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CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

ISA Workshop

Formation and Radiative Forcing of contrail cirrus

Friday, 13 December 2024

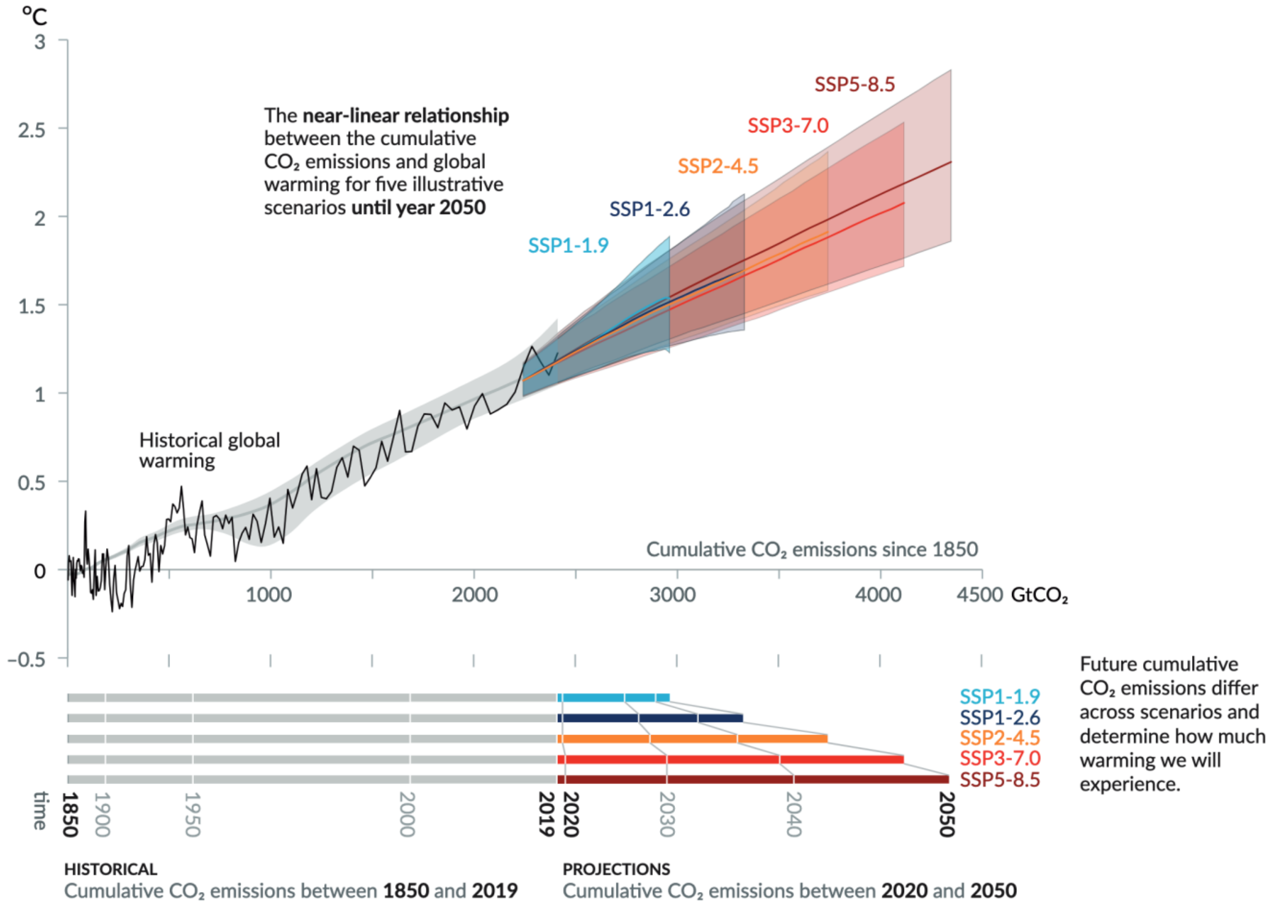
A general overview of contrail cirrus

Contrail cirrus and climate modelling

Global warming and aviation

- Carbon budget :
  - 400 $GtCO_2$ to stay below 1.5°C
  - 1200 $GtCO_2$ to stay below 2°C
- 2022 annual emission : 37 $GtCO_2$

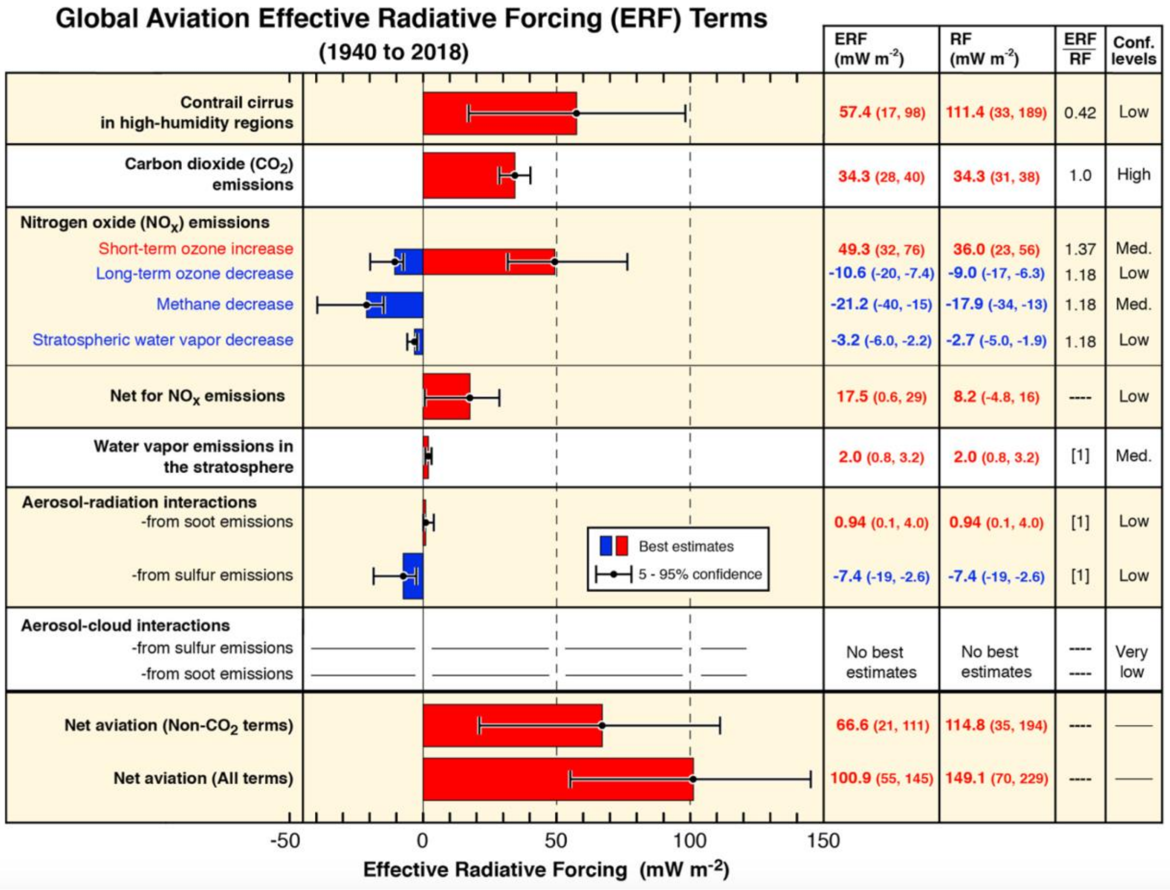
- Aviation accounts for **2.5% of the total anthropogenic CO_2 emissions** in 2018
- Projected 3-4% annual growth to 2050



ICAO, 2012
IPCC 6th Assessment Report, 2021
Lee et al., 2021

Impact of aviation on climate change

- Aviation accounts for 3.5% of the global anthropogenic effective radiative forcing
  - 66% due to non-CO2 effects
- **Low confidence level**
  - Especially on contrails (85% of non-CO2 effects)
  - Best estimate based on 3 values
- **Better quantify** (and eventually reduce) **uncertainties** for integrating non-CO2 effects in policy agreements



Lee et al., 2021

Impact of climate change on aviation

The Guardian

Eur

Extreme heat forces US airlines to limit passengers and fuel loads

High temperatures reduce engine performance and the lift airplane wings are able to produce, leading s… …rlines to warn of delays

Signs of ice buildup on plane before Brazil crash, says early report

Copilot recorded saying 'a lot of icing', indicating aircraft's de-icing system may have failed before August crash, according to investigators

Le Monde

ÉCONOMIE • TRANSPORTS

Passager mort lors d'un vol de la Singapore Airlines : les turbulences de haute altitude « sont très difficiles à prévoir »

Une personne est morte et plusieurs autres ont été blessées lors d'un trajet de Londres à Singapour, mardi. Si les accidents liés à des turbulences sont de plus en plus fréquents, les décès restent très rares, commentent des pilotes interrogés par « Le Monde ».

Par Guy Dutheil

Publié le 21 mai 2024 à 17h51, modifié le 22 mai 2024 à 01h15 • Lecture 2 min.

EL PAÍS

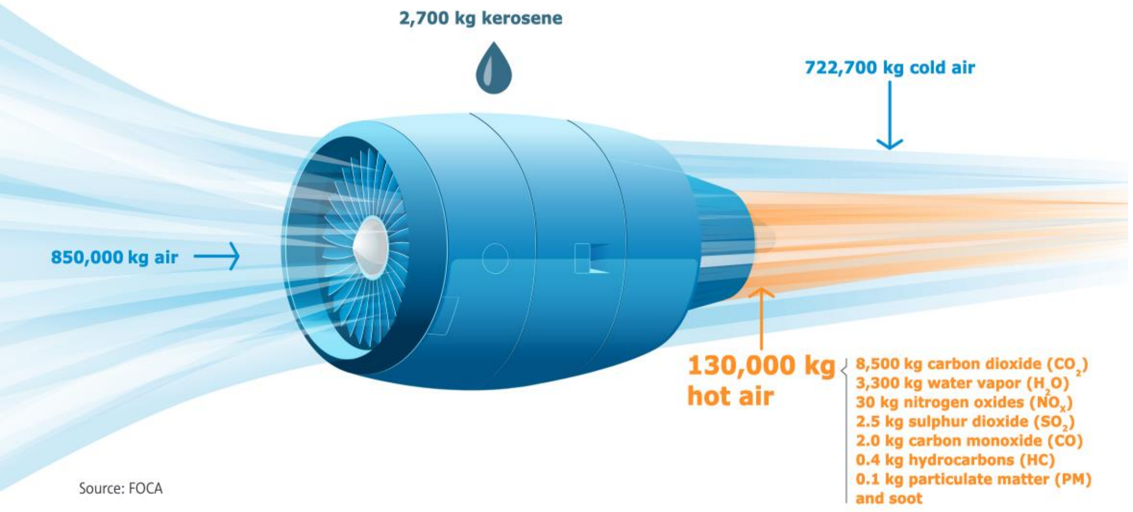
FLOODS IN SPAIN >

Barcelona on red alert for severe weather: Flights canceled and trains suspended

The same storm system that caused deadly flash flooding in Spain's Valencia region has now gripped parts of Catalonia

What are contrails (condensation trailing) ?

- **Mixing between cold/dry air** and **hot/moist** air creates contrails
  - Schmidt-Appleman criterion



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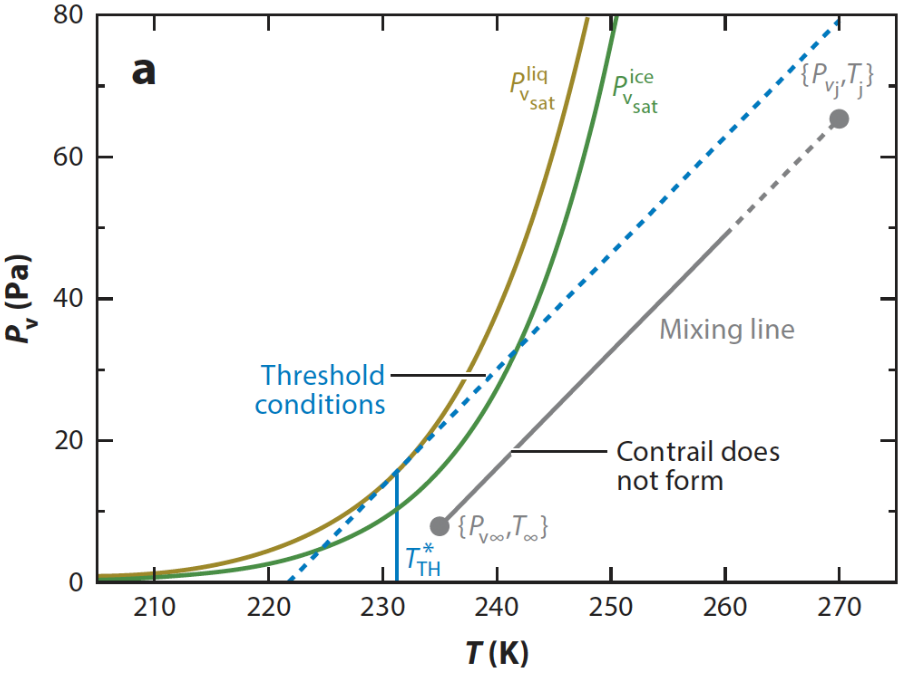
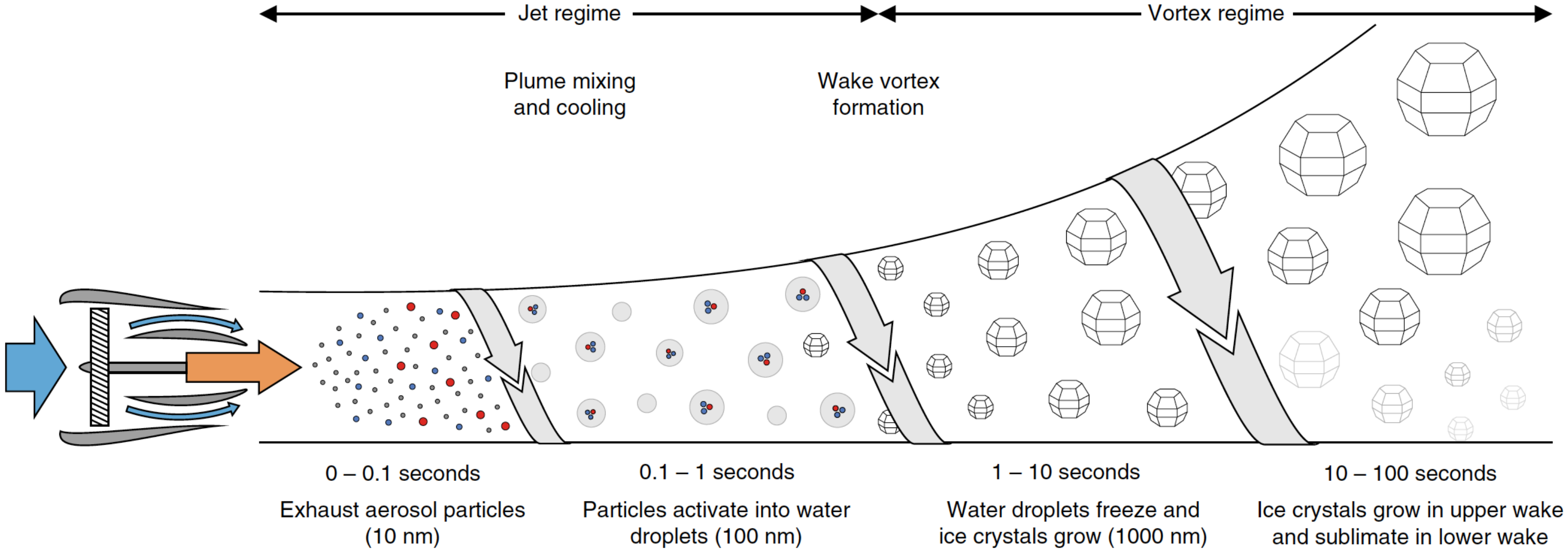


$$G = \frac{c_p P_\infty EI_{H_2O}}{\varepsilon Q(1-\eta)}$$

Schumann 1996
R. Paoli 2017

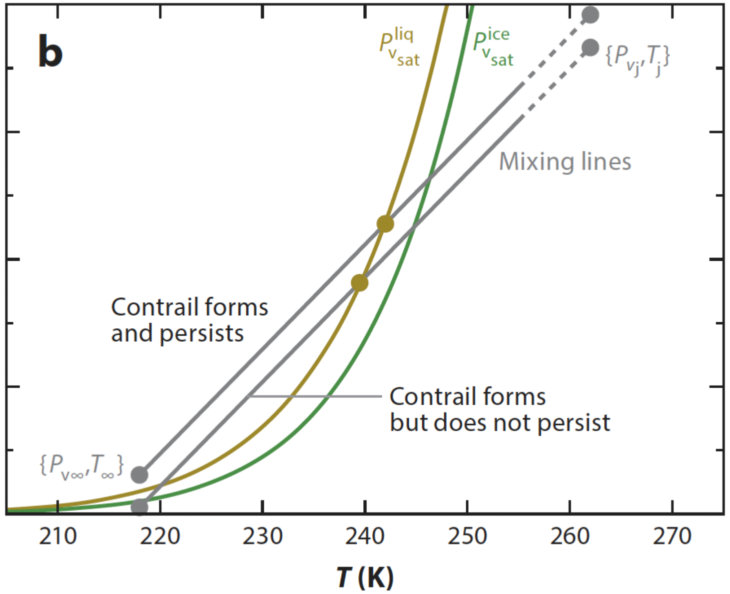
Contrail formation

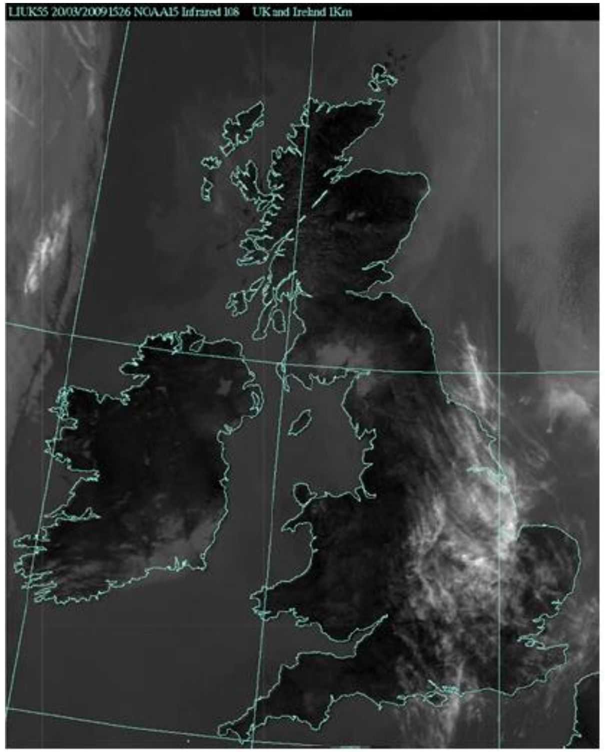


B. Kärcher, Formation and radiative forcing of contrail cirrus (2018)

Contrail formation

- Contrails persist if air is supersaturated with respect to ice (diffusion regime)
  - Width ~ 1-10 km
  - Depth ~ 400 – 600 m
  - Up to 100 000 km^2 cloud cover (~Portugal)





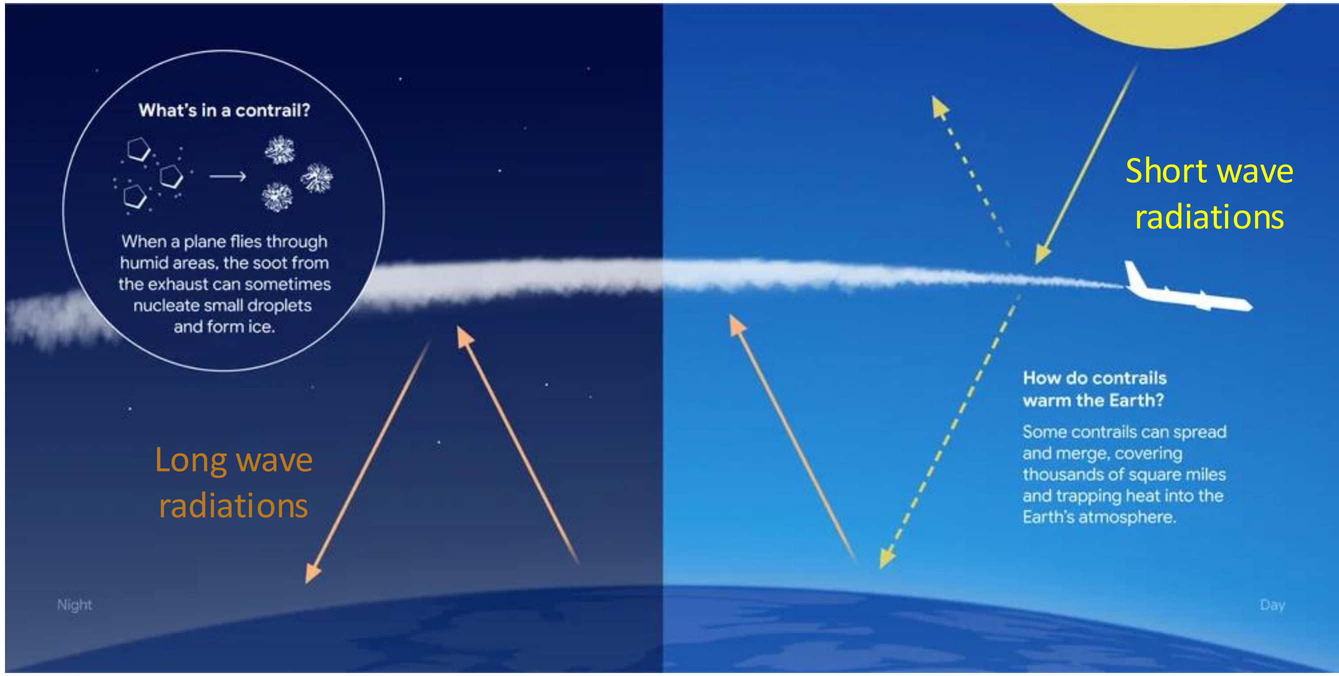
U. Schumann and A.J. Heymsfield, On the life cycle of individual contrails and contrail cirrus (2017)

Contrail radiative forcing

- Two opposing effects :
  - Cooling by scattering of solar radiation
  - Warming via absorption and re-emission of LW radiation

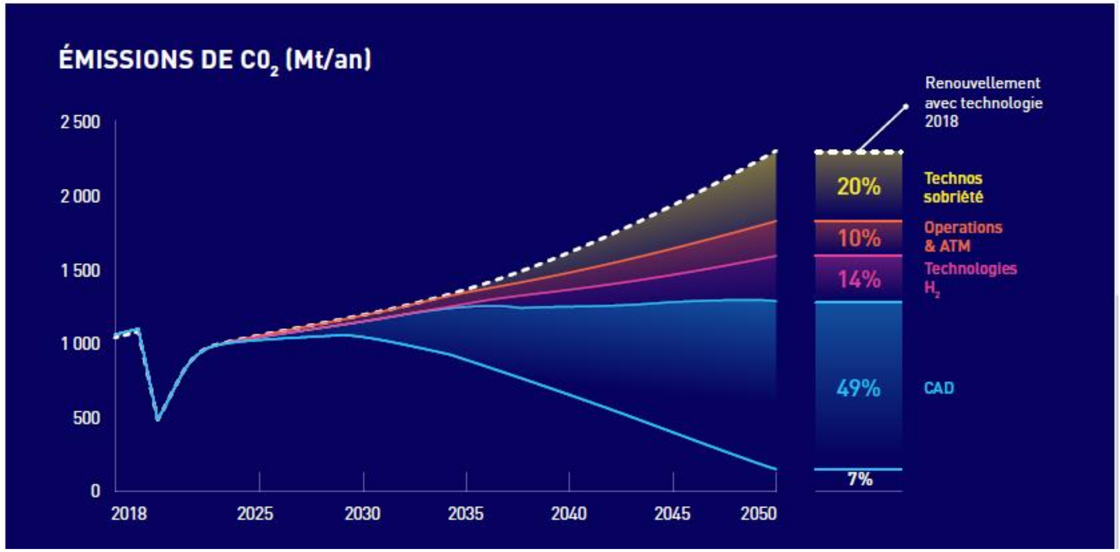
- **Net global warming**

- Driving parameters :
  - Coverage
  - Optical thickness
  - Crystals concentration/size/shape



Google

Mitigation strategies - Technological barriers



CORAC strategy « net zero emission » by 2050

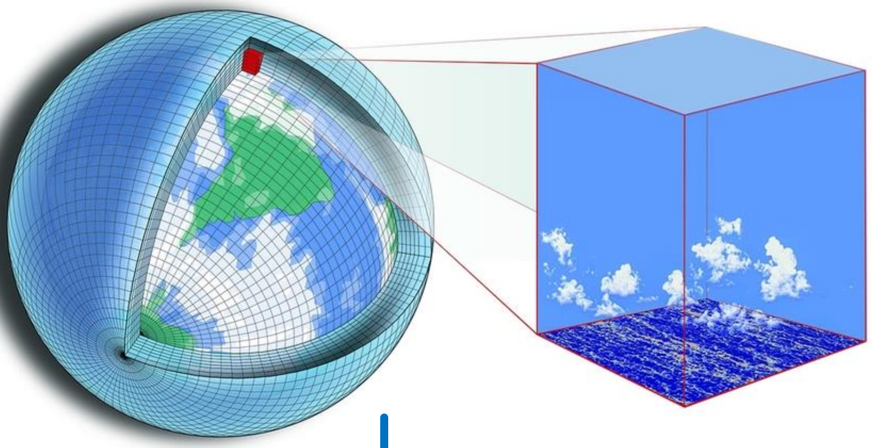
- **Contrail avoidance** is possible but complex
  - Ice Super Saturation Region (**ISSR**) **prediction**
  - Contrail radiative forcing **uncertainty**
  - **Metric** choice to compare with CO_2
  - Traffic management
- Impact of **new technology/fuel** on contrail properties

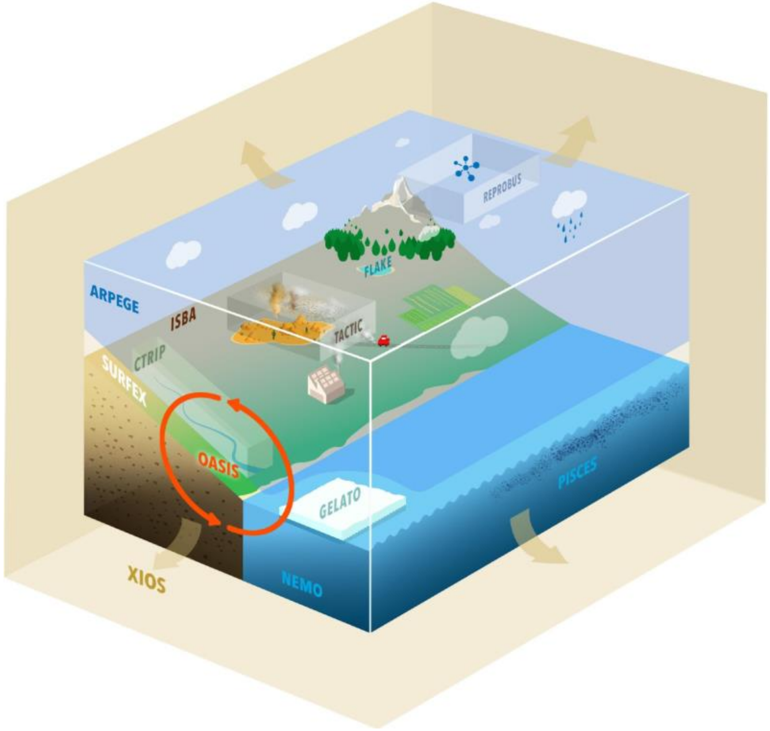
A general overview of contrail cirrus

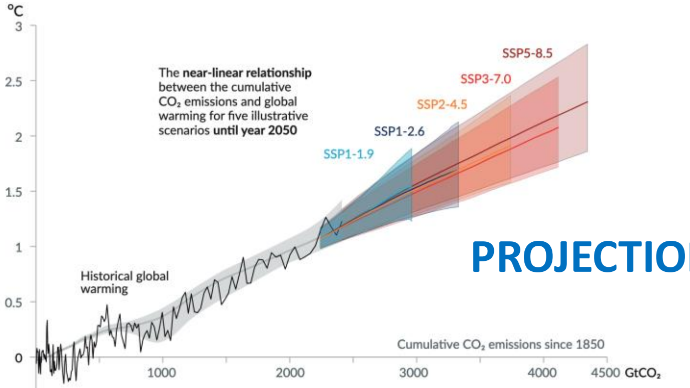
Contrail cirrus and climate modelling

What is an atmospheric model?

- Spatial resolution ~150km with 91 vertical levels
  - Solving the conservation equations
- Forcings :
  - Natural forcing (solar, volcanic)
  - Human forcings (GHG, aerosol, SSP scenario)



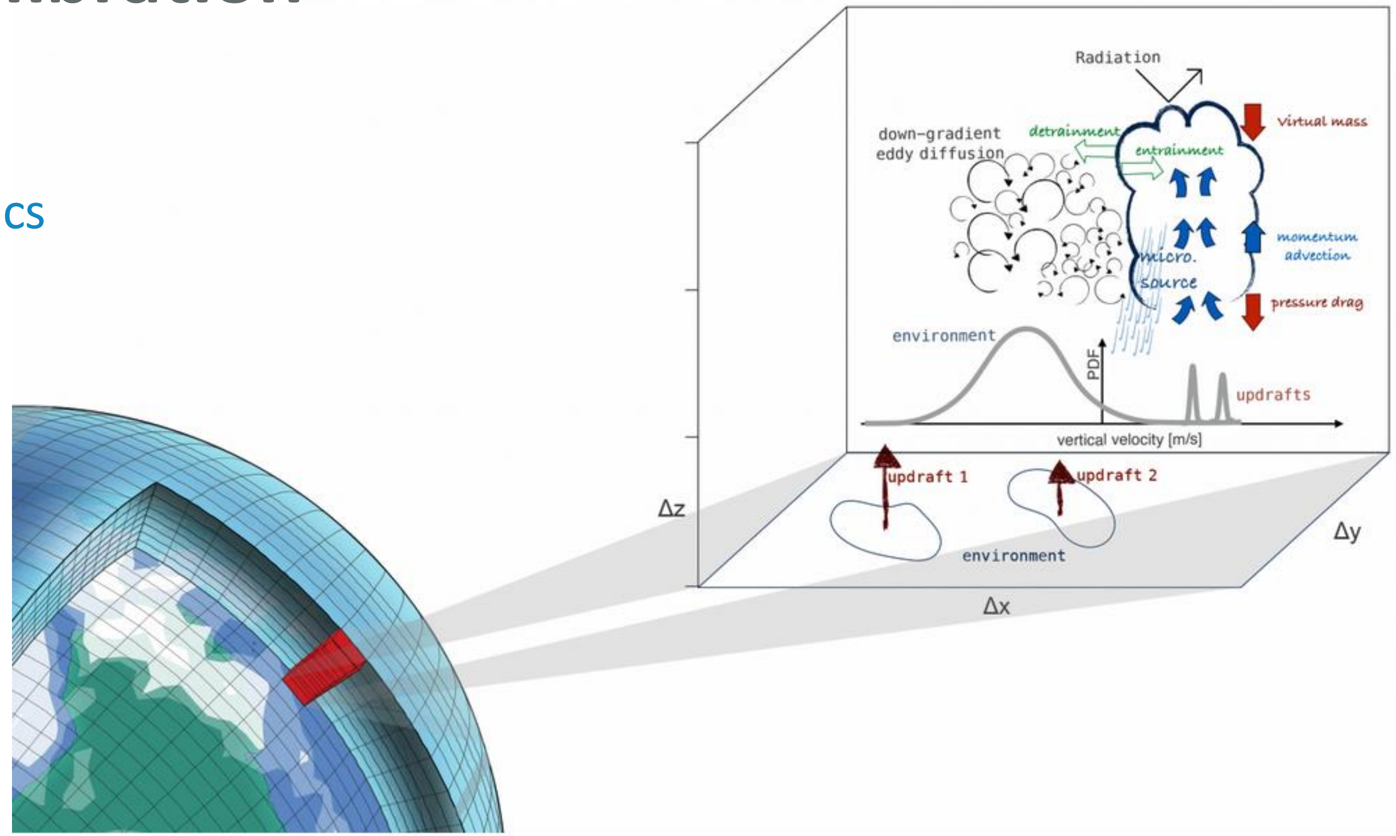




PROJECTIONS

Atmospheric model calibration

- **Parameterization** for subgrid-scale physics
  - Cloud microphysics
  - Convection
  - Radiation



- **Empirical** climate model **tuning**
  - Observation
  - Large **source of uncertainty**

- A single reference version of the model is used for global projection
  - **Multi-model ensembles**

https://clima.caltech.edu/

Contrail cirrus in ARPEGE-Climat

- Parameterization

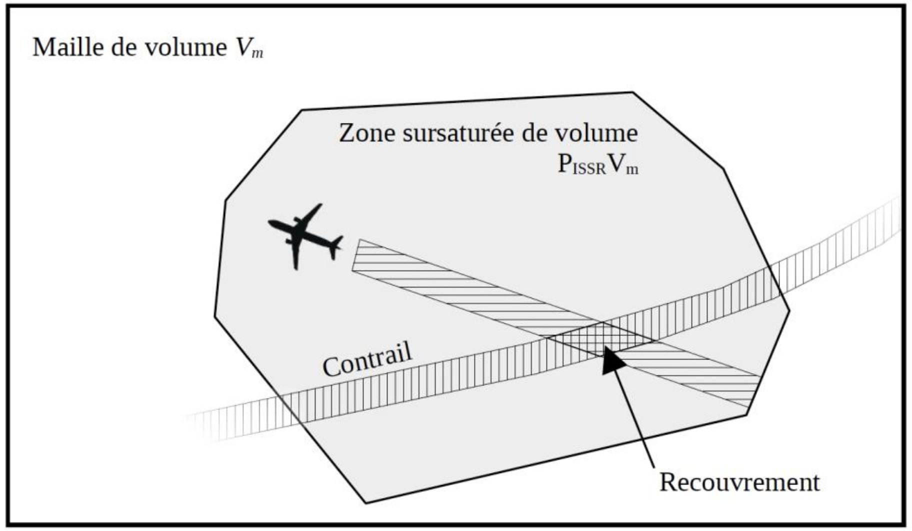
$$\begin{cases} \dfrac{dL}{dt} = vNP_{sa}(P_{ISSR} - a_c) - \dfrac{L}{\tau_1} \\ \dfrac{da_c}{dt} = vNP_{sa}(P_{ISSR} - a_c)\dfrac{b_0 h_0}{V_m} + Lb'\dfrac{h_c}{V_m}(1 - \dfrac{a_c}{P_{ISSR}}) \end{cases}$$

Distance flown by N aircraft at speed v

SAC probability

Horizontal expansion

Overlapping

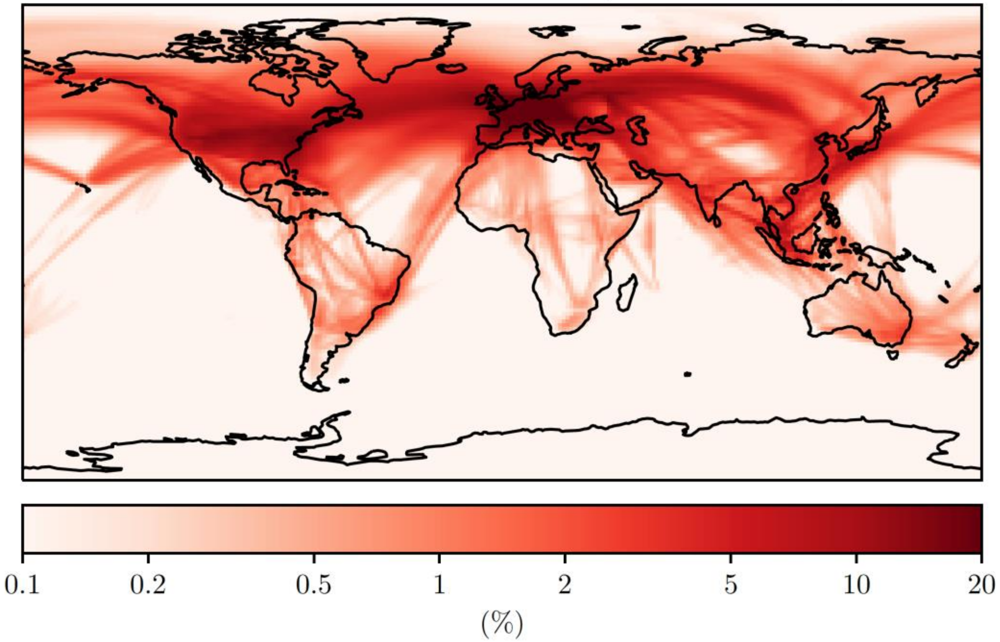


- Parameters
  - b_0,h_0, h_c, b'
  - All parameters influencing cloud micro physics, radiation, convection etc.

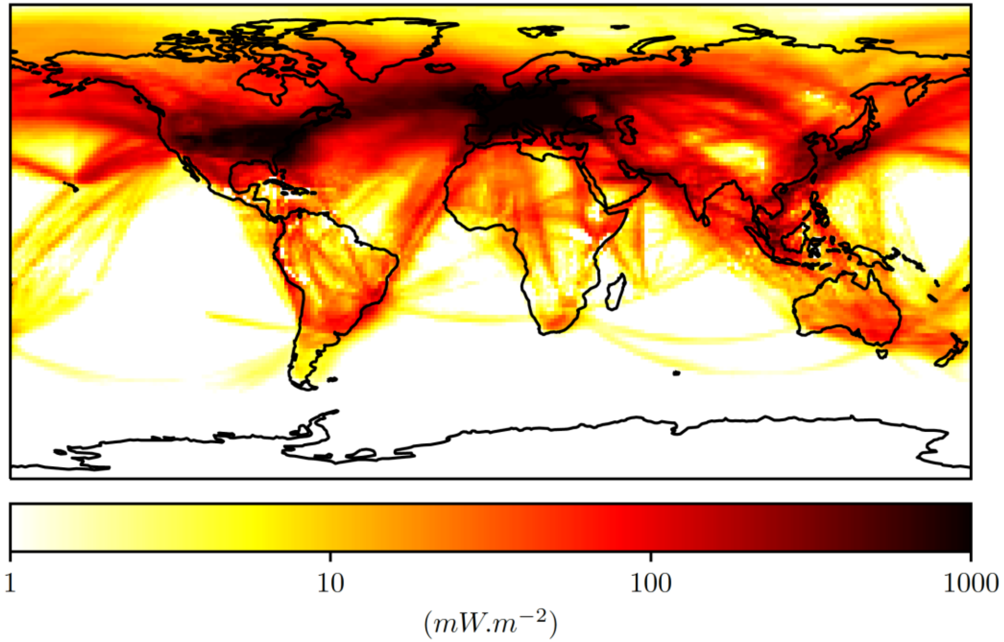
Contrail cirrus in ARPEGE-Climat (2019)

- Consistent with recent literature estimates
  - Lee et al. (2021) 111 (33-189) mW/m^2 for 2018
  - Bier and Burkhardt (2022) 43.7 mW/m^2 for 2006

Total contrail cirrus coverage (mean = 1.21 %)

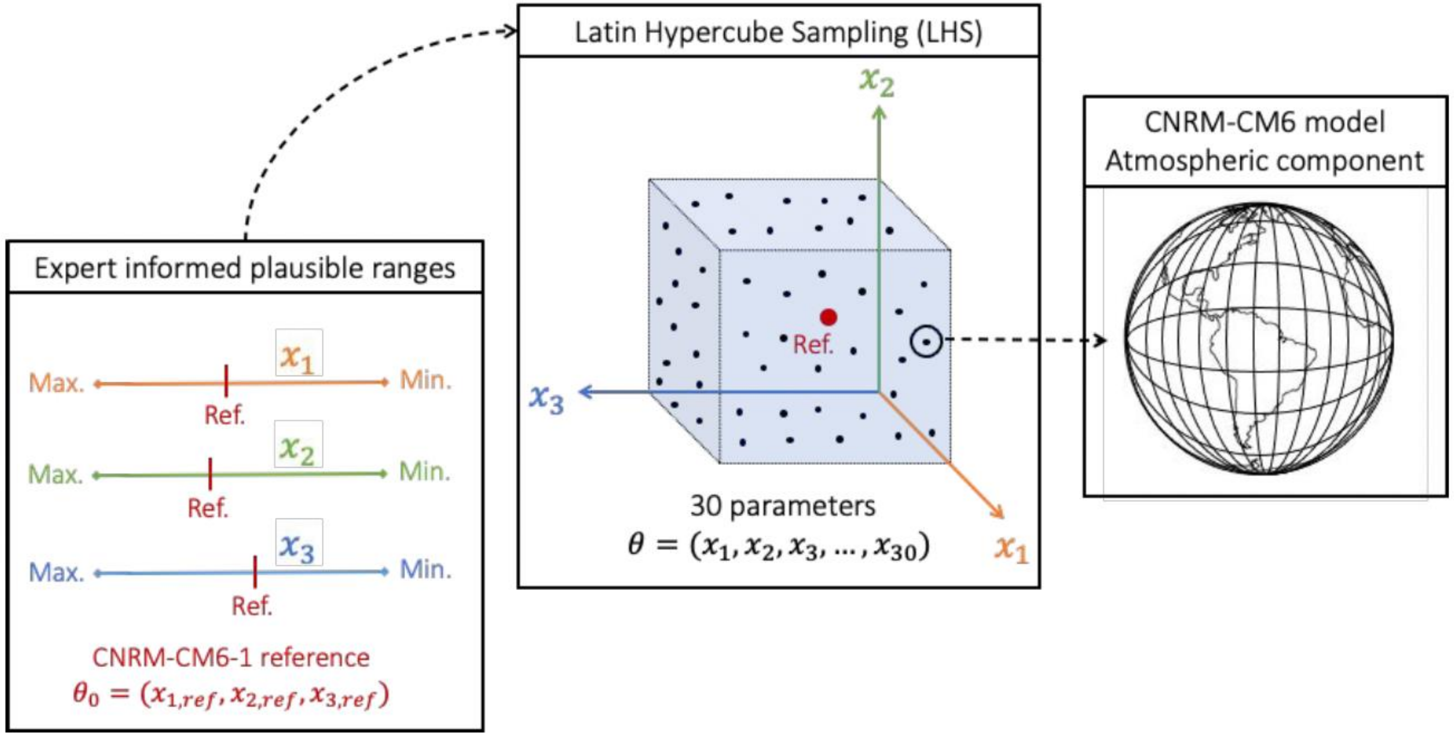


Contrail cirrus net radiative forcing (mean = 66.2 $mW.m^{-2}$)



Perturbed Parameter Ensemble and contrail cirrus RF

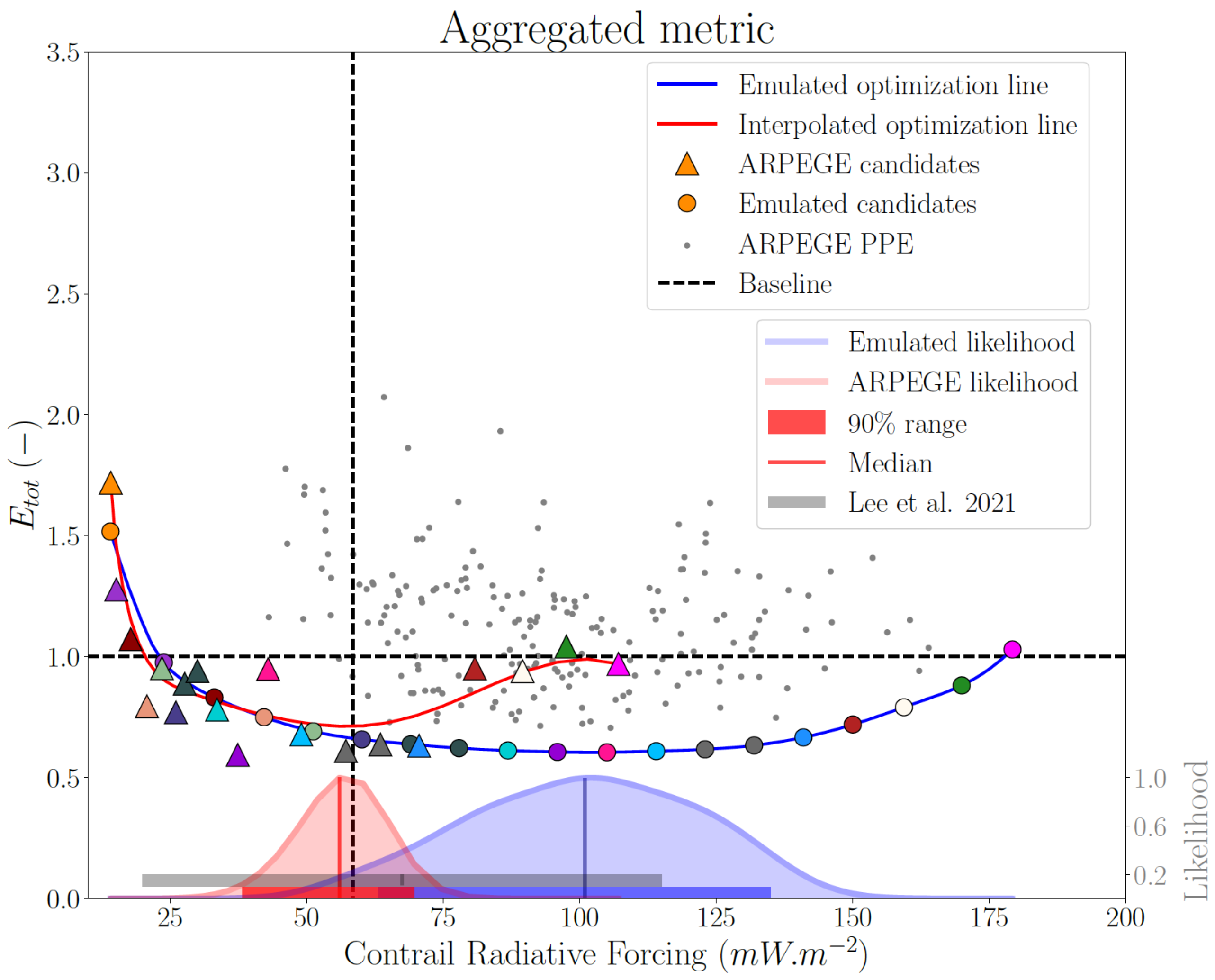
- Experiments :
  - 20 parameters
  - 192 members (8 crashes)
- Use of a **surrogate model**
  - Trained on 150 members
  - **100 000 calibrations**



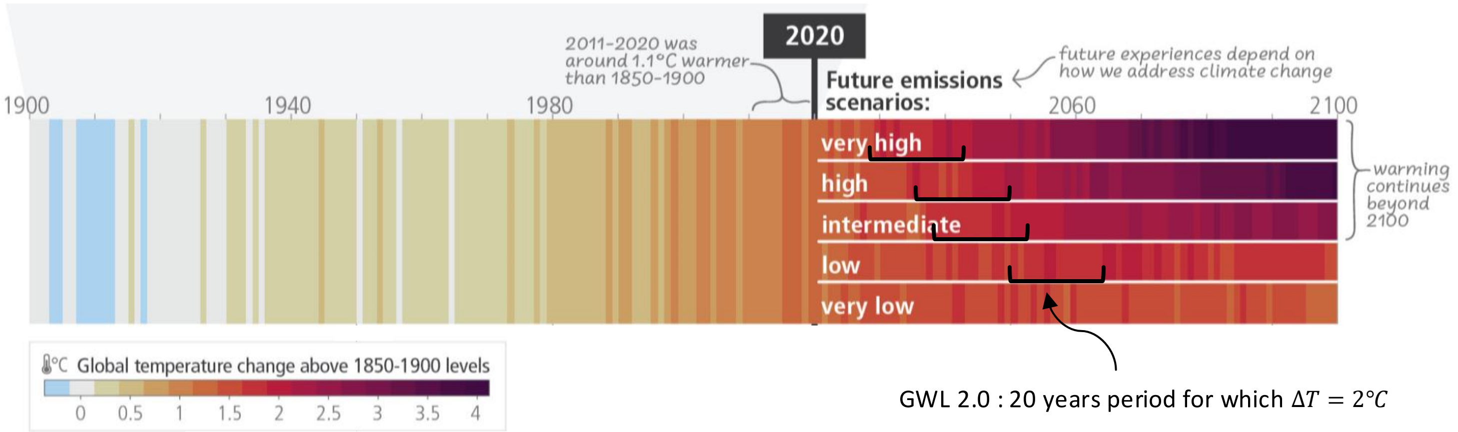
S. Peatier, 2022

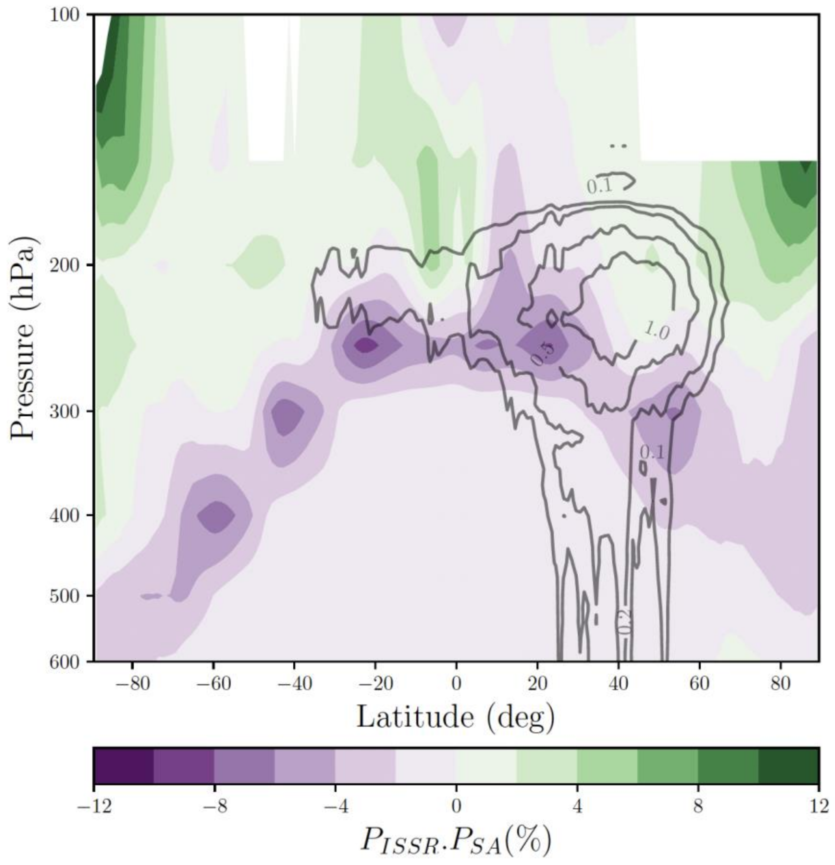
Perturbed Parameter Ensemble and contrail cirrus RF

- Exploration of model uncertainty
- **Large range of estimated contrail RF**
- **New estimate** : $56\ (38 - 70)\ mW/m^2$
  - Lee et al. 2021 : 67 (20-115) mW/m^2



Global warming projection





- SSP 3-7.0 scenario and $\Delta T = 4°C$
  - **10% decrease** in contrail radiative forcing

- Contrail formation and persistence will vary with altitude and latitude.

Conclusion

- (Re)new(ed) interest in contrails research after COVID
  - Complex physics
  - Low confidence level
  - A number of questions still need to be addressed

- Climate modelling is a useful tool
  - Lack of representations
  - Large parametric uncertainties

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Thank you for your attention !

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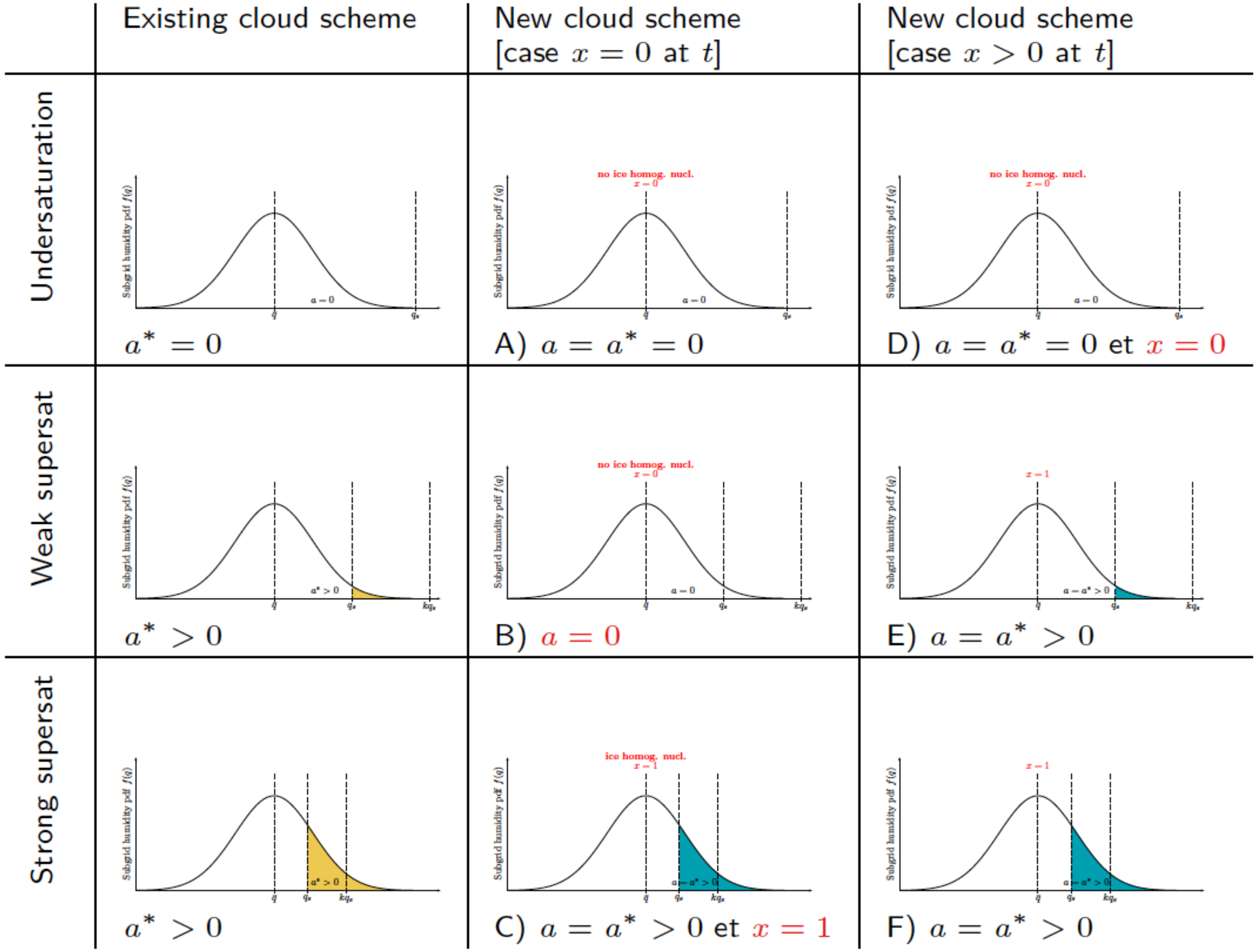
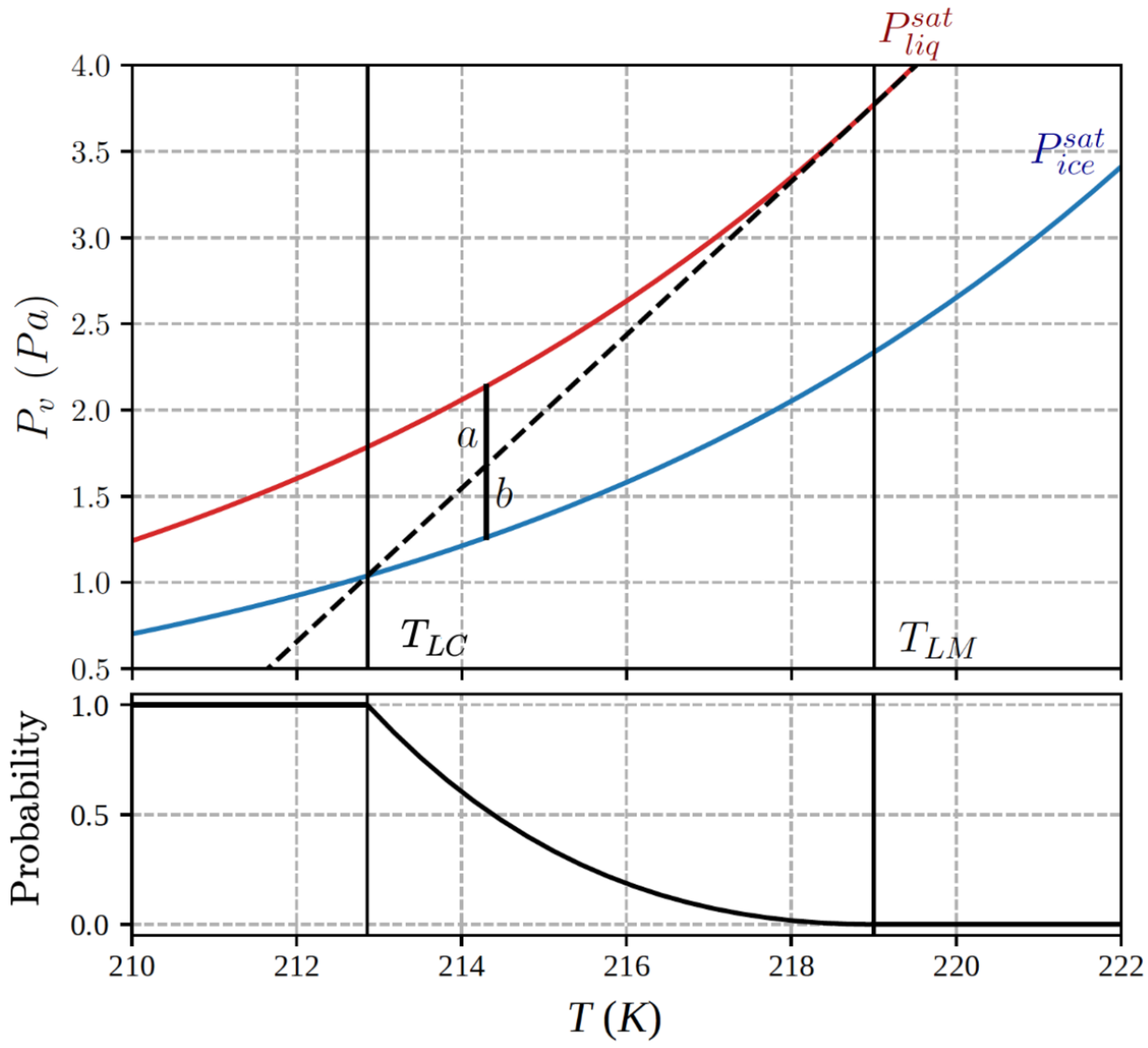
Back up – cloud scheme



Back up – SAC criterion



Back up - PPE method

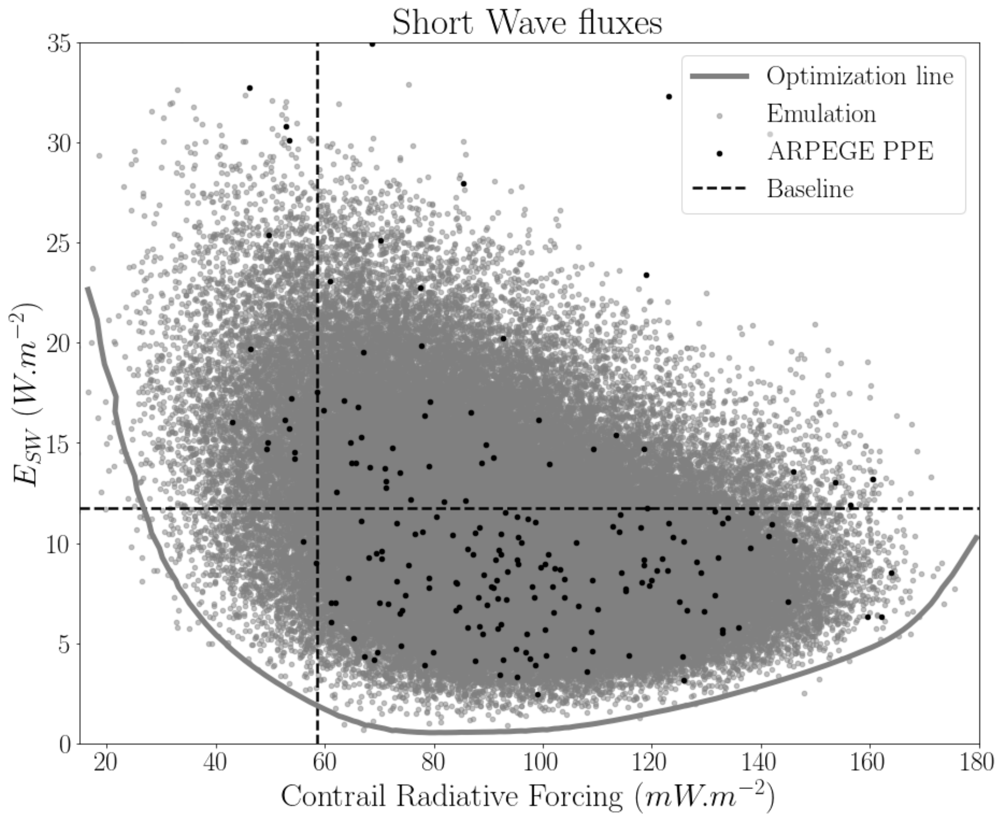
- Comparison with observational data
  - LW / SW (CERES), precipitation (GPCP) and T° at flight levels/mid latitude (ERA5)
- A score is given based on an area-weighted RMSE is given

$$E_{tot} = \frac{1}{P}\sum_{s=1}^{P}\frac{E_s}{E_{ESM,s}}$$

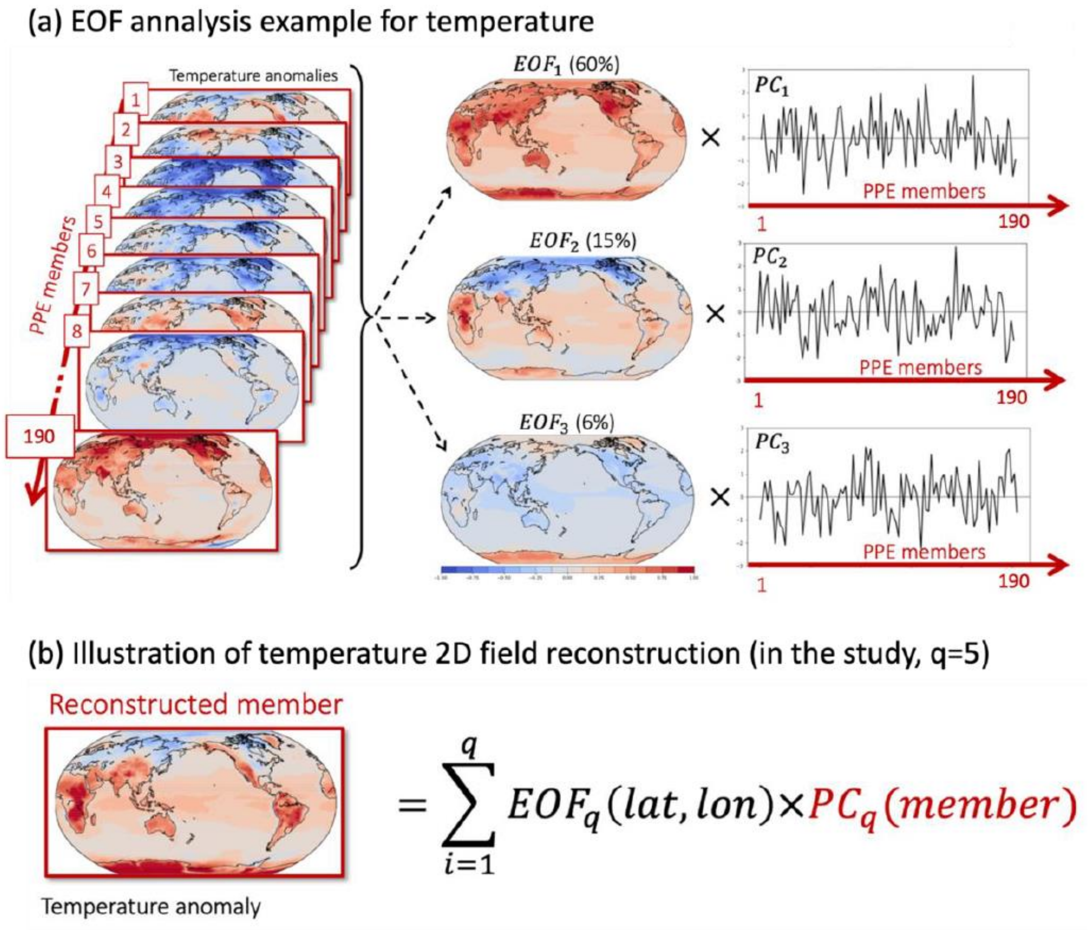
- Model emulation using multi-linear regression

$$Y = \sum_{j=1}^{K} a_j x_j + R$$

- Optimization to obtain new model calibrations



Back up - PPE method



Back up - Global warming projection