# Mitigating aviation climate impact by climate-optimized aircraft trajectories

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# Climate change and the role of ATM - Outline

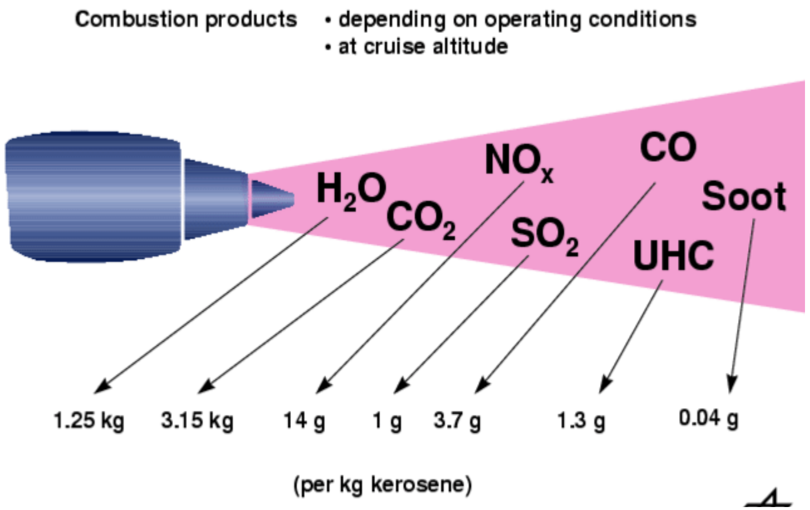
- Assessment of total climate impact of aviation – $CO_2$ and non-$CO_2$ effects

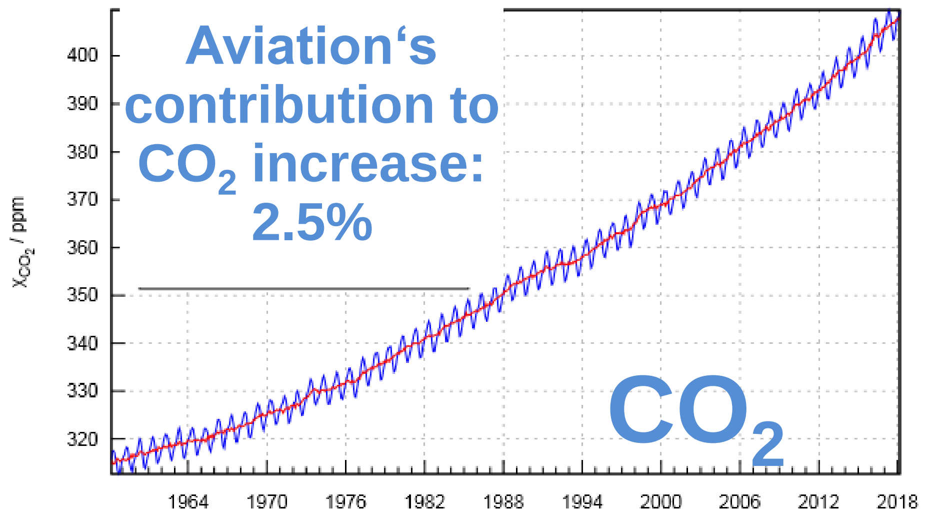
- Sensitivity of non-$CO_2$ effects when flying at alternative flight altitudes
- Concept to describe variation (spatially, temporally) of aviation non-$CO_2$ climate impacts
- Case studies on exploring mitigation potential by climate-optimized trajectories

- Towards implementation of MET services on aviation climate impact
- Towards integration of non-$CO_2$ effects in emission schemes, e.g. CORSIA

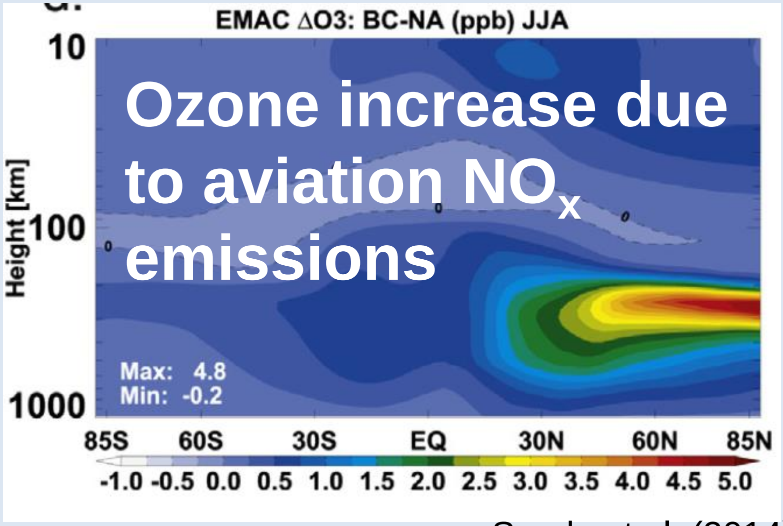
- Summary

# Aviation emission and climate impact



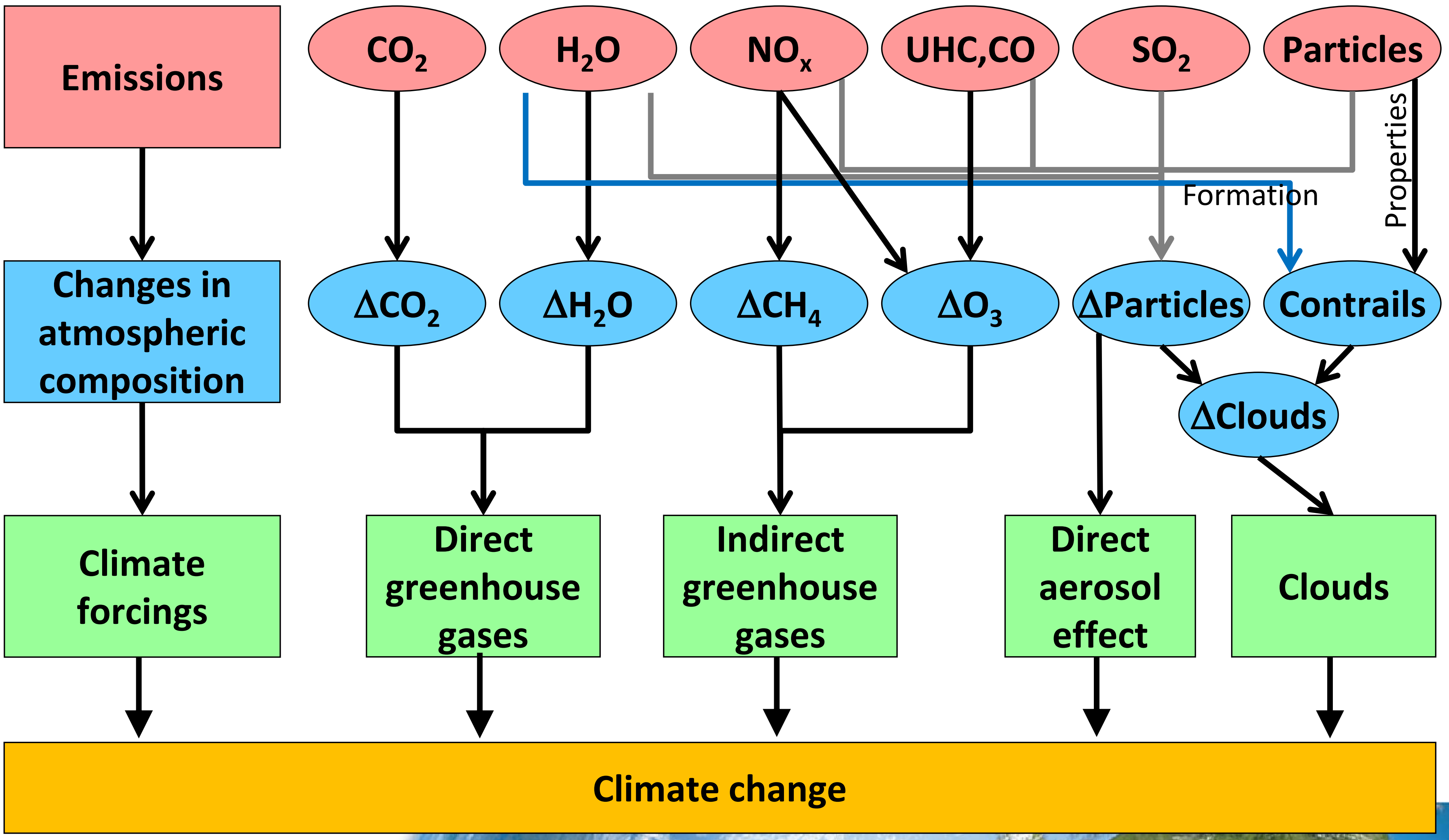




## Climate impact of non-$CO_2$-Effects



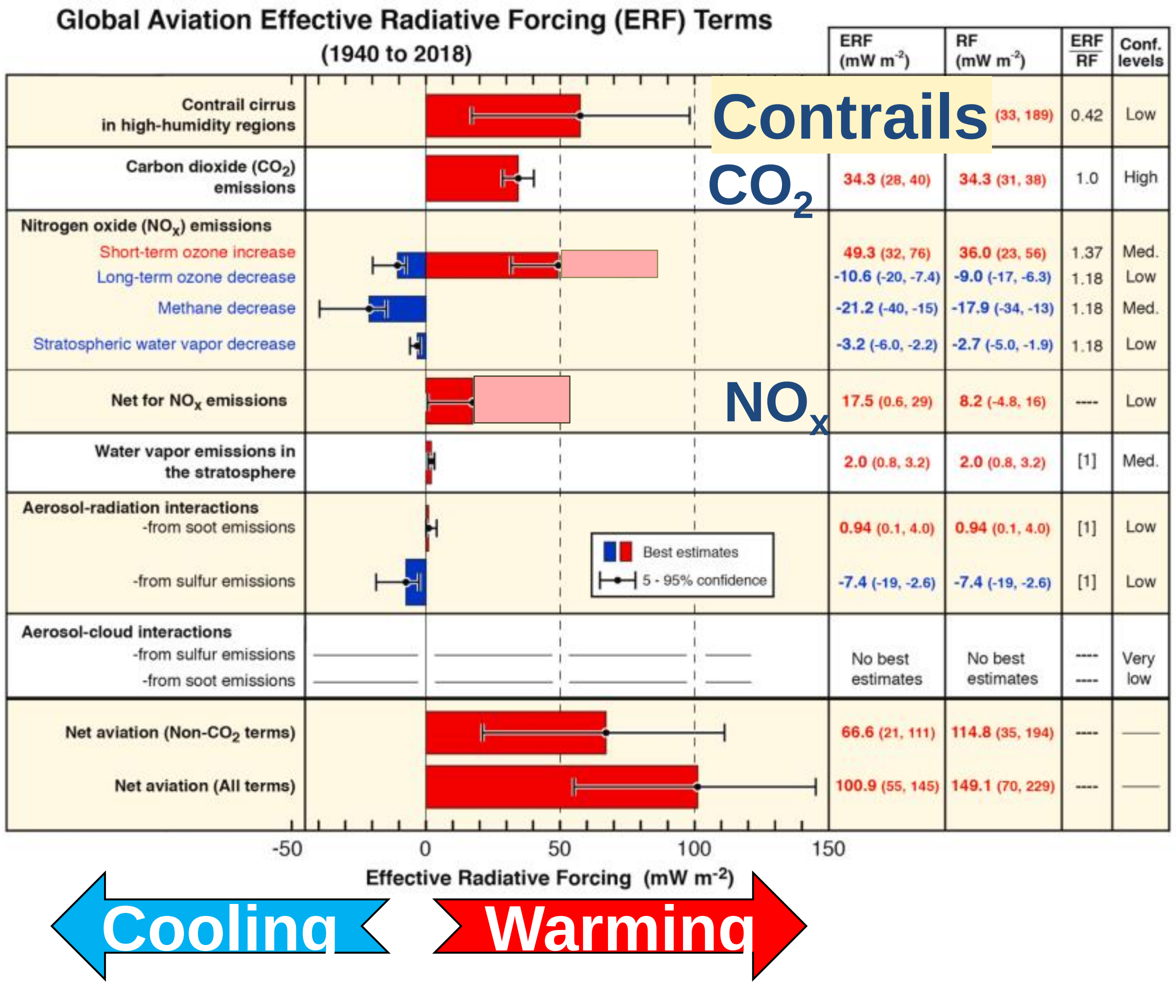

Søvde et al. (2014)


# Overview: Climate impact of aviation



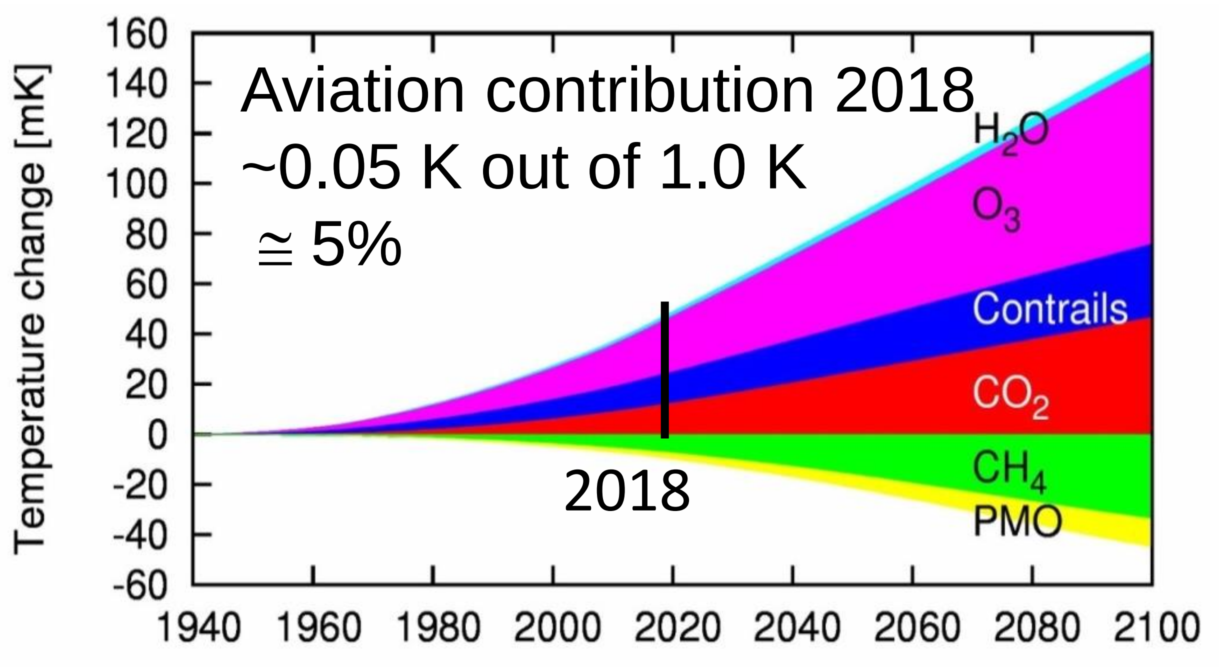
# How important are the aviation non-$CO_2$-effects?

## Radiation change




Lee et al. 2021
Grewe et al. (2019)

## Temperature change




**More than 50% of the aviation's climate impact results from non-$CO_2$ effects**

Grewe et al. (2020)

# Basic relation between inbalance in radiation budget (RF) and temperature change (dT)

$$dT = \lambda * RF$$

**Temperature change**

Radiative Forcing

**Climate Sensitivity Parameter**

# Radiative Forcing (RF), Effective Radiative Forcing (ERF) and Temperature change (dT)

Steady-state temp. change

Climate Sensitivity Parameter

Efficacy

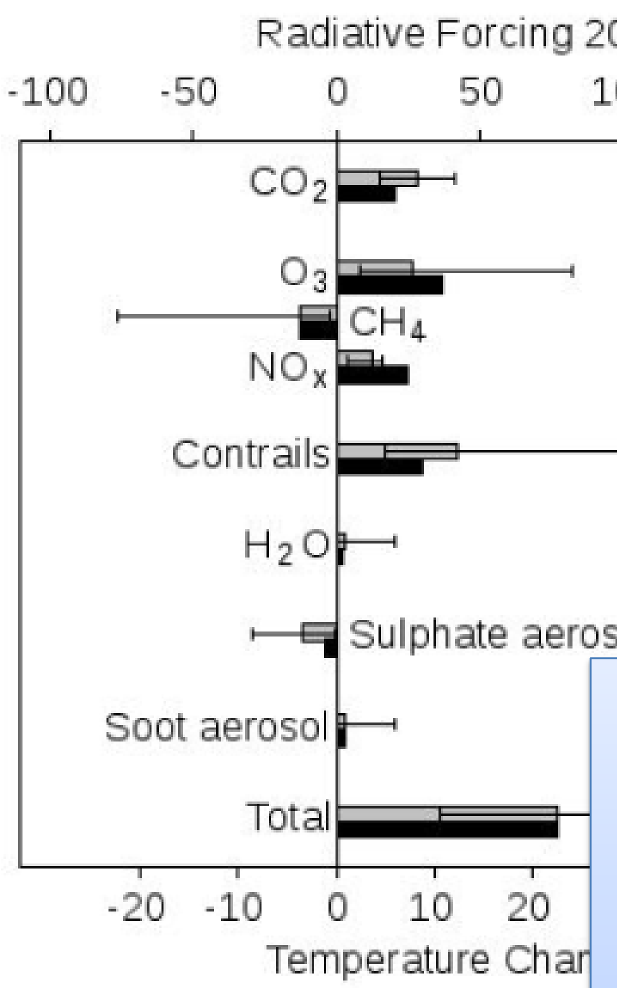
Radiative Forcing

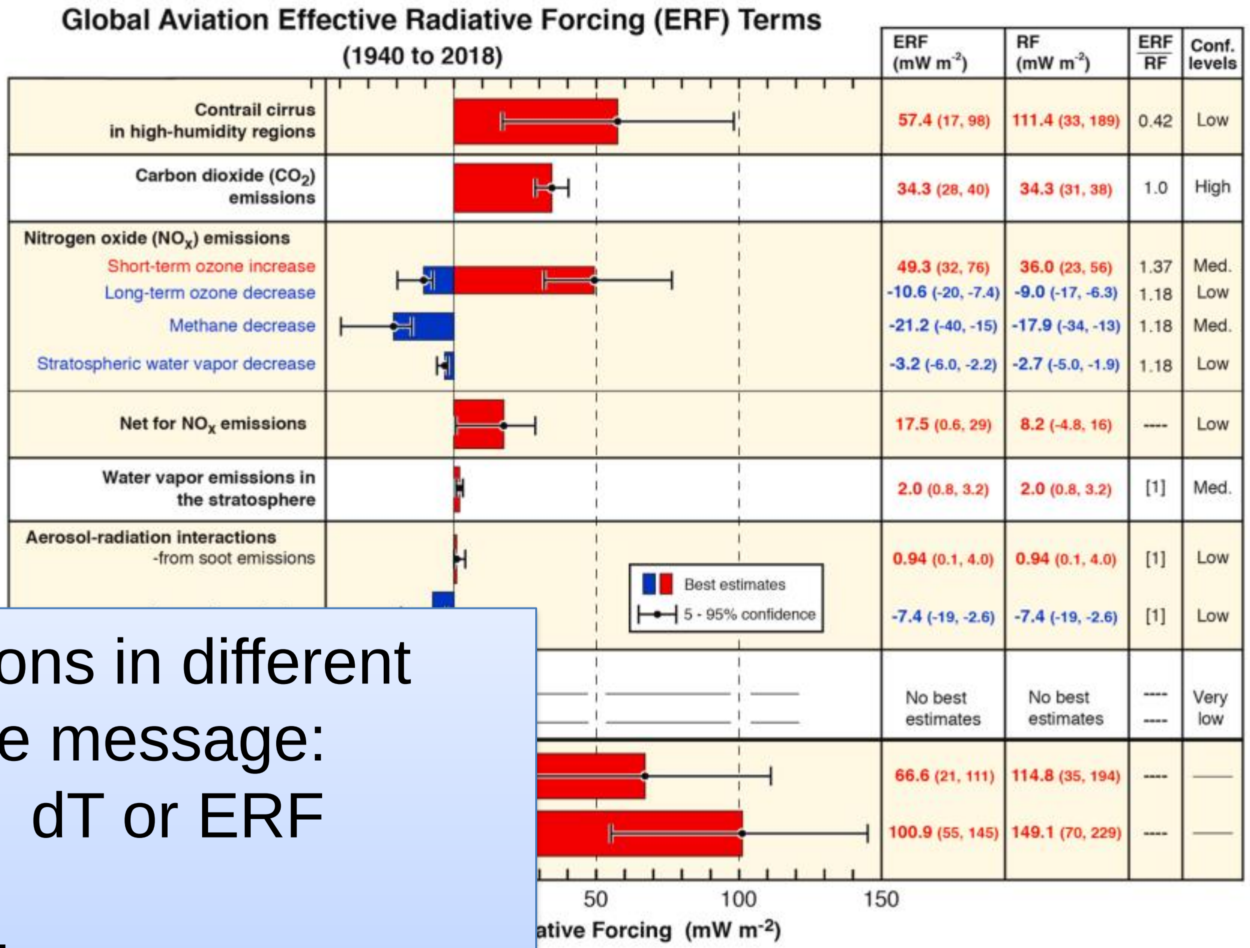
$$dT_{specie}(t=\infty) = \lambda_{CO2} * \underbrace{eff_{specie} * RF_{specie}(t=t_0)}_{\text{Roughly equal}}$$

$$= \lambda_{CO2} * ERF_{specie}(t=t_0)$$

Effective Radiative Forcing

# Radiative Forcing (RF), Effective Radiative Forcing (ERF) and Temperature change (dT)




Different presentations in different papers, but same message:

RF → dT or ERF

Contrails become less important

$NO_x$-Ozone becomes more important

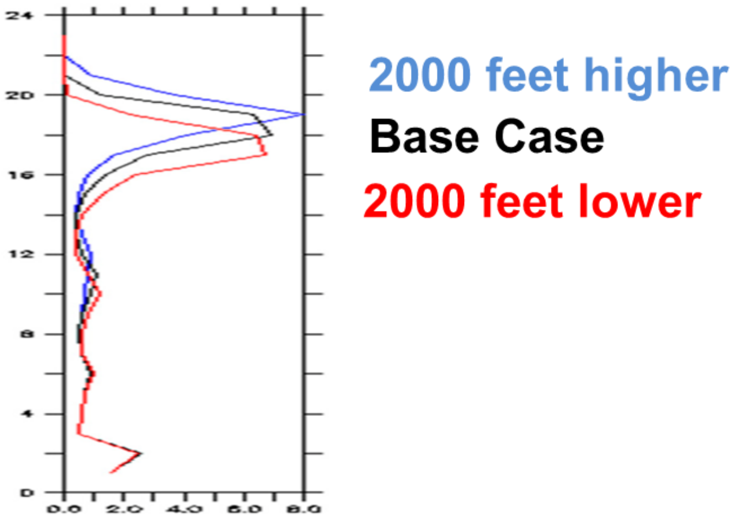
$CO_2$, Contrails and $NO_x$ all all important

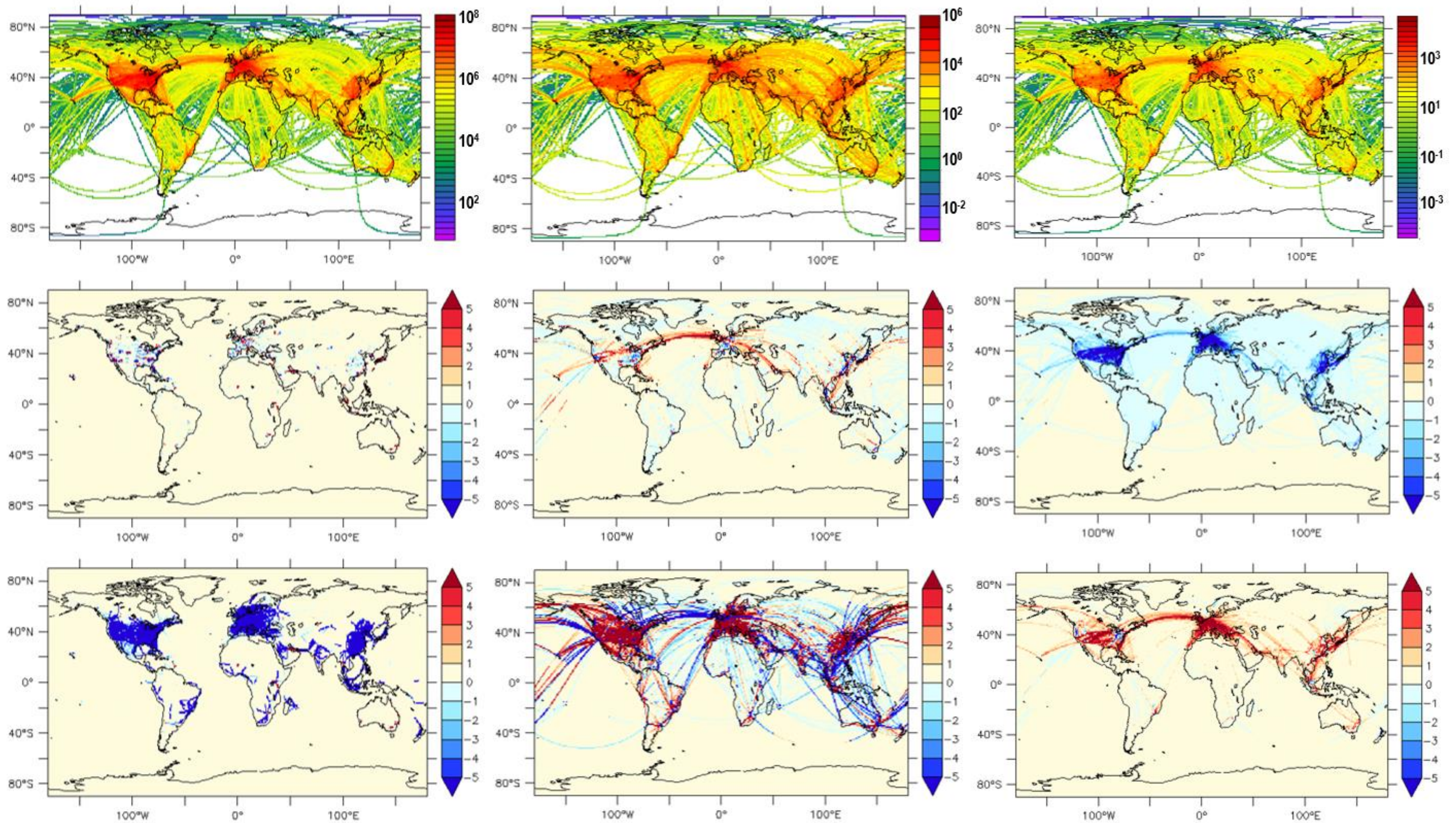
Grewe, 2020

Lee et al., 2021

# Altitude dependence of non-$CO_2$ climate impacts

In the **base case (reference),** it is assumed that aircraft fly at their optimal altitude, while in the alternative altitude scenarios ***Flying Higher*** (***Lower***) all aircraft are flying 2000 feet (~ 600 m) **higher** (lower).
In the ***Flying Higher*** scenario, only those aircraft which **are able to fly higher** are shifted to a higher altitude, otherwise they remain at their reference lower flight altitude.



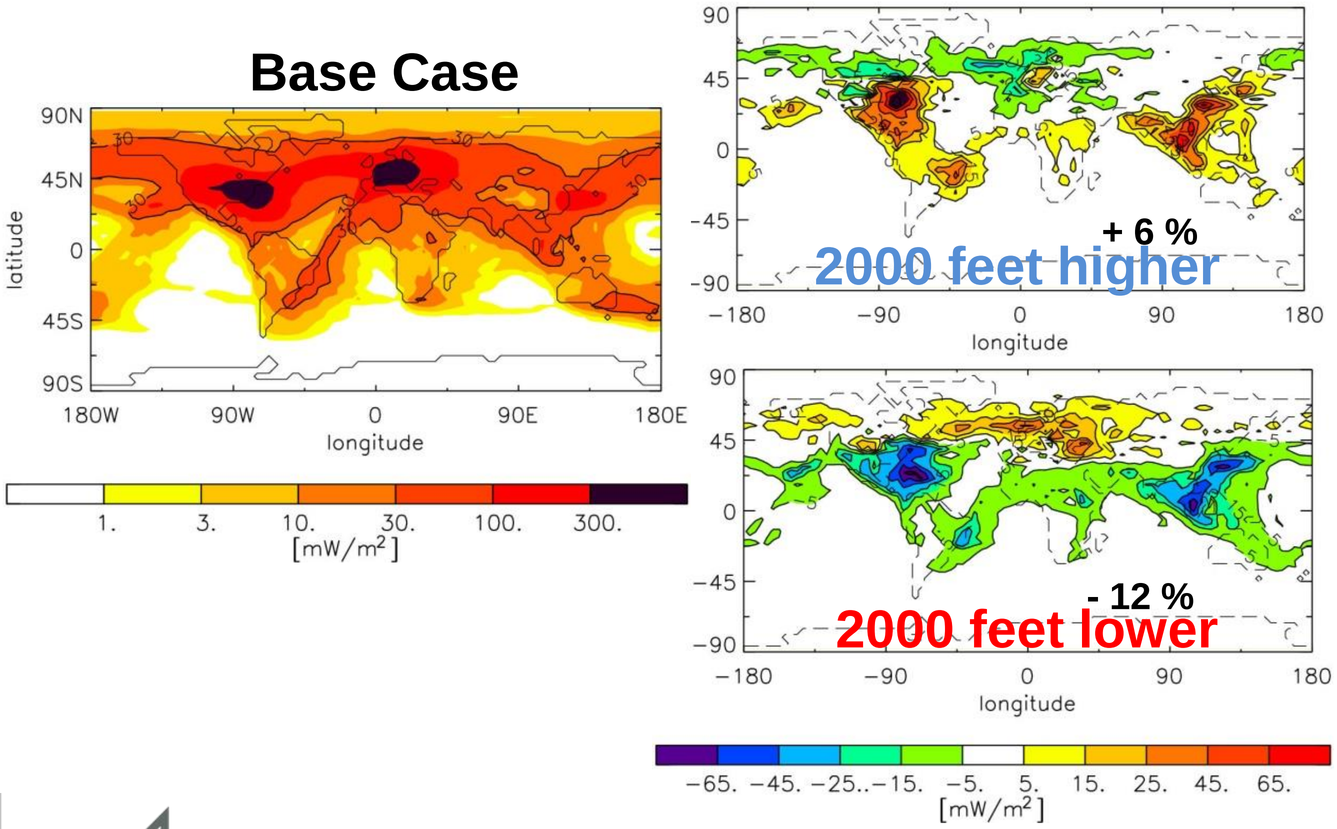
Matthes et al. 2021

# Altitude dependence of non-$CO_2$ climate impacts

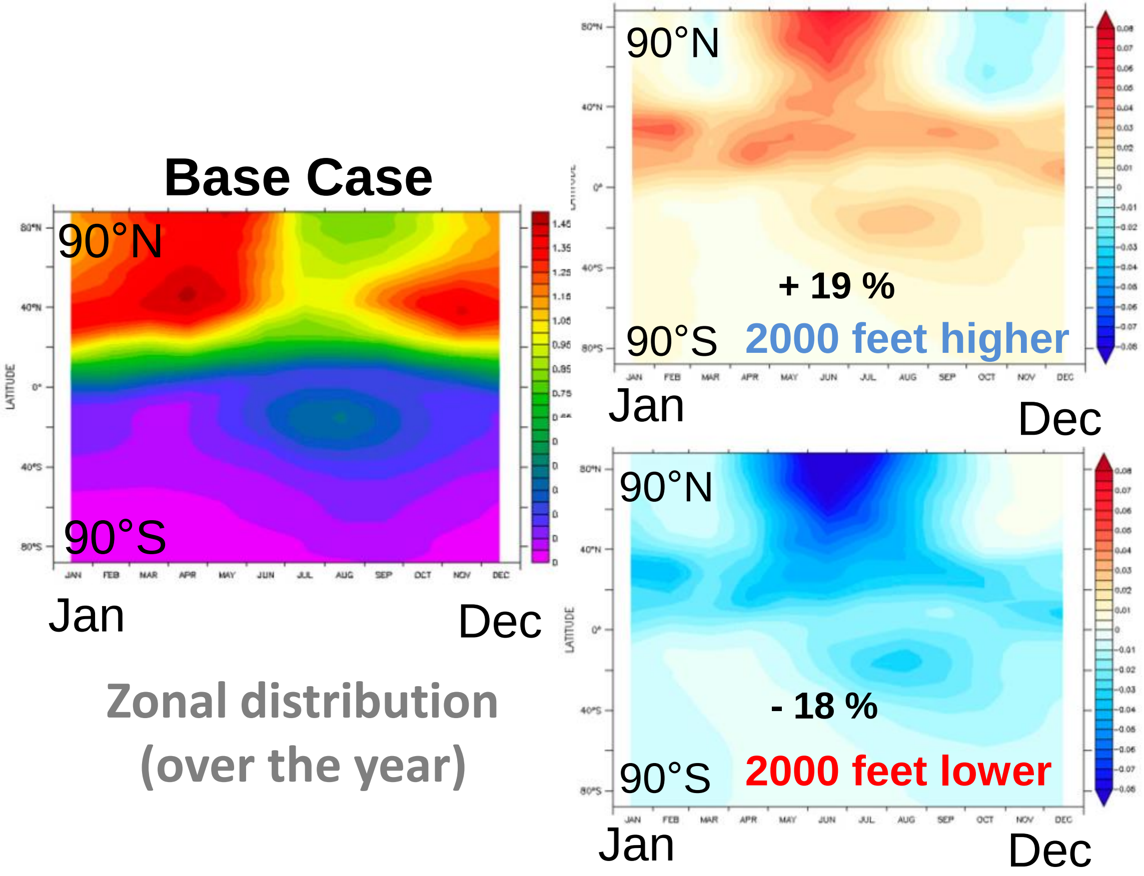
If aircraft **fly lower** aviation climate impact of **non-$CO_2$ effects** - water vapour, contrails, and aviation induced effects on warm clouds - **decreases**, while **$CO_2$** emission and impacts **increase** slightly.

Matthes et al. 2021

## Contrail-cirrus




## Aviation-induced ozone

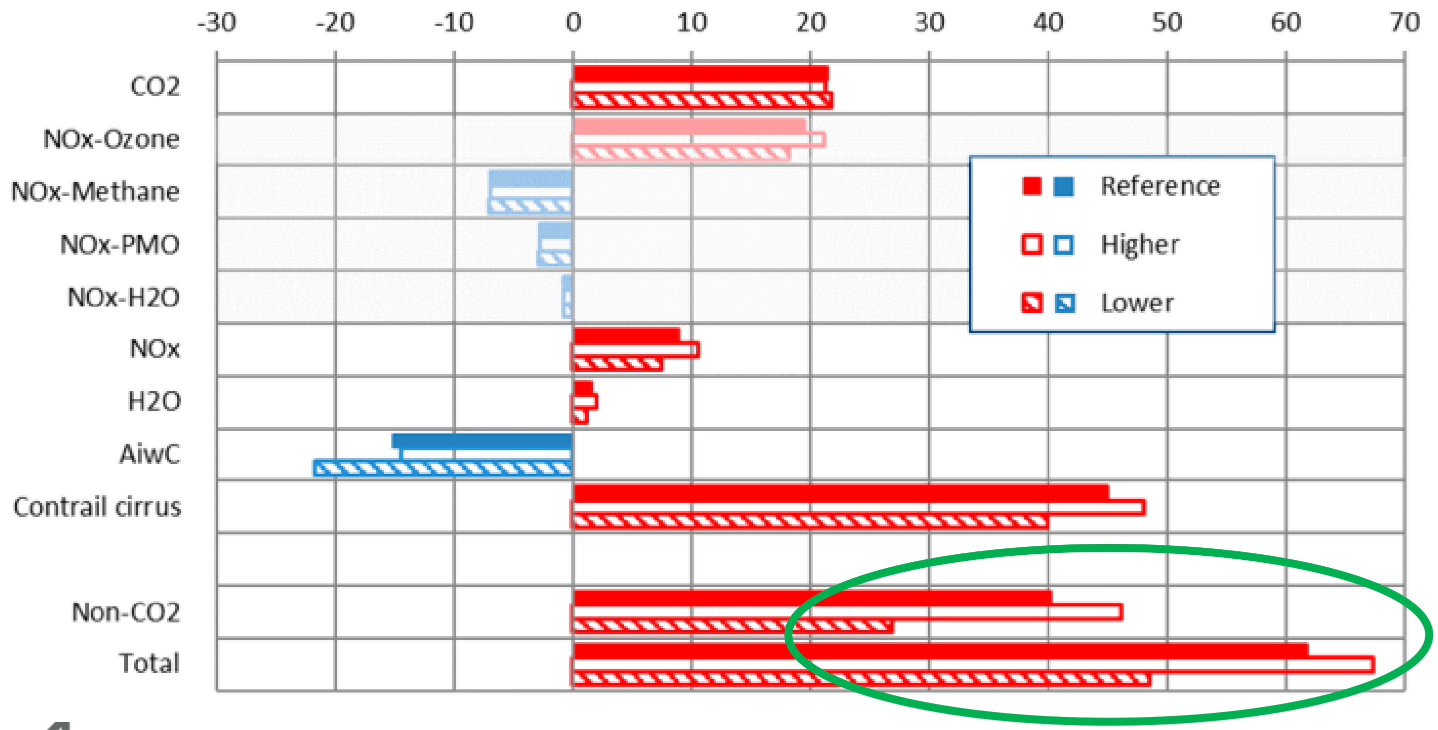



Zonal distribution (over the year)

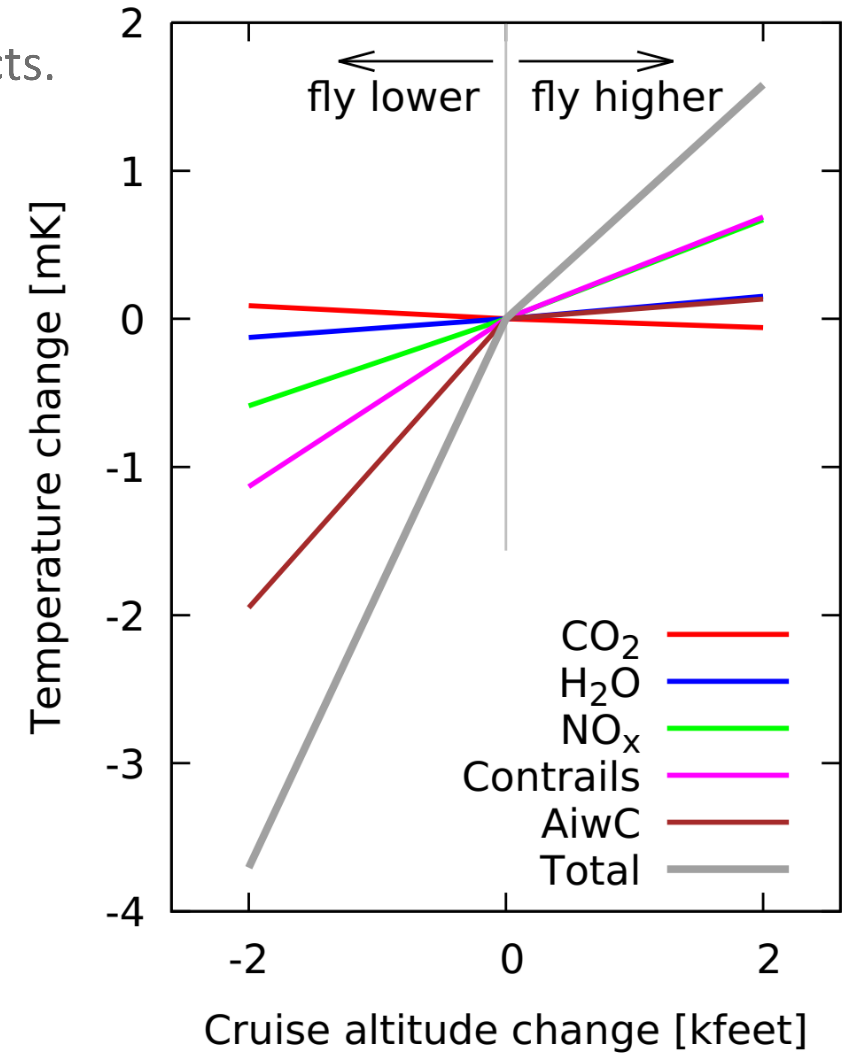
# Altitude dependence of non-$CO_2$ climate impacts

Parametric study to investigate **vertical dependence** of non-$CO_2$ impacts. If aircraft **fly lower** aviation climate impact of **non-$CO_2$ effects** - water vapour, contrails, and aviation induced effects on warm clouds - **decreases**, while **$CO_2$** emission and impacts **increase** slightly.

## Radiation change [mW/m²]



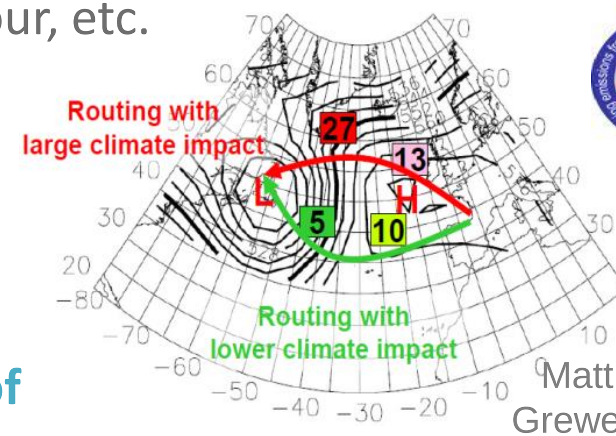

## Impacts



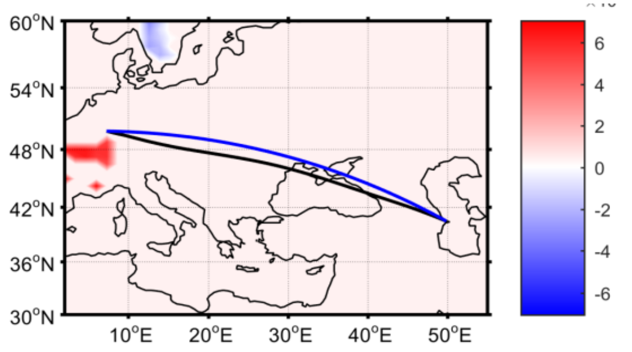

Matthes et al. 2021

# ATM4E Environmental-optimised trajectories

- Aviation is concerned by environmental impact of its operations, comprising **air quality**, **noise** and climate impact. **Aviation climate impact** is caused by $CO_2$ and non-$CO_2$ emissions, comprising contrails, nitrogen oxides impacting ozone and methane, water vapour, etc.
- However, during flight planning currently emission information is available, but no **environmental impact information** linked to the emitted amount is available along the trajectory.
- **ATM4E,** Exploratory Research project **SESAR 2020** (2016-2018)
- **Main objective** of the ATM4E project was to explore the **feasibility of a concept for environmental assessment** of ATM operations working towards environmental optimisation of air traffic operations in the European airspace.
- Explore a **multi-dimensional** and **multi-criteria** optimization.




Matthes et al., 2012
Grewe et al., 2014a,b

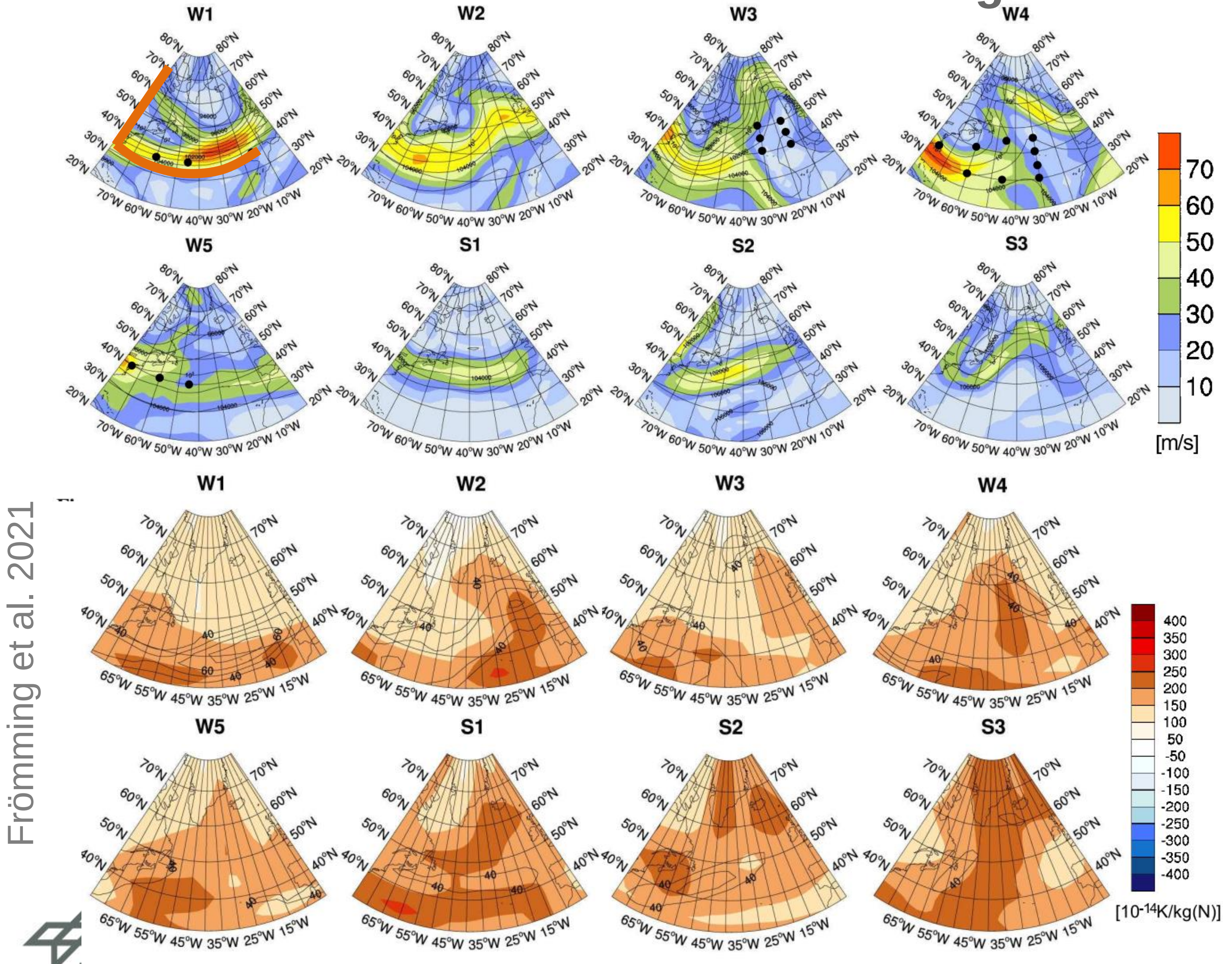



Matthes et al., 2020

ATM4E

…t has received funding from the SESAR Joint Undertaking under grant agreements No …nd No 891317 under European Union's Horizon 2020 research and innovation programme.

# Weather data and Ozone Climate-Change-Functions




**Climatology of aviation weather situations:**
**Winter W1-W5**
**Summer S1-S3**
**University Reading**
**Irvine et al. 2013**

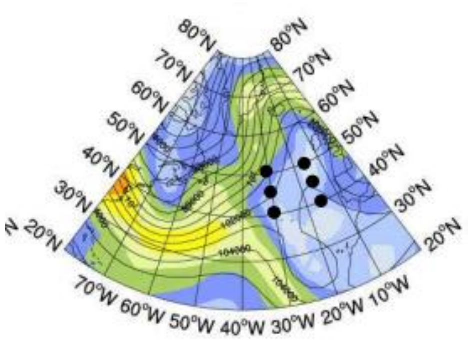
**Contribution of a local $NO_x$ emission to climate change via ozone formation**

**Clear relationship between weather and CCFs**

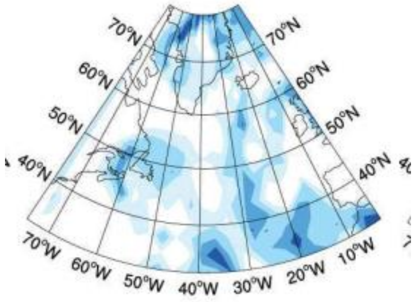
# Climate Change Functions (CCFs)

respresentive winter
weather situation,
250 hPa

**Weather**



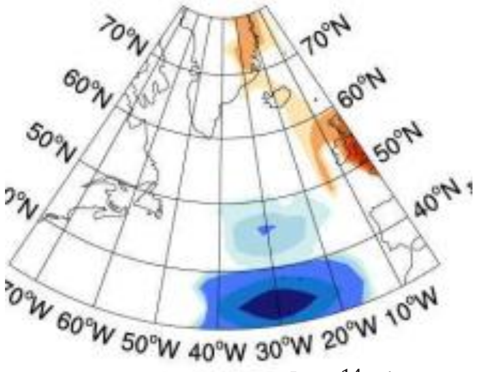

**Potential contrail coverage**




Frömming et al. 2021

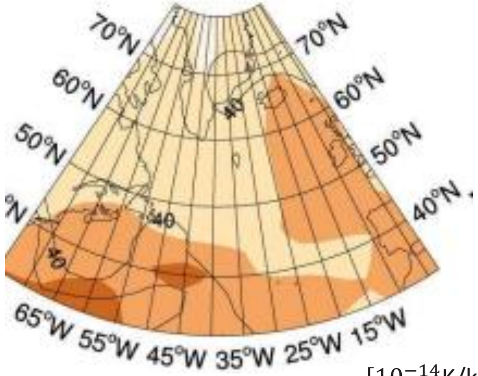
## Climate Change Functions = four dimensional functions (space & time)

**Contrail CCF**



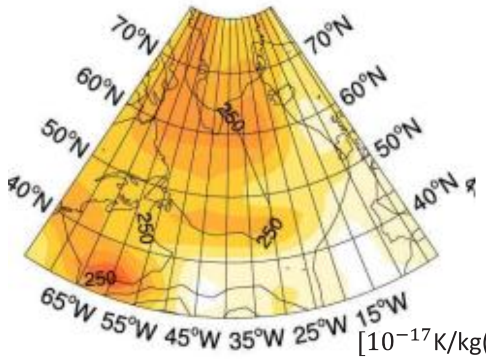

[$10^{-14}$K/km(contrail)]

**Ozone CCF**




[$10^{-14}$K/kg(N)]

**Water vapour CCF**




[$10^{-17}$K/kg(fuel)]

- Climate change functions characterize sensitivity of the atmosphere to aviation emissions at specific location (position, altitude, time). ⇒ **MET products for climate-optimized trajectory planning** require spatially and temporally resolved climate impact information.

# Step towards algorithmic Environmental Change Functions ECFs
# From climate change function to aCCFs

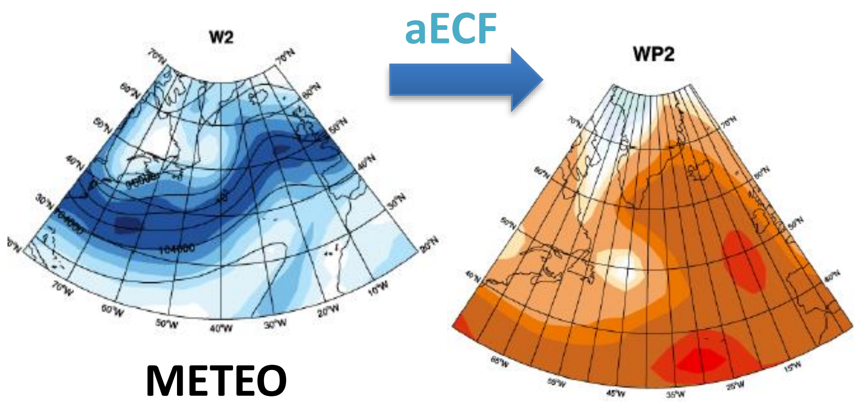
ATM4E

- The concept of **climate change functions** was developed within the European Collaborative project REACT4C *(see Volker Grewe talk yesterday)*

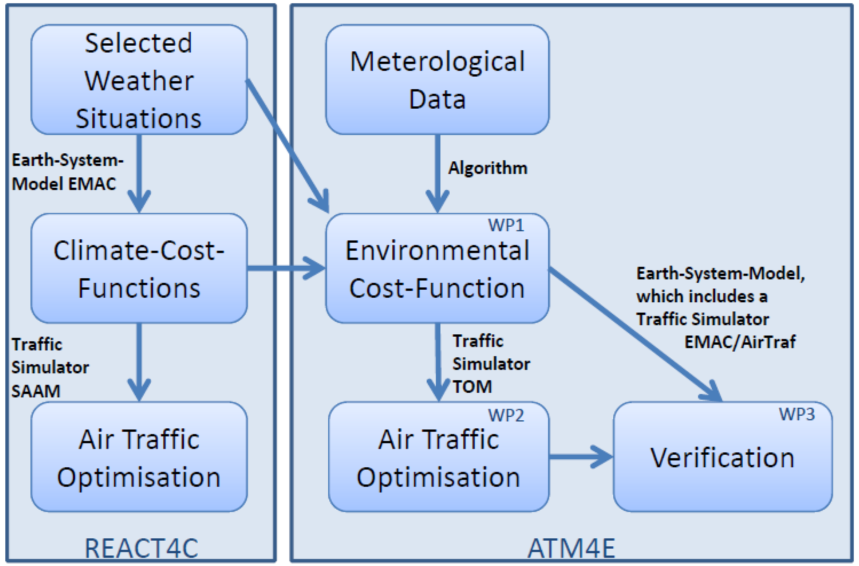
- The key step in ATM4E was to **relate** readily-available **meteorological data** to these existing detailed CCFs to allow the rapid generation of new CCFs (algorithmic CCFs) for specific (forecast) weather situations

- ⇒ **Advanced MET information**

- Integration of **environmental impact information** via a meteorological interface, e.g. to **SWIM infrastructure** (format, architecture) to make it available during flight planning.




Frömming et al., 2020




*Matthes et al., Aerospace,* 2017.

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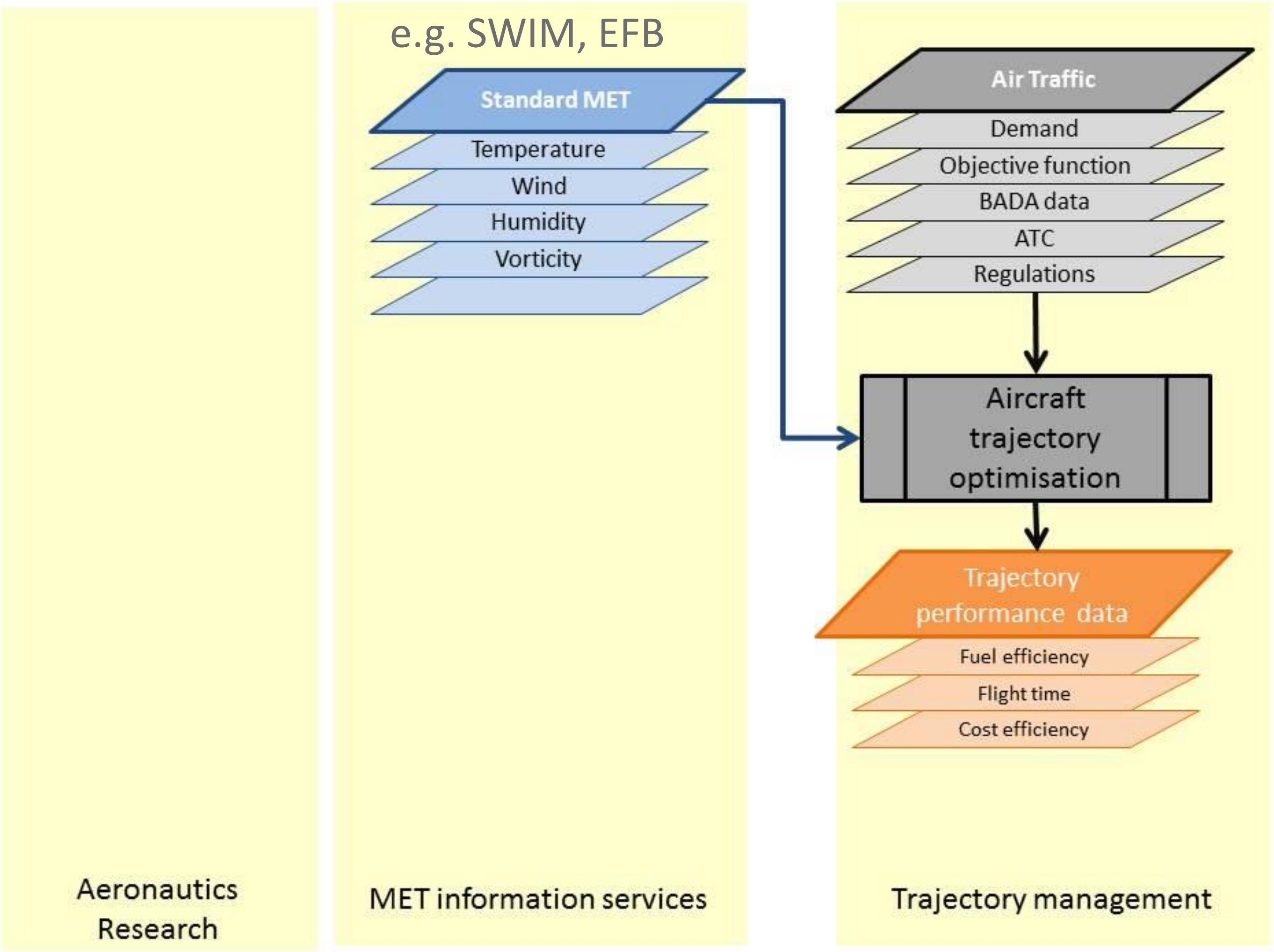
# Air traffic management for environment: SESAR/H2020-Project ATM4E

## ATM system




ATM4E

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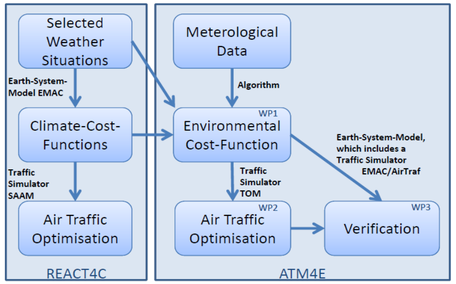
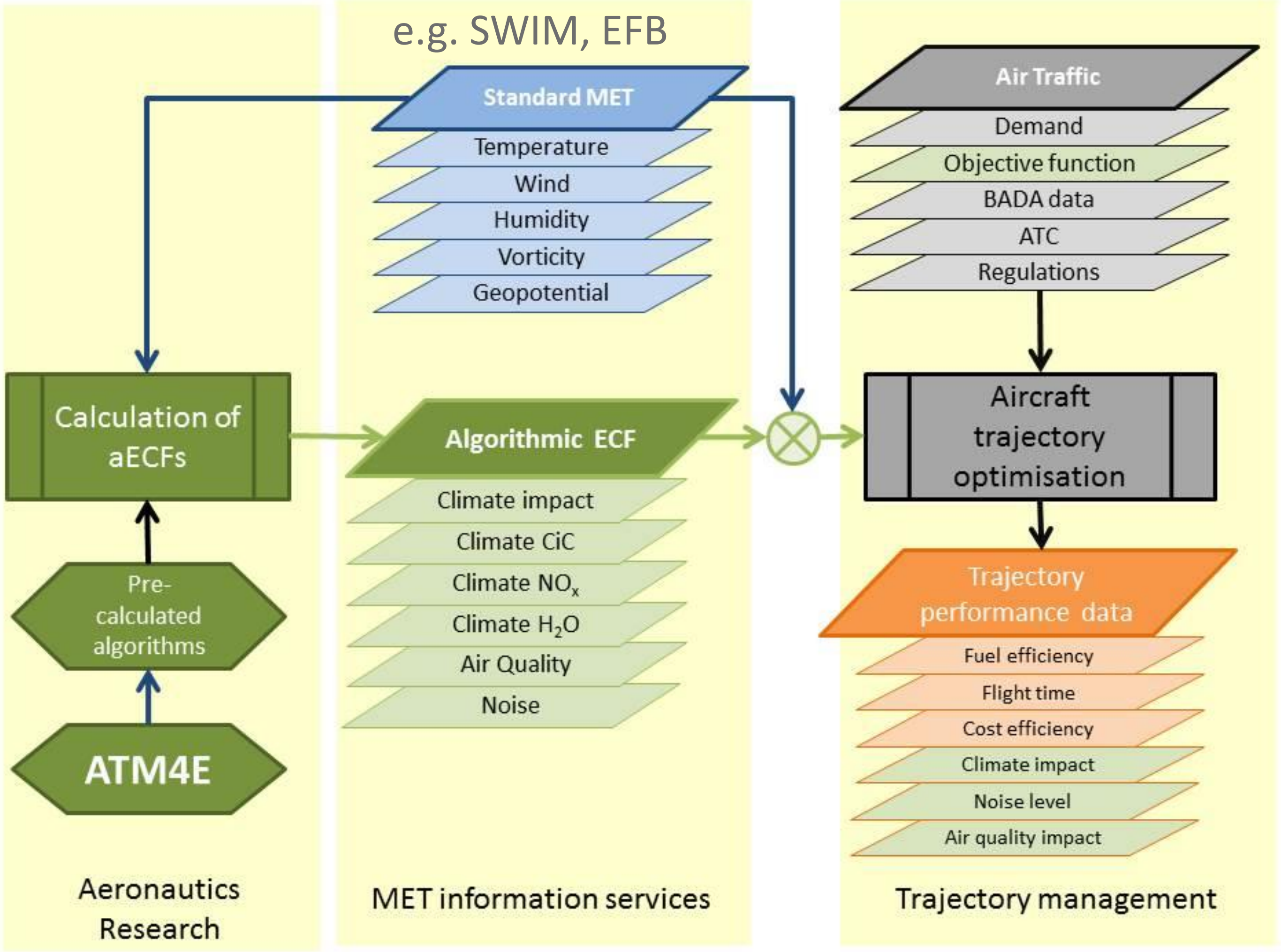
# Air traffic management for environment: SESAR/H2020-Project ATM4E




## Contribution of ATM4E




ATM4E

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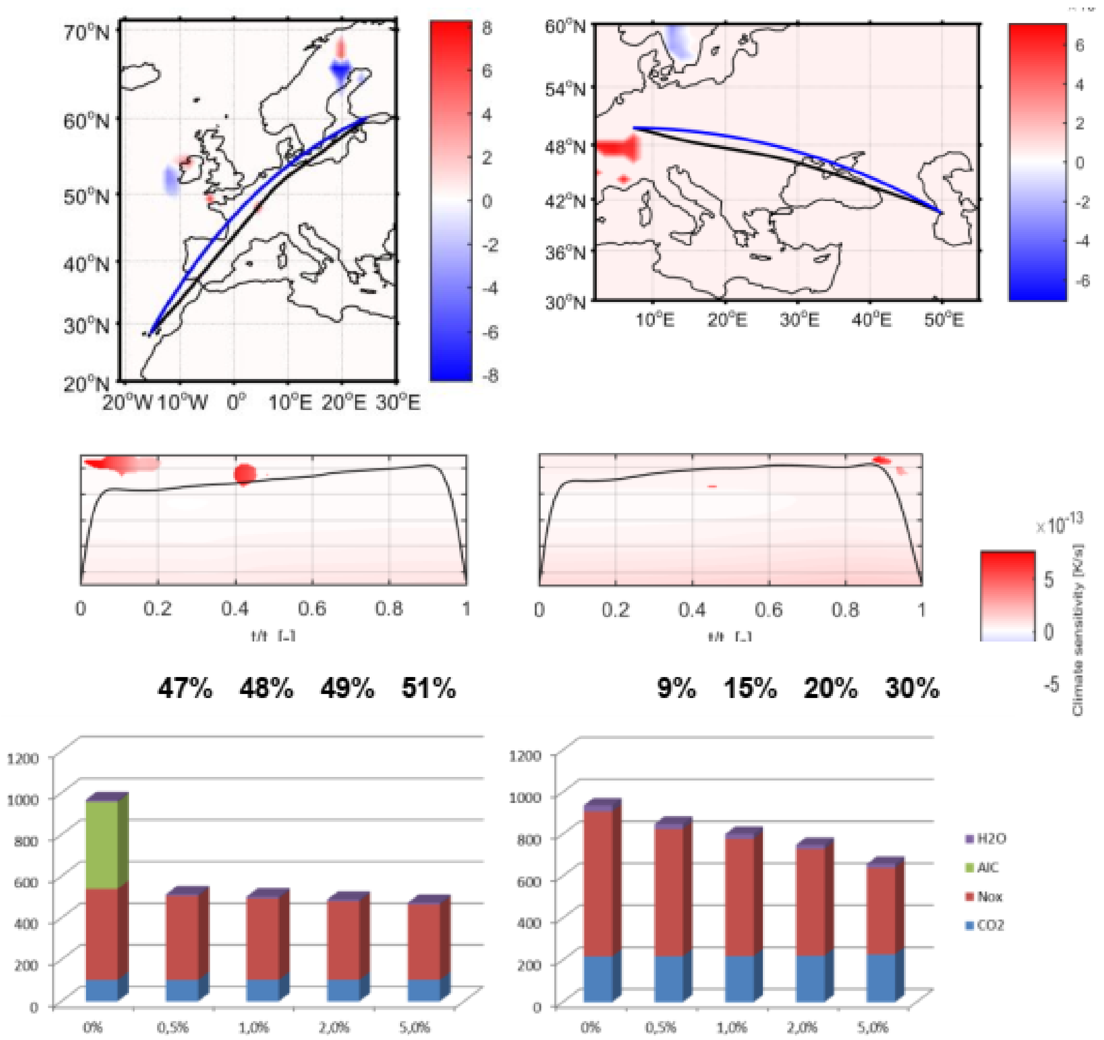
# Step towards algorithmic Environmental Change Functions aECFs

- Results from **ATM4E case study** – real day was selected with high potential impact due to aviation induced contrail and contrail cirrus.
- Case study for a winter situation in 2018 relying on **prototype aCCFs**.
- **Mitigation potential** due to contrail avoidance (*left*) and $NO_x$-induced climate impacts (*right*) quantified.




Matthes et al. 2020

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# Identified research needs in ATM4E on Environmental Change functions

1. **Enhancing the technological readiness of the algorithmic environmental change functions (aECF):** these need to cover all aircraft starting and landing in European airspace and represent uncertainties
2. **Expand the aECF concept from a case-study approach to a full European-scale application including performance indicators:** this would also need to consider expanding the aECFs (e.g. for air quality, other pollutants; for noise, the impact of airframe; for climate, additional non-$CO_2$ effects)
3. **Expand the aECF concept to include a robustness measure to minimize the risk of wrong decisions:** this would need to account for uncertainties in weather forecasts, environmental impacts, and exact routing knowledge

→ FlyATM4E

ATM4E

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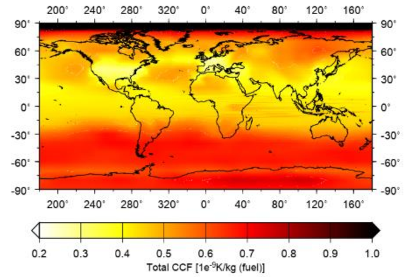
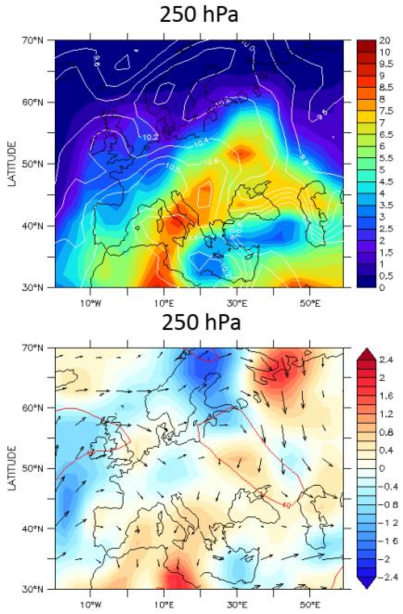
# Step towards robustness of climate-optimized trajectories
# Using algorithmic Environmental Change Functions ECFs (MET service)

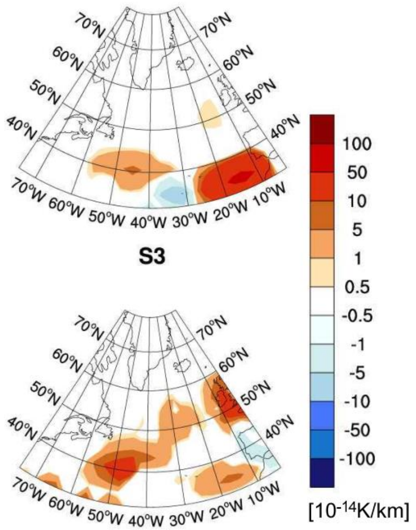
ATM4E

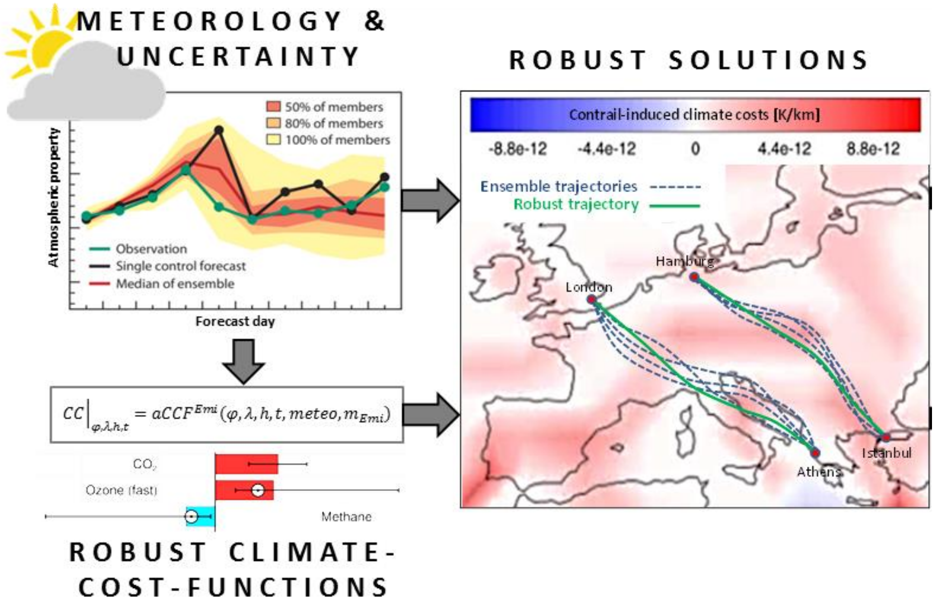



- Providing a technical description of **algorithmic climate change functions aCCFs** which represent **spatially and temporally resolved climate impact** of aviation emission to quantify $CO_2$ and non-$CO_2$ effects, comprising $NO_x$ and contrail-cirrus.

**Europe** **NAFC**




Matthes et al. 2017

Frömming et al. 2020

FlyATM4E

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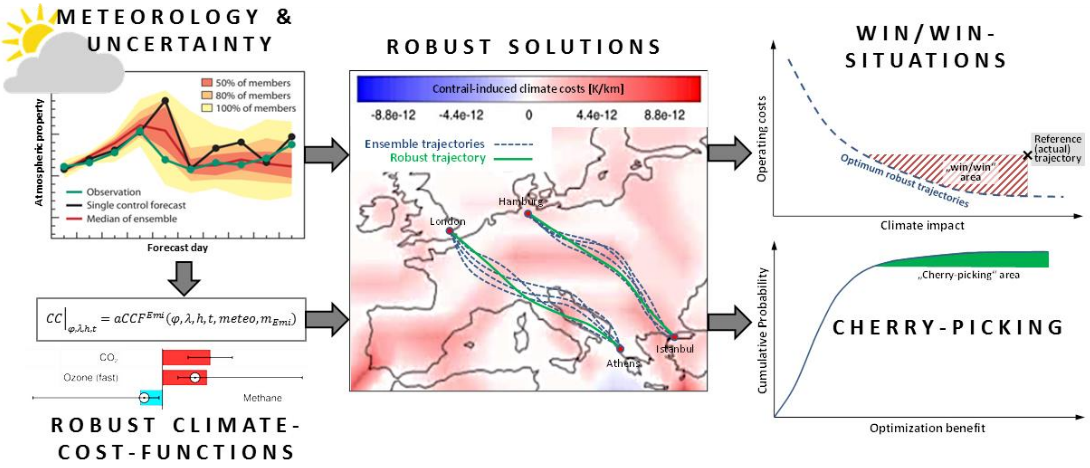
# FlyATM4E: Flying ATM for Environment (2020-2022)
## Project Objective

- FlyATM4E will develop a concept to identify climate-optimised aircraft trajectories which enable a robust and eco-efficient reduction in aviation’s climate impact.
- FlyATM4E will **identify those weather situations** and aircraft trajectories, which lead to a **robust climate impact reduction** despite **uncertainties** in atmospheric science that can be characterised by ensemble probabilistic forecasts. This will improve the assessment of aviation’s climate impact.
- It will further identify those situations where there is a **large potential to reduce the climate impact** with only little or even no cost changes (“**Cherry-Picking**”) and those situations where both, climate impact and costs can be reduced (“**Win-Win**”).

- As a summary, FlyATM4E will **formulate recommendations** how to implement these **strategies in meteorological (MET) products** and enable not only the understanding of ATM possibilities to reduce aviation’s climate impact, but moreover how to implement such eco-efficient routing.

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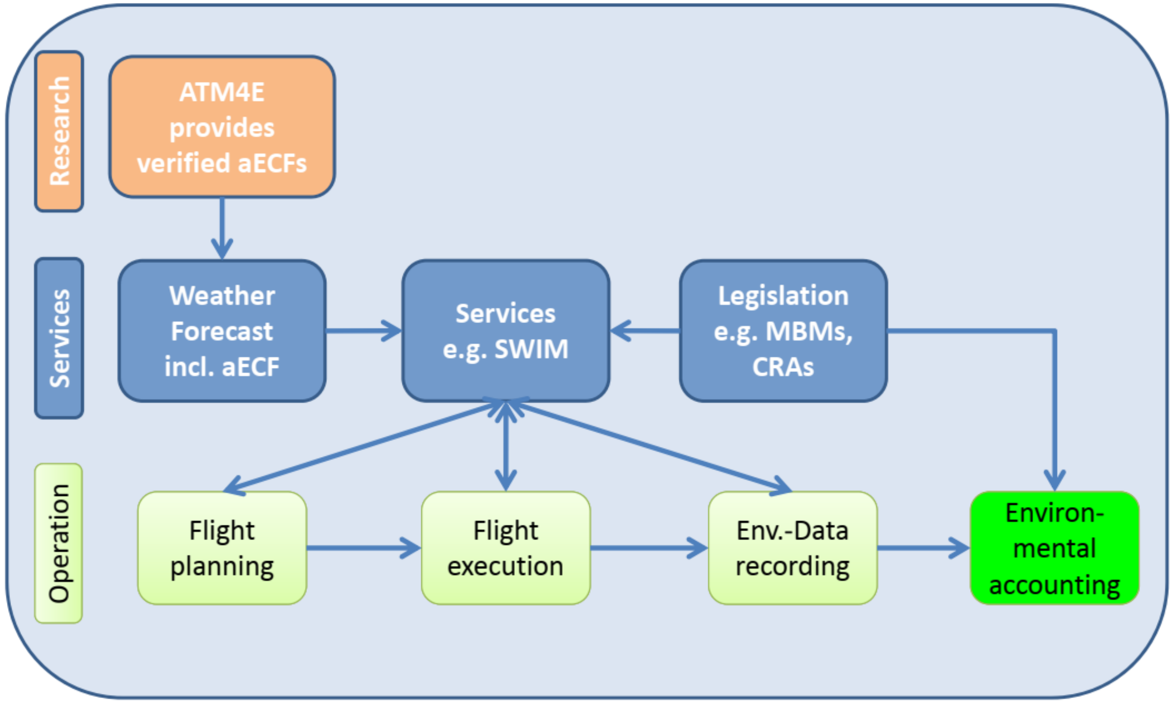
# Towards implementation of climate optimized trajectories

- Implementation relies on **provision of climate change functions to ATM** (trajectory optimisation)
- Feasibility study performed on **infrastructure** comprising MET components – roadmap definition

- Options **on how to integrate** such novel MET products have been studied, e.g. ATM4E, SESAR ATM4E, PJ18
- Further options on how to expand current ATM and how to identify overall **mitigation potential by climate-optimized trajectories** are currently explored, e.g. SESAR FlyATM4E, ALARM, but also in Aeronautics projects ClimOP.




Matthes et al. 2017

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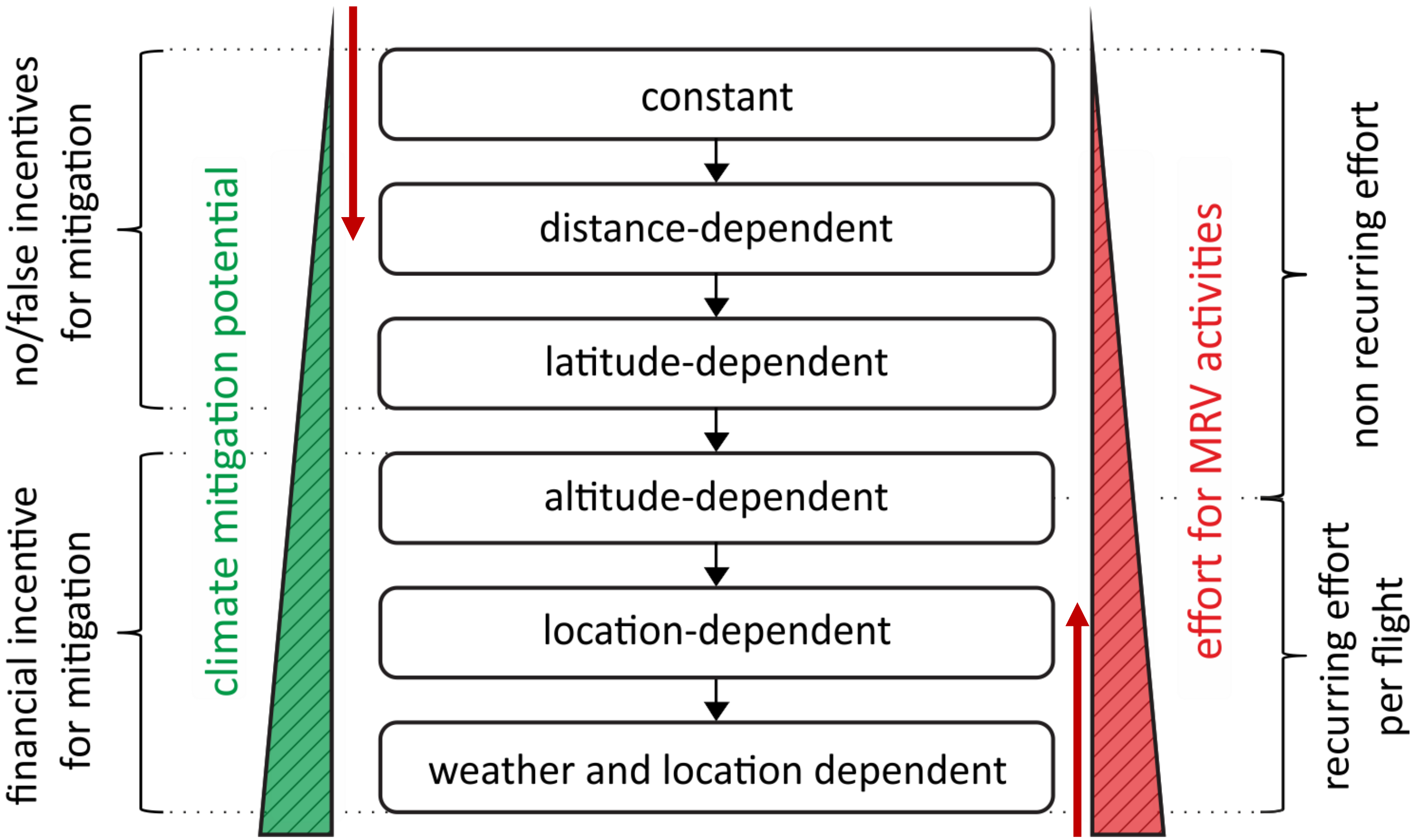
# Towards integration of non-$CO_2$ effects in emission schemes

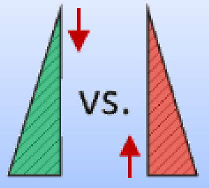
## Need for market-based / policy measures for integrating non-$CO_2$ effects of aviation into EU ETS and under CORSIA

**Integration based on $CO_2$ equivalents (CO2e)**




- From research on **climate impact of aviation**, e.g. IPCC (EASA) with current level of confidence in climate impact estimates we suggest a **risk analysis** to **quantify robust mitigation** potentials.
- **Decision making** under uncertainty conditions.

Choosing a $CO_2$e method is a trade-off between high climate mitigation incentives and low efforts for MRV activities.




**Key criteria for selecting a CO2e method**

- CO2e factors must provide an incentive for mitigating non-$CO_2$ effects
- CO2e factors should be easy to calculate, predictable and transparent

Niklaß et al., 2020

**MRV = Monitoring, Reporting, Verification**

# Ongoing research projects on sustainable aviation
# Focussing on topics related to ATM

- **FlyATM4E** investigates robustness criteria of **climate-optimized aircraft** trajectories and synoptical situations with large mitigation potential
  - Assessment strategies: Win-win situations and Cherry picking in the European Air Space
  - SESAR Exploratory Research Project, 06/2020-11/2022, coordinated by DLR Institute of Atmospheric Physics
- **ALARM** will to develop a prototype on global **multi-hazard monitoring** and Early Warning System (EWS).
  - Early warnings on volcanic ash, dust, severe weather, space weather as well as hot spots in terms of climate impact provided (nowcast, forecast)
  - SESAR Exploratory Research Project, 06/2020-11/2022, U3CM, DLR, BIRA, Satavia, UniPad, SymOpt
- **DYNCAT** will explore more **environmentally friendly** and more **predictable flight profiles** in the terminal manoeuvring area, or TMA. It will support pilots in their configuration management during approach.
  - DYNCAT will have available data (real-world, simulation)
  - SESAR Exploratory Research Project, 07/2020-12/2022, coordinated by DLR Institute of Flight Systems
- **Contrail avoiding** trajectories planning and satellite verification for night time traffic
  - Exercise to avoid night-time contrails over Europe, 01/2021-12/2023, DLR Institute of Atmospheric Physics, DWD, MUAC
- **ACACIA** improves **scientific understanding** on mechanisms and processes causing **aviation climate impact** and provides an updated climate impact assessment
  - Investigate **non-$CO_2$ climate impacts of aviation** comprising indirect aerosol cloud interaction
  - Aeronautics Project (RIA), 01/2020-06/2023 coordinated by DLR Institute of Atmospheric Physics
- **ClimOP** assesses strategies for **operational improvements** in order to reduce climate impact of aviation comprising $CO_2$ and non-$CO_2$ impacts
  - Most promising mitigation strategies are identified and their mitigation potential assessed
  - Aeronautics Project (RIA), 01/2020-06/2023, DeepBlue, DLR, NLR, TU Delft et al.

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# Climate change and the role of ATM - Summary

- **Total climate impact** of aviation is caused by $CO_2$ and non-$CO_2$ effects, with aviation contributing to anthropgenic climate change by 2.5% (only $CO_2$) and about 5 % (considering non-$CO_2$ effects as well).

- Non-$CO_2$ effects show a **strong spatially and temporally variation** which can be exploited by **alternative trajectories (climate-optimized)** in order to reduce climate impact of aviation.
- Climate change functions are a **concept to describe** these non-$CO_2$ climate impacts, and algorithms are currently under development which enable an direct linkage to weather forecast data.
- Using such **novel MET services** (prototypes) enables exploring **mitigation potential** by climate-optimized trajectories, e.g. in European traffic case study.

- **Towards implementation** of such novel MET services on aviation climate impact requires an expanded infrastructure, as well as concepts on **decision making under uncertainty conditions** (robustnest).
- Conceptual work on how to best integrate non-$CO_2$ effects in current emission schemes, e.g. CORSIA are delivering initial concepts with different levels of **complexity** and **accuracy** (Stakeholder dialogue).
- **Strategic partnership** between climate impacts research and air traffic management helps efficient integration.

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# Literature and references


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# Thank you