SPECIAL PROJECT FINAL REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2019
Project Title:	Ice-supersaturation and cirrus clouds and their feedbacks to tropopause dynamics
Computer Project Account:	SPDESPIC
Principal Investigator(s):	Prof. Dr. Peter Spichtinger (JGU Mainz) Dr. Klaus Gierens (DLR Oberpfaffenhofen)
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Name of ECMWF scientist(s) collaborating to the project (if applicable)	…………………………………………………………………… ……………………………………………………………………
Start date of the project:	February 2016
Expected end date:	December 2018

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)				
Data storage capacity	(Gbytes)				

Summary of project objectives

(10 lines max)

We investigate ice supersaturation and cirrus clouds in the upper troposphere and their interaction with tropopause dynamics and radiation. We want to address the following research questions:

- What are the dominant formation mechanisms for ice crystals in the tropopause region under certain environmental conditions?
- What is the radiative impact of cirrus clouds in the tropopause region in terms of net contribution and vertical profiles of heating rates?
- How often does shallow cirrus convection occur and how does it determine exchange processes at the tropopause?
- How are enhanced water vapour and tropopause inversion layer correlated? What is the role of cirrus clouds for the tropopause inversion layer?
- What are the atmospheric conditions that give rise to contrails with particularly strong warming impact?

Summary of problems encountered (if any)

(20 lines max)

N/A

Summary of results of the previous years

1. Lifetimes of contrails and ice-supersaturated regions and their relation

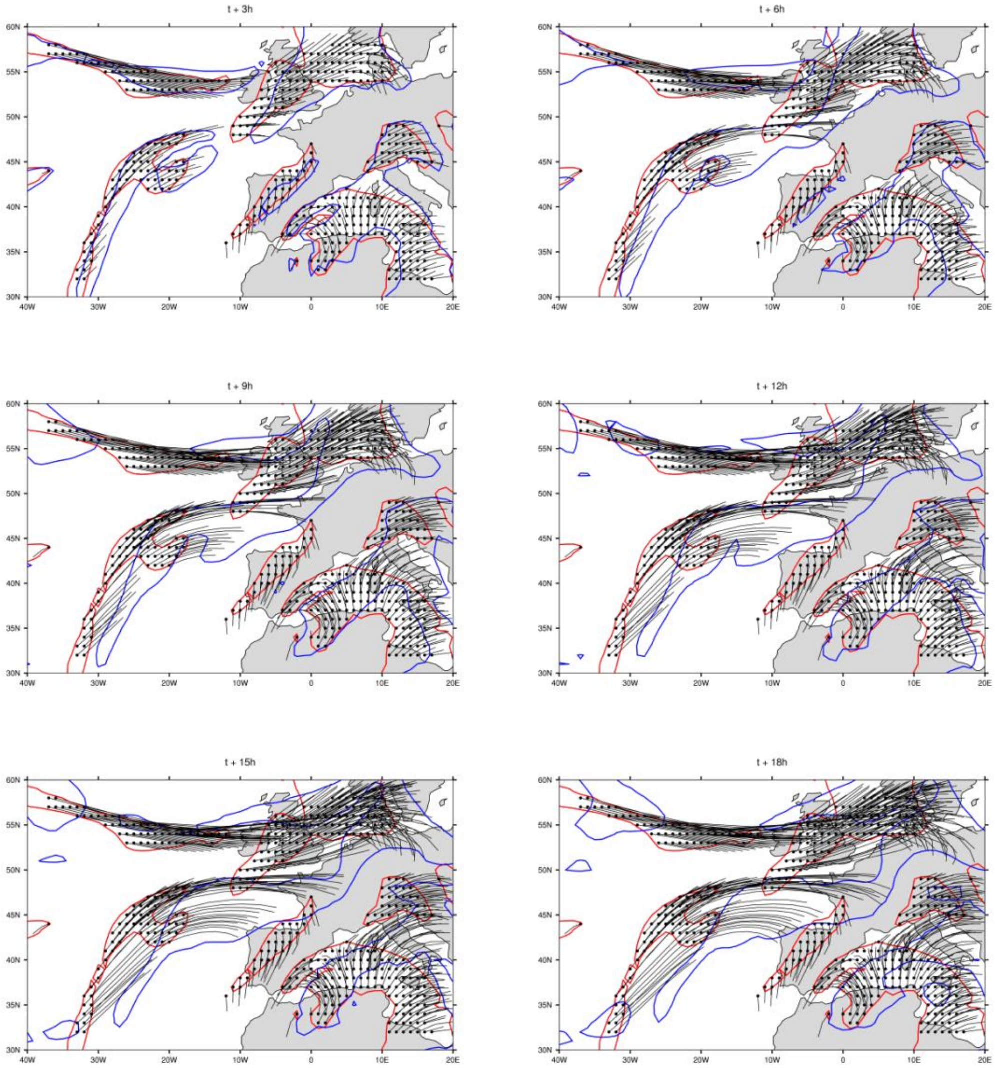
Individual contrails follow their trajectories through ice-supersaturated regions and terminate on average after a couple of hours, but the ISSRs themselves are often synoptic phenomena which can host contrails and contrail clusters for more than a day. There is no contradiction between the studies with global models which report quite long lifetimes of contrail clusters and studies on individual contrails and trajectories which find contrail lifetimes of a few hours on average. We must distinguish between individual contrails and large ensembles (clusters) of contrails. While the single contrail vanishes, the cluster it belonged to may remain for quite a long while.

As an illustration of this we show the following set of figures (next page) obtained from weather forecast data of the ECMWF Interim Reanalysis.

The figure shows a situation on 25 April 2006, on the 250 hPa pressure level. The red contour (representing RHi=95%) marks the outer rim of ISSRs at t=3 h. Horizontal trajectories are started within the ISSRs, the starting points are marked as black dots. After 3 (6, 9,..., 21) h the ISSRs are shifted, new ones have appeared and old ones have vanished. The new positions of the ISSRs are marked as blue contours. The trajectories proceed as long as they remain in supersaturated air masses. One can see that some trajectories follow essentially the outline and shift of the initial ISSR; they get quite long. Others immediately leave their ISSRs and remain short. By registering the times when trajectories end it is possible to estimate how long air remains ice supersaturated on this day in the region under study.

It turns out that trajectory lifetimes within ISSRs in this special situation follow an exponential distribution (this is a Weibull distribution with exponent k=1, in other cases we get Weibull distributions with k<1). The decay rate is λ=0.12 h-1, giving a mean duration within ISSRs of 8.3 h. Large ISSRs last much longer than the trajectories are within them. The ISSR that can be seen in the southwestern part of the domain, extending in northerly and northeasterly direction, can be followed for at least two days in the ECMWF data.

While the ISSRs move eastwards a distance of about 10° in 21 h (estimate from the distance between the blue and the red contours in the last panel of the figure), the displayed trajectories move on average with an eastward velocity of 0.93°±0.69° h^{-1}, which makes an average W-E distance of 19.5° within 21 h, that is, about twice the distance the ISSRs move in the same period.



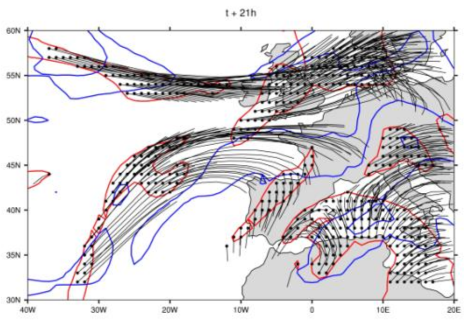


Figure 4-1: Evolution of ISSRs and trajectories representing potential contrails formed within ISSRs at the 250 hPa pressure level on 25 April 2006. Horizontal trajectories (black lines), start at t=3 h (black dots) within ISSRs (red contours; RHi>95%). They exist until the air is subsaturated. . The blue contours mark ISSRs at later times (6, 9, ..., 21, 24h). Trajectories end when they leave the ISSR or the domain of the investigation.

2. Conditions for contrails with high positive radiative forcing

Contrails affect climate if they are persistent, that is, if they are located in an ice-supersaturated region (ISSR). They do this by reflecting sunlight back to space (cooling) and by blocking thermal radiation from the Earth surface and lower atmosphere (warming). Radiative forcing (RF) is a measure for the immediate radiative impact of a contrail. A negative value means that the short-wave cooling effect

dominates while a positive value signifies a net warming. During night, there is always net warming since sunlight and thus its possible reflection is absent. In most (daytime) cases there is substantial cancellation of the warming and cooling effects, but occasionally (in particular during night) the long-wave warming effect dominates such that the respective contrail has a particularly strong contribution to climate warming. This is a Big Hit, and such contrails should be avoided already in the flight planning phase. Such an avoidance strategy needs of course a reliable prediction of the conditions under which contrails actually are that strong climate warmers.
The topic of this study is how situations with strong warming contrails can be characterised and whether and how reliably it is possible to predict them. For this we use forecast data from the ERA-Interim Reanalysis valid at 1-30 April 2006, 3-24 h in 3 h steps and all initialised at midnight each day. The analysis is confined to pressure levels 200, 250, and 300 hPa. The study region is 40°W to 20°E and 30 to 60°N. The data are used in $1° \times 1°$ spatial resolution.
First, temperature and relative humidity are used to check whether contrails are possible, applying the Schmidt-Appleman criterion. If contrails are indeed possible it is further checked whether there is ice supersaturation. As ISSRs (ice supersaturated regions) appear implausibly patchy if the real condition for ISS, namely RHi > 100% is used, we apply a correction of 5% and define ISSRs as regions with RHi > 95%. All computations of water vapour available for condensation take this 95% as base value.
The calculation of shortwave and longwave radiative forcing is done using the parameterisation given by Schumann et al. (2012), which uses radiation quantities and albedo from the forecasts.
This initial one month study shows what in principle has to be done to reach the aforementioned goal, but it suffers from insufficient statistics and autocorrelation. The remedy of these two problems is to employ a larger data set. But one robust result can be derived already from the preliminary analysis, namely that most Big Hits occur during night, which is advantageous because air traffic is not so dense and rerouting is easier than during day.

3. Quality of ERA water vapour data

We used in situ water vapour measurements as obtained from the MOZAIC/IAGOS project. The MOZAIC data provide a good temporal and spatial coverage over some parts in the Northern hemisphere, especially over the North Atlantic region (http://www.iagos.org/).

In a first step we compared the water vapour measurements with the ERA water vapour fields. In order to have a reliable inter comparison we collect MOZAIC data in the respective ERA grid boxes. We compared relative humidity with respect to ice (RHi) as well as absolute humidity (water vapour mixing rations) and temperature measurements. In these investigations we found that in ERA ice supersaturation is underestimated; however, the qualitative structures are represented quite well, if we consider large scale features. These results are submitted for publication to Atmospheric Chemistry and Physics Discussions (Reutter et al.).

4. Case studies on ice clouds and ice supersaturation over Northern Germany

During two aircraft campaigns in spring and autumn 2013 several situations of ice supersaturated regions (ISSRs) and cirrus clouds were investigated. For a better understanding of the processes of formation and evolution of ISSRs and cirrus clouds we use trajectory calculations and large eddy simulations.

For each case in the measurement campaign (ca. 8 relevant measurement flights) ECMWF analysis and 3 hourly forecasts were used as input for the trajectory tool LAGRANTO. The trajectories were started along the flight track of the aircraft and calculated backwards time in order to investigate the dynamical situation and especially vertical motions in the upper troposphere. Along these trajectories boxmodel calculations were carried out in order to investigate the onset of nucleation and the formation and evolution of the ice clouds. In addition the estimated mean vertical updrafts together with temperature and humidity data from ECMWF operational analyses were used to run the large eddy simulation model EULAG together with a detailed ice microphysics.

In a joint evaluation of ECMWF analysis data, trajectory calculations , satellite measurements and model calculations we could determine different interesting cases, which are currently further investigated and prepared for publications:

(a) in situ nucleation of ice clouds
A rare case of ice nucleation during the measurement could be found, the analysis of the ECMWF data indicated that the nucleation was triggered by slow upward motions. The investigations using model calculations showed that different nucleation pathways (heterogeneous or homogeneous nucleation) might have led to this event; however, a clear distinction is not possible.

(b) shallow cirrus convection
The ECMWF data indicate that during one flight the environmental situation was potentially unstable close to the tropopause; thus, the measured cirrus clouds might be formed via shallow cirrus convection, as suggested in former but more idealised investigations (Spichtinger, 2014).

(c) gravity wave induced cirrus clouds
A case of wave driven ice clouds could be determined from the analysis of ECMWF data; the air flow over mountains of Scotland leads to formation of ice clouds, which were later measured over Northern Germany in the downstream of the air flow.

5. Investigations of warm conveyor belts as seen from ECWMF data
In a first investigation, different cases of warm conveyor belts with strong outflow in the tropopause region, leading to cirrus clouds were identified using ECMWF data. These cases are currently evaluated in order to identify possible different ice cloud structures, i.e. formation pathways as "liquid origin" or "in situ formation" (see Wernli et al, 2016). The ECMWF data are used as initial/boundary conditions for ICON simulations, which will be used to clarify the different possible formation pathways.

6. Tropopause dynamics, water vapour and ice clouds

We used few days in May 2015 from ECMWF operational analyses for investigating the relation between the so-called tropopause inversion layer (TIL) and water vapour in the tropopause region. First investigations show that the TIL is very strong at occurrence of high relative humidities in the tropopause region and, in contrast, is quite weak at dry conditions. This points to the fact that cloud formation and/or radiation processes might have an impact on the development of the TIL. . We are currently using data from longer time intervals and for other situations in order to clarify the correlation between TIL and water vapour and ice clouds. This work will be continued beyond the end of the ending special project.

List of publications/reports from the project with complete references

P. Reutter, P. Neis, S. Rohs, and B. Sauvage, 2019: Comparison of IAGOS in-situ water vapour measurements and ECMWF ERA-Interim Reanalysis data. Submitted to Atmos. Chem. Phys.