Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Impacts of non-CO2 emissions from aviation on climate

An introduction

Peter van Velthoven

Contents

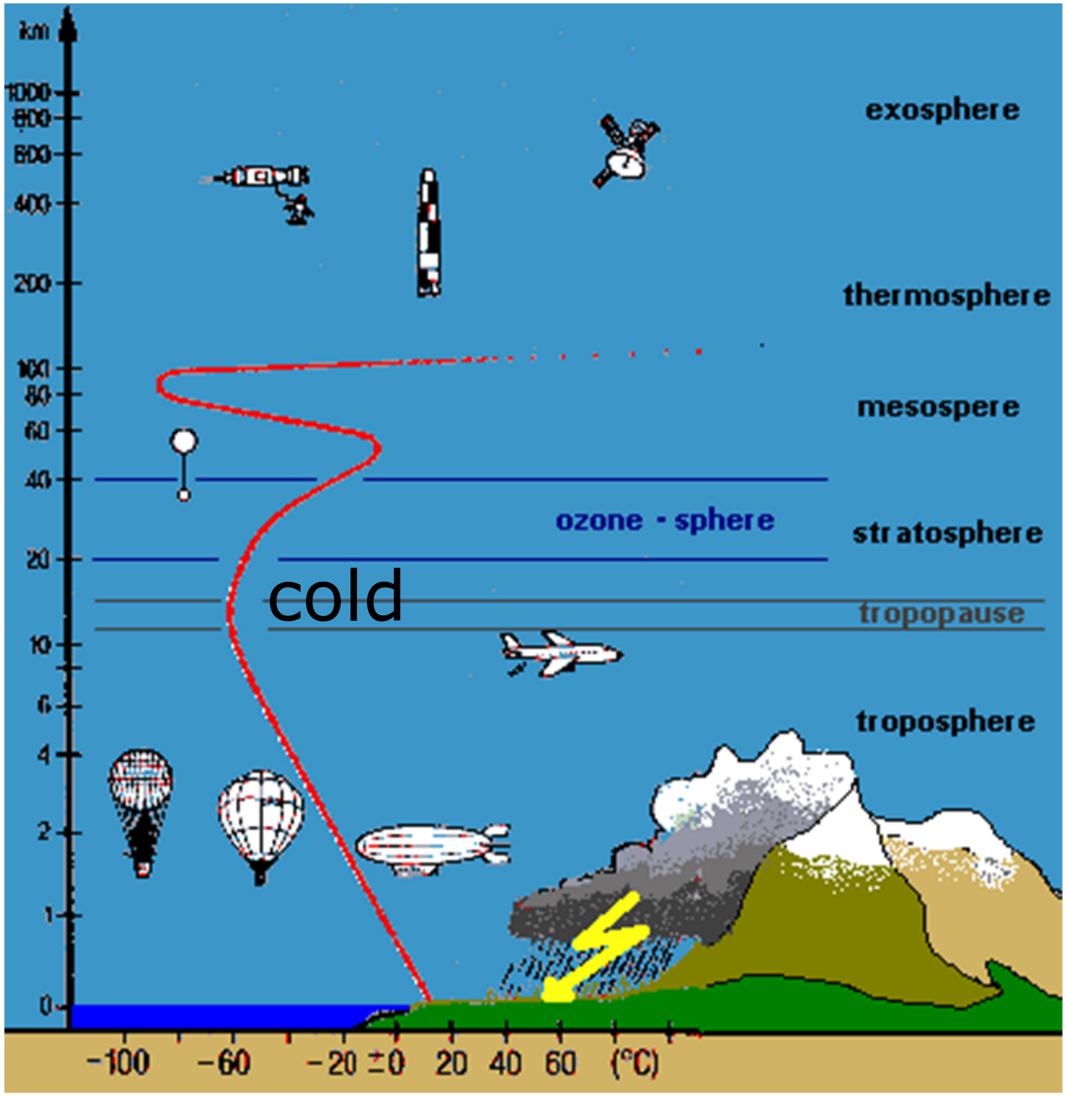
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

- Introduction : atmosphere, greenhouse effect, radiative forcing, non-CO2 greenhouse gases and their importance for the Paris goals
- Atmospheric effects of aircraft emissions:
  - nitrogen oxides
  - water vapor
  - contrails/aviation cirrus
  - sulfur and soot (particles)
- Radiative forcing by aviation
- How to take into account the climate impact of non-CO2 emissions? Which metric (equivalence)? (RFI, GWP, GTP, GWP*,..)
- Some mitigation options
- Summary

Atmospheric layers

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Height



cold

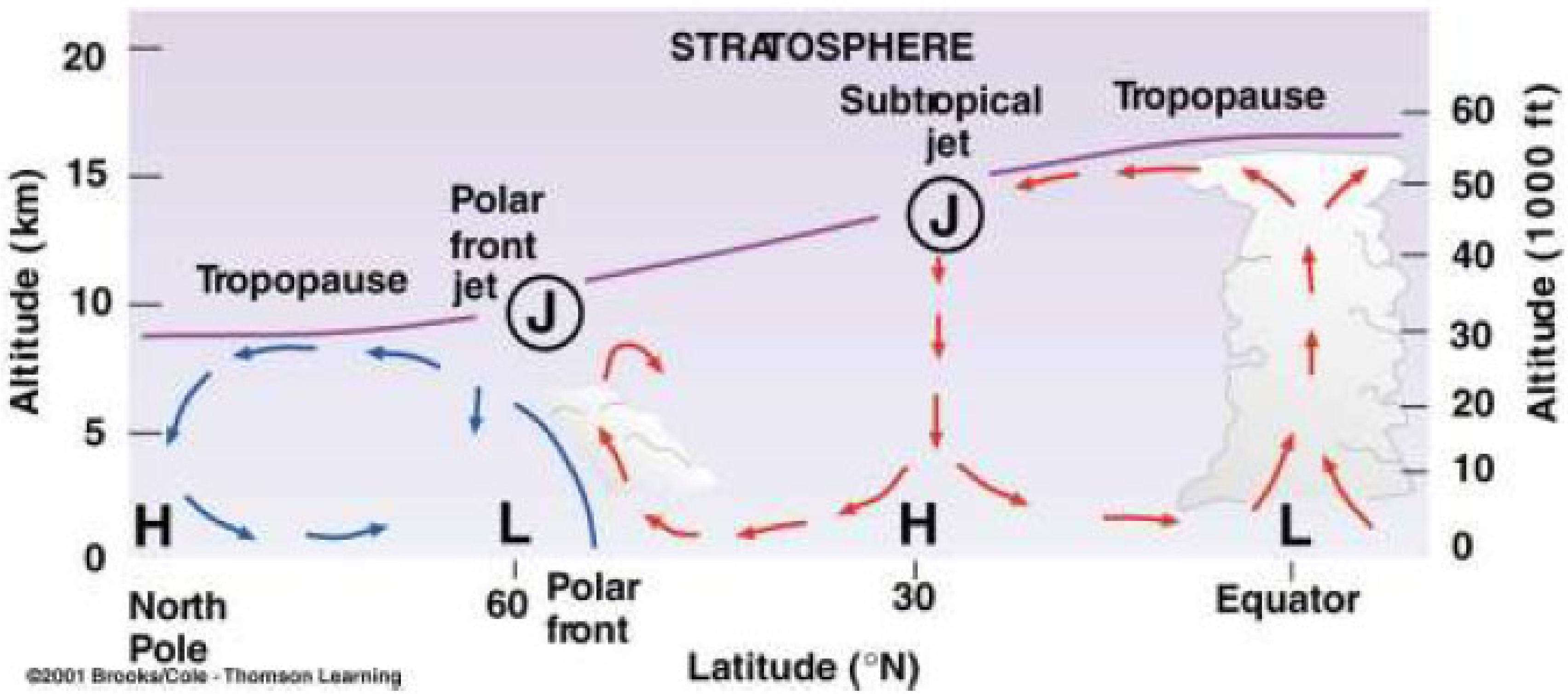
Temperature

stable

instable -
→well
mixed

The tropopause is higher in the tropics

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



44% of air traffic in the North Atlantic Flight Corridor is in the stratosphere (Hoinka, 1993)

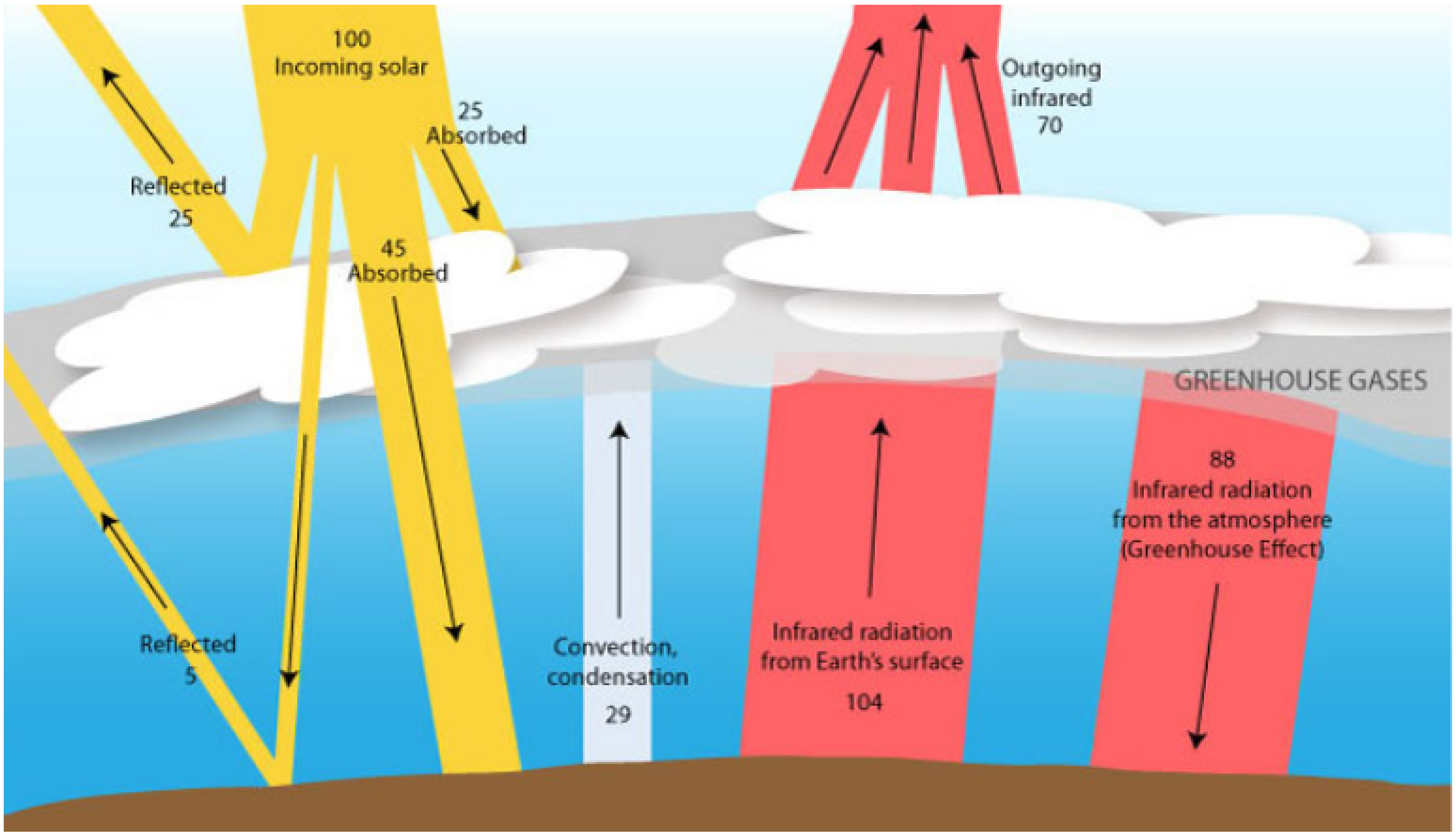
Table 2.1 Average composition of the lowest 100 km in the Earth's atmosphere

	Gas	Volume mixing ratio (percent)	Volume mixing ratio (ppmv)
	Fixed gases		
	Nitrogen (N_2)	78.08	780 000
	Oxygen (O_2)	20.95	209 500
	Argon (Ar)	0.93	9 300
	Neon (Ne)	0.0015	15
	Helium (He)	0.0005	5
	Krypton (Kr)	0.0001	1
natural GHG effect	Xenon (Xe)	0.000005	0.05
	Variable gases		
66-85%	Water vapor (H_2O)	0.00001–4.0	0.1–40 000
9-26%	Carbon dioxide (CO_2)	0.0375	375
	Methane (CH_4)	0.00017	1.8
	Ozone (O_3)	0.000003–0.001	0.03–10

Energy budget and greenhouse effect

Royal Netherlands Meteorological Institute

Atmospheric Radiation: The Earth receives energy from the sun (on average **344** W/m^2) and emits the same amount to space



Solar **Infrared ("longwave")**

The average surface temperature on earth is not -18°C but +15°C: 33°C warmer due to natural greenhouse gases !

Increase of greenhouse gases

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

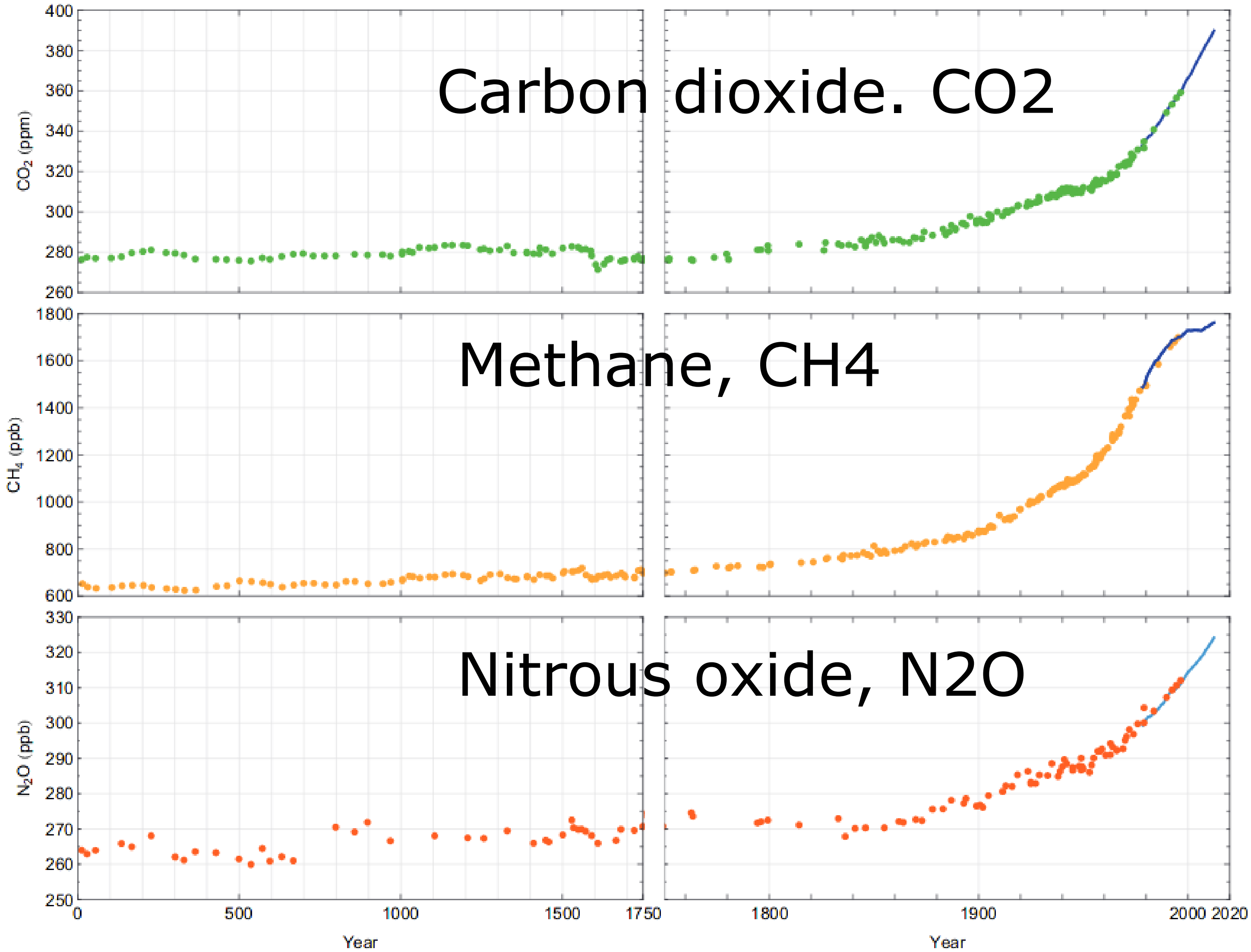
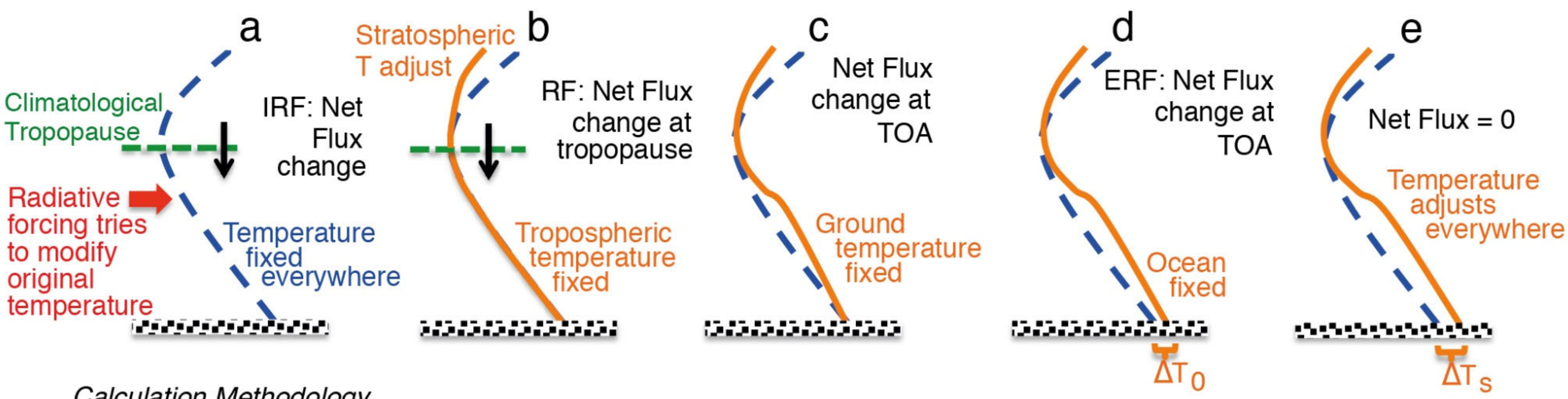


Figure 6.11 | Atmospheric CO_2, CH_4, and N_2O concentrations history over the industrial era (right) and from year 0 to the year 1750 (left), determined from air enclosed in ice cores and firn air (colour symbols) and from direct atmospheric measurements (blue lines, measurements from the Cape Grim observatory) (MacFarling-Meure et al., 2006).

Radiative Forcing RF as a measure of climate change

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



Calculation Methodology

Online or offline pair of radiative transfer calculations within one simulation	Difference between two offline radiative transfer calculations with prescribed surface and tropospheric conditions allowing stratospheric temperature to adjust	Difference between two full atmospheric model simulations with prescribed surface conditions everywhere or estimate based on regression of response in full coupled atmosphere-ocean simulation	Difference between two full atmospheric model simulations with prescribed ocean conditions (SSTs and sea ice)	Difference between two full coupled atmosphere-ocean model simulations

$$\Delta T_s = \lambda \,.\, RF$$

λ : climate sensitivity parameter

Radiative forcing from past emissions (AR5, 2013)

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

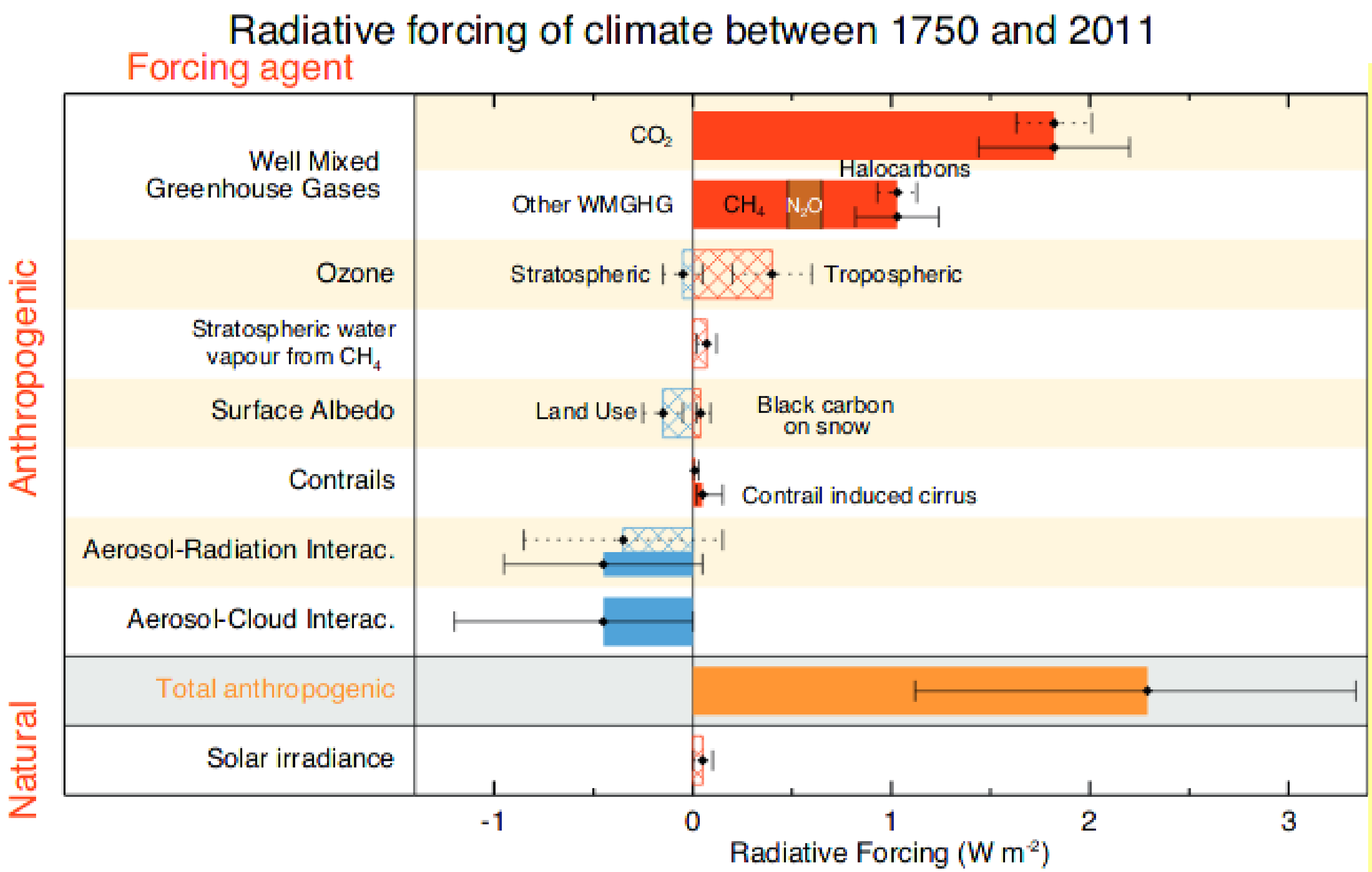


Figure 8.15 | Bar chart for RF (hatched) and ERF (solid) for the period 1750–2011, where the total ERF is derived from Figure 8.16. Uncertainties (5 to 95% confidence r are given for RF (dotted lines) and ERF (solid lines).

Broeikasgassen
(W/m2)

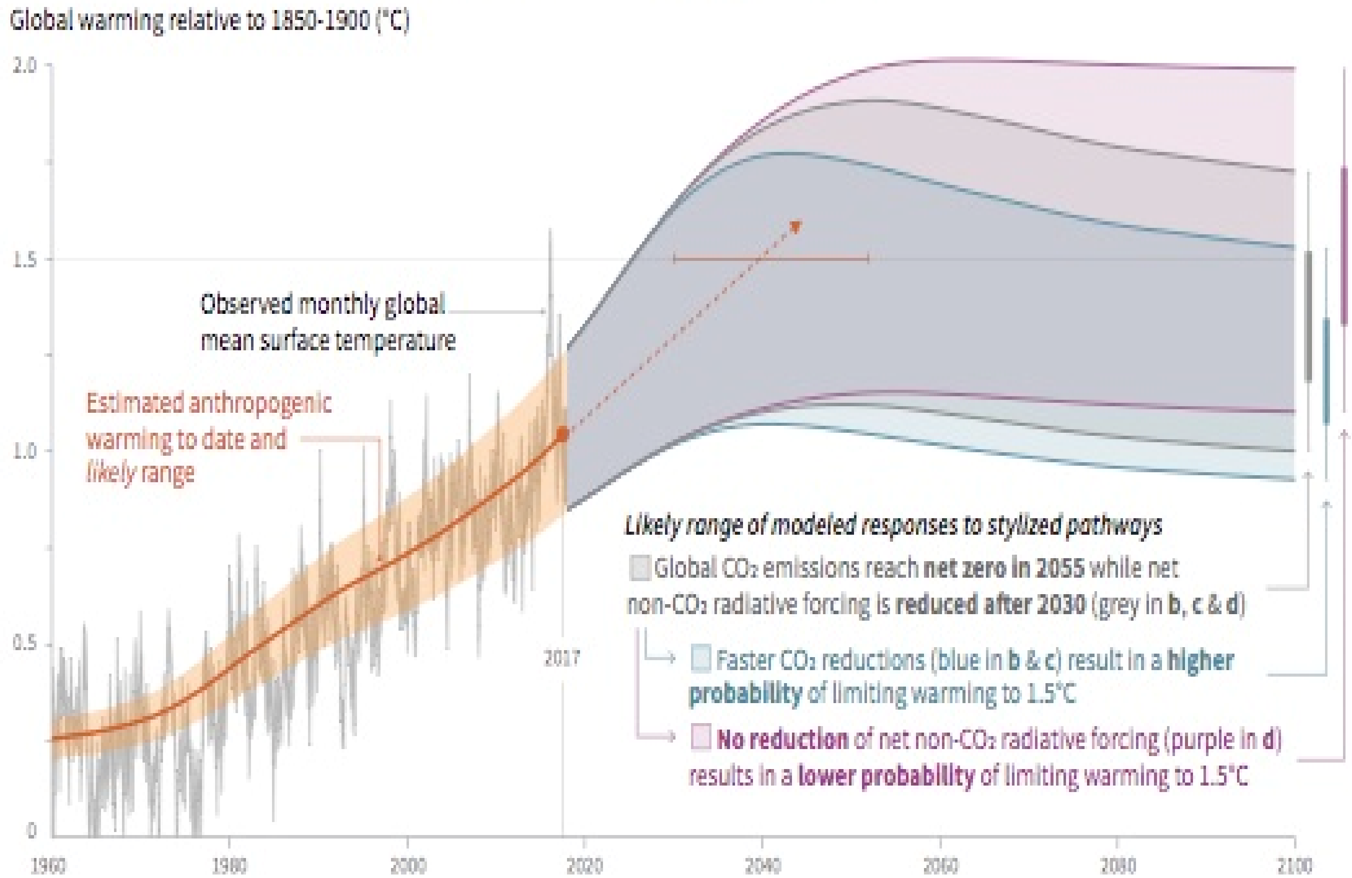
Totaal	**2.83**
CO_2	1.82
CH_4	0.48
N_2O	0.17
CFK's	0.36
O_3	0.35
Totaal (incl O_3)	**3.18**

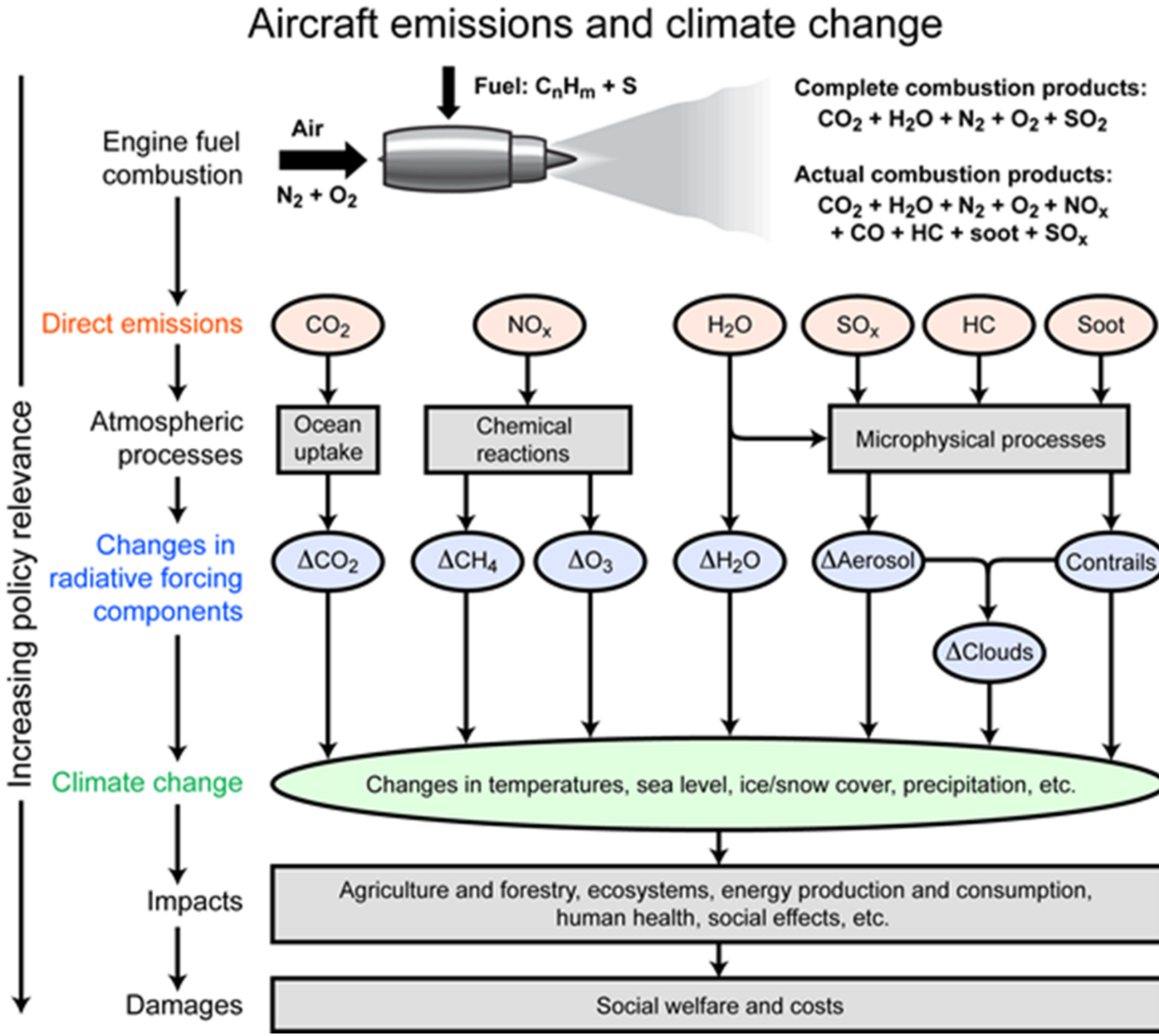
Importance of non-CO_2 for Paris goals

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways





nds
Institute
ructure and the

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Nitrogen oxides catalyse ozone production

Methane, volatile organic carbon compounds (VOCs) and nitrogen oxides, are emitted by fossil fuel combustion agriculture, natural sources, etc.

Oxidation of methane and VOCs leads to production of ozone and water vapour when nitrogen oxides NO_x=NO+NO_2 are present (as **catalyst**):

CH4 + ·OH → CH3· + H2O

CH3· + O2 + M → CH3O2· + M

CH3O2· + NO → NO2 + CH3O·

CH3O· + O2 → HO2· + HCHO

HO2· + NO → NO2 + ·OH

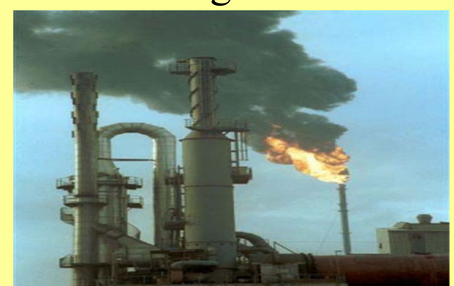
(2x) NO2 + hv → O(3P) + NO

(2x) O(3P) + O2 + M → O3 + M

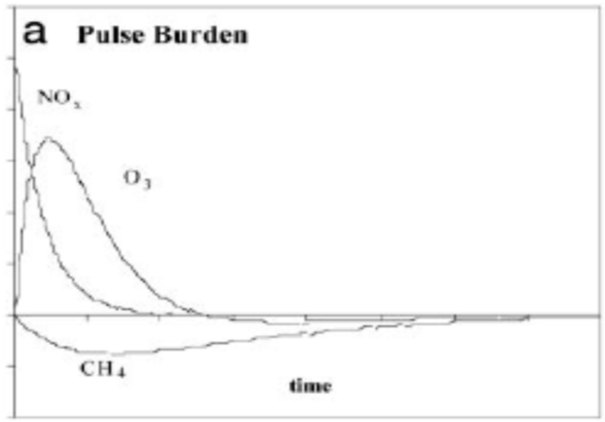
-- +

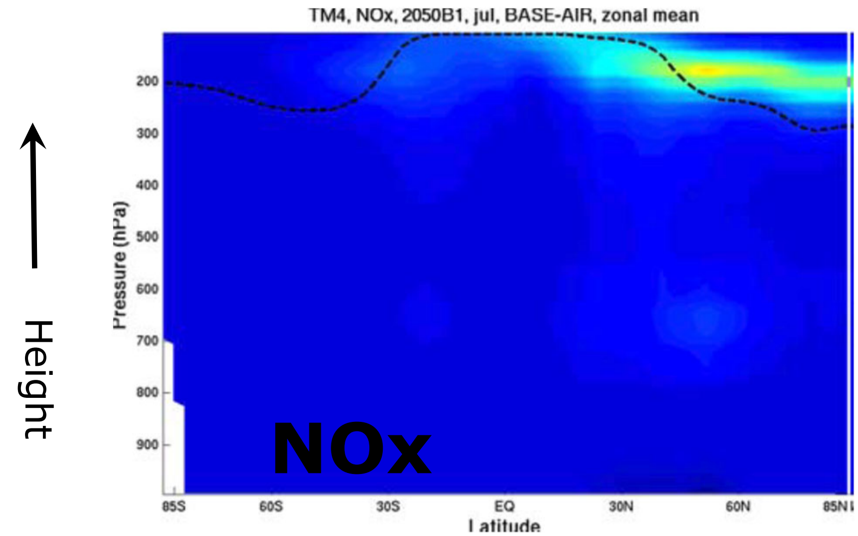
net: CH4 + 4O2 → HCHO + 2O3 + H2O

Ozone is a greenhosue gas and harmful for man, nature and materials !

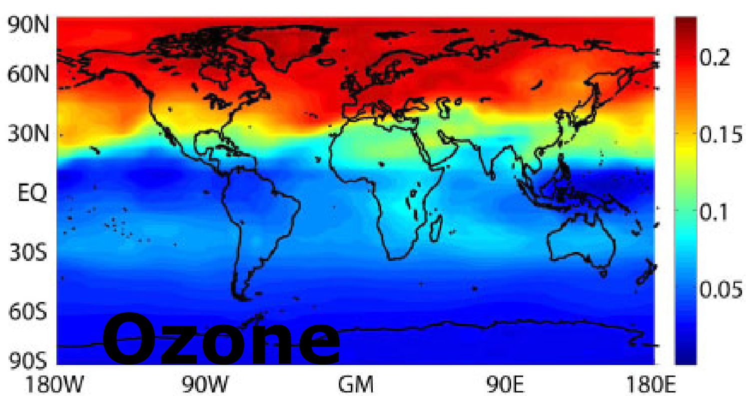


Primary effects of nitrogen oxides (NOx=NO+NO2) from aviation → o3 increase, CH4 decrease

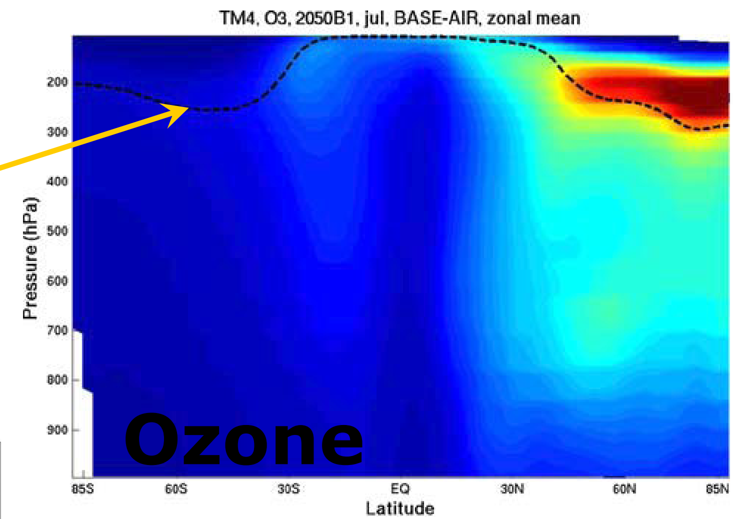


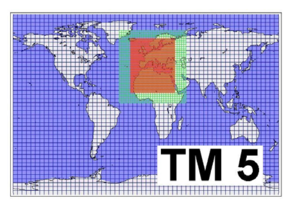


Secondary effects:
CH4 decrease→O3 & H20 decrease



Tropopause



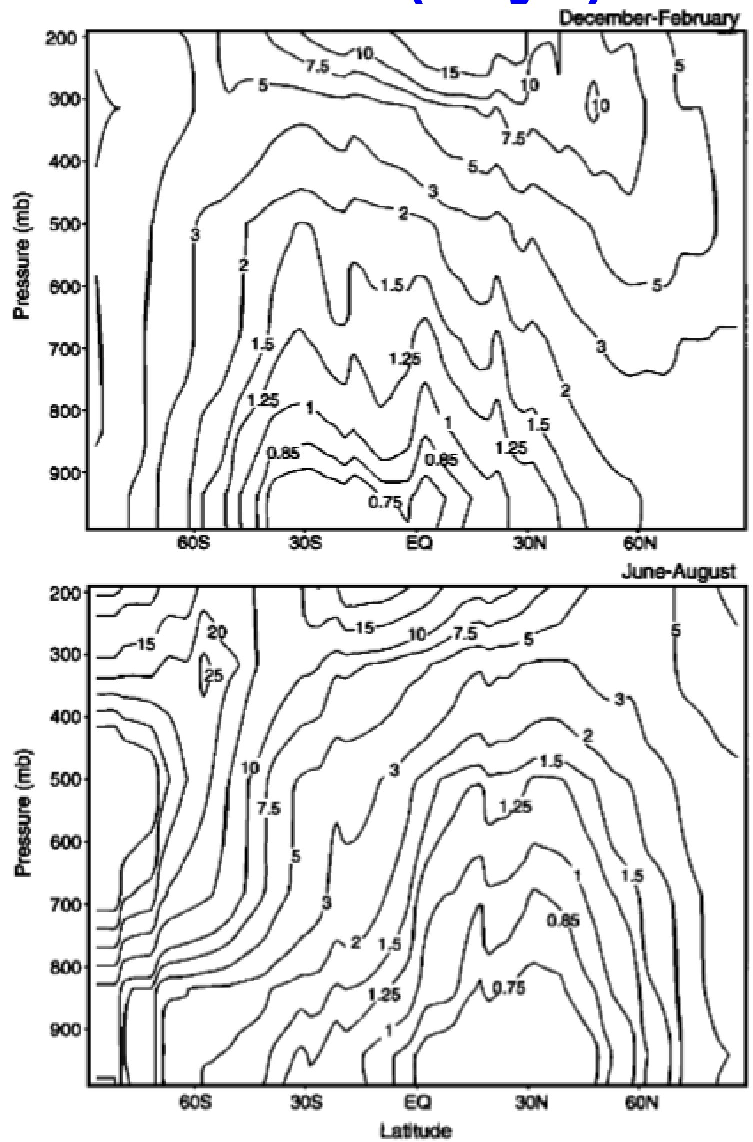


Southpole

Northpole

NOx atmospheric lifetime (days)

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

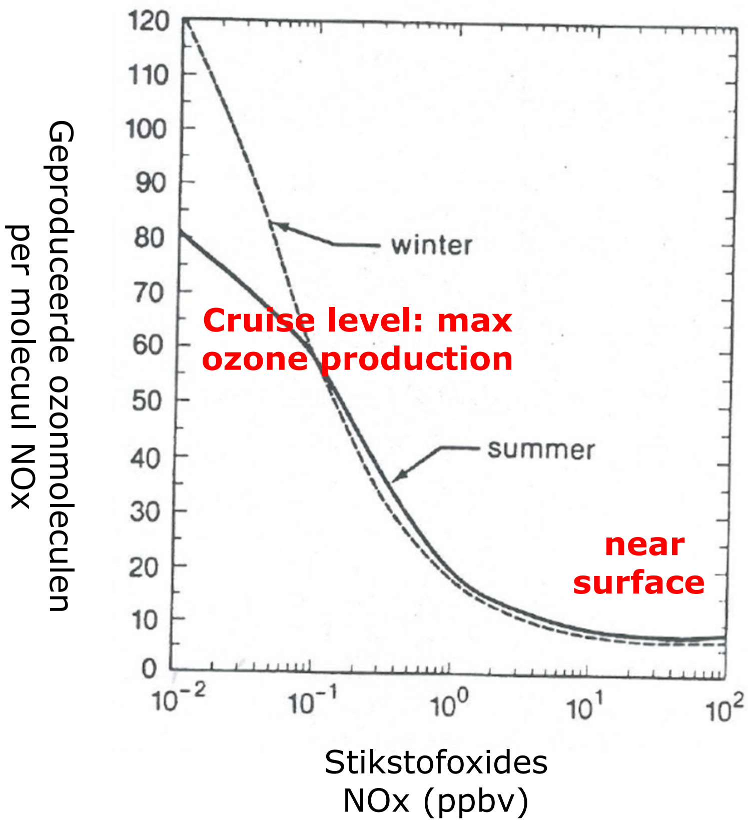


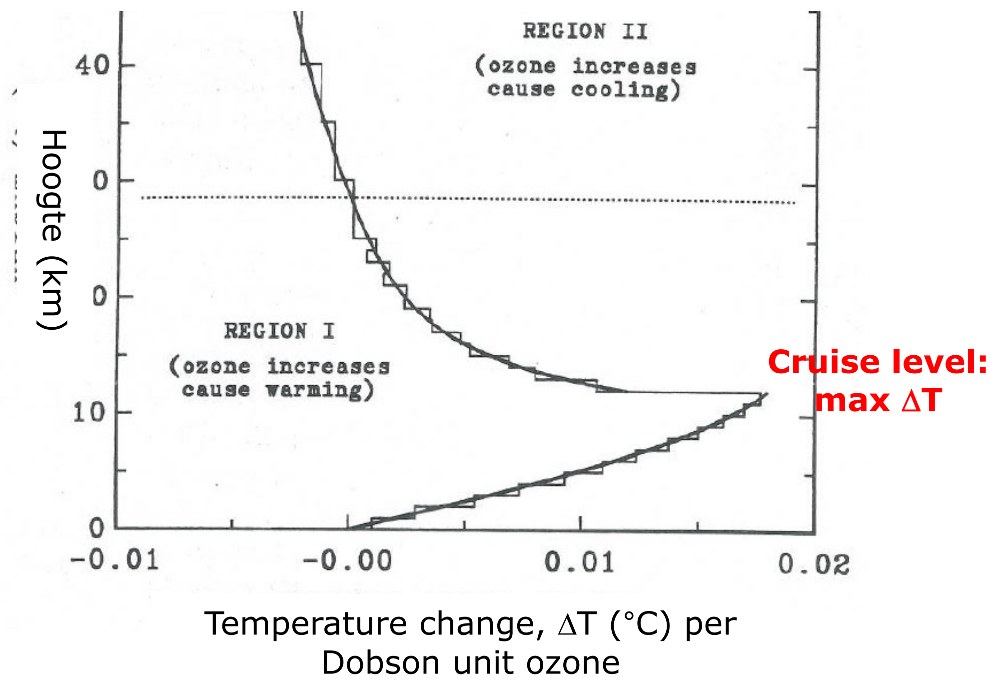
winter

summer

Figure A3. Zonal average NO_x to HNO_3 conversion times based on the gas phase OH reaction plus the night-time heterogeneous conversion via NO_3 and N_2O_5 for winter (December - February) and summer (June - August).

Nitrogen oxides from aviation have a relatively large impact on ozone production and climate

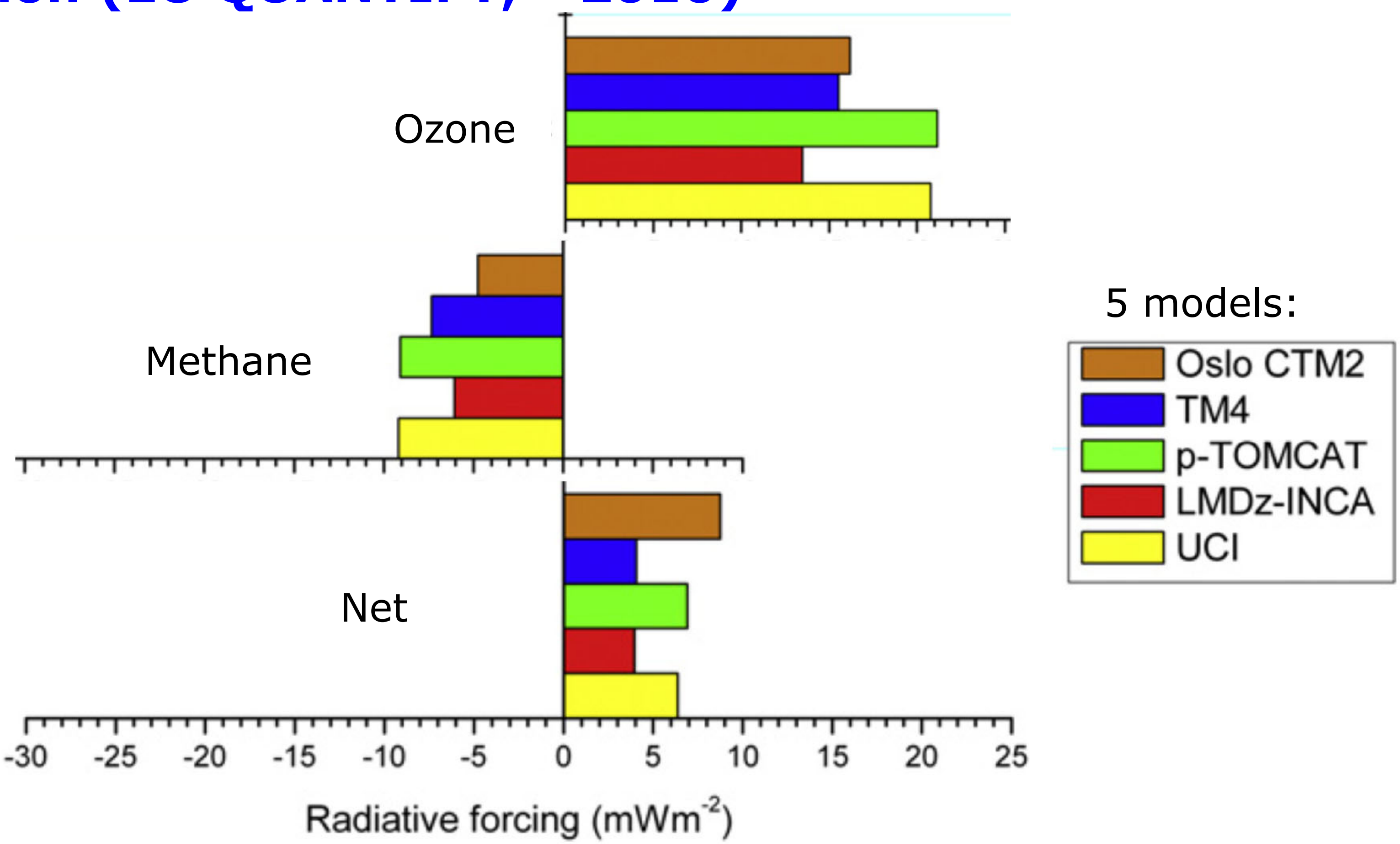




One NO_x molecule from aviation produces 5 x and 3 x more ozone than one from road traffic resp. shipping

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

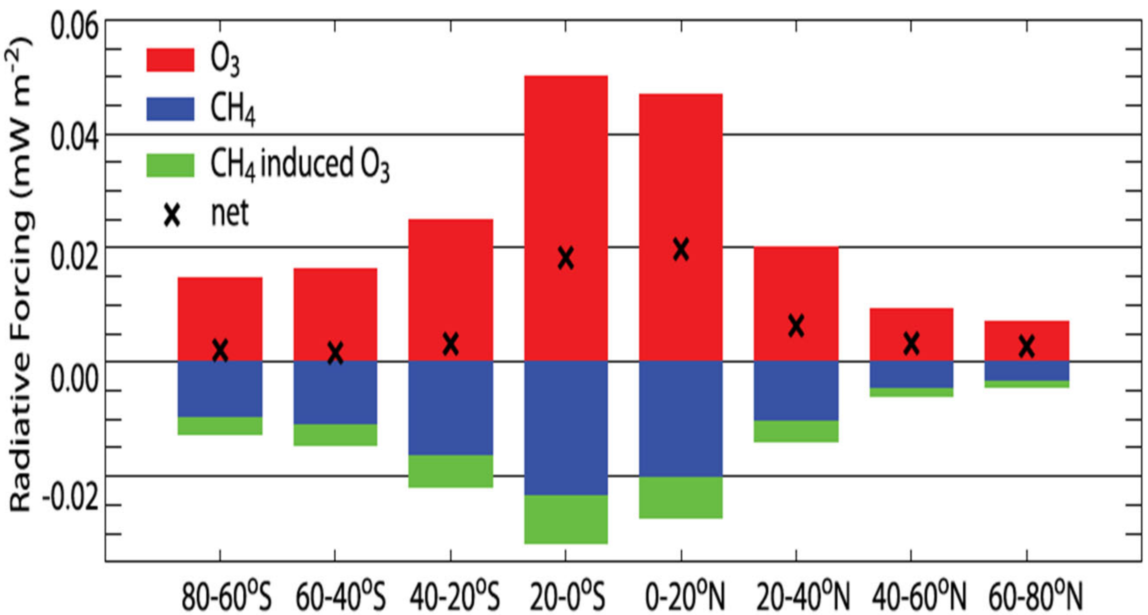
Radiative forcing due to nitrogen oxide emissions from aviation (EU QUANTIFY, ~2010)



Net effect of NOx emissions from aviation is probably warming

Effect of a nitrogen oxide emission pulse in a latitude band

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



1. Short term: ozone formation ➔
2. Shorter methane lifetime ➔
3. Long term: ozone decrease

Tropics most sensitive

(Koehler et al, 2013)

Aviation NOx growth in the tropics will lead to more warming !

Locally the net RF can also be negative (cooling) in some regions …

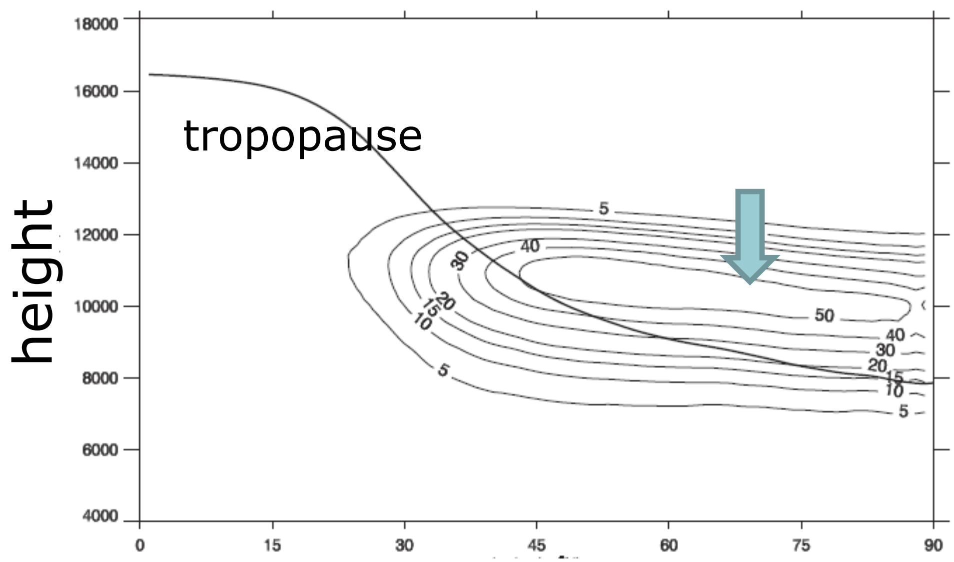
Water vapour from aviation

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

RF is small but largest when emitted in the stratosphere!

~ 1 week residence time in the troposphere (removal as rain, snow etc.)

Strong increase in age with height in the stratosphere. It first needs to be transported back into the troposphere by the slow downward transport outside the tropics before it is removed

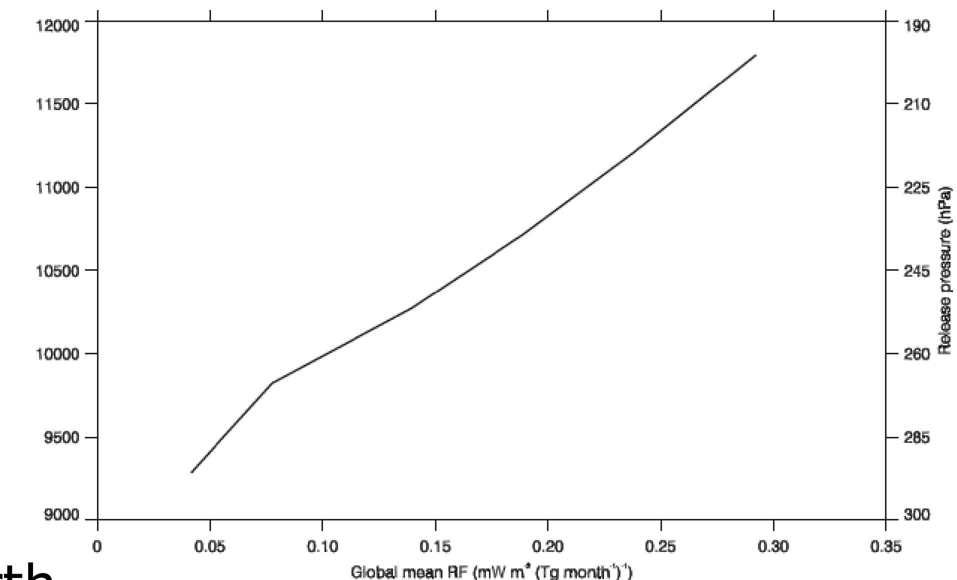


equator

latitude

north pole

H2O from aviation



RF per unit H2O emission

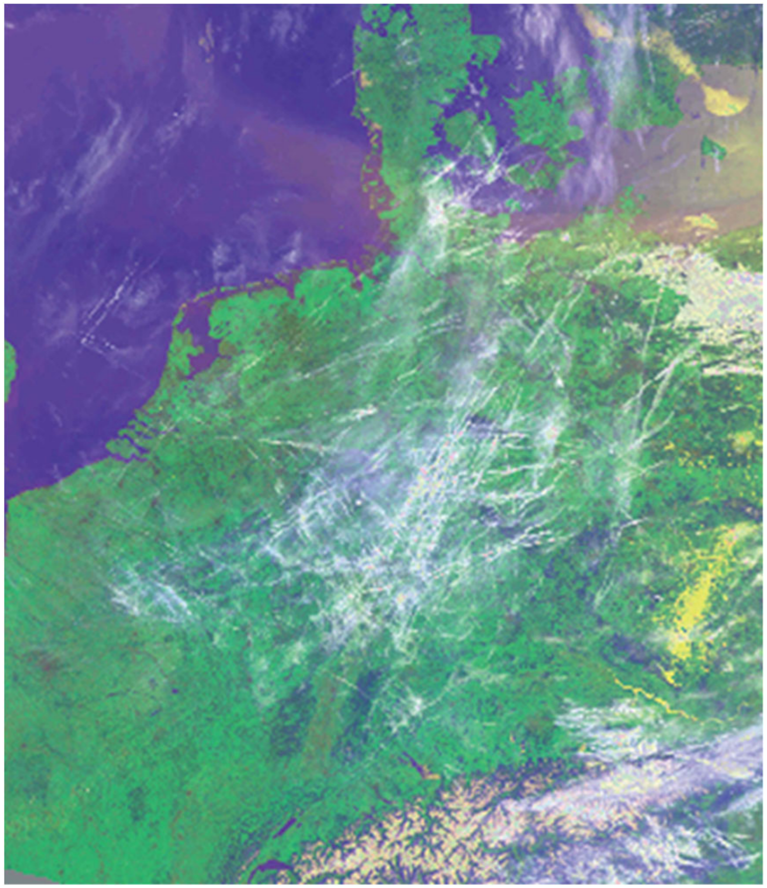
Climate effect of con(densation)trails

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Reflect solar radiation→cooling during daytime

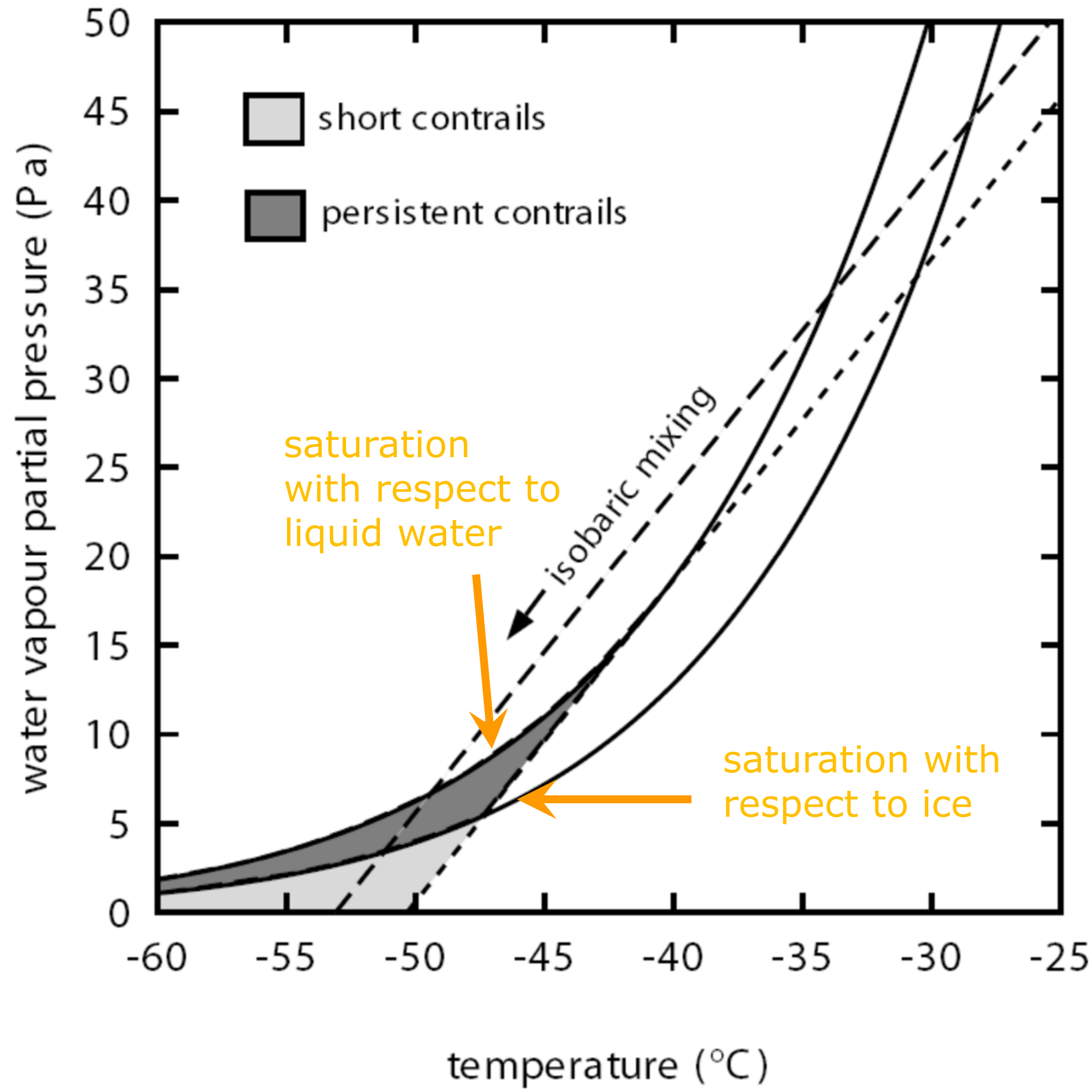
Absorb infrared radiation emitted by the surface & atmosphere → warming, mainly at nighttime

Net effect: warming



Con(densation)trail formation

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the
Environment

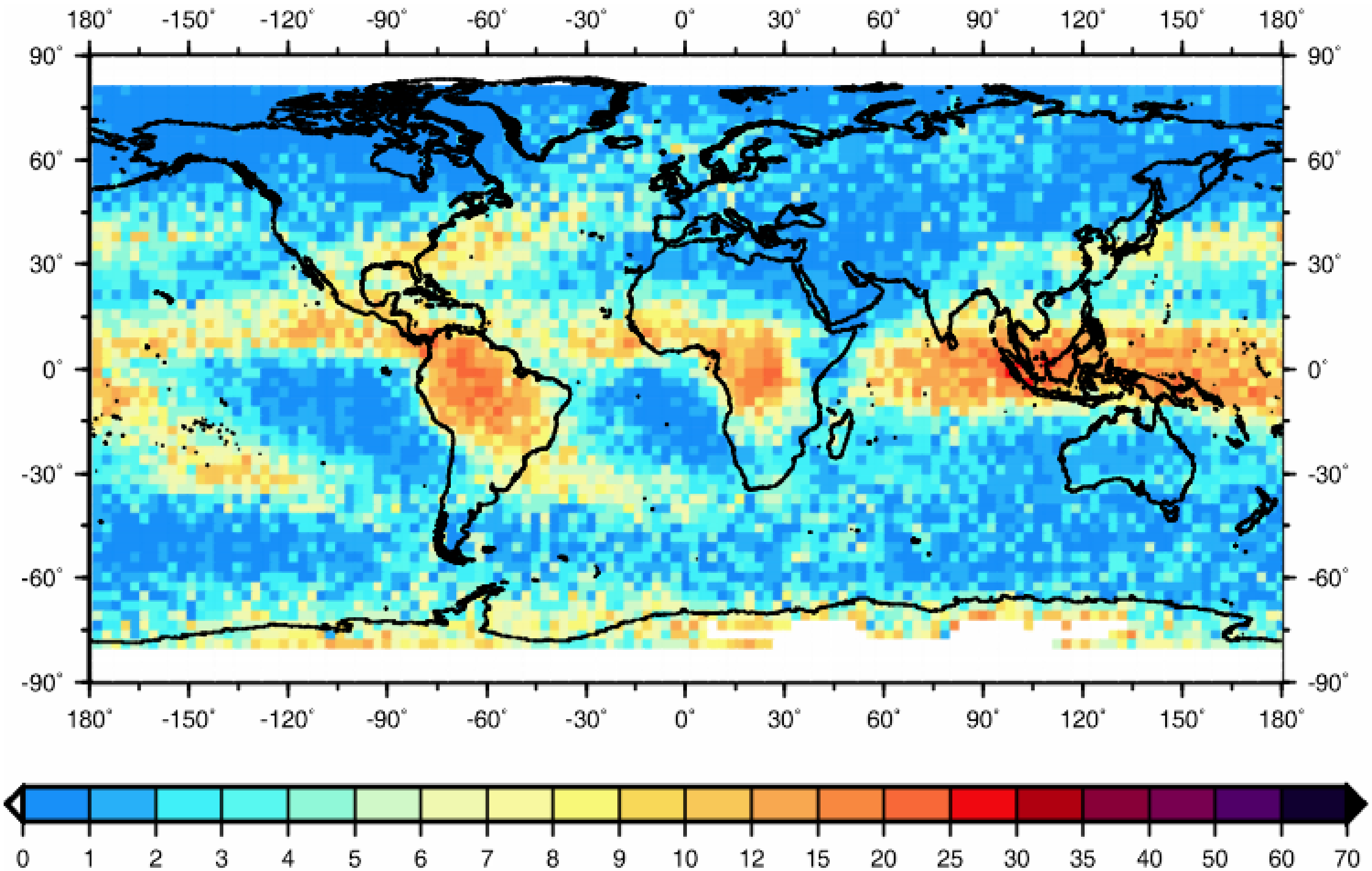


Gierens et al (OASJ, 2008)

Mixing of warm, moist air from aircraft exhaust with cold, dry ambient air
→ Con(densation) trails

Ice SuperSaturated Regions (ISSR)

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment



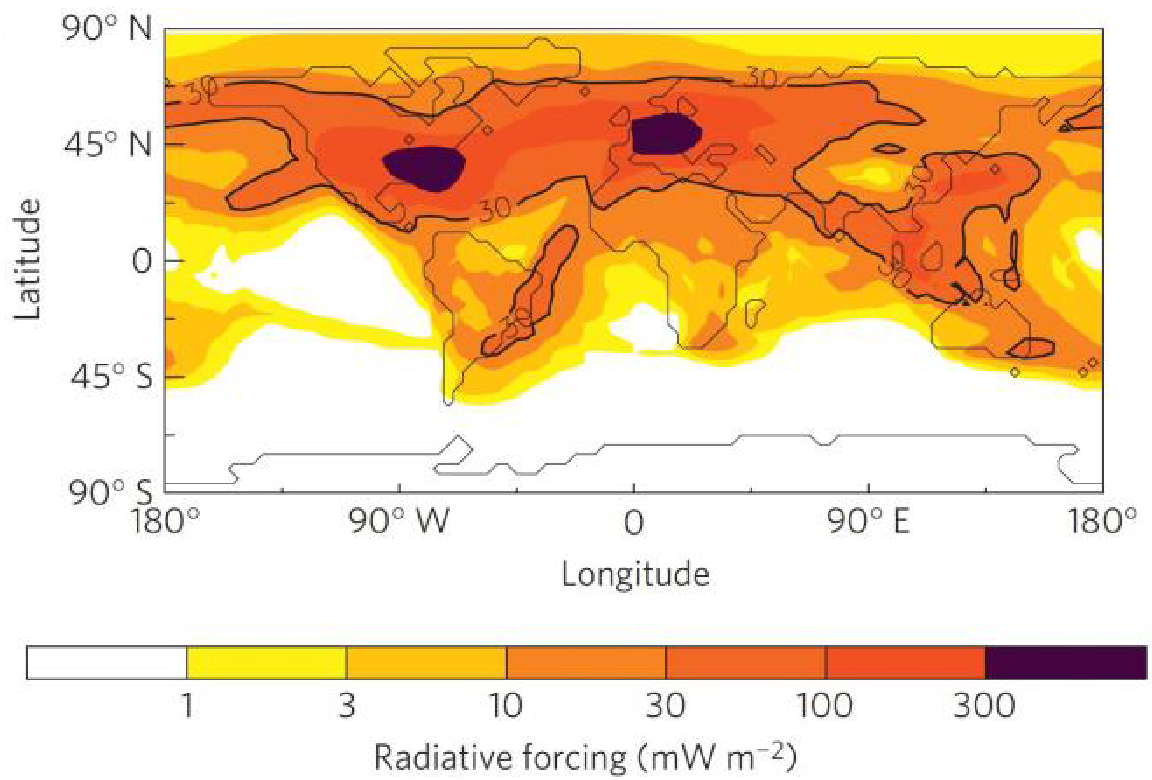
Occurrence frequency (%) of ISSR at 215 hPa from MLS (Spichtinger et al., 2003)

Long-lived contrails → Contrail cirrus

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Contrail cirrus reduces natural cloudiness!

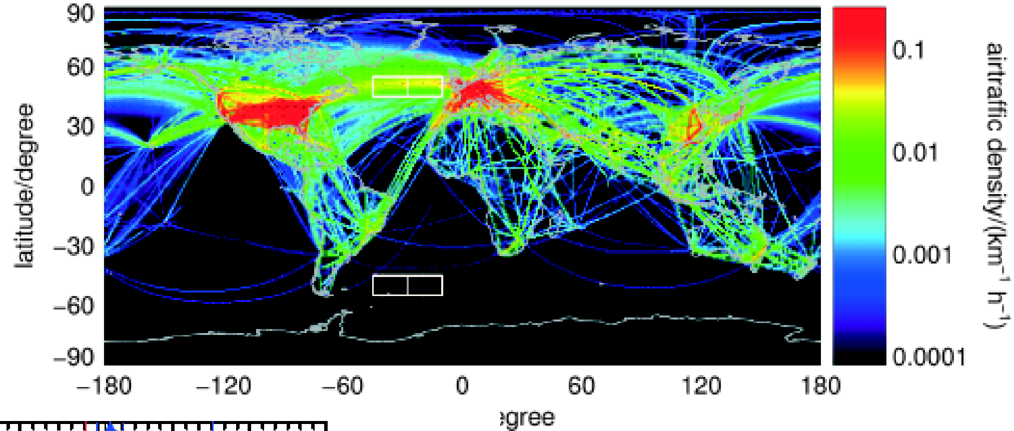
Burkhardt & Karcher model study (2011): global RF: ~38→~31 mW/m^2

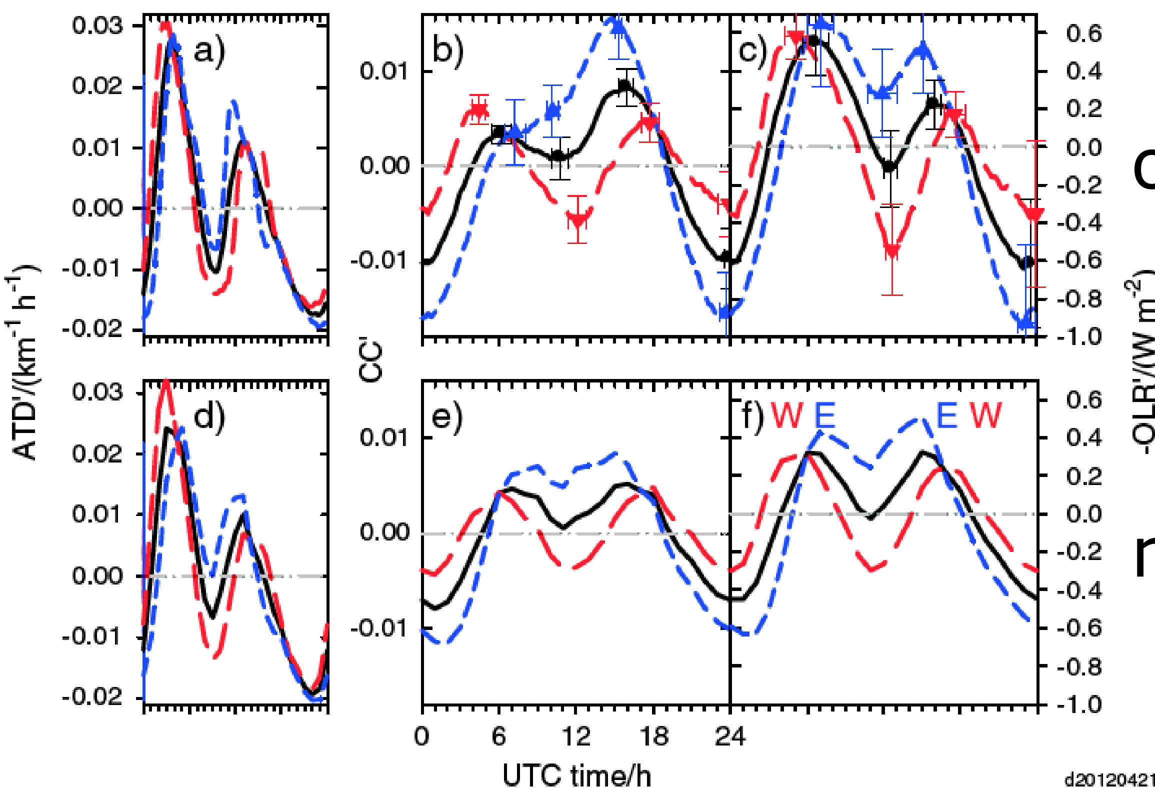


RF aviation cirrus estimated from satellite observations

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Comparison of selected regions





obs

model

Globally: RF~50 mW/m^2

Schumann et al., 2013

Sulfur and soot

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

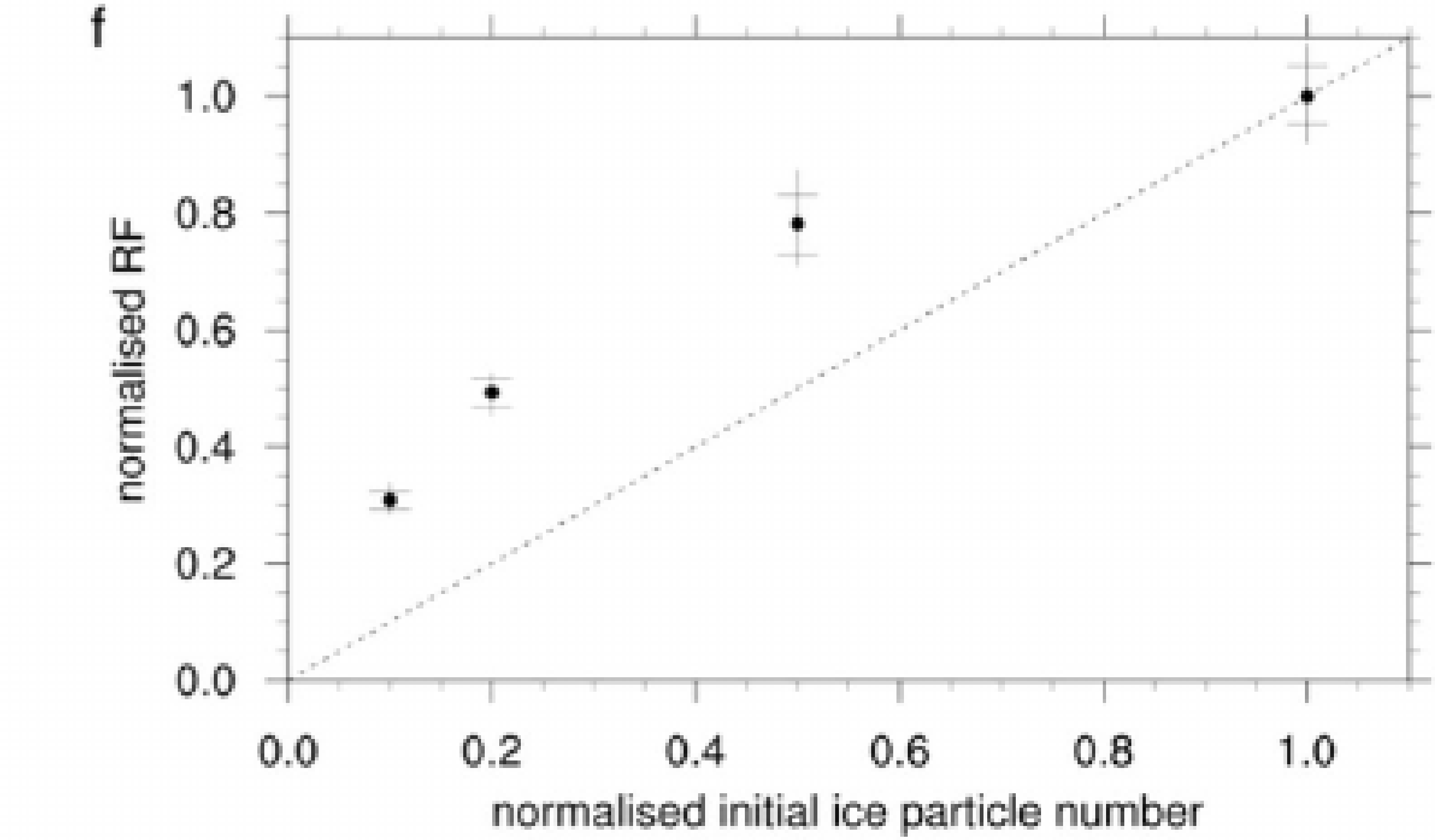
Sulfate aerosol has a small cooling effect and soot has a small warming effect

Potentially also large but very uncertain indirect effects through cloud modification

(Righi et al., 2016)

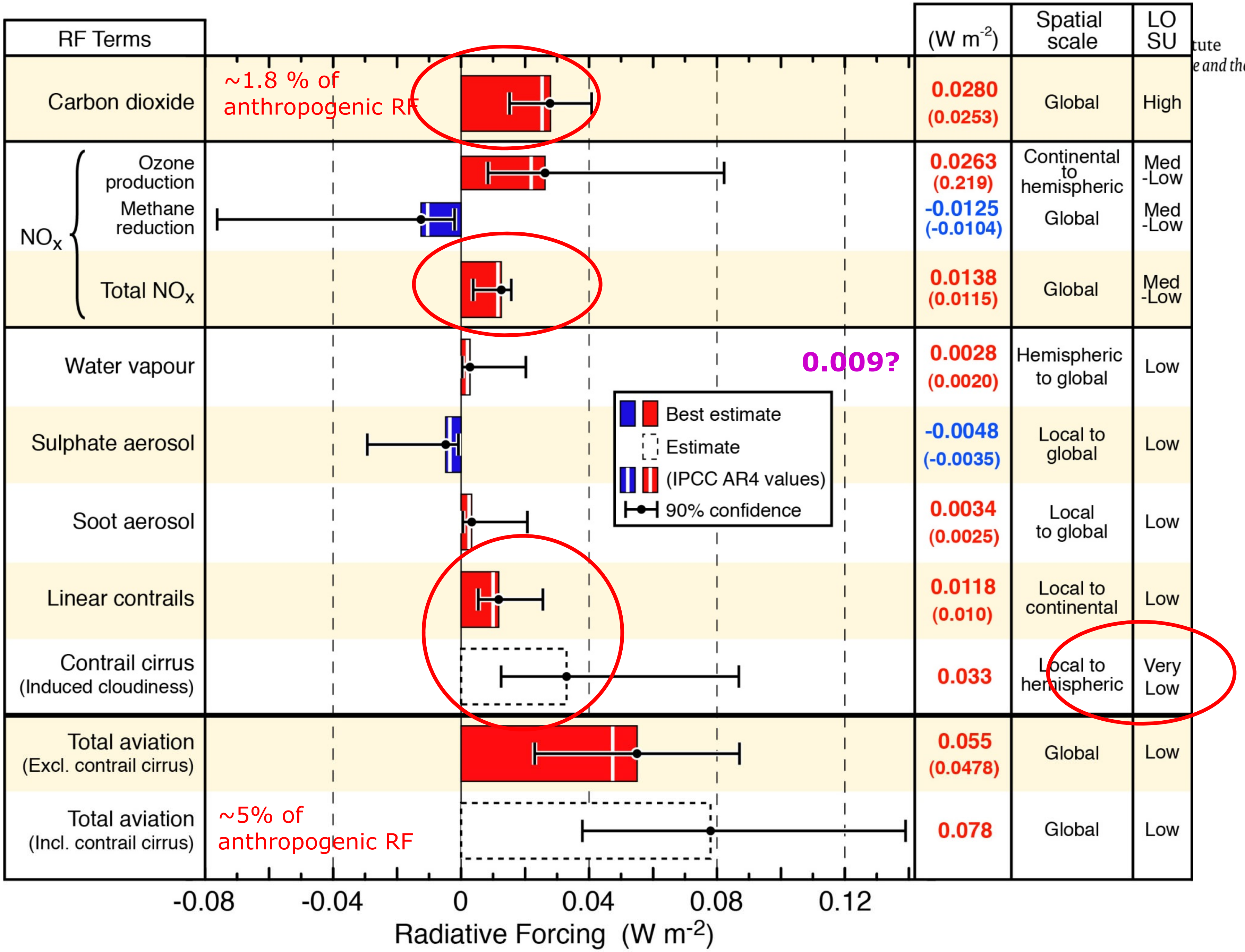
Aviation cirrus RF depends on soot (ice nuclei) emissions

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



Burkhardt et al., npj Clim. Atm. Sci., 2018

Aviation Radiative Forcing Components in 2005



Metrics

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

CO_2 equivalent units are based on GWP100, a globally averaged metric

Note:

- Non-CO_2 impacts depend on emission location (altitude, geographical location, time of day, season, actual weather situation etc) → may therefore require model calculations for each flight
- Residence times vary from centuries (CO_2, N_2O), decades (CH_4), weeks/months (O_3), to hours (contrails). GWP100 uses 100 years as time horizon
- Choice of metric depends upon the goal (e.g. temperature change)

Use RFI to include non-CO2 effects?

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Forster et al, 2006: “Radiative Forcing Index (RFI) for comparing emissions from different sources is **inappropriate ..**”

e.g. RF’s and RFI for constant emissions:

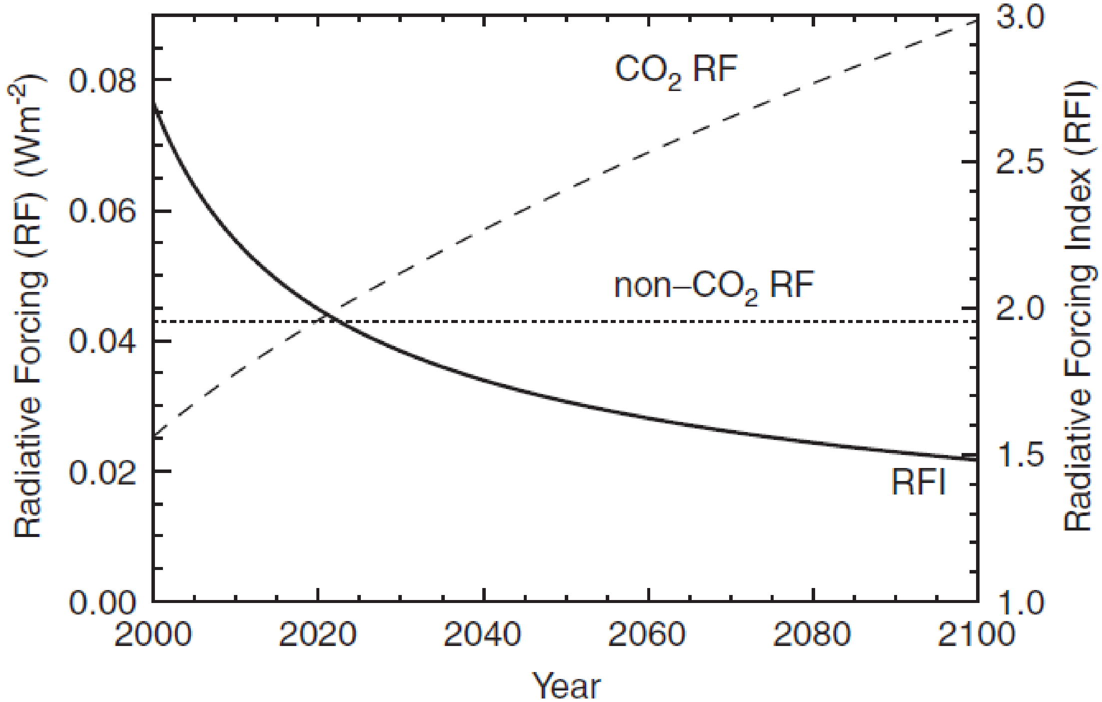


Fig. 1. The CO_2 radiative forcing (dashed line) and the non-CO_2 radiative forcing (dotted line) as a function of time from constant (year 2000) aviation emissions. The corresponding RFI is also shown (solid line). The scenario is deliberately chosen to have an RFI of 2.7 in 2000—the RFI from the IPCC (1999) report.

Common metrics: GWP, GTP

CO2 eq. are based on GWP (for a pulse (1-year) emission)

GWP = ratio of surfaces below GHG and CO2 RF curves

GWP100 is traditionally used

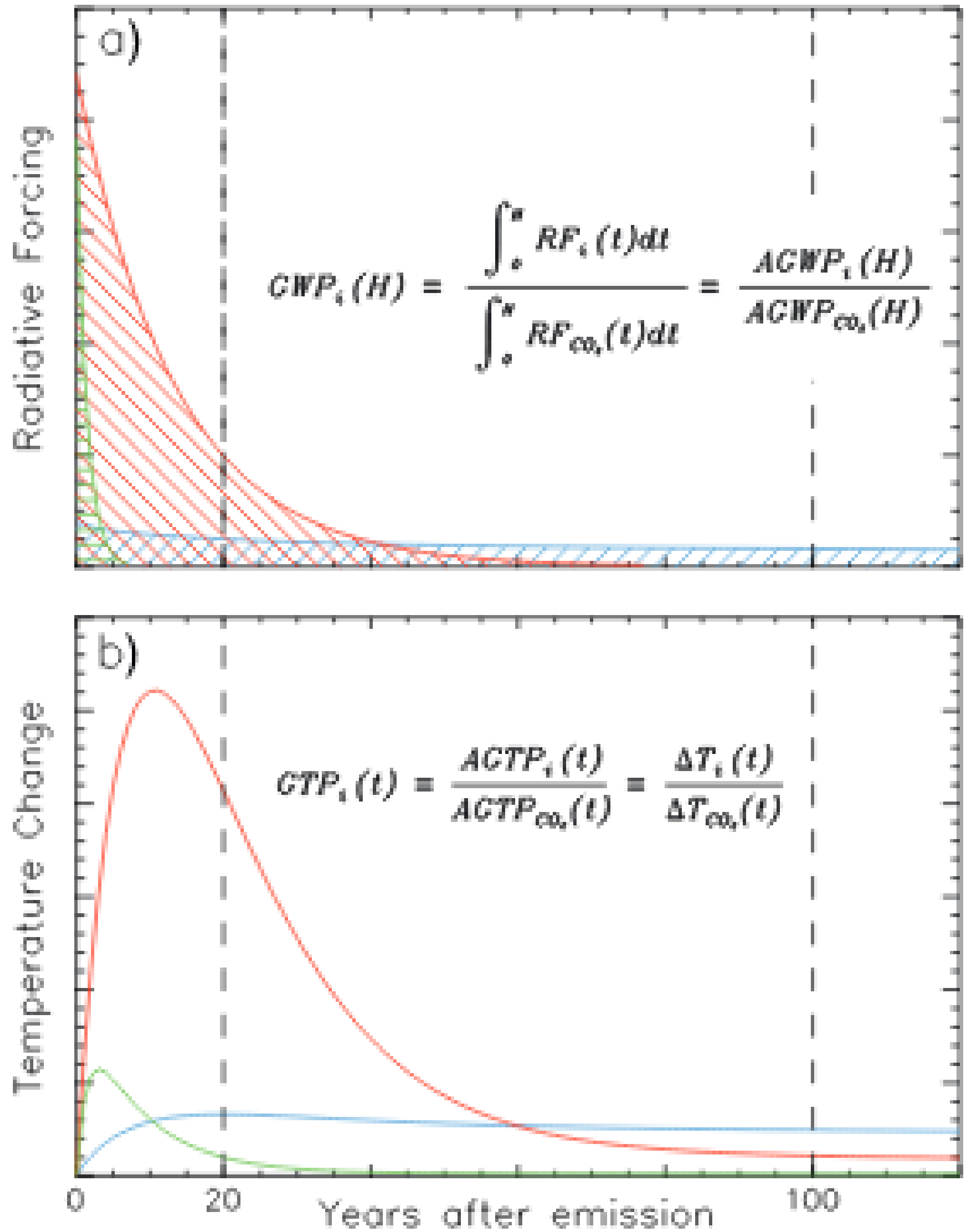
GTP = ratio of temperature values of GHG and CO2 curves

It can easily be used to calculate temperature change from an emission scenario

Blue: CO2

Red: GHG 13 year lifetime

Green: GHG 1.5 year lifetime



GWP(CH4) dependence on time horizon

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

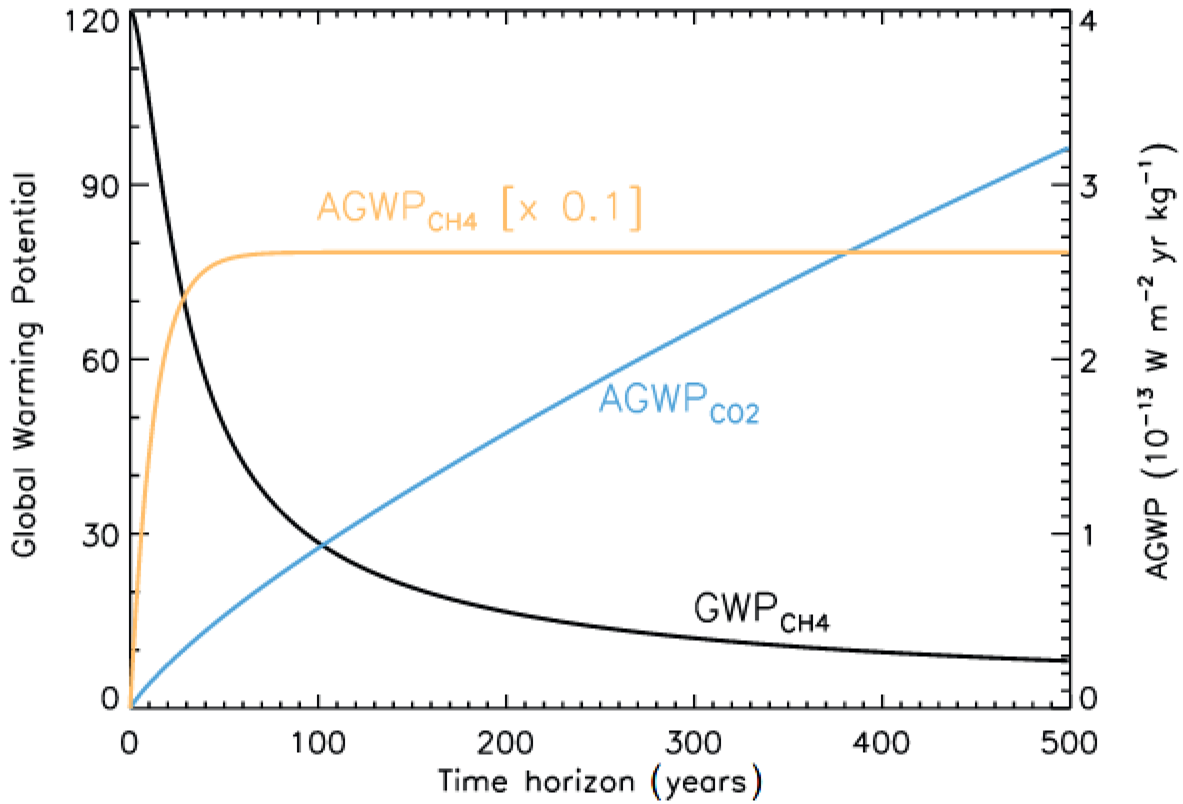


Figure 8.29 | Development of AGWP-CO_2, AGWP-CH_4 and GWP-CH_4 with time horizon. The yellow and blue curves show how the AGWPs changes with increasing time horizon. Because of the integrative nature the AGWP for CH_4 (yellow curve) reaches a constant level after about five decades. The AGWP for CO_2 continues to increase for centuries. Thus the ratio which is the GWP (black curve) falls with increasing time horizon.

Metric values listed in AR5

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Table 8.7 | GWP and GTP with and without inclusion of climate–carbon feedbacks (cc fb) in response to emissions of the indicated non-CO_2 gases (climate-carbon feedbacks in response to the reference gas CO_2 are always included).

	Lifetime (years)		GWP_{20}	GWP_{100}	GTP_{20}	GTP_{100}
CH_4[b]	12.4[a]	No cc fb	84	28	67	4
		With cc fb	86	34	70	11
HFC-134a	13.4	No cc fb	3710	1300	3050	201
		With cc fb	3790	1550	3170	530
CFC-11	45.0	No cc fb	6900	4660	6890	2340
		With cc fb	7020	5350	7080	3490
N_2O	121.0[a]	No cc fb	264	265	277	234
		With cc fb	268	298	284	297
CF_4	50,000.0	No cc fb	4880	6630	5270	8040
		With cc fb	4950	7350	5400	9560

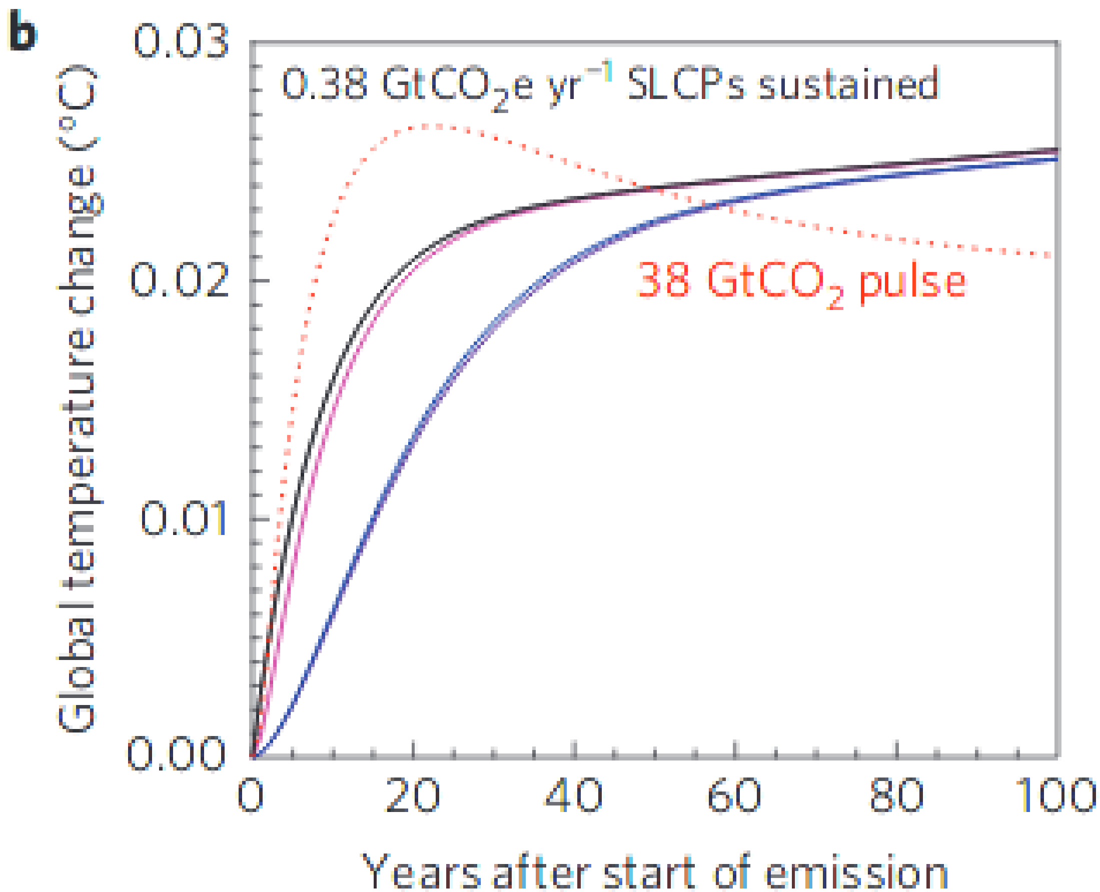
Notes:
Uncertainties related to the climate–carbon feedback are large, comparable in magnitude to the strength of the feedback for a single gas.

[a] Perturbation lifetime is used in the calculation of metrics.

[b] These values do not include CO_2 from methane oxidation. Values for fossil methane are higher by 1 and 2 for the 20 and 100 year metrics, respectively (Table 8.A.1).

GWP*

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



Cumulative CO2 emissions and SLCP rate of emission have a similar impact on the temperature goal!
Suggestion to use CO2 and SLCP GWPs differently …
Allen et al., 2018

IPCC AR5 on metrics:

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Emission metrics such as Global Warming Potential (**GWP**) and Global Temperature change Potential (**GTP**) can be used to quantify and communicate the relative and absolute contributions to climate change of emissions of different substances, and of emissions from regions/countries or sources/sectors. **The metric that has been used in policies is the GWP, which integrates the RF of a substance over a chosen time horizon, relative to that of CO2**. The GTP is the ratio of change in global mean surface temperature at a chosen point in time from the substance of interest relative to that from CO2. There are significant uncertainties related to both GWP and GTP, and the relative uncertainties are larger for GTP. There are also limitations and inconsistencies related to their treatment of indirect effects and feedbacks. **The values are very dependent on metric type and time horizon.** <u>The choice of metric and time horizon depends on the particular application</u> and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. **All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time.**

Summary

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

- Non-CO2 effects, esp. contrails (cirrus), have an important contribution to aviation climate impact, but have quite different behavior than well mixed GHG. Impact depends on time and location of the emissions.
- Non-CO2 mitigation may help attain the Paris goals

Metrics have drawbacks:

- Traditionally GWP(100) is used to calculate CO2 equivalence (e.g. CH4, N2O and SF6) but there are problems in using it for short lived GHG equivalence (even for CH4). .
- Choice of metric depends upon the aim of its application. GWP* might be an alternative in case limiting T change is the target
- Changing the metric leads to political discussions