SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	The impact of fluctuations of temperature, humidity and wind on cirrus clouds
Computer Project Account:	SPDEISSR (aka SPDEFLUC)
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	Dr. Klaus Gierens Prof. Dr. Peter Spichtinger (University Mainz)
Affiliation/Address:	Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt Münchener Str. 20 D-82234 Wessling
Other Researchers (Name/Affiliation):	

The following should cover the entire project duration.

Summary of project objectives

We have two major interests, namely 1) the ambient conditions that support cirrus formation and have an impact on their properties and frequency of occurrence. This is in particular ice supersaturation and the ambient dynamic situation. 2) Formation, evolution, and properties of cirrus clouds themselves. Additionally we are interested in condensation trails and aerodynamic contrails. We continue these studies on cirrus clouds and the ambient conditions that have an impact on cirrus and contrail formation. Decadal changes of these conditions may lead to trends in cirrus occurrence. This is a major interest to our group and will give us work for the next couple of years.

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

The Special Project framework is a very useful mechanism to get easy access to the MARS archive and computing resources. The application procedure is sensible and straightforward. What counts is scientific content alone, not extra-scientific considerations (like in EU projects). Progress reporting is once per year which is reasonable.

Summary of results

1. Ice supersaturated regions and cirrus clouds

1.1. Statistics of dynamical fields within ice supersaturated regions compared to the general upper troposphere

We have performed a statistical analysis of the dynamical fields divergence δ, relative vorticity ζ, and vertical velocity ω within ISSRs and outside for two geographical regions, namely Europe (250 hPa level) and the tropical belt from 30°S to 30°N on two pressure levels (200 and 150 hPa). The study was based on 24 h forecast data from the ECMWF for June, September, December 2011, and March 2012 (with 0 UTC initialisation for the tropics and 0 and 12 UTC initialisation for Europe). We find that histograms (frequency distributions) and low order moments mean, standard deviation, and partly skewness and kurtosis, of the dynamical fields differ substantially when the data are either unconditioned (i.e. all data are used) or conditioned on ice supersaturation (i.e. only data within ISSRs are used). The results can be summarised as follows:

- Upward wind and divergent airflow are favourable conditions for the formation of ice supersaturation. But ISSRs are not always present when these conditions are met. Ice supersaturation is rare in regions with downward or convergent flow.
- The fact that the wind field in ISSRs is mostly divergent rules out moisture convergence as an important ISSR formation process. ISSRs are mainly formed by uplifting.
- ISSRs in northern mid–latitudes are mainly confined to regions with anti–cyclonic flow. This is probably explainable by the organisation of the warm/moist and cold/dry air streams in mid–latitude synoptic disturbances— a kind of causal relation. In the tropics anti–cyclonic flow prevails due to the flow situation with mainly easterly wind at the equator and westerly wind northward and southward. Although the mean vorticity in tropical ISSRs is stronger anti–cyclonic than the corresponding average vorticity of the whole NH or SH part of the tropical belt, the relation of the appearance of ISSRs and anti–cyclonic flow seems to be coincidental.

As all parameter combinations (δ,ζ,ω) that occur in ISSRs occur in subsaturated air as well, it is not possible to forecast ISSRs using dynamical fields alone. The history of an air parcel has to be known as well, i.e., whether it was or was not in contact with moisture sources recently. But there are parameter combinations where the occurrence of ISSRs is extremely unlikely, such that even weather models without a representation of ice supersaturation can give good hints of regions where ice supersaturation is not to be expected. Such forecasts could be valuable for climate optimised, contrail avoiding planning of flight routes.
Using ERA interim analyses we checked the relation of ice supersaturation with potential vorticity (PV) in the same way (not published). The result is shown in the following figure:

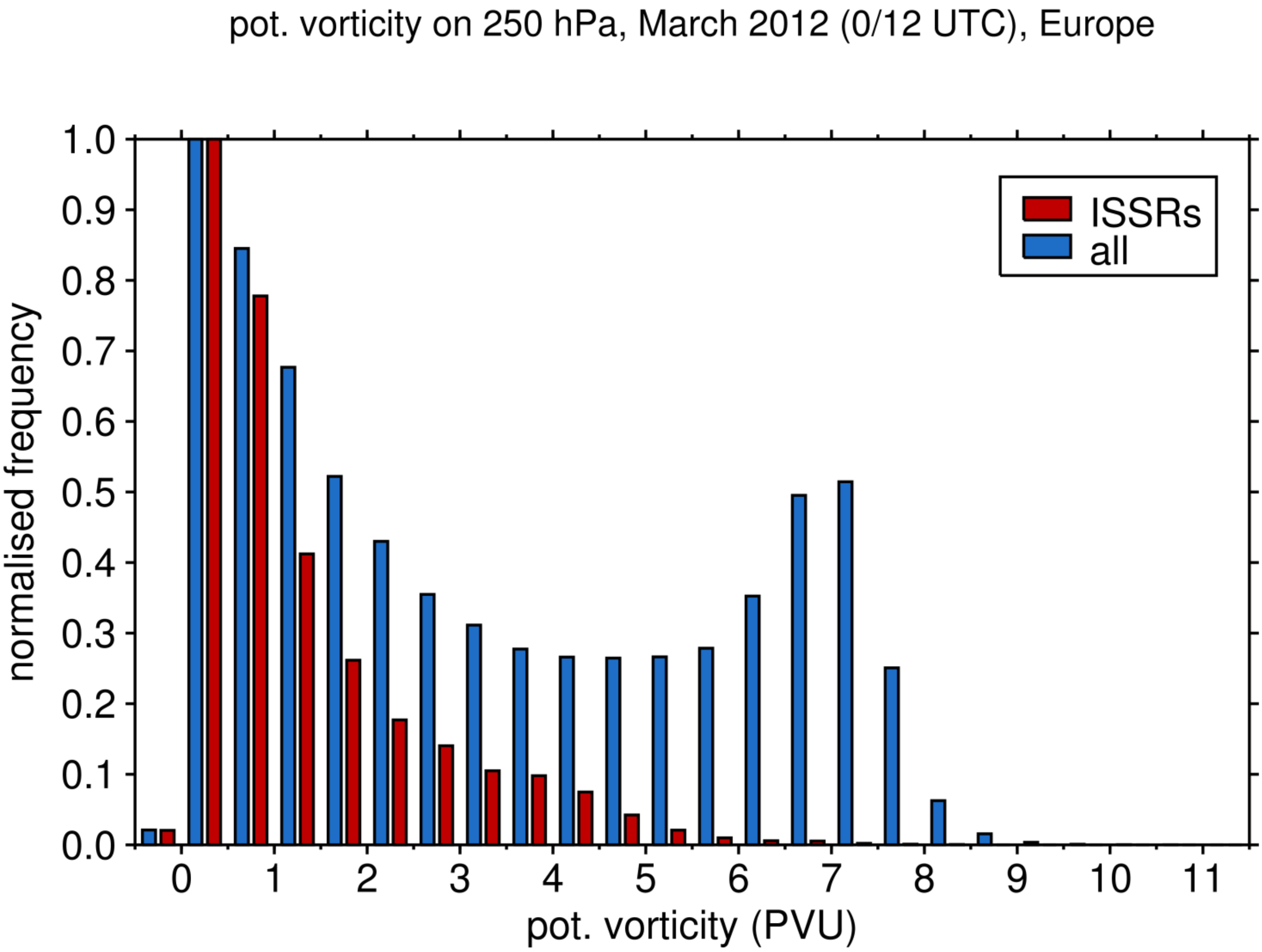

Figure 1: Histograms of potential vorticity over the region Europe (as defined in the MARS archive) for March 2012 (ERA interim analyses at 0 and 12h), on 250 hPa. The blue histogram takes every grid cell into account (resolution 0.25°×0.25°), the red histogram only grid cells with RHi≥100%. Surprisingly many cases of ice supersaturation are found in cells with PV>2PVU, that is formally in the stratosphere.

The result shows many ice supersaturated cases related to PV>2PVU, that is formally in the stratosphere. We will further investigate this finding.

1.2. Ice supersaturation and cirrus clouds on small scales

From investigations of radiosonde data and ECMWF analyses the occurrence of potentially unstable layers in the upper troposphere could be detected. We carried out extensive simulations – based on realistic profiles from ECMWF analyses – using a large eddy simulation model including a state-of-the-art bulk ice microphysics in order to investigate the impact of these layers in more detail. The basic setup is to superimpose a slow large-scale vertical updraft (i.e. to lift the whole domain) and investigate the formation of cirrus clouds in the upper troposphere originating from an ice-supersaturated region. The outcome can be summarized as follows:

- The latent heat release, although quite small, in the formed cells inside ice-supersaturated regions is large enough to trigger shallow convection inside the cirrus layers. Thus, quite high updraught s are formed and maintained up to hours.
- Inside the cells, high ice supersaturation can be found, i.e. the vertical updrafts as formed by the convective cells themselves act as a strong source for supersaturation, which cannot be compensated by the diffusional growth of ice crystals. Thus, high ice supersaturation can be found in these cirrus clouds, structured by shallow convection.

In comparison with in situ measurements, a very good agreement in the structure of potential temperature profiles as derived from simulation output could be found. Thus, we are quite confident that the mechanism found via modelling approaches is real and an important feature for structuring cirrus clouds on scales in the range 1-10 km.

A realistic case study was carried out in order to investigate shallow cirrus convection in potentially unstable layers. We investigated the impact of convective cells on relative humidity fields using 2D large eddy simulations using the EULAG model together with a state-of-the-art bulk ice microphysics scheme. These simulations were carried out at the HPC facilities of ECMWF; in addition, operational data were used for investigating the meteorological conditions for a realistic case. This study was published in Tellus A, the abstract of the paper is as follows:

The origin and persistence of high ice supersaturation is still not well understood. In this study, the impact of local dynamics as source for ice supersaturation inside cirrus clouds is investigated. Nucleation and growth of ice crystals inside potentially unstable layers in the tropopause region might lead to shallow convection inside (layered) cirrus clouds due to latent heat release. The intrinsic updraught inside convective cells constitutes a dominant but transient source for ice supersaturation. A realistic case of shallow cirrus convection is investigated using radiosonde data, meteorological analyses and large-eddy simulations of cirrus clouds. The simulations corroborate the existence of ice supersaturation inside cirrus clouds as a transient phenomenon. Ice supersaturation is frequent, but determined by the life cycle of convective cells in shallow cirrus convection. Cirrus clouds driven by shallow cirrus convection are mostly not in thermodynamic equilibrium; they are usually in a subsaturated or supersaturated state.

We will further investigate this phenomenon, using already available simulations, carried out at ECMWF HPC facilities.

Since cirrus clouds are located close to the tropopause, they have the potential to change the structure of the tropopause itself or even the distribution of trace gases and their exchange in the upper troposphere/lowermost stratosphere.

1.3. Life cycles of ice supersaturated regions

We conducted a master thesis at DLR-IPA (Sebastian Dietz) with an investigation of the life cycles of ice supersaturated regions using trajectory analyses. The trajectories have been computed mainly based on data from the COSMO-EU model, but some results have been cross-checked using data from the IFS. The following figure shows the probability density functions of relative humidity in two model versions of the COSMO-EU and the IFS:

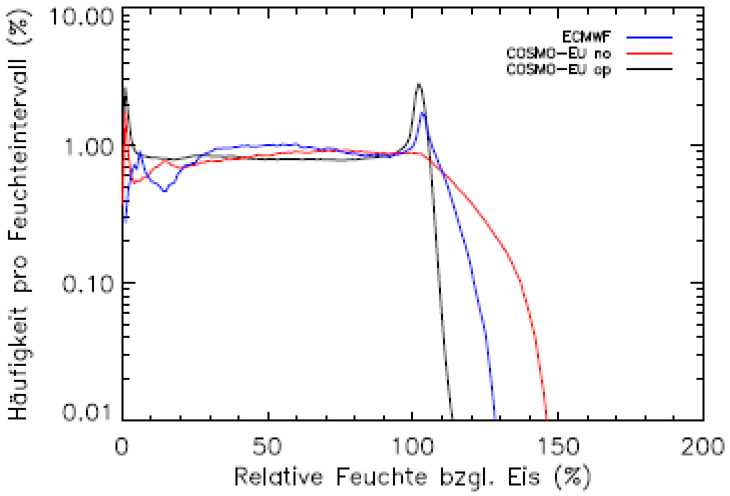

Figure 2: Probability density function of relative humidity with respect to ice on 300 hPa using 6 hr lead-time forecast data from two versions of COSMO-EU (the no, non-operational version, red curve, has an improved representation of ice supersaturation compared with the operational one, black curve) and the IFS.

Some important results can be quoted from the abstract: (note: "real" means as given in the data, "virtual" means that effects of cloud physics on the humidity evolution have been reverted in the trajectory calculation, as if the humidity evolved without cloud formation).
>>It is observed that the abundance of real ISSRs decreases with increasing time of supersaturation. The probability that a real ISSR occurs with a given lifetime is Weibull distributed with a Weibull parameter lower than one. The virtual ISSRs are found to be Weibull distributed as well. Compared to real ISSRs, virtual ISSRs have a longer lifetime.
Furthermore, the trajectory program and the COSMO-EU data allow studying the relation between the time of ascent of a ISSR and its lifetime. Therefore virtual ISSRs are in ascent approximately half of their lifetime, which is a consequence of neglecting the deposition of water vapor in virtual ISSRs. The time of ascent of real ISSRs depends on the ice microphysics scheme which is presupposed. Utilizing data from the improved ice microphysics scheme of the non-operational COSMO-EU model, we find that real ISSRs are in ascent approximately 60% of their lifetime. The ascent velocity of real ISSRs shows a characteristic pattern: During ascent, ISSRs with short lifetimes show all ascent velocities between zero and ten cm s^{-1}. In contrast, for ISSRs with lifetimes longer than ten hours, the relative frequency of ascent velocities slower than two cm s^{-1} increases, while the relative frequency of ascent velocities faster than four cm s−1 decreases.<<

1.4. Trends of upper tropospheric humidity

ECMWF Reanalysis data have also been used to underpin certain findings from the following study, whose abstract is as follows:
>>We use 30 years of intercalibrated HIRS data to produce a 30 year data set of upper tropospheric humidity with respect to ice (UTHi). Since the required brightness temperatures (channels 12 and 6, T12 and T6) are intercalibrated to different versions of the HIRS sensors (HIRS/2 and HIRS/4) it is necessary to convert the channel 6 brightness temperatures which are intercalibrated to HIRS/4 into equivalent brightness temperatures intercalibrated to HIRS/2, which is achieved using a linear regression. Using the new regression coefficients we produce daily files of UTHi, T12 and T6, for each NOAA satellite and METOPA, which carry the HIRS instrument. From this we calculate daily and monthly means in 2.5° ×2.5° resolution for the northern mid-latitude zone 30 to 60° N. As a first application we calculate decadal means of UTHi and the brightness temperatures for the two decades 1980–1989 and 2000–2009. We find that the humidity mainly increased from the 1980s to the 2000s and that this increase is highly statistically significant in large regions of the considered mid-latitude belt. The main reason for this result and its statistical significance is the corresponding increase of the T12 variance. Changes of the mean brightness temperatures are less significant.<<

As the abstract suggests, we used ECMWF data to look at decadal changes in temperature fields in the free troposphere of the northern extratropics. Further analyses and comparisons of HIRS and Reanalysis data are planned.

1.5. Warm-frontal cirrus and structure of the tropopause

In a Diploma project (Neis, 2013) we investigated cirrus clouds, driven by warm fronts and their relationship to the tropopause structure. For this purpose, we used operational analysis data for a case study of warm frontal cirrus clouds. In a first step, the meteorological fields were compared with in situ data from an aircraft campaign (CIRRUS III, November 2006), which was dedicated to investigate warm frontal cirrus clouds over middle Europe. There is good agreement between the high-resolution aircraft measurements and the large-scale fields of temperature, humidity and cloud parameters. In a second step, the thermal tropopause and the tropopause inversion layer were determined for this case for possible correlations between clouds and dynamic properties. Actually, we found for the first time that there is strong correlation between the occurrence of cirrus clouds and distinct tropopause inversion layers. Cirrus clouds are usually located in regions with very strong tropopause inversion layers, i.e. the maximum in Brunt-Vaisala frequency, which is close to the thermal tropopause, is very high in these cloudy regions. In figure 3, this correlation is shown. On the left panel, the strength of the tropopause inversion layer in terms of frequency difference is plotted. On the right panel, again the strength of the inversion layer is plotted, but only cloudy parts are shown, using a cloud mask for the data.

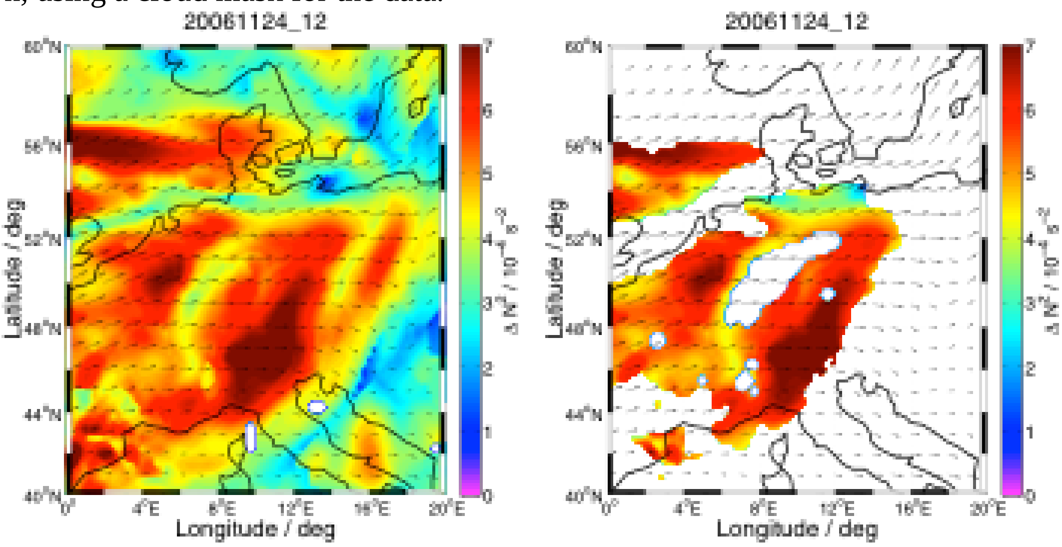

Figure 3: Left: strength of the tropopause inversion layer. Right: strength of the tropopause inversion layer restricted to cloudy regions. The TIL is particularly strong when there are clouds.

At the moment, it is not known why cirrus clouds and tropopause inversion layers behave in this way. We will investigate this feature in the next years, using ECMWF analysis data in a more extensive way. We are currently preparing a manuscript for publishing these new results.

1.6. Idealised warm-frontal cirrus simulations

In a diploma project (Bense, 2013) we investigated warm frontal cirrus clouds using the large eddy simulation model EULAG, including a state-of-the-art ice microphysics scheme. For simulating a frontal situation with a steady updraught, the lower boundary of the model domain is formed as a ramp. Air masses are transported by a constant horizontal motion; the ramp is mimicking the frontal updraughts, such that cirrus clouds are formed by adiabatic cooling. This two-dimensional setup provides an undisturbed large-scale upward motion; thus, the cirrus clouds can be investigated in a temporal and spatial way. The simulations were partly carried out at the HPC facilities of ECMWF.

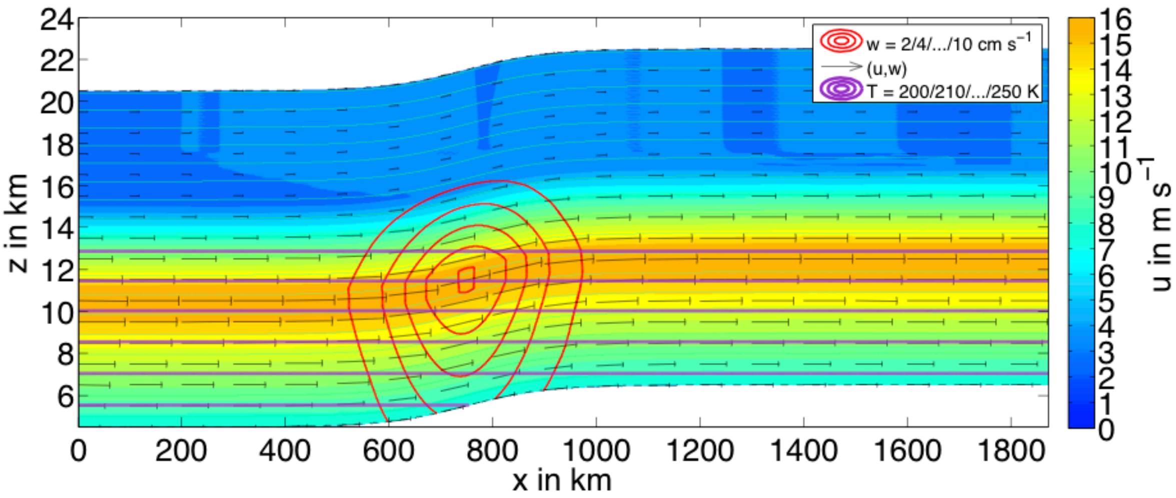

Figure 4: Configuration of the front, see text.

In Figure 4 the configuration of the front is shown. The ramp triggers homogeneous upward motions, which transport moist air masses and lead to adiabatic cooling and thus cloud formation. Although frontal cirrus clouds are a standard situation, our knowledge is quite limited. These simulations constitute the first systematic approach for simulating frontal cirrus clouds in an idealized framework in order to investigate the spatial and temporal features. We investigated different scenarios in terms of environmental thermodynamic conditions (temperature and humidity) as well as different ways of ice nucleation (pure homogeneous nucleation vs. competing heterogeneous and homogeneous ice nucleation).

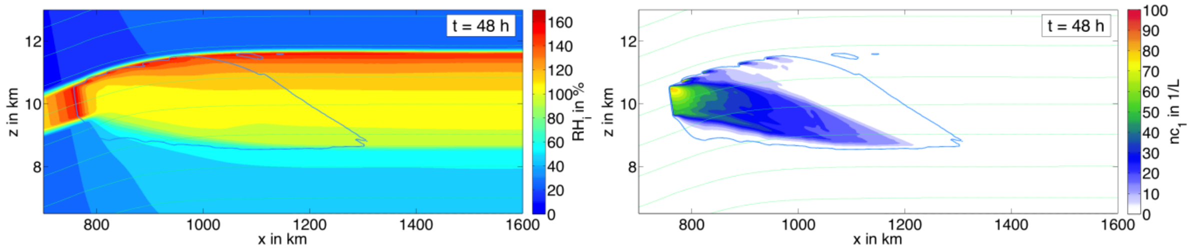

Figure 5: See text.

In Figure 5 a typical situation of a cirrus cloud is shown. The cloud is formed during the upward motion; horizontal advection as well as sedimenting ice crystals lead to a thick and horizontally extended ice cloud.
We are currently preparing a manuscript for publishing these new results in Atmospheric Chemistry and Physics.

1.7. Case study of the AIRTOSS campaign

For a recent aircraft campaign (AIRTOSS-ICE) dedicated to measuring ice clouds over middle Europe, we use ECMWF operational analysis data in order to investigate the aircraft measurements in a more comprehensive way. Actually, we were lucky to measure an ice nucleation event during one flight. We use a Lagrangian analysis tool for calculating trajectories on the basis of ECMWF wind fields in order to determine the airflow, which finally lead to ice formation over the North Sea.

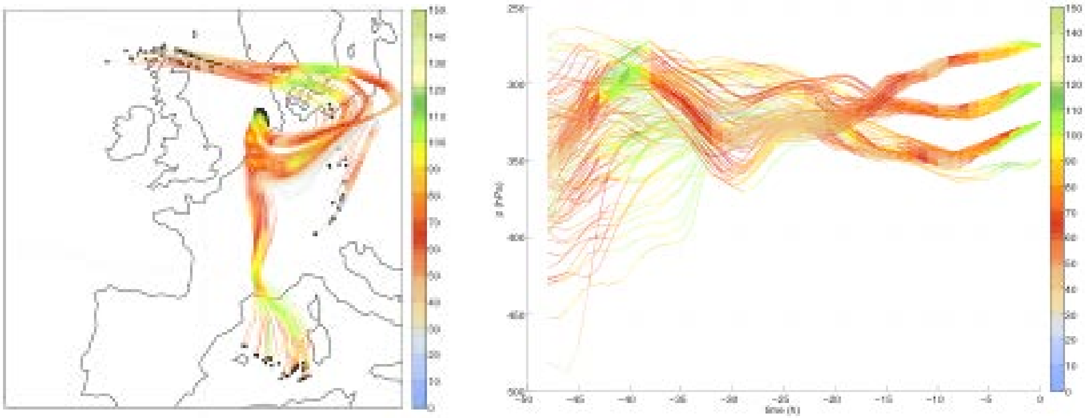

Figure 6: See text.

In figure 6 the trajectories are shown; the colours indicate relative humidity over ice. From trajectory analysis we were able to determine the situation as a close air stream with a very slow upward motion leading to ice formation after some hours. We additionally used the ECMWF data as boundary conditions for large eddy simulations of cirrus clouds. These simulations agree quite well with in situ measurements from the aircraft. Actually, due to the slow upward motion, the formation mechanism cannot be determined; however, all possible nucleation pathways would end up with the same results (qualitatively and quantitatively). Thus, this study is an important result for the ongoing discussion of dominance of nucleation pathways.
We currently prepare a manuscript for publishing these results as soon as possible.

2. 1. Climatology of aerodynamic contrails

ECMWF reanalysis data have been used to set up a climatology of aerodynamic contrails. Aerodynamic contrails complement the normal exhaust contrails in a sense, because they form preferentially at lower altitudes in warmer air. The study showed that currently aerodynamic contrails have a smaller climate impact than exhaust contrails. The study resulted in the following set of conclusions:

- Visible aerodynamic contrails are possible in a thick layer extending from 540 to 250 hPa. These pressure levels are determined by two temperature thresholds. Below 230K aerodynamic contrails generally stay invisible because there is insufficient water vapour to condense on the ice crystals. The high temperature threshold is determined by the requirement that the airflow over the wing must cool down to at least the supercooling limit of pure water droplets, 235 K, such that droplets freeze. This depends on the ambient pressure and the pressure change over the wing, and because of the latter it depends on aircraft type and its current weight.
- Too low ambient relative humidity is almost no constraint for the possibility to form aerodynamic contrails because the saturation water vapour pressure over the wings is almost always lowered sufficiently that water saturation occurs in the airflow.
- The altitude range where aerodynamic contrails can form declines from the tropics to the poles. In the tropics it is highest (250 hPa, typical for intercontinental and continental flights), in the extratropics and polar latitudes it is lower (350 and 450 hPa, continental and regional flights).
- The formation probabilities reach quite high values locally, but regions of high formation probabilities differ from regions with strong air traffic.
- Latitude bands where aerodynamic contrails can form shift in the course of the seasons because of the shift of the threshold isotherms.
- Persistent aerodynamic contrails are rare. Generally they occur with less than 10% probability, but more typically this probability is of the order 1 %. These values could indeed be even lower because aerodynamic contrails may well consist of metastable forms

of ice (e.g. cubic or amorphous ice due to their special formation conditions which are similar to hyper-quenching of cold micron sized droplets in the laboratory).

- Coexistence of aerodynamic contrails with exhaust contrails is possible but very improbable.

The most important question is whether aerodynamic contrails have an adverse effect on climate. From the results in this study we deem that a climate effect of aerodynamic contrails is currently considerably smaller than the climate effect of exhaust contrails, but it adds to it. This conclusion issues from the following argument: the contrail climate effect originates most from contrails at about 10 km altitude, about 250 hPa. Contrails at lower altitudes contribute much less. At 250 hPa there are currently many more exhaust contrails than aerodynamic contrails, thus exhaust contrails must have the lion's share in contrail climate impact. This may change in the future when more air traffic will occur in tropical latitudes.

List of publications/reports from the project with complete references

Bense, V., 2013: Simulationen zur Entstehung und Entwicklung von Zirruswolken an einer idealisierten Warmfront. Diploma thesis, Johannes Gutenberg University Mainz, Germany

Dietz, Sebastian, 2012: Untersuchung charakteristischer Lebenszyklen von eisübersättigten Regionen in der oberen Troposphäre, Master Thesis, University Innsbruck, Austria.

Gierens, K., S. Brinkop, 2012: Dynamical characteristics of ice supersaturated regions. Atmos. Chem. Phys., 12, 11933-11942. (http://www.atmos-chem-phys.net/12/11933/2012/acp-12-11933-2012.pdf)

Gierens, K., F. Dilger, 2013: A climatology of formation conditions for aerodynamic contrails. Atmos. Chem. Phys., 13, 10847–10857. (http://www.atmos-chem-phys.net/13/10847/2013/acp-13-10847-2013.pdf)

Gierens, K., K. Eleftheratos, L. Shi, 2014: Technical Note: 30 years of HIRS data of upper tropospheric humidity. Atmos. Chem. Phys., 14, 7533-7541. (http://www.atmos-chem-phys.net/14/7533/2014/acp-14-7533-2014.pdf)

Neis, P., 2013: Charakterisierung von Warmfrontcirren durch Messungen. Diploma thesis, Johannes Gutenberg University Mainz, Germany

Spichtinger, P., 2014: Shallow cirrus convection -- a source for ice supersaturation. Tellus A, 66, 19937, http://dx.doi.org/10.3402/tellusa.v66.19937 .

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 want to submit a proposal for a new special project about ice supersaturation and cirrus clouds in the tropopause region soon. This will serve as a kind of continuation of the finished special project.