

Aircraft Induced Condensation with a chapter on Ship Tracks



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Klaus Gierens
Institut für Physik der Atmosphäre
DLR Oberpfaffenhofen

Contents

1. Aerodynamically induced condensation
2. Contrails (jet exhaust contrails)
3. Ship tracks

Aerodynamically induced condensation



Aerodynamically induced condensation (1)

Clouds around aircraft appear for mostly the same reason as in the atmosphere, namely as a result of adiabatic cooling. Bodies and wings in the flow always change the temperature and pressure of the fluid. If the fluid is moist air, the saturation vapour pressure and relative humidity change as well. In most fluid flows and nearly every aerodynamic flow friction can be neglected outside of the boundary layer. Heat transfer by conduction and radiation work on much longer timescales than the flow time scales, so that the flow is adiabatic.

In aerodynamics we cannot, as in usual thermodynamics, neglect the kinetic energy of the flow. **The sum of kinetic energy and enthalpy of the gas is called total enthalpy.** In the flow around bodies and wings total enthalpy is conserved, which means that enthalpy can be transferred to kinetic energy and vice versa. Hence, flow acceleration is accompanied by cooling and deceleration by heating of the gas.

Aerodynamically induced condensation (2)

A well known consequence of this is the **Bernoulli equation**.

The Bernoulli equation for compressible flows is:

$$T = T_0 - \frac{\gamma - 1}{2\gamma R_a} (u^2 - u_0^2)$$

with $\gamma = c_p / c_v$.

From the Cloud Processes lecture we know that in adiabatic flows:

$$T/T_0 = (p/p_0)^\kappa$$

Thus, regions of low pressure correspond to regions of low temperature and enhanced relative humidity, and vice versa.

Aerodynamically induced condensation (3)

Flow over an aircraft wing:

The weight W of a flying aircraft is balanced by the pressure difference Δp (pressure below the wing minus pressure above the wing). The pressure difference is acting on the wing area A . Hence equality of both forces gives:

$$\Delta p = W/A$$

If we take usual values from aircraft inventories etc. we find that a **typical value for Δp is 50 hPa.**

Correspondingly, **temperature differences near ground are about 5 K, and at cruise altitude about 15 K.**

Aerodynamically induced condensation (4) low level flight

The temperature change is of course accompanied with a change in saturation vapour pressure (Clausius-Clapeyron), i.e. with a change in relative humidity, or saturation ratio:

$$\frac{S}{S_0} = \frac{pe_w^*(T_0)}{p_0e_w^*(T)} = \left(\frac{T}{T_0}\right)^{1/\kappa} \frac{e_w^*(T_0)}{e_w^*(T)}$$

When there is cooling, $S/S_0 > 1$ because of the vapour pressure effect. The effect is moderate at warm temperatures, near the ground. Hence, at low level flights, condensation effects are usually only observed when the air is moist (e.g. after rain), or when high-g manoeuvres or other manoeuvres with strong acceleration of the air are conducted.

Here are some examples:

Condensation during high-g manoeuvres



Note that pressure drops both above and below the wing.

Condensation caused by airflow acceleration over the wings



close to the ground

Aerodynamically induced condensation (5)

Condensation within vortices

The airflow around sharp edges or corners tends to evolve into vortex tubes. The pressure must drop toward the centre of a vortex tube, so that the pressure gradient force can balance the centrifugal force of the vortex flow. Hence there must again be a temperature drop and a rise of relative humidity towards the vortex centre.

The corresponding condensation can often be observed originating from aircraft wing tips and flap corners near the ground under moist conditions.

In the Flying Fortress example it seems that the droplets formed soon freeze, because they survive a quite long time, so that they appear almost as ordinary contrails. Survival needs supersaturation, and in the absence of other water clouds one must conclude that the “contrails” are ice crystals in ice-supersaturated air, albeit at low altitude.





Condensation at the tips of wings, flaps and propellers



Aerodynamically induced condensation (6)

Prandtl-Glauert condensation

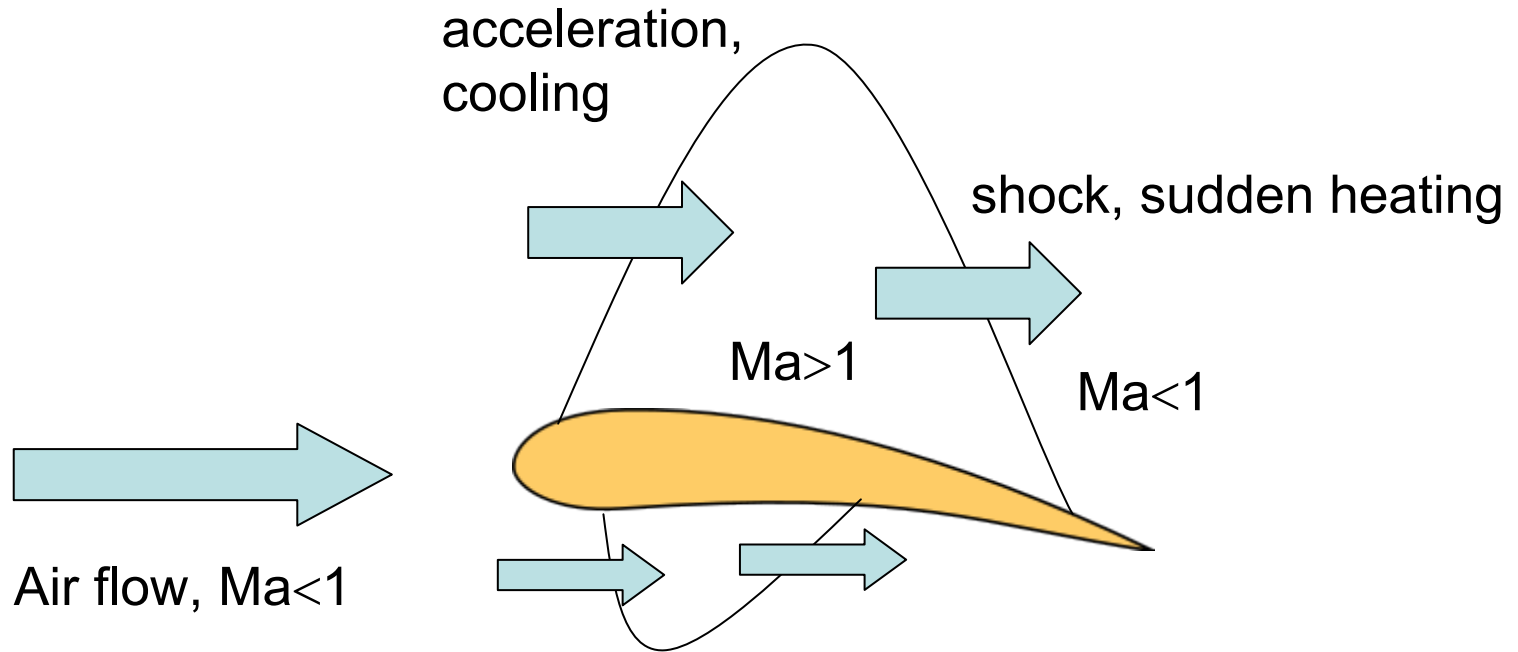
Pressure, temperature, and RH variations become very large at near-sonic speeds. In the so-called trans-sonic regime the flow over the wing becomes super-sonic while the aircraft still flies sub-sonic.

The so-called Prandtl-Glauert singularity requires that pressure and temperature perturbations approach $\pm\infty$ as the flight speed approaches the ambient sound speed. In terms of the temperature, the Prandtl-Glauert singularity takes the form:

$$T - T_0 \propto \frac{U^2}{2c_p \sqrt{1 - \text{Ma}^2}}$$

When the flow approaches $\text{Ma}=1$ the temperature perturbation approaches infinity (in practice: it gets very large).

Prandtl-Glauert condensation



While flow into the super-sonic regime proceeds smoothly, the flow out of it proceeds via a shock. The Prandtl-Glauert cloud has therefore a fluffy front and a sharp backside.

At fully trans-sonic conditions the conical shape of the cloud is lost.

Prandtl-Glauert condensation





Aerodynamically induced condensation (7) cruise level flight

The change in saturation ratio is as before:

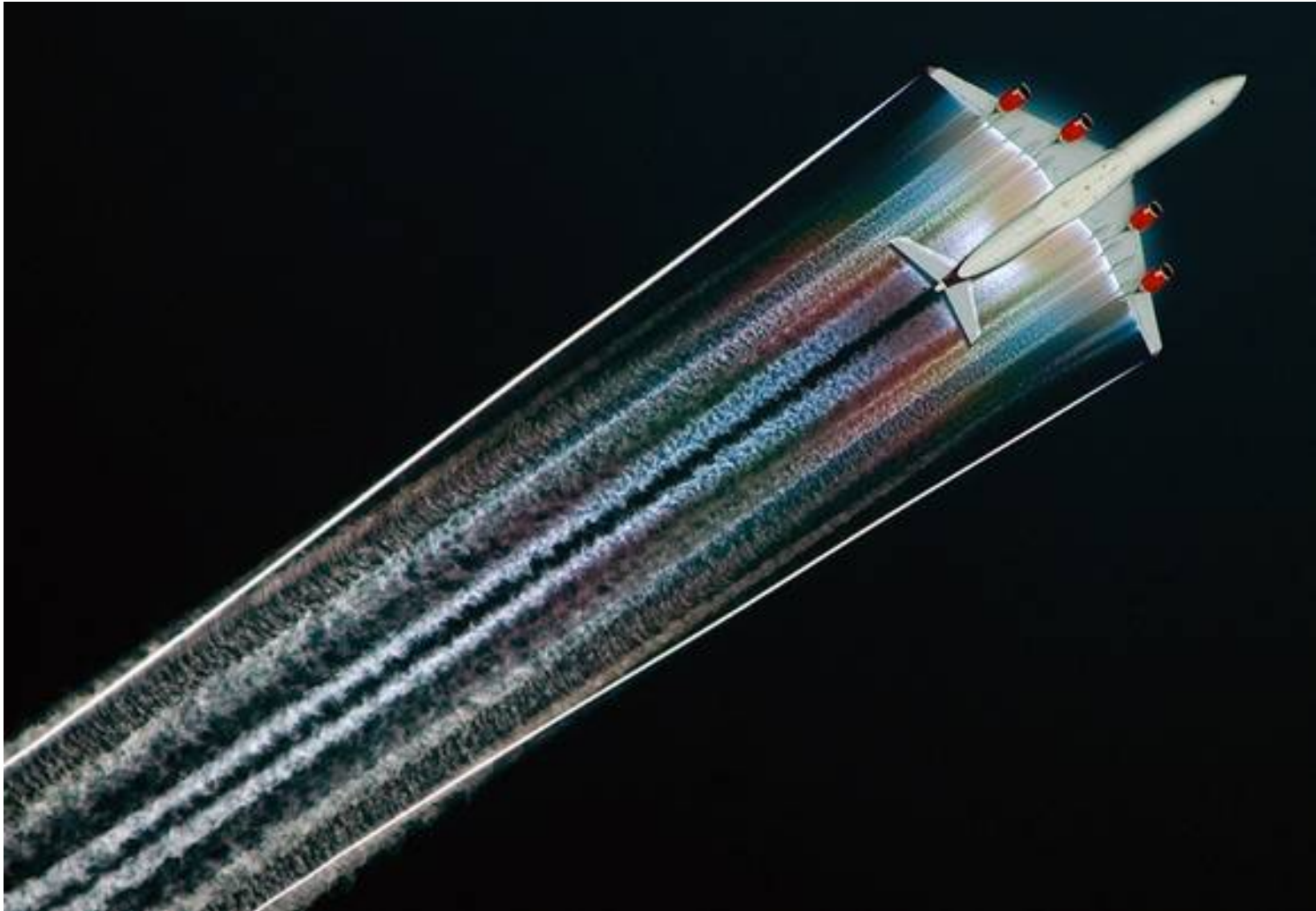
$$\frac{S}{S_0} = \frac{p e_i^*(T_0)}{p_0 e_i^*(T)} = \left(\frac{T}{T_0} \right)^{1/\kappa} \frac{e_i^*(T_0)}{e_i^*(T)}$$

Note the use of e_i^* instead of e_w^* .

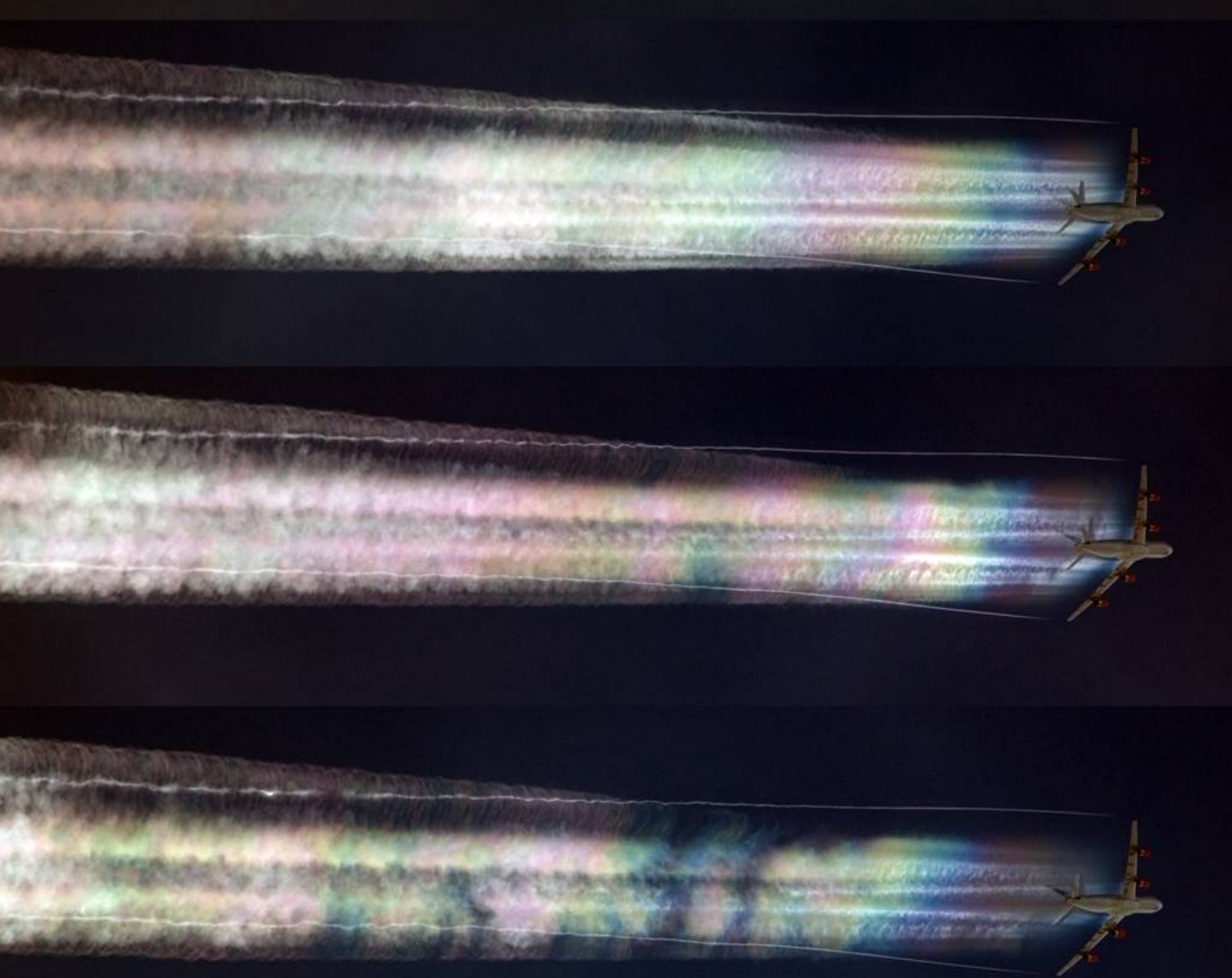
At high altitude, that is, in cold air and low ambient pressure, the effect on the saturation ratio is large. Even relatively dry air ($RHi \approx 20\%$) will achieve supersaturation upon flow over a wing. Thus, aerodynamic condensation should be an everyday phenomenon at cruise altitude, but it isn't.

When it happens, ice can form and the special optics of ice crystals may yield beautiful iridescence effects.

Here are some examples:



at cruise altitude (upper troposphere)



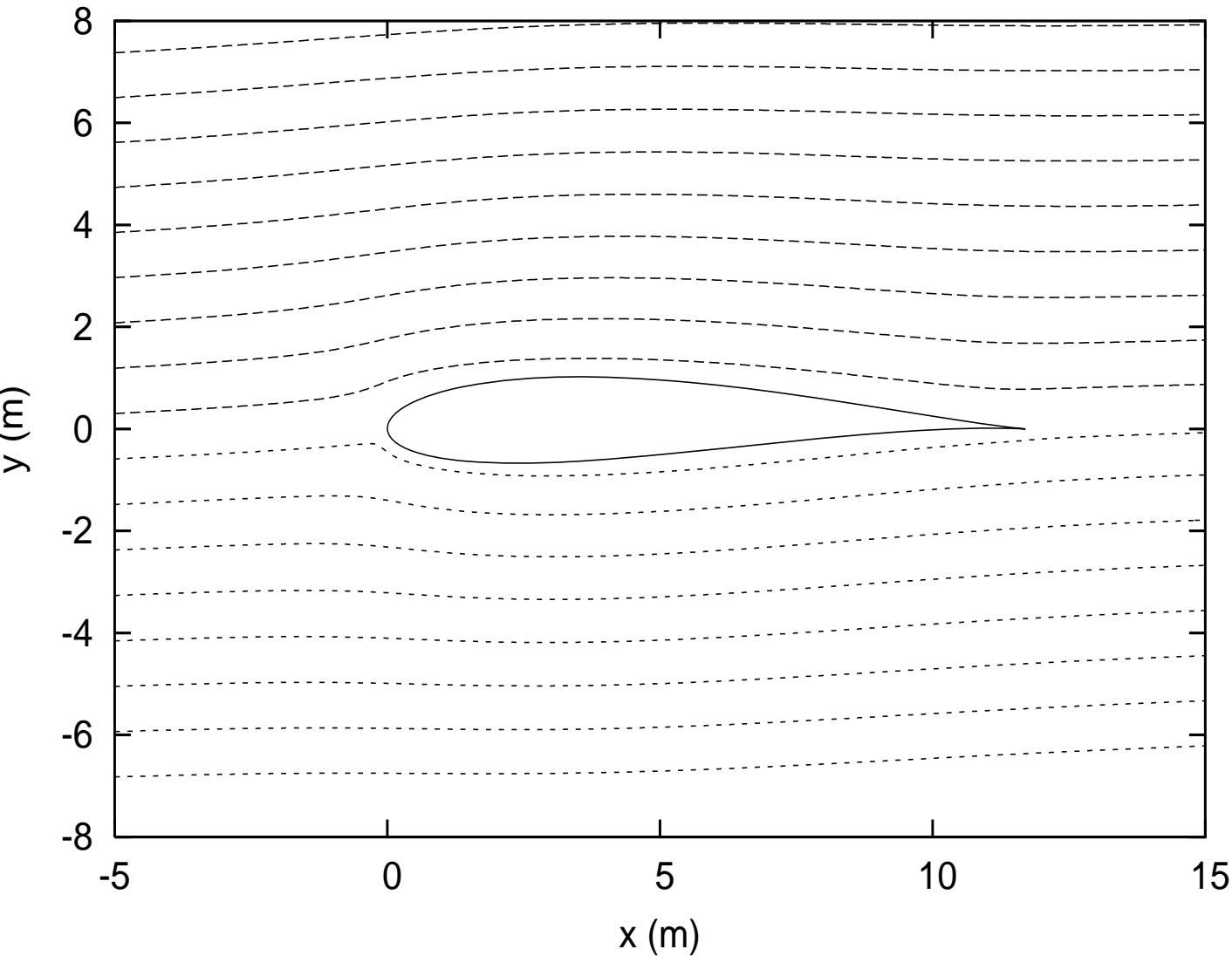
Photographs courtesy of Jeff Well (airliners.net)

Some contrails show iridescence, others don't. Note also, that contrails do not necessarily form over the whole wingspan. They form preferentially at the inner, deepest parts of the wings.



Aerodynamically induced condensation (8)

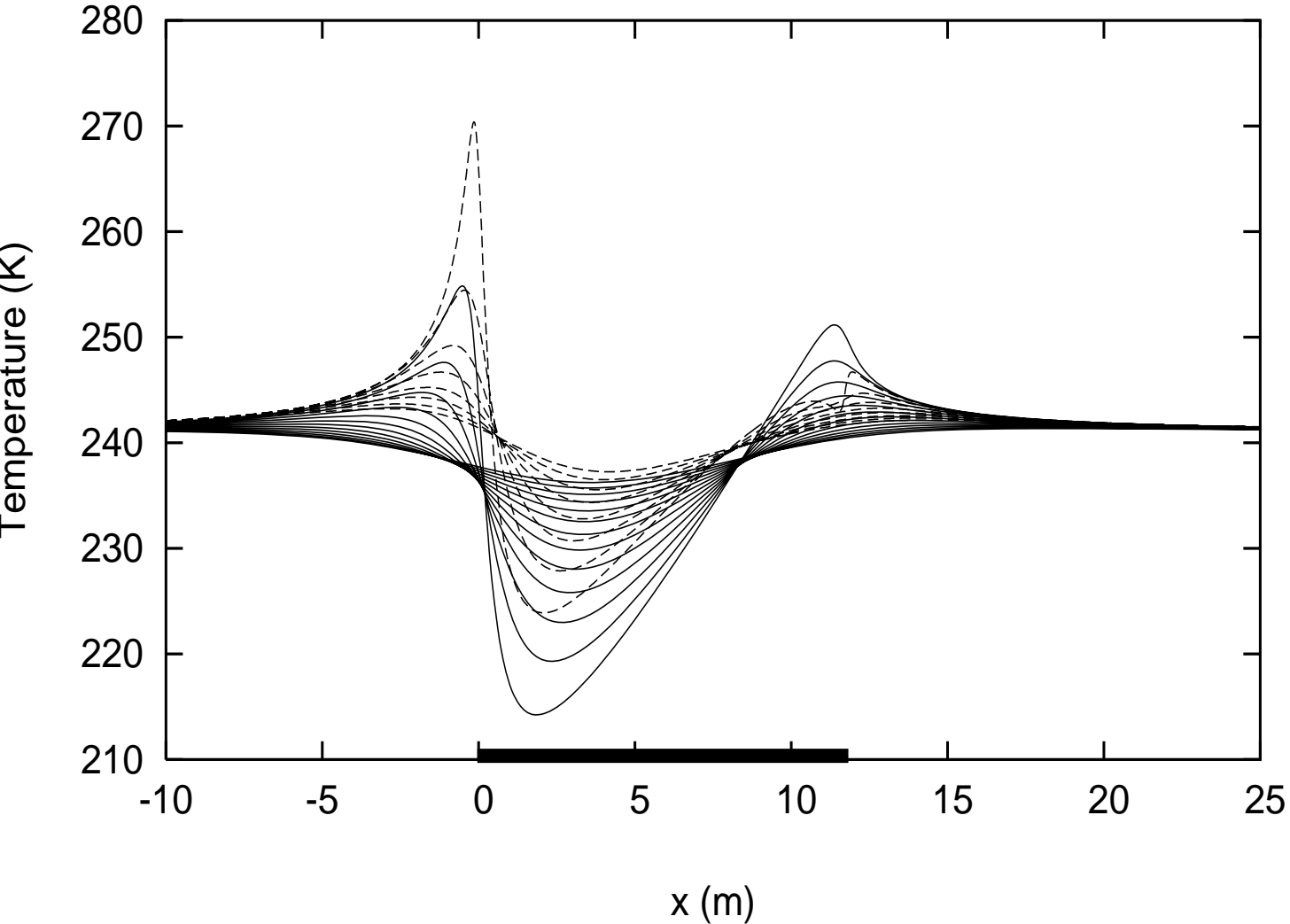
aerodynamic calculations of compressible flow



Compressible
airflow over a
wing profile,
 $T=241$ K,
 $p=300$ hPa,
 $Ma=0.8$,
effective attack
angle 1° .

Wide body
aircraft wing root
depth 11.7 m,
wing thickness
1.7 m

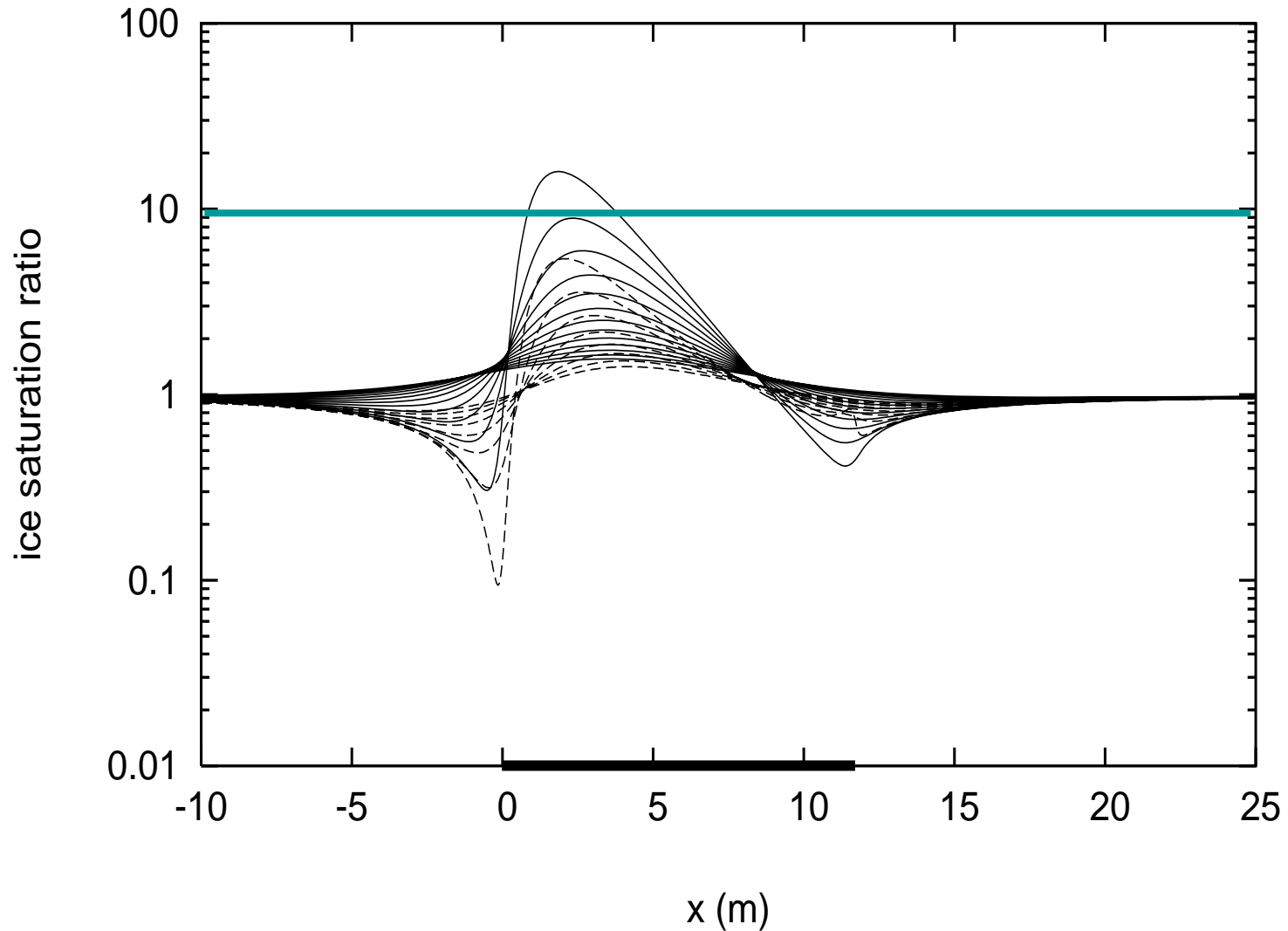
temperature effect



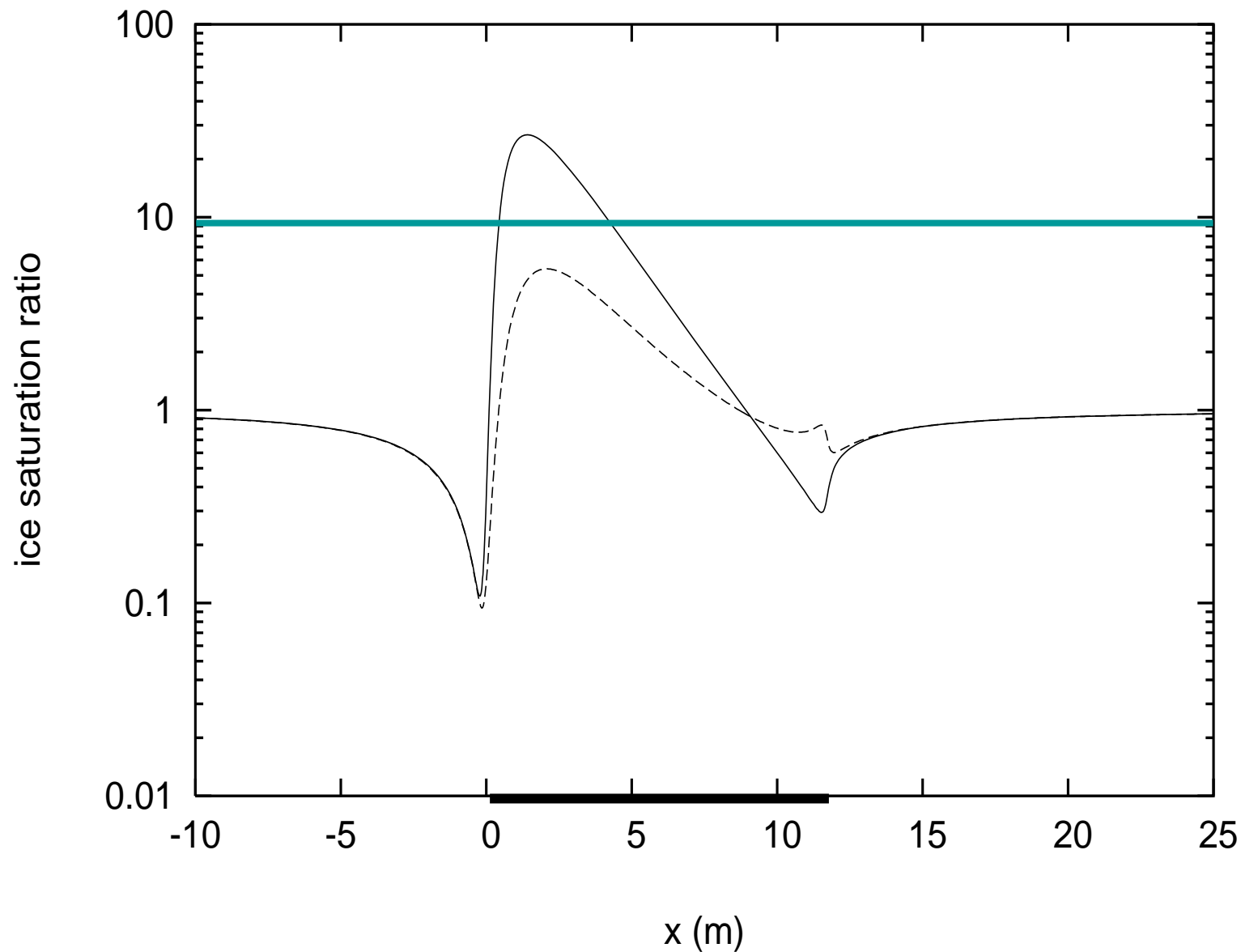
temperature changes exceed 20 K close to the wing surface

effect on saturation ratio

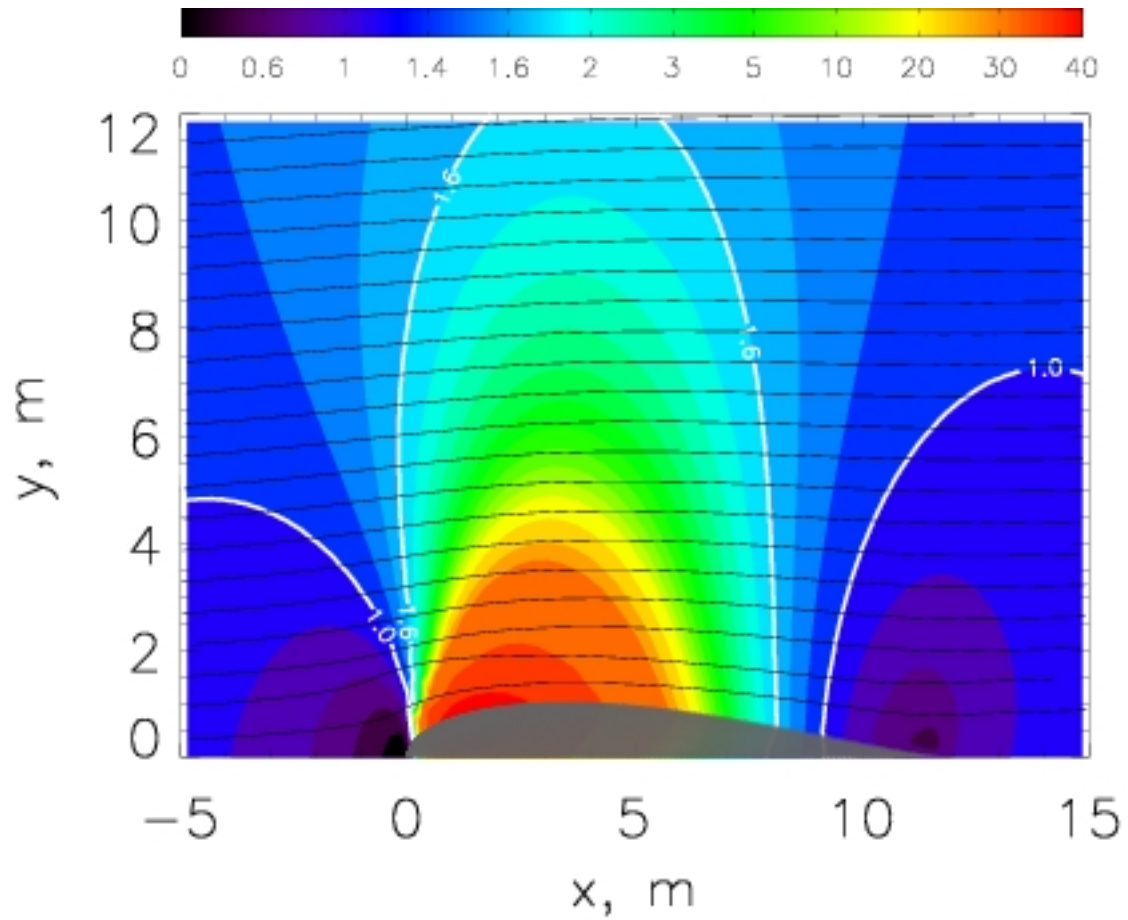
Maximum Saturation ratio exceeds 10.



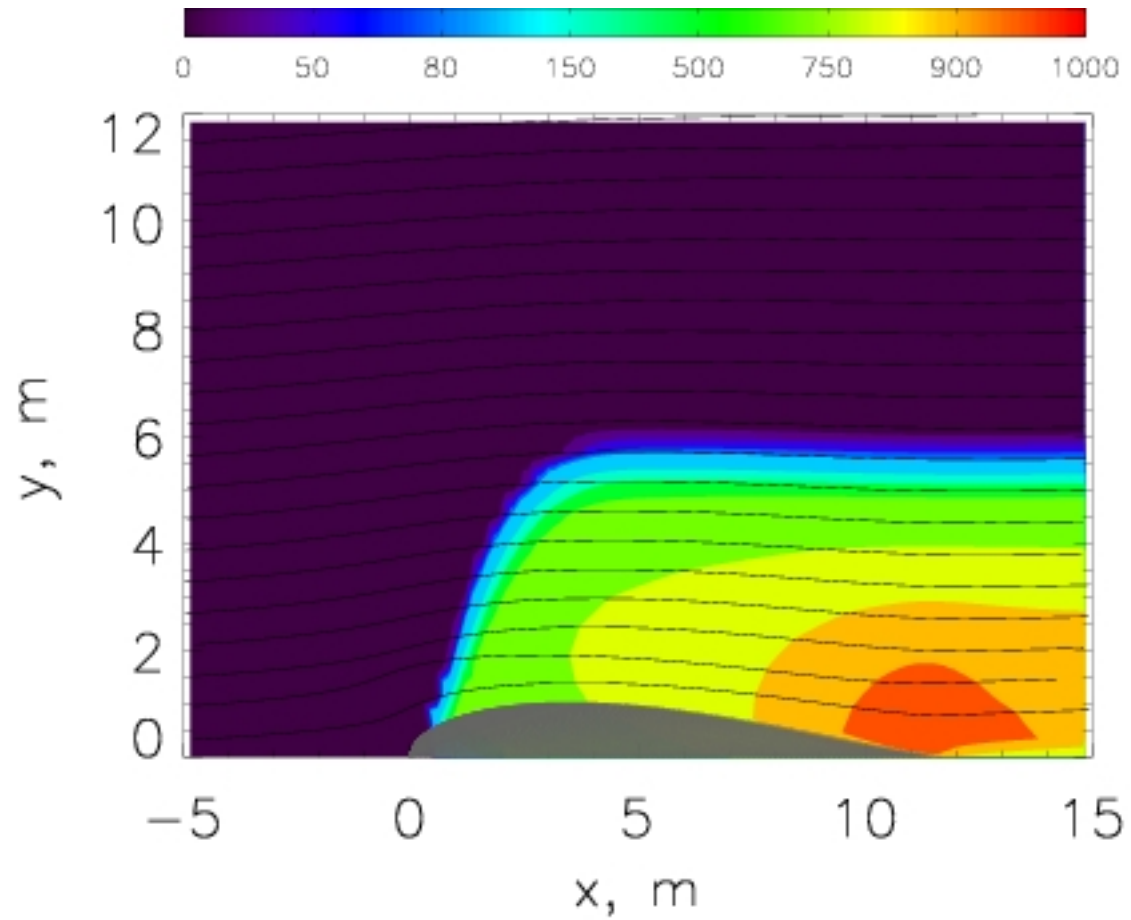
saturation ratio for two streamlines 0.45 m from the surface



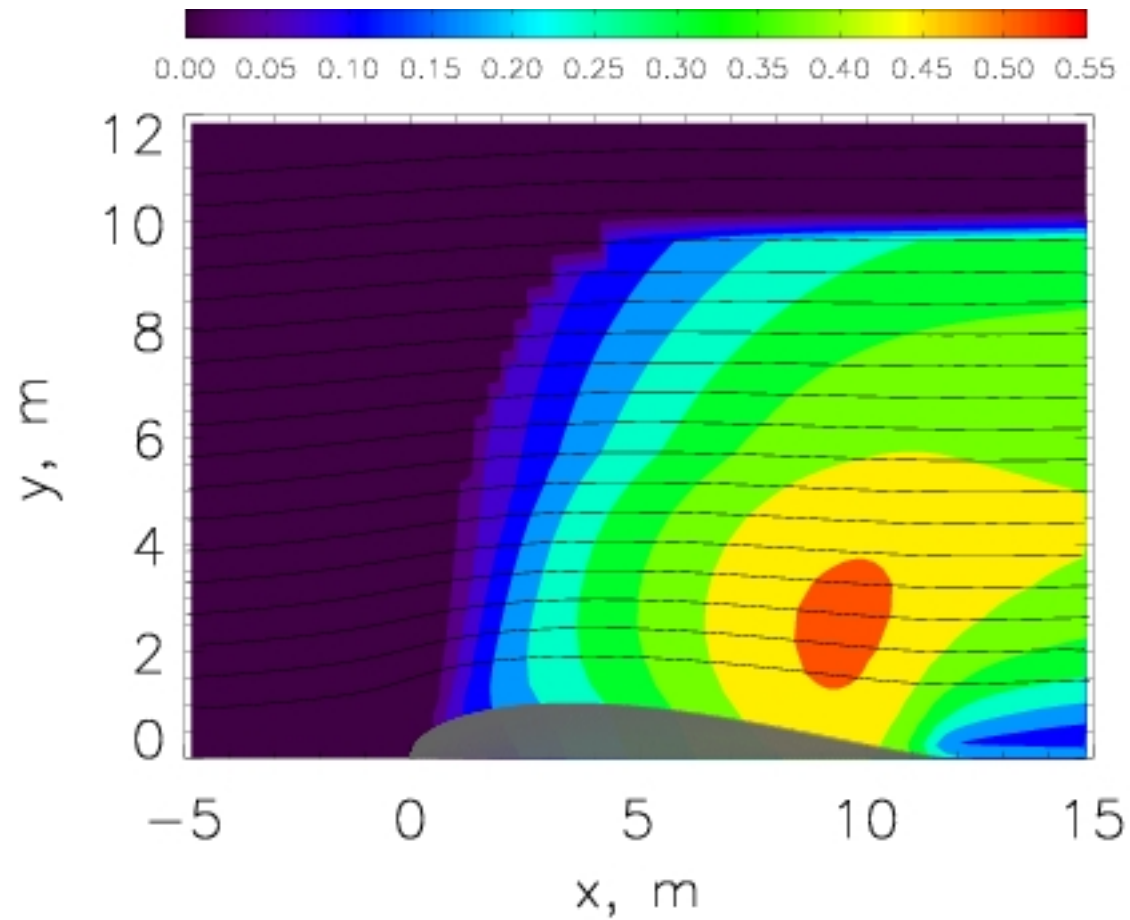
Saturation ratio above wing, $RH_{i0}=110\%$



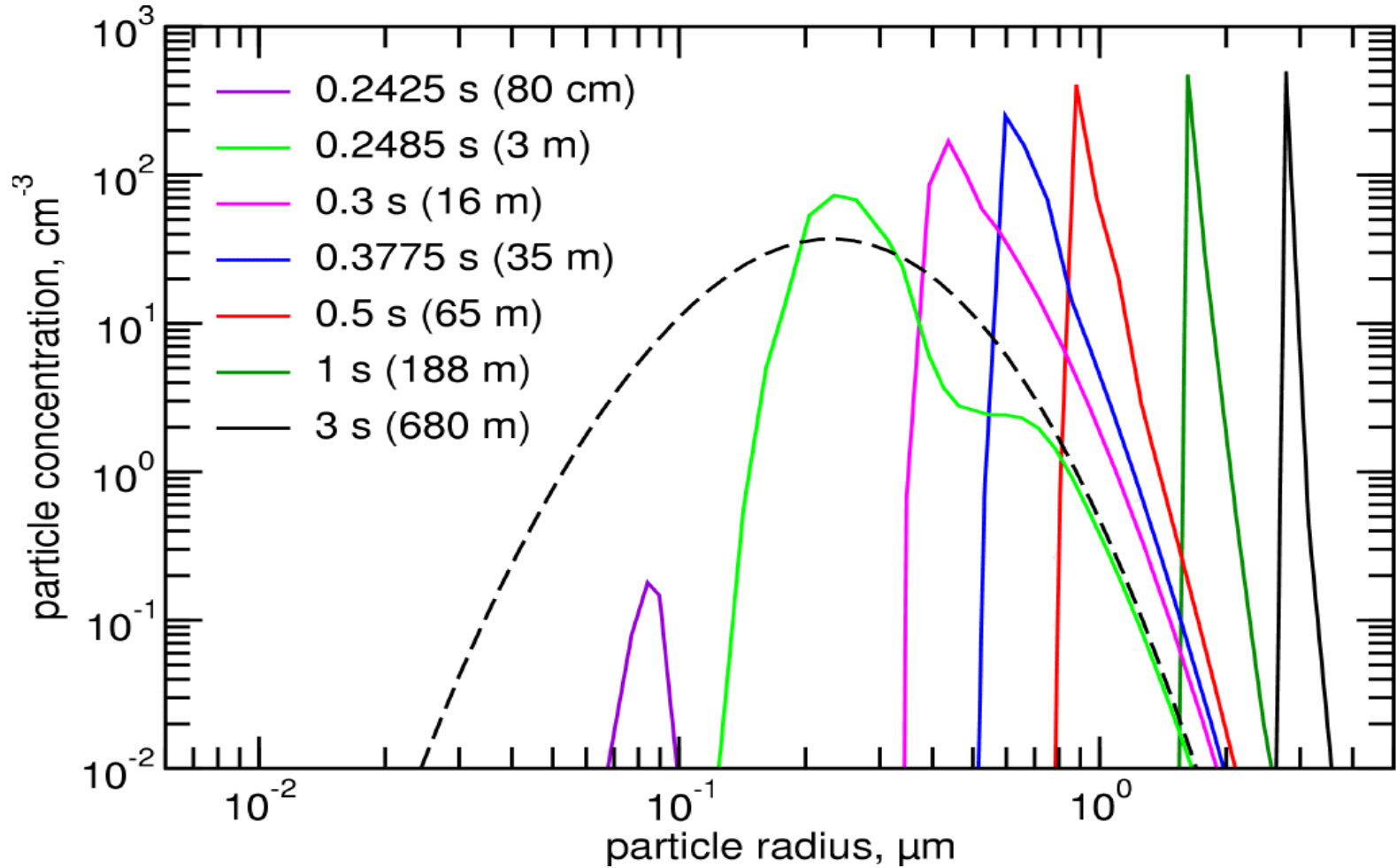
Crystal number concentration, $N_a=1000 \text{ cm}^{-3}$



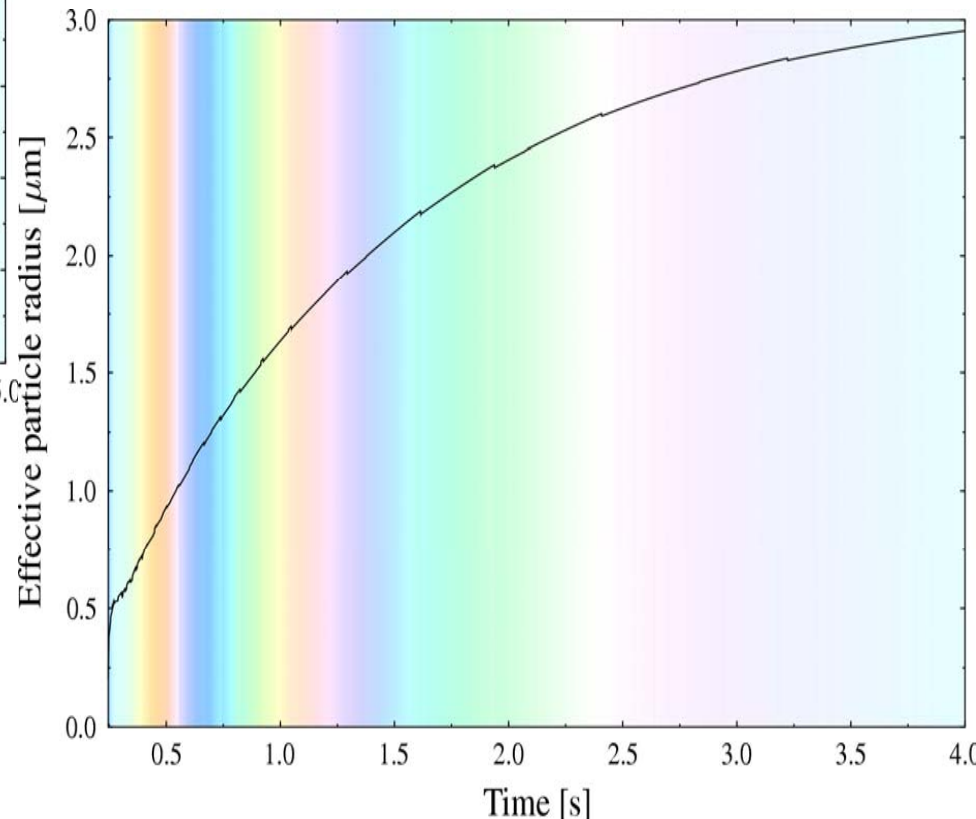
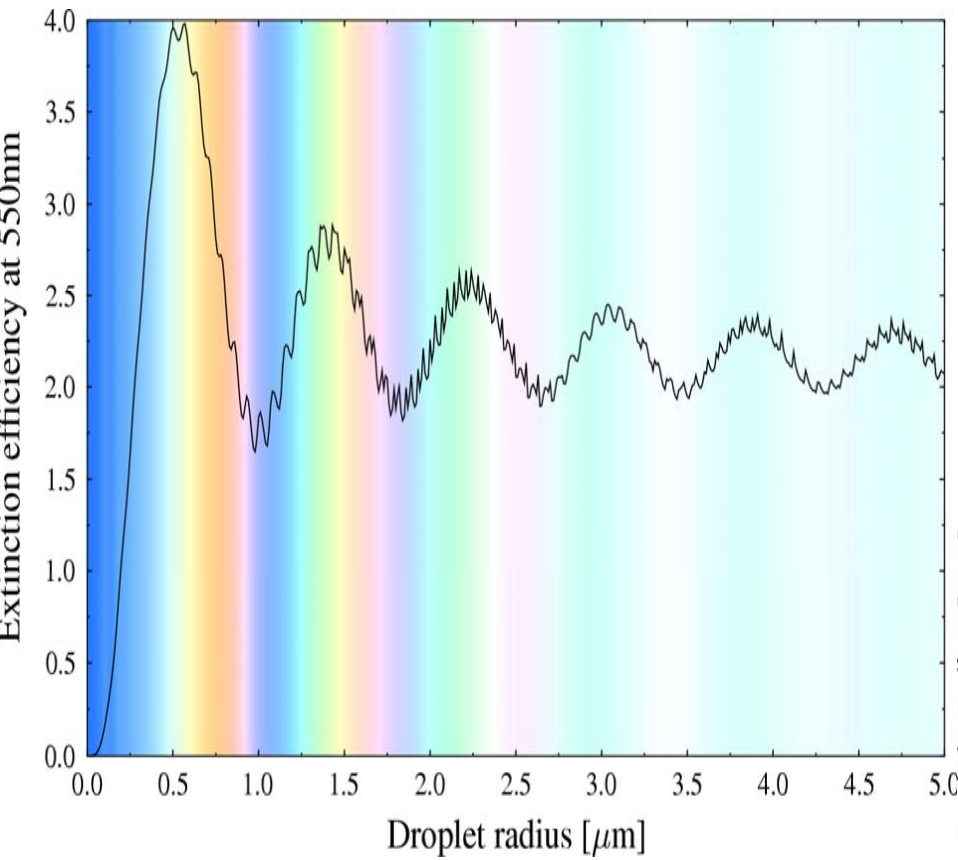
Effective crystal radius (μm)



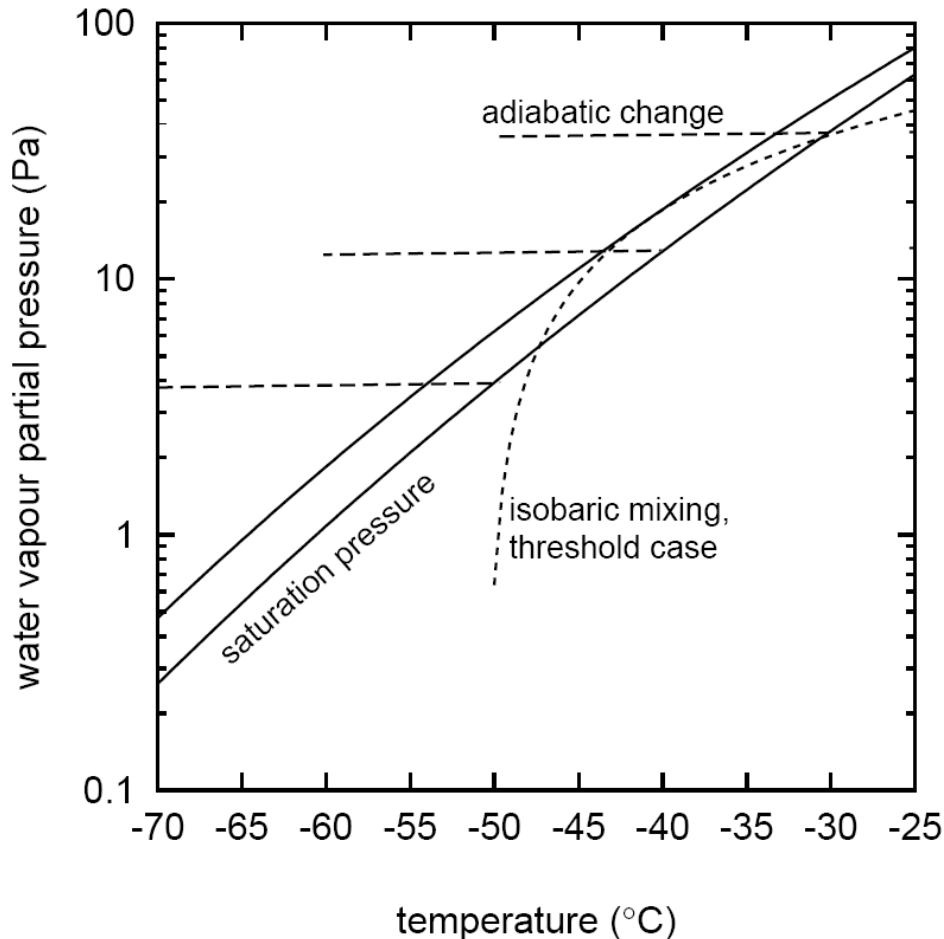
Crystal size distribution



optical calculation



Aerodynamically induced condensation (9) thermodynamics: adiabatic cooling



The highest saturation ratio for a given temperature change is reached in the coldest case. **Freezing nucleation rates increase with decreasing temperature.** However, the difference between ambient vapour concentration and ice saturation vapour concentration increases with increasing temperature. Hence **crystal growth is faster at warmer than at colder temperatures.**

Contrails





Contrails in 440 b.C.

Jet exhaust emissions

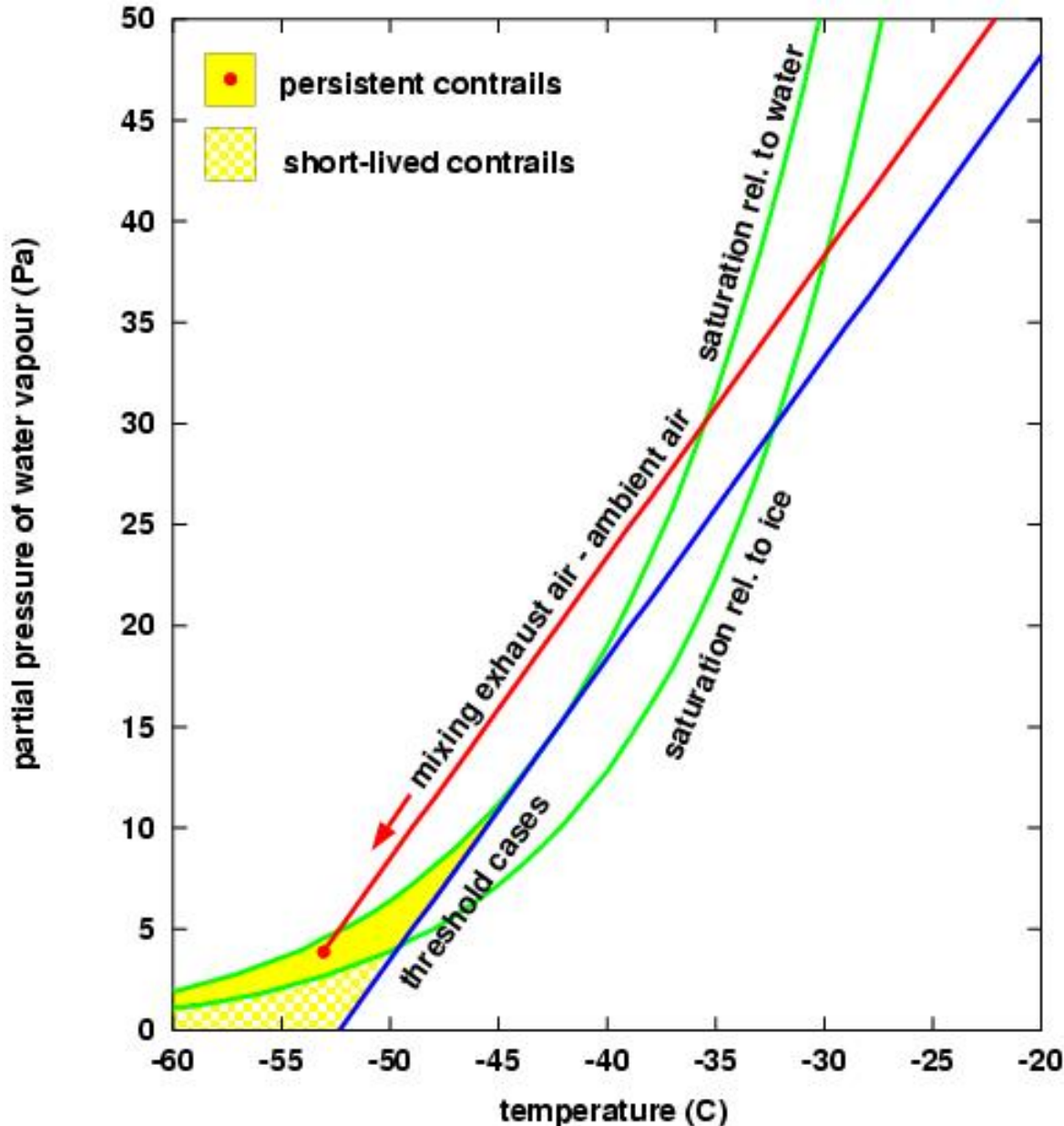
Aircraft engines emit under cruise conditions inter alia

- water vapour (1.25 kg per kg kerosene burnt)
- soot particles ($O(10^{15})$ per kg kerosene)
- sulphur dioxide, that gets oxidized into sulphuric acid
- heat (about 28 MJ per kg kerosene)

These emissions get quickly mixed with ambient air. The mixing proceeds isobarically, i.e. species concentrations and enthalpy in the plume decrease in a constant proportion, until eventually plume conditions are relaxed to ambient conditions.

As we know from the Cloud Processes lecture, isobaric mixing of two air masses can yield supersaturated conditions. **If water (super)saturation is temporarily achieved during the mixing process, a condensation trail (contrail) will form.** This is the Schmidt-Appleman criterion.

The Schmidt-Appleman criterion



Isobaric mixing of hot humid exhaust air with cold dry ambient air.

Slope of the mixing isobaric:

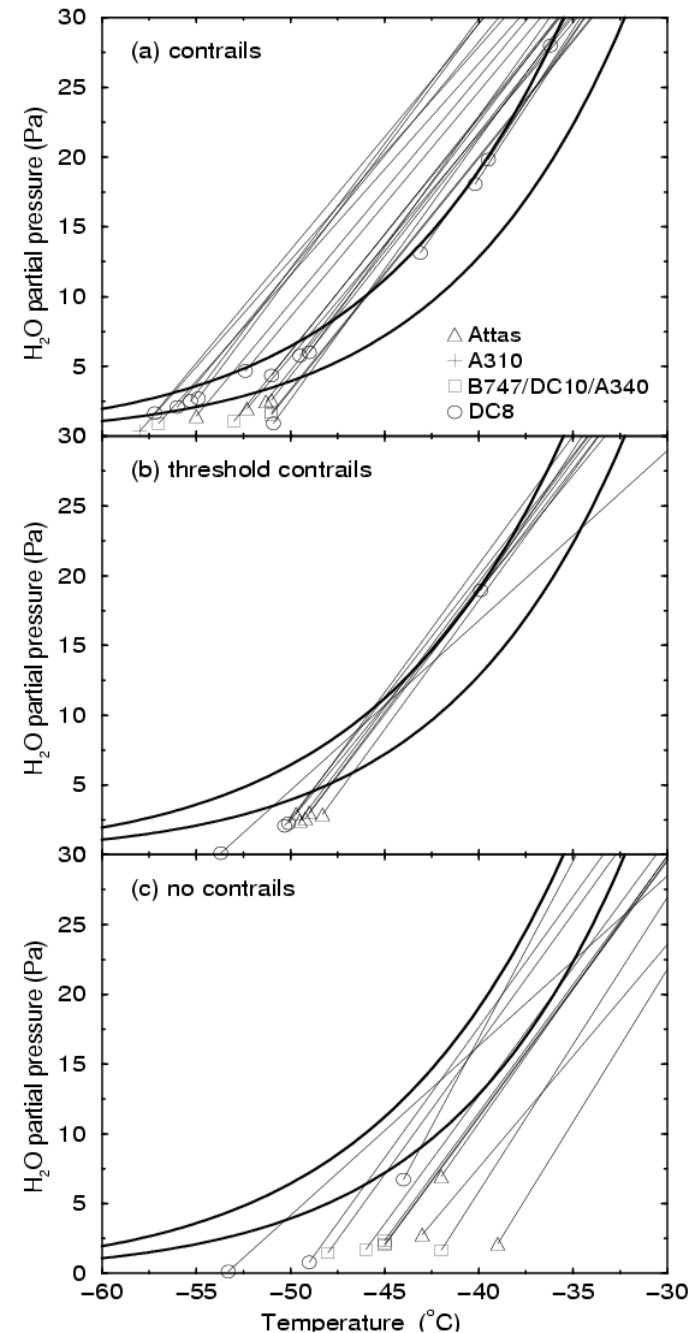
$$G = \frac{c_p p}{\varepsilon} \frac{EI_{H_2O}}{(1-\eta)Q}$$

Water saturation must be reached during the mixing process.

Thermodynamic contrail formation criterion: Schmidt (1941), Appleman (1953), reviewed and extended by Schumann (1996).

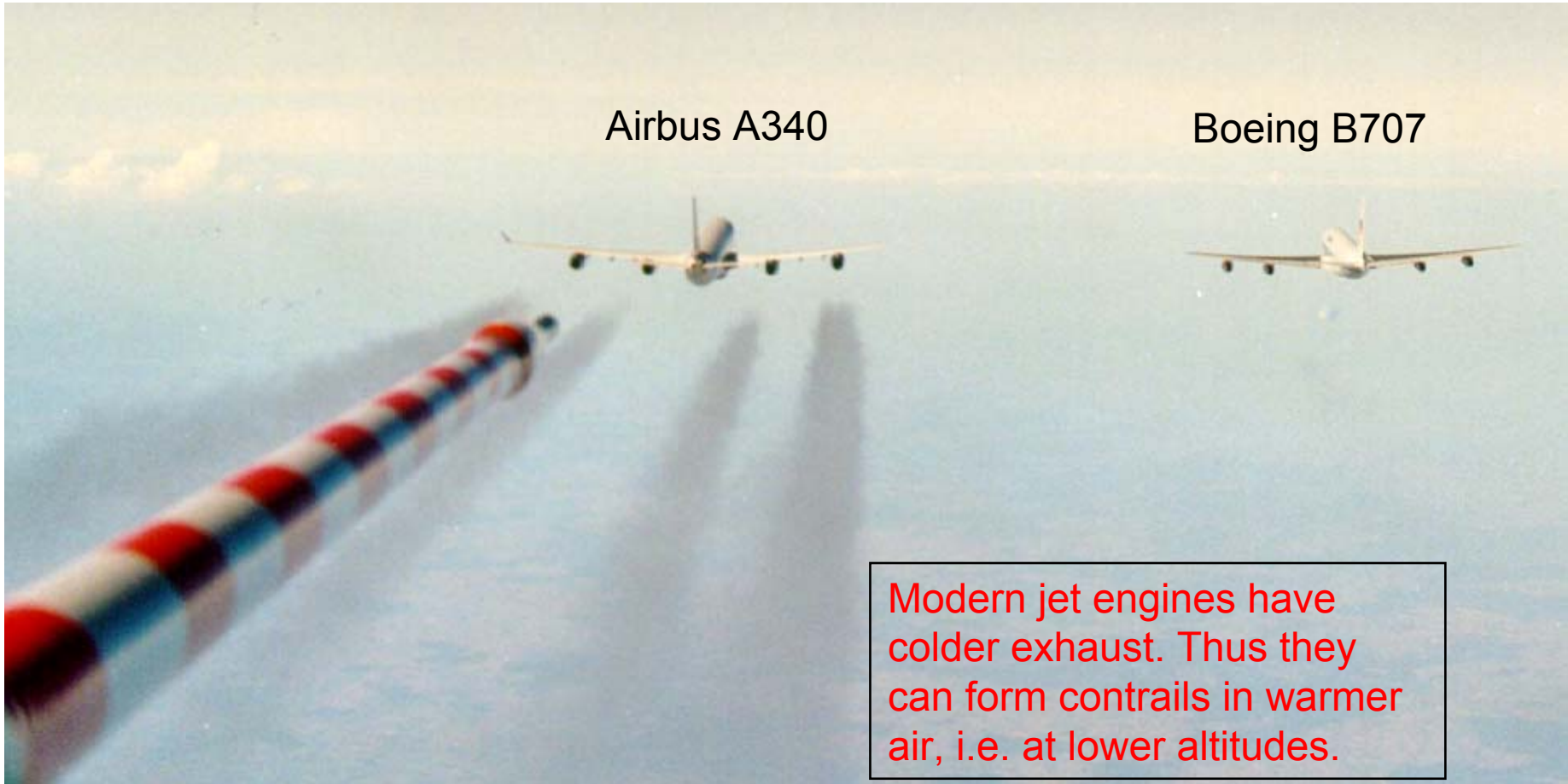
In contrast to natural cirrus clouds, contrails can already form at lower ambient humidity, in principle already under totally dry conditions ($RH_i=0\%$).

In-flight tests of the Schmidt-Appleman criterion have shown its validity.



Contrails from modern and old aircraft

altitude 344 hft



Schumann et al., 2000

$$G \propto \frac{1}{(1 - \eta)}$$

Contrail formation



Contrail formation takes about $1/3$ s. A small fraction (1%) of the co-emitted soot particles, serve as condensation nuclei. Lab measurements indicate that jet engine soot is hydrophilic, although BC is usually hydrophobic. The sulphuric acid can cover soot particles and so enhance their hydrophilicity.

Note: even if no particles were emitted, a contrail would form, because of entrained ambient particles.

Contrail lifetime is related to ambient RH_i

Contrails, consisting of **ice crystals**, cannot persist in air that is subsaturated with respect to ice.

In **subsaturated** air contrails will last no longer than about 2 min. In very dry air (RH_i≈10%) contrails can evaporate after only 4 sec (length 1 km).



Under **less subsaturated** conditions, ice crystals are **trapped** in the downward travelling **vortex pair**, shed by the aircraft wings. The vortices become unstable and start to break up into **waves and rings** after about 2 min. Ice crystals, released into the subsaturated environment, quickly evaporate.



In **slightly supersaturated** air the ice in the rings vanishes (because of adiabatic heating in the downward travelling vortices), however, a faint trace of an ice curtain, the **secondary wake**, stays persistent.



In **more supersaturated** air also the ice in the bursting vortices survives, a strong contrail appears that can undergo **contrail-to-cirrus transformation**.



Contrail-to-cirrus transformation
leads in regions with dense air traffic
to the development of contrail
decks.



Phases of contrail evolution (1)

Jet phase (0-20 s)

The exhaust leaves an engine with quite high speed relative to the ambient air, forming a jet. At the boundary between the jet and the ambient air the large speed gradient causes friction, hence turbulent mixing leads to an increase of the jet plume cross section and decelerates the jet.

The plume cross section increases nearly linearly with time.

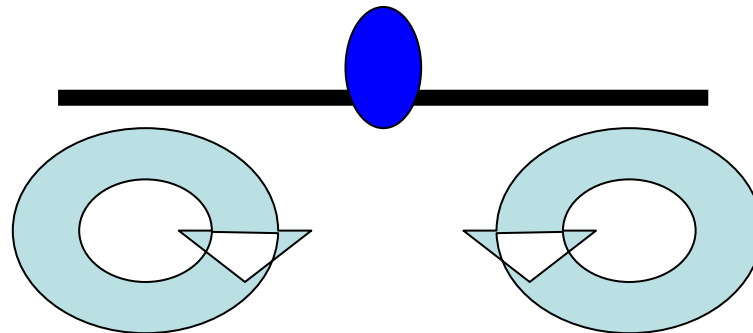
The mixing with ambient air causes temperature to decrease within the plume until the jet phase ends.

The jet phase ends when the plume evolution starts to become controlled by the wing vortices.

Phases of contrail evolution (2)

Vortex phase (20 – 150 s)

As mentioned before, aerodynamic flow around corners and tips tends to organise itself into vortices. In case of a pair of wings, the lift induced by the wings is equivalent – by the Kutta-Joukowski law – to a pair of vortices around the wings. Since the wings are of finite length, the vortices have also a spanwise component (the pressure difference leads to a flow around the wing tips from below to above). After passage of the aircraft these vortex motions evolve in a pair of counter-rotating vortices.



Phases of contrail evolution (3)

..... Vortex phase (20 – 150 s)

The counter-rotating vortex pair has certain kinematic properties:

The left vortex imposes a downward motion on the right vortex, and vice versa; hence the vortex pair travels downward. This can be viewed as a consequence of **conservation of momentum** (in order to lift the aircraft, one has to push downward the air).

With aircraft weight W , wing area A , wing span B , and speed V , the vorticity of one vortex is:

$$\Gamma = \frac{4}{\pi\rho} \frac{W}{V} \frac{1}{B}$$

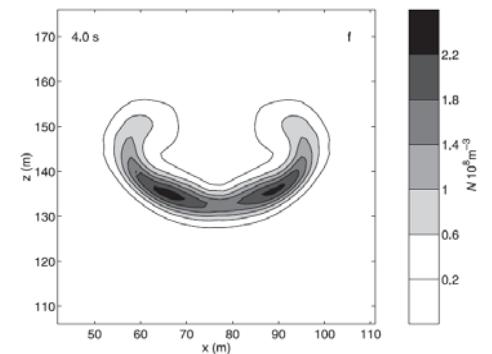
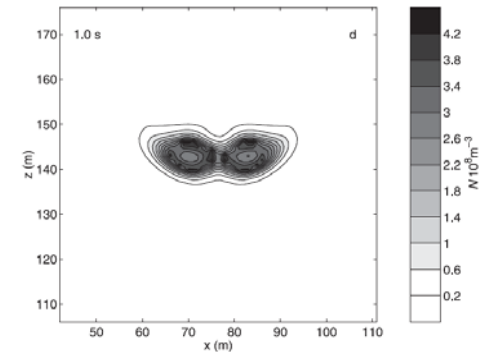
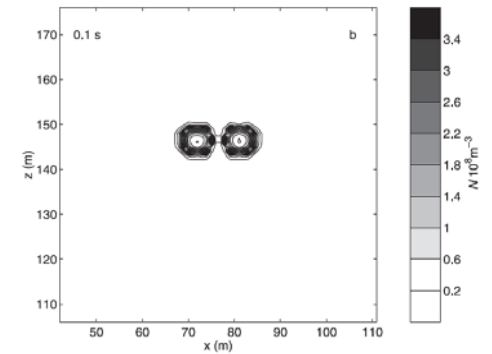
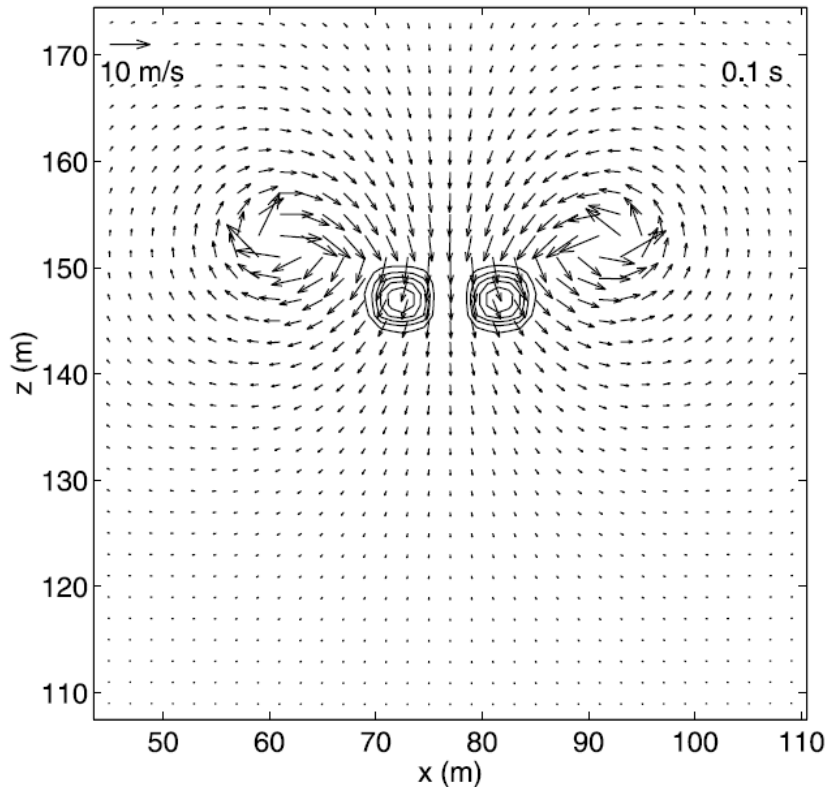
The mass contained in the vortex system (per meter) is $M = (\pi^3/8)\rho B^2$, the vortex pair travels downward with a velocity **$U=(W/V)/M$** .

Typical values of U are of the order 2 m/s.

Phases of contrail evolution (4)

..... Vortex phase (20 – 150 s)

The pressure gradient within the vortices attract the jets which are after about 20 s completely caught within the vortices.

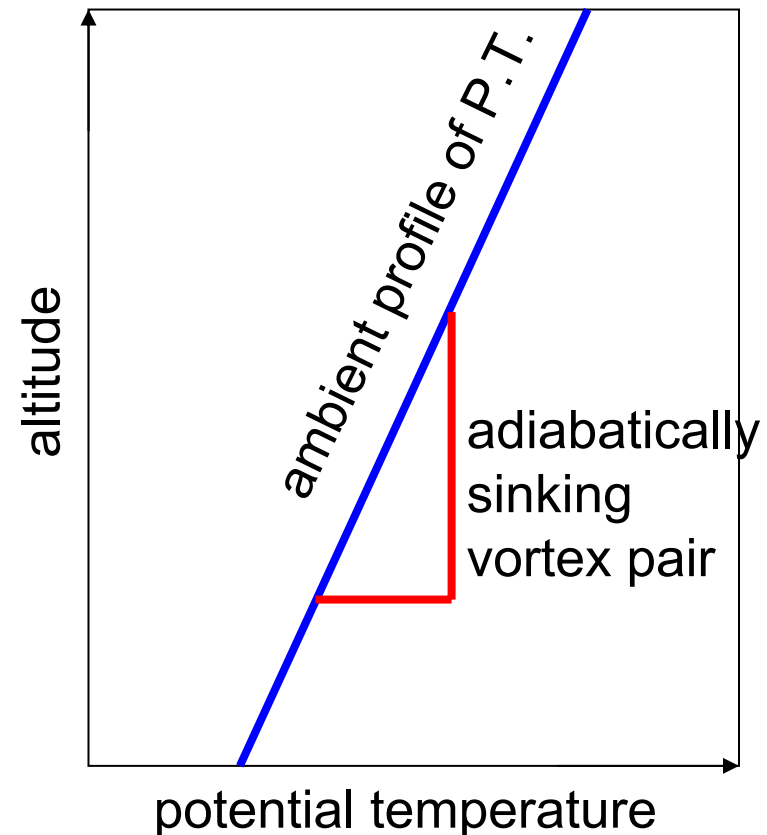


Phases of contrail evolution (5)

..... Vortex phase (20 – 150 s)

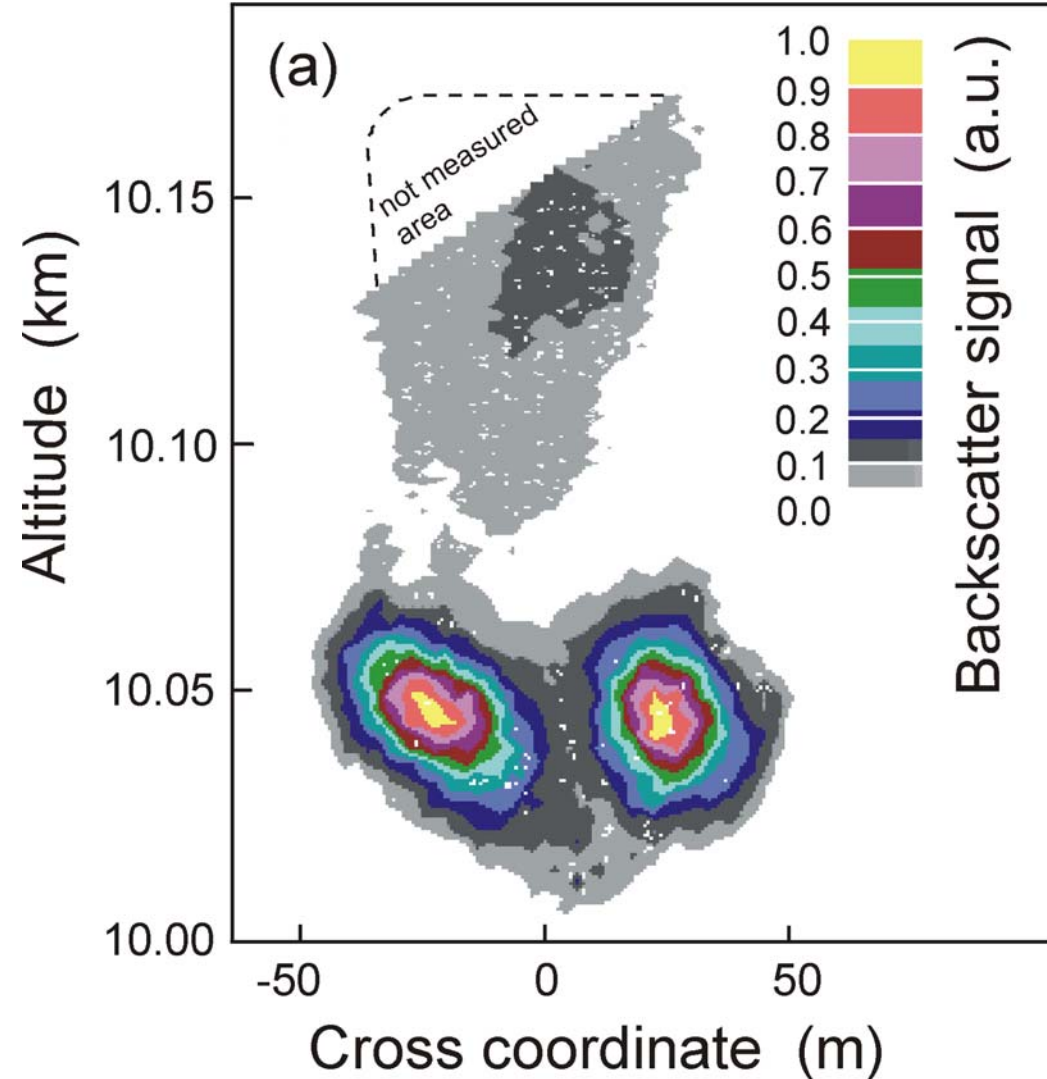
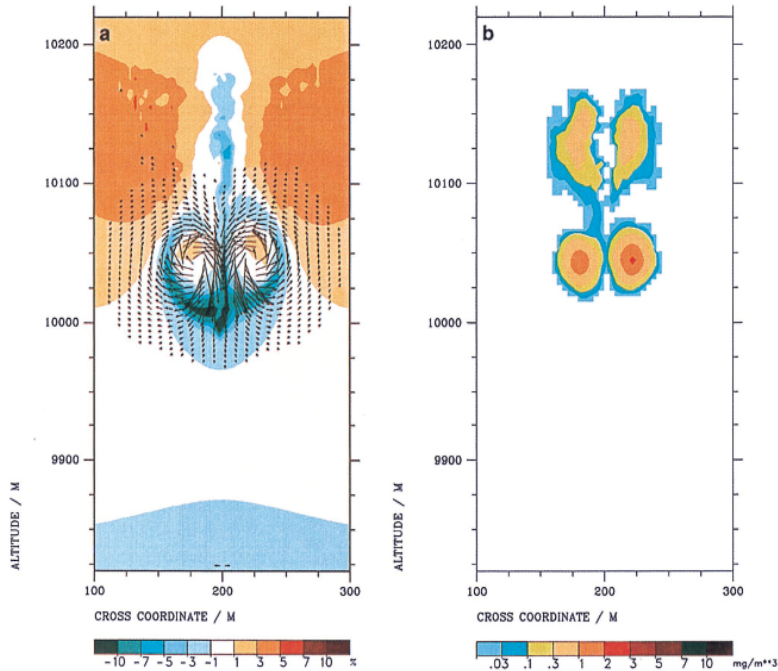
The downward motion of the vortex pair leads to layers with higher pressure; thus it is accompanied by adiabatic compression. There are two important effects during this period:

- a) adiabatic heating leads to evaporation of ice (loss of ice mass, loss of ice crystals)
- b) around the upper stagnation point of the vortex system a baroclinic instability causes ice crystals and caught vapour to leave the sinking vortex pair. The lost ice forms the so-called secondary vortex.



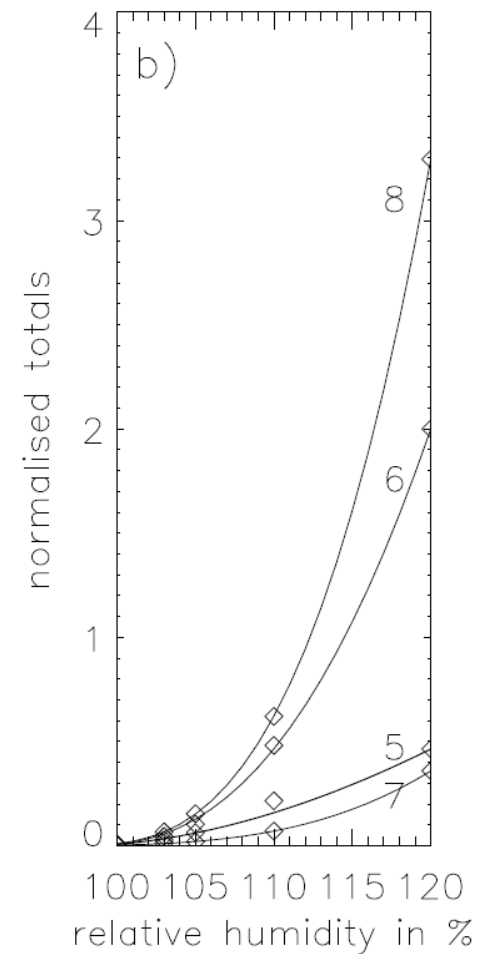
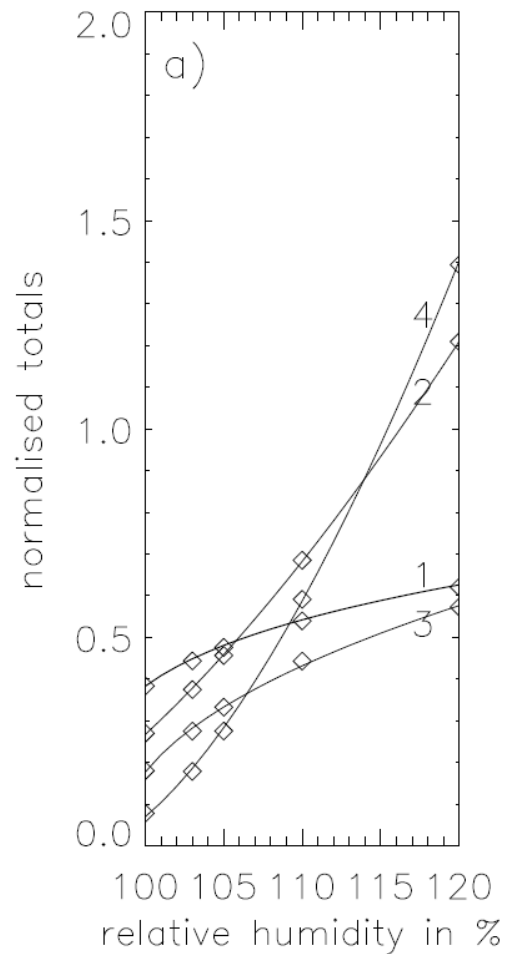
Phases of contrail evolution (6)

..... Vortex phase (20 – 150 s): secondary wake



Phases of contrail evolution (7)

..... Vortex phase (20 – 150 s): ice loss due to adiabatic compression



Phases of contrail evolution (8)

Dispersion phase (after 150 s)

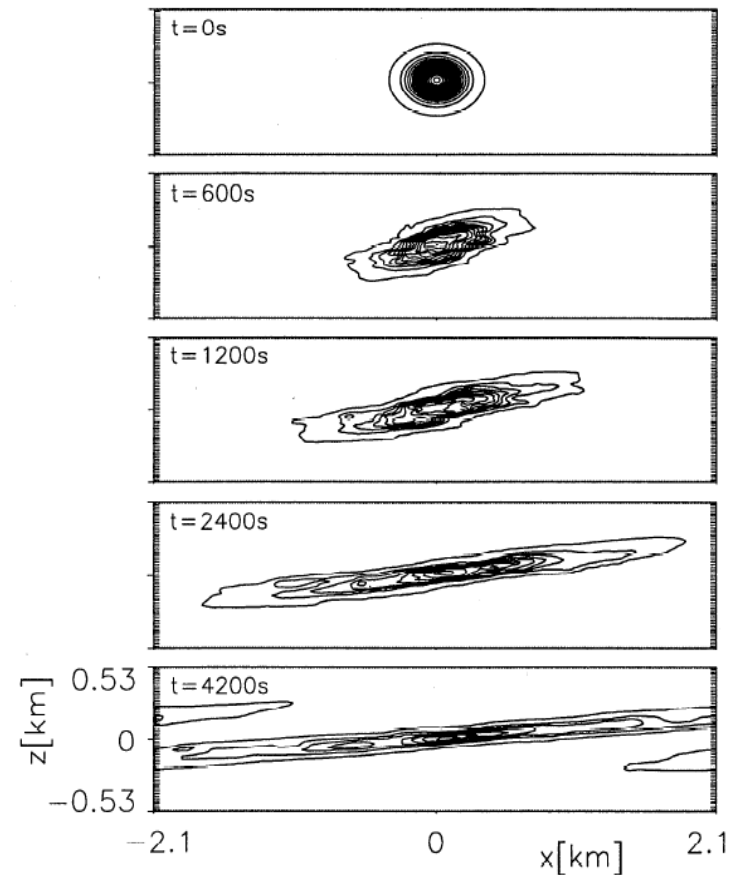
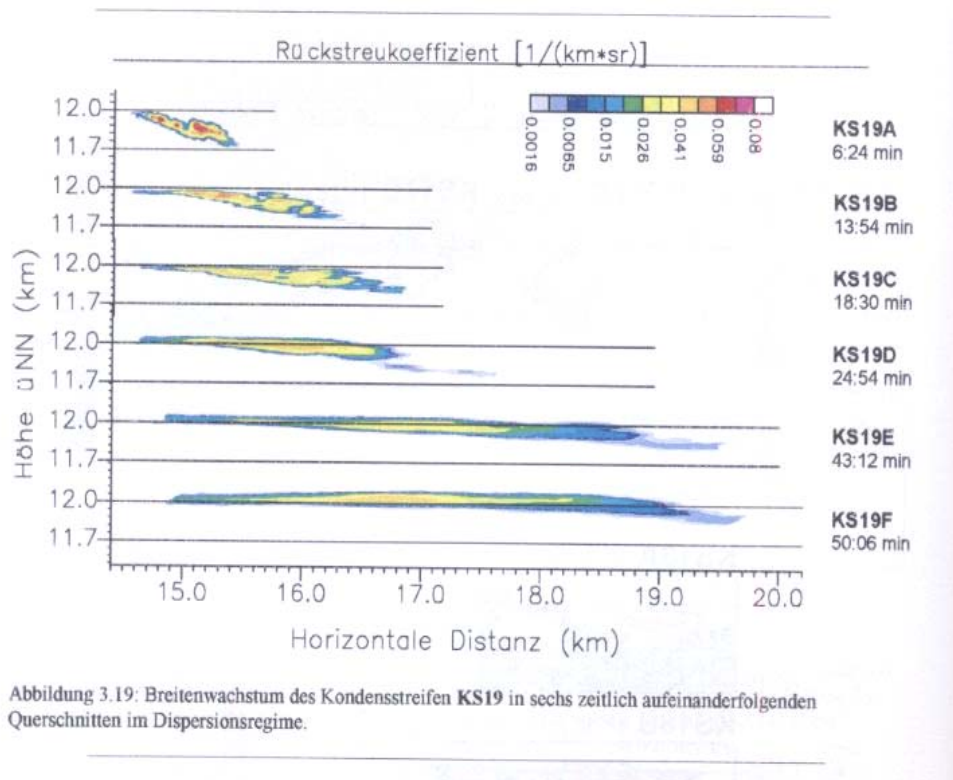
The ongoing mass loss of the vortices lets them approach each other until they make contact. Contact means that they destroy each other. The remaining ice is released to the atmosphere where it can form a long living cloud, termed contrail-cirrus, when RH_i is at least 100%.

The later fate of the cloud is determined by the state of the atmosphere, in particular temperature, RH_i , and wind shear.

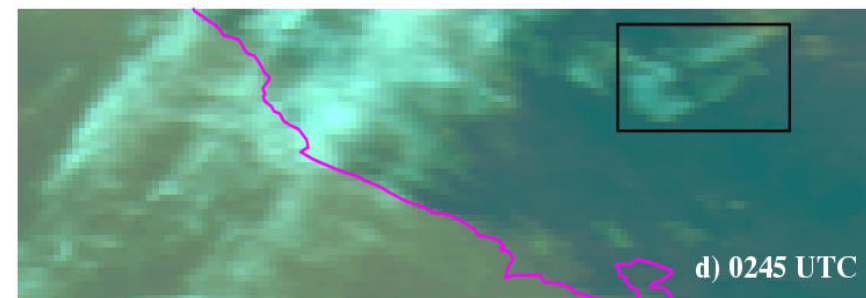
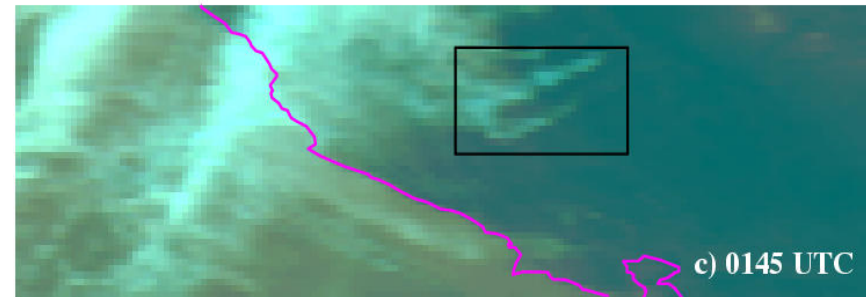
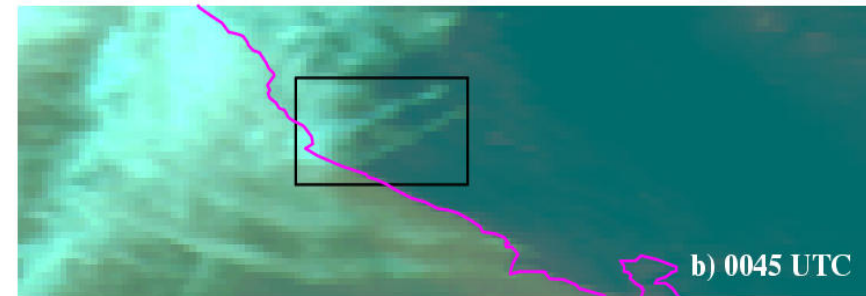
Wind shear drives the contrail-cirrus lateral expansion and leads to entrainment of fresh moist air.

Phases of contrail evolution (9)

... Dispersion phase: contrail expansion due to wind shear

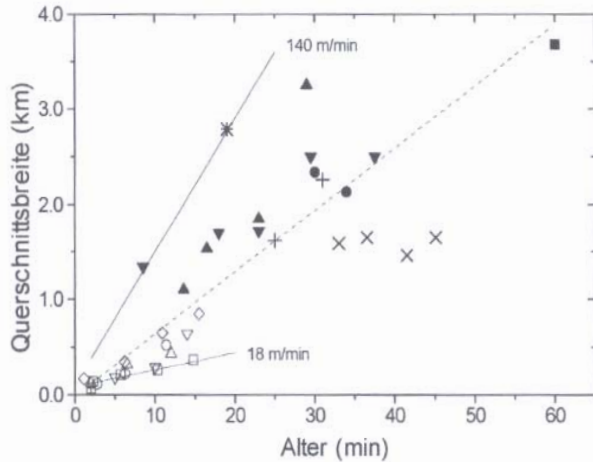


Contrail spreading observed per satellite during several hours



Minnis et al., SUCCESS campaign

Phases of contrail evolution (10)



Horizontal spreading rates:
range: 18 – 140 m/min



Abbildung 3.30: Breite der Querschnittsflächen von Kondensstreifen über dem Kondensstreifenalter. Messungen aufeinanderfolgender Scans desselben Kondensstreifens sind mit denselben Symbolen versehen. Volle und offene Symbole unterscheiden Kondensstreifen mit schnellem Wachstum von solchen, die langsam wachsen. Sie sind getrennt durch die Strichlinie mit einem Anstieg von 65 m/min. Die durchgezogenen Linien markieren das maximale und das minimale Breitenwachstum mit 140 m/min bzw. 18 m/min.

Cross section spreading rates:
range: 3500 – 25000 m²/min

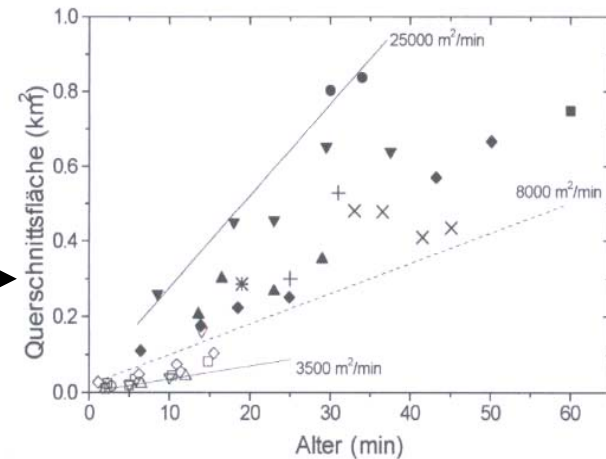


Abbildung 3.31: Querschnittsflächen von Kondensstreifen über dem Kondensstreifenalter. Die Symbole und Linien entsprechen denen in Abb. 3.30.

Phases of contrail evolution (11)

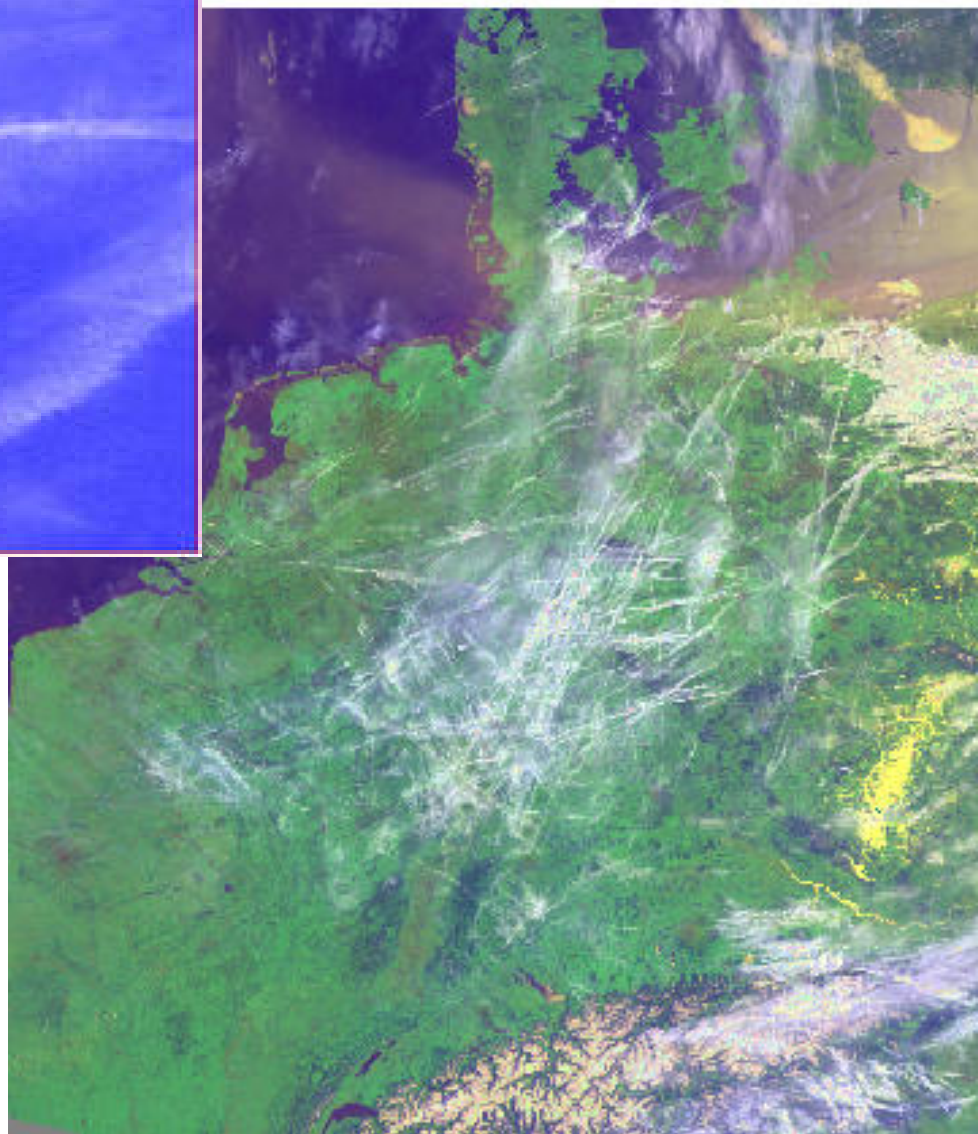
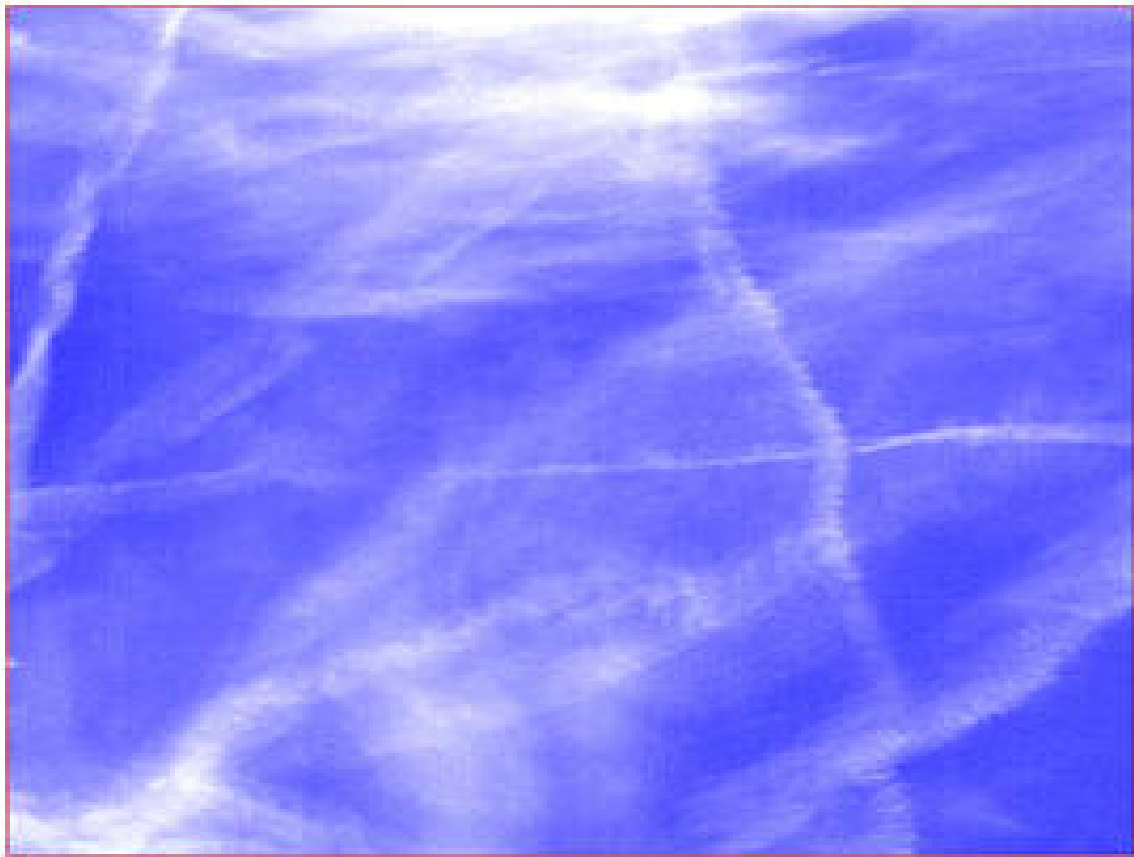
... Dispersion phase

(after 150 s):

contrail decks

Contrails usually appear in groups, at least in regions of intense air traffic.

Hence wind shear driven contrail expansion expands all contrails of a group simultaneously. The end result often is a cloud deck composed of old contrails, as in the following examples:



Phases of contrail evolution (12)

... Dispersion regime:

High sensitivity of microphysical initial conditions to aircraft and ambient parameters \Rightarrow Wide variety of contrail-cirrus microphysical and optical properties.

Contrail spreading into moist air \Rightarrow further growth of ice crystals, optical thickness can

- increase if crystal growth rate dominates over geometrical growth rate
- decrease if geometrical growth rate dominates over crystal growth rate

Contrail cirrus vanishes ultimately by

- crystals falling into subsaturated air below
- getting invisible by too large geometric growth (strong wind shear)
- airmass generally starts subsiding due to synoptic situation

Aviation impact on cloud cover and RF (1)

A number of statistical studies since 1971 indicate that aviation increases local cirrus cloud cover, at least over regions with heavy air traffic.

Aside from young contrails that can be detected on satellite images due to their linear shape, there is currently no method to distinguish natural cirrus clouds from contrail-cirrus, neither from ground observations nor from satellite data. Cloud cover is affected by a large variety of processes, in particular the meteorological situation, implying large local and temporal variability; aviation's share to cloudiness is still small (on average).

Hence, only statistical methods with long time series can be used to quantify the amount and trends of aviation induced cloudiness. Natural influences on cloudiness must be carefully filtered before the aviation effect can be seen. The time series must be carefully made homogeneous in order to avoid data artefacts that might be misinterpreted as trends.

Aviation impact on cloud cover and RF (2)

Zerefos et al. 2003:

ISCCP D2 data (1984 – 1998)

time series analysis (multiple regression):

$$C(t) = S(t) + ENSO(t) + QBO(t) + NAO(t) + R'(t)$$

$S(t)$ is the annually averaged seasonal variation

$R'(t)$ is the residual, which contains, if at all, the aviation influence.

Consider trends of $R'(t)$ in winter, summer, annually, in regions with high and low air traffic.

Remove possible effects of changing tropopause temperatures and convective activity by linear regression on $R'(t)$, leaving $R(t)$

Determine statistical significance of the trends of $R(t)$.

$R(t)$ increases, sometimes statistically significantly, in regions with heavy air traffic; generally, there is a decrease in cirrus cloud cover.

Aviation impact on cloud cover and RF (3)

- a) increasing trends in Ci between 1984 and 1998 over North America, North Atlantic, and Europe (regions with heavy air traffic)
- b) Ci trends over regions with low air traffic insignificant or even negative
- c) Ci trends of opposite signs not caused by different trends in dynamics
- d) Correlation between fuel consumption and longitudinal variability of Ci is significant (+0.7) over the mid-latitudes

Table 1. Seasonal and annual trends in (CCC) (% per decade) from ISCCP satellite cirrus cloud data set (1984–1998) for regions categorized as having high and low air traffic for 1992 aircraft operations. Values in brackets refer to statistical significance of each trend. Dashes in brackets indicate a confidence level less than 95%

Trend (%/decade)	Winter (DJFM)		Summer (JJAS)		Annual	
	HATR	LATR	HATR	LATR	HATR	LATR
North America	+2.1 (95%)	+0.9 (-)	+0.5 (-)	-1.4 (95%)	+1.3 (-)	-0.2 (-)
North Atlantic	-0.4 (-)	-0.7 (-)	+2.6 (99.5%)	+1.2 (-)	+1.2 (95%)	+0.3 (-)
Europe	0.0 (-)	-1.3 (-)	+1.3 (-)	-0.2 (-)	+0.3 (-)	-0.8 (-)

HATR: high air traffic region

LATR: adjacent low air traffic region

Aviation impact on cloud cover and RF (4)

There is evidence of a possible aviation effect on high cloud positive trends in regions with heavy air traffic.

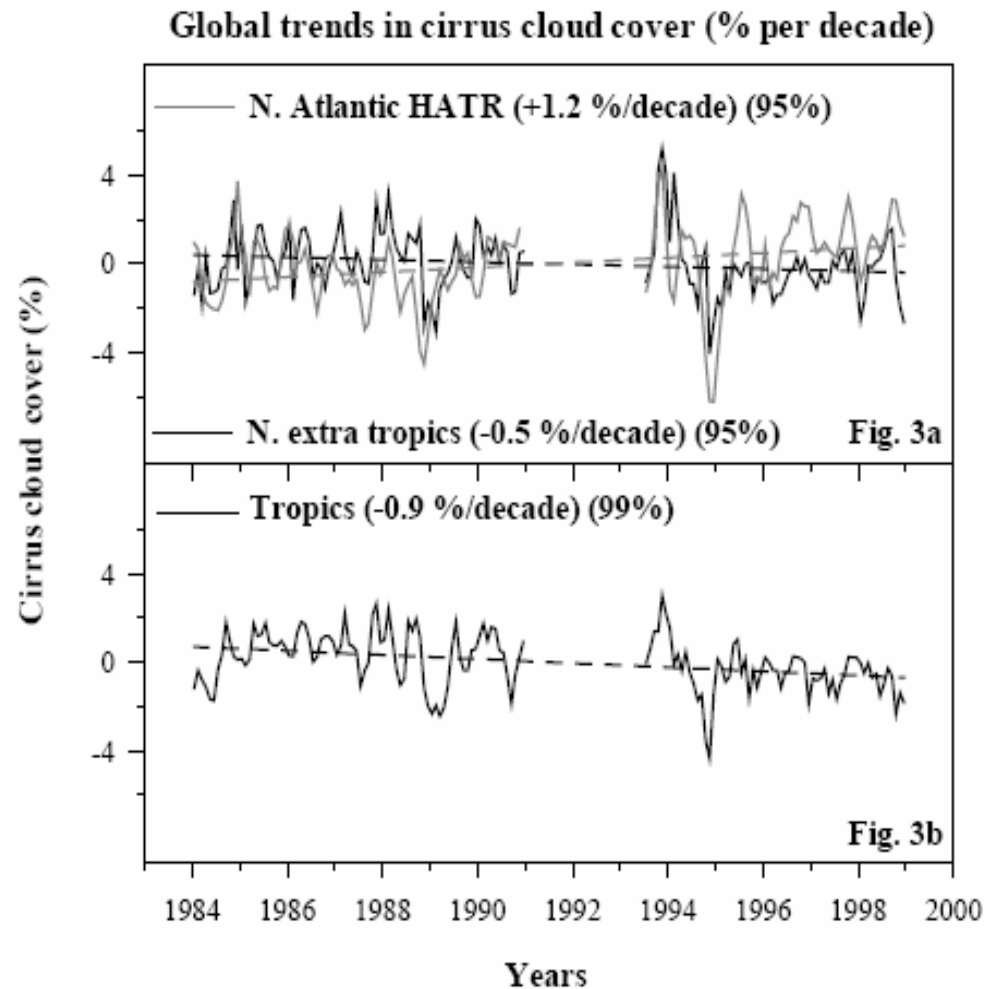
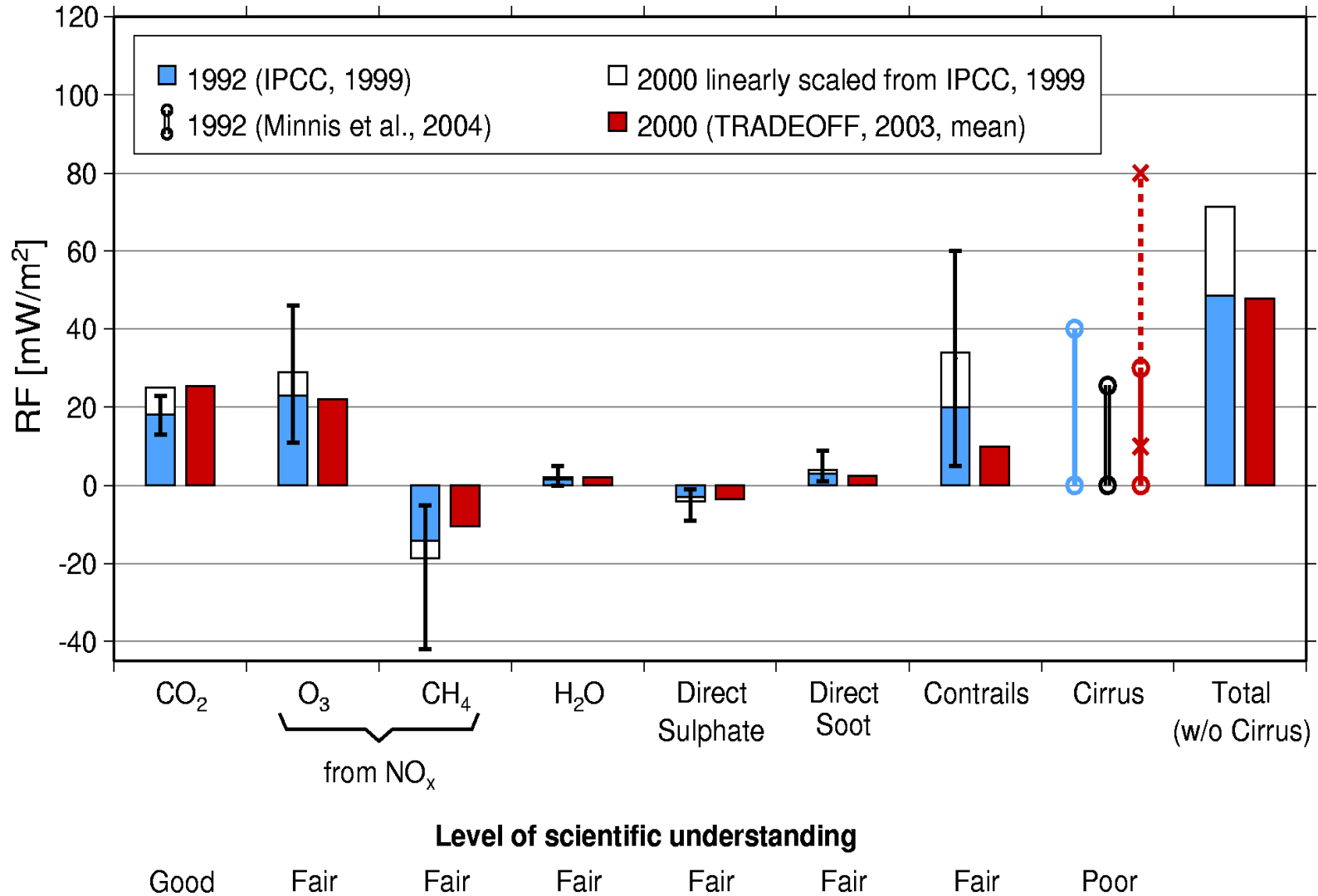


Fig. 3. (a) Trends in (CCC) (% per decade) for the period 1984–1998 over the northern extra tropics (30°N – 70°N , 180°W – 180°E) and the North Atlantic high air traffic region (40°N – 60°N , 35°W – 60°W). (b) Same as (a) but for the tropics (30°S – 30°N , 180°W – 180°E).

Radiative forcing of contrail cirrus

Aircraft RF



Contrail mitigation strategies (1)

As we have seen, contrails and in particular contrail-cirrus contribute significantly to aviation's radiative forcing of the climate. It is therefore justified to develop strategies for contrail suppression, mitigation, or change. There are 4 groups of options:

1. Technical options
2. Hard constraints of flight altitude (flying lower or even higher)
3. Shifting of flight time into daylight hours
4. Flexible operational reactions according to meteorological situation

Contrail mitigation strategies (2)

1. Technical options

Since there is a contrail formation criterion, i.e. the Schmidt-Appleman criterion, technical measures for contrail avoidance can only be such ones that change one or more parameters relevant for that criterion, expressed via the slope G :

- **decrease the water vapour emission index, EI_{H_2O}** ; there is a potential technical solution to this, using heat exchange in the engine exit that lets the water condense before it is emitted.
- **increase in the specific heat content of the fuel, Q** ; alternative fuels
- **decrease of the overall propulsion efficiency, η** ; increases fuel consumption.

Fuel additives might be used not for contrail suppression, but for changing contrail properties such that they get optically thinner.

Contrail mitigation strategies (3)

2. Hard operational constraints of flight levels

Since the formation of persistent contrails needs cold moist air, there are two possibilities to avoid contrails:

- flying in the dry stratosphere;
- flying in the too warm layers of the middle troposphere.

Both options have adverse consequences. The “Flying higher” option means that emissions occur in the stratosphere with longer residence times of chemicals and problems for the ozone layer. It also implies that flight personnel receives higher doses of cosmic radiation.

The Flying lower option requires harsh reductions of max. flight levels in order to be effective. This implies increases in fuel consumption, journey times, increase load on aircraft structures, extremely increases of work load on AT controllers, more close encounters of AC, i.e. more dangerous flying.

Contrail mitigation strategies (4)

3. Shifting of flight time into daylight hours

Contrails effect both the incoming solar radiation and the outgoing terrestrial infrared radiation. Reflexion of solar radiation means cooling, absorption and re-emission of terrestrial radiation implies heating. During night when the solar part is absent, contrails heat the atmosphere. Also during winter when the solar zenith angle is high, the reflexion of solar radiation is weaker than in summer. Hence winter flights are worse than summer flights, and night time flights are worse than daylight flights.

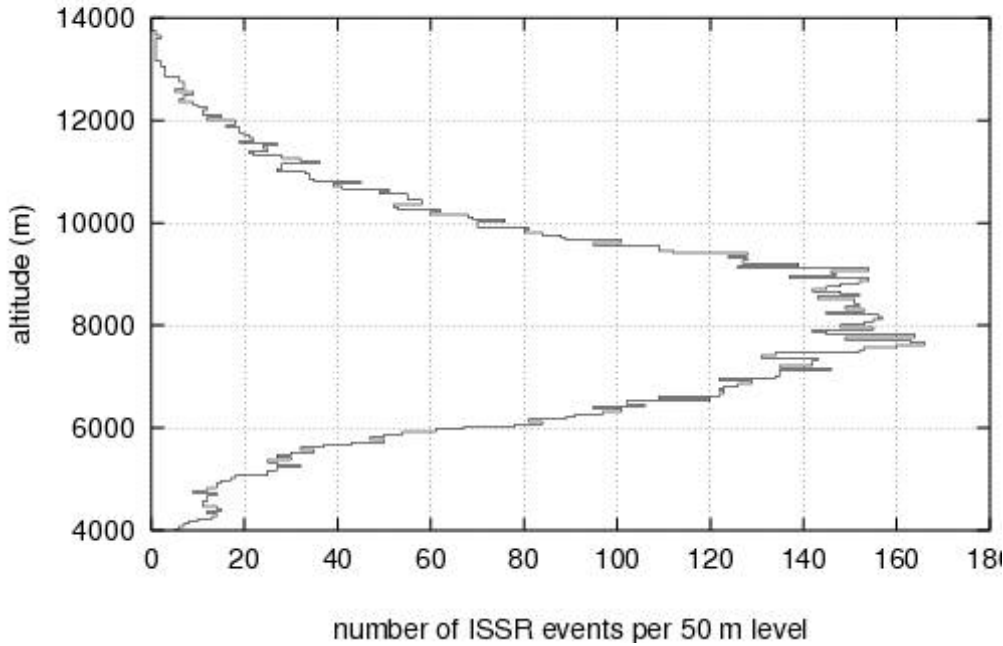
Also other circumstances affect the RF of a single contrail, e.g. the ambient cloudiness and the albedo of the underlying surface or lower cloud decks.

Since the air traffic system is already full, and because of other constraints, it is hard to see how a significant number of flights could be shifted to daylight hours.

Contrail mitigation strategies (5)

4. Flexible operational reactions according to meteorological situation
Short contrails hardly effect climate; it is not necessary to suppress them. Only persistent contrails that evolve into contrail cirrus should be avoided. Since persistence requires ice supersaturation, those regions where $RHi \geq 100\%$ (ISSRs) must be avoided. Often ISSRs are shallow, and change of flight level by 10 or 20 hft suffices to get into subsaturated air, once an aircraft enters an ISSR.
Prerequisite for such a strategy is that aviation weather forecast is able to predict the time and location of ISSRs with sufficient accuracy. Aircraft could carry an RHi sensor and report its readings to the aviation weather centres for the assimilation process.

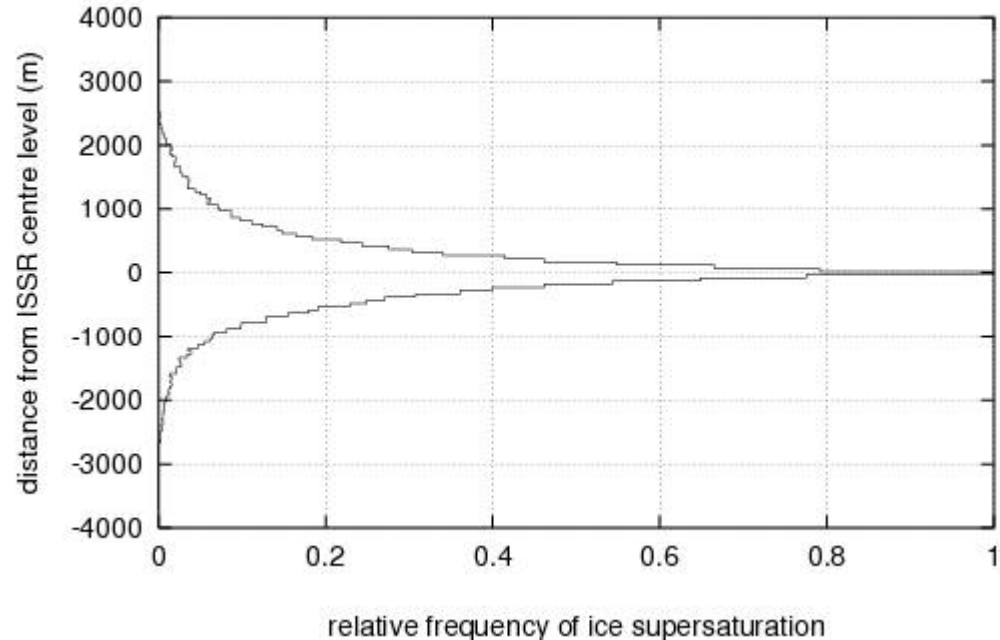
Radiosonde Lindenberg, 2000/2 - 2001/4



altitude distribution of ISSRs
over Lindenberg, Germany

distribution of altitudes
relative to ISSR centres
over Lindenberg, Germany

Radiosonde Lindenberg, 2000/2 - 2001/4



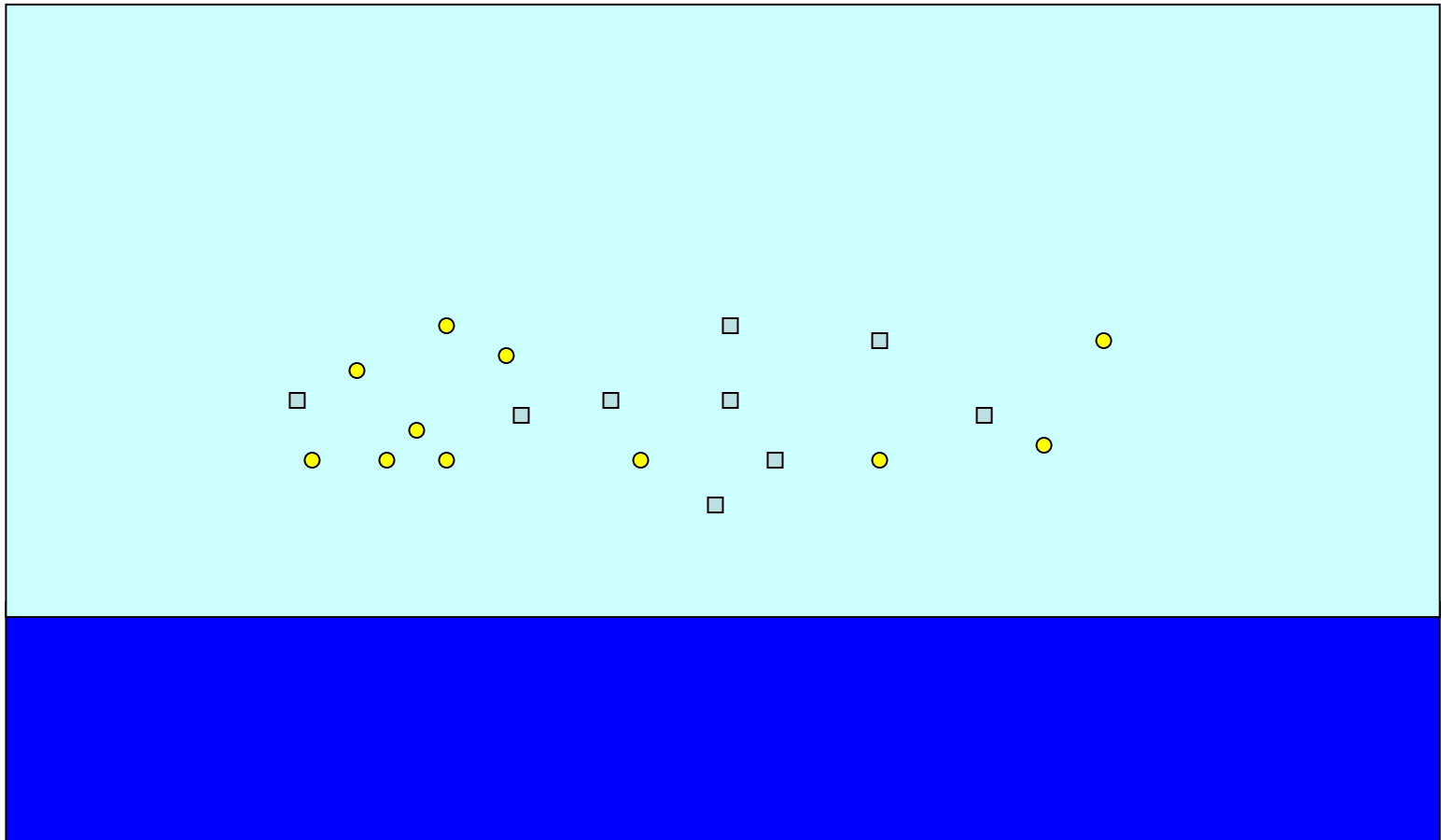
Ship tracks



Formation of ship tracks

“Normal” Conditions in the maritime boundary layer:

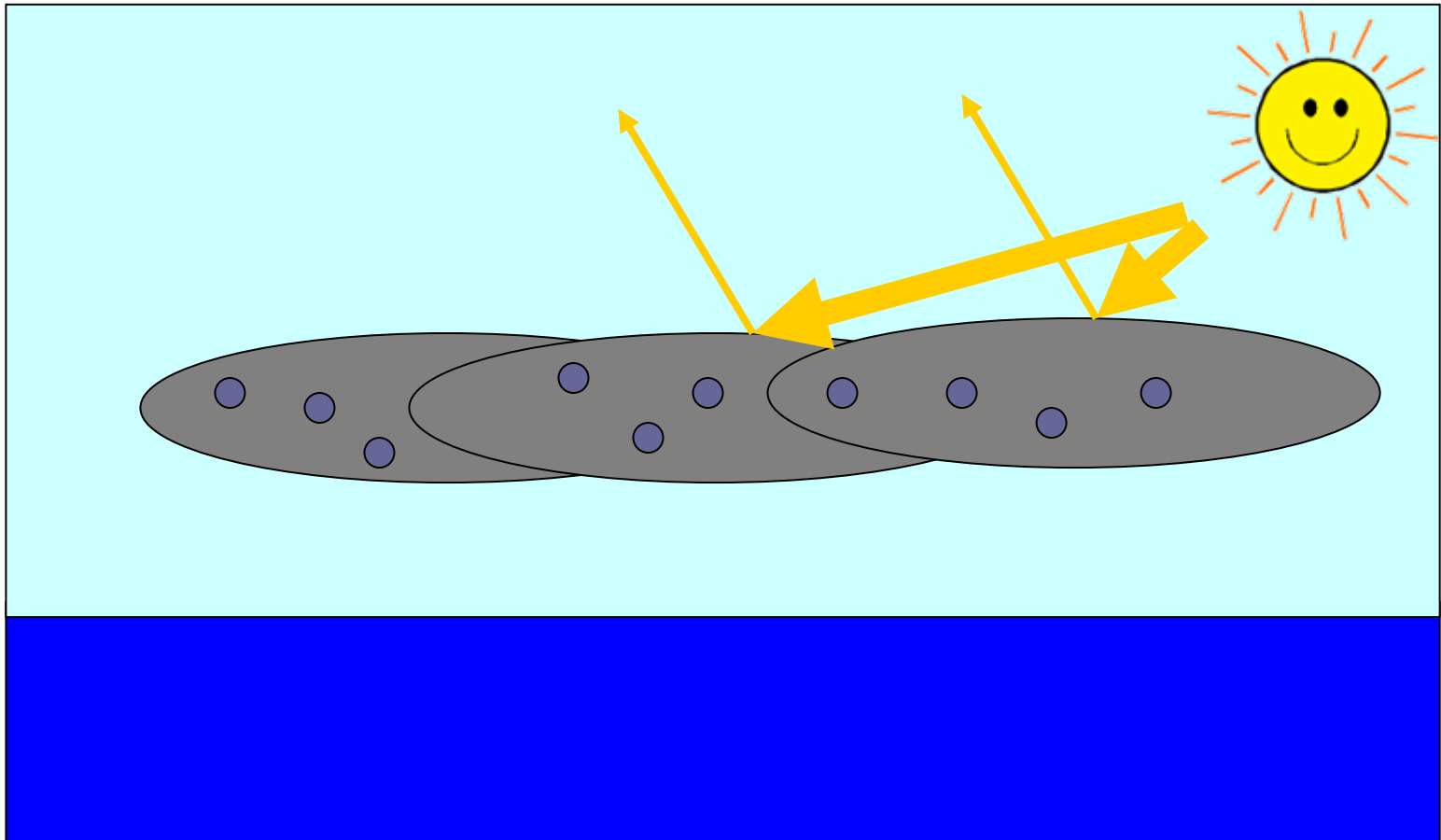
Small amount of aerosol, mainly sea salt and sulphate aerosol



Development of cloud over the ocean:

small amount of cloud condensation nuclei from Aerosol,
to form droplets

=> Small number of big cloud droplets

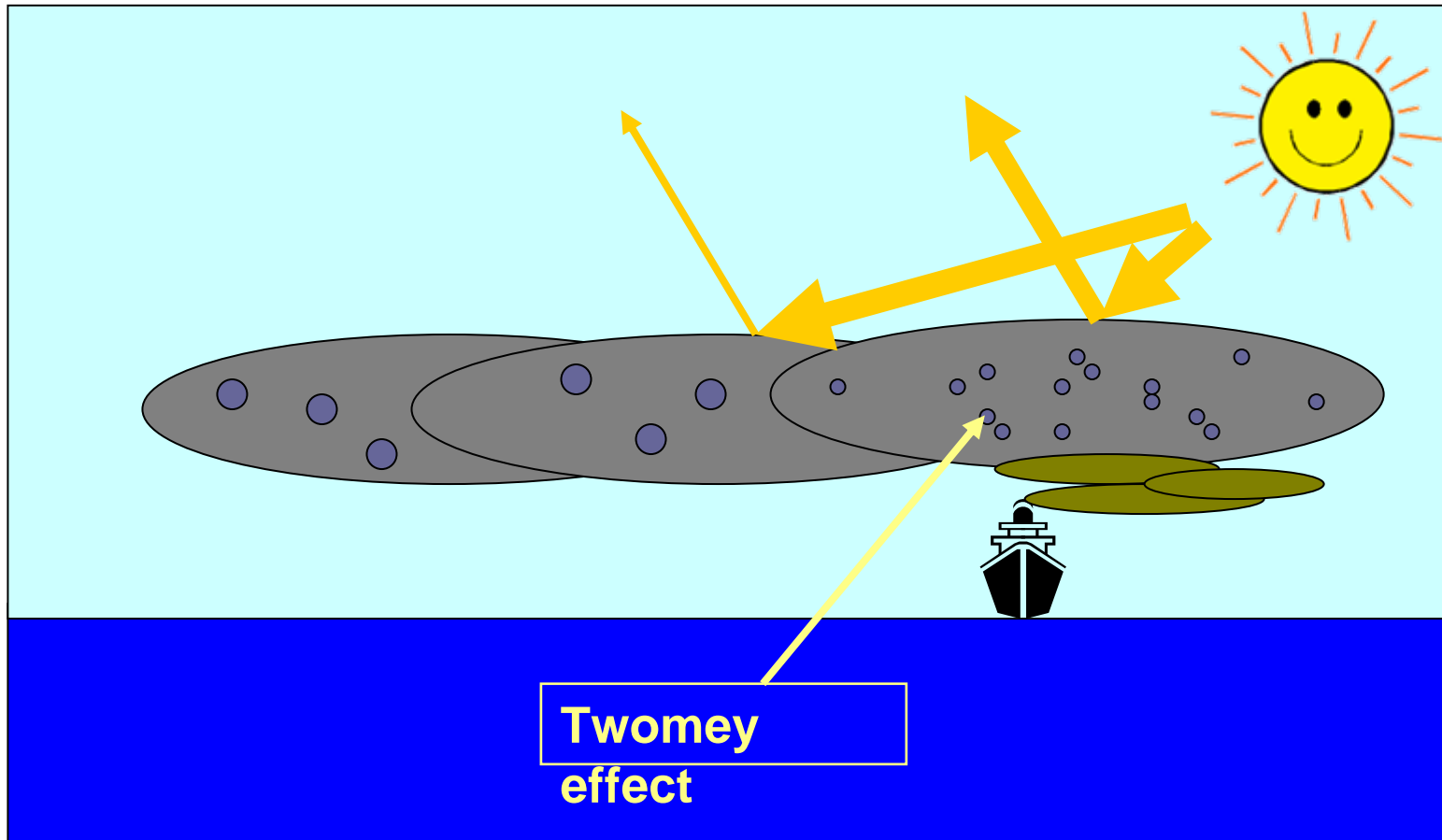


Ship emissions below the cloud:

Part of this emissions can act as cloud condensation nuclei

⇒ Change in droplet size and number

⇒ Change in reflectivity



The Monterey Area Ship Track Experiment

MAST took place in June 1994 off the coast of California.



It produced the largest dataset so far of direct measurements of the effects of ship emissions on the $\mu\phi$ and rad. properties of marine Sc clouds as an analog for the indirect effects of anthropogenic pollution on cloud albedo.

Composite Ship Track Characteristics (Durkee et al.)

Analysis of 131 ship-ship track correlation pairs:

Significant variability around average values

length: 296 ± 233 km, width: 9 ± 5 km

age: 7.3 ± 6 h, but many tracks get older than 12 h

head of the ship track is 16 ± 8 km behind , or 25 ± 15 min. after the ship

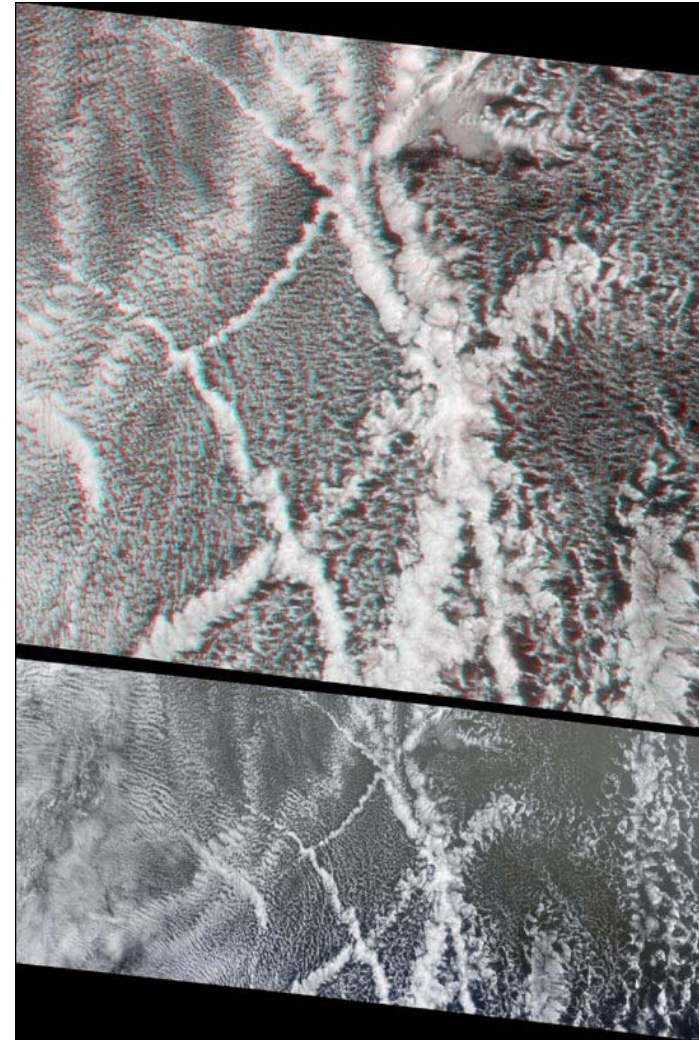
Characteristics of areas where ship tracks formed:

MBL is between 300 and 750 m deep, never deeper than 800 m.

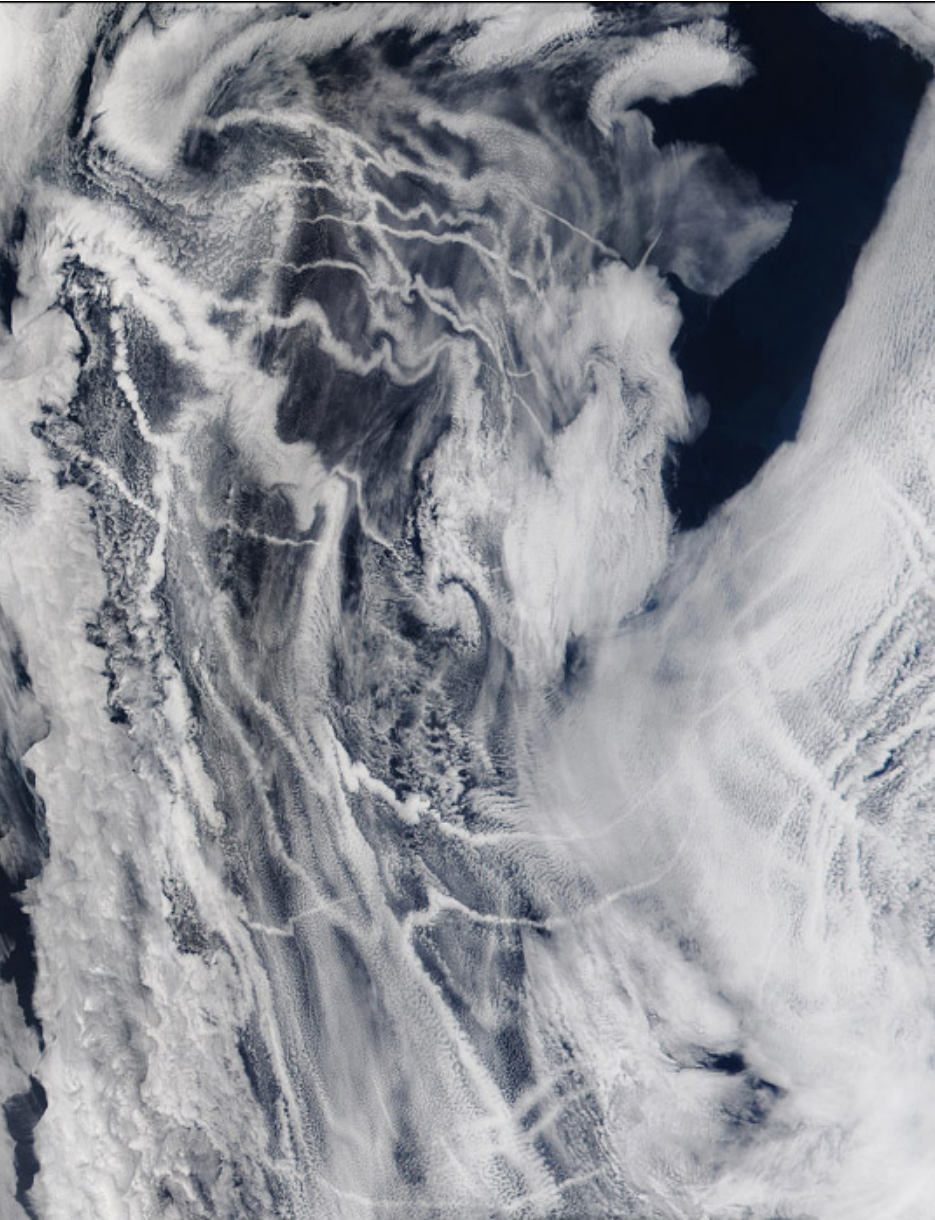
high RH, small air-sea temperature differences

moderate winds: 7.7 ± 3.1 m/s

Distributions of MBL and cloud properties overlap a lot for ship track and no-ship track regions. Statistical significance of differences in the mean not clear.



Not all ships produce tracks ...



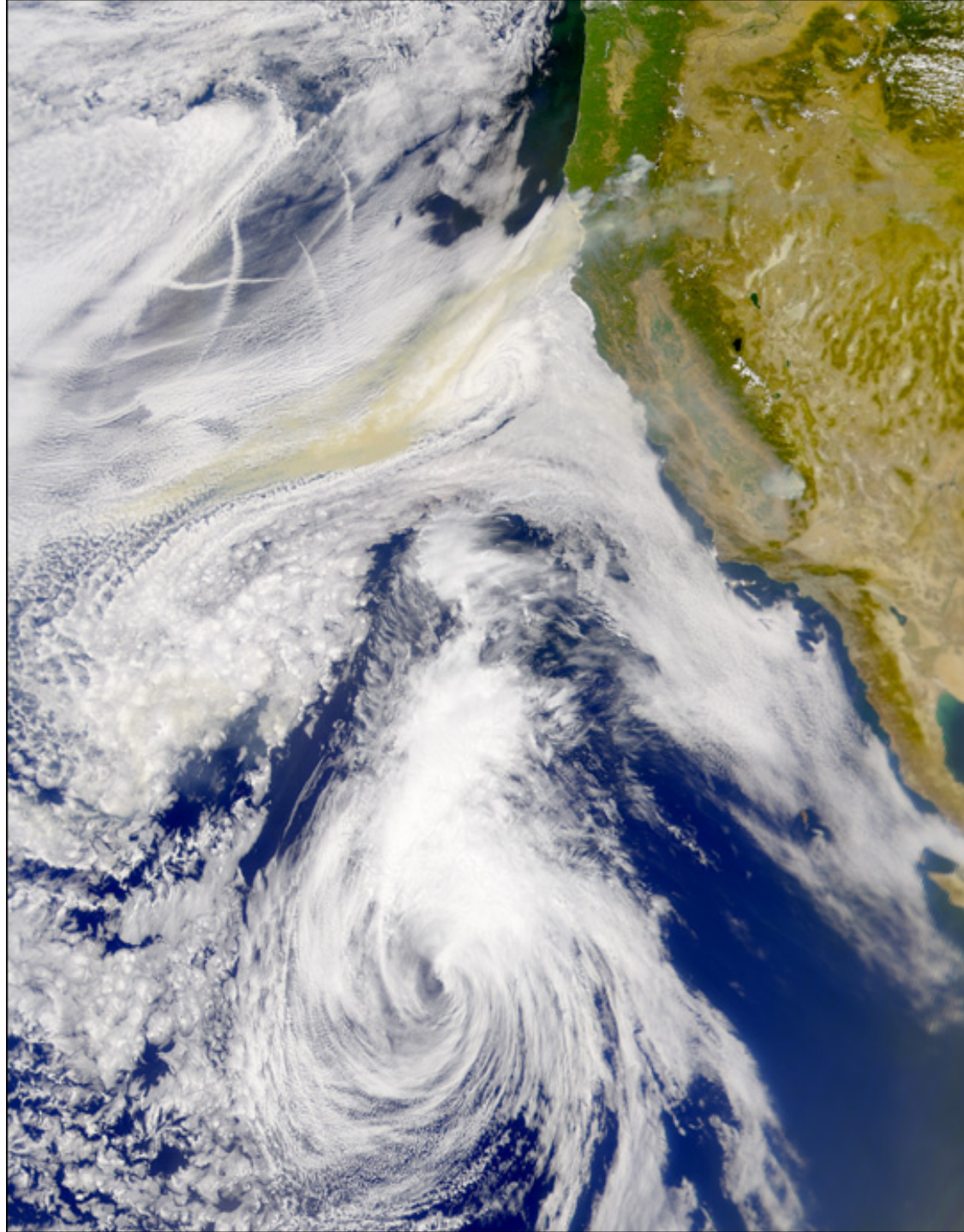
Provided a cloud layer is susceptible to an aerosol perturbation, and the atmospheric stability enables aerosol to be mixed throughout the BL, the **direct emission of CCN from the stack of a Diesel powered ship** is the most likely, if not the only, cause of the formation of ship tracks.

... not all particles are involved

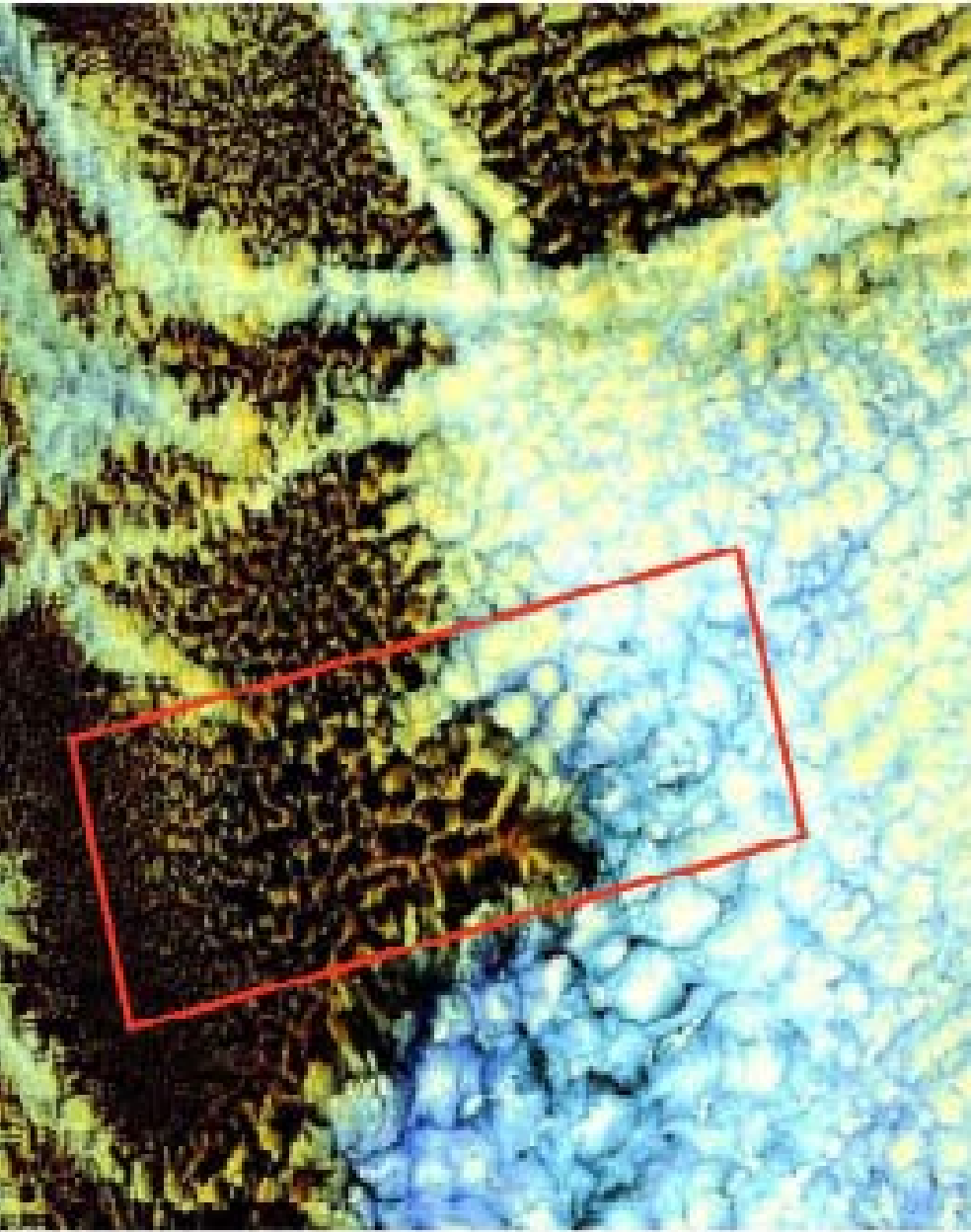
The **type of fuel burned** seems to be more important than the type of ship engine in determining whether a ship will produce a track or not.

Only about 12% of the particles from MFO burning serve as CCN.

Water and heat fluxes don't produce detectable perturbations.



Microphysical effects of ship tracks



- Ship tracks **suppress drizzle** formation.
- This affects **cloud life time** and budget of **latent heat**
- Transition between **closed and open convection** does not occur in regions with ship tracks.
- Influence of ship tracks on liquid water path is probably insignificant.

Impact of ship emissions on the microphysical, optical and radiative properties of marine stratus: a case study
(Schreier et al., 2006)

Comparison between non-ship-track pixels and ship-track pixels gives:
Significant **decrease of effective radius** from 12 to 6 μ ,
optical thickness of unpolluted clouds is 20-30, of ship track up to 45
droplet number concentration increases from 100 cm^{-3} to 800 cm^{-3}
Liquid water path hardly affected.

Summary: Ship-tracks

What we know:

Ship particulate emissions modify cloud properties, in particular

- a) smaller average droplet size (Twomey effect)
- b) enhanced cloud reflectance in the NIR
- c) drizzle suppression, break of the closed-to-open cell convection transition

Ship track formation needs certain ambient conditions. Selective phenomenon.

What we don't know or don't know well:

Climatology

Ship track formation independent of the Twomey effect

Why do ship-tracks be relatively long in shape?