Project: **832**
Project title: **Cloud-resolving modeling of contrails and cirrus**
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We employ the LES model EULAG-LCM for simulations of naturally forming cirrus and for aircraft induced cirrus, so-called contrail-cirrus. The microphysical module LCM uses Lagrangian particles to transport the ice crystals and calculate the microphysical processes along their paths (Sölch & Kärcher, 2010). The simulations can be grouped into two categories: Simulations of young contrails (age < 5min) and simulations of contrail-cirrus and natural cirrus.

The BMBF-project "FORMIC" project deals with the potential climate benefits of formation flight. During a formation flight, several aircraft fly in a pattern similar to that of migrating birds. Fuel usage and CO2-emissions are reduced compared to isolated flights due to aerodynamic benefits of this special flight pattern. Besides this fuel effect, the climate impact of contrails may be strongly altered, as several contrails start to overlap and interact already at a very early stage of their lifetime. This saturation effect is expected to reduce the contrail radiative forcing (RF), i.e the RF of one contrail cluster formed by ten aircraft flying in a formation is smaller than that of ten isolated contrails.

Young contrails

Many simulations of young contrails and their interaction with the aircraft-induced wake vortices have been performed within this DKRZ project in the former years. See publications of Unterstrasser et al (2014), Unterstrasser (2014) and Unterstrasser & Görsch (2014). A last publication summarized all simulation results in a way that the most important findings can be incorporated in a GCM in order replace the rather crude contrail initialisations used so far therein (Unterstrasser, 2016). This will allow for more robust climate-related estimates, e.g. how biofuels alter the contrail radiative forcing. All of the above simulations treated the evolution of single isolated contrails.

A first step towards assessing the contrail RF of the formation flight scenario is the high resolution simulation of two contrails that have been generated in close proximity (see Figure 1).

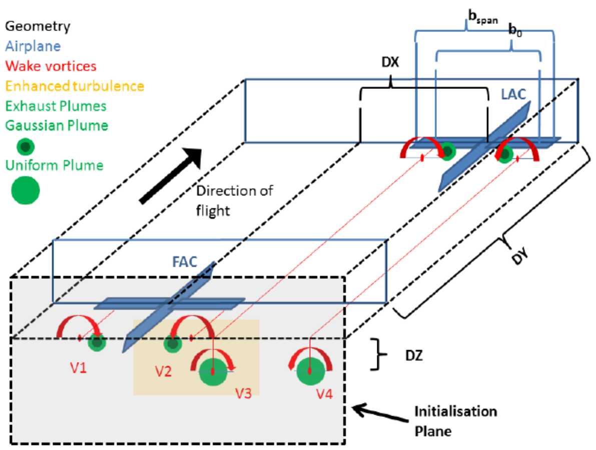

Figure 1: Sketch of the formation flight setup with two aircraft leading to a four vortex system and four exhaust plumes.

Whereas in the classical setup with one aircraft the pair of counter-rotating wake vortices descends for a few hundreds of meter and leads to a strong vertical expansion of the contrail, the evolution of the four-vortex system in our new setup is much more intricate. The strongest dynamical interactions occur between the two inner vortices V2 and V3 (see labels in Fig. 1) and were found to depend sensitively on the relative positions of V2 and V3 which are controlled by the lateral offset DX and the vertical offset DZ of the two aircraft. Figure 2 illustrates the vortex positions over the first two minutes (shown is the vorticity distribution averaged along flight direction) for various DX-DZ-combinations. In all panels, we see that the two vortices V1 and V2 move downward in a rather regular fashion. The evolution of the V3-V4 pair, however, changes from panel to panel. The left panel shows a case where the two vortices spiral upwards in counter clockwise sense, whereas in the middle and right panel the two vortices have a pronounced lateral component to the right. Upward and laterally moving vortex pairs are a unique phenomenon of formation flight scenarios and do not occur behind single aircraft. Figure 3 shows the effect of this unprecedented vortex behaviour on the vertical distribution of ice crystals after three minutes for various lateral aircraft separations DX (left), relative humidity values (middle) and vertical offsets DZ (right). The middle panel shows additionally the vertical profiles of regular single contrails. Obviously, those regular contrails descend much further down,

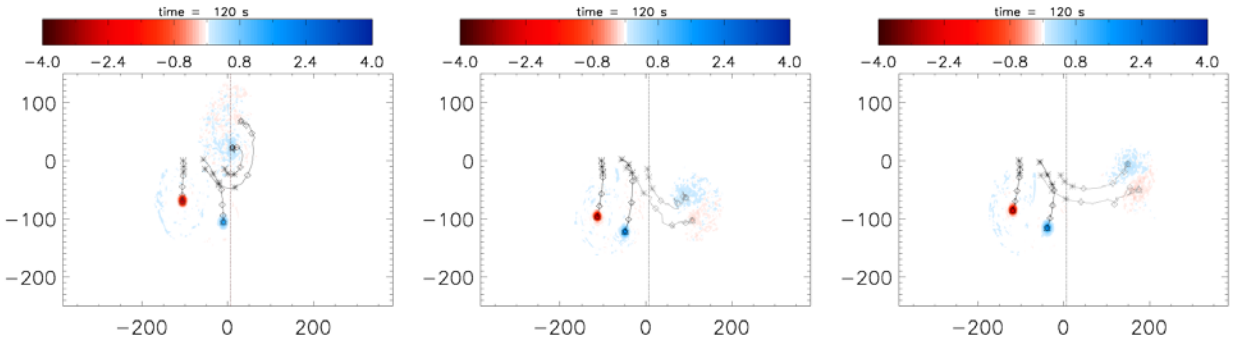

Figure 2: vorticity distribution in a plane perpendicular to the flight direction (averaged along this direction) after 2 minutes. The black lines show the position of the vortex centres over the first two minutes. The x-axis (units of meter) runs along the transverse direction and the y-axis along the vertical direction. The three panels show simulations with different combinations of DX and DZ.

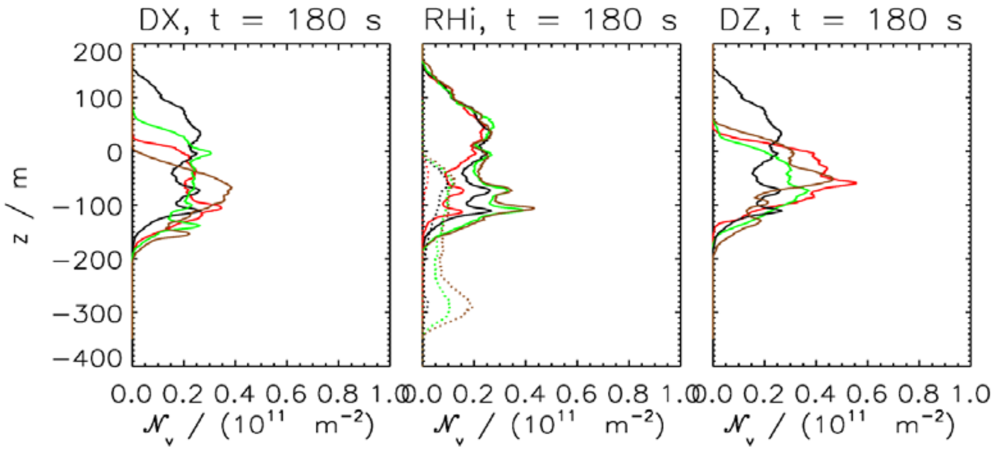

Figure 3: vertical profile of ice crystal number after 3 minutes for various values of DX (left) relative humidity (middle) and DZ (right). In the middle panel, results for regular single contrails are added for comparison.

whereas for “formation” contrails a large fraction of the ice crystal is located above flight level (z=0m).

To my knowledge, those simulations are the first ones that simulate the so called far field evolution of the wake vortices of formation flight scenarios. As such, the results are unprecedented and a publication focusing on those aspects and the implications on young contrail properties is prepared right now.

Due to the added complexity of the new simulations it required some testing to find a suitable simulation setup (choice of domain size and decomposition, mesh size and simulation period etc.). In the end, each production run needed around 200 Nh. However, the most expensive sensitivity runs with larger domains needed more than 1000 Nh. In total, 13000Nh have been consumed for those simulations.

Contrail-cirrus simulations

Generally, we use the output of vortex phase simulations (contrails after 5 minutes) to initialise contrail-cirrus simulations which cover the remaining life cycle of a contrail. It is pending to carry out a representative set of such simulations for formation flight scenarios. So far only a few simulation of this type have been performed in order to obtain a better estimate of the required computer resources. The simulations need about 100Nh.

The production of those contrail-cirrus simulations is foreseen for the remainder of this year and for 2018.

Summary

For the moment, expensive simulations of young contrails produced by aircraft flying in formation have been completed (more or less) and the results are right now summarised in a manuscript. During the manuscript preparation and the review process additional simulations may be required.

Contrail-cirrus simulations of the formation flight scenario will follow this year and in 2018.

Moreover, former simulations of contrail-cirrus contributed to an updated assessment of aviation climate impact and its mitigation (Grewe et al, 2017) and a study on an efficient algorithmic treatment of aggregation in particle-based microphysics approaches such as EULAG-LCM appeared.

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