Contrail-Cirrus – Man-made Experiments on Complex Cloud Physics

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TOPICS:
• Cirrus
• Contrails
• Past: Brewer-Dobson, TIL, Ice Supersaturation, Nucleation
• Present: Contrail Prediction, Validation, Climate Impact
• Future: Mitigation
Cirrus clouds are thin ice clouds covering about 40% of the Earth.

They affect climate by contributions to the Earth albedo and the natural Earth Greenhouse effect, with a net global warming effect.

The physical and chemical effects of ice clouds are complex.
Cirrus Optical properties (optical depth and altitude) derived from Caliop and Seviri (“COCS”)

(Kox et al., AMT, 2014)
Contrails

Contrails are a specific type of cirrus clouds induced in cool and humid air masses by aircraft.

Contrail cirrus contribute the largest and most uncertain part to the climate forcing from aviation.

Contrail formation is predictable and controllable to some extent.

Contrail cirrus formation can be interpreted as a man-made experiment in the atmosphere.
Contrail formation, requires liquid saturation -> water vapor condenses on soot-CCN and then freezes

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(Schumann, 1996, 2000)
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A340, A380 observed during CONCERT (Voigt et al., 2010)

(Schumann, 1996, 2000)
Since the first observations of contrails in 1915, the investigation of contrail formation led to important general insight into the atmosphere system, such as the detection of ice supersaturation, homogeneous and heterogeneous ice particle formation, and the Brewer-Dobson circulation.
Brewer (1946, Bakerian Lecture): *frost-point profiles were measured to explain short contrails above tropopause → the stratosphere was found to be very dry.*
Discovering the Stratospheric Circulation

Brewer (1949): “... dryness is maintained by a slow circulation of the air in which air rises at the equator moves poleward in the stratosphere and then descends into the troposphere in temperate and polar regions ...”

Fig. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.
Discovering the Stratospheric Circulation

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Tropopause Inversion Layer (TIL), detected in 2002

\[ N^2 = \frac{g}{\Theta} \frac{\partial \Theta}{\partial z} \]

Subsidence

Tropopause (contrails/cirrus)

Moist convective mixing

Baroclinic mixing

Birner et al. (GRL, 2002; JGR, 2006)
Physics questions

Relative humidity over ice: Supersaturation
Ice particle formation: Homogeneous or heterogeneous
Particle growth and persistence: Ice supersaturation
Contrails/cloud spreading: Shear driven
What limits particle size/ lifetime: Sedimentation
Predictability
Climate impact
Relative humidity over ice: departure from thermodynamics

A-A: liquid saturation
B: homogeneous ice nucleation limit (Koop et al. (2000))

Measured with frostpoint instrument on DLR-Falcon
Ovarlez et al. (2002)
Ice supersaturation in Numerical Weather Prediction scheme of ECMWF: Comparison to MOZAIC humidity measurements

![Diagram showing frequency distribution of relative humidity over ice with new and old supersaturation schemes compared to MOZAIC data.](image)

Tompkins, Gierens, Rädel (2007)
ML-CIRRUS 1
Learn from model-observation comparisons

Voigt, Minikin, Schumann et al., ML-CIRRUS team
Contrails persist in ice supersaturated air masses
Contrail Prediction with the Contrail Cirrus Simulation and Prediction Model (CoCiP)

**Input:**
- Aircraft (BADA)
- Traffic (e.g., FAA 2006)
- Meteorology (e.g., ECMWF)

**Output:**
- Contrail, life cycle, cover, radiation
- Cirrus Simulation (insitu, Lidar, MSG, Modis)
- Sensitivity studies
- Prediction & Mitigation

Contrail Cirrus Prediction Tool
- From regional to global
- Comparable to observations

(Schumann, 2012)
Optical depth of contrails + cirrus from CoCiP/ECMWF during ML-CIRRUS

(K. Graf and U. Schumann)

Optical depth of thin cirrus derived from METEOSAT SEVIRI IR data using the COCS algorithm (Kox, 2014),

Data processed and plotted by L. Bugliaro, 2015
Correlation between forecast and observations

- Dust period: 29.3. - 7.4.
- Correlation: 70-90% outside dust period

Heterogeneous nucleation on dust not yet modelled in ECMWF IFS model

Schumann, Bugliaro et al.: ML-CIRRUS
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice water content for 10 April 2014

preliminary data, Schumann, Voigt, Jurkat, et al.: ML-CIRRUS
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice particle number concentration for 10 April 2014

preliminary data, Schumann, Voigt, Jurkat, Krämer et al.: ML-CIRRUS
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS. Here IWC for all ML-CIRRUS flights
Comparisons of observed and modelled contrail-cirrus properties along flight path during ML-CIRRUS.

Here: Ice particle concentration for all ML-CIRRUS flights

![Graph showing ice particle concentration vs. temperature]

strong contrail contributions

preliminary data, Krämer, Schumann, Voigt et al.: ML-CIRRUS
Global mean cirrus cover and cover of contrails ($\tau$>0.1)

Schumann, Penner, Chen, Zhou, Graf, (ACPĐ, 2015)
Pdf of contrail solar optical depth occurrence from MODIS-CALIPSO Observations and CoCiP-CAM Model

(Iwabuchi et al., 2012, JGR) (Schumann, Penner et al., ACPD, 2015)
Annual mean radiative forcing by contrails

Schumann, Penner, Chen, Zhou, Graf, (ACPД, 2015)
Local RF per unit contrail area: contrails may cool or warm

Schumann, Penner, Chen, Zhou, Graf, (ACPD, 2015)
Green Aviation: what can be done?

Route optimisation: avoid contrails

Maximum Altitude

Considered Flight Levels

Top of climbs

Contrail Region

Selected FLs according to fuel use optimum

Mannstein, Meilinger et al. (2010), referred to in Mannstein and Schumann (patent, 2015)
Better: avoid warming contrails but enforce cooling contrails

Mannstein, Meilinger et al. (2010), referred to in Mannstein and Schumann (patent, 2015)
Conclusions

Cirrus clouds are thin ice clouds affecting Earth’s albedo and greenhouse effect, and hence climate.
Contrails are reproducible prototypes of cirrus clouds.
Investigations of contrail formation led to important general insight into the atmosphere system.
Examples: Brewer-Dobson circulation, detection of ice supersaturation, homogeneous and heterogeneous ice particle formation.
Understanding requires model-observation comparisons.
Contrail Cirrus is predictable to some quantifiable degree.
Contrails cool or warm - this opens mitigation options.
Outlook

Improve prediction reliability (e.g. soot and dust aerosols)
Include other emissions (NOx, SO$_2$, etc.)
Include other traffic modes (ships, car traffic)
Support sustainable development by better science
Science does not exclude applications

(Foto from Falcon: ships in the Strait of Malacca - Courtesy Hans Schlager)