SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Ice Supersaturation and Cirrus Clouds
Computer Project Account:	spdeissr
Start Year - End Year :	2004 - 2011
Principal Investigator(s)	Dr. Klaus Gierens
Affiliation/Address:	Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt Münchener Str. 20 D-82234 Wessling Germany
Other Researchers (Name/Affiliation):	Prof. Dr. Peter Spichtinger Institute for Atmospheric Physics (IPA) Johannes Gutenberg University Mainz Becherweg 21 D-55128 Mainz Germany

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

This project had two objective directions. The first was to implement the representation of ice supersaturated regions in the IFS. After this was achieved the further objectives in this direction were to see how the IFS actually represents ISSRs, what is the spin-up behaviour, how does it compare to satellite data.

The second direction was to study the relation of ISSRs with cirrus and contrails (including contrail cirrus). This was done using cloud resolving simulations. The idea was that the IFS could benefit from this research in its ability to represent cirrus clouds (microphysics and fractional coverage) and that it might become able to predict contrail formation as well, which might become an interesting feature once contrails become a part of a European emission trading scheme.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

none

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

We are pleased that the administrative effort for Special Projects is low. It was always easy to apply for continuation of the project, to get additional computing resources, and to do the reporting. In fact, the easy procedures made it interesting for us to submit a proposal for a new Special Project.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

NOTE: Our project work resulted in a lot of scientific papers and we think it is the most convenient way to summarize its results by quoting the abstracts of the papers.

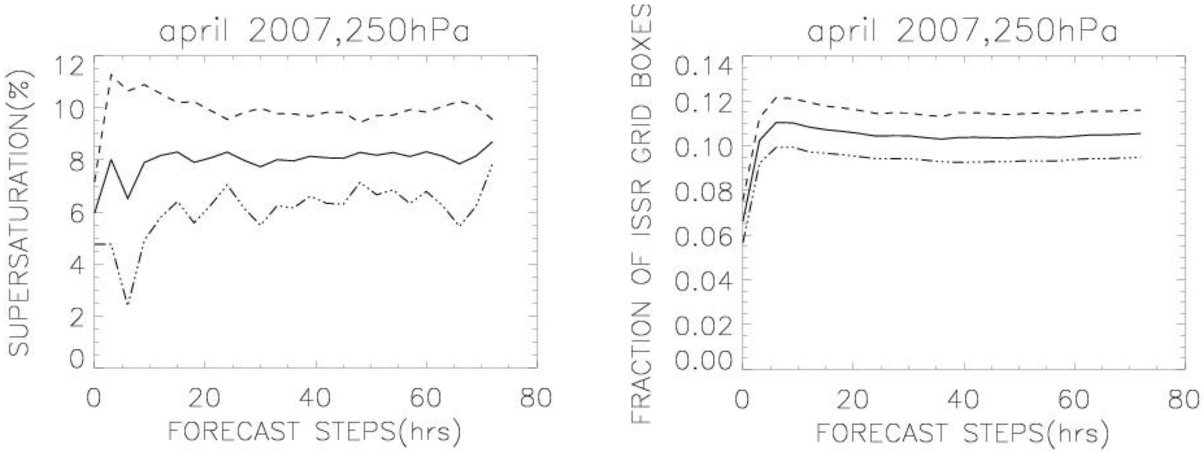
Ice supersaturation in the IFS

The first objective of this project was to implement ice supersaturation in the IFS. This objective was achieved in co-operation with Adrian Tompkins (formerly at ECMWF).The new stratiform cloud scheme allowing supersaturation went operational in October 2006 after successful testing (in further co-operation with Gaby Rädel from Univ. of Reading). This has been described in a Technical Memo and in the scientific literature (Tompkins et al. 2007). The abstract of this paper is as follows:

A parametrization for ice supersaturation is introduced into the ECMWF Integrated Forecast System (IFS), compatible with the cloud scheme that allows partial cloud coverage. It is based on the simple, but often justifiable, diagnostic assumption that the ice nucleation and subsequent depositional growth time-scales are short compared to the model time step, thus supersaturation is only permitted in the clear-sky portion of the grid cell.

Results from model integrations using the new scheme are presented, which is demonstrated to increase upper tropospheric humidity, decrease high-level cloud cover and, to a much lesser extent, cloud ice amounts, all as expected from simple arguments. Evaluation of the relative distribution of supersaturated humidity amounts shows good agreement with the observed climatology derived from in situ aircraft observations. With the new scheme, the global distribution of frequency of occurrence of supersaturated regions compares well with remotely sensed microwave limb sounder (MLS) data, with the most marked errors of underprediction occurring in regions where the model is known to underpredict deep convection. Finally, it is also demonstrated that the new scheme leads to improved predictions of permanent contrail cloud over southern England, which indirectly implies upper-tropospheric humidity fields are better represented for this region.

Initially, the new supersaturation scheme was only implemented in the forecast model but not in the assimilation scheme where a simplified physics scheme was used. Therefore, supersaturation was only established in the analyses during the last time step when the model switched to the full ice physics. Consequently, forecast runs experienced a spin-up for ice supersaturation during the first 12 to 24 hours into the simulation. This spin-up was studied in 2007. We repeat here a typical result that was shown later in a paper by Lamquin et al. (2009).



The right panel shows the evolution of the fraction of supersaturated grid boxes with forecast step for April 2007, on the 250 hPa pressure level, in 0.5°×0.5° resolution. There is a steep rise of the fraction of ISSR grid-boxes in about the first half day into the forecast. During that period the average supersaturation (left panel) shows distinctly more noisy behaviour than later (it is worse in other month). At that time we recommended not to use the first 12h forecast of ISSRs. Meanwhile the problem seems to be solved, i.e. the assimilation run produces the full amount and degree of ice supersaturation for the analyses (not tested by ourselves).

Tests of the new IFS supersaturation and stratiform cirrus scheme using data from AIRS and CALIPSO/CALIOP

Certain features of the new supersaturation scheme have already been tested by Tompkins et al. (2007), but further comparisons with satellite data from AIRS and CALIPSO/CALIOP have been performed later. These have been described in a paper by Lamquin et al. (2009). Here we include the abstract of that paper:

An evaluation of the upper tropospheric humidity from the European Centre of Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) is presented. We first make an analysis of the spinup behaviour of ice supersaturation in weather forecasts. It shows that a spinup period of at least 12 h is necessary before using forecast humidity data from the upper troposphere. We compare the forecasted upper tropospheric humidity with coincident relative humidity fields retrieved from the Atmospheric InfraRed Sounder (AIRS) and with cloud vertical profiles from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). The analysis is made over one year, from October 2006 to September 2007, and we discuss how relative humidity and cloud features appear both in the IFS and in the observations. The comparison with AIRS is made difficult because of the vertical resolution of the sounder and the impossibility to retrieve humidity for high cloudiness. Clear sky relative humidities show a rather good correlation whereas cloudy situations reflect more the effect of a dry bias for AIRS increasing with the relative humidity. The comparison with CALIPSO shows that the IFS predicts high relative humidity where CALIPSO finds high clouds, which supports the good quality of the ECMWF upper tropospheric cloud forecast. In a last part, we investigate the presence of ice supersaturation within low vertical resolution pressure layers by comparing the IFS outputs for high resolution and low-resolution humidity profiles and by simulating the interpolation of humidity over radiosonde data. A new correction method is proposed and tested with these data.

The mentioned new correction method yields a probability for having at least one ice supersaturated thin layer embedded in a thick (i.e. low resolution) layer that is on average sub-saturated. A similar probabilistic description for the fraction of ice supersaturated thin layers embedded in thick on average sub-saturated layers has been developed by Dickson et al. (2010) from an analysis of high-resolution radiosonde data. Note the difference between the two probability measures: While Lamquin et al. determine whether there is an ISSR at all embedded in a thick layer, the Dickson et al. metric yields the fraction of ISS layers. In principle such information could also be used in a formulation of vertical sub-grid scale variability in a weather forecast or climate model.

As a continuation of the work of Lamquin et al. (2009) we have further compared satellite data with ECMWF supersaturation statistics. This time the satellite RHi data have been "corrected" with the correction function derived in the former paper. This has been achieved using MOZAIC measurements. A paper with the following abstract has been submitted to ACP:

Ice supersaturation in the upper troposphere is a complex and important issue for the understanding of cirrus cloud formation. Infrared sounders have the ability to provide cloud properties and atmospheric profiles of temperature and humidity. On the other hand, they suffer from coarse vertical resolution, especially in the upper troposphere and therefore are unable to detect shallow ice supersaturated layers. We have used data from the Measurements of OZone and water vapour by AIrbus in-service airCraft experiment (MOZAIC) in combination with Atmospheric InfraRed Sounder (AIRS) relative humidity measurements and cloud properties to develop a calibration method for an estimation of occurrence frequencies of ice supersaturation. This method first determines the occurrence probability of ice supersaturation, detected by MOZAIC, as a function of the relative humidity determined by AIRS. The occurrence probability function is then applied to AIRS data, independently of the MOZAIC data, to provide a global climatology of upper-tropospheric ice supersaturation occurrence. Our climatology is then related to high cloud occurrence from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and compared to ice supersaturation occurrence statistics from MOZAIC alone. Finally it is compared to model *climatologies of ice supersaturation from the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) and from the European Centre HAmburg Model (ECHAM). All the comparisons show good agreements when considering the limitations of each instrument and model. This study highlights the benefits of multi-instrumental synergies for the investigation of upper tropospheric ice supersaturation.*

Numerical studies of contrails and contrail to cirrus transformation

This work package comprises mainly the PhD thesis work by Simon Unterstraßer. Cloud resolving model simulations of contrails and their spreading have performed at the HPC facilities of ECMWF. While the ultimate goal was to understand the transformation of contrails into cirrus clouds by spreading within ISSRs induced by windshear, it was necessary first to analyse the fate of the ice in the so-called vortex phase. The results of these simulations are described in Unterstraßer et al. (2008). An important result of this study was that a large fraction of initially formed ice crystals can be sublimated due to adiabatic heating in the downward travelling vortex system behind aircraft. The highest sensitivity of this loss is to the ambient relative humidity and temperature. While these results have been obtained with a bulk-microphysics code (Spichtinger and Gierens, 2009a), they have later been checked with the new Lagrangian particle tracking method developed by Ingo Sölch (see below). It turned out that the bulk microphysics often overestimates the crystal loss by sublimation under the special conditions in an aircraft contrail (Unterstraßer and Sölch, 2010). Gierens and Bretl (2009) have investigated the conditions that lead to an overestimation of ice sublimation. It turns out that these problems are more important for contrail than for cirrus studies. For contrail to cirrus transition studies they are unimportant as well.

With the vortex phase simulations the required initial fields for the subsequent dispersion phase simulations were available. These simulations led to the results described in the following abstract from Unterstraßer and Gierens (2010, Part 1):

Simulations of contrail-to-cirrus transition over up to 6 h were performed using a LES-model. The sensitivity of microphysical, optical and geometric contrail properties to relative humidity RHi , temperature T and vertical wind shear s was investigated in an extensive parametric study. The dominant parameter for contrail evolution is relative humidity. Substantial spreading is only visible for RHi>120%. Vertical wind shear has a smaller effect on optical properties than human observers might expect from the visual impression. Our model shows that after a few hours the water vapour removed by falling ice crystals from the contrail layer can be several times higher than the ice mass that is actually present in the contrail at any instance.

Further sensitivity studies have been performed and described by Unterstraßer and Gierens (2010, Part 2). It suffices to quote the relevant parts of the abstract:

Here, we study atmospheric parameters like stratification and depth of the supersaturated layer and processes which may affect the contrail evolution. We consider contrails in various radiation scenarios herein defined by the season, time of day and the presence of lower-level cloudiness which controls the radiance incident on the contrail layer. Under suitable conditions, controlled by the radiation scenario and stratification, radiative heating lifts the contrail-cirrus and prolongs its lifetime. The potential of contrail-driven secondary nucleation is investigated. We consider homogeneous nucleation and heterogeneous nucleation of preactivated soot cores released from sublimated contrail ice crystals. In our model the contrail dynamics triggered by radiative heating does not suffice to force homogeneous freezing of ambient liquid aerosol particles. Furthermore, our model results suggest that heterogeneous nucleation of preactivated soot cores is unimportant. Contrail evolution is not controlled by the depth of the supersaturated layer as long as it exceeds roughly 500 m. Deep fallstreaks however need thicker layers. A variation of the initial ice crystal number is effective during the whole evolution of a contrail. A cut of the soot particle emission by two orders of magnitude can reduce the contrail timescale by one hour and the optical thickness by a factor of 5. Hence future engines with lower soot particle emissions could potentially lead to a reduction of the climate impact of aviation.

As a minor study we have analysed the meteorological conditions that allowed the formation of an aerodynamic contrail over northern Germany in June 2008. For this study we have used analyses fields from ECMWF (Gierens et al., 2011).

Numerical studies cirrus using the Lagrangian Particle-tracking Method (LCM)
This work comprises the PhD thesis of Ingo Sölch. The model development and simulations have been performed on the ECMWF's HPC systems as well. The LCM is described by Sölch and Kärcher (2010), the abstract of which is reproduced here:
We introduce a novel large-eddy model for cirrus clouds with explicit aerosol and ice microphysics, and validate its central components. A combined Eulerian/Lagrangian approach is used to simulate the formation and evolution of cirrus. While gas and size-resolved aerosol phases are treated over a fixed Eulerian grid similar to the dynamical and thermodynamical variables, the ice phase is treated by tracking a large number of simulation ice particles. The macroscopic properties of the ice phase are deduced from statistically analysing large samples of simulation ice particle properties. The new model system covers non-equilibrium growth of liquid supercooled aerosol particles, their homogeneous freezing, heterogeneous ice nucleation in the deposition or immersion mode, growth of ice crystals by deposition of water vapour, sublimation of ice crystals and their gravitational sedimentation, aggregation between ice crystals due to differential sedimentation, the effect of turbulent dispersion on ice particle trajectories, diabatic latent and radiative heating or cooling, and radiative heating or cooling of ice crystals. This suite of explicitly resolved physical processes enables the detailed simulation and analysis of the dynamical–microphysical–radiative feedbacks characteristic of cirrus. We draw special attention to the ice aggregation process which redistributes large ice crystals vertically and changes the ice particle size distributions accordingly. We find that aggregation of ice crystals is the key process to generate precipitation-sized ice crystals in stratiform cirrus. A process-oriented algorithm is developed for ice aggregation based on the trajectories and sedimentation velocities of simulation ice particles for use in the dynamically and microphysically complex, multi-dimensional large-eddy approach. By virtue of an idealized model set-up, designed to isolate the effect of aggregation on the cirrus development, we show that aggregation and its effect on the ice crystal size distribution in the model is consistent with a theoretical scaling relation, which was found to be in good agreement with in situ measurements.
The mentioned effect of aggregation turned out important in a case study that has been conducted with the LCM in the frame of GEWEX (Sölch and Kärcher , 2011). A part of the abstract showing this is the following:
The large mode (sizes up to several 1000μm) forms and grows by aggregation. We demonstrate that the formation of the largest crystals by aggregation in deep cirrus is controlled in part by the nucleation of new ice crystals in dynamically active, highly supersaturated upper cloud regions. Furthermore, a pronounced increase in the number of aggregation events is predicted in sublimation zones. The combined effect of sublimation and sedimentation leads to the formation of a very thin (vertical extension ~100 m) sublimation microlayer mainly composed of aggregated ice crystals, containing relatively high total ice crystal number concentrations (~ 0.02 cm^{-3}) comparable to those generated locally by homogeneous freezing in the upper cloud layers.
One LCM result pertaining to contrail vortex phase microphysics has been mentioned above.

Development of a state-of-the-art cirrus cloud model on the basis of a consistent bulk scheme
Using the HPC system of ECMWF we developed a state-of-the-art cirrus cloud model on the basis of the anelastic non-hydrostatic model EULAG. The main purpose was to use a consistent ansatz using general moments in order to describe processes inside cirrus clouds on the large eddy simulation scale physically correct. The model is described in the publication Spichtinger % Gierens (2009a), here is an excerpt of the abstract:
A double-moment bulk microphysics scheme for modelling cirrus clouds including explicit impact of aerosols on different types of nucleation mechanism is described. Process rates are formulated in terms of generalised moments of the underlying a priori size distributions in order to allow simple switching between various distribution types. The scheme has been implemented into a simple box model and into the anelastic non-hydrostatic model EULAG. The new microphysics is validated against simulations with detailed microphysics for idealised process studies and for a well documented case of arctic cirrostratus. Additionally, the formation of ice crystals with realistic

background aerosol concentration is modelled and the effect of ambient pressure on homogeneous nucleation is investigated in the box model. The model stands all tests and is thus suitable for cloud-resolving simulations of cirrus clouds

Synoptically driven cirrus clouds

The newly developed cirrus cloud model (see above) was used in order to investigate the impact of large-scale dynamics, small-scale temperature variations and additional heterogeneous nucleation on the formation and evolution of warm front cirrus clouds. Here are two excerpts of the two relevant articles (Spichtinger & Gierens, 2009b,c):

Impact of dynamics and small-scale variations:

A recently developed and validated bulk microphysics scheme for modelling cirrus clouds (Spichtinger and Gierens, 2009), implemented into the anelastic non-hydrostatic model EULAG is used for investigation of the impact of dynamics on the evolution of an arctic cirrostratus. Sensitivity studies are performed, using variation of large-scale updraughts as well as addition of small-scale temperature fluctuations and wind shear. The results show the importance of sedimentation of ice crystals on cloud evolution. Due to non-linear processes like homogeneous nucleation situations can arise where small changes in the outer parameters have large effects on the resulting cloud structure. In-cloud ice supersaturation is a common feature of all our simulations, and we show that dynamics is as least as important for its appearance than is microphysics.

Impact of aerosols/heterogeneous nucleation

We study the competition of two different freezing mechanisms (homogeneous and heterogeneous freezing) in the same environment for cold cirrus clouds. To this goal we use the recently developed and validated ice microphysics scheme (Spichtinger and Gierens, 2009a) which distinguishes between ice classes according to their formation process. We investigate cases with purely homogeneous ice formation and compare them with cases where background ice nuclei in varying concentration heterogeneously form ice prior to homogeneous nucleation. We perform additionally a couple of sensitivity studies regarding threshold humidity for heterogeneous freezing, uplift speed, and ambient temperature, and we study the influence of random motions induced by temperature fluctuations in the clouds. We find three types of cloud evolution, homogeneously dominated, heterogeneously dominated, and a mixed type where neither nucleation process dominates. The latter case is prone to long–lasting in–cloud ice supersaturation of the order 30% and more.

Internal dynamics of cirrus clouds

This work is ongoing research on an analogue of classical cloud dynamics in the framework of ice supersaturated regions. The simulations have been carried out at the HPC machines of ECMWF. From radiosonde ascents one could find potentially unstable layers in the tropopause region; these layers could have a quite large vertical extension (1-2 km), such that they also could be found in ECMWF analyses. A realistic case is analysed using the cirrus cloud model as developed by Spichtinger and Gierens (2009a). The thick potentially unstable layer is located within an ice supersaturated layer. Due to large-scale lifting by a warm front the ice supersaturation increases until ice nucleation takes place. The latent heat release then triggers formation of convective cells, similarly to shallow convection in the boundary layer. The cells produce their own updrafts and thus lead to persistent ice supersaturation inside the ice cloud. Thus, this mechanism seems to be a possible answer to the ice supersaturation puzzle, i.e. the occurrence of high and persistent ice supersaturation inside cirrus clouds. The convective cells are embedded into a layer cloud, leading to the typical fall streak characteristics, which is often found in the upper troposphere. In addition to the realistic case sensitivity studies are carried out in order to investigate the impact of environmental conditions as stratification, temperature, relative humidity and wind shear. Additionally, the impact of heterogeneous nucleation on the formation and evolution of the cirrus clouds is investigated.

List of publications/reports from the project with complete references

Dickson, N.C., K.M. Gierens, H.L. Rogers, R.L. Jones, 2010: Probabilistic description of ice-supersaturated layers in low resolution profiles of relative humidity. Atmos. Chem. Phys., 10, 6749-6763.

Gierens, K., S. Bretl, 2009: Analytical treatment of ice sublimation and test of sublimation parameterisations in two-moment ice microphysics models. Atmos. Chem. Phys., 9, 7481-7490.

Gierens, K., M. Kästner, D. Klatt, 2011: Iridescent aerodynamic contrails: The Norderney case of 27 June 2008. Meteorol. Z., doi: 10.1127/0941-2948/2011/0497

Lamquin, N., K. Gierens, C.J. Stubenrauch, R. Chatterjee, 2009: Evaluation of Upper Tropospheric Humidity forecasts from ECMWF using AIRS and CALIPSO data. Atmos. Chem. Phys., 9, 1779-1793.

Lamquin, N., C.J. Stubenrauch; K. Gierens, U. Burkhardt, H. Smit, 2011: A 6-year global climatology of occurrence of upper-tropospheric ice supersaturation inferred from the Atmospheric Infrared Sounder after synergetic calibration with MOZAIC. Atmos. Chem. Phys. Discuss., 11, 12889-12947.

Peter, T., C. Marcolli, P. Spichtinger, T. Corti, M. Baker, T. Koop, 2006: The high supersaturation puzzle. Science, 5804 (314), 1399-1402.

Sölch, I., 2009: Ein Euler-Lagrange'sches Zirruswolken Modell mit expliziter Aerosol- und Eis-Mikrophysik: Studien zur Aggregation von Eispartikeln. Dissertation, LMU Munich. DLR-FB 2009-06, 132 pp.

Sölch, I., B. Kärcher, 2010: A large-eddy model for cirrus clouds with explicit aerosol and ice microphysics and Lagrangian ice particle tracking. Q. J. R. Meteorol. Soc., 136, 2074-2093.

Sölch, I., B. Kärcher, 2011: Process-oriented large-eddy simulations of a midlatitude cirrus cloud system based on observations. Q. J. R. Meteorol. Soc., 137, 374-393.

Spichtinger, P., 2011: Cirrus cloud dynamics – a source for ice supersaturation. To be submitted to Tellus A.

Spichtinger, P., K. Gierens, 2009a: Modelling of cirrus clouds - Part 1a: Model description and validation. Atmos. Chem. Phys., 9, 685-706.

Spichtinger, P., K. Gierens, 2009b: Modelling of cirrus clouds - Part 1b: Structuring cirrus clouds by dynamics. Atmos. Chem. Phys., 9, 707-719.

Spichtinger, P., K. Gierens, 2009c: Modelling of cirrus clouds - Part 2: Competition of different nucleation mechanisms. Atmos. Chem. Phys., 9, 2319-2334.

Tompkins, A.M., K. Gierens, G. Rädel, 2007: Ice supersaturation in the ECMWF Integrated Forecast System. Q. J. R. Meteorol. Soc., 133, 53-63.

Unterstrasser, S., 2009: Numerische Simulationen von Kondensstreifen und deren Übergang in Zirren. Dissertation, LMU Munich. DLR-FB 2009-15, 185 pp.

Unterstraßer, S., K. Gierens, P. Spichtinger, 2008: The evolution of contrail microphysics in the vortex phase. Meteorol. Z., 17, 145-156.

Unterstrasser, S., K. Gierens, 2010: Numerical simulations of contrail-to-cirrus transition - Part 1: An extensive parametric study. Atmos. Chem. Phys., 10, 2017-2036.

Unterstrasser, S., K. Gierens, 2010: Numerical simulations of contrail-to-cirrus transition - Part 2: Impact of initial ice crystal number, radiation, stratification, secondary nucleation and layer depth. Atmos. Chem. Phys., 10, 2037-2051.

Unterstrasser, S., I. Sölch, 2010: Study of contrail microphysics in the vortex phase with a Lagrangian particle tracking model. Atmos. Chem. Phys., 10, 10003-10015.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We have recently submitted a proposal for a Special Project SPDEFLUC. In this project we want to analyse instantaneous fluctuations of temperature, humidity, and vertical wind in the upper troposphere, and want to model their effect on the supersaturation field and cirrus cloud properties using models of different scales (e.g. LES). The newly proposed work aims at a better understanding of the nature and origin of such fluctuations. The idea is, that such studies contribute to the improvement of implicit assumptions of variability in the IFS cloud scheme, or that eventually a novel kind of statistical cloud scheme could arise from such work.