REACT4C
Mitigation potential of flying lower or higher

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REACT4C TEAM, EU FP7 research project

DLR

An approach for a weather-dependent climate-optimized Flight Planning to mitigate Aviation climate impact

REACT4C = Reducing Aviation Climate impact by changing trajectories for the benefit of climate (2010 - 2014)

Sigrun Matthes, DLR, IPA, Oberpfaffenhofen

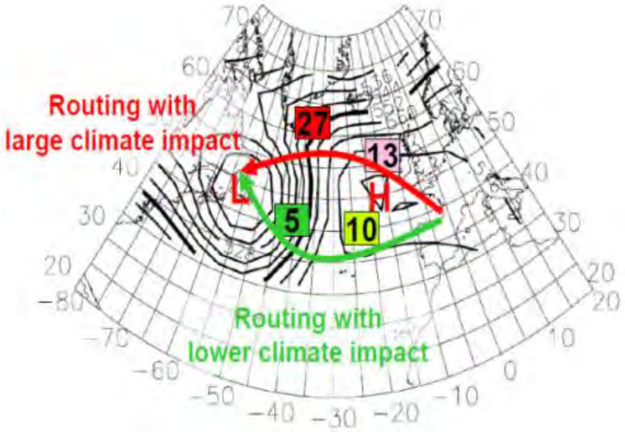
REACT4C Team

European Consortium DLR, Airbus, CICERO, Universities - Aquila & Manchester & Reading, Eurocontrol and UK Met Office

Funded under EU Commission 7th Framework Programme (FP7)

REACT4C (EU aeronautics project) Overall objective

REACT4C addresses **inefficiencies** which exist in the aviation system with respect to fuel consumption and emissions by investigating the **potential of alternative flight routing for lessening** the atmospheric impact of aviation.



Main objectives of **REACT4C** were

to explore the feasibility of adopting flight altitudes and flight routes that lead to reduced fuel consumption and emissions, and lessen the climate impact;

to estimate the overall global effect of such optimized flight routing measures in terms of climate change.

Impact of CO_2, NO_x, sulphate and black carbon aerosols and contrail-cirrus are considered.

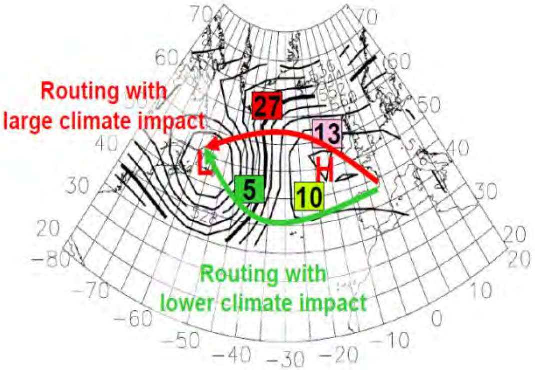
Conceptual approach

Climate cost functions

Aviation climate impact depends on **geographical location, altitude and time** of aircraft. Non-CO_2 climate impact of aviation emissions depends on **fate of emissions** and strongly varies with actual atmospheric chemistry and physics.

Some regions are more and some less sensitive to aviation emissions., which allows to identify climate-optimized aircraft trajectories (routes).

This requires an **interface** between flight planning tools and climate impact information from atmospheric chemistry-climate models.



Such an interface is established with a **climate-cost function (CCF)**.

$$I_C = \int_{flight\ \ time} R(\bar{s}(t), t, e(t))\, dt,$$

$$I_C = \int_{flight\ \ time} \bar{r}(s_x, s_y, s_z, t) \cdot \bar{e}(t)\, dt$$

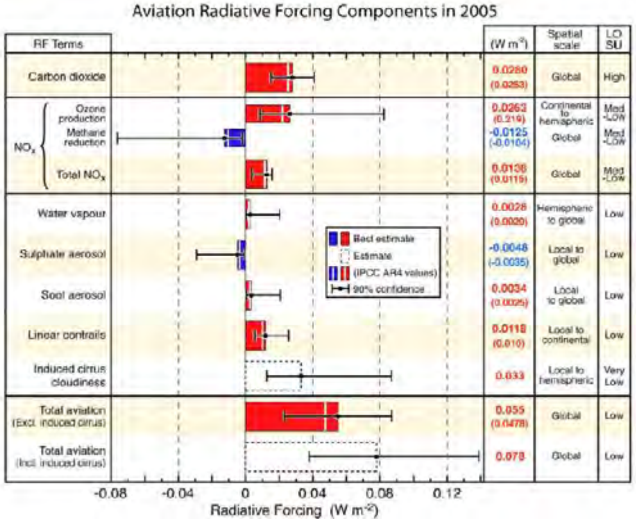
$$f = w_C m_C I_C + w_{DOC} I_{DOC}$$

Climate cost function [Matthes et al., 2012]

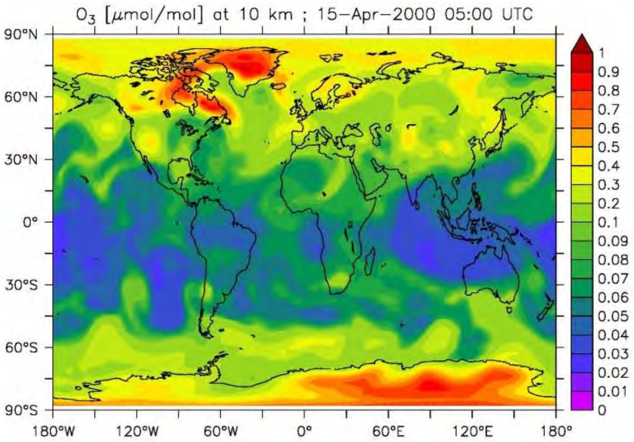
Aviation climate impact
Overview

Climate impact of aviation emissions

- emitted compound (direct & indirect effect)
  - CO_2, black carbon (soot) - direct
  - NO_x (O_3, CH_4)
  - H_2O (contrail cirrus)
  - soot (AIC, aviation induced cloudiness)



Lee et al., 2010 (IPCC)



- Climate impact of non-CO_2 emissions depends
  - time and position of aircraft
  - actual weather conditions (processes, transport pathways, temperature, humidity)
  - background concentrations

Matthes, Jöckel et al. 2011

Sigrun Matthes, DLR et al.

Aerodays 2011 > Climate optimized flight planning
Sigrun Matthes, DLR

Aviation induced cloudiness

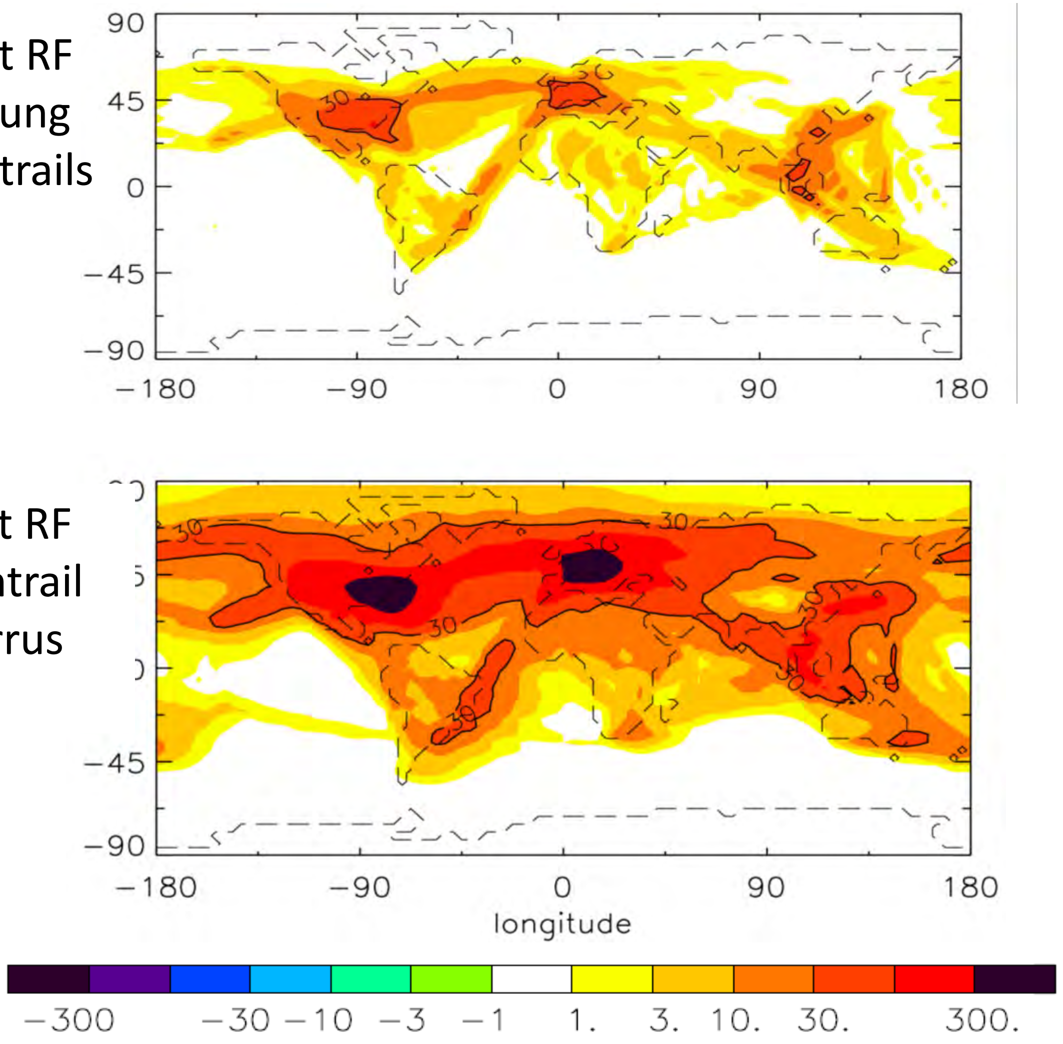
Formation of line-shaped contrails, contrail-cirrus, change in size of ice particles and change in natural cirrus

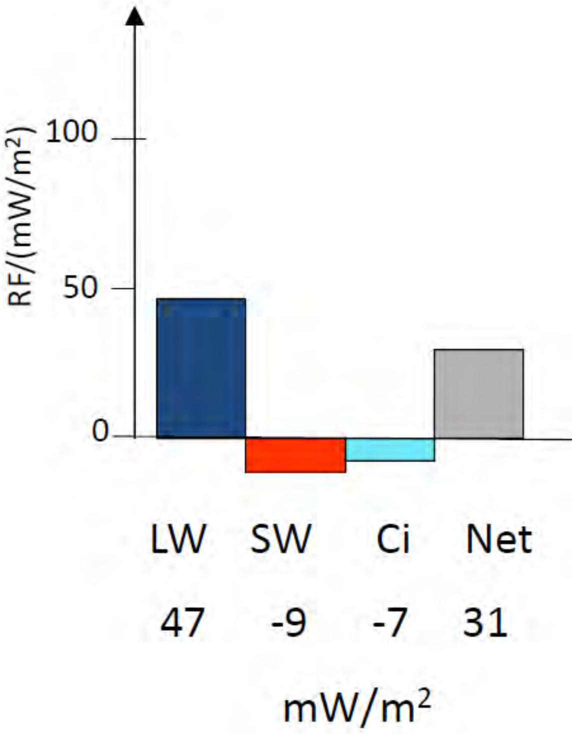
Contrails spread in humid air masses, they warm or cool

Radiative forcing by Contrail Cirrus from ECHAM GCM

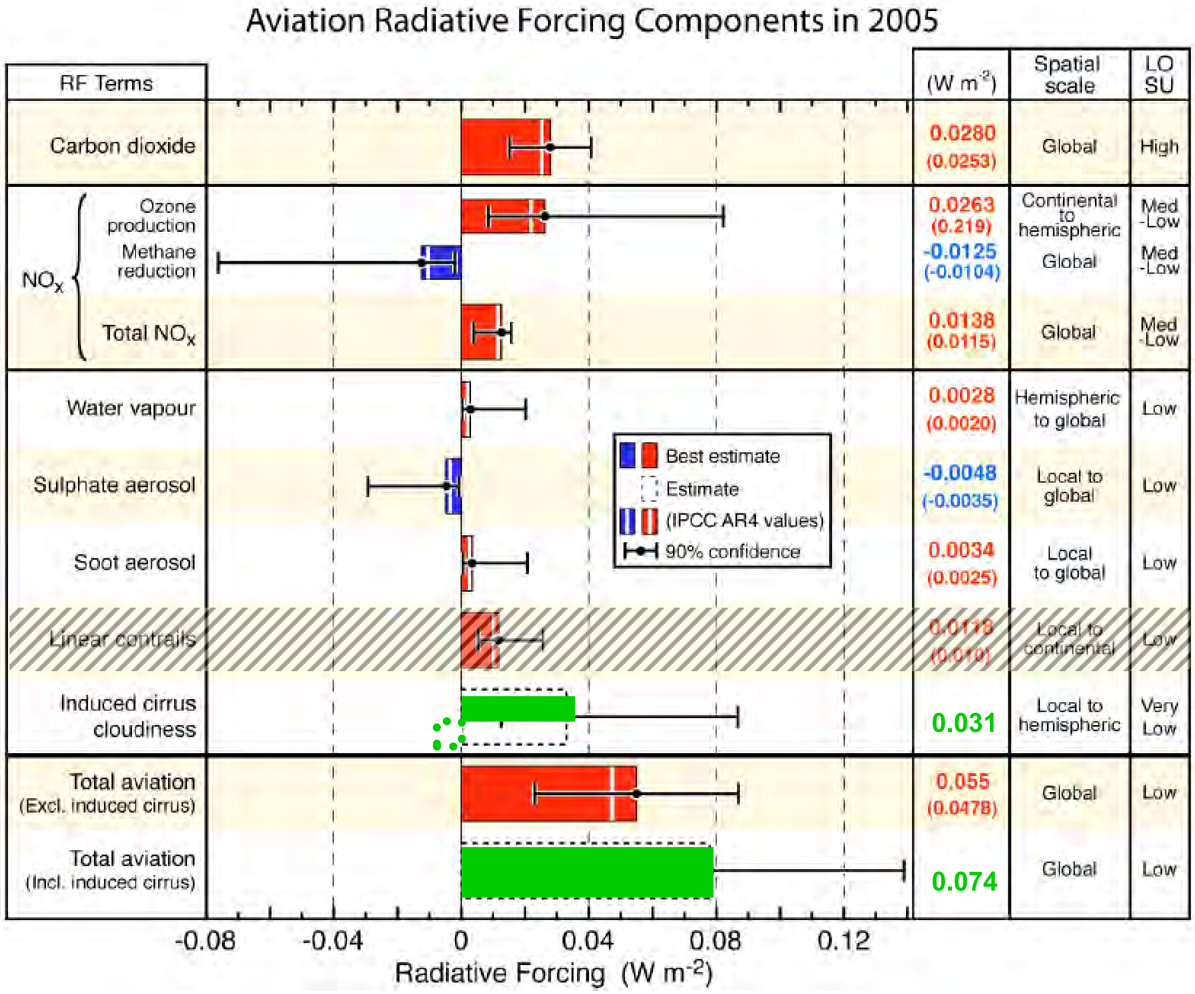
net RF
young
contrails

net RF
contrail
cirrus





Burkhardt and Kärcher
(Nature Clim. Change, 2011)



Lee et al., 2010

updated with Burkhardt&Kärcher, 2011

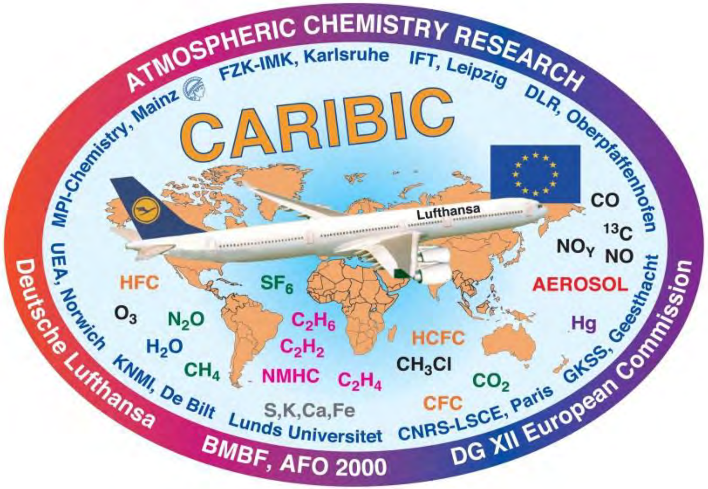
Main contributors:
Contrails
CO_2
NO_x

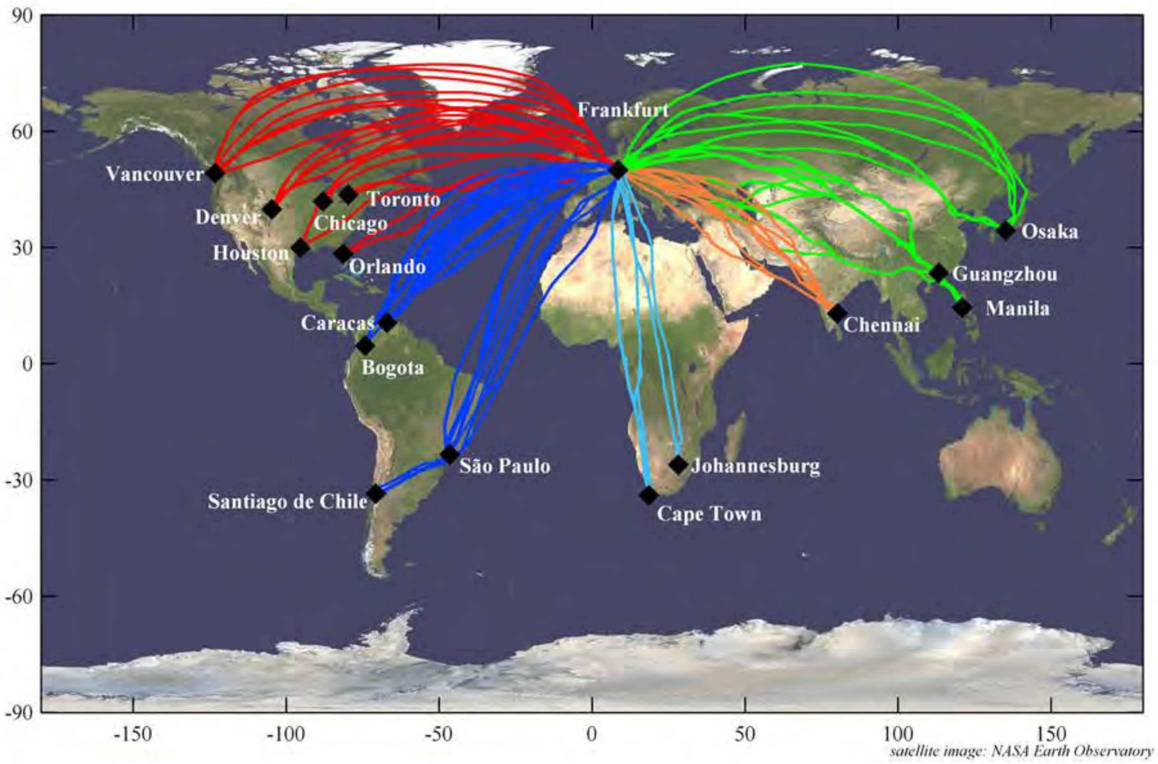
3.5-5.0% of warming attributed to air traffic

ACARE, 2008

The findings of the IPCC point very clearly to the need to do something but there are areas of detail where more understanding is needed.

CARIBIC - Civil Aircraft for the regular investigation of the atmosphere based on an instrument container

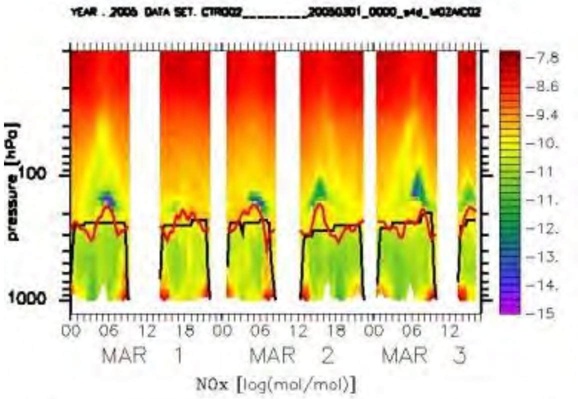


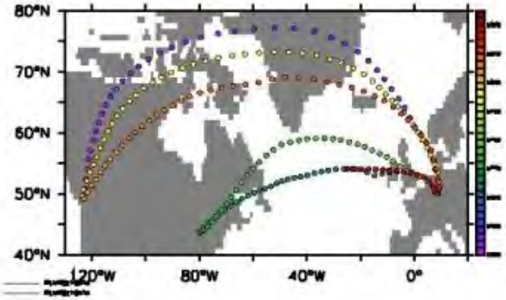


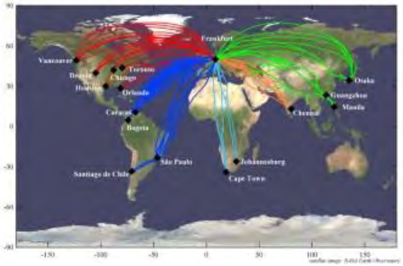
satellite image: NASA Earth Observatory

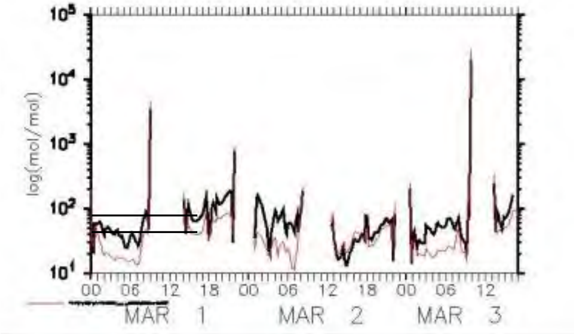
Brenninkmeijer, Ziereis, Stratmann et al.

S4D module in nudged simulation
Aircraft Measurements Intercomparison









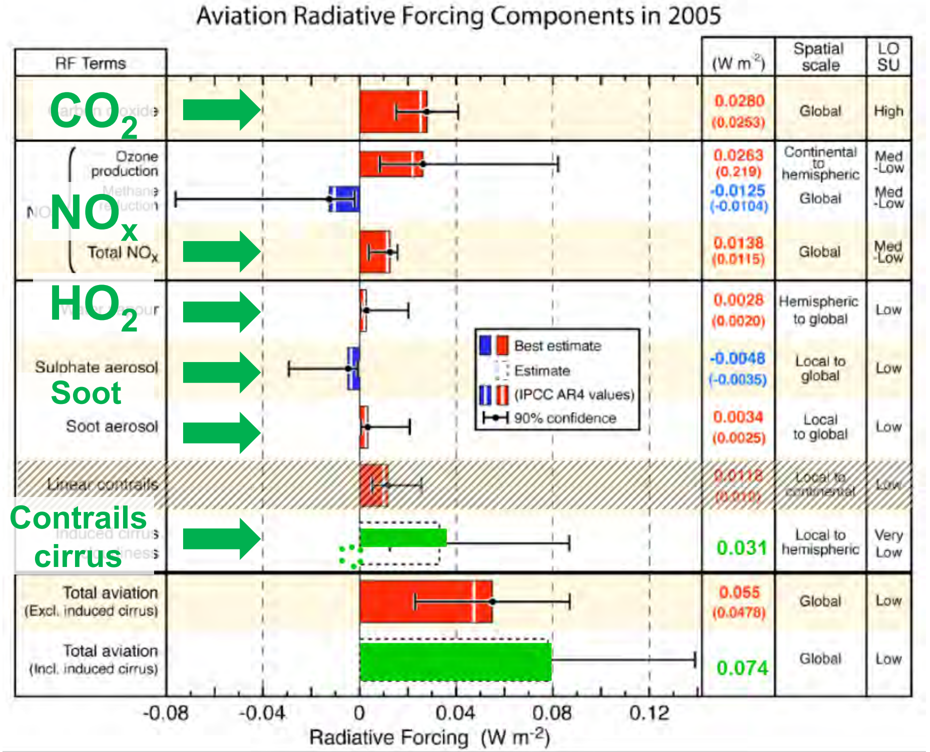
- Module s4d allows to generate user defined data set along flight trajectory
- Aircraft measurement of scheduled air traffic is analysed (MOZAIC, CARIBIC)
- QCTM study quantifies aviation contribution to atmospheric concentrations on tracks
- Perturbation signal in NO_x from aviation amounts to up to 30% on aircraft flight trajectories and varies for two weather pattern (strong zonal *vs.* confined jet)

Mitigation of Aviation Impact
by
flying lower or higher

Nitrogen oxide emissions (direct / indirect)
water vapour emissions,
aerosols sulfate and black carbon,
contrail and contrail-cirrus

REACT4C Mitigation studies
Flying lower and flying higher

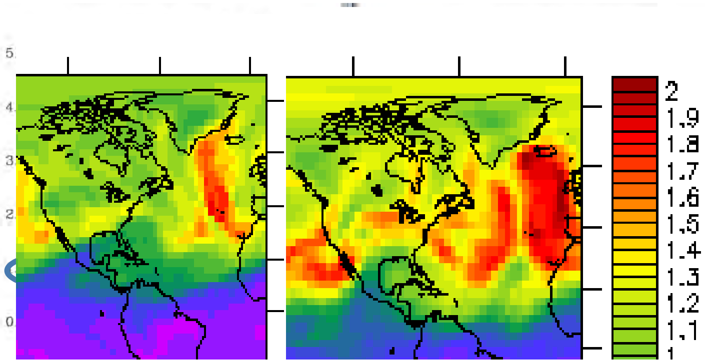
- **Mitigation option**
  - Mitigation options cause changes in total amount of emission and their spatial distribution
- **Assessment of mitigation potential by estimating changes in RF**
  - Methods are required which provide a robust measure and metric
- **Generation of scenarios flying higher and flying lower**
  - Alternative emission scenario (FAST, provided by MMU)



- **Set of of state-of-the art global atmosphere-climate models investigate changing atmospheric impact and climate impact of alternative routing**

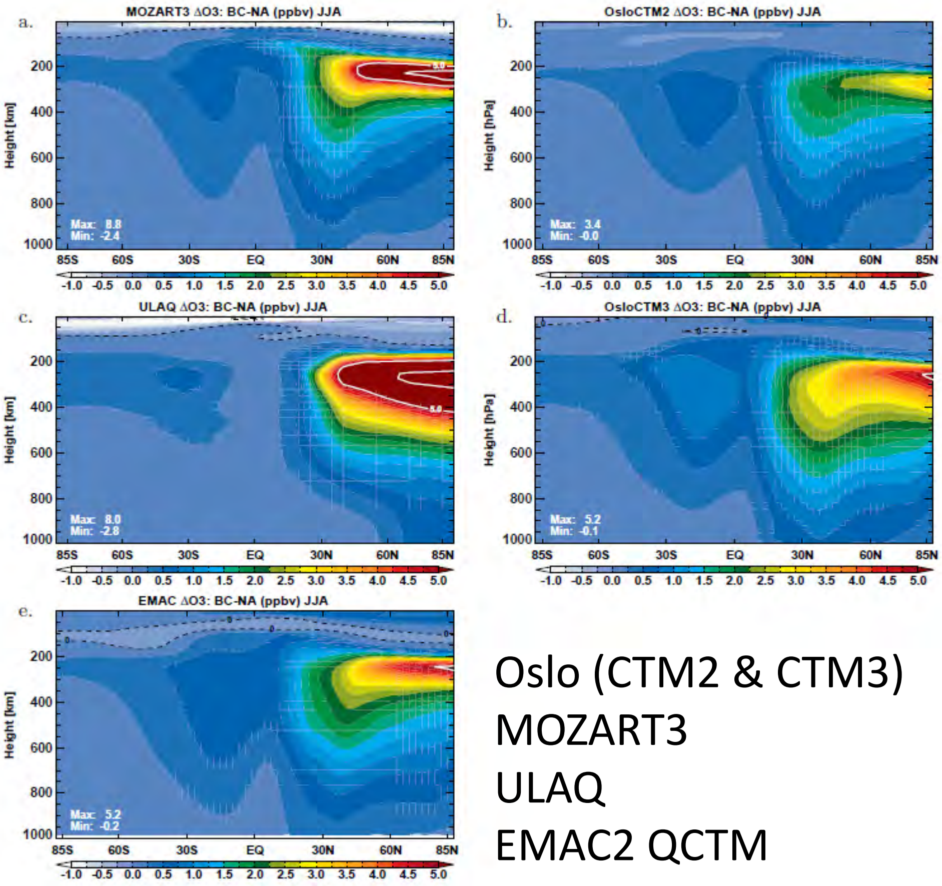
Modelling intercomparison : Weather pattern analysis

Variability aviation ozone



- Five **models** participating
- Updated (mitigation) **a/c emission inventory,** identical emission sets
- Harmonised parameterisations (e.g. lightning NO_x)
- Additional **diagnostics** (ozone production rates – diagtrac (ozone production & destruction channels)

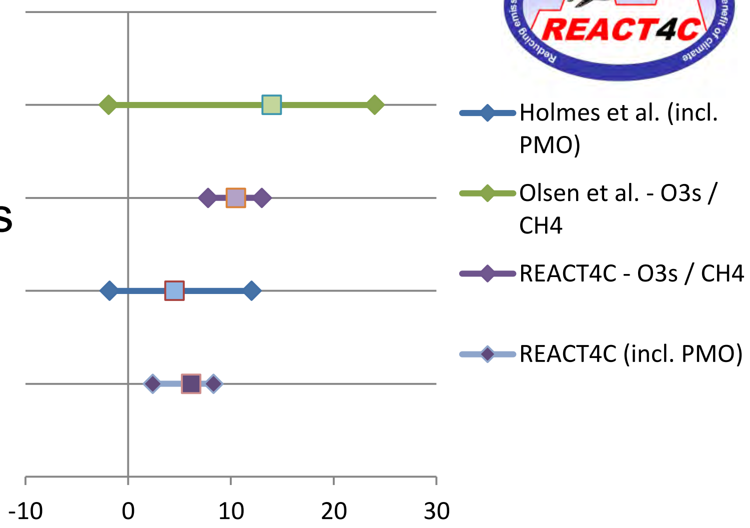
Aviation ozone perturbation (July)



Oslo (CTM2 & CTM3)
MOZART3
ULAQ
EMAC2 QCTM

Aviation climate impact - NOx

- Detailed study on **atmospheric impact** of nitrogen oxide emissions (NO_X) and inventories
- Short term ozone & long-term CH_4 & O_3
- Multi-model estimate for **uncertainty analysis**
- Five CTM models participating for evaluating



	Net [mW/m²]		Range [mW/m²]	Reference
O_3 short – CH_4	**10.5**	**19.2/-8.7**	**7.8-13.0**	**this study**
CTM2	12.1	21.1/-9.0		
CTM3	13.0	22.4/-9.4		
EMAC2	7.8	18.5/-10.7		
ULAQ	10.2	17.4/-7.2		
MOZART	9.3	16./-7.1		
	14.0	*24.8/-10.8*	*-1.9 – 24.0*	*Olsen et al., 2013*
Long term O_3	**-4.34**		**-5.4 -- -3.6**	**this study**
	-6.6		*-17.0 -- -1.9*	*Holmes et al., 2011*
O_3 s+PM +CH_4	**6.1**		**2.4 – 8.3**	**this study**
	4.5		*-1.8 – 12.0*	*Holmes et al., 2011*

- **REACT4C Basecase 2006 (Inventory)**
- Multi-model mean 6.1 mW/m² (O_3s, CH_4, PMO)
- Holmes et al., 2011 results correspond well
- Olsen et al., 2013 present considerable higher O_3s

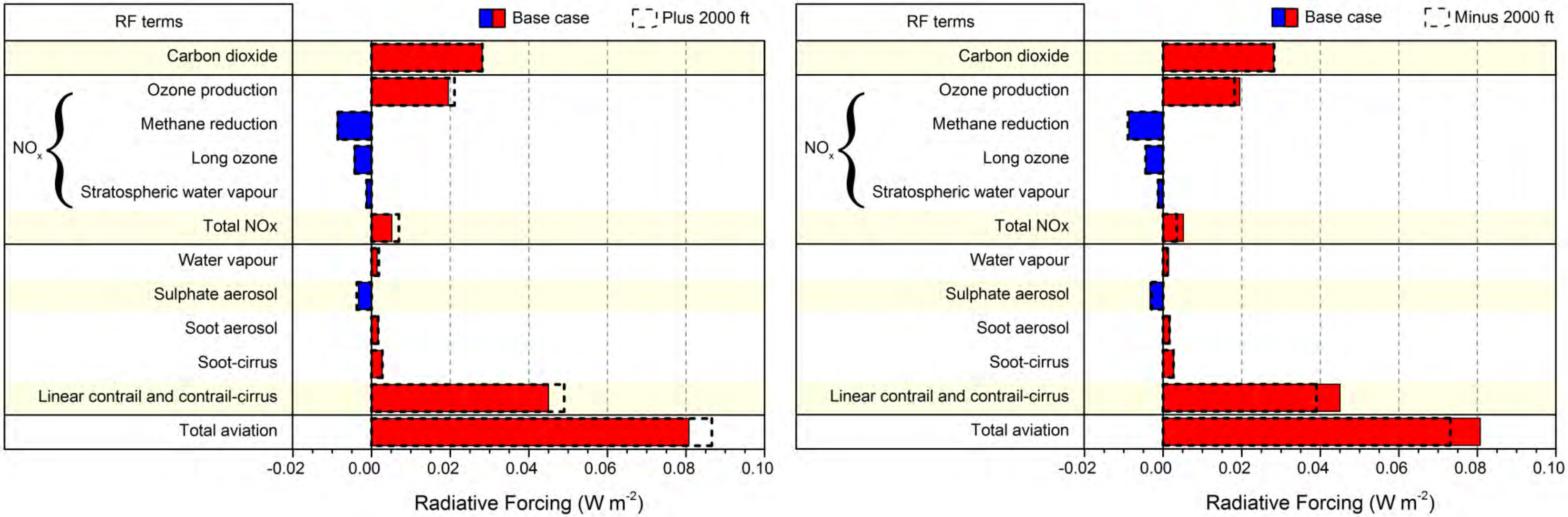
Mitigation of aviation NO_x impact

- **Mitigation options**
  - Aviation aims to reduce its climate impact and investigates mitigation options
  - Mitigation options cause changes in emission and their spatial distribution
- **Assessment of mitigation options**
  - Methods are required which provide a robust measure and metric
- **Case study on aviation NO_x emissions**
  - Set of chemistry-transport-models (chemistry-climate) provides estimates
  - In Olson et al., 2013 scenario is not robust with a “mitigation” from -48.5 to 8.9 mW/m^2
  - REACT4C: Assessment of mitigation options are robust (Sovde et al., 2013)

Mitigation cases	**O_3**	**CH_4**	**O_3 s + CH_4**
Flying higher	1.5 (0.3-2.8)	0.1 (0.1-0.2)	1.6 (0.5-2.8)
Flying lower	-1.3 –(2.2-0.5)	-0.2 –(2.2-0.5)	-1.5 –(2.3-0.6)

Radiative forcing of alternative routing

Nitrogen oxide emissions (direct / indirect) water vapour emissions, aerosols sulfate and black carbon, contrail and contrail-cirrus

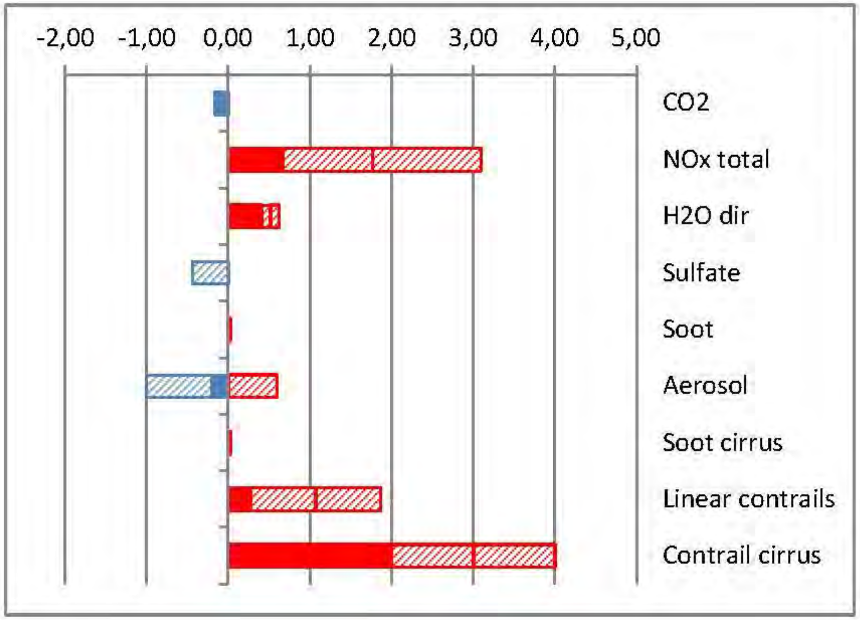


Result from Multi-model study involving nine atmospheric models [Figure L. Lim]

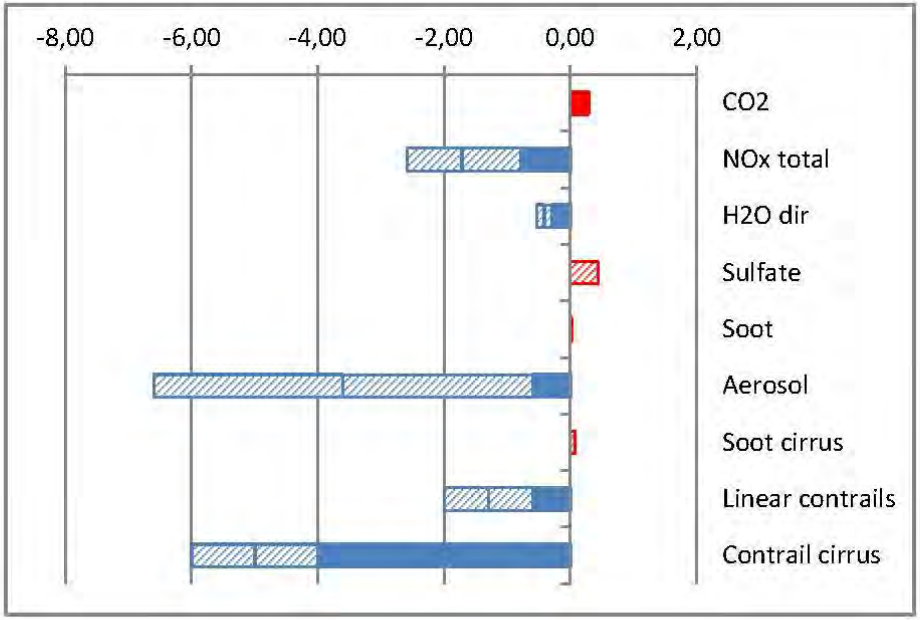
Mitigation potential of alternative routing Radiative Forcing

- Results from multi-model study show
  - “flying higher” **reduces CO_2** impact, but **increases non-CO_2** climate impacts,
  - “flying lower” **increases CO_2** impact but **reduces climate impact of non-CO_2** impacts at the same time.

Flying higher



Flying lower



Result from Multi-model study involving nine atmospheric models

Summary & Conclusion

- **Aviation climate impact of alternative routing**
  - Alternative emission scenarios used to calculate climate impacts of aviation with set of state-of-the-art **models**
  - Climate impact of CO2 and non-CO_2 impacts have opposite sign, resulting in non-CO2 representing a trade-off on CO_2 benefits when flying higher.
  - Emission scenario was constructed as generic mitigation strategy, which means e.g. routing strategy was not adapted to synoptical situation

- **Quantitative estimates of mitigation potential of alternative flight altitudes were provided for nitrogen oxides, water vapour, soot and sulfate aerosol, contrail and contrail cirrus was quantified**

- **Assessment of aviation climate impact**:
  - Results show need for comprehensive assessments of mitigation strategies to evaluate individual effects, their uncertainty and trade-offs
    - Which processes dominates **overall climate impact**?
    - Which effects to be studied with **mitigation options**?

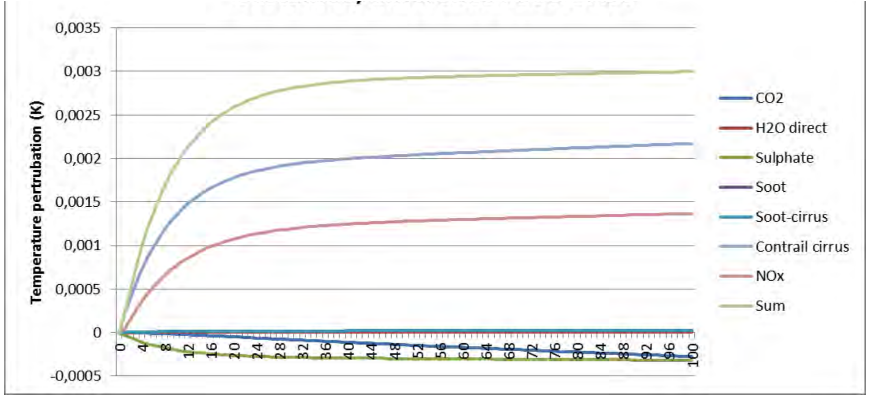
Thank you

Assessment of climate metrics

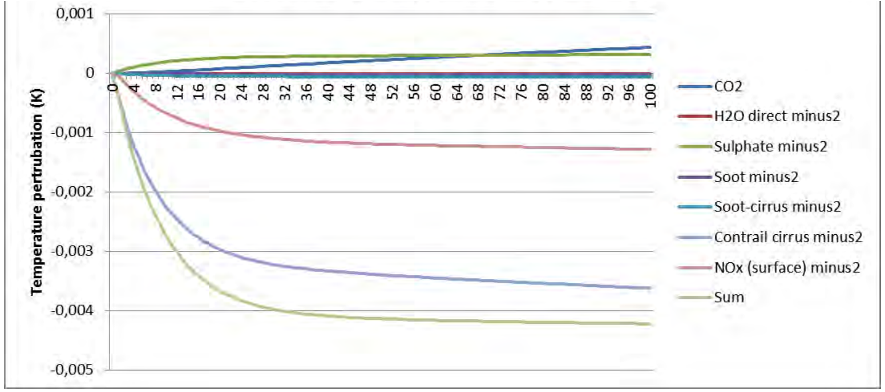
- CO_2 (and other "Kyoto" gases) can easily be included in an **emission trading scheme**.
- Large **uncertainty** exists with respect to the climate impact of non-CO_2 emissions from aviation.
- In general, **radiative forcing** at a certain time is no good measure for the expected climate change. Therefore, the RFI is not suitable for emission trading.
- Multiplying CO_2 emissions by any simple multiplication factor would weaken incentives to reduce the total climate impact beyond a reduction of the fuel consumption.
- Eventually, it might become possible to include non-CO_2 effects by their individual contributions to climate change.
- Often emissions have further effects beyond climate change, e.g., impact on air quality (**trade-offs** & **interdependencies**).

Alternative metrics
Temperature perturbation of sustained emissions

Flying higher



Flying lower



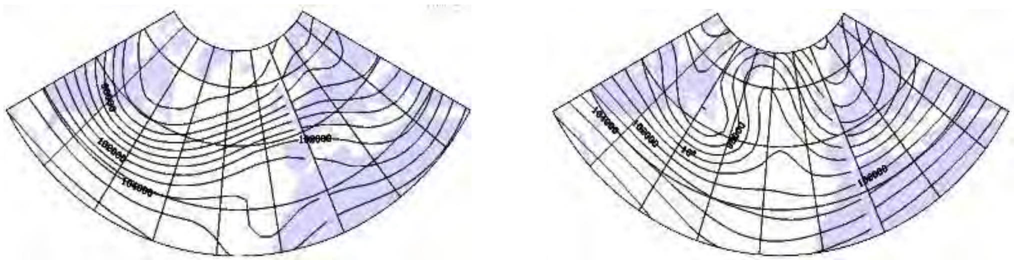
- Changing cruise altitude changes the radiative forcings and our results suggest that in a sustained emission scenario, **contrail cirrus** have a larger impact on temperature than does the change in CO_2 due to fuel changes. Also changes **originating from NOx** are larger than the CO_2 changes.
- However, the total **temperature change for** sustained BASE emissions is about 0.07 K after 100 years of emissions, so the overall temperature reduction when flying lower is less than 10%. Flying higher gives less than 5% increase in temperature after 100 years compared to the base case.

Variations of aviation impact on atmospheric ozone in North Atlantic weather patterns (QCTM)

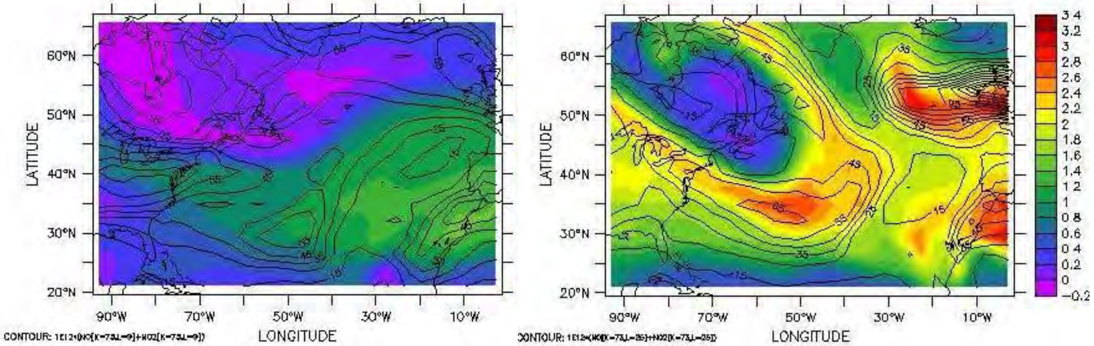
- Climate-optimal trajectories are taking advantage of spatial variation of atmospheric response to aircraft emissions

Weather Pattern 1
Strong (EA pos)

Weather Pattern 4
Confined (NAO neg)



Geopotential height [m]



Aviation induced concentration change (O_3 & NO_x)

- **QCTM EMAC2 study** to investigate relationship between atmospheric response and weather pattern
- **Weather pattern** analysis performed in EMAC
- **Pattern probability** is evaluated vs. ERA (*more or less reproduced*) (*Irvine et al.)*
- Perturbation signal O_3 and NO_x shown for two weather pattern (strong zonal *vs.* confined jet)

Inventories	absolute amounts				relative changes			
	Fuel [Tg C]	CO_2	NO_x	soot	Fuel	CO_2	NO_x	soot
Base Case	178.3	563.4	2.33					
Minus 2000 ft *flying lower*	180.7	571.0	2.33		+ 1.33		- 0.02	
Plus 2000 *flying higher* ft	176.8		2.35		- 0.83		+ 0.80	

Perturbations of the altitudes flown up by 2000ft and down by 2000ft show an increase in fuel usage for the lower altitude flying (by about 1.3%) and a very small increase in flying 2000ft above the determined flight altitudes in the base case inventory. The perturbations from REACT4C and TradeOff are shown in Table 3.

Table 1: Comparison of Base Case and mitigation cases flying lower (minus 2000 ft) and flying higher (plus 2000 ft) from REACT4C project, annual fuel consumption.

A small increase (1.3%) in fuel use is shown for the minus 2000ft case when compared with the Base Case. Conversely a very small decrease (-0.8%) in fuel use is shown for the plus 2000ft case. This pattern is to be expected as generally the fuel efficiency increases with higher altitude although in reality there is a complex array of factors including aircraft weight determining the optimum altitude.

Climate cost functions

used as interface between atmospheric modelling and flight planning

Aviation climate impact – short lived ozone and long-lived methane effect

- Contribution of aviation to total ozone induces a short-lived effect
- Associated change in OH induces a long-lived methane effect

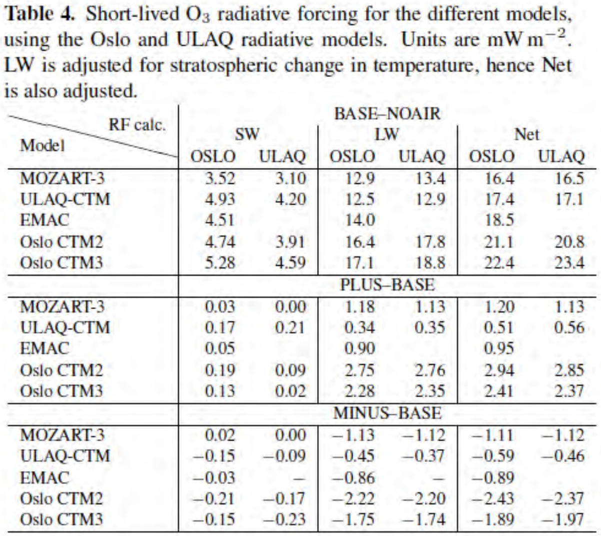
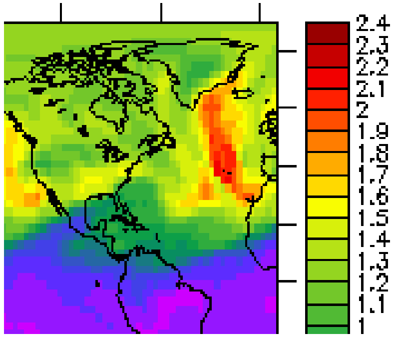
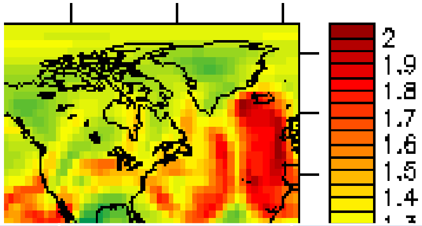


Table 4. Short-lived O_3 radiative forcing for the different models, using the Oslo and ULAQ radiative models. Units are $mW\,m^{-2}$. LW is adjusted for stratospheric change in temperature, hence Net is also adjusted.

Model \ RF calc.	SW OSLO	SW ULAQ	LW OSLO	LW ULAQ	Net OSLO	Net ULAQ
	BASE–NOAIR					
MOZART-3	3.52	3.10	12.9	13.4	16.4	16.5
ULAQ-CTM	4.93	4.20	12.5	12.9	17.4	17.1
EMAC	4.51		14.0		18.5	
Oslo CTM2	4.74	3.91	16.4	17.8	21.1	20.8
Oslo CTM3	5.28	4.59	17.1	18.8	22.4	23.4
	PLUS–BASE					
MOZART-3	0.03	0.00	1.18	1.13	1.20	1.13
ULAQ-CTM	0.17	0.21	0.34	0.35	0.51	0.56
EMAC	0.05		0.90		0.95	
Oslo CTM2	0.19	0.09	2.75	2.76	2.94	2.85
Oslo CTM3	0.13	0.02	2.28	2.35	2.41	2.37
	MINUS–BASE					
MOZART-3	0.02	0.00	−1.13	−1.12	−1.11	−1.12
ULAQ-CTM	−0.15	−0.09	−0.45	−0.37	−0.59	−0.46
EMAC	−0.03	–	−0.86	–	−0.89	
Oslo CTM2	−0.21	−0.17	−2.22	−2.20	−2.43	−2.37
Oslo CTM3	−0.15	−0.23	−1.75	−1.74	−1.89	−1.97





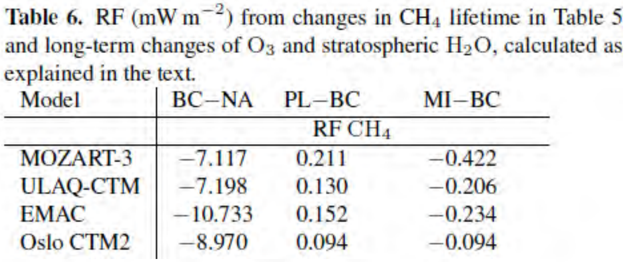
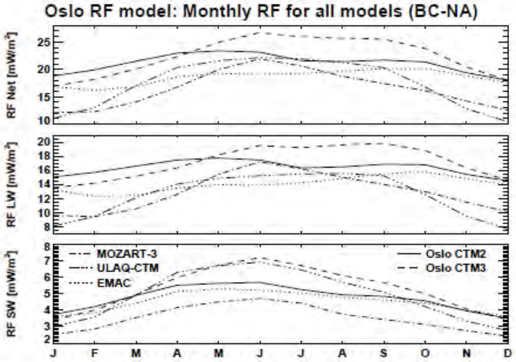


Table 6. RF ($mW\,m^{-2}$) from changes in CH_4 lifetime in Table 5 and long-term changes of O_3 and stratospheric H_2O, calculated as explained in the text.

Model	BC−NA	PL−BC	MI−BC
	RF CH_4		
MOZART-3	−7.117	0.211	−0.422
ULAQ-CTM	−7.198	0.130	−0.206
EMAC	−10.733	0.152	−0.234
Oslo CTM2	−8.970	0.094	−0.094

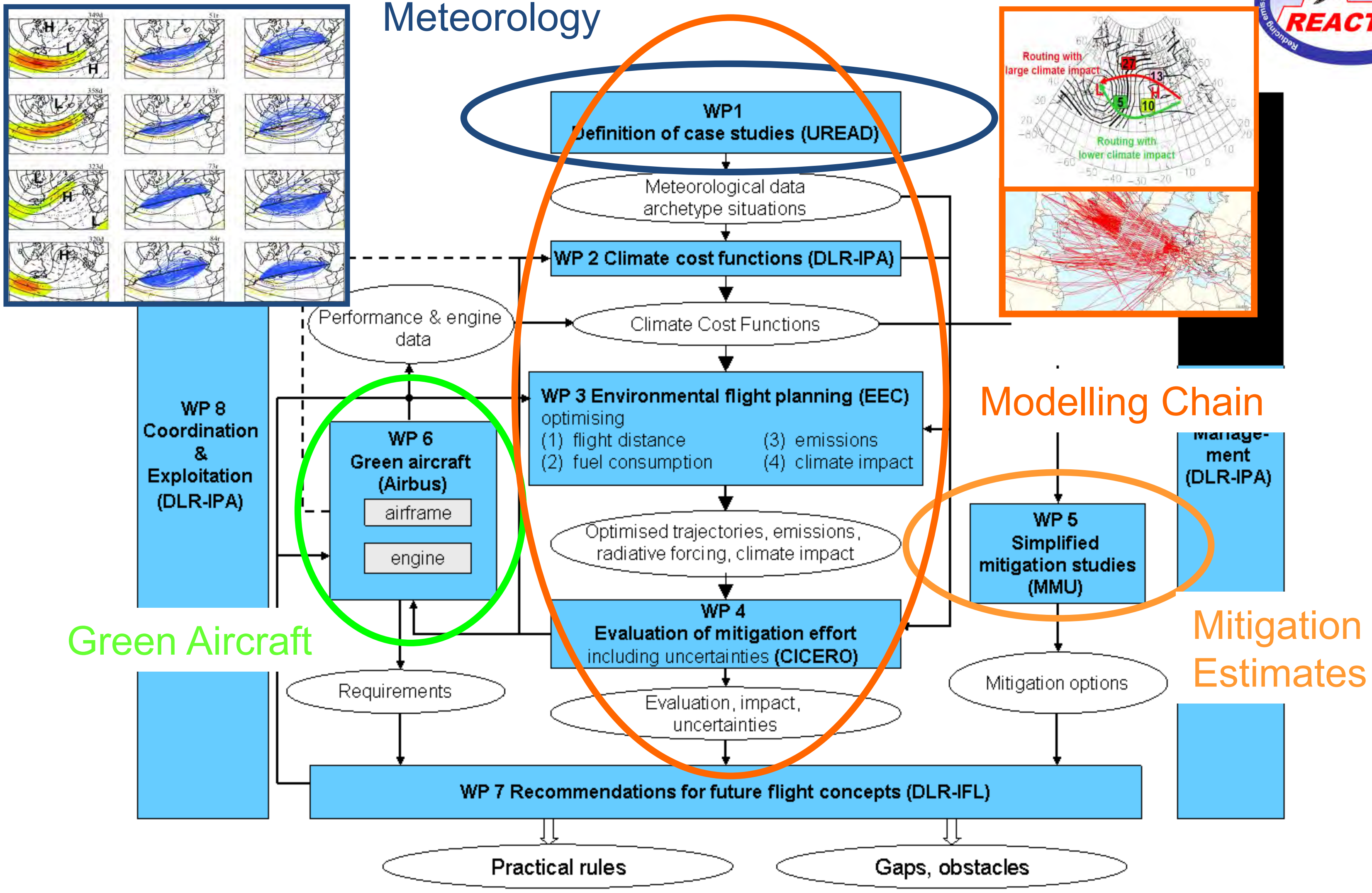


Oslo RF model: Monthly RF for all models (BC-NA)

as cal-

Effect	Net [mW/m2]	SW	LW	Change „higher“	Change „lower“	
O3 short	16.4 / 22.4	3.5 / 5.3	12.9 / 17.1	0.5 / 2.9	-2.4 / -0.6	
CH4	-10.7 / -7.1			0.1 / 0.2	-0.4 / -0.1	

Workplan Structure



Meteorology

WP1 Definition of case studies (UREAD)

Meteorological data archetype situations

WP 2 Climate cost functions (DLR-IPA)

Performance & engine data

Climate Cost Functions

WP 3 Environmental flight planning (EEC)
optimising
(1) flight distance
(2) fuel consumption
(3) emissions
(4) climate impact

Optimised trajectories, emissions, radiative forcing, climate impact

WP 4 Evaluation of mitigation effort including uncertainties **(CICERO)**

Evaluation, impact, uncertainties

WP 8 Coordination & Exploitation (DLR-IPA)

WP 6 Green aircraft (Airbus)
airframe
engine

Requirements

Green Aircraft

Modelling Chain

Management (DLR-IPA)

WP 5 Simplified mitigation studies (MMU)

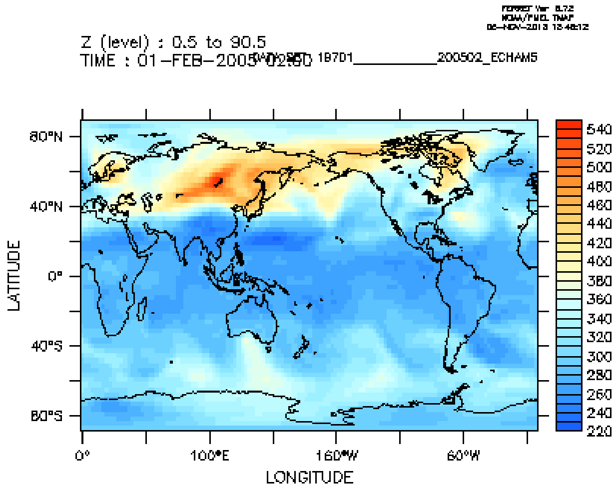
Mitigation options

Mitigation Estimates

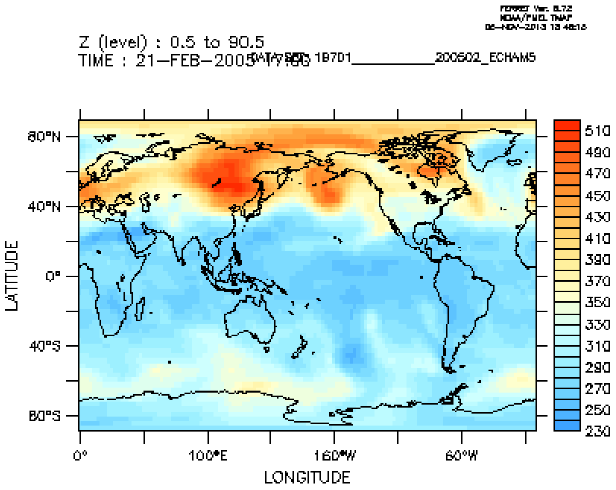
WP 7 Recommendations for future flight concepts (DLR-IFL)

Practical rules

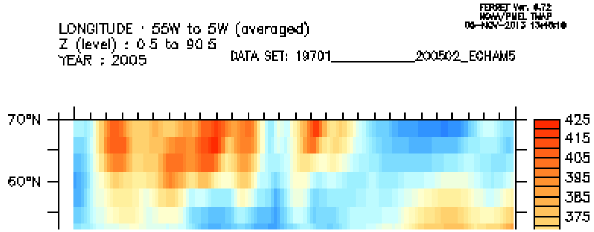
Gaps, obstacles

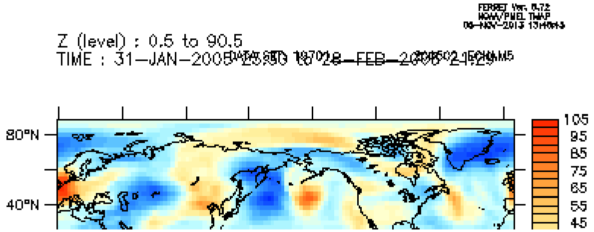


total ozone (DU)



total ozone (DU)

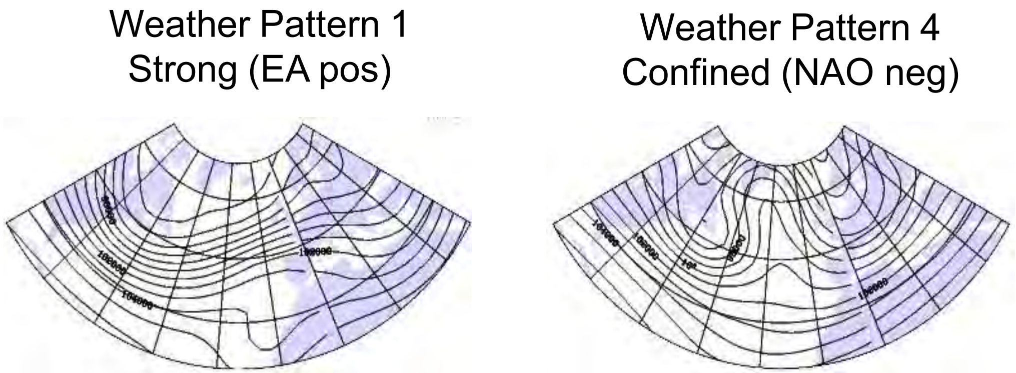




Effect	Net [mW/m2]		SW		LW	
O3 short	16.4-22.4	*18.5*	3.5-5.3	4.5	12.9-17.1	14.0
CH4	-10.7 / -7.1	*-10.7*				
O3 PMO	-5.4 / -3.6	*-5.4*				
H2O	-1.6 / -1.1					

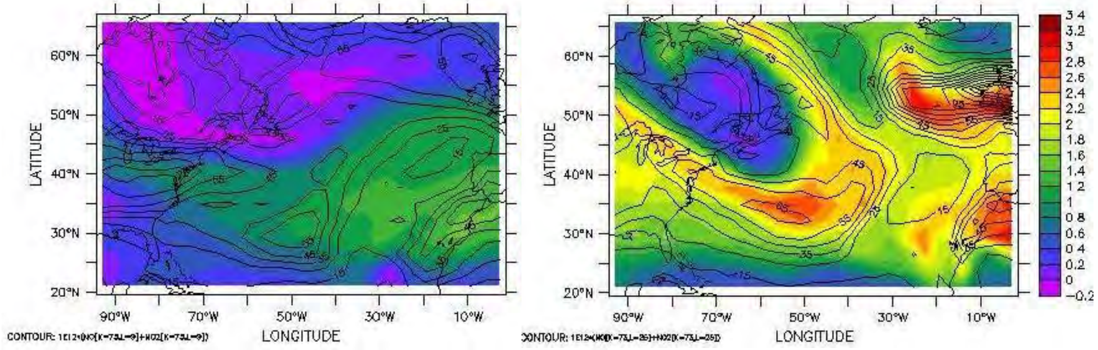
Variations of impact of aviation emissions in North Atlantic weather patterns (QCTM)

- Climate-optimal trajectories are taking advantage of spatial variation of atmospheric response to aircraft emissions


Weather Pattern 1
Strong (EA pos)

Weather Pattern 4
Confined (NAO neg)

Geopotential height [m]



Aviation induced concentration change (O_3 & NO_x)

- QCTM EMAC2 study to investigate relationship between atmospheric response and weather pattern
- Weather pattern analysis performed in EMAC
- Pattern probability is evaluated vs. ERA (*Irvine et al.)*
- Perturbation signal O_3 and NO_x shown for two weather pattern (strong zonal *vs.* confined jet)