], and later confirmed by various studies [Schumann, 2000; Schumann *et al.*, 2000; 2002; Detwiler and Jackson, 2002]. Still details of mixing and microphysics [Kärcher *et al.*, 1996, Paoli *et al.*, 2004; Vatazhin *et al.*, 2007] matter for formation of particles in the young contrail, their visibility, radiative effects, and possibly also for their later fate [Schumann, 1996].

According to basic thermodynamics, the maximum temperature and minimum relative humidity at which contrails form (i.e., threshold conditions) are determined by ambient temperature, pressure and relative humidity, specific heat of fuel combustion, emission index of water vapor, and the overall aircraft propulsion efficiency. The amount of fuel consumption is as such unimportant for contrail formation, but often used as a proxy for flown kilometers or water vapor emissions.

Microphysics of contrail formation

The sole empirical constraint consists of assuming that at least plume water saturation is required to nucleate contrail particles. Observations of contrail formation in threshold conditions at very low and normal fuel sulfur content showed small visible differences in both contrail onset and appearance [Busen and Schumann, 1995]. Numerical simulations [Kärcher *et al.*, 1995] consistent with observations [Schumann *et al.*, 1996] suggested that emitted soot particles must be involved as nucleation centers for contrail ice particles, as close to the formation threshold, liquid plume aerosols (consisting of water, sulfuric acid and organics) forming at subsaturations relative to ice do not freeze rapidly. Visible contrail formation in threshold conditions within one wingspan behind jet engines at very low fuel sulfur content was rather explained by the rapid formation and subsequent freezing of a (partial) water coating on ~10^4 cm^{-3} exhaust soot particles [Kärcher *et al.*, 1996]. The coating is enhanced by condensation of sulfuric acid created by oxidation fuel sulfur precursor gases [Schumann *et al.*, 1996]. In-situ measurements provided quantitative indication that a significant part of soot emissions contributed to contrail ice formation [Schröder *et al.*, 1998; Schumann *et al.*, 2002]. Threshold conditions, the water saturation criterion and the impact of fuel sulfur content, have been confirmed by in-situ measurements within the measurement uncertainties [Schumann *et al.*, 1996; Jensen *et al.*, 1998b; Kärcher *et al.*, 1998; Schumann, 2000].

A sufficient number of ice crystals are needed to make the contrail visible very quickly [Schumann, 1996]. Those are provided by exhaust soot particles acting as nucleation centers. Emitted metal particles, that have been found as residual in contrail ice particles [Twohy and Gandrud, 1998; Petzold *et al.*, 1998], or entrained ambient particles are not abundant enough. If ambient temperatures decrease below the formation threshold, plume supersaturations increase, leading to activation of the large reservoir of liquid plume particles (exceeding that of soot particles by orders of magnitude) in addition to soot and increasing the number of nascent contrail ice crystals up to ten times [Kärcher *et al.*, 1998]. The initial contrail ice particle number is limited to ~10^5 cm^{-3}, because they remove the excess supersaturation within fractions of a second.

Large plume cooling rates (~1 K/ms) exert a strong dynamical control on contrail formation. This causes properties of nascent contrails to be rather insensitive to details of the ice nucleation process. In fact, contrail formation can be explained by homogeneous freezing of the water droplets either containing soot cores or sulfuric acid traces as passive inclusions. The assumption of perfect ice nucleation behavior of the majority of freshly emitted soot particles would contradict observational evidence as contrails then would become visible under threshold conditions significantly closer to the jet engine exit as soon as ice saturation is reached. It should be noted that contrails become visible within meters from the engine exit if the ambient air temperature is more than an order 10 K cooler than the threshold temperature. However, it cannot be excluded that a small fraction of the coated soot particles nucleate ice without passing a water activation stage [Kärcher *et al.*, 1996, Schumann *et al.*, 1996]. Some contrail observations would be consistent with such soot particles forming ice from about 140% relative humidity over ice up to water saturation [Kärcher *et al.*, 1998]. If that happens, contrails would also form in a small temperature range above the threshold temperature if the plume did not reach water saturation, but the contrails would stay invisible.

Wake processing of contrails

During jet mixing the gas and particle mixing ratios decrease until the jet plumes become captured in a pair of trailing vortices after several seconds of plume age. When the ambient air is ice-supersaturated and secondary ice nucleation occurs on ambient aerosols, contrail regions that formed at the plume edges or in upwelling limbs of the vortices may contain a few much larger crystals [Heymsfield *et al.*, 1998]. At this point, the majority of ice particles are still very small (mean diameters 0.5-1 μm) and their total concentrations are reduced considerably (by up to a factor 500) [Schröder *et al.*, 2000]. The capturing virtually suppresses further mixing until the vortices become unstable and break-up after 1-3 min [Lewellen and Lewellen, 1996]. The aircraft influence on wake dynamics ceases after several Brunt-Väisälä periods (several 10 min). Hereafter, plume dispersion is under the control of atmospheric turbulence, gravity waves and wind shear (dispersion regime) [Schumann *et al.*, 1995, 1998; Gerz *et al.*, 1996]. Contrails persist and further accumulate ice mass only at ambient ice supersaturation.

At low ambient shear, vortex dynamics is the primary determinant of the vertical extent of young contrails [Sussmann and Gierens, 1999] and can have dramatic impact on ice crystal properties. Ice crystal number densities can be significantly reduced during adiabatic compression that results from the downward motion of the vortex system (typically ~300 m at a few m/s) [Lewellen and Lewellen, 2001]. The sinking induces baroclinic instability at the top of the vortex pair from which a few ice particles can escape (secondary vortex).

Systematic analyses of the wake effects on young contrail properties are hampered by the large number of influencing factors. Contrail properties depend on ambient stability, turbulence conditions and aircraft type, as well as on ambient temperature and supersaturation. Almost all ice crystals survive in the sinking primary vortices at ambient supersaturations exceeding 30%, which are rare [Spichtinger *et al.*, 2003a; Gettelman *et al.*, 2006]. The surviving ice particle fraction decreases with decreasing supersaturation and is smallest (factor 100 reduction) for the highest temperatures still allowing contrail formation, because sublimation rates are fastest [Unterstrasser *et al.*, 2008]. The secondary vortex is favored in wakes of heavy aircraft at slight ambient supersaturations, resulting in faint contrails at the original cruising altitude [Sussmann and Gierens, 2001]. The exact loss of ice crystal number is difficult to quantify accurately because this depends on the spread of ice particle sizes which is only poorly known. In-situ measurements reveal a range of total ice crystal concentrations between 10-1000 cm^{-3} after a few minutes of plume age [Gayet *et al.*, 1996; Heymsfield *et al.*, 1998; Schröder *et al.*, 1998, 2000; Febvre *et al.*, 2008], a spread consistent with the variability in the wake processes discussed above.

Ice mass is typically concentrated within ~200 m deep vertical layers that extend ~100 m horizontally after vortex breakup, determined by wake dynamics. Despite wake-induced variations, the total contrail ice mass after the early dispersion regime is roughly given by the saturation vapor excess and is therefore strongly temperature-dependent [Lewellen and Lewellen, 2001]. Ice crystal number densities generally remain high enough (exceeding ~1 cm^{-3}) to ensure depletion of saturation vapor excess and therefore thermodynamic equilibrium in young contrails. This view is consistent with observations which additionally point to a large variability range in ice water content [Schumann, 2002]. Presumably, in the dispersion regime the respective ice water path will be largely determined by the vertical extent of the supersaturated layer in which the contrail particles sediment given sufficiently high supersaturations.

The effective ice crystal size is affecting the optical depth and radiative forcing of ice clouds. It varies in proportion to the inverse of the cubic root of ice crystal number and is therefore expected to exhibit a certain variability range ($\sim 100^{1/3} \approx 5$) [Meerkötter *et al.*, 1999]. The high number of small particles [Petzold *et al.*, 1997] implies high optical extinctions due to contrails a few minutes old, as confirmed by in-situ measurements [Febvre *et al.*, 2008]. Another factor affecting radiative effects is the shape of ice crystals. Replica images reveal that the majority of ice particles in young (< 30-60 min) contrails bear a quasi-spherical shape (droxtals) [Gayet *et al.*, 1996; Schröder *et al.*, 2000], but other crystal habits have been detected as well sometimes even in young (< 15 min) contrails [Strauss *et al.*, 1997; Goodman *et al.*, 1998; Lawson *et al.*, 1998; Febvre *et al.*, 2008]. The factors determining the ice particle shapes in aging contrails remain unclear but may include factors such as pressure, temperature, relative humidity and vertical velocity.

Development of contrail cirrus

Aircraft measurements of contrail ice particle size distributions only exist for line-shaped contrails because nonlinear contrails are very difficult to identify for pilots without additional support. Most of these probed contrails were less than 1 h old [Gayet *et al.*, 1996; Schröder *et al.*, 2000; Febvre *et al.*, 2008; for new evaluations we refer to one SSWP from Key Theme 4]. The data indicate smaller mean ice particles sizes in contrails than found in cirrus clouds developing in similar conditions. Typical effective diameters and total ice water contents in contrails at least 3 min old range from 2.5-10 μm and 2-5.5 mg/m^3, respectively, at temperatures near 218 K [Schröder *et al.*, 2000]. These values are systematically smaller than those measured with the same instrumentation in nearby cirrus at similar temperatures. At higher temperatures sizes and ice water content can be larger [Heymsfield *et al.*, 1998]. When sorted according to their age, contrail ice particle concentrations have been shown to decrease (due to plume mixing) and effective diameters to increase (due to condensation), approaching typical values characteristic for the small particle mode found in midlatitude cirrus clouds (0.3-30 cm^{-3} and 20-30 μm, respectively). Despite significant differences in ice particle number and size, the scattering phase function, asymmetry parameter and optical extinction may not always differ substantially between natural cirrus and young (15-20 min) contrails [Febvre *et al.*, 2008].

Cirrus clouds including subvisible cirrus exhibit a wide range of morphologies and microphysical properties, depending on formation mechanisms and ambient conditions [Dowling and Radke, 1990]. Not much is known about the properties of older contrails and contrail cirrus because of the lack of in-situ observations and the difficulty to simulate those clouds with process models owing to the increased spatial and extended time scales. Contrail cirrus particle sizes and concentrations may approximate those of natural cirrus with time but there may remain differences in geometry and vertical distribution of cloud ice and particle shapes. One observed contrail with unknown age contained near spherical particles with an effective diameter of 30-36 μm and an ice water content of 18 mg/m^3 [Gayet *et al.*, 1996]. The cirrus cloud probed nearby was characterized by values of 48-60 μm and 15-50 mg/m^3, respectively. The larger effective diameter in the cirrus was brought about by a second, large particle mode centered at a maximum particle dimension of 300-400 μm and containing only few irregular crystals. Causes for the generation of a large particle mode include aggregation and sedimentation, as well as early nucleation of few efficient heterogeneous ice nuclei. A large particle mode has not been detected in contrails. Whether such a mode can develop during the contrail life cycle remains open, and its potential impact on radiative forcing remains to be studied. Sedimentation is likely to be more important in cirrus than in young contrails. The few existing data [Schumann, 2002] do not allow drawing general conclusions on difference between contrail cirrus and natural cirrus at similar temperatures.

At a given layer depth, large supersaturation leads to rapid ice particle growth and sedimentation, limiting the contrail life time. Contrail fall streaks may extend temporarily into subsaturated air thus causing the contrail to have a larger vertical extent than the depth of the supersaturated layer. Three studies report heavily precipitating contrails with unusually deep fallstreaks, large ice water content and very large maximum crystal dimensions (> 1 mm) [Knollenberg, 1972; Schumann and Wendling, 1990; Atlas *et al.*, 2006]. It is conceivable that such geometrically (and presumably optically thick) contrails develop only at large layer thicknesses (> 1-2 km) and high persistent supersaturations (> 20-30%), both of which are rare events [Gierens *et al.*, 1999a; Spichtinger *et al.*, 2003b]. More commonly contrails experience lower supersaturations (< 15%) and evolve in supersaturated layers ~ 500 m deep.

One numerical study revealed that interactions between radiation and dynamics can affect the early development of contrails [Jensen *et al.*, 1998a]. The numerous ice crystals in a young contrail in a sheared environment subject to ice supersaturation absorb upwelling longwave radiation. The resulting strong diabatic heating drives turbulence-induced updrafts (updraft speeds 5-8 cm/s, exceeding synoptic values), enhancing the vertical depth and changing the contrail microstructure. Radiative cooling in the top layers opens the possibility of secondary ice formation by homogeneous freezing there by generating high supersaturations. These processes are most effective in a neutrally or unstably stratified atmosphere. Such interactions are known to occur in cirrus clouds as well, potentially prolonging their life time [Dobbie and Jonas, 2001]. Under less humid and more stably stratified ambient conditions, radiative effects have been shown to be less important [Gierens, 1996; Chlond, 1998].

Contrail cirrus have been shown to survive for many hours and hence synoptic processes become significant. Contrail cirrus can be advected over long distances during their life time. Given upper tropospheric wind speed of 30 m/s, they move at ~100 km/h possibly into regions with little or no air traffic. The vertical shear of the horizontal wind spreads contrails into tilted layers. The vertical wind shear perpendicular to the contrail axis pulls the contrail apart at a rate proportional to the contrail height. Spreading rates observed at a midlatitude site range from 18-140 m/min [Freundenthaler *et al.*, 1995], causing line-shaped contrails to grow quickly to widths of several km. Turbulence that is connected with strong shear causes contrails to loose their line shape. When acting in isolation, wind shear reduces the ice water path and optical depth in each vertical contrail column, but at the same time increases the horizontal coverage. The overall effect on radiative forcing is not clear, as this is determined by the product of coverage and optical depth. Given the variability in upper tropospheric shear rates [Dürbeck and Gerz, 1996] and a typical spread of ice particle growth rates (0.3-2 µm/min) there is no unique relationship between contrail age and linearity, nor between age and optical depth (visibility).Virtually no information is available about the coverage due to older and nonlinear contrails mainly since in satellite images, contrail cirrus cannot be identified when they loose their line shape and/or cease to be visibly brighter than cirrus due to the high concentration of small ice particles.

Supersaturation with respect to the ice phase is a prerequisite for contrail cirrus to persist and to accumulate ice mass [Brewer, 1946]. Synoptical processes determine the regional areas of ice supersaturation [Spichtinger *et al.*, 2005] and therefore control to a large extent the life time of contrail cirrus. Contrails develop often in special synoptic situations like ahead of a warm front and are connected with cirrus clouds [Detwiler and Pratt, 1984; Kästner *et al.* 1999, Sassen 1997, Immler *et al.,* 2007]. Hence contrails appear before natural cirrus form. According to satellite images, line-shaped contrails already showing a significant degree of spreading often appear in clusters (outbreaks) in heavily traveled areas [Schumann and Wendling, 1990; Mannstein *et al.*, 1999; DeGrand *et al.*, 2000]. In supersaturated areas mean relative humidity as well as its variability is high [Gettelman *et al.*, 2006]. This is obvious when comparing areas with a large frequency of supersaturation with the spatial distribution of high clouds, both exhibiting similar patterns. During the contrail life time, the synoptic and mesocale variability of the atmosphere influence the contrails in the same way as natural cirrus. This variability stems from fluctuations of temperature and moisture which have a variety of sources, including gravity and orographic waves, convection, and wind shear induced turbulence, among others. It leads to local cooling and heating. Whether contrail cirrus properties are sensitive to such forcings depend on the relative magnitude of these dynamical and microphysical time scales (e.g., for ice mass growth). Given identical dynamical forcings, microphysical changes may be different at different stages of the contrail cycle because the associated time scales in turn are determined by particle number and size.

Contrail cirrus competes with natural cirrus for condensable water and therefore has the potential of delaying cirrus onset and replacing natural cirrus. Sedimentation of contrail ice crystals may lead to additional drying of upper tropospheric air masses but it is not known whether this transport is enhanced by contrail cirrus due to the additional cloudiness or reduced due to the smaller mean particle size. On the one hand, inferred statistical connections between changes in cirrus cloudiness and air traffic using remote sensed data are uncertain. On the other hand, the contrail cirrus life cycle has not been represented in global models yet.

Trends of cirrus cloudiness

Remote sensing methods cannot distinguish between aged contrail cirrus and natural cirrus. Further insight into trends of cirrus cloud coverage that could at least in part be forced by air traffic is gained by monitoring cirrus coverage and relating it to air traffic. Ground-based observations of monthly mean high cloud coverage show a step-like increase around 1965, possibly correlated with the onset of jet air traffic. Coverage increases more rapidly during 1965-1982 than before the jet era 1948-1964 [Liou *et al.*, 1990] possibly due to the introduction of jet aircraft in air travel. Contrails may be responsible for degradation in the observability of the solar corona and photosphere in the period 1961-1978 (Schumann, 2002). Based on ship- and ground-based observations, a change in the occurrence frequency of cirrus was found to be correlated with aviation fuel consumption and was largest in the main flight corridors over the north east of the U.S.A. and the northern Atlantic [Boucher, 1999]. A similar study based on satellite data reported consistency in trends of cirrus and linear contrail amounts over the USA [Minnis *et al.*, 2004]. They used the 300 hPa moisture fields from the NCEP (National Center for Environmental Prediction) reanalysis data as a proxy for natural cirrus coverage and found a 1% increase of contrail cirrus per decade over the continental US. Removing ENSO, NAO and QBO trends from time series of cirrus occurrence and eliminating the effects of convection and changing tropopause temperature revealed increases in cirrus trends in regions with high air traffic density [Zerefos *et al.*, 2003]. Contrary to these works, another satellite study suggests extra cirrus coverage over in regions with high air traffic density over Europe but remains inconclusive because other factors impacting high cloudiness have not been removed from the data set [Stordal *et al.*, 2005]. Satellite data for trends in high cloud amount and retrieved upper tropospheric humidtity showed a clear positive trend in the high cloud occurrence over the North Atlantic flight corridor when the humidity was insufficient for cirrus formation but allowed persistent contrail formation [Stubenrauch and Schumann, 2005]. Two months of cirrus cover deduced from METEOSAT data and actual air traffic data from EUROCONTROL suggested a strong linear growth of cloud coverage and air traffic density which eventually becomes saturated when approaching the fractional coverage of ice-supersaturation [Mannstein and Schumann, 2005]. Later the correlation was shown to be inconclusive because of natural spatial variations of cirrus coverage in the domain investigated [Mannstein and Schumann, 2007].

These few attempts to infer relationships between cirrus amount and aviation suffer from the poor knowledge of trends in natural cirrus and their dependence on a plethora of dynamical factors acting from the mesoscale up to planetary scales and by aerosol-related processes affecting upper tropospheric ice initiation. Further, these approaches are unable to discriminate between contrail cirrus effects and effects caused by aircraft soot emissions. The latter could modify the cirrus properties and indirectly the background moisture fields in which contrails grow. Hence, current trend analyses invoking a contrail impact are noteworthy but not conclusive.

Contrail effects on the radiation budget

The radiative impact of clouds depends strongly on cloud optical depth and their inhomogeneity [Fu *et al.*, 2000]. A few satellite studies inferred probability distributions of linear contrail optical depths at visible wavelengths, which are a useful measure of this inhomogeneity [Meyer *et al.*, 2002; Minnis *et al.*, 2005; Palikonda *et al.*, 2005]. These distributions exhibit maxima in the range 0.1-0.4, consistent with optical depth values derived in several case studies. It is conceivable that contrail cirrus developing from the secondary vortex, contrail cirrus that is subject to large wind shear, or evaporating contrails become subvisible. While Lidar data point to the existence of subvisible contrails [Sassen, 1997; Immler *et al.*, 2007], quantitative evidence on larger spatial scales is lacking as satellite sensors are not capable of detecting contrails with low (perhaps < 0.05-0.2) visible optical depths. Optical depth distributions of thin cirrus clouds detected by Lidar [Immler and Schrems, 2002] exhibit a shape that is skewed towards small values, comprising a significant fraction of subvisible clouds (optical depth < 0.01-0.03) even at midlatitudes. Subvisible cirrus cause a small radiative forcing per area but if occurring frequently may have a large effect.

Global radiative forcing estimates obtained using general circulation models (GCMs) depend crucially on the assumptions made about the optical depth of the contrails. When simulating contrails offline, optical properties of contrails are assumed constant and radiative forcing estimates are simply scaled linearly with optical depth. Only one climate modeling approach [Ponater *et al.*, 2002; Marquart *et al.*, 2003] attempts the simulation of the regional variability of the optical properties of contrails.

Another crucial factor affecting radiative forcing of contrail cirrus is their coverage. Analyses that consider at least regional scales (useful for global model validation) must rely on satellite remote sensing techniques. Only few studies investigated sufficiently long time series of contrails to provide average regional linear contrail coverage over western Europe, USA and the greater Thailand region [Bakan *et al.*, 1994; Meyer *et al.*, 2002, 2007; Palikonda *et al.*, 2005]. Some of these observations reach back to the 1980s, requiring scaling with average fuel consumption to obtain estimates for more recent air traffic which introduces an unspecified uncertainty. Specifications of what has been observed in terms of false alarm rates and other technical issues of the detection algorithm, optical depth detection limits and detection efficiency, average optical depth and width and associated variability and ice crystal effective sizes or other optical properties are vague or missing in most cases. Therefore, the inferred coverage is difficult to compare among each other and are of limited use for model validation. Current estimates of the global distribution of linear contrail coverage diagnosed with a climate model rely on sorting out contrails with minimum optical depths < 0.02 to compare with observed coverages [Ponater *et al.*, 2002; Marquart *et al.*, 2003, Fichter *et al.*, 2005]. Choosing different lower detection limits would result in global mean and especially in regional changes of simulated coverage. Global mean coverage due to line-shaped contrails are estimated to range between 0.04% and 0.09%.

The effect of contrail cirrus on the radiation budget depends on the size, habit, number and vertical distribution of crystals, surface albedo, solar zenith angle, height and thickness of contrail, spatial inhomogeneity and presence of clouds and water vapor column below the contrails (effecting brightness temperature). During night radiative forcing is always positive. Contrails with optical depths of 0.2-1 have been shown to exert a net warming in the chosen combinations of controlling parameters [Meerkötter *et al.*, 1999] even though parameter combinations could be specified that could cause net cooling [Myhre and Stordal, 2001; Mannstein and Schumann, 2005; Schumann, 2005; Sausen *et al.*, 2005]. The effect of contrails replacing cirrus has not yet been studied. If contrails should replace natural cirrus on a larger scale, and if aged contrails retain different optical properties (many small ice particles) then it is conceivable that even though those contrails are warming the net forcing of contrails replacing natural cirrus is a cooling. Moreover, contrails may increase cirrus optical thickness beyond the point where this increase causes a cooling.

Mitigation options such as fuel additives or cryoplane technology are not expected to decrease contrail radiative forcing significantly [Marquart *et al.*, 2001, 2005; Gierens, 2007], whereas changes in flight levels can change contrail coverage significantly [Sausen *et al.*, 1998; Fichter *et al.*, 2005] making contrail avoidance due to flight rerouting a viable option.

b. Critical role of contrails and contrail cirrus

Contrail cirrus are the most obvious effect of air traffic but are presently the most uncertain component in aviation climate impact assessments. Since they may be the largest component in aviation radiative forcing they require a large research effort.

Contrails develop at lower relative humidity than natural cirrus and therefore increase high cloudiness. This increase can be significant in or near regions with high air traffic density. Contrails just as natural clouds are a major part of the climate system changing the radiation budget. Due to differences in the ice particle size distributions and in horizontal and vertical cloud structure the optical properties of and radiative forcing by contrails are different to those of natural clouds. Furthermore, the multitude of possible parameter combinations (e.g., solar zenith angle, surface albedo and overlap with natural cloudiness) makes contrail radiative impact extremely space- and time-dependent. In any case, all studies currently available have indicated a time mean global net warming effect on the atmosphere [Sausen *et al.*, 2005]. Contrails may also change the radiation budget by changing the optical properties of natural cirrus or even preventing natural cirrus from forming.

The additional coverage caused by aviation is predicted to grow strongly due to a forecasted increase in air traffic increasing the radiative effect of contrails. Radiative forcing estimates due to contrails cannot be simply scaled with an increased air traffic since future air traffic is forecasted to increase mainly in the more humid subtropics of southeast and east Asia. Model estimates of radiative forcing are mainly describing the effect of contrails in the areas of strongest current air travel, the extratropics. Observational studies as well have been focusing on the mid latitudes. In the subtropics there is little observational evidence of the optical properties and radiative effects of contrails. Additionally, air traffic in the future will take place in an already changed climate, that is itself subject of research.

Contrary to CO_2, contrails and the possible indirect soot effect have a short life time, probably not much longer than days to weeks. On short term, contrails have a far larger climate impact than CO_2 emissions. Contrail avoidance therefore reduces the climate effects of aviation on the short term. This may be achieved by flight rerouting, which is discussed also for future minimization of NO_x-induced ozone changes due to aviation. More careful flight routing with most accurate meteorological data may also help to reduce fuel consumption. Advanced air traffic management operations have the potential to reduce contrail formation by avoiding flights through supersaturated regions. Because route optimizations need to take also the effects of NO_x and CO_2 emissions into account it is not clear whether flight rerouting reduces contrail induced radiative forcing. The inclusion of such climate aspects in aircraft design or air traffic management tools have been proposed but not yet fully analyzed.

A greater portion of the upper troposphere will support contrail formation if future aircraft should have greater overall propulsion efficiency. Reductions of soot emissions due to improved engine technology may only change contrail properties if the reductions are very large but would not avoid contrails, since ambient aerosol particles would replace them as nucleation centers. However, reductions of soot emissions would diminish possible soot-induced changes of cirrus clouds.

c. Advancements since the IPCC 1999 report

Remote sensing

An automated satellite-based detection algorithm for line-shaped contrails has been published [Mannstein *et al.*, 1999] which was applied by several groups using AVHRR data over Europe [Meyer *et al.* 2002], the continental USA [Duda *et al.*, 2004; Palikonda *et al.*, 2005], eastern north Pacific [Minnis *et al.*, 2005] and southeast and east Asia [Meyer *et al.*, 2007]. First estimates of the amount of older contrail cirrus which cannot be identified by their line shape have been given by Minnis [2004] and Mannstein and Schumann [2005]. Some detailed Lidar and in-situ case studies have added knowledge on structure and optical parameters of individual contrails [Freudenthaler *et al.*, 1995, 1996; Atlas *et al.*, 2006; Febvre *et al.*, 2008]. Several cirrus trend analyses have been carried out after 1999 [Zerefos *et al.*, 2003; Minnis *et al.*, 2004; Stordal *et al.*, 2005; Stubenrauch and Schumann, 2005] (section 2.a), but detected cirrus changes could not be unambiguously ascribed to aviation.

Upper tropospheric humidity and supersaturation

In the last years increased effort has been put into obtaining reliable statistics of supersaturation. MLS and more recently AIRS retrievals have been used to infer global supersaturation statistics [Spichtinger *et al.*, 2003a; Gettelman *et al.*, 2006] showing extended areas with large frequencies of supersaturation in the upper troposphere, reaching in the midlatitudes maxima of up to 30%. The overall frequency of supersaturation in those studies is relatively uncertain but agrees relatively well with estimates from measurements along commercial flight routes (MOZAIC) in the upper troposphere of ~13% [Gierens *et al.*, 1999a]. Minimum frequencies are found in equatorial areas. The large scale structures of supersaturation resemble those of humidity. The vertical extent of supersaturated areas has been estimated using humidity-corrected radiosonde data [Spichtinger *et al.*, 2003b; Rädel and Shine, 2007a]. Parameterizations of cloud microphysics describing the formation of ice crystals at substantial supersaturation have been devised [see Kärcher *et al.*, 2006 for most recent developments including the impact of heterogeneous ice nuclei] and implemented in climate models [Lohmann and Kärcher, 2002]. Nevertheless cloud coverage has remained to be uniquely dependent on humidity making microphysics and cloud coverage inconsistent. Other modeling approaches consist of simply changing the humidity threshold of cloud coverage to a higher supersaturated value, neglecting the fact that cirrus form and evaporate at different humidities. As long as the life cycle of cirrus is not consistently modeled, there will be a need to parameterize contrail formation.

Wake processes

To describe contrail formation and the early interaction of contrails with wing tip vortices a highly sophisticated two phase flow model has been developed [Paoli *et al.*, 2004]. LES methods have been used for the carrier phase, solving the fully compressible 3D Navier

Stokes equations and water vapor, while a Lagrangian particle tracking approach has been adapted to ice formation from exhaust soot particles. Simulated mixing histories of air parcels and probability distributions for ice particle size and water vapor reveal much of the complex structure of nascent contrails as a result of strong interactions between particle microphysics and turbulence. In general terms, the overall findings of much simpler approaches using classical mixing assumptions [Kärcher *et al.*, 1996, 1998] have been confirmed. Three-dimensional LES studies with a simpler treatment of ice microphysics have also been presented shedding light on the evolution of contrails during the vortex phase [Lewellen and Lewellen, 2001]. A similar 2D-approach has been developed recently aiming at a more systematic survey of atmospheric parameters influencing contrails up to the dispersion phase [Unterstrasser *et al.,* 2008]. Contrary to the prior approaches, the latter model can straightforwardly be extended to study the contrail-to-cirrus transition on larger scales using LES methods. After 1999, a 2D cloud-resolving model has been employed to simulate contrails up to 30 min of age [Chen and Lin, 2001], yielding information on ice crystal size distributions similar to the model of Jensen *et al.* [1998a]. Both works agree upon the importance for radiative processes in simulating young contrails. A regional climate model has been fed with results from the cloud-resolving simulations (contrail coverage, effective sizes and short-/longwave optical depths) to estimate the climate impact of contrail layers in an area surrounding Taiwan using ensemble simulations [Wang *et al.*, 2001]. The regional study concluded that contrail radiative forcing is dominated by contrail coverage and radiative properties play a smaller role owing to the spatial inhomogeneity of the coverage.

Contrail coverage

First global estimates of the radiative forcing due to contrails were derived in 1998 based on the calculation of potential contrail coverage from offline calculations using temperature, humidity and pressure from ECMWF reanalyses and folding this potential contrail coverage with some measure of flight density [Sausen *et al.*, 1998]. Since then this approach has been upgraded resulting in a climate model parameterization of contrails, calculating online contrail occurrence and the contrail ice water content from the condensable water at the time step [Ponater *et al.*, 2002; Marquart *et al.*, 2003]. This allows for capturing the dependence of contrail occurrence on the weather regime and the regional and temporal variability of contrail ice content. Still this method consists of calculating the potential contrail coverage and tuning the simulated contrail coverage to the observed contrail coverage over a selected region assuming that the tuning coefficient is temporally and locally universal. Most if not all studies scaled the contrail coverage to that derived by Bakan *et al.* [1994] for Europe (30°W-30°E, 35°N -75°N). Other approaches still calculate contrail coverage by folding offline the potential contrail coverage with data of flight density or use estimates of contrail coverage from older studies and assume globally and temporally fixed optical depth. They concentrate on using more sophisticated radiative transfer models analyzing the variability of radiative forcing due to different background parameters [Meerkötter *et al.*, 1999], due to the daily cycle of air traffic [Myhre and Stordal, 2001; Stuber *et al.*, 2006; Stuber and Forster, 2007] and 3D effects on radiative transfer [Chen *et al.*, 2001; Gounou and Hogan, 2007]. It was generally found that global contrail radiative forcing does not vary strongly depending on the radiation code used; it may depend, however, strongly on the method to treat cloud overlap in GCMs [*Marquart and Mayer*, 2002]. However, most of these studies apply the same contrail ice crystal size distribution [Strauss *et al.*, 1997] and ignore vertical variability in ice water content and effective radii, so that large deviations between these estimates may not be expected in the first place. Chen *et al.* [2001] rely on simulated ice crystal spectra showing a persistent small particle mode at 2-3 µm within supersaturated air leading to net cooling by contrails. This persistent small particle mode disagrees with earlier findings by Schröder *et al.* [2000]. According to these observations the small particles grow substantially within the first 30 minutes. Differences may also be caused by a more advanced treatment of horizontal inhomogeneities in radiative transfer and the different atmospheric background in the subtropics.

Contrail optical depth

Lower estimates of radiative forcing due to line-shaped contrails since 1999 are based on lower estimates of mean contrail optical depth. Usually a global mean optical depth of 0.1 is assumed instead of 0.3 used by IPCC [1999]. It is unclear whether this lower optical depth of contrails is more realistic. Satellite observations estimate mean optical depth of contrails to range between 0.2-0.4 over the U.S.A. [Minnis *et al.*, 2005; Palikonda *et al.*, 2005] and 0.05-0.2 over Europe [Meyer *et al.*, 2002]. For comparison, Ponater *et al.* [2002] compute mean visible optical depths of 0.1-0.13 and 0.06-0.09, respectively, over these regions, with individual values covering several orders of magnitude. The models compute mean values for ensembles of contrails within rather large grid boxes (e.g. ~300 x 300 km^2 for T30 resolution), while the observations provide optical depth for individual contrails or contrail clusters at the cloud scale or the scale of satellite resolution. Presently, one cannot decide how accurate the model results are.

A reason for the low contrail optical depth simulated by the ECHAM4-GCM may be a general low bias in the ice water content of natural clouds. Comparison with observational data hints at an underestimation of ice water content and effective radii of cirrus by ECHAM4 [Lohmann *et al.*, 2007]. Furthermore, it is assumed that the condensable water at one time step (of 30 min) is a good proxy for the ice water content of the contrail while ice water content of natural cirrus is accumulated using a prognostic variable. It is likely that the spatial and temporal variability of the ice water content and therefore of optical depth as simulated by Ponater *et al.* [2002] is more realistic than the overall amount. On the other hand, it is also unclear whether observations of optical depth are representative since the optical depth detection threshold of satellite sensors is usually not specified and detectability may be biased towards optically thicker contrails. The decrease in radiative forcing due to the studies performed after 1999 has been compensated by the use of an air traffic inventory for 2002 which includes an increase in air traffic from the 1992 values used earlier [Sausen *et al.*, 2005; Forster *et al.*, 2007].

Future scenarios

Recently mitigation studies have been performed, analyzing the use of fuel additives [Gierens, 2007], cryoplane propulsion [Marquart *et al.*, 2001, 2005] and flight level changes [Fichter *et al.*, 2005] indicating that flight rerouting may be the most successful mitigation option (section 2.e).

d. Present state of measurements and data analysis

Relative humidity

Relative humidity measurements in the upper troposphere and lower stratosphere with sufficient vertical resolution are needed in order to validate the humidity fields simulated by global models which is the basis for modeling the occurrence and optical properties of contrails and natural cirrus. Relative humidity is difficult to measure in the upper troposphere and lower stratosphere.

Satellite observations are employed to infer supersaturation [Spichtinger *et al.*, 2003a; Gettelman *et al.*, 2006] without having been designed to measure relative humidities. The influence cirrus clouds have on the inferred values is uncertain. While spatial patterns of relative humidity are reliable, the inferred magnitudes of supersaturations are highly uncertain. Most satellite instruments suffer from relatively coarse horizontal and/or vertical resolution, greatly limiting their use for detailed model validation. The applicability of more recent improved instrumentation such as CALIPSO/CloudSat or Odin-SMR [Ekström *et al.*, 2007] in contrail research remains to be shown. A promising, still developing technique for the retrieval of moisture is the GPS tomography [Troller *et al.*, 2006], but for the time being the resolution and the sensitivity to the low water vapor contents in the tropopause region is not sufficient.

Older operational radiosondes are known to have dry biases and cannot be employed to measure relative humidity reliably at altitude without suitable corrections [Miloshevich et al., 2001]. However, carefully calibrated and corrected RS80A radiosondes [Nagel *et al.*, 2001] and follow up instruments can be used to detect supersaturated vertical layers [Spichtinger *et al.*, 2003b; Rädel and Shine, 2007a]. In-situ (airborne and balloon-borne) research instruments measure clear-sky relative humidity relatively well in the extratropical regions (with an uncertainty of about ±10 % relative humidity) and are therefore the best option for contrail studies. To date, the MOZAIC program [Marenco *et al.*, 1998] provides 9 years of in-situ measurements onboard commercial aircraft along major flight routes and is a powerful data source not only for relative humidity [Gierens *et al.*, 1999a] but also for temperature and water fluctuations [Gierens *et al.*, 2007]. Aircraft measurements of water vapor with forward-facing inlets are more difficult inside clouds because care has to be taken to avoid the additional detection of small particles. However, there are known differences in the water vapor measurement between different in-situ instruments and satellite retrievals [Kley *et al.*, 2000] and between different satellite retrievals [Read *et al.*, 2007]. These pending discrepancies between different in situ instruments are most relevant in the cold atmosphere mostly found in the tropical tropopause region [Peter *et al.*, 2007] too high to be affected by commercial subsonic air traffic. More information on this subject will be provided by SSWPs of Key Theme 3.

Contrail measurements

Aircraft measurements use a suite of techniques to describe the number size distribution, ice water content and scattering phase function of contrail particles and are the best tool to provide a detailed optical and microphysical characterization of contrails. Fresh contrails that can clearly be related to their source aircraft are straightforward to probe (near field measurements), although only very experienced pilots can handle the perils of close encounters between contrail-producing and contrail-detecting aircraft. Due to the highly turbulent microstructure of fresh contrails, many crossings at similar plume ages are needed to obtain statistically robust data. It has been recognized for a long time that measurements of particle concentrations with optical particle spectrometers that have inlets could overestimate the number concentrations of small ice crystals due to shattering of large ice crystals on the inlets or aircraft bodies. This is highly relevant to young contrails, as those are expected to consist of high numbers of small crystals. As laid out in an SSWP in Key Theme 4, existing contrail measurements appear to be reliable mainly because large crystals (> 100 µm) are largely absent in fresh contrails, so that available near-field measurements are in agreement with theoretical expectations [Kärcher *et al.*, 1998].

Much less is known about the contrail life cycle and their decay, which is essential for the assessment of the radiative forcing of contrails and contrail cirrus. Only few measurements, mostly from Lidar or airborne measurements exist for the first 60 minutes. Some case studies using satellite imagery discuss the evolution of radiative parameters and forcing of contrail clusters for up to about 6 hours [Duda *et al.*, 2001]. These measurements do not allow representative statistics. Tracking of contrails and contrail outbreaks from satellite data has been performed in some case studies, but a general description of the life cycle and the resulting radiative forcing of contrails and contrail cirrus is available only for some specific cases [Minnis *et al.*, 1998; Schumann, 2002].

The climate impact of contrails and contrail cirrus cannot be measured directly, it has to be derived from model studies. Measurements and data analysis is necessary to validate their optical properties over the life cycle.

Visual or photographic detection of contrail occurrence [Bakan *et al.*, 1994] covers only linear contrails similar to those detectable in satellite measurements. The frequency of occurrence at a given site indicates how often the thermodynamic formation conditions are met. The occurrence of linear contrails observed from airports in the contiguous United States has been analyzed by Minnis *et al.* [2003]. It shows a strong seasonal cycle and regional differences, but almost no daily cycle, pointing to the very dense air traffic during the daylight observing period. About 80-90% of the contrails occurred along with cirrus clouds. In Fairbanks, Alaska, a region with relatively low air traffic, Stuefer *et al.* [2005] validated mesoscale model forecasts of contrail formation conditions by visual observation of single aircraft. Sassen [1997] published the results from 10 years of observations of high clouds and contrails at the FARS site in Utah using a combined data set of all-sky camera images, polarization Lidar and radiometers. These ground based Lidar observations of contrails rely on the drift of contrails directly over the fixed location. Lidar observations resolve contrails and cirrus clouds with a high spatial resolution and give information on altitude, optical depth and, in combination with near-IR spectroscopy [Langford *et al.*, 2005] also on ice particle size.

Ground-based contrail observations have been performed using a scanning Lidar with tracking capability operated near Garmisch-Partenkirchen, Germany [Jäger *et al.*, 1998]. The tracking of many single contrails in meteorological conditions favorable for their formation and persistence yielded surveys of the evolution of cross section, height and optical parameters (e.g., depolarization) up to 60 min of estimated contrail age [Freudenthaler et al., 1995, 1996]. In combination with an air traffic data base [Garber *et al.*, 2005], MODIS satellite images and ground based photographs, Atlas *et al.* [2006] have assessed the age of 18 contrails probed by the NASA/GSFC micropulse Lidar. This Lidar provided information on particle fall speeds and estimated sizes, optical extinction coefficients, optical, and ice water path for contrails and their fall streaks with ages up to 2 hours. Lidar observations of thin cirrus and contrails have been carried out in Lindenberg, Germany [Immler *et al.*, 2007]. The classification of cirrus clouds was aided by a CCD camera, and a high resolution radiosonde corrected for the dry bias was also operated at this site. In 90% of the cases where ice supersaturation was indicated by the radiosonde, cirrus clouds have been detected. As the Lidar is capable of detecting very thin cirrus (visible optical depths of 10^{-4} or less), a high detection frequency may not come as a surprise. Cirrus including a large fraction of subvisible cirrus have been observed in 55% of all observations. Visual inspection of the camera images showed that 5% of the observed cirrus could be identified as aging contrails, but only ~10% of the identified contrails were line-shaped. The rest consisted of significantly spreaded contrail cirrus or was connected to pre-existing cirrus.

Few measurements of contrails with airborne Lidar systems have been reported. During the ICE89 campaign Kästner *et al.* [1993] derived optical depths of three contrails and surrounding cirrus clouds and compared them to optical depth values derived from AVHRR data. They found an agreement within 10% between both methods and optical depths of the contrails were by 0.1-0.25 higher than in the cirrus. A scanning Lidar system was also flown on the NASA DC-8 aircraft during the SUCCESS campaign [Uthe *et al.*, 1998]. This system was primarily designed to help locate and direct the DC-8 into thin cirrus and contrail layers, but also provided high resolution data on the vertical cloud structure. Although the recorded Lidar data have not been fully analyzed, they have been claimed to be useful for the interpretation of data collected in-situ and from radiometric sensors and for inferring optical and radiative cloud properties.

Cirrus detection using satellite imagery

New passive instruments of unprecedented quality like the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) aboard the geostationary Meteosat Second Generation (MSG) allow for the first time the quantification of cloud properties during the life cycle of clouds from space. The new "MSG cirrus detection algorithm" (MeCiDA) has been developed using the seven infrared channels of SEVIRI [Krebs *et al.*, 2007] thus providing a consistent scheme for cirrus detection at day and night. MeCiDA combines morphological and multi-spectral threshold tests and detects optically thick and thin ice clouds. The thresholds were determined by a comprehensive theoretical study using radiative transfer simulations as well as manually evaluated satellite observations. The results have been validated by comparison with the Moderate Resolution Imaging Spectroradiometer (MODIS) Cirrus Reflection Flag: An extensive comparison showed that 81% of the pixels were classified identically by both algorithms. On average, MeCiDA detected 60% of the MODIS cirrus. The lower detection efficiency of MeCiDA was caused by the lower spatial resolution of MSG/SEVIRI, and the fact that the MODIS algorithm uses infrared and visible radiances for cirrus classification. The advantage of MeCiDA compared to retrievals for polar orbiting instruments like MODIS or previous geostationary satellites is that it allows the derivation of quantitative data every 15 min, 24 h a day. This high temporal resolution allows the study of diurnal variations and life cycle aspects. MeCiDA has been used to derive cirrus coverage over Europe and the North Atlantic for a complete year in the frame of the ESA project CONTRAILS (Validation of the Eurocontrol contrail detection model with satellite data).

Contrail detection using satellite imagery

Linear contrails with widths of the order of the horizontal resolution of satellite sensors (~1 km for NOAA AVHRR type sensors) or larger are an obvious feature in satellite imagery, but automated or manual identification of contrail cirrus is not possible. Besides geometrical matters, contrails detected by Lidar or by ground-based observers may not be detectable by satellites owing to their moderately high optical depth detection thresholds (mostly ~0.1 in the visible wavelength range).

The main criteria to identify a linear contrail in satellite imagery are its shape and its contrast to the background. The best contrast for young contrails composed of small ice particles is usually found in the difference of temperatures measured in the thermal infrared split window channels (at ~11µm and 12µm) originally designed to retrieve the sea surface temperature. Over a homogeneous surface and a dry atmosphere even fresh contrails with a width smaller than the image resolution can be identified, but classical retrieval methods for the optical properties fail in this case, because the true width remains unknown.

Purely visual interpretation of satellite images is influenced by human factors but is usually more efficient in detecting linear contrails than automated methods. The first published visual data analysis was performed by Bakan *et al.* [1994]. An automated contrail detection algorithm [Mannstein *et al.*, 1999] has been applied to AVHRR over Europe [Meyer *et al.*, 2002], the continental USA [Duda *et al.*, 2004; Minnis *et al.*, 2005; Palikonda *et al.*, 2005] and southeast and east Asia [Meyer *et al.*, 2007].

The contrail detection algorithm indicates pixels in satellite infrared data which are covered by linear contrails. Contrail width (wider than pixel size) and length are easily derived from the resulting contrail mask. Integration over larger areas and/or times enables derivation of contrail coverage. In case studies with additional information on air traffic and wind conditions it is also possible to derive spreading rates [Duda *et al.*, 2004]. Based on the automated identification of linear contrails, their optical properties and radiative forcing has been estimated from the brightness temperature difference between the contrails and their surrounding assuming that the contrail temperature equals the atmospheric temperature at the same altitude [Meyer *et al.*, 2002, Minnis *et al.*, 2005; Palikonda *et al.*, 2005]. For all derived parameters it has to be kept in mind, that they are related to the spatial resolution of the sensor, which is in the order of at least 1.3 x 1.3 km^2 in the nadir of the satellite for the AVHRR, which was used for all of these studies. The sub-pixel variation of contrails is not considered in the algorithms.

False alarms in the contrail detection algorithm are usually [90% according to Meyer *et al.*, 2002] caused by natural cirrus clouds with a shape similar to contrails, the detection efficiency decreases with increasing the background inhomogeneity, which might also be caused by other contrails. Tuning the algorithm to a low false alarm rate reduces also the detection efficiency, enhancing the detection efficiency results in a higher false alarm rate. The false alarm rate can be reliably determined statistically from observations in regions without air traffic, but the detection efficiency has to be assessed by comparison to visual inspection, as no other truth is available.

A major problem with this algorithm is its sensitivity to minor differences in the spectral and spatial performance of the sensor. Both, detection efficiency and false alarm rate have to be determined for each instrument independently by visual inspection, which introduces a high level of uncertainty. A direct cross calibration between different instruments is not possible because the satellites are on different orbits. Therefore, time series using contrail analyses of different satellites suffer from large uncertainties.

Another more general problem of the interpretation of data from satellites in a sun-synchronous orbit is the sampling at slowly drifting local times. The sampling interferes in this case with the daily pattern of air traffic, resulting in aliasing effects. For case studies, the algorithm has also been applied to MODIS, A(A)TSR, MSG and GOES data, the latter in geostationary orbits allowing for nearly continuous observation at the expense of the high resolution of the polar orbiters.

The majority of contrail studies using satellite data are based on the thermal infrared channels, but contrails are also detectable in the visible and near infrared part of the spectrum [Minnis, 2003]. A systematic derivation of optical properties like optical depth, effective particle size, ice water content, or particle number using these channels has not been reported.

e. Present state of modeling capability

Contrails and contrail cirrus form at lower relative humidities than natural clouds and therefore change the overall cloud coverage. The additional cloud coverage due to contrail cirrus together with the specific optical properties of contrail cirrus, that are different from those of natural cirrus, are the two main factors influencing the radiative forcing due to contrail cirrus. Therefore a realistic radiative forcing, and thus a realistic climatic impact of contrail cirrus, can only be obtained if the estimates of contrail cloud coverage and optical properties of contrails are themselves realistic. Detailed modeling of contrails in concert with field observations help to parameterize the processes as a function of large-scale meteorology. So far a more process-oriented treatment of contrails in large scale models is missing. These are until now only based on the criterion for contrail formation and inventories of air traffic and constrained by contrail statistics obtained from satellite observations. In a climate model, only the effect due to linear contrails has been simulated so far and contrail coverage has been limited to source areas.

Large-Eddy simulations

The interplay between near-field observations and models of contrail formation have unraveled many features of the contrail formation process. It can be explained sufficiently well with existing knowledge and does not introduce significant uncertainty in models describing the subsequent evolution [Kärcher, 1999]. Contrail evolution in the vortex regime is mostly described by 2D or 3D LES, few of which have been coupled to a simplified description of the ice phase using bulk microphysical methods [Lewellen and Lewellen, 2001; Unterstrasser *et al.*, 2008]. Those simulations are complex and suggest a range of factors influencing contrail development up to the dispersion regime. Comparisons to Lidar measurements in case studies [Sussmann and Gierens, 1999] showed that these models are sufficiently well developed to study the impact of wake dynamics and atmospheric parameters on the contrail ice mass, but must invoke assumptions about underlying ice crystal size distributions to make inferences about particle number densities. The latter point is an important constraint when employing such information in global model contrail parameterization schemes. Besides contrail ice mass, information on ice particle number is required to estimate effective crystal sizes for use in the radiation schemes. This information must currently be drawn from in-situ measurements.

A study of the mesoscale evolution of contrail cirrus has been performed and parameters such as initial crystal number, shear and supersaturation have been varied [Jensen *et al.*, 1998a]. Radiation was found to be important for contrail development. Large-Eddy simulations could also be used to study the contrail to cirrus transition on successively increasing spatial and temporal scales, but such efforts have not yet been reported. In such an approach, it is not clear at which point large-scale processes take over a dominant role in determining contrail cirrus evolution and their interaction with cirrus. Contrail properties simulated by LES models can be prescribed in regional models in order to estimate the regional climate effect of contrails [Wang *et al.*, 2001].

Global modeling

The overall synoptic situation connected with supersaturated regions can probably be well represented in weather forecast and climate models, although low resolution models only allow for a statistical subgrid scale description. Humidity is a critical variable in atmospheric models due to the strong influence of subgrid scale processes and the presence of strong spatial humidity gradients. While areas of supersaturation can be identified in such models, the prediction of its magnitude and small-scale variability is much more demanding. Most global models do not allow supersaturation on the grid scale but rely on assumptions about its subgrid variability in their cloud schemes. Only the ECMWF integrated forecast system currently allows for explicit ice supersaturated states that are consistently simulated with cirrus cloud fraction although cirrus microphysics is still highly simplified [Tompkins *et al.*, 2007]. Few climate models prognose explicit supersaturation [Wilson and Ballard, 1999; Lohmann and Kärcher, 2002; Liu *et al.*, 2007] but simulate cloud coverage inconsistent with ice microphysics.

Contrails cannot be treated as a mere source term to the cloud parameterization in a climate model because of differences in the number and particle size distribution of contrail cirrus and natural cirrus. Instead contrails need to be parameterized in global models. Most global modeling approaches rely on a variation of a single contrail cover parameterization proposed by Sausen *et al*. [1998]. Contrail cloud coverage is introduced into the model which must be parameterized consistently with the model's cloud physics. In the absence of explicit supersaturation in the model a potential contrail coverage is defined. The potential contrail coverage is the area which would support contrail formation. This critical relative humidity for contrail formation is then made consistent with the cloud parameterization. Since contrails can form at a lower relative humidity than natural clouds, the critical humidity for contrail formation in the GCM grid box is defined as a combination of the two critical humidities. Potential contrail coverage is then limited by natural cirrus coverage. The dependency between natural cirrus coverage and relative humidity is unchanged. As a result the contrail parameterization can only simulate an additional coverage due to contrails and cannot replace natural cirrus. Potential contrail coverage is usually interpreted as the maximally attainable additional coverage due to contrails. This is not correct since only the formation conditions of contrails are modeled and not the persistence conditions. Once contrails are formed they can persist whenever the air is supersaturated, or in the modeling framework moister than a specified critical humidity. Potential contrail coverage was calculated using ECMWF reanalysis data or ECMWF operational data or simulations of the global climate model ECHAM4, which originated from an older version of the ECMWF model.

In order to arrive at a global contrail coverage, potential contrail coverage is then folded with an air traffic inventory [Gierens *et al.*, 1999b; Marquart *et al.*, 2003; Ponater *et al.*, 2002; Sausen *et al.*, 1998]. In Sausen *et al.* [1998] folding was done linearly and with the square root of air traffic, the latter to account for saturation effects such as contrail merging and consumption of condensable water. Gierens [1998] argues that in the presence of advection, saturation effects are not likely to happen. Duda *et al.* [2005] determines that the folding should be done with the fourth root of air traffic. In most studies the global DLR and the newer AERO2K data set have been used. As a measure of air traffic density mostly fuel usage or flown kilometers were used. Using flown kilometers or fuel usage was shown to lead to different results especially in the long distance flight corridors [Gierens *et al.*, 1999b] but since flown kilometers are not available in some data sets, fuel usage is often used. The folding of the air traffic data with the potential contrail coverage is either done online or in most cases offline. The resulting field describes the frequency of contrail formation.

The computed frequency of contrail formation is then related to the observed coverage of line-shaped contrails by a tuning coefficient. Within the parameterization contrails exist only for one time step. This results in a contrail coverage that is limited to the areas of air traffic. Advection, spreading and persistence of contrails is not covered. Contrail coverage is always zero in areas of no air traffic while in reality strong winds in the upper troposphere can advect contrails over hundreds of kilometers. The tuning coefficient is set so that the calculated line-shaped contrail coverage agrees with the observed contrail coverage over a particular area without taking into account physical mechanisms. This tuning coefficient is assumed to be temporally and spatially constant. Until now the mean European contrail coverage of Bakan *et al.* [1994] was always used for tuning the parameterization. Rädel and Shine [2007b] estimate that contrail coverage may be significantly changed when using a model that simulates explicitly supersaturation instead of the potential contrail coverage as defined by Sausen *et al.* [1998].

Duda *et al*. [2005] use in a very similar approach to Sausen *et al.* [1998] but employ a short term regional forecasting model, different definition of potential contrail coverage and a different tuning data set. The regional air traffic inventory of Garber *et al*. [2005], which describes air traffic over the contiguous U.S.A. is used. Potential contrail coverage is calculated from a regional forecasting model that contains explicit supersaturation, as the frequency at which persistent contrails can form. Comparison of the patterns of simulated contrail coverage with the satellite inferred contrail coverage quantified the influence of parameters such as the relative humidity threshold and order of relationship between air traffic and contrail coverage.

All global studies restrict themselves to studying only line-shaped contrails. Contrail cirrus coverage cannot be estimated in global climate models using the parameterization used for line-shaped contrails because no estimates of contrail cirrus coverage exist since older contrail cirrus is difficult to distinguish from natural cirrus. Instead a process based approach must be chosen in order to simulate contrail cirrus coverage and ice water content.

Optical properties and radiative forcing

Most parameterizations make only crude assumptions about the optical depth of contrails. In most offline studies, optical thickness has been set to a temporally and spatially constant value. The choice of this value has a large impact on the resulting radiative forcing. Since observations and climate model simulations point at optical thickness being very variable in time and space, any kind of constant optical depth value introduces an error in the radiative forcing calculations. Even if an average value of contrail optical depth is chosen and only global radiative forcing is of interest, the forecasted increase of air traffic in the subtropics is likely to result in a change in the mean contrail optical depth. Only one global contrail parameterization simulates optical properties of contrails as a function of ambient conditions online in the climate model [Ponater *et al*., 2002; Marquart *et al.*, 2003; Ponater *et al.*, 2005]. In contrails water condenses just like in natural cirrus a fraction of the moisture excess but since contrails exist only for one time step the contrail ice water content equals the condensed water at the time step. Contrary to cirrus they do not accumulate ice water in the model.

It is not clear how contrails overlap but the overlap assumption influence the simulated contrail coverage and the resulting radiative forcing very strongly. Usually it is assumed that contrails overlap randomly because they are far from filling the potentially contrail-supporting area and the flights are assumed to not overlap. This assumption will be especially justified if contrails are allowed to advect away from the source area [Gierens, 1998]. In areas where a substantial fraction of the potential contrail-supporting area is filled up, contrail overlap depends on the overlap of those areas. The finding that the vertical depth of supersaturated areas is small hints at random overlap being a reasonable choice even when the contrail-supporting area is filled up. Nevertheless, for the radiative calculations, maximum random overlap of contrails and natural cirrus is assumed.

Feedbacks of contrails on the simulated climate have not been studied yet. It is not clear whether contrails dry the atmosphere more strongly than air traffic moistens it. Furthermore it is not clear if contrails can replace natural clouds by a significant amount and if they replace natural clouds how large the net radiative forcing might be due to the different optical properties of contrails and natural clouds.

Offline radiative transfer models

As an alternative to global modeling, radiative transfer models have been used calculating the effect of prescribed contrails. Some of these models have underlying ice water paths, effective ice crystal radii and ice crystal shapes as a basis to parameterize their microphysics. Those parameterizations have been optimized for cirrus clouds based on the state of knowledge in the mid 1990s and include high values for the ice water path and effective radius that are not representative for contrail cirrus [Plass *et al.*, 1973; Fu and Liou, 1993; Fortuin *et al.*, 1995]. Up to date, most studies actually prescribing contrail microphysical properties base their results on a single ice particle size distribution [Strauss *et al.*, 1997], although in-situ data show a marked temporal evolution of radiatively relevant contrail properties and effective sizes are smaller initially [Schröder *et al.*, 2000]. The plane parallel assumption for contrails adopted by virtually all studies causes contrail radiative forcing to grow strictly in proportion to the fractional coverage, disregarding inhomogeneity effects [Schulz, 1998; Chen *et al.*, 2001; Gounou and Hogan, 2007]. Improved optical data sets for ice crystal radiative properties that have become available [Yang *et al.*, 2000, 2005] have not yet propagated into radiative transfer models used to study contrails. Attempts to overcome the assumption of vertical homogeneity of contrail optical properties have not been reported.

Future air traffic and mitigation scenarios

Projected air traffic rise causes an increase of linear contrail coverage [Gierens *et al.*, 1999b] assuming that the atmosphere stays the same and when allowing for climate change [Marquart *et al.*, 2003]. The expected rise depends strongly on the used air traffic scenario [Gierens *et al.*, 1999b]. However, the simulated development of upper tropospheric relative humidity and cirrus clouds in a future climate, and hence their impact on contrails, must be considered uncertain due to known difficulties of representing these variables in climate models. Changes in propulsion efficiency cause contrail formation at higher temperatures and therefore at lower altitudes [Schumann, 1996]. Areas in which potentially contrails can form are increased by more than 10% when changing the propulsion efficiency by 0.1 [Sausen *et al.*, 1998]. Actual contrail coverage, on the other hand, is expected to increase by only 0.1% since air travel usually takes place in areas colder than the temperature formation threshold. Flight level changes have a major impact on contrail coverage [Sausen *et al.*, 1998; Fichter *et al.*, 2005]. Air traffic at about 10 km has the strongest impact on radiative forcing [Rädel and Shine, 2007b] and should therefore be avoided if the contrail impact is to be minimized. If the cryoplane technology is used aerosol output is decreased and moisture output increased lowering the relative humidity threshold for contrail formation and causing an increase in ice crystal sizes. The former leads to an increase in contrail coverage and the latter possibly to a reduction in optical thickness. Both effects are estimated to cancel when calculating radiative forcing [Marquart *et al.*, 2003]. Fuel additives designed to change the ice nucleation behavior of exhaust soot particles are not likely to have a significant impact on contrail radiative forcing because the formation process is not sensitive to details of the ice formation process [Gierens, 2007].

f. Current estimates of climate impacts and uncertainties

Contrails increase the planetary albedo and hence cause a negative radiative forcing in the shortwave (SW) range. Contrail temperature is usually lower than the brightness temperature of the atmosphere without the contrails. Therefore, contrails induce a positive radiative forcing in the longwave (LW) range. The net radiative forcing is the difference between the SW and LW values. In most cases, the net radiative forcing is positive at the top of the atmosphere. Radiative forcing is mostly negative at the Earth’s surface, in particular during daytime. The radiative forcing increases with ice water path, or optical depth, and with contrail coverage [Meerkötter *et al.*, 1999]. For a given ice water path, the SW dominates over the LW effect for sufficiently small effective ice crystal radii. The cross-over point depends also on assumed ice crystal habit [Zhang *et al.*, 1999]. We emphasize that the net radiative forcing is generally the difference between two large values: negative SW forcing and positive LW forcing. Hence, any small error in either of them has a large impact on the computed net effect.

Global mean radiative forcing estimates for persistent line-shaped contrails have been reported that differ by a factor five. This results mainly from the use of different values for contrail coverage and optical depth. For 1992 air traffic, Marquart *et al.* [2003], Myhre and Stordal [2001], and Minnis *et al.* [1999] have yielded values of 3.5 mW/m^2, 9 mW/m^2, and 17 mW/m^2, respectively. Minnis *et al.* [1999] assume global contrail coverage of 0.1% for 1992, an optical thickness of 0.3, contrails at 200 hPa altitude, and hexagonal ice particles; they also included a simplified diurnal cycle with a globally uniform 2:1 day-to-night ratio. Myhre and Stordal [2001] use the same optical depth and coverage but find smaller radiative forcing values because of different approaches for the daily traffic cycle, scattering properties of ice particles, and contrail altitude. Marquart *et al.* [2003] normalize the contrail coverage computed with a climate model by reference to more recent satellite observations [Meyer *et al.*, 2002] implying a smaller global contrail coverage (0.05-0.07% for 1992); they compute smaller optical thickness values [Ponater *et al.*, 2002], including the daily cycle, improved altitude distributions of the contrails, and an update of the LW radiation scheme of the global model [Marquart and Mayer, 2002]. Their radiative forcing result for 1992 is five times smaller than the value used in the IPCC [1999] assessment.

IPCC [2007] adopted the result of Sausen *et al.* [2005] to conclude that the best estimate for the radiative forcing of persistent line-shaped contrails for aircraft operations in 2000 is 10 mW/m^2. The value is based on independent estimates derived from Myhre and Stordal [2001]

(15 mW m^{-2}) and Marquart *et al.* [2003] (6 mW/m^2). The two values were used by the IPCC [2007] to set the uncertainty range of a factor of two. This best estimate is significantly lower than the IPCC [1999] value of 34 mW/m^2, linearly scaled from 1992 to 2000 air traffic. The change results from reassessments of persistent linear contrail coverage and lower optical depth estimates, as detailed above. The new estimates include diurnal changes in the shortwave solar forcing, which decreases net forcing for a given contrail cover by about 20%.

Regional cirrus trends were used as a basis to compute a global mean radiative forcing value for AIC (aircraft-induced cloudiness) in 2000 of 30 mW/m^2 with a range of 10-80 mW/m^2 [Stordal *et al.*, 2005; Sausen *et al.*, 2005]. This value is not considered a best estimate because of the uncertainty in the optical properties of AIC and in the assumptions used to derive AIC coverage. However, this value is in agreement with the upper limit estimate for AIC radiative forcing in 1992 of 26 mW/m^2 derived from surface and satellite cloudiness observations [Minnis *et al.*, 2004]. A value 30 mW/m^2 is close to the upper limit estimate 40 mW/m^2 derived for AIC without line-shaped contrails in IPCC [1999].

A by far larger climate impact has been deduced by Minnis *et al.* [2004], who have analyzed a cirrus trend of ~1%/decade over the continental USA between 1971 and 1995, which was attributed almost exclusively due to air traffic increase during the period. Assuming an optical depth of 0.25 this increase of high clouds was calculated to induce a global mean radiative forcing of up to 25 mW/m^2 and a surface temperature response of 0.2-0.3 K/decade in the region of the forcing, which would explain practically all observed warming over the respective area between 1973 and 1994. In response to the Minnis *et al.* [2004] conclusion, contrail forcing was examined by Shine [2005] and in two global climate modeling studies [Hansen *et al.*, 2005; Ponater *et al.*, 2005]. These studies stressed that it is not possible to derive a regional climate response from a regional climate forcing and concluded that the surface temperature response calculated by Minnis *et al.* [2004] is too large by about one order of magnitude. For the Minnis *et al.* [2004] result to be correct, the climate efficacy of contrail forcing would need to be much greater than that of other forcing terms (e.g., CO_2). Instead, model simulations hint at a smaller efficacy of contrail forcing than equivalent CO_2 forcing [Hansen *et al.*, 2005; Ponater *et al.*, 2005].

For contrail cirrus, no reliable estimate of the optical properties and of the radiative forcing exists. The IPCC estimate of an upper bound of radiative forcing of 40 mW/m^2 by contrail- and soot-induced cirrus changes is based on the assumptions of 0.2% global additional cirrus coverage with an optical thickness of 0.3 (same as for line-shaped persistent contrails) [IPCC, 1999] . Both assumptions are very uncertain. The optical properties of the contrail cirrus are likely different from that of line-shaped contrails. The radiative forcing depends nonlinearly on the optical depth. It increases approximately linearly for small optical depth values, reaches a maximum in between 2 and 5 and may be negative for optical depth values larger than 10 [Meerkötter *et al.*, 1999]. Contrails within cirrus may enhance the optical depth of the cirrus beyond the limit where an increase in optical depth causes a reduction of the radiative forcing. Hence, a reliable estimate of the radiative forcing by contrail cirrus cannot be given.

For 1% additional cirrus cloud coverage regionally (optical depth 0.28), a regional surface temperature increase of the order 0.1 K was expected from a study by Strauss *et al.* [1997]. With a 2D radiative convective model, a 1 K increase was found in surface temperature over most of the Northern Hemisphere for additional cirrus coverage of 5% [Liou *et al.*, 1990]. For 1% additional cirrus cloud coverage globally (optical depth 0.33) a general circulation model coupled to a mixed layer ocean model computed 0.43 K global warming [Rind *et al.*, 2000]. Ponater *et al.* [2005] find a smaller specific climate response from contrails than for CO_2 increases in their climate model: the equilibrium response of surface temperature to radiative forcing from contrails is 0.43 K/(W m^{-2}) while 0.73 K/(W m^{-2}) for CO_2. For a global contrail coverage of 0.06 % and 0.15 %, with mean radiative forcing of 3.5 mW/m^2 and 9.8 mW/m^2 in 1992 and 2015, respectively (optical depth 0.05-0.2 depending on region and season, Meyer *et al.* [2007]), the computed transient global mean surface temperature increase until 2000 amounts to ~0.0005 K in this model [Ponater *et al.*, 2005].

Contrails cool the surface during the day and heat the surface during the night, and hence reduce the daily temperature amplitude. The net effect depends strongly on the daily variation of contrail coverage. A reduction of solar flux by an order 50 W/m^2, as measured by Sassen [1997], is to be expected locally in the shadow of optically thick (optical depth > 1) contrails. The surface LW forcing is small because of the shielding of terrestrial radiation by water vapor in the atmosphere above the surface. Hence, the Earth's surface locally receives less solar energy in the shadow of contrails [Sassen, 1997]. This does not exclude a warming of the atmosphere-surface system driven by the net flux change at the top of the atmosphere [Meerkötter *et al.*, 1999]. As shown by a 1D radiation-convection model, vertical heat exchange in the atmosphere may cause a warming of the surface even when it receives less energy by radiation [Strauss *et al.*, 1997].

Travis *et al.* [2002] claimed observable increases in the daily temperature range due to reduced contrails in the three days period of September 11-14, 2001, when air traffic over parts of the USA was reduced. They report that the daily temperature range was 1 K above the 30-year average for the three days grounding period, which was interpreted as evidence that jet aircraft do have an impact on the radiation budget over the USA. Several studies discussed these findings and pointed out that the statistical significance is weak and does not allow for strong conclusions [Schumann, 2005; Forster *et al.*, 2007; Dietmüller *et al.*, 2007]. Moreover, unusually clear weather in that region could also explain the observed daily temperature range [Kalkstein and Balling, 2004; Travis *et al.*, 2007].

Radiative forcing due to contrails is expected to increase in future due the projected increase in air traffic. Marquart *et al.* [2003] simulated the radiative forcing due to the increase of air traffic and due to climate warming. By 2015 the radiative forcing of line-shaped persistent contrails is simulated to be 9.4 mW/m^2 and by 2050 14.8 mW/m^2, compared to 3.5 mW/m^2 in 1992. Neglecting climate change the radiative forcing would be larger since the simulated temperatures in the tropical upper troposphere would be colder and the frequency of contrail formation larger than when allowing for climate change.

The majority of global contrail studies rely on a single modeling approach to simulate line-shaped contrail coverage, relying on assumptions such as constant tuning factor, representativeness of the coverages reported by Bakan *et al.* [1994] and constant optical depth. Furthermore studies are not independent since they are carried out with only few different models and always tuned to the same observed contrail coverage over Europe. Newer and lower estimates of radiative forcing are partly based on the assumption of a lower constant optical depth than in the 1990s. One-dimensional radiation schemes seem to agree on RF due to linear contrails and therefore do not add to the range of forcing estimates. However, most of these studies apply the same contrail ice crystal size distribution [Strauss *et al.*, 1997] so that the uncertainty in radiative forcing may be underestimated. Three-dimensional effects on radiative transfer are not insignificant but are not considered in global models yet.

Rädel and Shine [2007b] estimate the combined error due to the assumption of constant optical depth and due to the use of scaling factors for tuning the contrail coverage to be about 60%. Additionally smaller errors due to assumptions of ice crystal parameters, neglect of 3D radiative transport, assumption of constant engine parameters, diurnal cycle of contrail coverage, errors due to the cancellation of between long wave and short wave forcings. All errors together are estimated to account for a factor of two in net radiative forcing.

g. Interconnectivity with other SSWP theme areas

Our theme is closely connected to theme area 3 in terms of observations of ice supersaturation in the upper troposphere and lower stratosphere, both globally from satellites and locally from aircraft or balloons. We have emphasized that such measurements are difficult to perform and, in the case of remotely sensed data, highly uncertain. While we principally understand the causes of supersaturation, prediction in global models is at its infancy. A physically consistent representation of supersaturation, ice microphysics and coverage of contrail cirrus and natural cirrus including their subgrid-scale features requires new modeling approaches.

Our theme is also connected to theme area 4 regarding measurements of contrail cirrus. A global homogeneous data set of relevant contrail cirrus properties (primarily optical depth and coverage) is not available. We have emphasized that available measurements (comprising Lidar and Radar instruments, satellite sensors and standard cloud physics instrumentation onboard high flying aircraft) do not cover the full contrail cirrus life cycle. Virtually all quantitative in-situ information available covers only contrail ages up to ~30-60 min or perhaps up to ~2-3 h when tracking individual contrails in remotely sensed data.

3. OUTSTANDING LIMITATIONS, GAPS AND ISSUES REQUIRING IMPROVEMENT

a. Science

Representing contrail life cycle in global models

It is currently not possible to simulate the complete life cycle of contrail cirrus (i.e. fractional coverage, microphysical properties, radiative forcing) from formation to decay. The radiative effect of short lived (up to ~30 min) and non line-shaped contrails has not been properly discussed yet. Further, physical mechanisms that remain unconsidered by current approaches include advective transport of contrail cirrus out of the major contrail-forming areas. Interactions of contrails with the moisture field and cirrus clouds cannot be treated well in current models. Contrail cirrus taps condensable water and might remove the moisture by sedimentation, therefore changing the relative humidity. This may cause the atmosphere not to reach or to reach later the moisture thresholds for formation of natural cirrus therefore delaying cirrus onset.

More emphasis has to be put in estimating the climate effect of contrail cirrus. New process based methods have to be developed since results cannot be tuned to observations. These efforts would benefit from a better knowledge of the temporal development of contrail properties from in-situ and remote sensing measurements. It remains unclear if and, if at all, when contrails acquire similar properties as natural cirrus. The apparent lack of aged contrail cirrus measurements hinders progress in this area.

Contrail cirrus optical depth and coverage

Any confidence in estimated global radiative forcing of contrail cirrus will remain low unless the underlying optical depth mean and variability of contrail cirrus has been fully explored and the radiation schemes in global models have been adapted to contrail-specific optical properties. Clouds produce different flux changes depending on the environmental circumstances (cloud, surface or atmospheric properties). As a class, thin cirrus cool the surface and exert a net warming within and at the top of the atmosphere [Chen *et al.*, 2000]; optically thicker cirrostratus and anvil cirrus still warm the atmosphere on the whole but cool the surface and top of the atmosphere. This annual and global mean picture derived from ISCCP-D2 data has largely confirmed earlier studies regarding cirrus radiative forcing [Hartmann *et al.*, 1992], but still contains substantial simplifications in treating the vertical layering of cloud, the radiative transfer in cirrus, and in assumptions about the nighttime radiative fluxes, so that these findings cannot be viewed as a final conclusion. Contrail cirrus belonging to the class of thin cirrus are therefore also expected to warm the atmosphere on average. However, a host of underlying factors controlling radiative forcing by contrail cirrus, including their radiative impact when coexisting with cirrus, need to be explored further to build more confidence in predictions of their net radiative effect.

The actual radiative relevance of clouds is also controlled by the product of their typical spatial coverage and their frequency of occurrence (cloud amount). In the case of contrails the latter is determined by the formation probability along aircraft flight paths while the former is more closely tied to the factors controlling atmospheric supersaturation, transport and contrail dissipation. The total coverage is the sum of coverage due to line-shaped contrails and contrail cirrus. A separate estimate of the latter contribution has not yet been reported. IPCC [2007] estimates the ratio of total (contrail cirrus plus soot cirrus) coverage due to aircraft-induced cloudiness to that of persistent linear contrails in the range 1.8-10 [Minnis *et al.*, 2004; Mannstein and Schumann, 2005]. The upper bound is currently not supported by Mannstein and Schumann [2007]. The study by Stubenrauch and Schumann [2005] would imply even smaller lower bounds [Schumann, 2005]. Locally, this ratio is ill-defined if considering regions into which contrails have been advected but where air traffic is low or absent.

A further open question is the radiative effect of producing contrails inside existing cirrus (or other high level clouds). Such contrails may increase the optical depth of the combined cirrus/contrail systems compared to the cirrus, or high level cloud, alone. If the optical depth is thick already (~3-6), then an increase in optical depth may cause a cooling. If the optical depth is small, the increase in optical depth will still cause a warming. The importance of this effect depends on at least three factors. (i) The relative frequency of occurrence of contrails inside thick cirrus (high level clouds) compared to contrails outside cirrus or in thin cirrus; (ii) the change in optical depth for solar and terrestrial radiation caused by the contrail forming inside the existing high level cloud; (iii) the gradient of the radiative forcing with optical depth. To our knowledge this problem has not been studied yet, but without solving it, one cannot exclude that contrails cool.

Soot effects

Whereas it is feasible to use as a first step a proxy for supersaturation when simulating contrails, the simulation of the soot effect relies on the explicit simulation of supersaturation. The lack of consistency between ice supersaturation, cirrus microphysics and cirrus cloud coverage in most global models currently does not allow the simulation of the indirect effect on climate induced by soot emissions with confidence. Satellites cannot discriminate between pure contrail effects and soot effects on cirrus, therefore hampering a sound model validation of contrail impact on climate.

To tackle the soot effect, an in-situ experiment should be designed to demonstrate the ice-forming capability of aircraft soot emissions (experimentum crucis). Such a measurement should be performed first in relatively unpolluted air because the background cirrus in flight corridors could already be affected by aviation soot. The soot should be emitted along with tracers marking the air mass. Difficulties in interpretation may arise from dynamical effects that can easily mask aerosol-induced cirrus changes and the impact of ice nuclei from other sources such as mineral dust.

Metrics

The climate impact of contrails is usually reported in terms of global mean or regional mean contrail-cirrus cover [Sausen *et al.*, 1998], and forcing in terms of shortwave (SW), longwave (LW) and net (LW+SW) radiative forcing values [Minnis *et al.*, 1999]. In order to assess the climate impact one needs to know the equilibrium global mean surface temperature change ΔT per net radiative forcing (RF), $\Delta T = \lambda_{contrail}$ RF, or the efficacy, i.e. the value $\lambda_{contrail} / \lambda_{CO2}$

relative to that for RF from CO_2 concentration changes [Hansen *et al.*, 2005; Ponater *et al.*, 2005]. Since contrails are strongly correlated with air traffic density, even when accounting for drift of contrails during their life-time, the contrail-induced climate impact occurs mainly at northern midlatitudes [Minnis *et al.*, 2004]. Moreover, contrails cirrus is special in respect to its potential impact on the hydrological cycle, with many still unexplored mechanisms.

Generally, our gap analysis is in agreement with the findings of the 2006 Boston Workshop on climate impacts of aviation summarized by Wuebbles and Ko (2007) (http://web.mit.edu/aeroastro/partner/reports/climatewrksp-rpt-0806.pdf).

b. Measurements and analysis

Upper tropospheric relative humidity

The global distribution of humidity in the upper troposphere is not well determined since satellites have a low resolution in the area of the tropopause. Relative humidity is even more uncertain since it relies on consistent temperature and humidity measurements. In satellite data, only large-scale features such as geographical or seasonal patterns are robust features, the magnitude of inferred supersaturation is uncertain [Gettelman *et al.*, 2006]. Such observations need to be refined and continued to infer reliable statistics and better quantitative information on magnitude, frequency of occurrence, and variability of supersaturation. Despite pending issues in measuring relative humidity in-situ, ice supersaturation can be measured with aircraft with sufficient accuracy in the extratropics. Those measurements are particularly useful for aviation-related research (and for the general understanding of upper tropospheric/lower stratospheric processes as well) when performed on a regular basis on commercial aircraft. In-flight measurements using the already existing Tropospheric Aircraft Meteorological Data Relay (TAMDAR) system should routinely include reliable humidity measurements at flight level, thus providing a climatology of relative humidity and cirrus coverage. TAMDAR and NOAA’s Water Vapor Sensing System 2 (WVSS2) might improve the situation in the future when adapted to and used at cruising altitudes.

Whereas the formation of ice supersaturation in the extratropics is understood (Section 2.a), a reliable statistic of the magnitude, vertical layering and horizontal extent of supersaturation are not available. Field measurements support the predominance of homogeneous freezing as a major source of cloud ice mass [Jensen *et al.*, 2001]. This inference has been made based on frequently measured maximum supersaturations being consistent with the homogeneous freezing process and the frequent occurrence of a large number of small ice crystals [Kärcher and Ström, 2003; Gayet *et al.*, 2004; Hoyle *et al.*, 2005]. However, it is not clear why high ice supersaturations can persist in the presence of cold thin cirrus and why some values are exceptionally high (above the homogeneous freezing level) outside of clouds at very low (< 200 K) temperatures [Jensen *et al.*, 2005; Peter *et al.*, 2007].

Remote sensing of contrails

Global coverage by linear contrails, their optical properties and also the related radiative cloud forcing are in principle deducible from satellite measurements. Instruments like MODIS on Aqua and Terra or the A(A)TSR(2) series on ERS1, ERS2 and ENVISAT offer this possibility, as their data is available in a resolution of ~1 km for nearly the whole globe. A systematic study of contrail cover from AVHRR on METOP, AATSR and MODIS (~1 km resolution), in connection with air traffic data may provide very useful results for model validation.

A fine tuning of the automated contrail detection algorithm to these instruments followed by a thorough characterization of the performance in terms of detection limits, false alarm rates and detection efficiencies are necessary prerequisites. Contrails may be detected as soon as they show a significant contrast from background in terms of measurable radiation, but quantification of what can be detected and what not is difficult. False alarm rates and error bounds limit accuracy of contrail cover deduced from NOAA AVHRR channels to ~0.1% cover [Meyer *et al.*, 2002]. The optical depth values may be uncertain to an order 0.05 or more. Error bounds on detection limits, effective radius, life time, spreading rates, etc. have still to be determined.

The transition of linear contrails into contrail cirrus, which cannot be identified from shape, will remain poorly defined. Polar orbiting satellites observe clouds only once in long periods (typically a day) and can therefore not be used to follow the life cycles of individual contrails. Tracking of contrails and contrail cirrus in data from geostationary satellites with a high temporal resolution (5 min in MSG 'rapid scan', 1 min in GOES) can be used to retrieve a portion of the life cycle and the radiative forcing, ice water path, optical depth and effective particle size as function of contrail age and in relation to ambient conditions. Because of the lower spatial resolution of sensors in geostationary orbit this approach can detect only thicker and wider contrails. Systematic studies of such kind have still to be performed. For the interpretation of all measurements it is an advantage to know precisely the actual air traffic, which might have caused the observed contrails. Such data sets are usually not available to the research community. Moreover, knowledge of actual wind fields, temperature and humidity fields is needed at high spatial and temporal resolution to check for contrail formation threshold conditions and to identify the lateral displacement of contrails for given meteorology. Such data can be made available from meteorological analyses from numerical weather prediction centers.

Because of the sensor dependence of the observed cloud properties, satellite observation results (such as cloud cover) cannot be compared with model results directly. For proper comparison of satellite data and model results, one should apply a sensor simulator to the model results which simulates what the sensor would see for the given model state. Such an approach is essential for model validation.

One should note that the value of contrail cirrus coverage may depend strongly on its definition, namely whether it includes only the coverage observable to a specific sensor, or whether is limited to contrail cirrus above a certain optical depth threshold. Hence, optical depth and contrail coverage should always be reported together with the implied thresholds.

Identification and characterization of aged contrail cirrus

A major limitation in studies of older contrail cirrus is the difficulty to track single contrails with time, or to detect a contrail once it has lost its line shape. Ground-based Lidar can follow linear contrail evolution for a certain time, limited by the wind speed advecting the contrails away from the site. Research aircraft pilots quickly lose track of contrails without additional guidance, for instance from concomitant satellite observations. These are the major reasons for the lack of in-situ or Lidar measurements of contrail cirrus. Poor airborne sampling statistics for evolving large ice crystals and the difficulty in determining the exact sampling position (and hence, infer contrail age from measurements of NO) remain serious problems in any aircraft-based measurement. In-flight measurements of radiative fluxes of aging contrails should be easier to perform, but this requires two aircraft for a proper characterization of up- and downwelling flux densities. As very limited information is available from both in-situ and remote sensing measurements, and measurement uncertainties are often not clearly quantified, the optical properties of even line-shaped contrails and their subsequent time evolution remain a matter of debate. Remote sensing of the optical parameters of ice clouds relies on assumptions about the shape and size distribution of ice crystals. The lack of precise information from direct measurements leads to uncertainties regarding their radiative impact. Even though observational case studies would provide useful information for validation of process models, these measurements do not allow representative statistics. A general description of the contrail cirrus life cycle and the resulting radiative forcing of contrails and contrail cirrus is therefore hardly achievable without the help of models.

Correlations between cirrus coverage and air traffic

The statistical analysis of the correlation between cirrus properties and air traffic data may be the only method allowing the determination of AIC from observations [Mannstein and Schumann, 2005]. The method may be used to study cirrus not only in terms of cover but also directly in terms of radiation signals measurable from satellites. The method is attractive in principle, because it offers chances to detect the mean life time of contrail-cirrus.

For proper interpretation of such correlation results one has to know any cross-correlation of the observables with other parameters, such as geographical latitude and longitude because of land-ocean contrasts. Model results are useful to identify such cross-correlations [Mannstein and Schumann, 2007]. Even for nonzero cross-correlations, the method may be useful to determine upper bounds on the amount of AIC changes. Moreover, the same kind of statistical analysis may also be applied to model results, which helps not only to identify cause-effect relationships but also supports validation.

From ongoing work, we see chances that such methods provide useful correlation analyses for regions over the globe where the natural variability of cirrus statistics is small.

This method requires input in terms of temporally highly resolving geostationary satellite data over long periods and large regions (continents, oceans, hemispheres), together with information on air traffic movements at high spatial (~50 km) and temporal (~1 h) resolution, and corresponding meteorological analysis data for the same regions and time periods.

c. Modeling capability

Scale problem

One of the key problems in cloud and, even more so, in contrail modeling is the large range of spatial scales involved. The scale of young contrails (width ~50 m, comparable to the aircraft wing span) up to the scale of ice supersaturated regions (~500 km). Contrails can either be simulated using a Eulerian or a Lagrangian approach.

In a Lagrangian approach one would follow a finite set of typical individual contrail segments over their life-time and derive estimates of the properties of the ensemble of all contrails from the Lagrangian contrail segments. This approach could be an extension of a Gaussian plume model used to simulate the highly inhomogeneous concentration field of emitted trace species in a flight corridor [Schumann and Konopka, 1994; Schumann *et al.*, 1995; Schlager *et al.*, 1997]. The idea of this approach has been demonstrated in an idealized simulation of contrail coverage [Gierens, 1998]. Such a model needs input in terms of spatially and temporally highly resolved air traffic movement data. Moreover, the contrail model needs meteorological data input (temperature, humidity, horizontal and vertical wind) from a numerical weather prediction model, preferably one which simulates ice supersaturation [Tompkins *et al.*, 2007]. The change in contrail properties of a Lagrangian contrail segment with time for given ambient conditions can be parameterized based on detailed contrail simulations [Unterstrasser *et al.*, 2008]. Offline simulations would be useful for applications such as route optimization and for direct comparison with observations. For climate simulations it is necessary to simulate climate feedbacks which require an online scheme. This would be computationally extremely expensive.

Using the Eulerian approach (parameterization) contrail cirrus properties are described by a suitable set of variables at each grid point of a global circulation model. The variables have to characterize fractional coverages and mean properties of contrails of various ages within a grid cell of the Eulerian model. The model simulates the variation of contrails by integrating budget equations including contrail cirrus sources and sinks, in time and space. Such a parameterization is an extension of a GCM cloud scheme. It allows accounting for the feedback of contrail cirrus on the ambient (cloudy) atmosphere. Such a model is suitable for analysis of contrail cirrus both in the present and in a future climate.

Uncertainties in global modeling

Climate models need to be improved in two main aspects. In order to reduce the uncertainty regarding contrail radiative forcing the simulation of upper tropospheric fields needs to be improved and validated. A realistic simulation of the upper tropospheric relative humidity field is crucial since the frequency of contrail occurrence and the optical properties of contrails are strongly dependent on the relative humidity field. The coverage due to line-shaped contrails has been shown to agree reasonably well with observations in specified areas. Nevertheless, the method is unsatisfactory relying on the assumption of a constant scaling between contrail formation frequency and coverage. This assumption is likely to introduce errors especially calculating coverage for future scenarios in which air traffic increases in areas the parameterization was not tuned to. The optical properties of contrails are still under debate, with the modeling community usually assuming or simulating a mean optical depth of ~0.1. Some remote sensing observations suggest similar values and other remote sensing observations, including Lidar and high resolution remote sensing, deriving optical depths of 0.3 or 0.4.

Improvements and validation necessary for relative humidity and cloud coverage

It has become apparent that many climate models have problems simulating the humidity field in the upper troposphere. Models often have problems representing moisture in the area of the tropopause [John and Soden, 2007]. Errors in the upper tropospheric humidity field and associated errors in the temperature field, that manifest themselves often dramatically in the model's cold bias, have an impact on the simulated contrail statistics. Only recently more observations of the upper tropospheric humidity field (MOZAIC, MLS, AIRS) have become available enabling the validation of climate models in the upper troposphere. When evaluating the water budget in climate models, the emphasis is usually put into warm clouds. The microphysics of ice clouds has not been systematically evaluated and may be even used for tuning the model [DelGenio, 2002; Jakob, 2002]. Consequently there are indications that the optical properties of natural clouds may not be represented well at least in some climate models. Specifically it has been noted that the ice water content and effective ice crystal radii are too small in the ECHAM4 climate model [Lohmann *et al.*, 2007]. Size spectra that have a large impact on the microphysics and on the optical properties of clouds have not yet been updated according to the newest measurement results.

Climate models do not explicitly capture the formation of cirrus clouds. Nearly all climate models diagnose cirrus coverage in the same way as coverage due to water clouds, purely from the surrounding humidity, and apply saturation adjustment. They do not allow for explicit supersaturation relative to ice. Some modules have been developed to represent ice-supersaturation in global models [Kärcher *et al.*, 2006; Tompkins *et al.*, 2007] that might in the long term lead to a sufficiently accurate physically-based parameterization of contrail development. Future weather forecast and climate models must increase their vertical resolution to enable the simulation of stacked thin layers of supersaturation. They must include proper parameterizations for subgrid-scale dynamical processes that drive ice nucleation, and adapt their cloud schemes to cirrus clouds consistent with observations. The introduction of supersaturation at the grid scale of such models, however, requires current cloud fraction parameterization to be fundamentally modified to be consistent with known cirrus microphysics and supersaturation [Kärcher and Burkhardt, 2008]. A consistent cirrus coverage defining the formation and the evaporation of cirrus at different relative humidity levels and allowing for non-equilibrium states has not been implemented yet. Once this is implemented and validated for natural cirrus, parameterizations of contrails can be based on the improved physics.

Improvements necessary for contrail cirrus

Meanwhile, contrails can be parameterized requiring a proxy for supersaturation instead of the explicit representation of supersaturation, as applied for natural clouds. This approach has been used successfully for simulating line-shaped contrails. Line-shaped contrail coverage has been simulated by tuning an area-averaged coverage to observational data and assuming a globally and temporally constant tuning coefficient. This approach precludes the simulation of the contrail life cycle and assumes that the ice water content can be estimated from the condensable water at a single time step. Because of the former the estimation of global mean radiative forcing due to aircraft-induced cloud changes has until now been limited to the forcing due to line-shaped contrails. Contrail cirrus cannot be modeled globally with existing methods so that a best estimate of radiative forcing due to contrail cirrus does not exist.

One possibility that may lead to substantial progress in global modeling is a process-based treatment of contrail cirrus as an individual cloud type with specific sources and sinks. Such an approach will allow uncertainties to be systematically reduced by properly representing and evaluating the processes that determine the entire contrail cirrus life cycle. Instead of constraining contrail coverage, the processes influencing contrail cirrus coverage must be identified, described and adequately constrained. The contrail cirrus parameterization should have a similar amount of subgrid scale information as the natural cloud scheme. Microphysical process rates have to be adjusted to contrails. In this way an independent estimate of line-shaped contrail coverage may be obtained that does not suffer from assuming a constant tuning coefficient and estimating contrail ice water content from the model state at a single time step. Furthermore the coverage due to contrail cirrus and the associated ice water content could be simulated. Nevertheless, as long as natural cirrus coverage is only diagnosed natural cirrus limits contrail cirrus coverage. Therefore contrail cirrus can replace natural cirrus and compete for condensable water with natural cirrus only in a limited way.

A realistic simulation of the interaction between contrail cirrus and natural cirrus may be achieved by calculating both coverages prognostically. A prognostic treatment of natural cirrus as suggested by Kärcher and Burkhardt [2008] enables the use of different formation and evaporation humidity levels for natural cirrus and therefore the simulation of supersaturation.

Radiation

Radiation codes in GCMs have a number of deficiencies that make the estimation of contrail radiative forcing uncertain. Three-dimensional effects in radiative transfer are thought to be non-negligible but are not covered routinely even in sophisticated radiative transfer calculations [Gounou and Hogan, 2007]. The microphysical basis for the application of radiative transfer simulations should be improved using real contrail size spectra and realistic vertical layering. This may eventually lead to improved radiation schemes for GCMs for contrail cirrus. Removing uncertainties in contrail radiative forcing must face the general difficulty that the net radiative effect of contrails and cirrus is difficult to evaluate accurately because it results from counteracting effects of large shortwave and longwave forcing terms.

Validation

Besides model development and improvement it is indispensable to also focus on validation. A GCM should be validated using statistical and climatological data. Generally the humidity fields and cloud coverages and optical properties simulated by climate models need to be validated. Suitable data to do this are just becoming accessible. Furthermore fields and frequency of supersaturation simulated by GCMs need to be validated. Available in-situ data for young contrails (up to 30-60 min age corresponding to one GCM time step, section 2.a) could be used to check whether contrail ice water contents are properly initialized in process-based contrail parameterization schemes. Although LES models are available to simulate individual contrails and their evolution within a few hours, those approaches are computationally demanding and are not straightforward to use for GCM validation. Available in-situ measurements provide only snapshots of possible contrail realizations. There still is a marked gap of climatological data describing contrail and contrail cirrus coverages and optical properties that are needed for the validation of simulated contrail and contrail cirrus coverages. Often the conditions under which contrails could be detected are not specified in detail and different observation-based statistics may have different detection thresholds. When developing process-based parameterizations of contrail cirrus coverage, data describing those processes, such as spreading, ice particle sizes and initial conditions after formation, are needed to constrain the parameterization. This calls for novel and innovative theoretical methods to infer contrail cirrus microphysical and optical properties on a statistical basis.

Another problem for GCM validation using remote sensing is the difficulty to discriminate between contrail cirrus and possible effects caused by aircraft soot emissions in such data. As a first step, it would be necessary to demonstrate experimentally whether soot modifies cirrus cloudiness (section 3.a). Even if aircraft aerosols should not lead to a significant change in cirrus cloudiness, properties of aerosols from other sources would still be required to predict the formation of natural cirrus by homogeneous and heterogeneous ice nucleation.

d. Interconnectivity with other SSWP theme areas

Limitations, gaps and issues requiring improvement connect to SSWP theme areas 3 and 4 covering upper tropospheric relative humidity and contrail-specific microphysics. We recall our statements in section 2.g. Concerning uncertainties in developing appropriate metrics to describe aviation-induced climate change, we refer to the SSWPs from theme area 7.

4. PRIORITIZATION FOR TACKLING OUTSTANDING ISSUES

Modeling and validation (A)

In the last section a number of open issues were identified that preclude progress in estimating the global climatic impact of contrails. Some of those issues are known shortcomings in climate models. Eliminating those shortcomings, which relate to the moisture budget and cloud representation in the models, may require several years of attention but would be required to reduce uncertainty of the estimates of the global climate effect of contrails and contrail cirrus. The improvements would increase confidence in our ability to simulate contrails only on the long time scale and therefore would not reduce uncertainty of the climate forcing of contrails for quite a few years to come.

On the other hand existing contrail parameterizations should be tested regarding the tuning and validated with more observational data and contrail resolving models as they become available. The high degree of interdependency of current results on global persistent linear contrail radiative forcing that arises from the use of identical data sets for tuning and validation should be reduced. Furthermore parameterizations should be based on processes so that only those processes would need to be constrained. Schemes should be extended covering not only contrails but also contrail cirrus. Radiative parameterizations and overlap calculations should be expanded to cover not only natural cirrus but also contrails. In the future improved parameterizations could then be implemented in models that have an improved representation of the moisture budget and cirrus representation.

1. Improving and validating the representation of the moisture and clouds in the upper troposphere in atmospheric models.
2. Including microphysical parameterizations leading to supersaturation in atmospheric models and representing processes of cirrus formation.
3. Testing the sensitivity of current contrail parameterization to tuning and assumptions influencing optical properties of contrails.
4. Development of a process based contrail / contrail cirrus parameterization for use in climate models.
5. Improving representation of radiative response to contrail cirrus in atmospheric models (including optical properties and cloud overlap).
6. Analyzing under which conditions contrails cool when forming inside high level clouds.
7. Development of a plume-based contrail model to simulate the scale transition for fresh contrails to extended contrail cirrus decks.
8. Inclusion of the plume-based contrail model in a weather forecasting model for short-term prediction and validation purposes (long term goal may be inclusion in climate models).
9. Models need to be validated with a number of observational data sets. Critical observations include absolute and relative humidity, ice water content, ice particle size distributions and habit, optical depth, vertical motion, wind shear, turbulence, etc. Further measurement campaigns are needed. CALIPSO and CLOUDSAT data should be analyzed regarding the detection of contrail cirrus.

Remote sensing and in-situ experiments (B)

An important issue is the quantification of aviation induced cloud changes AICC (including contrail cirrus, soot cirrus, changes to existing cloud systems; and changes in terms of coverage, microphysical and optical properties, radiative forcing etc.) from observations. Besides the modeling approach described in (A), we suggest a strategy to determine AICC directly by remote sensing. A second important issue is the homogeneous analysis of the precise coverage and properties of line-shaped contrails over a large region of the Earth with specified accuracy. Finally, one needs specific in situ soot experiments with aircraft soot sources in remote regions and measurements of the soot impact on cirrus that may form or may be changed due to the presence of soot [Kärcher *et al.*, 2007].

1. Improving and validating the representation of contrail and cirrus remote sensing analysis schemes providing cloud coverage, optical thickness, brightness temperature, reflectance, microphysical properties, contrail age, etc.
2. Provision of simple aircraft impact prediction tools such as contrail cover as a function of air traffic with prescribed spreading and life time [Gierens, 1998; Mannstein and Schumann, 2005].
3. Testing of correlations between observed cloud properties (from B1) and predicted aircraft impact (from B2) and investigation of any cause-and-impact relationship.
4. Improved determinations of the line-shaped contrail coverage and properties of line-shaped contrails over many regions of the Earth.

5. Soot experiments investigating the impact of soot on cirrus in the atmosphere.

B1-B3 would be similar to the approach tried by Mannstein and Schumann [2005]. Instead of comparing cirrus coverage and air traffic data over Europe, areas need to be selected where air traffic induces an observable change. The observations (B1) would be based on METEOSAT (MSG) cirrus observations; in a first step cirrus cover is used as observable; in a second step radiances can be employed additionally [Krebs *et al.*, 2007; Mannstein and Schumann, 2005]. The simple model (B2) simulates contrail coverage along aircraft flight paths as a function of contrail age with a few free parameters (e.g., contrail lifetime) [Mannstein and Schumann, 2005]. From correlating these results (B3), the amount and radiance contributions of aviation-induced cirrus changes are determined including best fitting model parameters. In a next step, one might also correlate a more advanced contrail prediction scheme (driven with meteorological analysis data) to observations to determine further AIC parameters.

B4 would make use of a generalized (i.e. used with various sensors) version of the automated satellite-based detection algorithm for line-shaped contrails [Mannstein *et al.*, 1999], which was applied by several groups using AVHRR data over Europe [Meyer *et al.* 2002], the continental USA [Duda *et al.*, 2004; Palikonda *et al.*, 2005], eastern north Pacific [Minnis *et al.*, 2005] and southeast and east Asia [Meyer *et al.*, 2007]. The method should be applied to AVHRR, MODIS, A(A)TSR, MSG and GOES data, the latter in geostationary orbits allowing for nearly continuous observation at the expense of the high resolution of the polar orbiters.

B5 would be similar to the SUCCESS [Toon and Miake-Lye, 1998] and the SULFUR experiments [Schumann *et al.*, 1996, 2002]. The experiment should allow tackling the soot-cirrus issue. The in-situ experiment should be designed to demonstrate the ice-forming capability of aircraft soot emissions. Soot source can be either a dedicated soot generator, or a strongly sooting engine or a modern normal engine with typical soot properties but low soot emission amounts, depending on the measurement methods used to detect the soot source. Such a measurement should be performed first in relatively unpolluted air (perhaps in the Southern Hemisphere, Punta Arenas) because the background cirrus in flight corridors could already be affected by aviation soot. The soot should be emitted along with tracers marking the air mass. It might be advisable to investigate in addition the cirrus properties in regions with high soot loading from other sources (biomass burning, surface traffic sources, etc.) injected into the upper troposphere by convection or large-scale cyclonic events. However, this will require a far larger experimental set-up then the initial idea to follow the fate of soot emissions from a well defined source.

a. Impact

Modeling and validation (A)

A1 and A2 would have a large impact on the reliability of contrail simulations. Until now contrails are simulated by models that have known biases and that have not been rigorously tested regarding the moisture and clouds in the upper troposphere. More model development and improvement is needed so that we can be more confident about contrail simulations.

A3 would give us an improved estimate of the uncertainty of existing estimates of contrail radiative forcing that may still be underestimated due to the fact that most estimates use only slight variations of the same method and largely identical data sources.

A4 would be a completely new approach and has therefore the ability to give us an independent estimate of contrail radiative forcing. Furthermore this approach would for the first time enable the estimation of the effect of contrail cirrus.

A5. Cloud overlap assumptions and radiative response are not yet adapted to contrails or/and the coexistence of contrails and clouds. But different cloud overlap assumptions and assumptions about particle size and habit have a strong impact on the radiative forcing estimates.

A6. This approach requires (i) a statistical model of cloud properties (frequency distribution of high level clouds of various optical thickness); (ii) a model study to understand the microphysical differences between contrails forming in cloud free air from contrails forming inside clouds; and (iii) radiative transfer calculations to determine the change in SW and LW radiative forcing values due to inserting a contrail into the high level cloud.

A7. Simulating scales from ~50 m (width of young contrails) to ~500 km (grid scale of global models) as a function of aircraft movements, aircraft emissions, altitude, ambient temperature (including stratification), humidity, vertical and horizontal wind (including rising motion and wind shear), turbulence, ambient aerosols, ambient clouds, requires special model development.

A8. Including the plume-based contrail model in a NWP model (such as the ECMWF-IFS) would allow comparison with individual (past and new, in situ and remote sensing) observations. Moreover the plume-based contrail model in the NWP can be used to predict contrail coverage at time scales needed for air traffic management to minimize the effect of contrails. Model results obtained with a GCM in climate mode could on the other hand be compared only to observations in a statistical sense except when nudging the GCM with observational fields.

A9 would support the development of contrail cirrus parameterizations or simulations.

Remote sensing and in situ measurements (B)

The activity could provide upper and lower bounds on aviation impact on cloud changes. Furthermore activities B1 and B4 are critical for validating global model simulations of contrail cirrus A8, see outline below.

b. Ability to improve climate impacts with reduced uncertainties

Uncertainty of radiative forcing due to contrails has not yet been properly estimated. Therefore research should not aim at reducing error bars but at developing independent approaches and using those approaches to estimate sensitivities to assumptions.

Modeling and validation (A)

A1 might not reduce uncertainties of contrail radiative forcing unless the representation of supersaturation has been validated itself. Application using several different host GCMs is likely to increase uncertainties since contrail forcing estimates have until now been mainly calculated using a single model (ECHAM) or using the related (ECMWF model).

A2 might actually first lead to an increase of the uncertainty since more processes need to be represented or parameterized in models. Those processes need to be constrained and validated with observational data which are scarce.

A3 would not reduce the uncertainty but yield more reliable estimates of uncertainty.

A4 would give an independent estimate of linear contrail radiative forcing and therefore may increase the estimate of uncertainty. In the case of contrail cirrus this approach would give a first estimate and at the same time could be used to provide an estimate of uncertainty.

A5 might be able to decrease uncertainty due to providing a mean and variability of cloud optical properties since different assumptions in cloud optical properties were the main reason for different radiative forcing estimates.

A6 needs to be solved to exclude or confirm the potential of contrails-in-cirrus inducing cooling.

A7 and A8. The plume-based contrail model can be used to test simulations of supersaturation in NWP models by comparing predicted and observed contrail cirrus. Hence, the activity also contributes to improving global models and their ability to simulate climate impacts with reduced uncertainty and to determine strategies to reduce this climate impact.

A9 is crucial for reducing uncertainties in models.

<u>Remote sensing and in situ measurements (B)</u>

Activity (B) would provide an observational basis for an assessment of future climate change due to aviation impact on cloud changes.

Improved and validated contrail and cirrus remote sensing analysis schemes are required to obtain data on cloud coverage, optical thickness, brightness temperature, reflectance, microphysical properties, contrail age, etc.

By correlating results from aircraft impact prediction tools with observed cirrus properties, insight on cause-and-impact relationships between air traffic and cirrus changes and constraints on important model parameters can be obtained.

A uniform approach to determine the line-shaped contrail coverage and properties of line-shaped contrails over many regions of the Earth would provide data from which the global amount of line-shaped contrail cover could be determined experimentally; moreover these results would be essential for model constraining and validation.

By measuring the properties of soot, cirrus and other aerosol behind a soot source, one learns about the change of soot with time and about the soot impact on cirrus. We believe that such an experiment is essential to tackle the soot-cirrus issue.

c. Practical use

Results from (A) and (B) would contribute to the next available IPCC assessment of global climate change and for related ICAO activities.

A1, A2 and A5 are prerequisites for a microphysically consistent simulation of ice clouds and their optical properties in general. After development they contribute to a better estimation of the climatic impact of contrail cirrus only in conjunction with A3 and A4. A3 and A4 are based on existing methods and need validation A9. This activity will lead immediately to more realistic estimates of the radiative forcing of contrails and contrail cirrus and the associated uncertainty. A6 would reduce the uncertainty on the lower bound of the radiative forcing by contrails (relevant also for contrail-cirrus). A7 and A8 combined enable the validation of contrail simulations and therefore are not of immediate practical use. Using A7 and A8 for air traffic management on the other hand would be immediately useful.

B1 is crucial for validating contrail models. B2 and B3 would provide model-independent data on AIC. B3 provides one basis for validating global contrail models. B5 is crucial to understanding soot ageing and soot-cirrus interaction and for demonstrating a measurable impact of soot on cirrus.

d. Achievability

Many of the suggested subjects require cooperation of researchers across several fields including basic research. This underlines the need for cooperation beyond several institutes. In most of the subjects DLR (internally and with external partners) is already active. Those areas have additionally been indicated below in order to facilitate cooperation.

Modeling and validation (A)

A1. Due to the availability of new satellite based data sets in the upper troposphere (e.g., AIRS) validation should now be possible. However, it must be recognized that remote sensing of humidity and clouds itself is fraught with significant uncertainties. A number of transport schemes for climate models have been developed that need to be implemented (if they aren't already) and validated in the upper troposphere. Cooperation in the field of remote sensing is necessary.

A2. Only recently supersaturation has been included in a few models [Tompkins *et al.*, 2007] but not always consistently with microphysics or cloud coverage parameterizations. This work should be continued [Kärcher and Burkhardt, 2008] and extended to include recent advances in ice nucleation microphysics [Hendricks *et al.*, 2005].

A3 is straightforward.

A4 requires expertise in both atmospheric dynamics and cloud microphysics. A process based parameterization needs to be consistent with the existing model cloud scheme. Therefore such a parameterization will vary depending on the host cloud scheme. The development, introduction and validation of such a scheme into the ECHAM GCM is currently followed by U. Burkhardt and B. Kärcher at DLR.

In A5 radiative transfer models and LES models can be used studying properties and radiative effects of individual contrails. LES modeling of contrail development and the transition into cirrus is performed by S. Unterstrasser and K. Gierens.

A6. The cloud properties may be derived from CALIPSO data. The study to understand the differences between contrails forming in cloud free air from contrails forming inside clouds can be performed with an LES-model [Unterstrasser *et al.*, 2008]. The radiative transfer calculations can be performed with existing tools [Meerkötter *et al.*, 1999]. A preliminary study has been started by U. Schumann and R. Meerkötter.

A7 and A8. The following ingredients for the plume-based contrail model are available: Gaussian plume models, meteorology from a NWP model, validation data (including MODIS, MSG observations, CALIPSO, Cloudsat, in situ data, LES model results), aircraft movement data base for periods for which MSG-data are available. Corresponding work has been started within the European Integrated Project QUANTIFY by K. Gierens, U. Schumann and QUANTIFY-partners.

A9. A large community is required to tackle validation issues, including validation of cloud and moisture variables retrieved by remote sensing via in-situ measurements and advanced cirrus modeling. In support of the latter, I. Sölch and B. Kärcher currently couple a multiscale LES model with a sophisticated aerosol-ice-radiation package to simulate cirrus by means of Lagrangian tracking, an approach opening up new ways of analyzing cirrus clouds in conjunction with field measurements.

Remote sensing and in situ measurements (B)

B1: A good basis is the method MeCiDA developed at DLR because of its suitability for geostationary satellites and all day and night times. So far MeCiDA has been used to derive cirrus coverage over Europe and the North Atlantic for a complete year.

B2: This requires input in terms of actual aircraft movements. A dataset is needed including 3D position vectors as a function of time along the flight paths for each aircraft. The type of aircraft and engine has to be known for emission estimates. The data should be available for the region covered by geostationary satellites (i.e., Europe, North Atlantic, Eastern North America) and should be available for the time periods for which satellite observations are being performed. Unless better data get available, the use the global data set from AERO2K for the year 2002 is recommended, or special data sets provided for smaller regions e.g., by EUROCONTROL (Europe and Atlantic, year 2004) and DFS (Germany, Sept. 2002).

B3: Limited experience exists in correlating observed and predicted contrail cover. Since results of correlation analyses are easily misinterpreted regions have to be selected where only the aircraft impact is relevant. Alternatively modeling is needed to discriminate between aircraft impact and other reasons for cloud changes. Presently, K. Graf, H. Mannstein, B. Mayer and U. Schumann at DLR are working on this topic.

B4 requires the application of the algorithm of Mannstein *et al.* [1999] to as many remote sensing data sets as possible covering a large part of the globe, with quantifiable and comparable accuracy.

B5 would make use of a suitable soot source (the source could be a normal aircraft engine, but the plume soot particles should be easily traceable for at least hours and hundreds of kilometers) and at least one research aircraft measuring aerosol and cirrus properties. The measurement should be performed in relatively unpolluted air because the background cirrus in flight corridors could already be affected by aviation soot. The soot should be emitted along with tracers marking the air mass. To overcome possible difficulties in interpretation, the project needs to be supported by proper model activities, addressing, e.g., dynamical effects that can mask aerosol-induced cirrus changes and the impact of IN from other sources such as mineral dust. The experiment could be performed with or including the new High Altitude and Long Range Research Aircraft (HALO) research aircraft, which should become operational in summer 2009. A first demonstration mission CIRRUS-ML is being prepared under the coordination of DLR. HALO will be equipped with a powerful set of aerosol and cirrus instruments. HALO will also be available for emission and identification of a passive tracer gas (H. Schlager and others). A laboratory-style aircraft engine soot generator has been developed at DLR Stuttgart; its use for airborne applications could be studied. The experiment can also be performed with US-aircraft (DC-8, HIAPER) or Russian aircraft. Cooperation with the Atmospheric Soot Network (http://www.asn.u-bordeaux.fr) on this topic would also be possible.

e. Estimated cost

Modeling and validation (A)

Costs are determined by individual salaries of experienced research scientists (timelines are suggested in section 4.f) and the use of observational tools needed for validation purposes. Computing costs should also be considered.

Remote sensing and in situ measurements (B)

Cost besides salaries include those for obtaining and evaluating satellite data and aircraft movement data bases as well as designing and carrying out a large-scale field campaign including personnel preferably in the southern hemisphere including the development of a proper soot source.

f. Timeline

The necessary research can be performed within the time frame associated with projected doubling of air traffic, as estimated below.

Modeling and validation (A)

A1 and A9. Model development and validation is an ongoing process and makes progress when new data sources become available. It is usually required that both modelers and data teams work closely together. It is difficult to associate a timeline because the amount of dedicated work depends on the type of model improvement and validation parameter and progress in verifying retrievals.

A2. Development of a theoretical ice nucleation scheme that describes physically based ice particle formation in cirrus requires at least one year of work of an experienced research scientist (1 PY). Its implementation in a climate model and thorough testing requires ~2 PY. Achieving consistency between microphysics and cloud coverage in the model is even more time-consuming. We estimate 1 PY to develop a consistent cirrus cloud scheme and ~3 PY for implementation and validation depending on the original model's cloud scheme. Adapting to an improved radiation scheme would be a significant additional effort (2-3 PY).

A3 would require few months work testing the impact of one parameter change.

A4 and A5 would require ~2 PY each, covering the design and development of the parameterization (A4) and performing detailed contrail studies as a basis for upgrading radiation parameterizations (A5).

A6. A preliminary study can be performed within a few months time.

A7 and A8. the initial model development until demonstration of the feasibility and first validation results requires ~2 PY for 3 years, plus support by the NWP team, and the team providing input in terms of observation data and aircraft movement data base.

<u>Remote sensing and in situ measurements (B)</u>

B1, B2 and B3 would require funding of at least ~3 PY for 3 years.

B4 requires cooperation of teams working in the field of contrail detection, and access to all relevant satellite data around the globe. The initial phase would be devoted to a careful comparison and adjustment of the detection algorithm. Thereafter, a large set of data would be processed. This expensive task may require ~10 PY within a 3 year period.

B5 may require 2 PY to develop an appropriate soot source and 5 PY for experiment and analyses. Parts of this work can be done in parallel.

5. RECOMMENDATIONS

Pure literature research or compilations of existing knowledge is not going to advance science any further. There are definite gaps of understanding (see section 3) that need to be addressed before any more definite conclusions about climate forcing of contrails can be drawn. Methods exist that could be applied gaining e.g. a homogeneous data base of contrail properties from remote sensing. Progress in simulating climate forcing due to contrails requires considerable effort developing new concepts.

a. Options

Options depend strongly on the amount of funding and support available. Activities (A) and (B) can be carried out simultaneously. They both offer large advances in understanding and potentially lead to significant progress within 3-5 years. However, problems are highly complex so that final conclusions cannot be drawn in such a short period. With the proper timing, this research may contribute considerably to the upcoming (fifth) IPCC report or a second dedicated IPCC aviation assessment.

<u>Modeling and validation (A)</u>

To make headway in evaluating the climatic impact of contrails and contrail cirrus, we recommend concentrating efforts on both, climate and radiative transfer modeling and on improving the data basis needed for validating those models. On the one hand a combination of remote sensing, along the lines explained in section 4, and in situ measurements would be useful and on the other hand LES and simple modeling in order to provide validation data sets or enhance process understanding.

Without new concepts in global modeling, no true progress estimating the climate impact of contrails will be made. Physically-based parameterizations describing microphysical and optical properties of contrail cirrus need to get developed and realized in different global models to ensure independent estimates.

On the long term, treating supersaturation, contrail cirrus, soot cirrus and natural cirrus consistently, global models will be able to provide more robust predictions of radiative forcing with reduced uncertainty.

A large effort needs to be put into obtaining validation data sets in order to constrain global model parameterizations. The data sets must be exactly characterized by the thresholds of the observational tools in order to enable a direct comparison with global model output.

Observations (see below) and global modeling should be accompanied by modeling of contrail cirrus on the cloud scale and by radiative transfer simulations. Together they benefit model development and remote sensing alike by providing or depending our understanding of processes.

With a range of matured climate models, we finally recommend to carry out IPCC-type assessment simulations focusing on the contrail climate impact. To this end, emission scenarios need to be employed that capture the most recent estimates of future air traffic and climate change parameters.

Remote sensing and in situ measurements (B)

Remote sensing provides regional statistics of alterations of coverage and contrail optical properties. Analysis tools (such as those developed at DLR) should be applied to global observations yielding homogeneous data sets. Those could also be used in conjunction with improved methods in order to investigate possible correlations between air traffic and high cloudiness changes quantifying the aircraft-induced component. Activity B4 requires the application of an automated detection algorithm (such as that one developed at DLR) to different satellite sensors.

In parallel, we recommend to carry out in-situ measurements, preferably of old contrail cirrus. Such measurements must be carefully designed and supported by on-line meteorological analyses to enable probing of contrails in later stages of their life cycle. Again, remote sensing including Lidar can be employed in support of this goal by locating and tracking individual contrails and guiding the aircraft experimenters. In-situ measurements should cover both, microphysics and radiation, ideally using a number of research aircraft at the same time. Those measurements should also address the soot impact on cirrus.

The activity B5 requires the characterization of the soot source, the knowledge of the exact position of the aircraft and measurements of the undisturbed meteorology.

b. Supporting rationale

The rationale behind our recommendation is that one approach alone or several approaches in isolation are insufficient to improve the current state of knowledge. Only when all options noted above are tied together can significant progress be made and uncertainties reduced.

c. How to best integrate best available options

A 10 year research plan, organized in two steps, should suffice to address the most pressing issues raised in this SSWP. Research must be closely coordinated with the scientific community interested in upper tropospheric / lower stratospheric transport, chemistry and aerosol and cloud physics. Moreover, the research should be embedded in general climate and climate mitigation research activities. The design and performance of a large-scale measurement campaign must involve experimentalists, modelers and theoreticians alike. Coordinated model assessments of aviation-induced climate change could take place in an early stage after about 3 years and at the end of the research project. Funding must be large enough to integrate the international science community and to enable several independent approaches.

We recommend an intense cooperation between the US-agencies (FAA, NASA, NSF) with European agencies (DLR, EU, DFG). We also recommend an intense cooperation between research-oriented teams and agencies or companies having access to details on air traffic (e.g. EUROCONTROL, FAA, ICAO), and engine emissions. For direct access to meteorological fields inclusion of teams from the leading weather services may be helpful.

For the purpose of maximum acceptance and maximum use of existing knowledge, we recommend performing these projects in an environment of open information exchange and open participation. The classical “Virginia Beach” meetings as in 1992-1997 should be revived.

6. SUMMARY

A number of issues were identified indicating pressing research need regarding better validation data sets and climate model improvements. Long term efforts are required both in observations and modeling, developing new process parameterizations for ice clouds and their radiative effects, since model improvements are interdependent. Nevertheless, improvements building on the current state of cloud parameterizations in climate models could also lead to significant progress in understanding the aviation impact on climate at a shorter time scale.

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