Aviation science and research needs

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ICCT - International workshop on black carbon

Contents

This presentation covers the following areas

- Aviation RF and black carbon
- Aviation induced cloudiness
- Something on metrics

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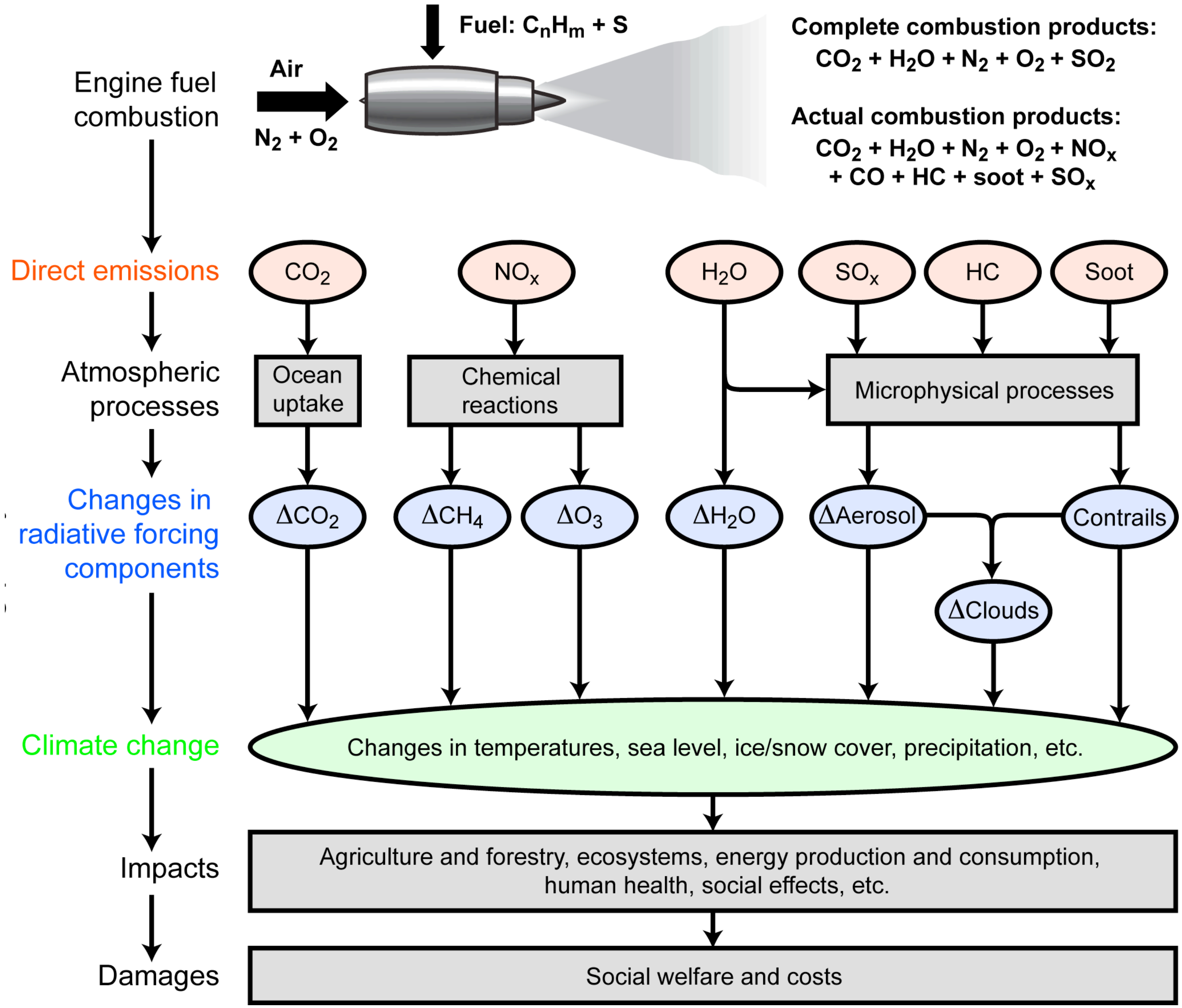

Courtesy: Dave Fahey - Adapted from Wuebbles et al. 2007

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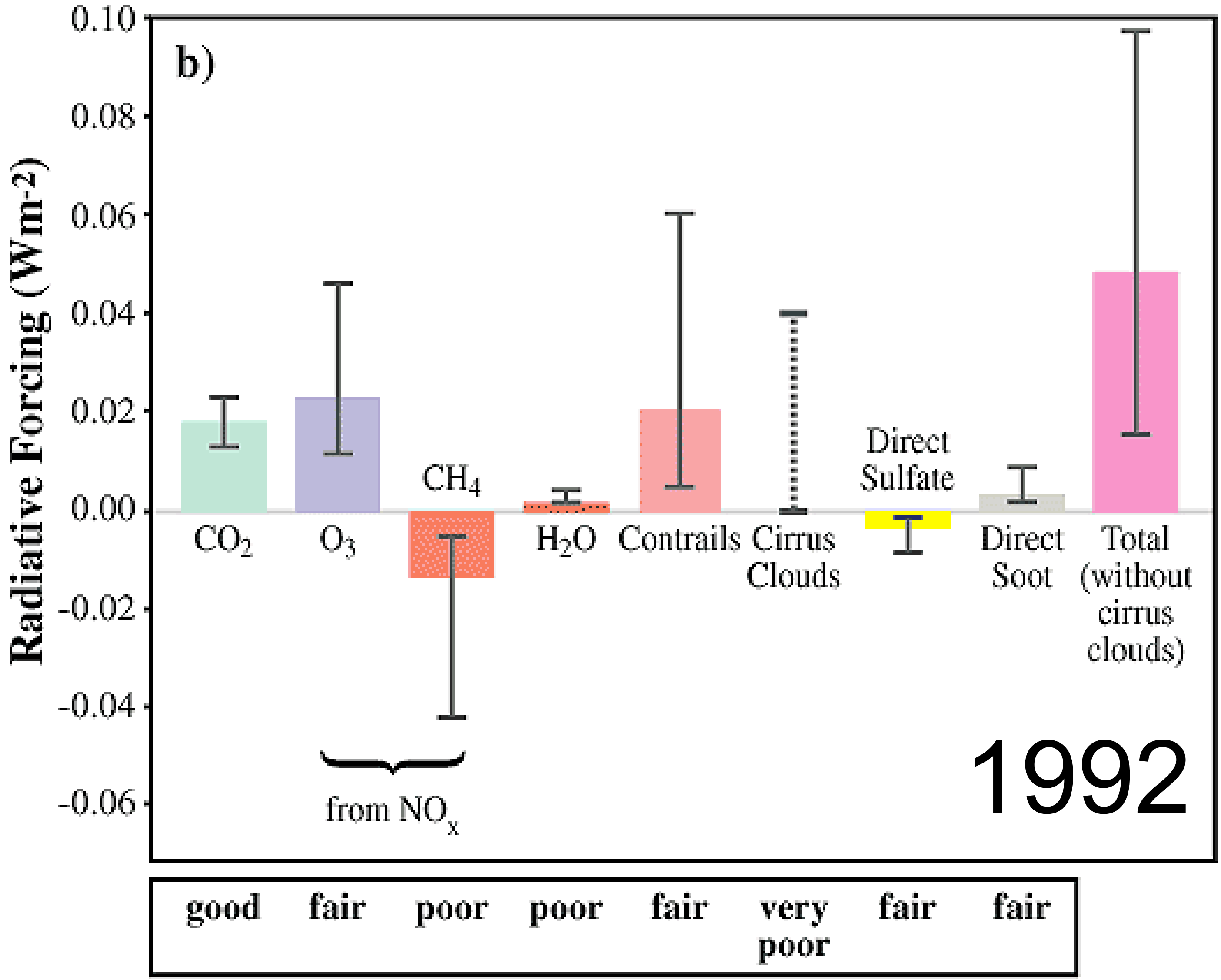
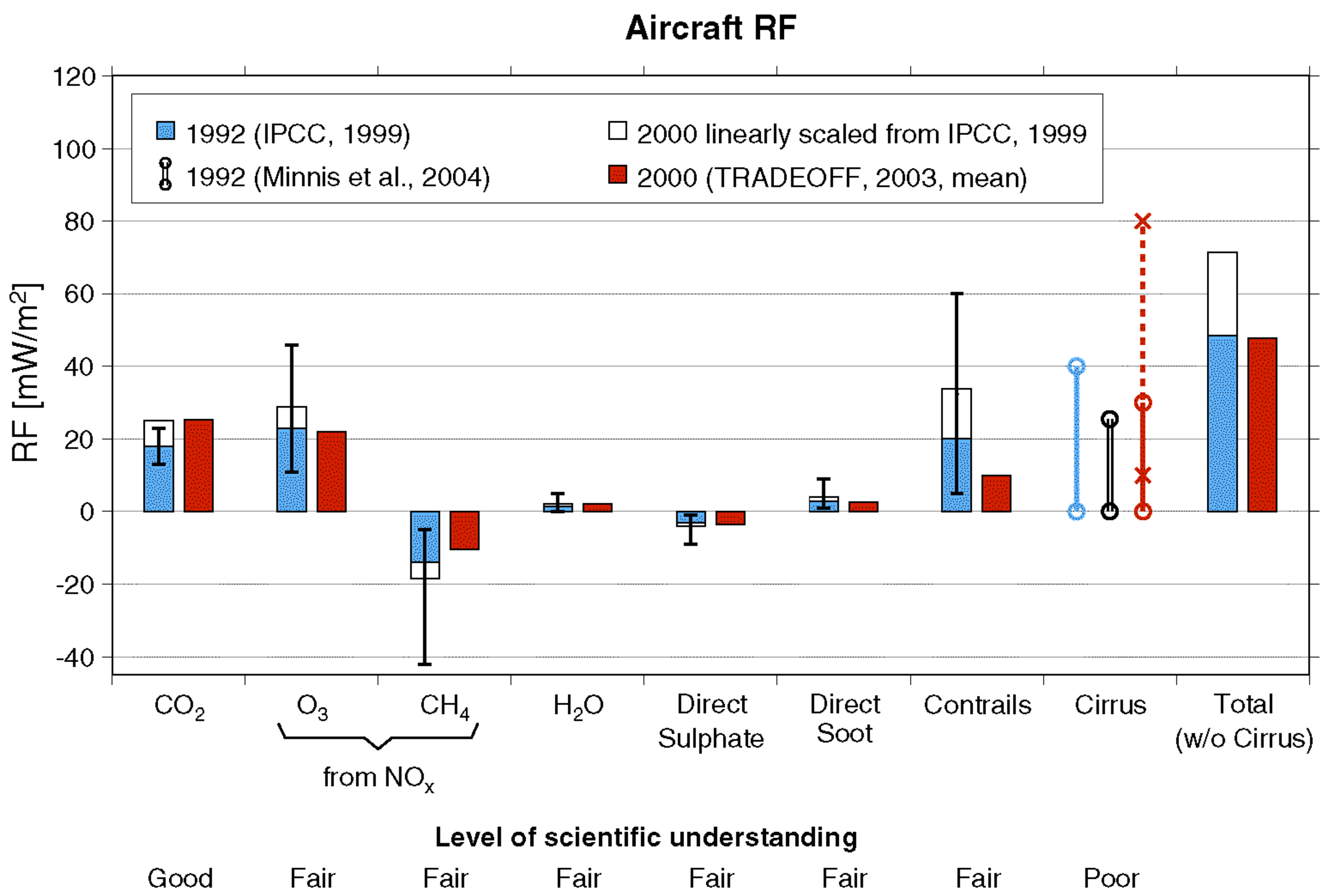


IPCC – special report - 1999



Sausen et al. (2005)

Aviation emissions of BC

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<u>IPCC (1999):</u>

0.0015 to 0.015 Tg C/yr in 1992

relative to 12 Tg C/yr @surface => 0.013% to 0.13% of total BC

<u>Hendrick et al., ACP (2004):</u>

0.005 Tg C/yr in 2000

relative to 14 Tg C/yr @ surface => 0.036% of total BC

<u>For comparison:</u>

Aviation is responsible for about 650 TgCO_2/yr in 2000, or 2.6% of total fossil-fuel CO_2 emissions in 2000.

Aviation represents 11.6% of total CO_2 emissions from the transport sector in 2000.

Direct RF from aviation BC

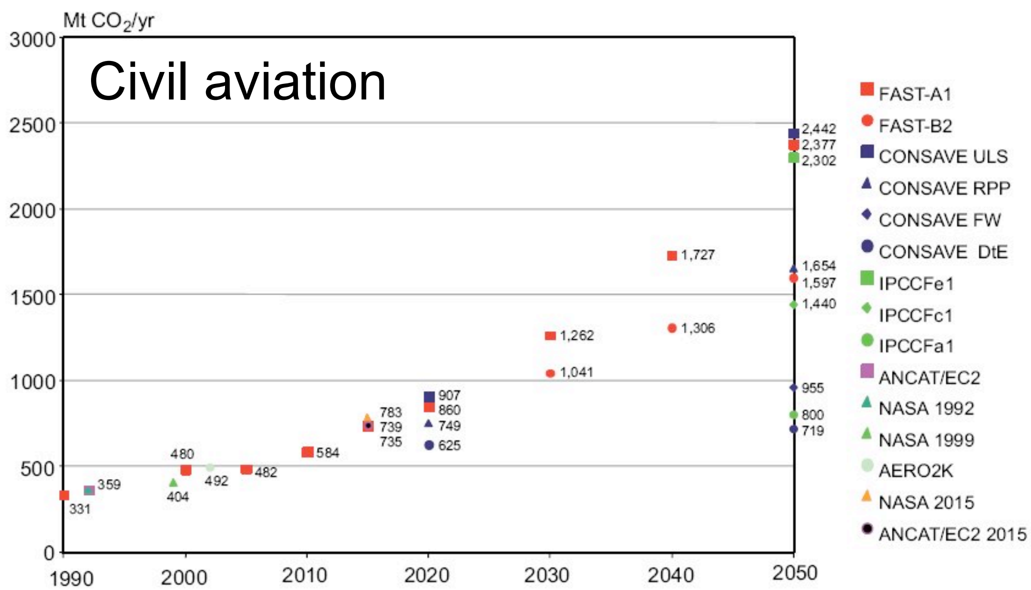
<u>IPCC (1999):</u>
- 0.0015 to 0.015 Tg C/yr (compared to 12 Tg C/yr @surface)
- Relative contribution of aviation to BC levels in the UT unclear
- Longer lifetime in the UTLS
- 0.003 Wm^{-2} in 1992

<u>Sausen et al. (2005):</u>
- 0.002 Wm^{-2}

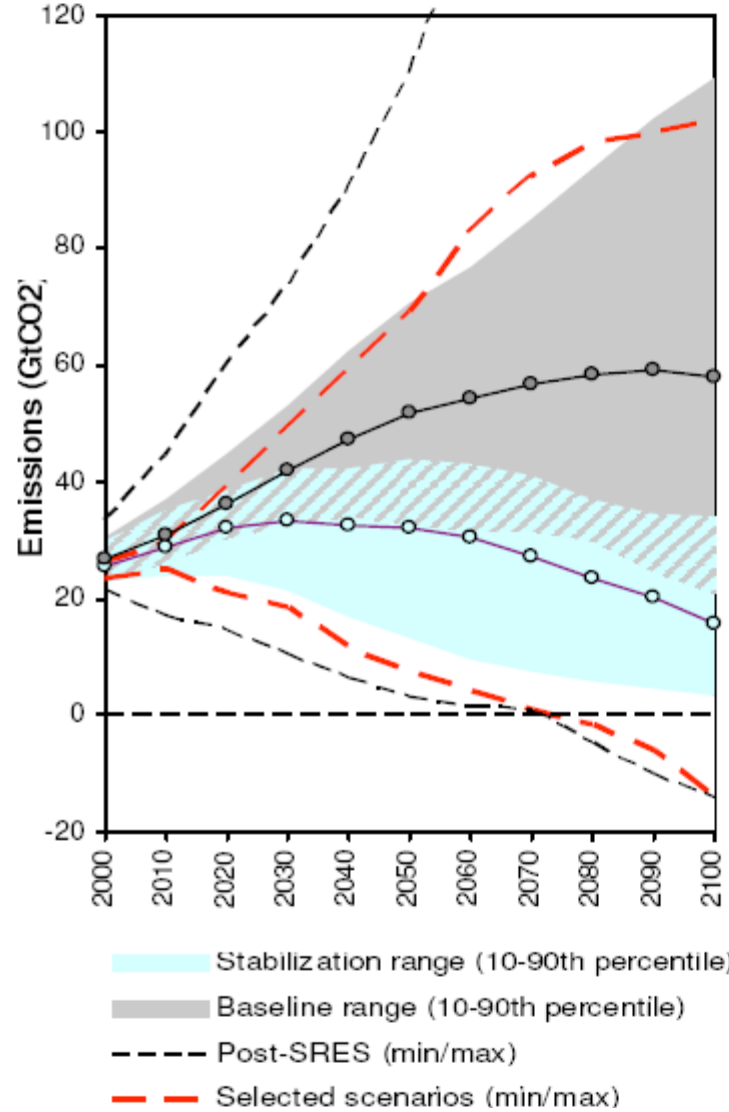
<u>Hendrick et al., ACP (2004):</u>
- 0.005 Tg C/yr (compared to 14 Tg C /yr @ surface)
- Maximum relative contribution to BC mass concentration from aircraft is 2-3% during winter and 1-2% during summer.
- Larger relative contribution to BC number concentration with maxima of 10-30% in the UTLS with implication for IN numbers.

<u>ATTICA report (2008)</u>

Future scenarios



IPCC – WGIII – 2007



IPCC – expert meeting on emissions - 2008

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RF by contrail and induced cirrus still very uncertain

Table 2.9. *Radiative forcing terms for contrail and cirrus effects caused by global subsonic aircraft operations.*

	Radiative forcing ($W\ m^{-2}$)[a]		
	1992 IPCC[b]	2000 IPCC[c]	2000[d]
CO_2[d]	0.018	0.025	0.025
Persistent linear contrails	0.020	0.034	0.010 (0.006 to 0.015)
Aviation-induced cloudiness without persistent contrails	0 to 0.040	n.a.	
Aviation-induced cloudiness with persistent contrails			0.030 (0.010 to 0.080)

Notes:

[a] Values for contrails are best estimates. Values in parentheses give the uncertainty range.

[b] Values from IPCC-1999 (IPCC, 1999).

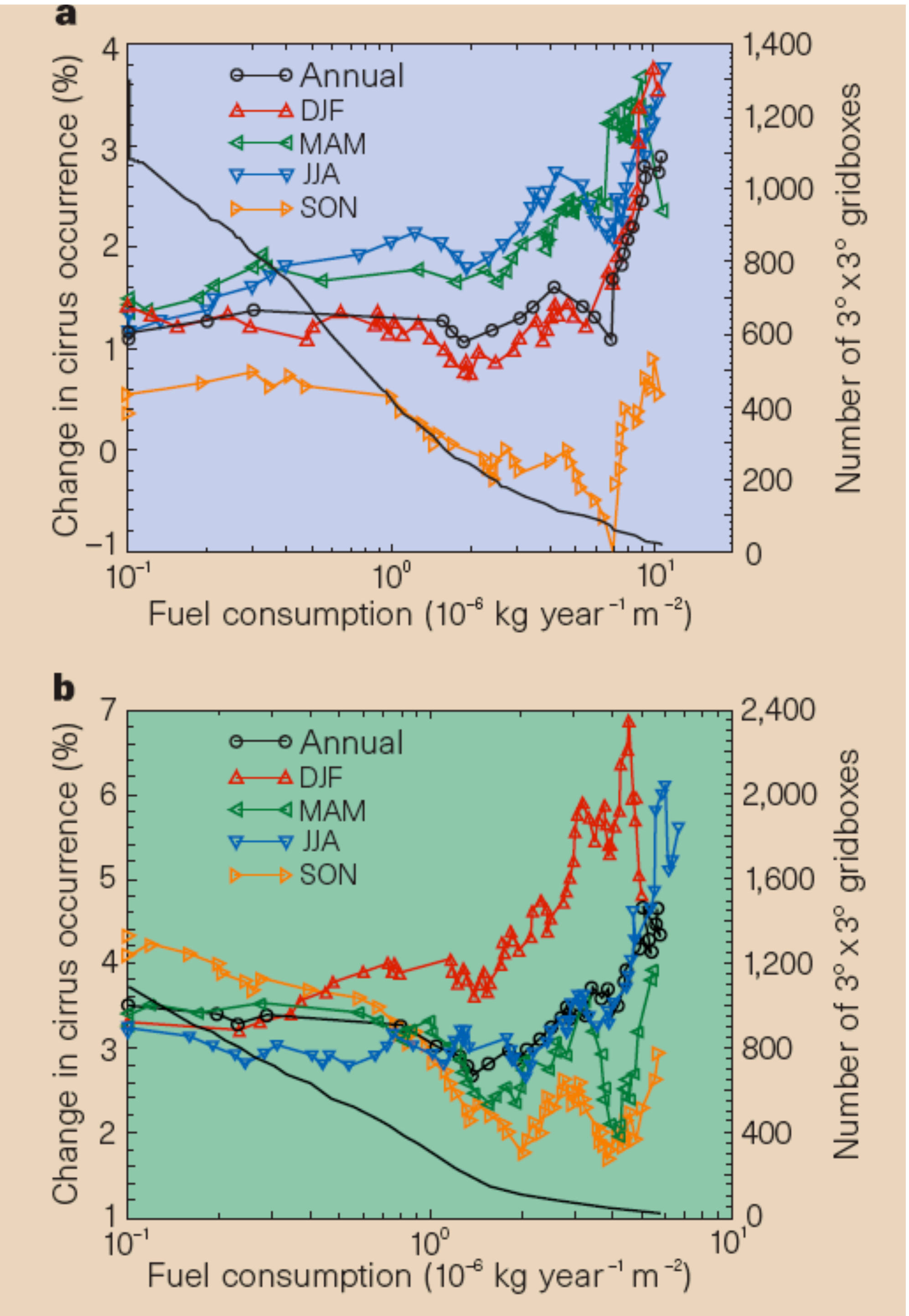
[c] Values interpolated from 1992 and 2015 estimates in IPCC-1999 (Sausen et al., 2005).

[d] Sausen et al. (2005). Values are considered valid (within 10%) for 2005 because of slow growth in aviation fuel use between 2000 and 2005.

IPCC – WGI (2007)

Aviation-induced cloudiness

Boucher, *Nature*, 1999
Stordal et al., *ACP*, 2004
Stubenrauch and Schumann, *GRL*, 2005



Difference in cirrus occurrence frequency between 1987-1991 and 1982-1986. a, Land; b, ocean. Results are averaged over grid-boxes with the 1992 fuel consumption at altitudes more than 8 km greater than the values displayed on the x-axis, and show annual means (circles) and seasonal means (triangles).

Boucher, *Nature*, 1999.

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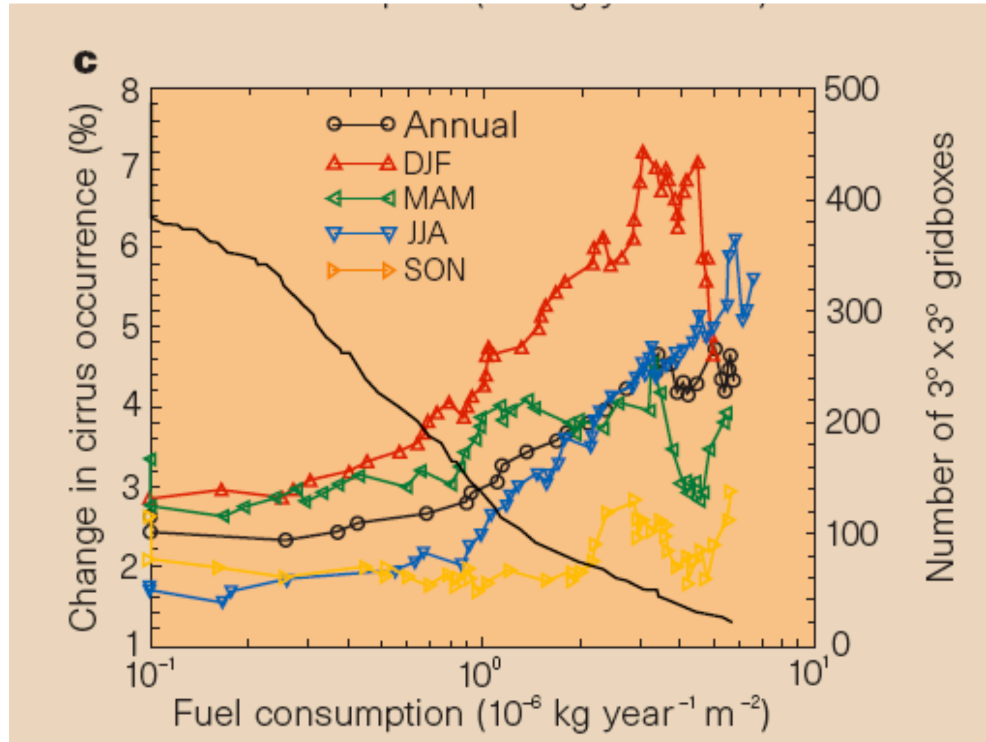
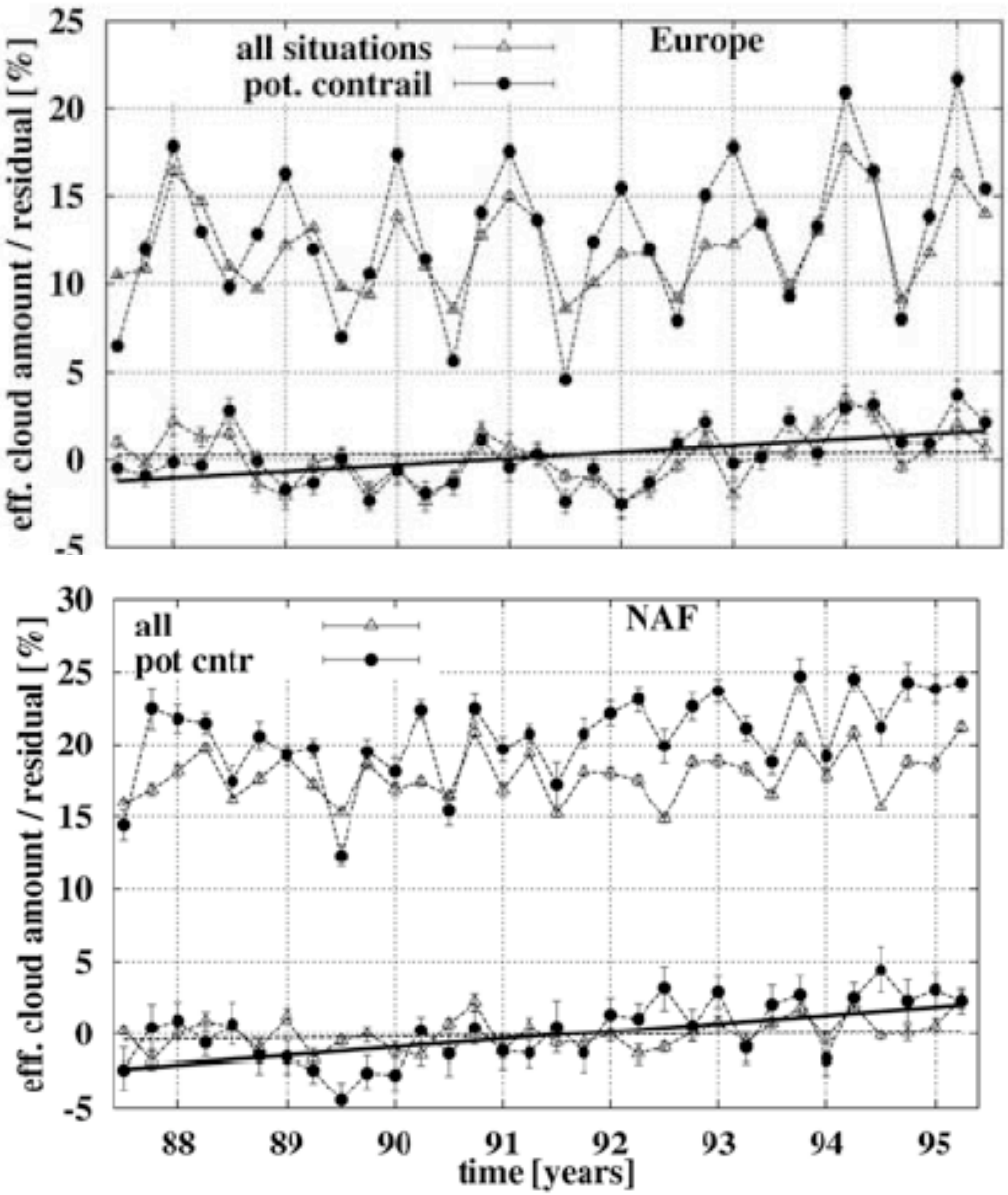


Difference in cirrus occurrence frequency between 1987-1991 and 1982-1986 over the North Atlantic Ocean. Results are averaged over grid-boxes with the 1992 fuel consumption at altitudes more than 8 km greater than the values displayed on the x-axis, and show annual means (circles) and seasonal means (triangles).

Boucher, *Nature*, 1999.

==> Unfortunately surface-based cloud climatology more or less discontinued



Stubenrauch et al., *GRL*, 2006.

Aviation-induced cloudiness

Boucher, *Nature*, 1999
Stordal et al., *ACP*, 2004
Stubenrauch and Schumann, *GRL*, 2005

Contrails become cirrus

IPCC, 1999

Unrelated to BC emissions

Aerosols serve as IN

Hendricks et al., *GRL*, 2005

Could be related to BC emissions

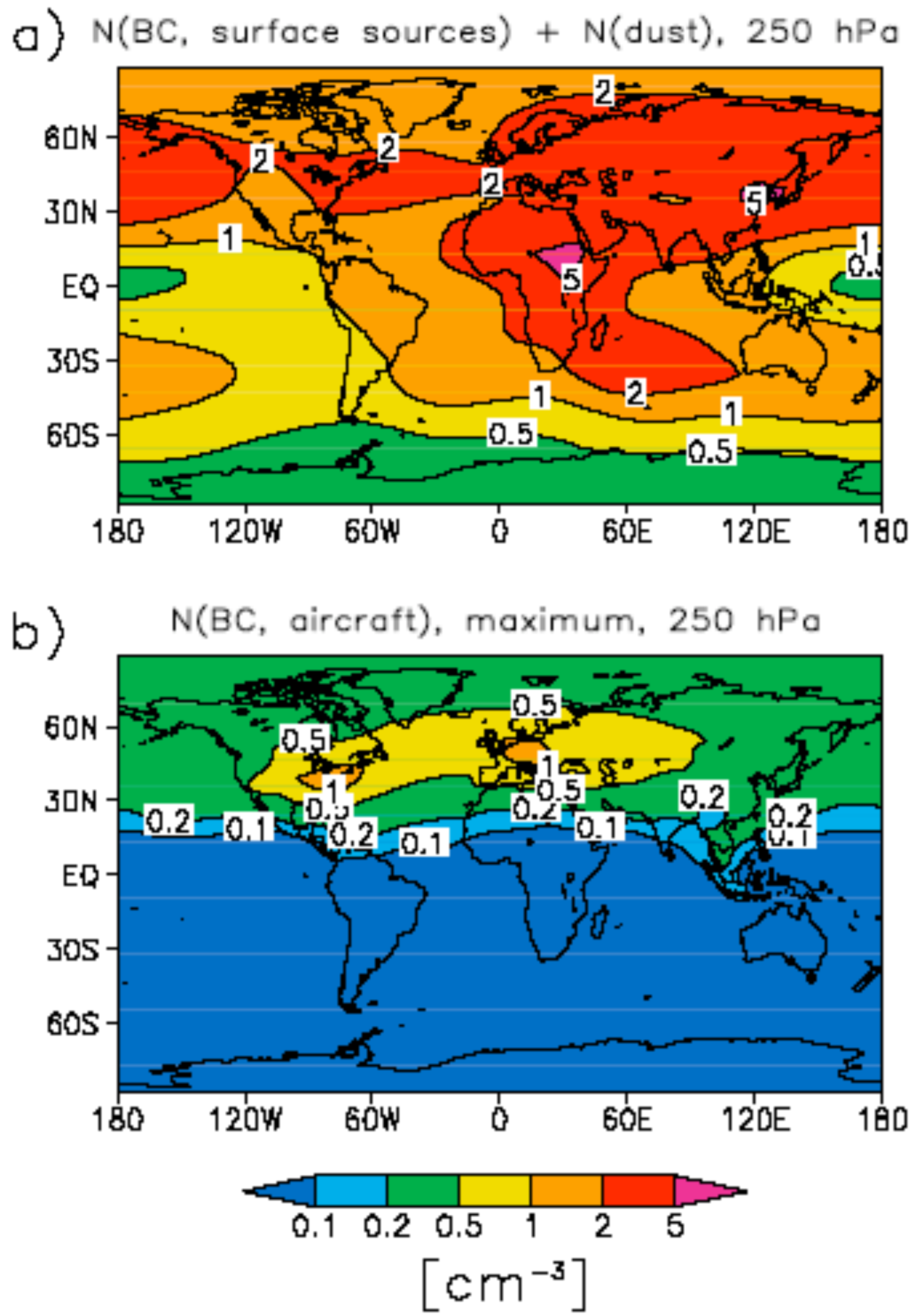


Figure 1. Annual mean number concentrations [cm^{-3}] of potential IN at 250 hPa (main aircraft flight level). (a) Hydrophilic BC and mineral dust particles originating from surface sources. (b) BC particles from aircraft (maximum estimate by *Hendricks et al.* [2004]). The results were taken from the HOM simulation.

Hendricks et al., *GRL*, 2005

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Non-CO_2 effects of aviation are significant.

Some non-CO_2 effects, in particular induced cirrus, are uncertain
(but correspond to positive RF, hence global warming)
(therefore possible to calculate a conservative estimate)

A non-CO_2 multiplier has been suggested to factor in the non-CO_2 effects of aviation into an equivalent CO_2 alone effect for:

* Carbon calculators

* Emission Trading Scheme

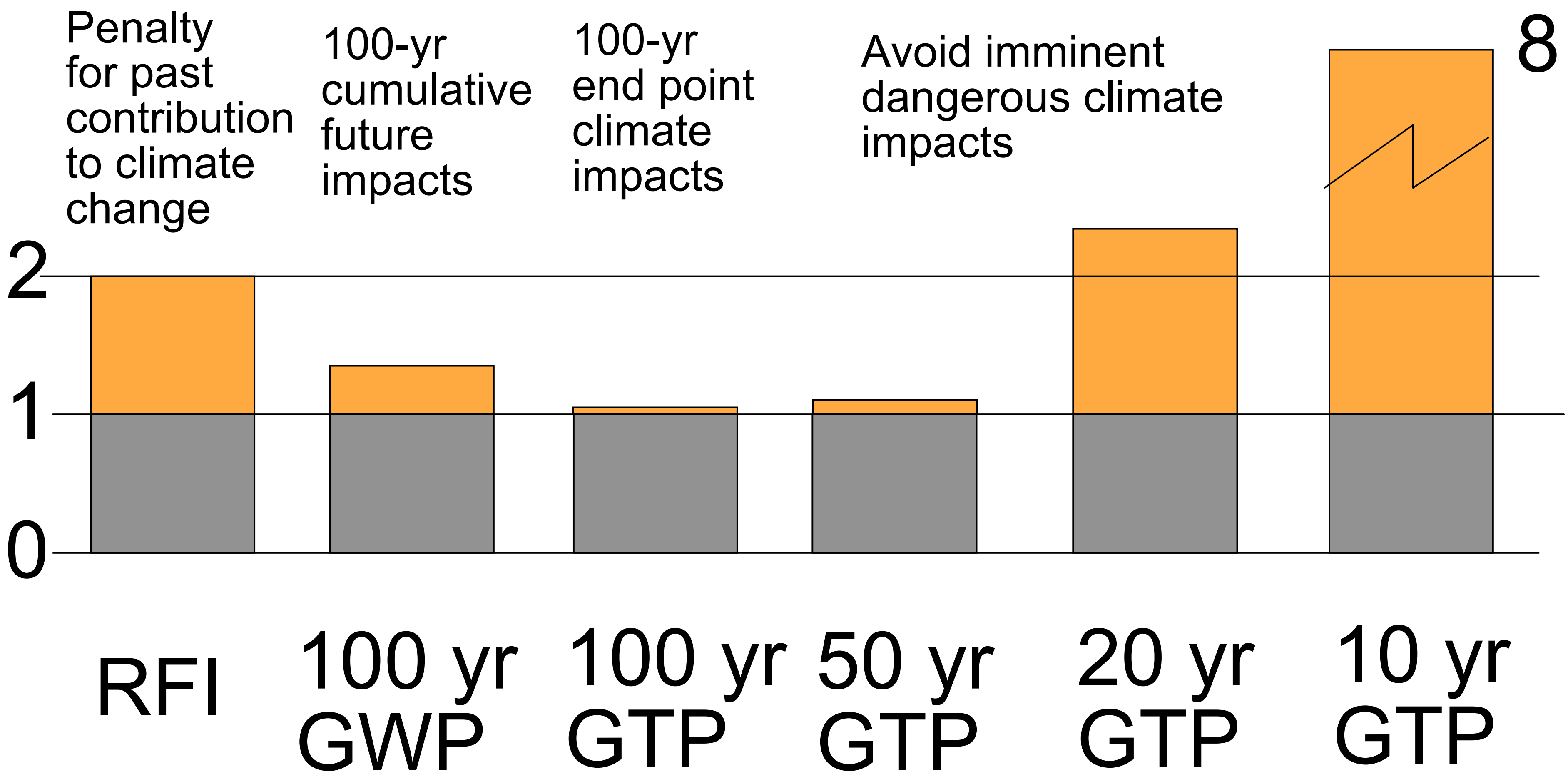
RFI is inappropriate as a non-CO_2 multiplier

But other climate metrics are more appropriate…

What is the right multiplier?

A simple example

CO_2 RF = 0.02 Wm^{-2}, contrails&cirrus=0.02 Wm^{-2}, 650 Gt CO_2/yr



Non-CO_2 effects can be an opportunity for the aviation sector…

- Non-CO_2 multiplier does not allow much flexibility
- Minimising the total effect of aviation on climate (through the optimal combination of fuel consumption, NOx emissions and contrail formation) might be a more flexible solution
- It can be achieved
  - by optimal air traffic management (route & altitude)
  - by optimising engines and aircraft
  - by optimal deployment of a mixed fleet of aircraft

Right metric for comparing CO_2 and non-CO_2 effects!!

Mixed fleet of aircraft


Aircraft can be deployed to minimise the overall climate effect

Potential for contrail formation depends on latitude/altitude

Deploy new aircraft on routes where contrail formation is minimised

Conclusions

- The direct effect of black carbon from aviation is thought to be small (primarily because of small emissions).
- Aviation-induced cloudiness is still the largest uncertainty in aviation effects on climate. Trends in cirrus are difficult to detect because of natural variability and inappropriate datasets. Aviation-induced cloudiness could be due to spreading contrails or from aviation-induced ice nuclei or both.
- Black carbon aerosols are thought to be efficient ice nuclei and therefore may lead to increased cirrus cloudiness.
- If this is true, both aviation and surface BC emissions would lead to increased cirrus cloudiness (a positive RF).

Research priorities on aviation

INVESTIGATE THE BIG UNKNOWNS

- Contrail persistence, contrail-spreading cirrus (formation and prevalence), induced cirrus, BC aerosols as ice nuclei, detection of cirrus trends

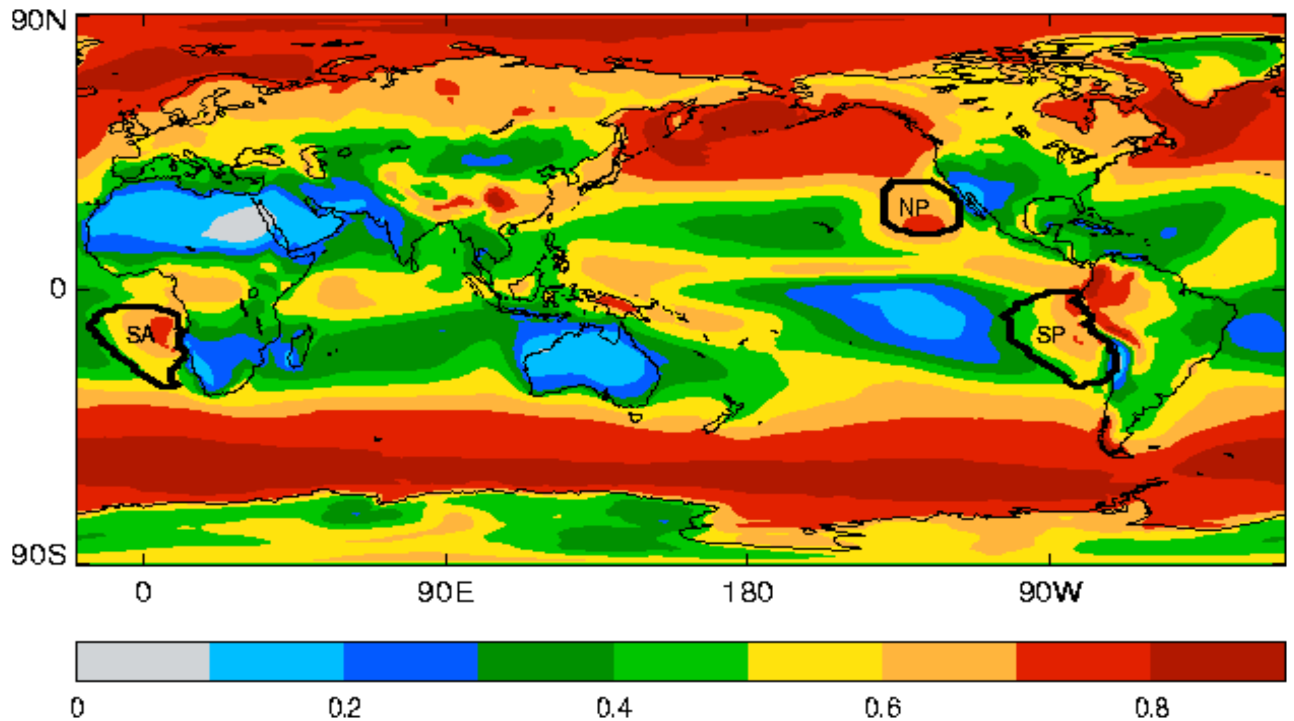
CONSOLIDATE EXISTING KNOWLEDGE

- Methane and ozone chemistry in the upper troposphere / lower stratosphere, contrail formation, RF by linear contrails
- Develop policy-relevant climate metrics (compare CO_2 and non-CO_2 climate effects)
- Work out and forecast the climate impacts of individual flights

Climate simulations

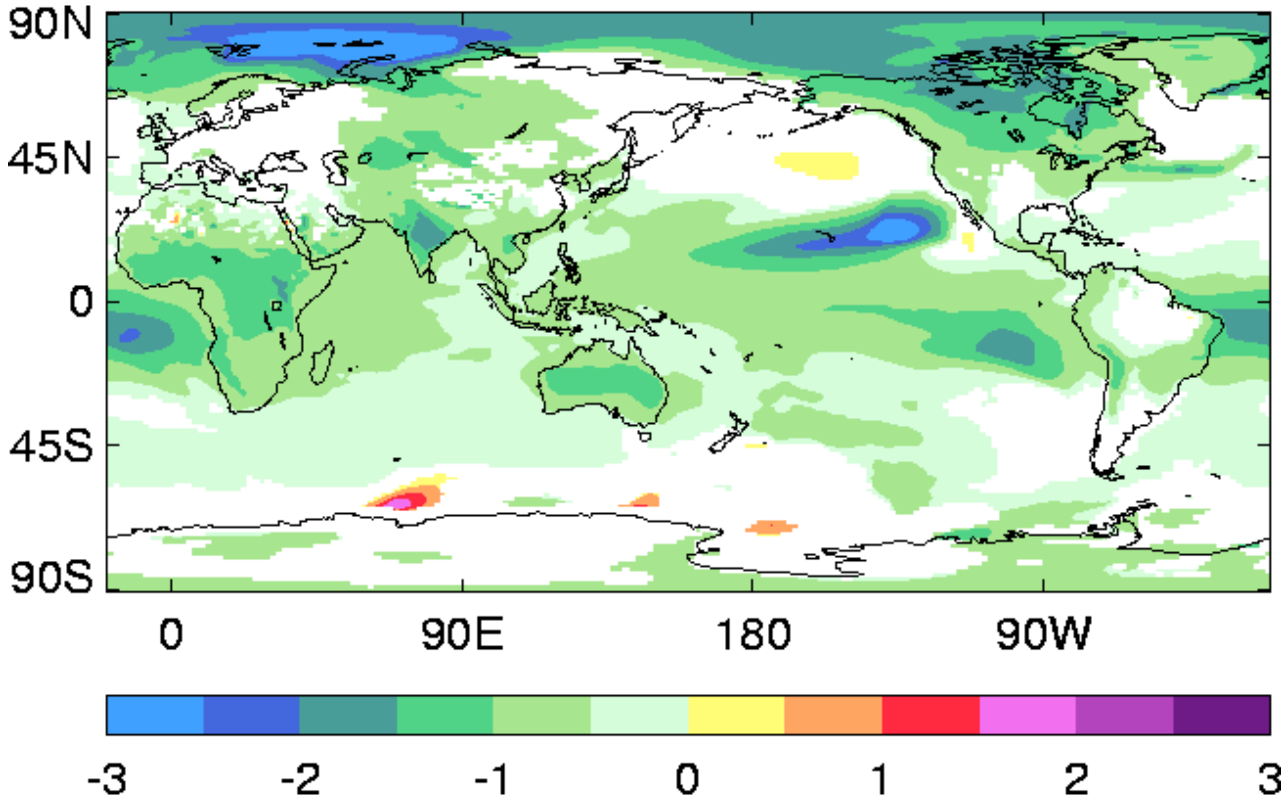
CDNC of 375cm^{-3} is changed in three areas defined by ISCCP climatologies (which agree reasonably with HADGEM2 Sc):

- **ALL (A/AML/AO)**
- **SP: South Pacific (Peruvian Sc) (A/AML/AO)**
- **NP: North Pacific (Californian Sc) (A/AML/AO)**
- **SA: South Atlantic (Namibian Sc) (A/AML/AO)**



However, global mean temperature change is a very small part of the story:

Spatial pattern of surface temperature change:



Mean 2030-2059 temperature change due to geoengineering of the three main marine stratocumulus cloud areas (ALL minus A1B). Areas where the difference is not statistically significant at the 5% level are left white.

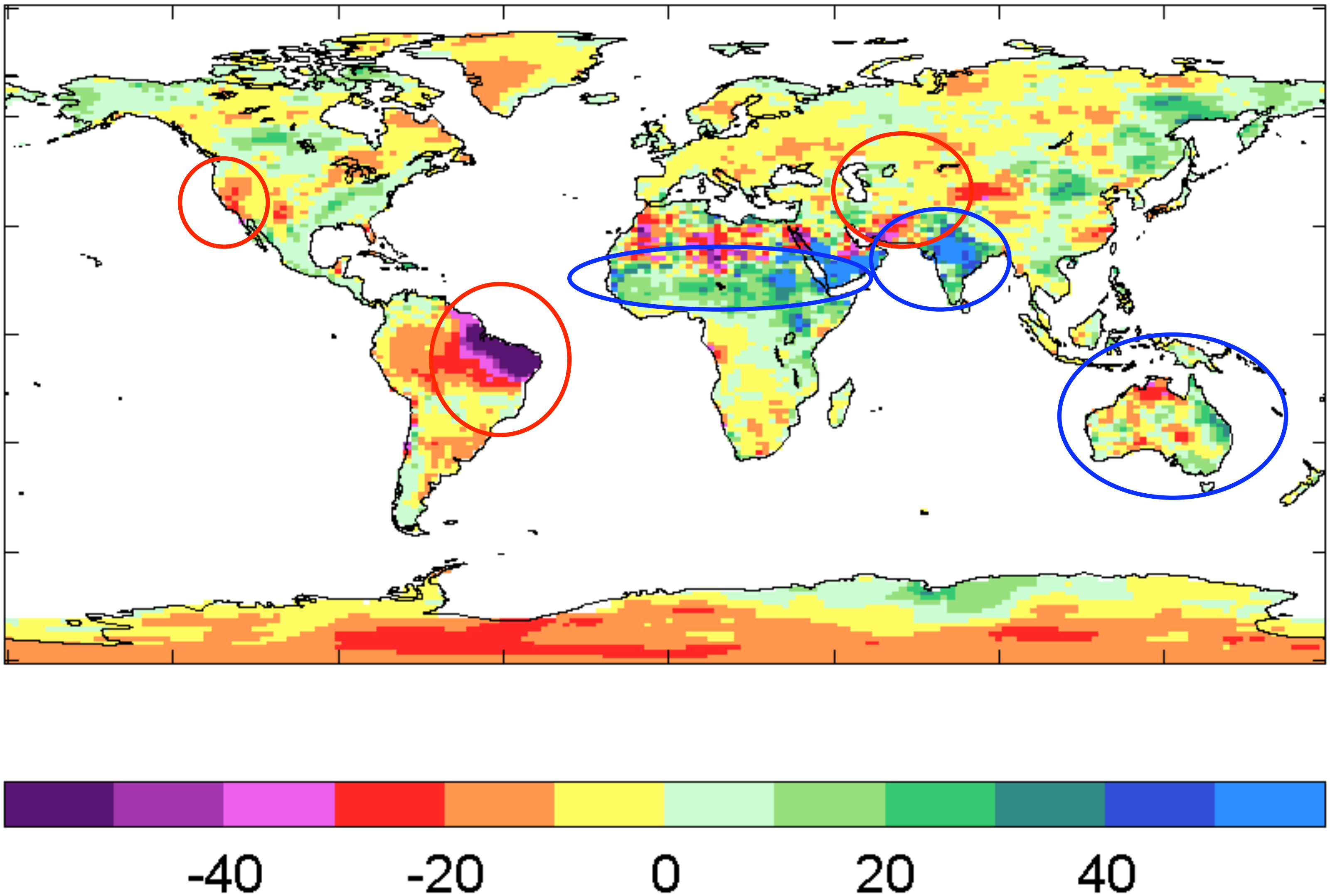
Change in precipitation relative to A1B

Winners

Losers

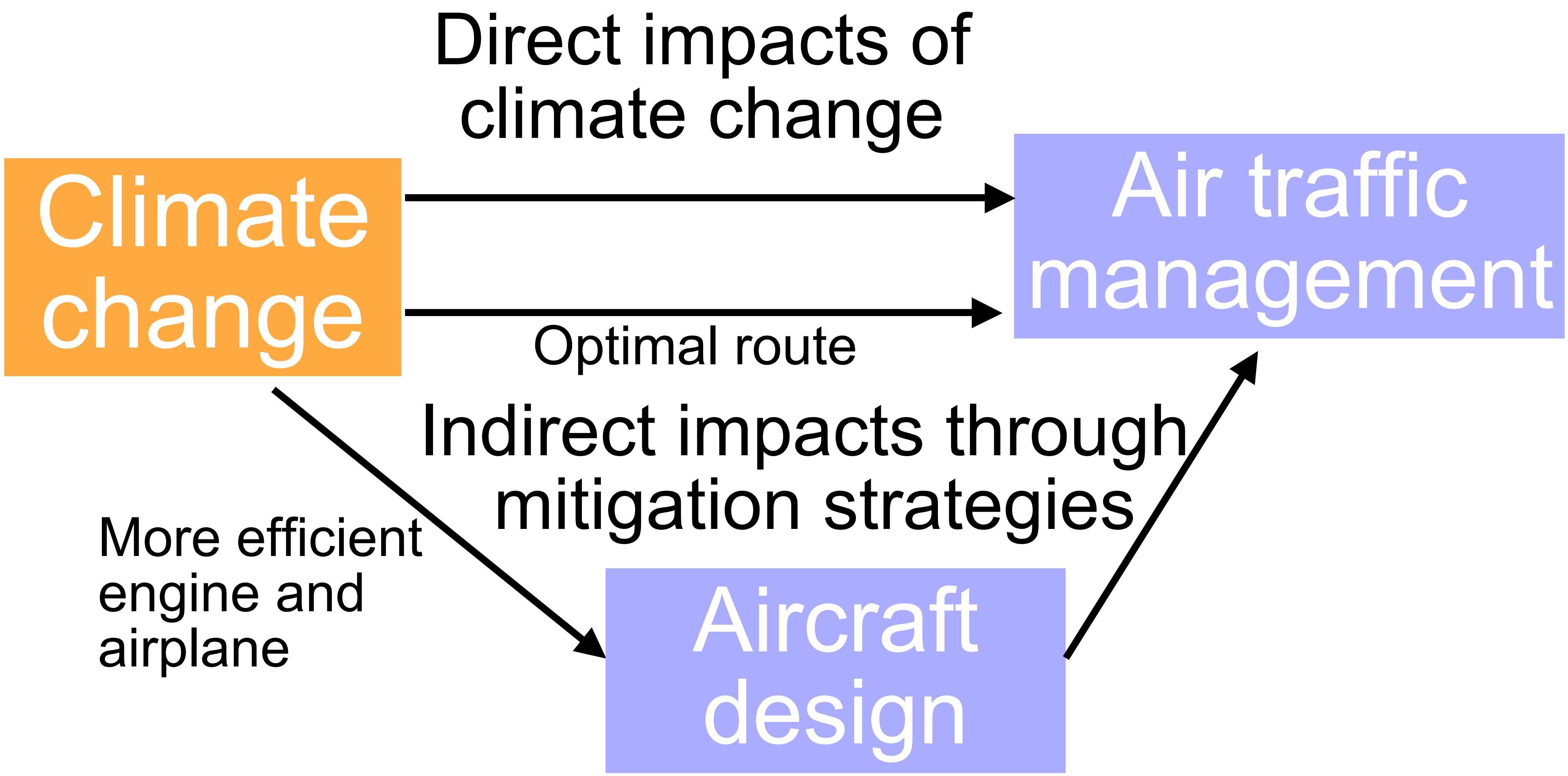
Year 2060

9-year mean



Thank you for your attention
Questions?

Direct and indirect impacts of climate change on ATM



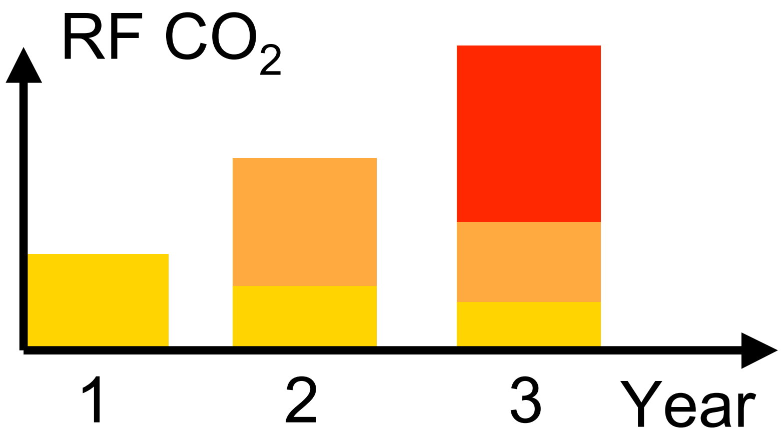
The climate impact and non-CO_2 multiplier are different for each **individual flight**

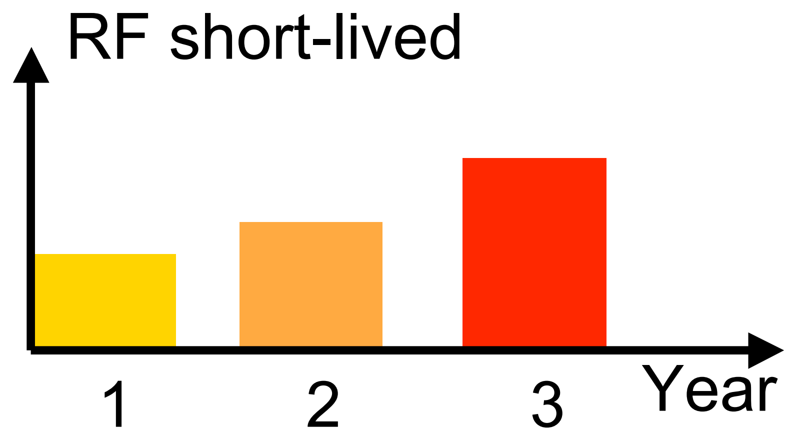
WHAT MAKES CLIMATE IMPACTS OF AVIATION FLIGHT-DEPENDENT?

- Flight altitude
  - Troposphere versus stratosphere: water vapour
  - Ozone formation and radiative efficiency
  - Contrail formation
- Flight latitude
  - Ozone and contrail formation
- Temperature and humidify conditions
  - Contrail formation
- Engine efficiency
  - CO_2
  - Contrail formation
- Time of flight
  - Contrail RF different at day and at night

Radiative Forcing Index

Radiative forcing measures the change in the radiative budget from pre-industrial to present-day. It is a measure of the cumulative effect of aviation on the radiation budget.





RFI=2 As of now, the non-CO_2 climate change mechanisms associated with aviation have doubled the climate warming due to CO_2 only emissions from aviation.

Global Warming Potential (GWP)

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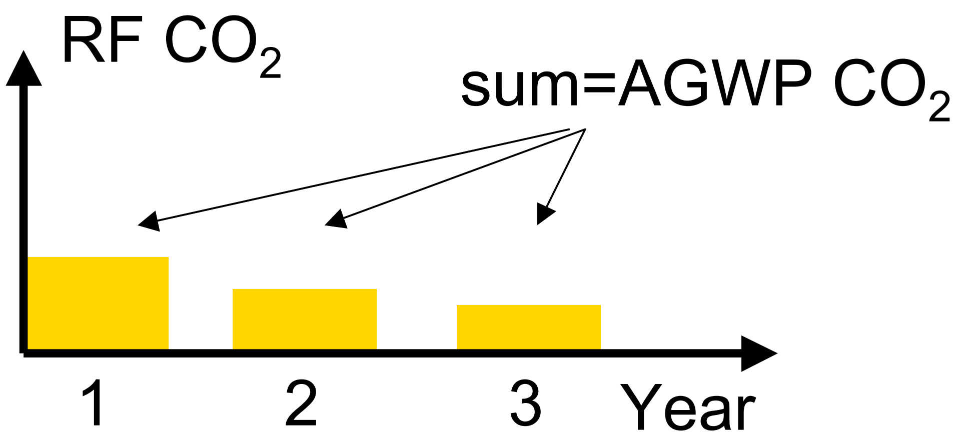
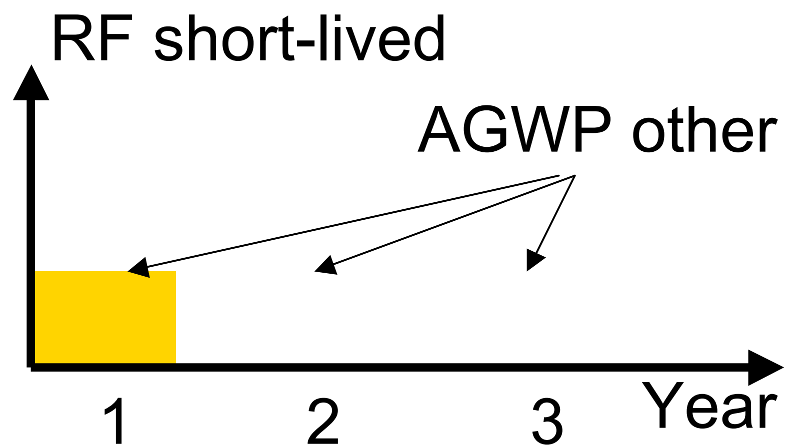
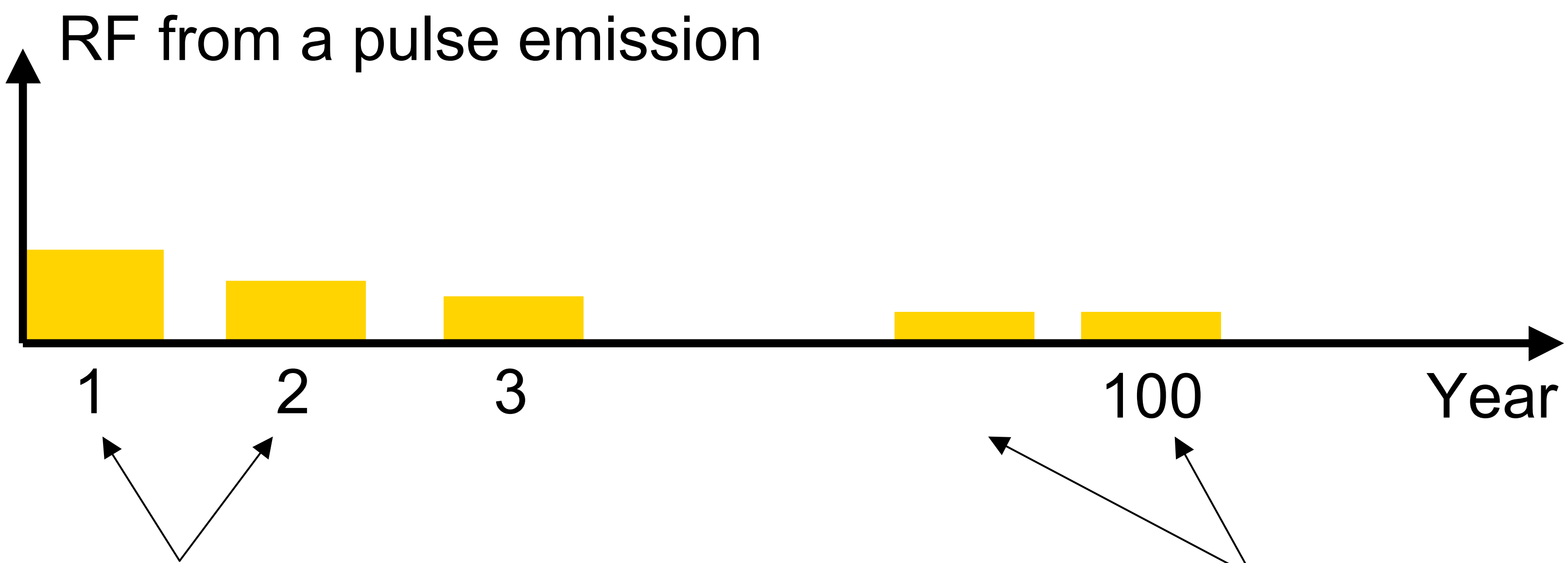
Absolute GWP measures the cumulative radiative forcing into the **future** of a **pulse** emission made **today**.





Can be used to define a GWP index that is a non-CO_2 multiplier
Future means 20, 50, or more usually **100** years
Pulse emission means that the index can change with technology

Global Warming Potential (GWP)



<u>This radiative forcing</u> is less efficient than **<u>this radiative forcing</u>** at creating climate change in a 100 year time from now.

A GWP index is recommended if you are interested to limit a cumulative effect over a period of time but it is not if you are only interested to limit the amount of climate change in 2100.

Global Temperature Potential

The (absolute) GTP is defined as the change in surface temperature at a given time horizon due to a pulse emission at the beginning of the time horizon.

More suited for policy making. We can define a GTP index.
In particular it makes a lot sense if a temperature target is agreed on.

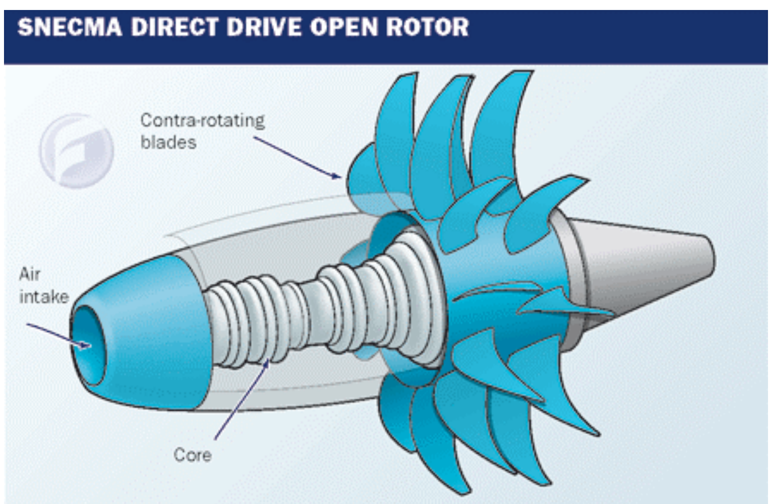
But GTP is more model-dependent than GWP.

So which climate metric is best?

It depends on the policy question:

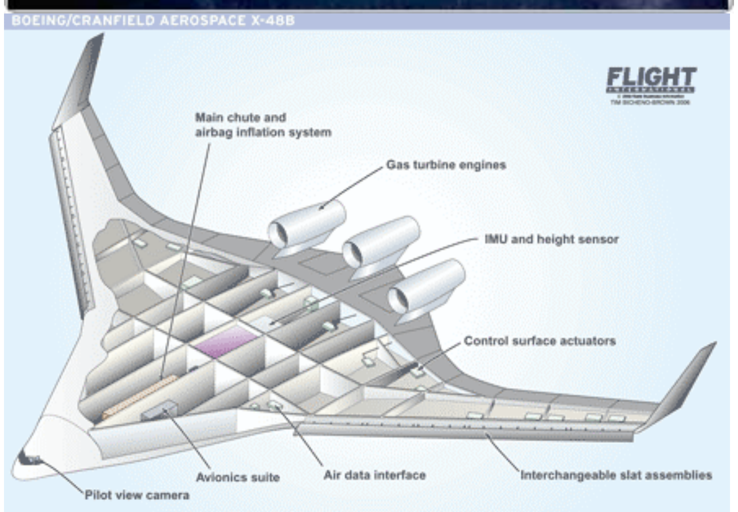
- Penalty for past contribution of aviation to today's climate change
- Trade/offset the future climate impacts of today's emissions against a saving in another economical sector
  - How do we measure impacts of climate change in the future?
    - End point? e.g. 2050, 2100, 2200
    - Cumulative? i.e. integrated over all timescales
    - Rate of change?
  - Targets to avoid dangerous climate change (eg 3°C or 550 ppm CO_2 eq)

Example 1: Open rotors



- Lower speed
- Less fuel consumption
- Suitable for short- and medium-haul operations
- More air traffic space
- Different flight altitude ➔ Different climate effects (ozone and contrails)

Example 2: Blended wing body



Lower fuel consumption

Higher cruise altitude

➔ Stratospheric water vapour

➔ Ozone formation and RF

➔ Contrails & Induced cirrus

(Tropics versus Mid-latitudes)

A few key figures

Aviation is responsible for about 650 TgCO_2/yr in 2000, or 2.6% of total fossil-fuel CO_2 emissions in 2000.

Aviation represents 11.6% of total CO_2 emissions from the transport sector in 2000.

The RF from aviation CO_2 emissions is 0.025 Wm^{-2} in 2000, against a total CO_2 RF of 1.46 Wm^{-2} in 2000 and 1.56 Wm^{-2} in 2005.

The growth rate of CO_2 emissions from aviation is more than the growth rate of total fossil-fuel CO_2 emissions.

Can we estimate and forecast the climate effect of individual flights?

- CO_2
- NOx => Ozone and methane
- Contrail: expected progress in NWP forecast of temperature, humidity and ice supersaturation
  - high vertical resolution
  - new satellite data to be assimilated
  - humidity sensors on commercial aircraft
- Induced cirrus ??

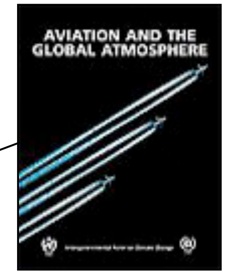
We should move from estimating the climate impacts of a **fleet** to the climate impacts of individual **flights**

WHY?

- A greater variety of aircraft and flight patterns in the future
- A larger potential for climate mitigation
- More flexibility to mitigate emissions makes it cheaper
- Fairer

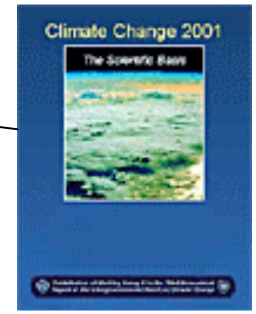
BUT

- Makes ATM more complicated
- Makes the science more challenging
- Has to fit within existing or future convention / legislation



IPCC special report on Aviation and the global atmosphere (1999)

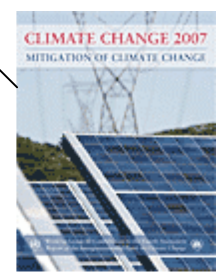
IPCC TAR WGI contribution (2001)



IPCC AR4 WGI contribution (2007)

IPCC AR4 WGII contribution (2007)

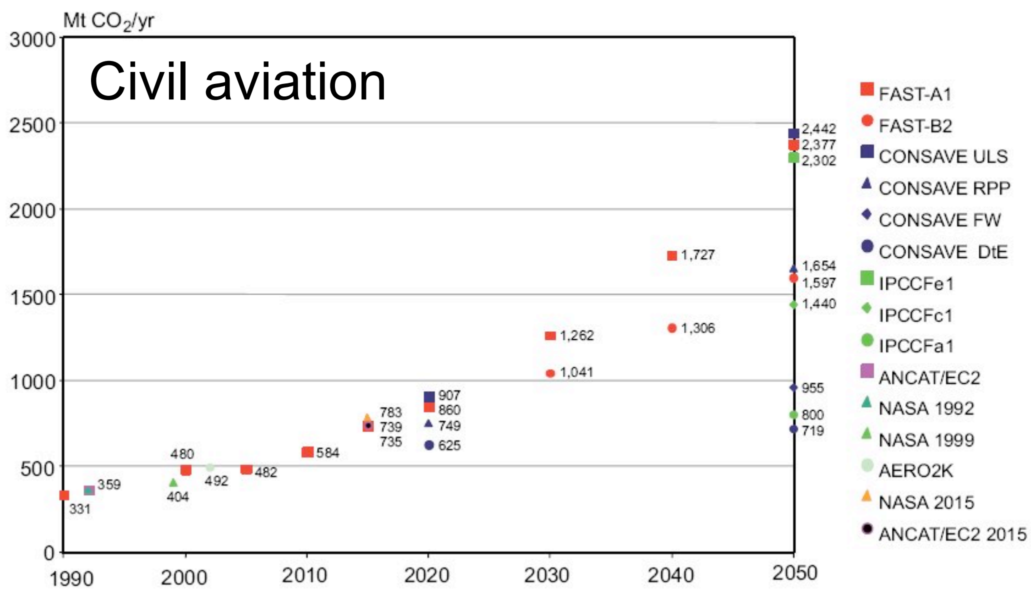
IPCC AR4 WGIII contribution (2007)



ATTICA report (2008)

(Assessment of Transport Impacts on Climate and Ozone)

Future scenarios



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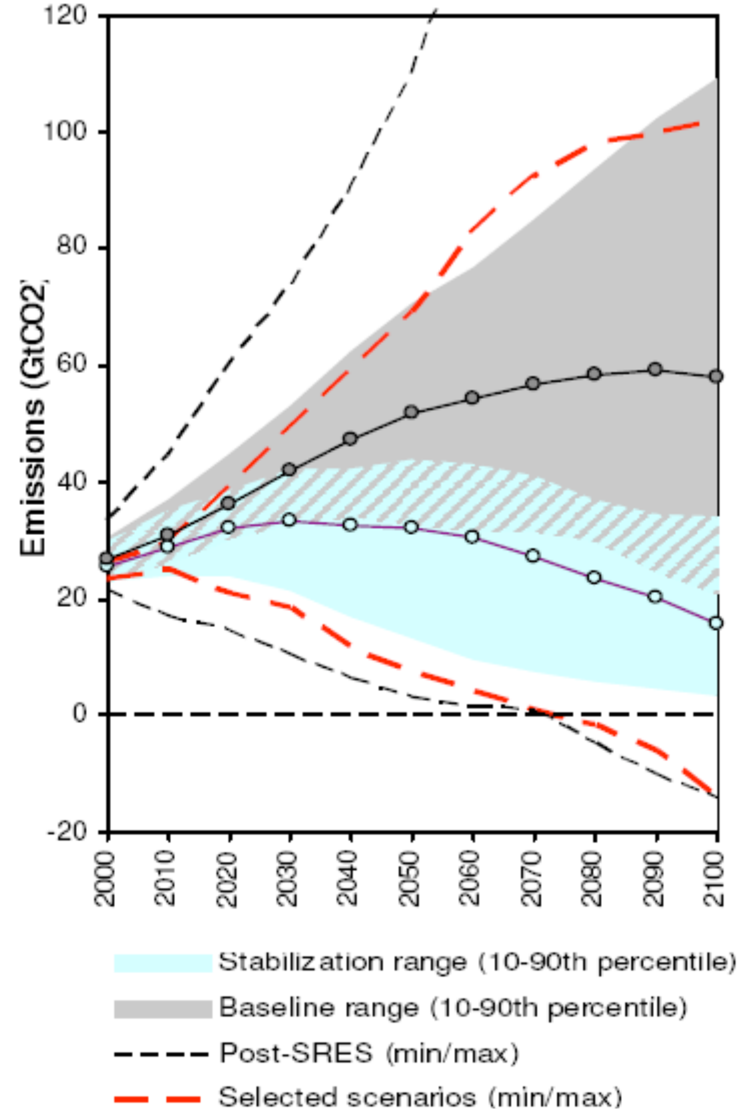

IPCC – expert meeting on emissions - 2008