Action de recherche sur Aviation et Climat

Climaviation

Contrail modeling activities in Climaviation project

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SORBONNE UNIVERSITÉ · cnrs · IPSL Institut Pierre-Simon Laplace (IPSL) Sciences du climat · RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité · ONERA THE FRENCH AEROSPACE LAB

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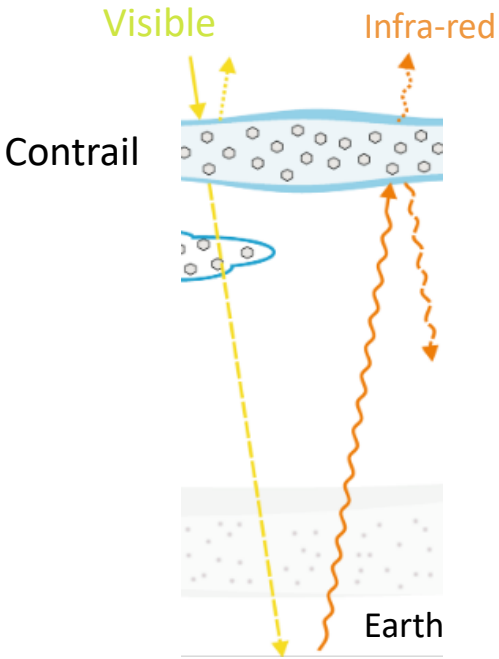
What are contrails?

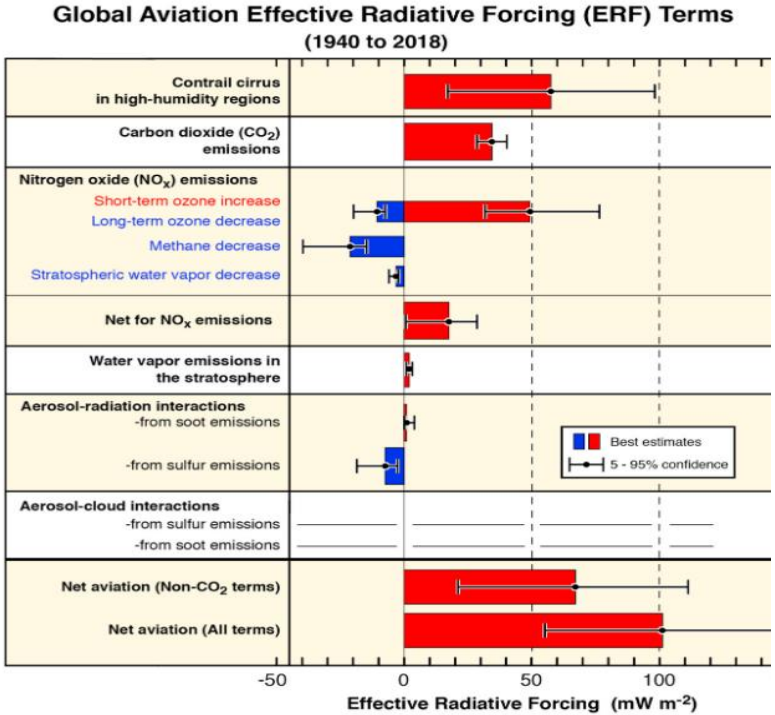
- Ice clouds which can remain several hours
- Their initial linear shape can evolve to become undistinguishable from natural Cirrus

Effect on light



- Contrail reflects part of visible light (Cooling effect)
- But also infra-red (warming effect)
- Some contrail may cool the atmosphere, some may warm
- What is the overall energy balance?

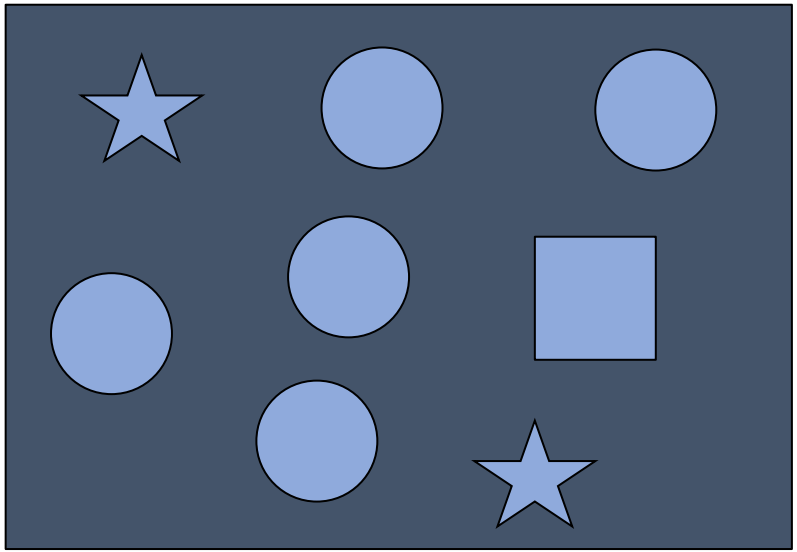
Different contributions of aviation to energy balance



Lee et al. 2021 Atmospheric Environment

- Overall contrail have a heating effect
- About twice as much as the CO_2
- The uncertainty is high
- Overall a high uncertainty on aviation climatic impact

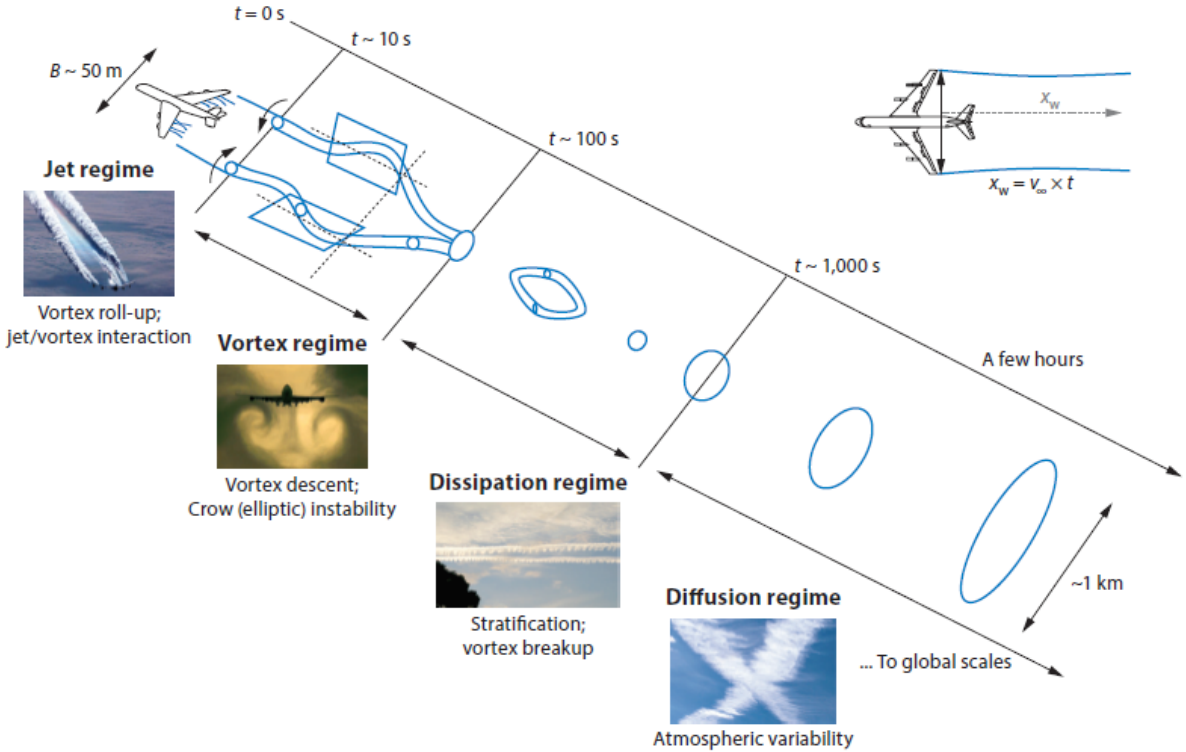
What are the parameters which are relevant for radiative impact of contrail?



- Probability of interaction between ice crystals and a photon: $\boldsymbol{P} = \frac{\boldsymbol{S_p}}{\boldsymbol{S_{vol}}}$
- P is a function of:
  - Contrail's surface
  - Its height
  - Density in ice crystals
  - Size of the ice crystals
  - Shape of the ice crystals
- Need to understand the evolution of all these parameters

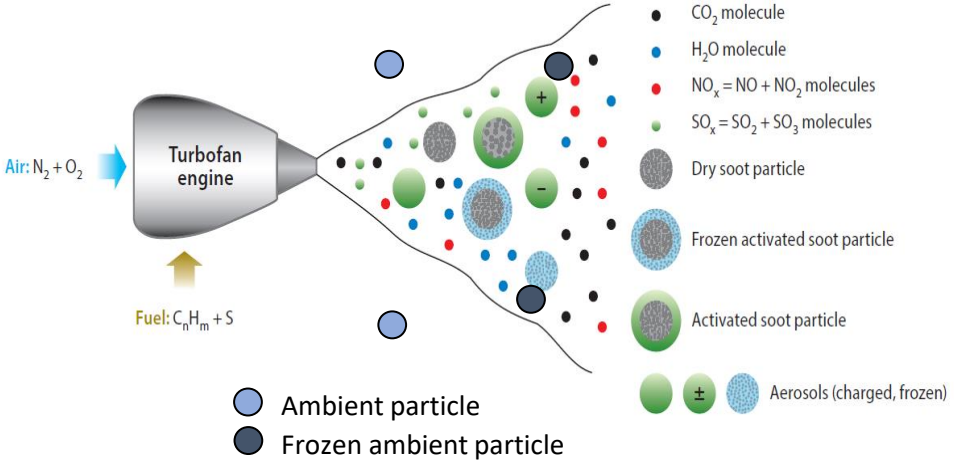
Physics and simulation of contrail

Life of a contrail



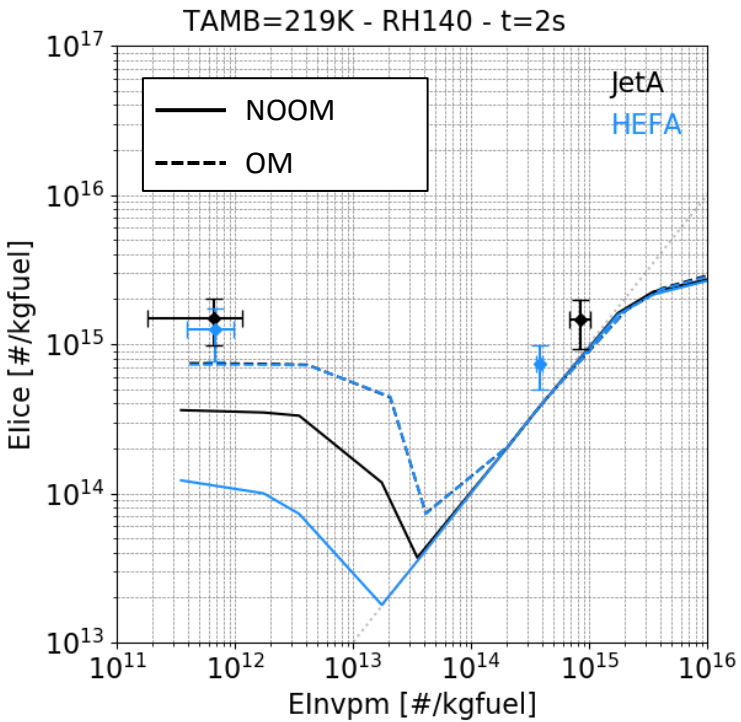
Formation pathway of ice crystals

- Combustion produces:
  - Soots
  - Water
  - NOx
  - SOx
  - CO_2
  - Unburned organic molecules, lubrification oil
- SOx and NOx can transform in H_2SO_4 and HNO_3
- Acids+water can form clusters which can transform in ice crystals
- Soots can act as condensation nuclei which can transform in ice crystals
- Ambient particles are dragged into plume and can transform into ice due to available water in the plume



Depending of the fuel, ambient conditions, combustion technology, the dominant pathway can change (Fuel sulfur content/ Soot emission index)

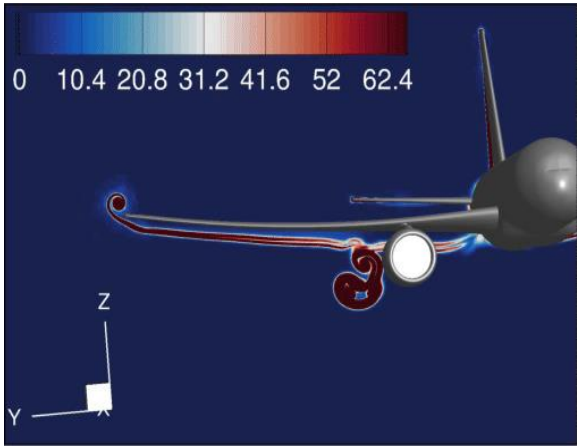
Modeling of contrail formation (MoMiE)

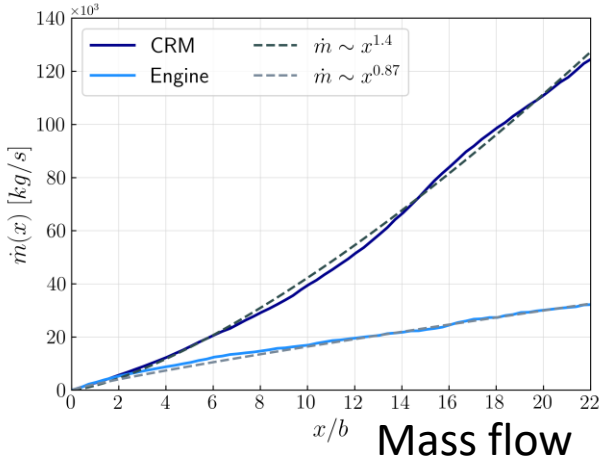


- Detailed microphysic scheme
  - Nucleation
  - Condensation
  - Coagulation
  - Freezing
- Set for carbon based fuel
- Lubrification oil considered as insoluble organics but can't create new particles (hypothesis)
- Mainly reproduce experimental results even in lean burn mode
- Need to introduce a new nucleation process?
- Nitric acid? Lubrification oil?
- Climaviation studies nitric acid pathway for H_2 combustion engine

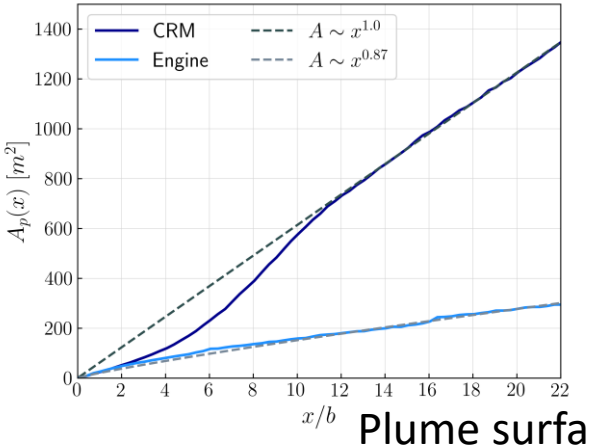
Measurement from DGAC Volcan project made by DLR (preliminary)

Plume mixing and interaction with aircaft wake (R. Annunziata - PhD thesis)





Mass flow



Plume surface

MoMie predicts a constant ice crystal number after 0.75 – 1 s

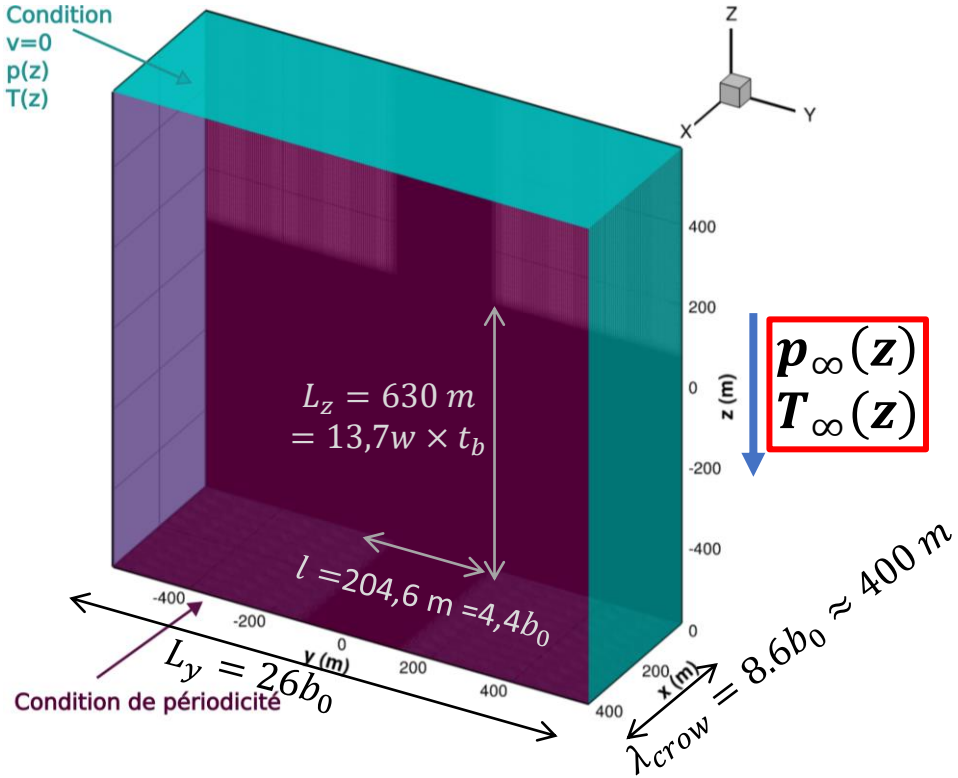
Nucleation code uses a dilution based on engine simulation or a dilution law based on measurement (neglecting evolution of by-pass ratio)

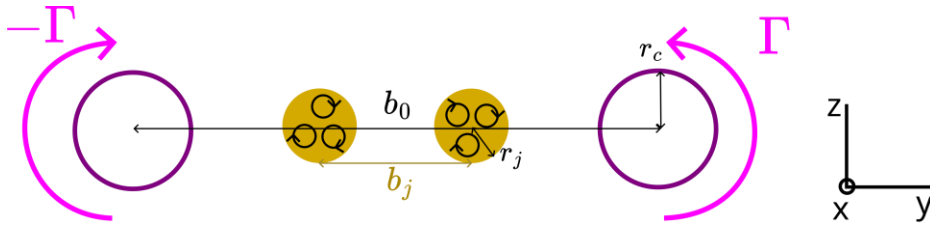
In Climaviation: 2 simulations, one considering full aircraft and one considering an engine only have been made

⇒ Clear change in dilution law after 0.5 s (2 spans)

⇒ Consequences on ice crystal number and size?

Vortex and dissipation phase

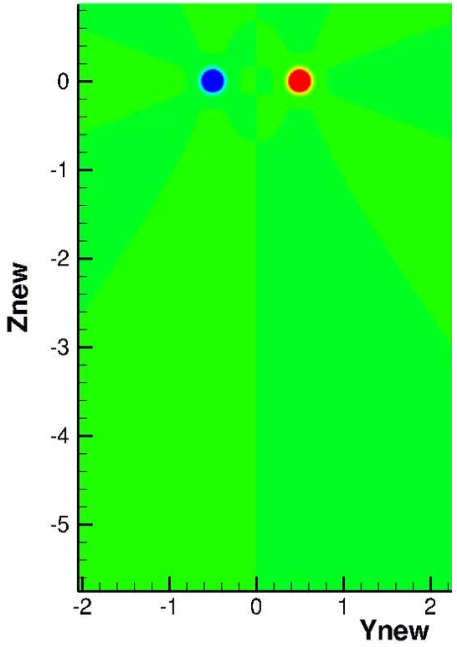




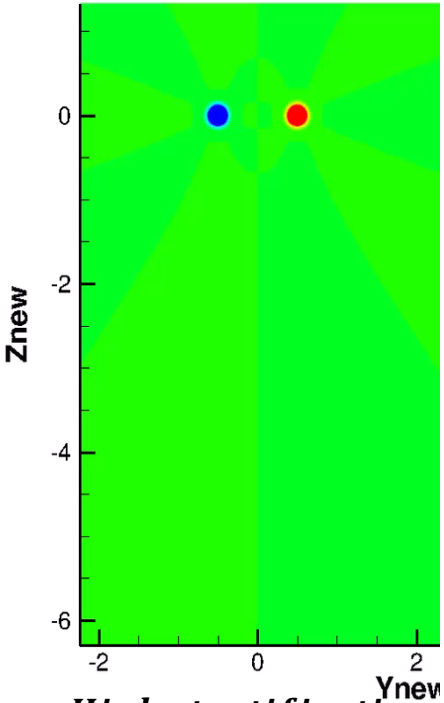
Analytic initialisation (Litterature)

- Usually a plume is added to two contrarotative vortices scaled on aircraft data
- Stratification of the atmosphere is added as well as atmospheric turbulence
- A slice of the contrail only is simulated up to 5 - 7 min

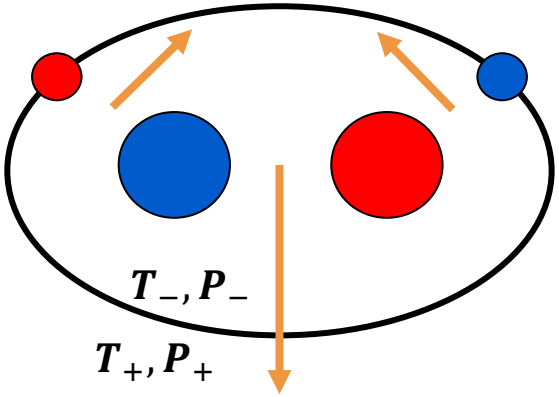
Vortex behaviour in 2D



Low stratification



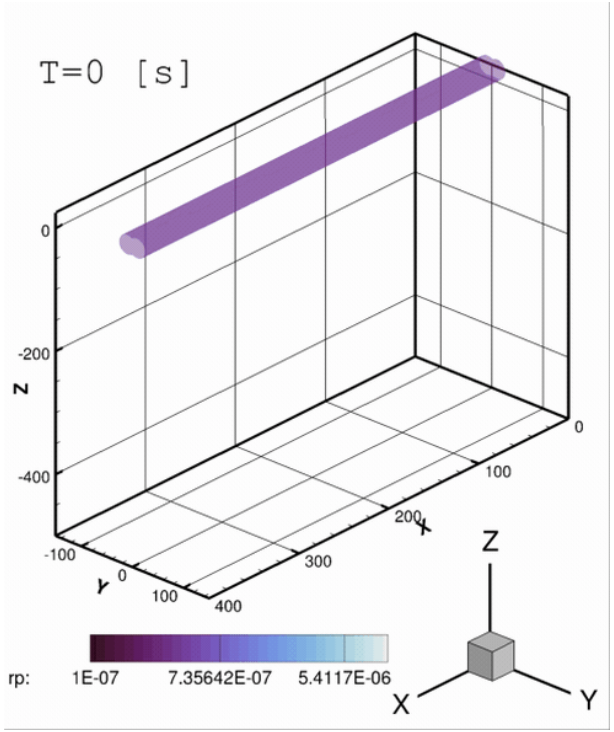
High stratification

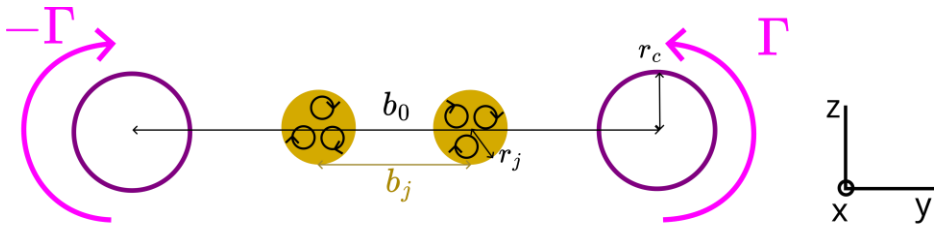


$$\frac{dw}{dt} = \frac{1}{\rho^2}\nabla P \times \nabla T + \nu \Delta w$$

- Creation of a vorticity map due to pressure and temperature gradient
- Acts like we have more vorticies which will slow the descent and bring the vorticies closer which at the end will accelerate the descent

3D simulations of a contrail



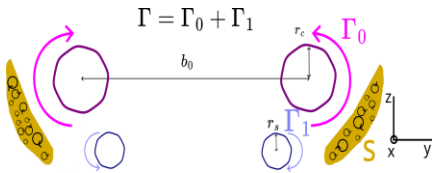


Analytic initialisation (Litterature)

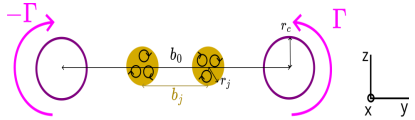
- For the first 30 s, ice cristals follow the descent of the vortices
- Then, some of them are ascending, going even above flight altitude (due to stratification)
- Then vorticies are breaking up due to Crow instability forming a ring vortex and a puff of ice crystal below the linear secondary wake

Vortex phase including aircraft geometry (Y. Bouhafid - Phd Thesis)

RANS initialisation



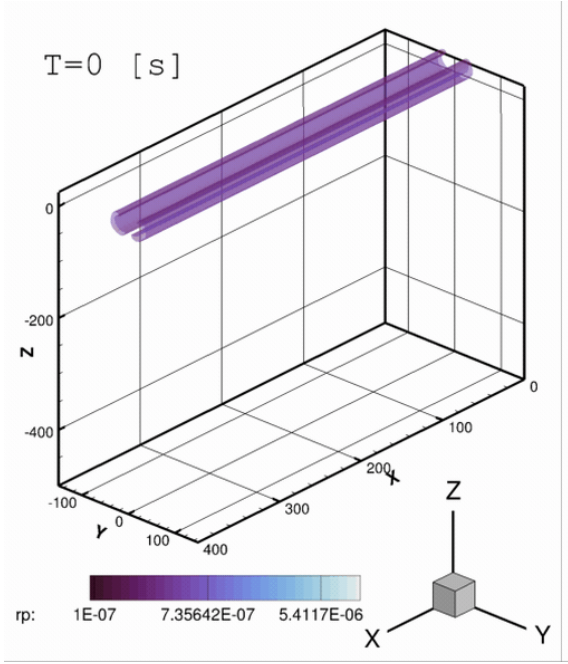
Analytic initialisation



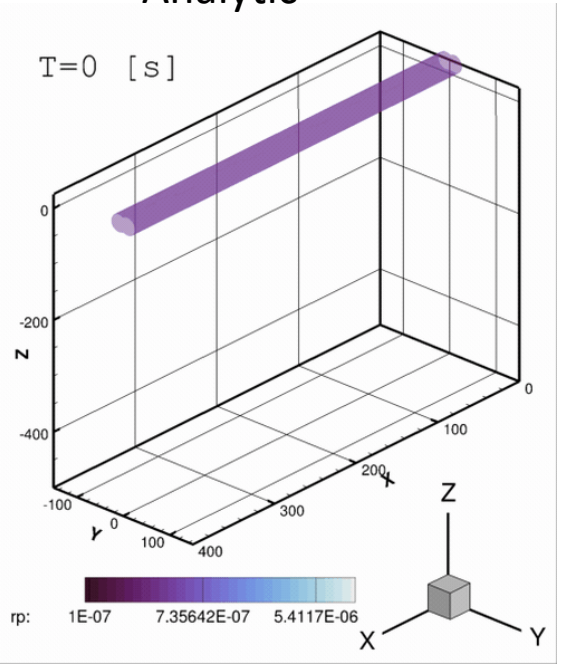
- RANS initialisation presents a much turbulent secondary wake
- The secondary wake is then bigger
- Are the tail plane vorticies responsible?

$$N_b = 0.012\ s^{-1}$$
$$\epsilon_{atm} = 6 \times 10^{-5}\ m^2 s^{-3}$$

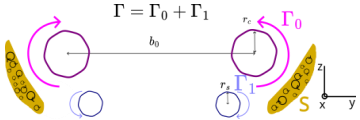
RANS



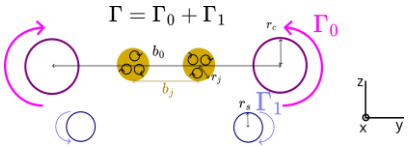
Analytic



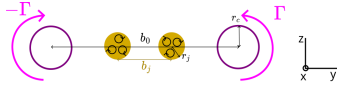
Comparison with 4 analytical vorticies



RANS

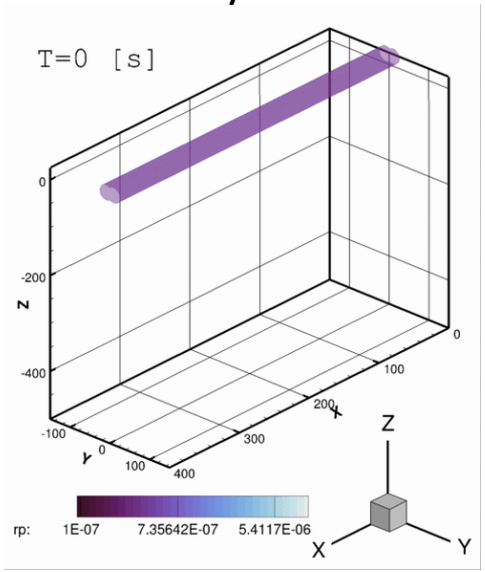


4 vortices

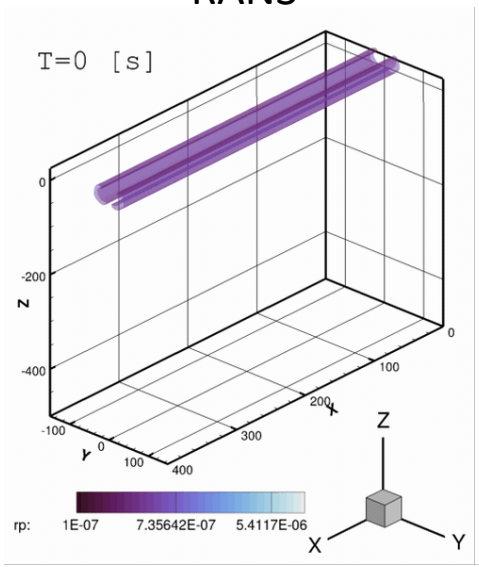


2 vortices

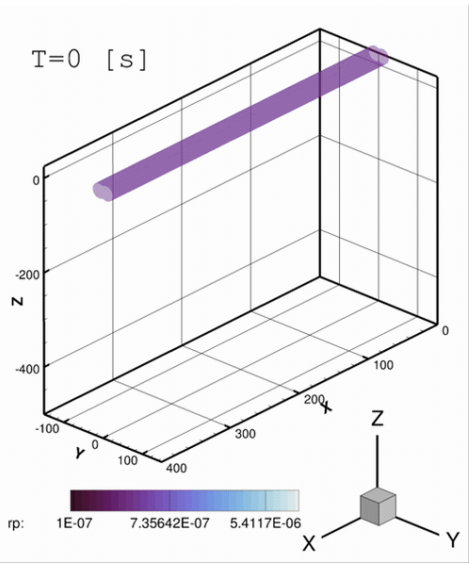
Analytic



RANS



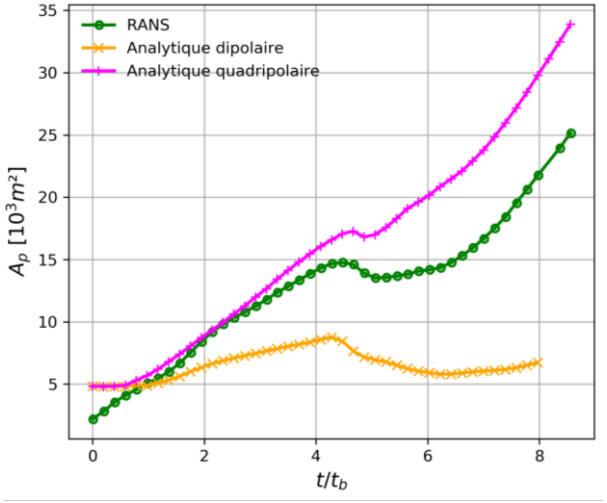
4 vorticies



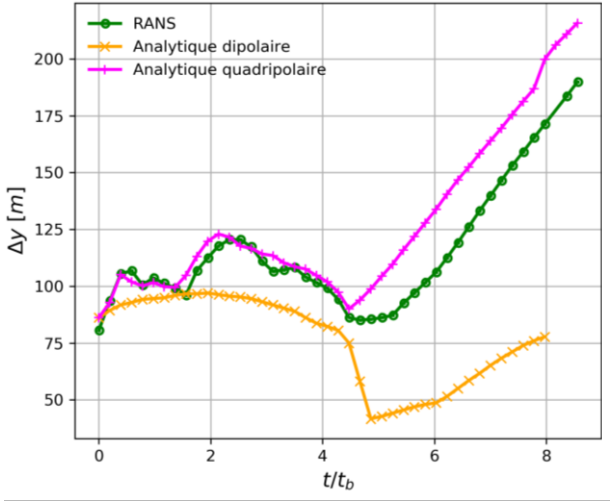
4 vorticies is much closer from the RANS than the 2 vorticies

A 4 vortex system has been shown being more unstable to short wave instability (depending on vorticies characteristics)

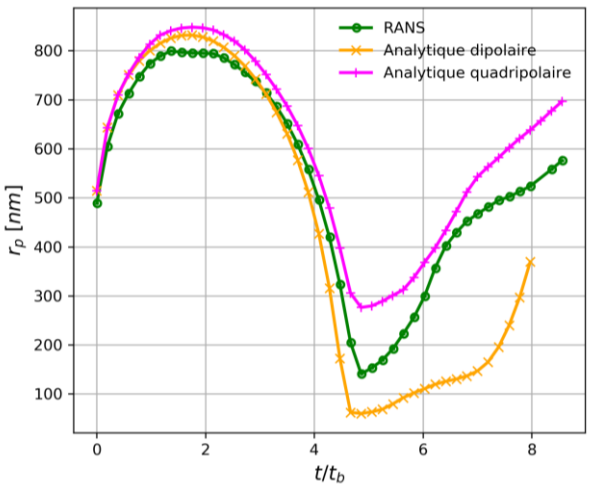
Effect on contrail characteristics



Area of the contrail



Width



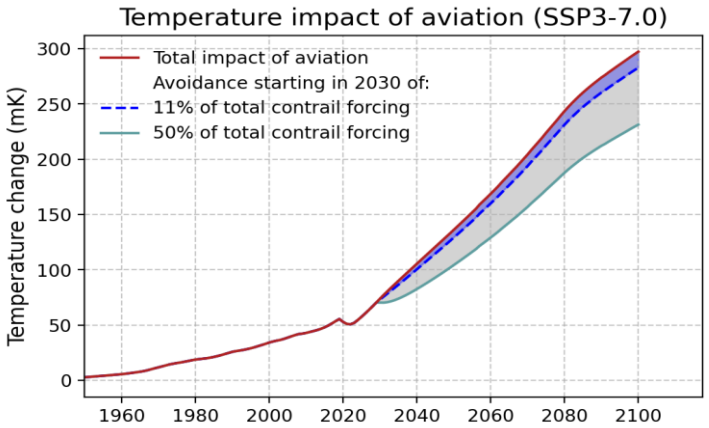
Ice crystal radius

Not taking into account the tail plan vorticies can lead to great error on the parametrization in climate model

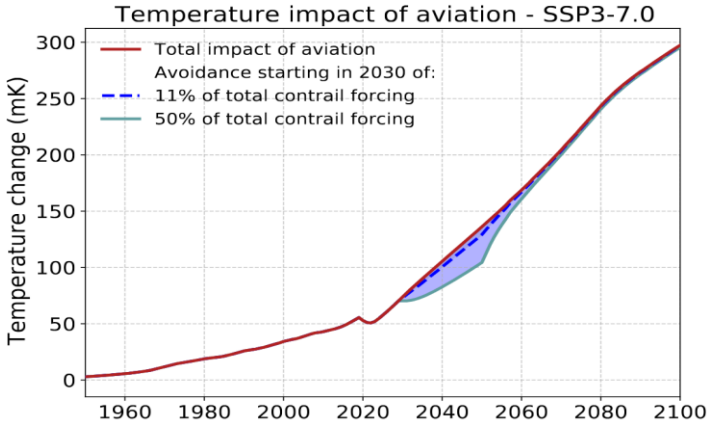
Re-routing for contrail avoidance

Why trying to avoid contrail?

Reduction of forcing due to contrail
11 % (blue) and 50 % (green) in 2030
0 % in red



If we reduce forcing of contrails in 2030 and stop doing so in 2050

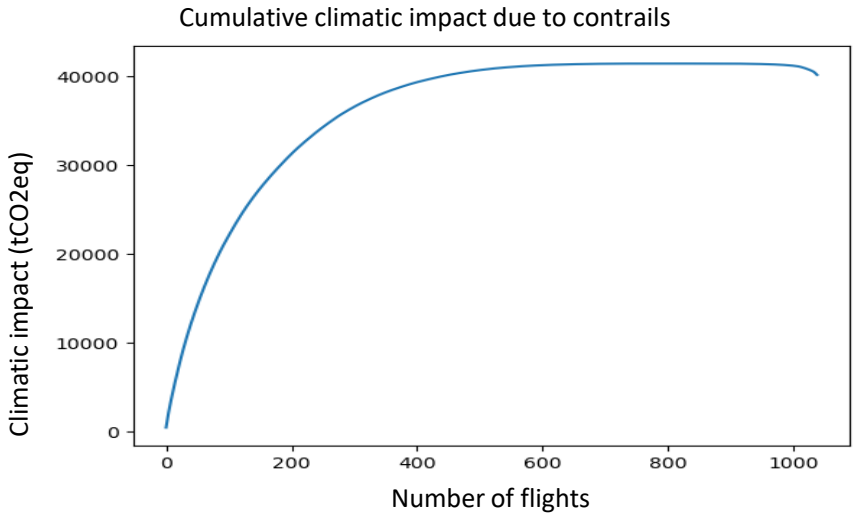


OSCAR model, Audrey Lecouffe (Climaviation)

What proportion of flight should be re-routed?

A small number of flight represents the majority of the radiative impact

Depending of the studies 2 – 20 % of flights make 80 % of the radiative impact



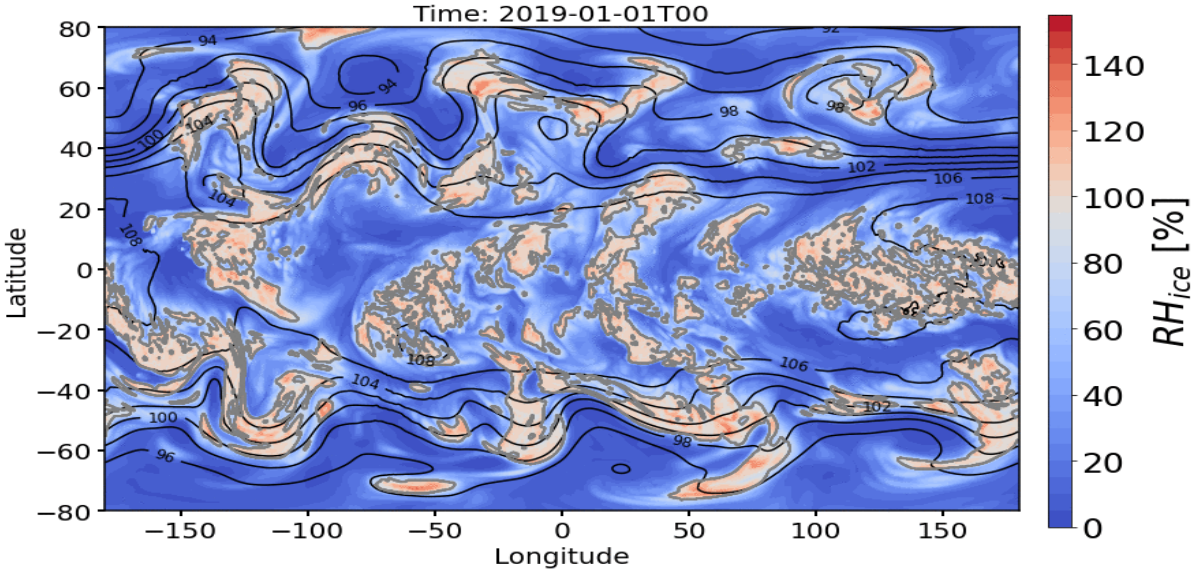
1000 transatlantic flights in january 2025

Climatic impact due to contrails (40,000 t CO_2eq)

200 flights represents 80 % of the effect

How?

Need to avoid Ice Super-Saturated Region

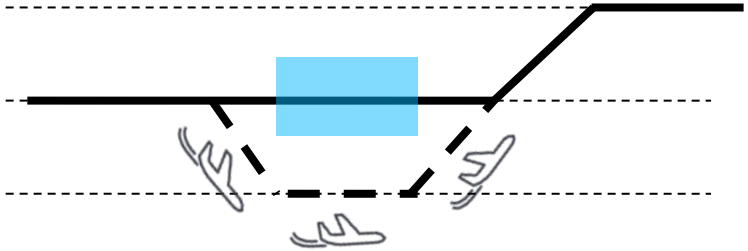


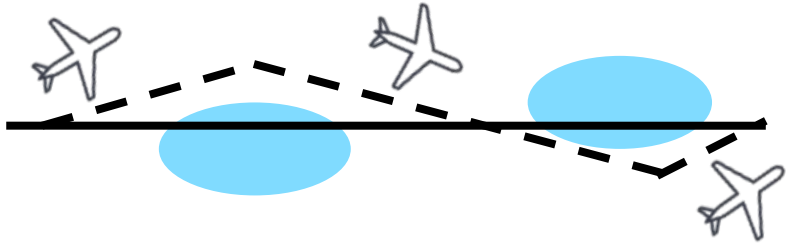
From Kevin Wolf (Climaviation)

Evolution of ISSRs at 250 hPa between 1 - 4 January 2019

How?

Need to avoid ice super-saturated region



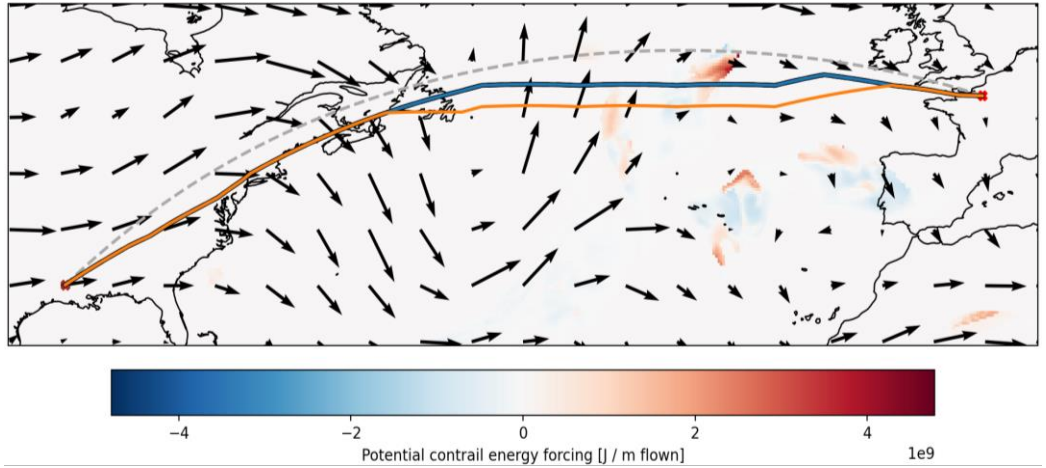


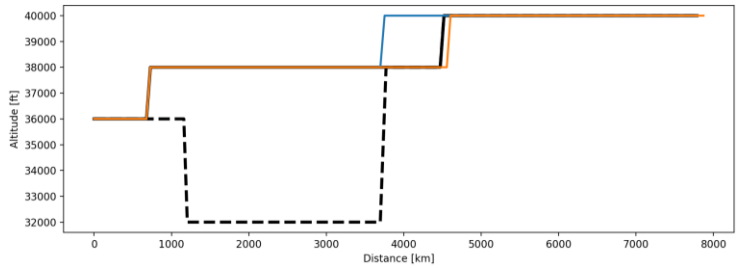
By vertical avoidance

Horizontal avoidance?

Or both?

Results of optimisation



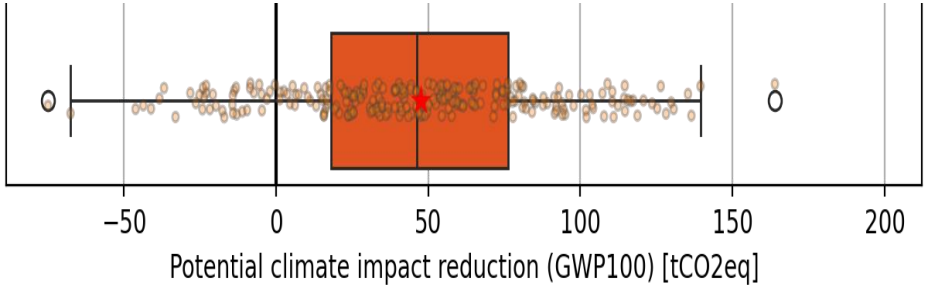


Grand circle
Optim fuel
Optim climate
Optim climate tiers

	Fuel (tCO_2)	Climate (tCO_2eq)
Optim fuel	52.15	236
Optim climate	52.91 (+1.4 %)	199 (-15 %)

Carried out with FlightOptima (Audran Borella)

Uncertainty sources: Model of climate impact, meteorology data, other…



Takes into account the uncertainties of the contrail code (CoCiP)

16 % chance that the rerouting was a mistake

But still right 84 %

In mean, rerouting seems a good thing

Conclusion

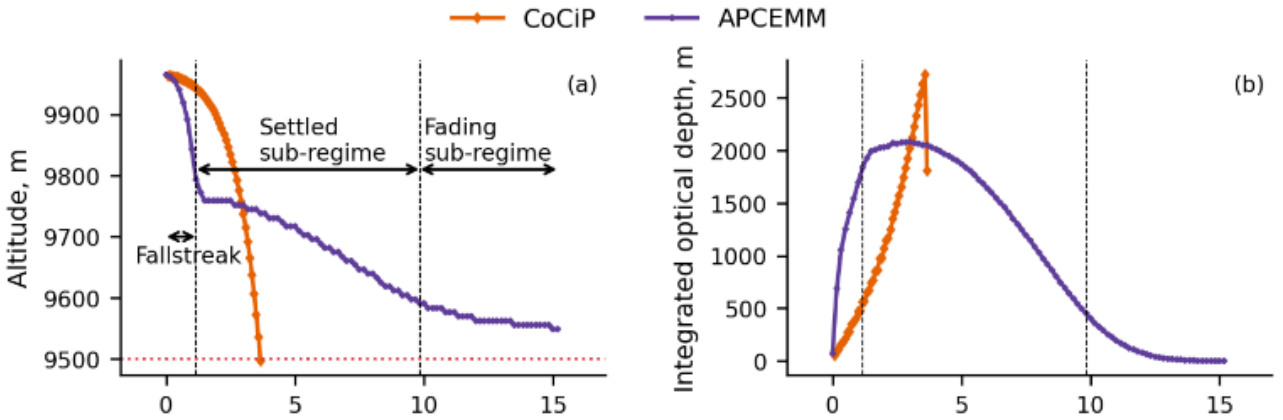
- Climaviation looks at:
  - The detailed physics of a contrails
  - Their climatic impact
  - Mitigation strategies such as rerouting but also the influence of the aircraft geometry in contrail properties (not shown here)

- Detailed contrail simulations have shown the importance of tail plane vortices (if they are strong enough)

- Re-routing strategy shows that contrail avoidance is very likely to be good for climate however it uses a simplified contrail code (CoCiP)

Comparison of two contrail simplified models

With same meteo conditions:



Martìnez et al. (preprint) https://doi.org/10.5194/egusphere-2025-278

Which model is the most relevant?

How this difference can influence the statement on rerouting?