Evaluating the Importance of Aviation on Climate Change

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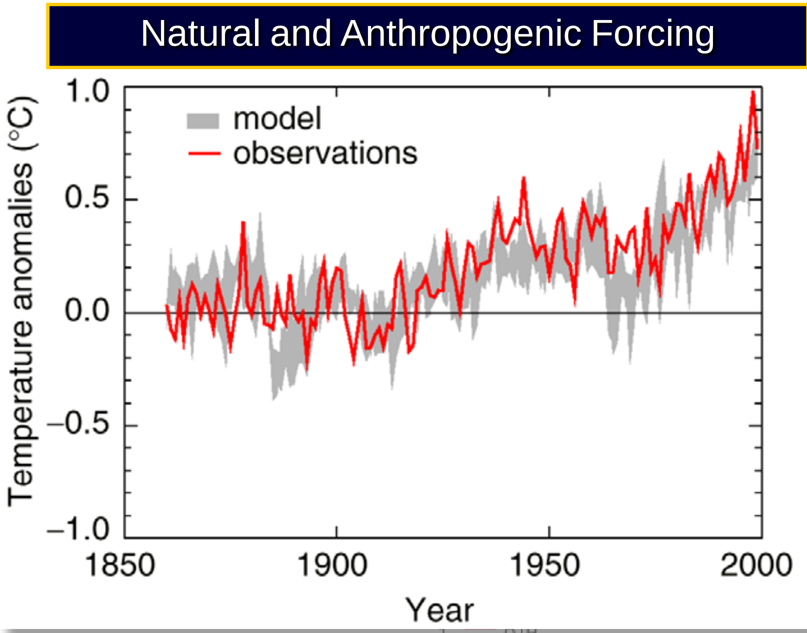
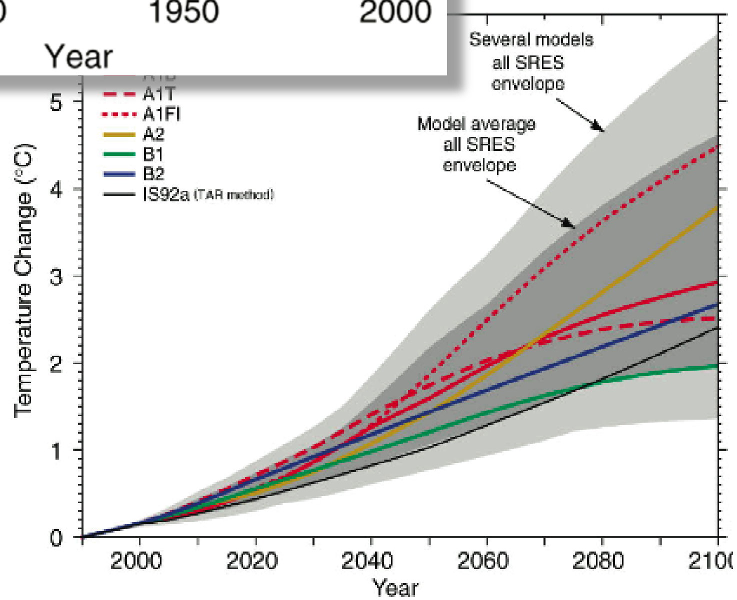
Climate Change is one of the most important issues facing humanity and our planet





- *There is strong evidence that significant global warming is occurring*
- *Most of this warming can be attributed to human activities*
- *Changes also occurring in extreme events*
- *Climate throughout our planet will continue to change significantly unless we take major action*

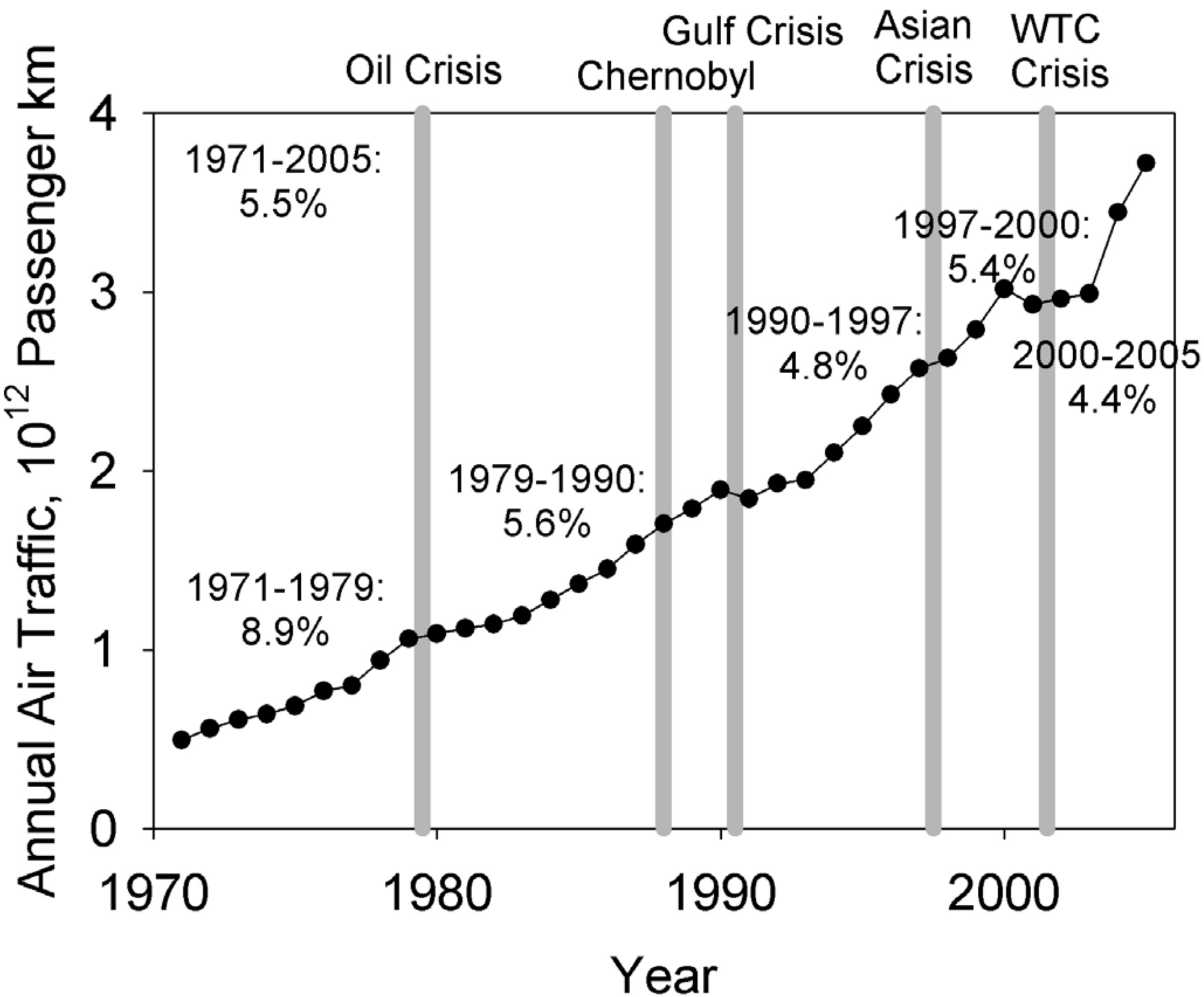
Aviation and Climate

Climate change impact is potentially the most serious long-term issue facing the aviation industry

Aviation plays a key role in the world economy

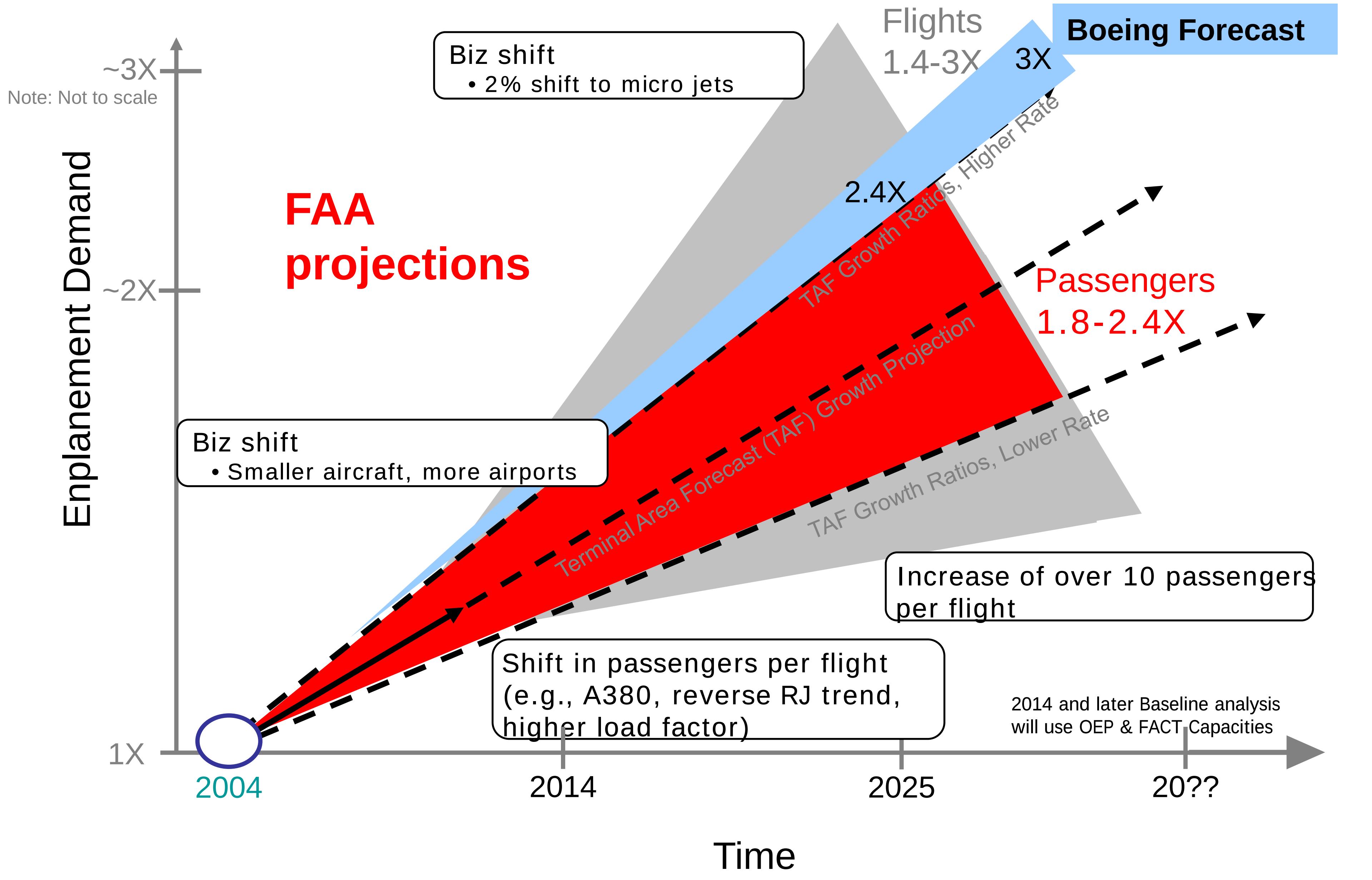
- Aviation supports 8% of global economic activity and carries 40% of the value of freight
- Aviation activity has generally outpaced economic growth
- U.S. has 4% of world's population and 40% of aviation activity

Past Growth in Aviation Traffic

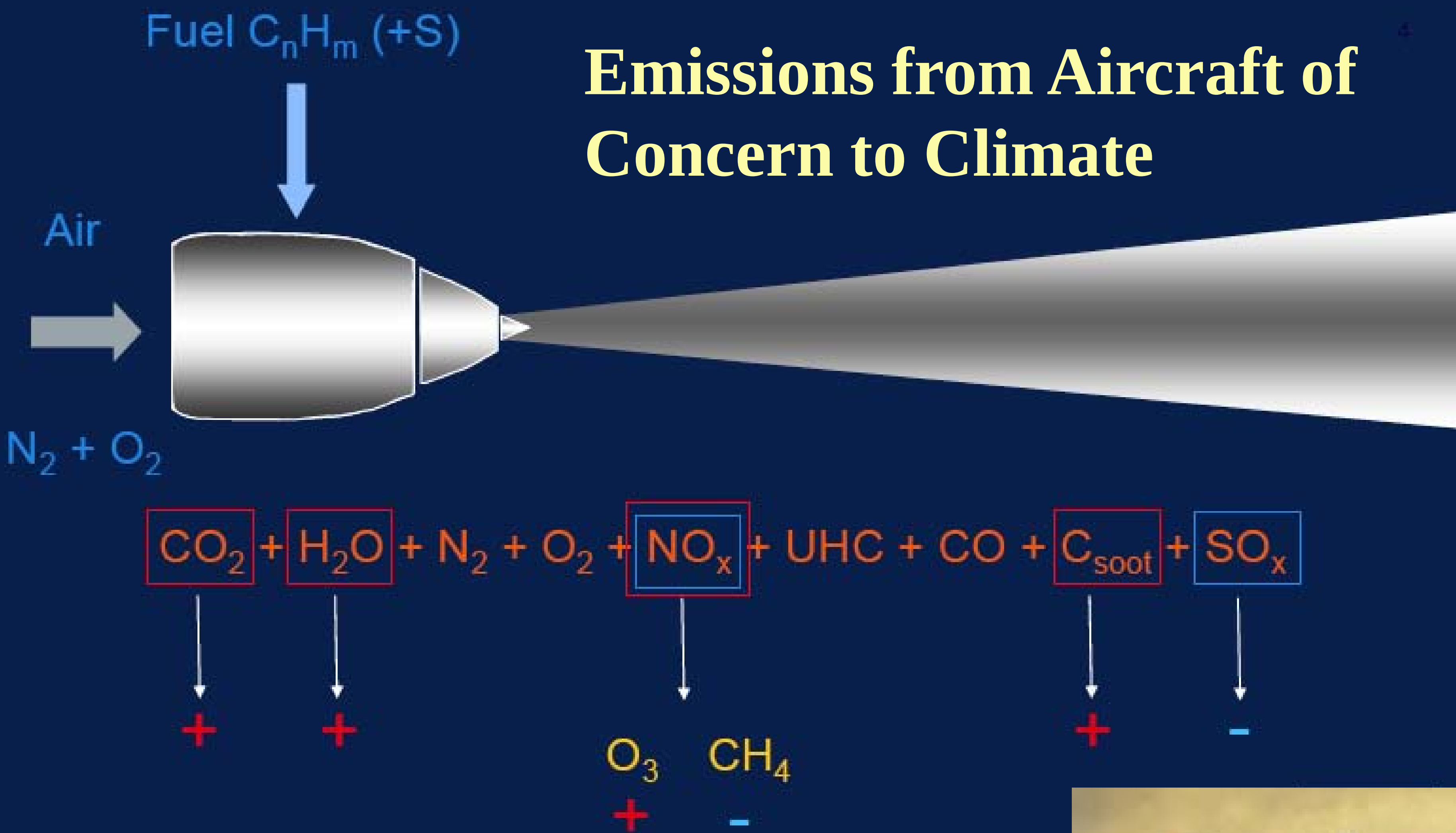


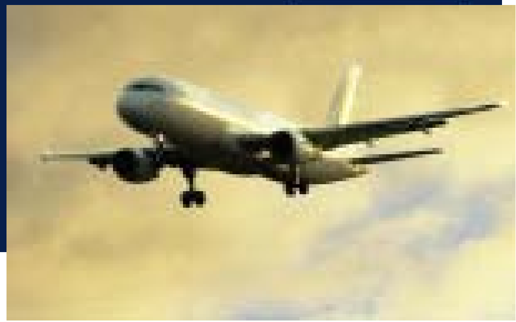
Fischer et al., 2007

Projected U.S. Aviation Services Demand

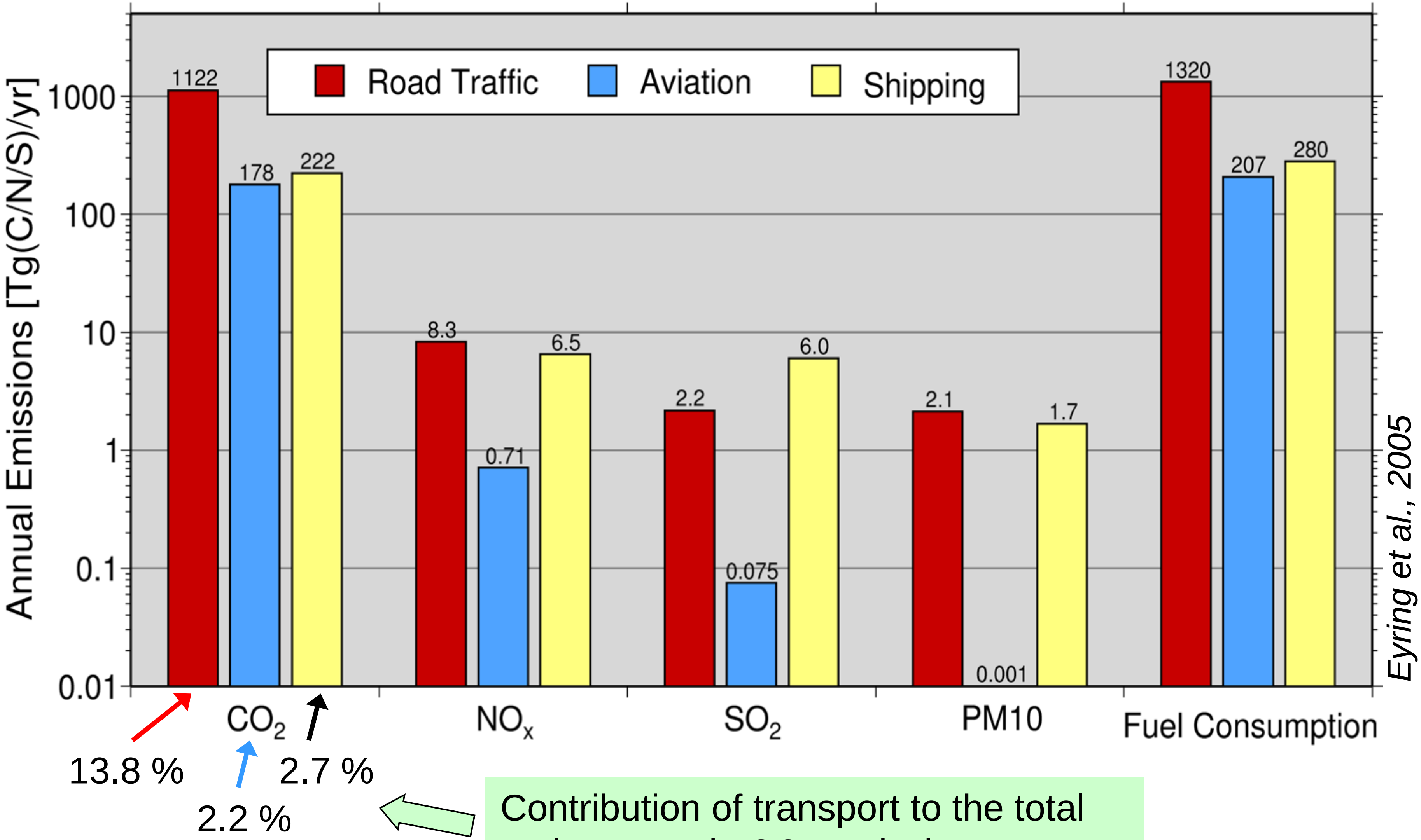


Emissions from Aircraft of Concern to Climate





Emissions from different modes of transport in 2000



Contribution of transport to the total anthropogenic CO_2 emissions

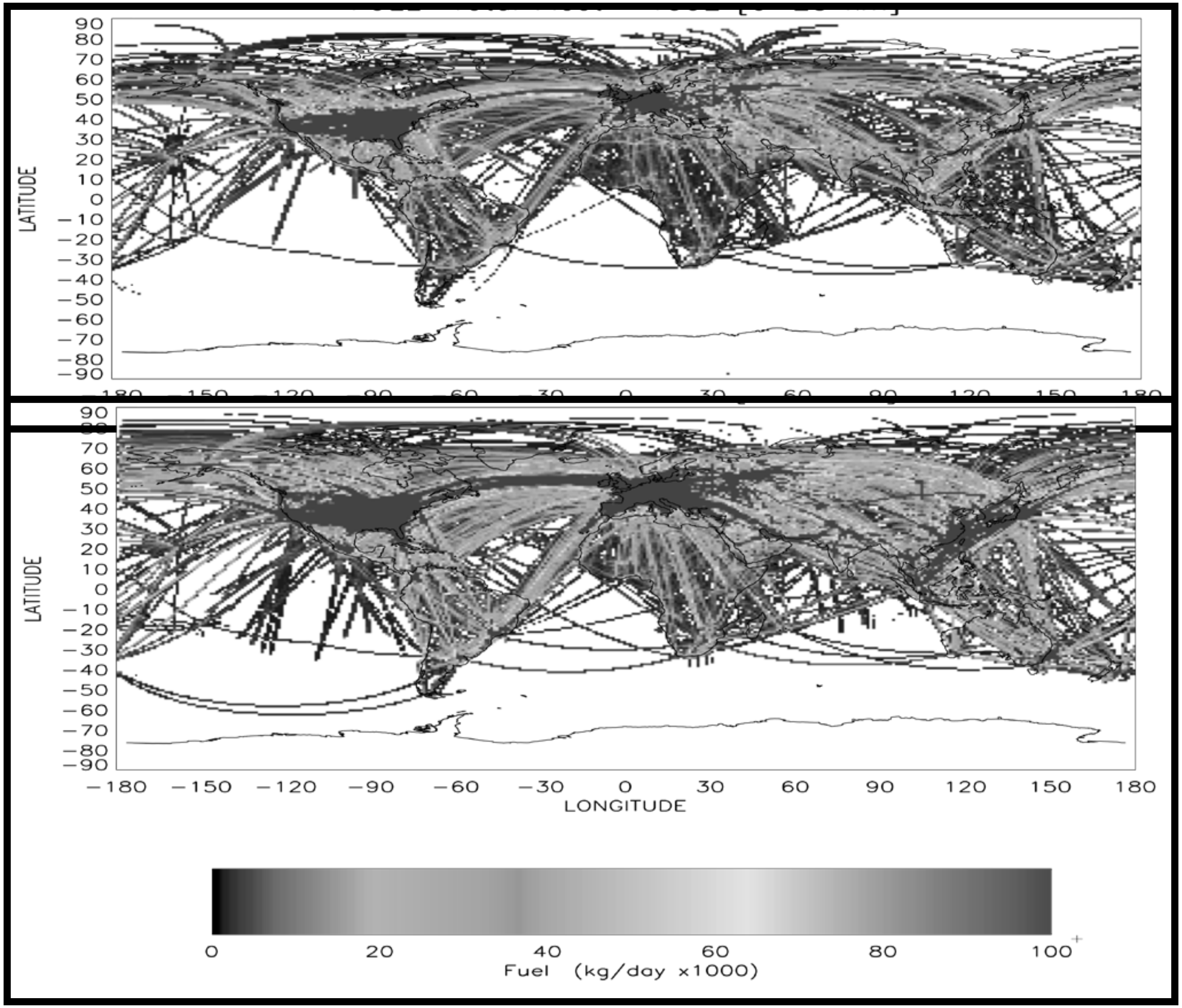
Aviation and Climate

- Aviation ~2% of global emissions of human-related CO_2
- Aviation total climate effect could be more than double the CO_2 effect, but these other impacts highly uncertain.
- Aviation may grow as a climate contributor relative to other contributors
- New aircraft are a long-term (~30 year) investment

Policy Focus Has Been on Emission Inventories

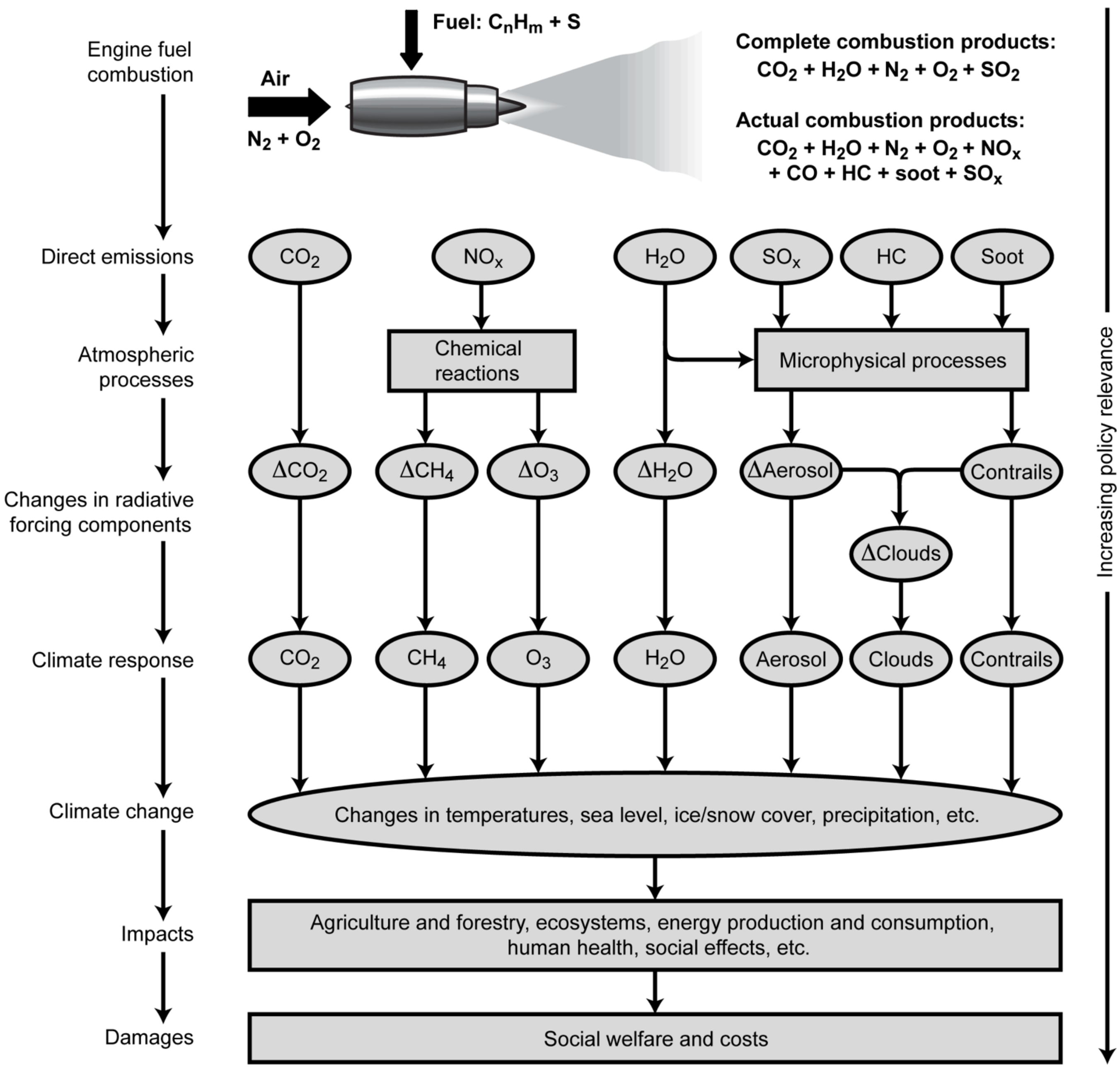
1992

2015

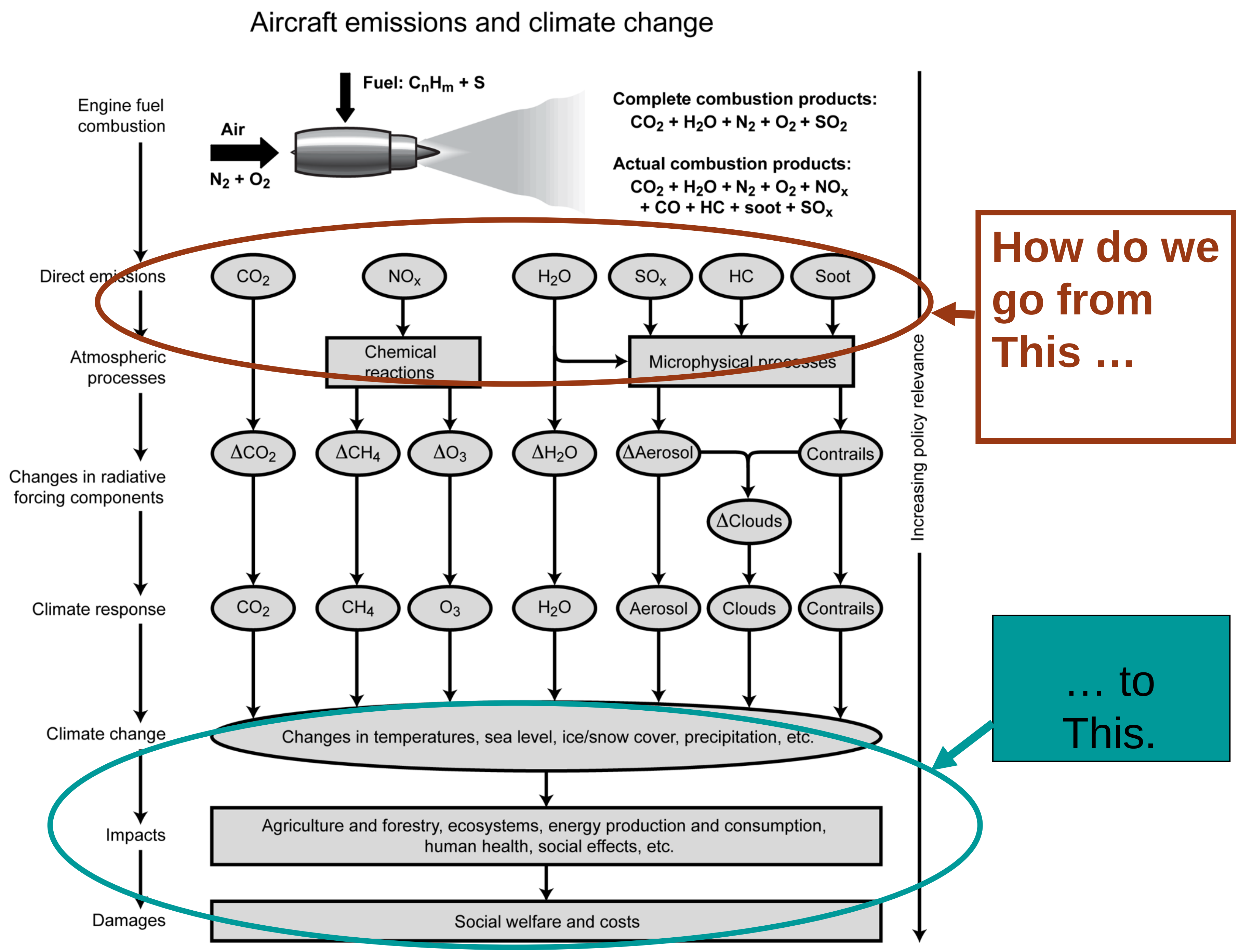


Fuel Burn

Aircraft emissions and climate change



There is increasing policy relevance as go from Emissions to Climate Response to Impacts and Resulting Costs / Benefits



Aircraft emissions and climate change
Engine fuel combustion
Fuel: C_nH_m + S
Air
$N_2 + O_2$
Complete combustion products:
$CO_2 + H_2O + N_2 + O_2 + SO_2$
Actual combustion products:
$CO_2 + H_2O + N_2 + O_2 + NO_x$
+ CO + HC + soot + SO_x
Direct emissions
CO_2
NO_x
H_2O
SO_x
HC
Soot
Atmospheric processes
Chemical reactions
Microphysical processes
Changes in radiative forcing components
ΔCO_2
ΔCH_4
ΔO_3
ΔH_2O
ΔAerosol
Contrails
ΔClouds
Climate response
CO_2
CH_4
O_3
H_2O
Aerosol
Clouds
Contrails
Climate change
Changes in temperatures, sea level, ice/snow cover, precipitation, etc.
Impacts
Agriculture and forestry, ecosystems, energy production and consumption, human health, social effects, etc.
Damages
Social welfare and costs
Increasing policy relevance
How do we go from This …
… to This.

The Challenge: understand and address climate effects from aircraft emissions

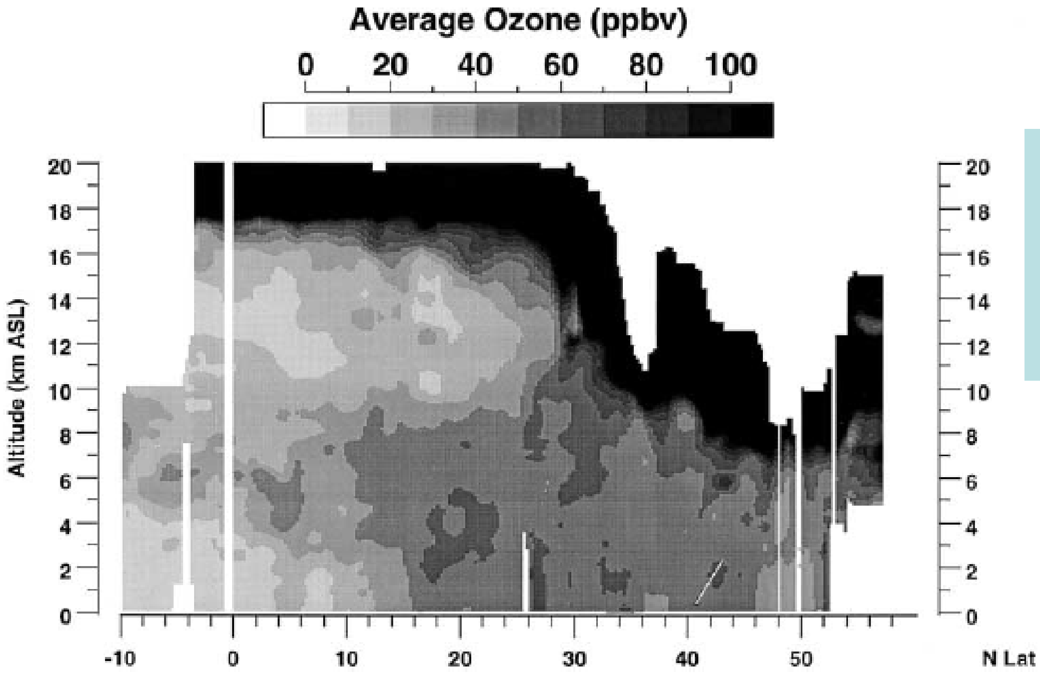
Most emissions occur at cruise altitudes in the UT/LS

- **Direct effects of carbon dioxide (CO_2) emissions**
- **Indirect effects from changes in ozone and methane from NOx emissions**
  - At these altitudes, NOx emissions produce O_3
  - Increase in ozone results in increased tropospheric OH and reduced CH_4
- **Indirect effects from water vapor and particle emissions due to contrail formation and corresponding effects on cloudiness**
- **Direct effects from aerosols (particles) either emitted directly (e.g., soot) or produced from emitted precursor gases (e.g., SO2)**
- **Direct effects from water vapor emissions in stratosphere**

Factors Affecting Aviation's Climate Impact

- Time scales **of climate effects after emission**
  - CO_2 effects are for many decades (τ ~ 100 yrs)
  - Other emission effects much shorter
    - O_3 : 1-2 years or less
    - CH_4: ~10-12 years (but only get full effect if NOx emitted for >10 yrs)
    - Particles: < 1 year
    - Contrails: hours to days (cirrus longer?)
- **Particles** can have direct climate effects and indirect effects by acting as cloud condensation nuclei
- **Except for the CO_2 effects,** large uncertainties remain

Upper Troposphere / Lower Stratosphere



Airborne lidar during NASA PEM-Tropics, February–March 1994.

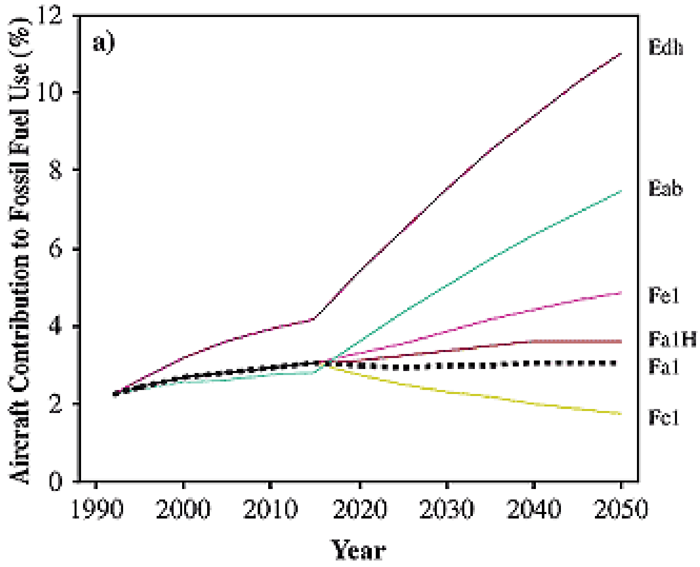
UT/LS affects climate in two primary ways:

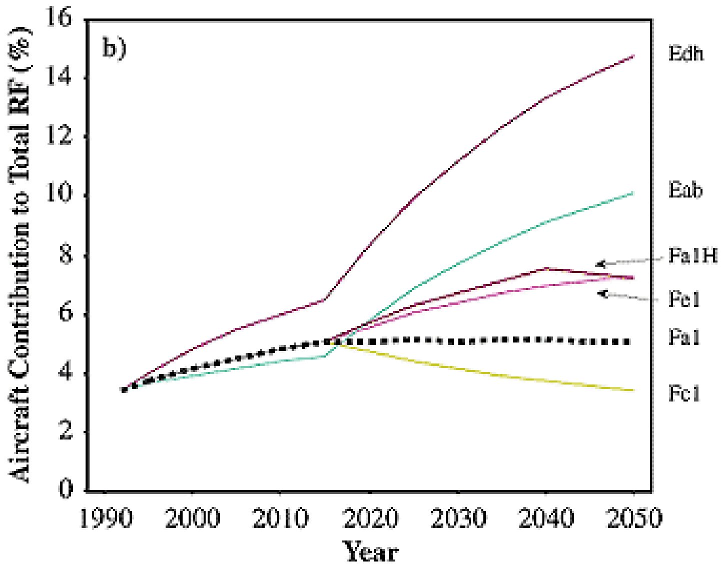
1. Physical and dynamical effects of tropopause

   e,g., water vapor barrier, temperature gradient effects on transport

2. Transport and mixing of chemical species

How determine aviation effects on climate?





IPCC (1999):

"Detecting the aircraft-specific contribution to global climate change is not possible now and presents a serious challenge for the next century"

Extremely difficult to detect aviation effects (through observations or in a detailed climate model) -- the signal not big enough relative to natural variability.

Need metrics to inform mitigation and policy decisions

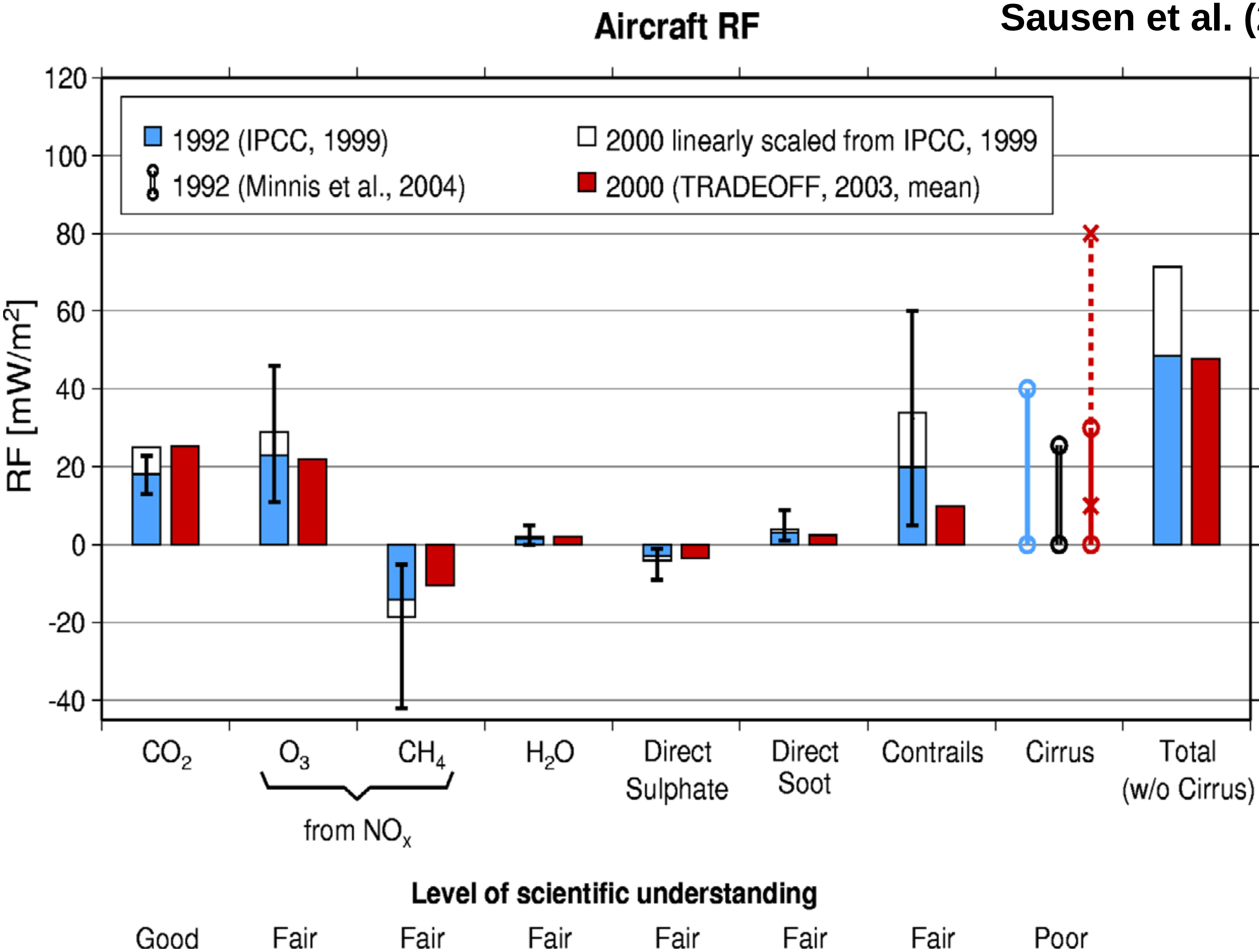
The Traditional Metric of Climate Change: Radiative Forcing

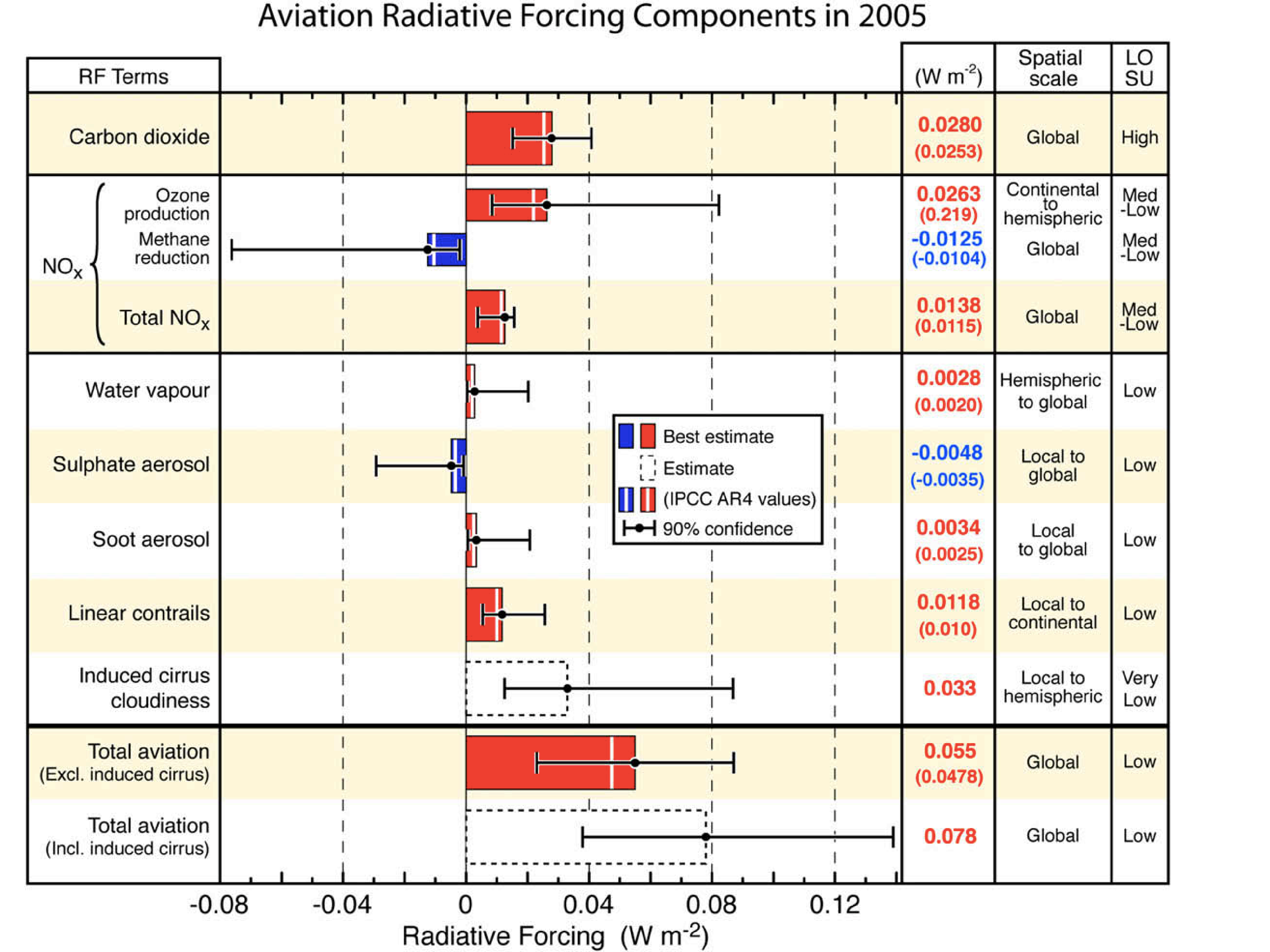
$$\Delta T_{surface} = \lambda \, RF_{trop}$$

- RF is usually defined as the net change in irradiance at the tropopause after allowing for stratospheric radiative equilibrium.
- RF assumes there is a linear relationship between the forcing on climate and the resulting temperature change.

Analyses of Radiative Forcing from Aviation

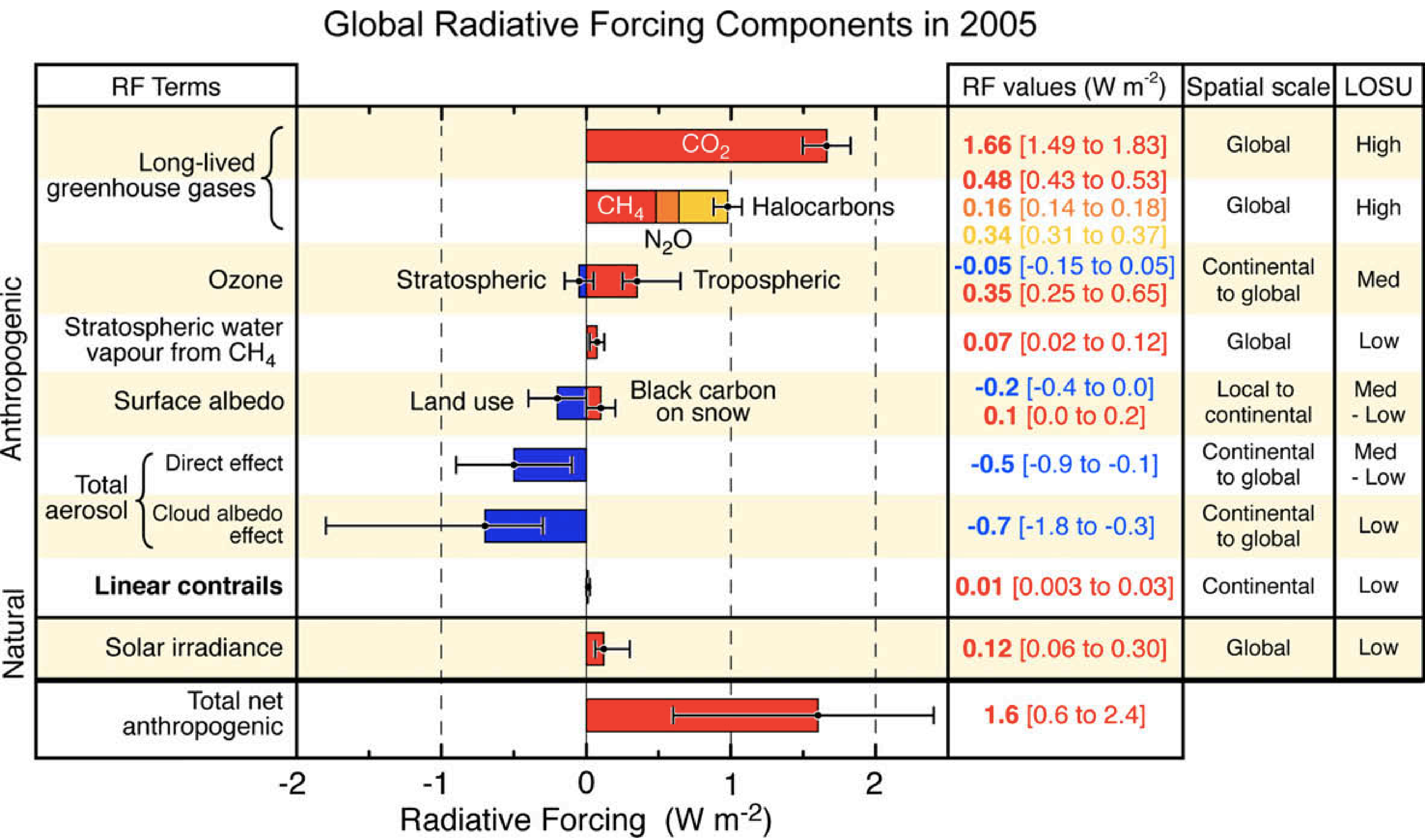
Sausen et al. (2005)





Aviation Radiative Forcing Components in 2005
RF Terms
(W m-2)
Spatial scale
LOSU
Carbon dioxide
0.0280
(0.0253)
Global
High
Ozone production
0.0263
(0.219)
Continental to hemispheric
Med -Low
Methane reduction
-0.0125
(-0.0104)
Global
Med -Low
NOx
Total NOx
0.0138
(0.0115)
Global
Med -Low
Water vapour
0.0028
(0.0020)
Hemispheric to global
Low
Sulphate aerosol
-0.0048
(-0.0035)
Local to global
Low
Soot aerosol
0.0034
(0.0025)
Local to global
Low
Linear contrails
0.0118
(0.010)
Local to continental
Low
Induced cirrus cloudiness
0.033
Local to hemispheric
Very Low
Total aviation (Excl. induced cirrus)
0.055
(0.0478)
Global
Low
Total aviation (Incl. induced cirrus)
0.078
Global
Low
Best estimate
Estimate
(IPCC AR4 values)
90% confidence
-0.08
-0.04
0
0.04
0.08
0.12
Radiative Forcing (W m-2)

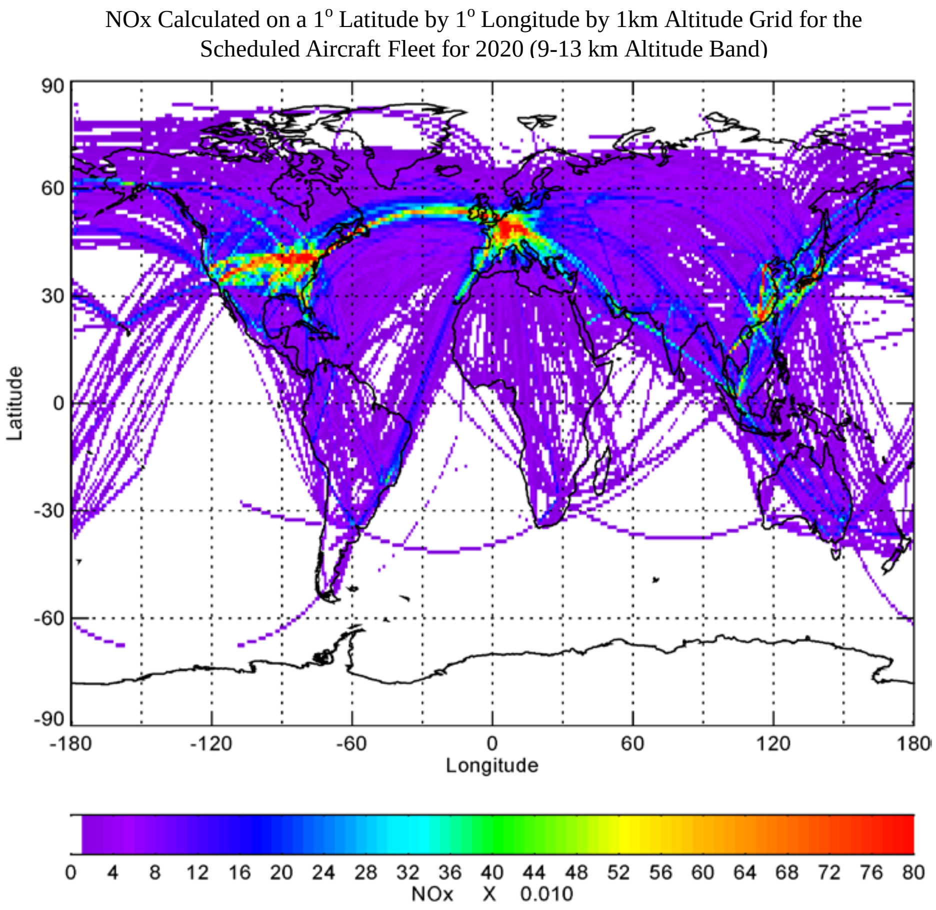
Radiative forcing on climate since 1750



Accurate Emissions Scenarios Necessary to Assessing Impacts

Aviation emissions depend on:

- **Aircraft design and engine characteristics**
  - Engine emissions over flight path
- **Operational assumption**
  - Load factor, amount used (utilization, transit time, turn-around time)
- **Number of operational aircraft and their usage characteristics**
- **Flight characteristics (City pairs criteria, route diversions, supersonic over land?)**

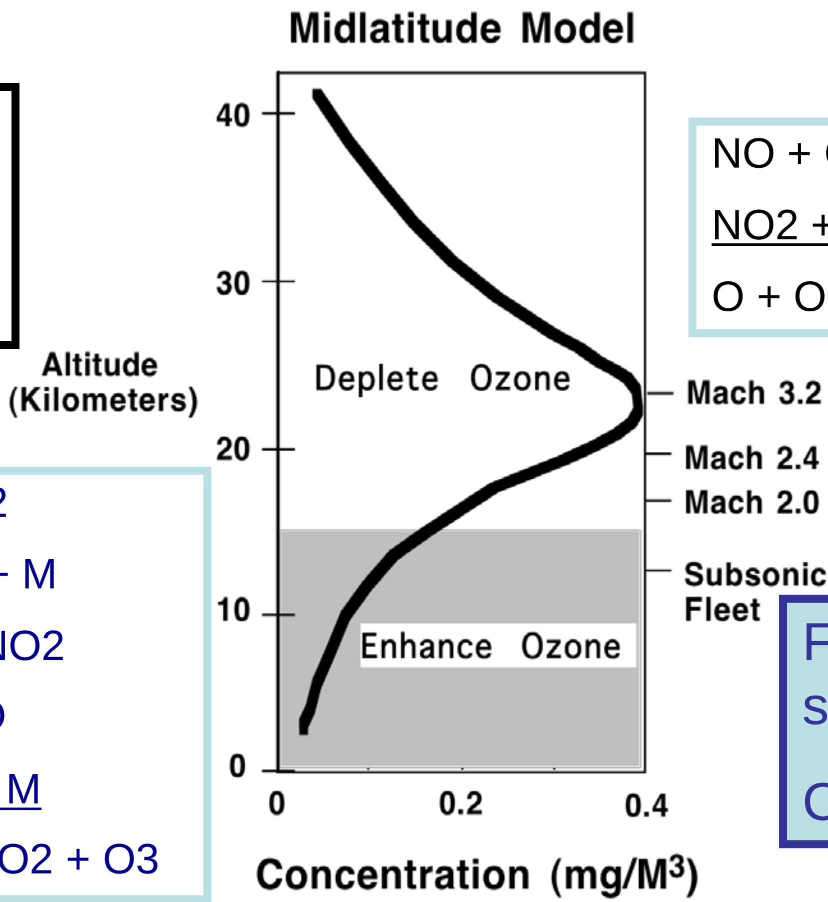


From S. Baughcum

Effect of Aviation on Ozone (and Methane) Depends on Where Emissions Occur

3-D Models have greatly improved physics and chemistry since IPCC (1999)

NOx emissions and stratospheric H_2O emissions are important to O_3



NO + O3 --> NO2 + O2

NO2 + O --> NO + O2

O + O3 --> O2 + O2

OH + CO --> H + CO2

H + O2 + M --> HO2 + M

HO2 + NO --> OH + NO2

NO2 + hν --> O + NO

O + O2 + M --> O3 + M

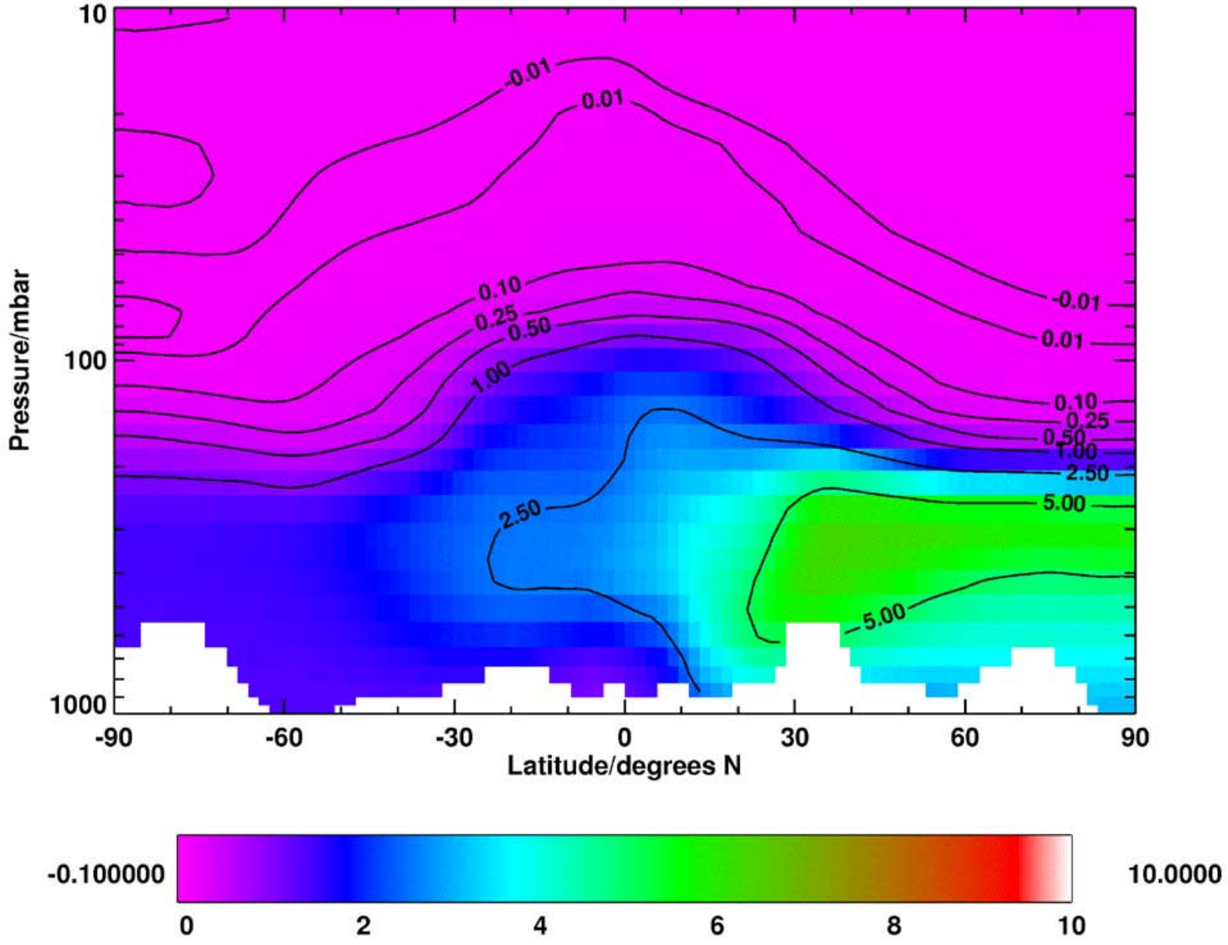
CO + 2O2 + hν --> CO2 + O3

Focus is on subsonic aircraft

Cruise: 8-13 km

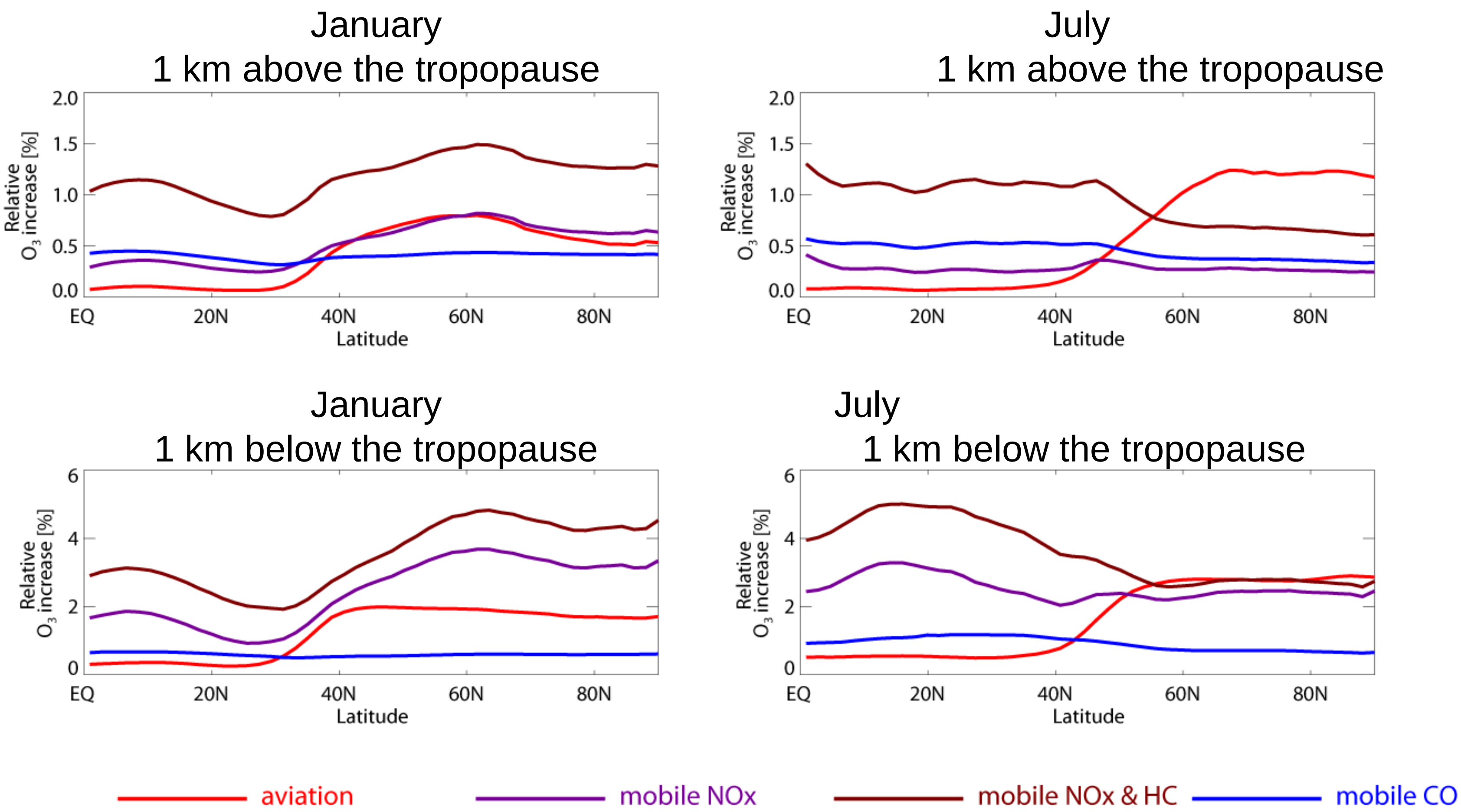
Effect of Aviation Emissions on Ozone (% change) – 2020

Annual/Zonal Mean

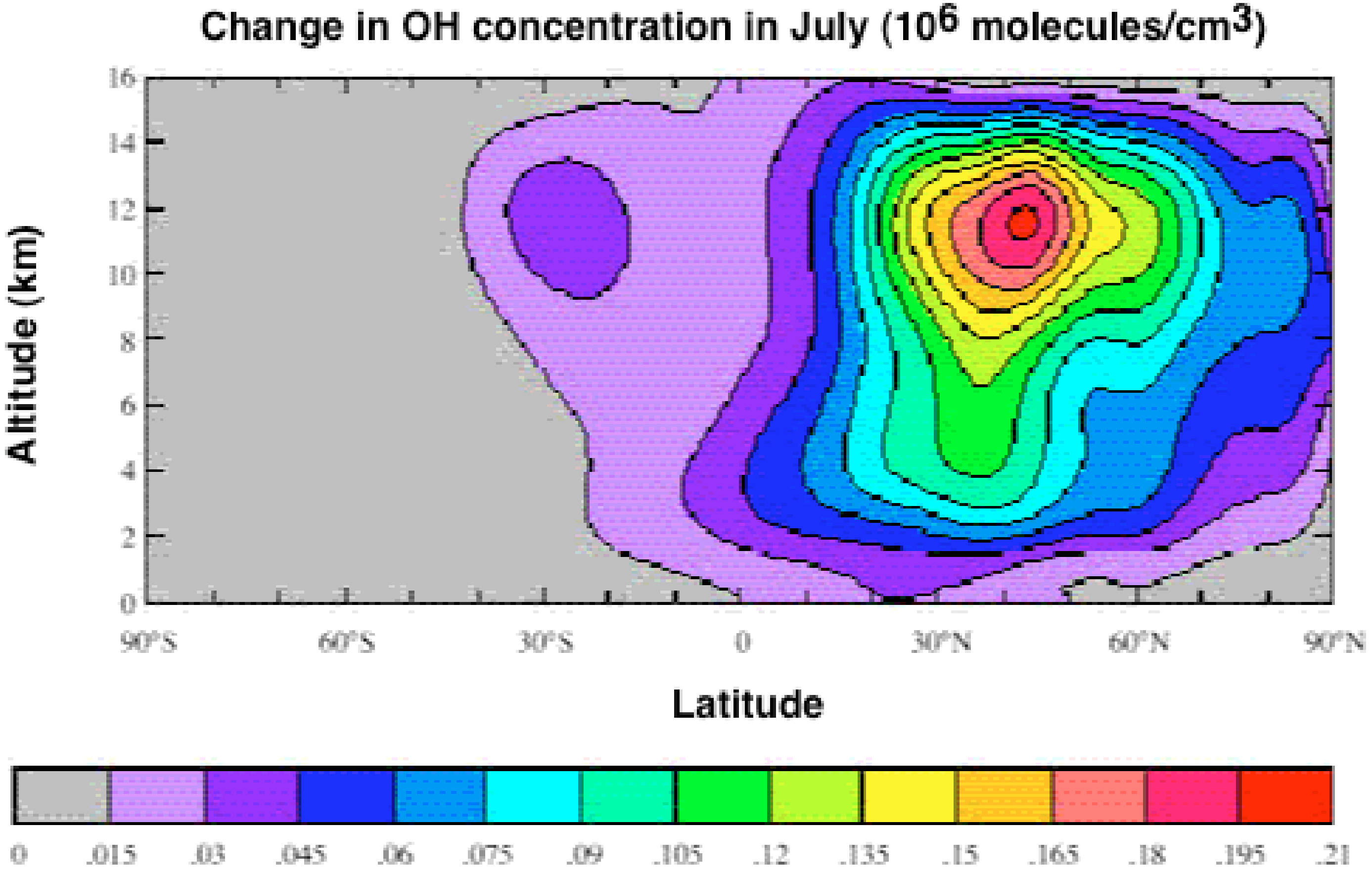


UIUC result; Includes new HO_2 + NO reaction channel

Effects on O_3 in the upper troposphere and lower stratosphere



Changes in O_3 concentration cause increase in OH which decreases methane



IPCC (1999)

Key Findings and Research Needs

- Emissions in the UT/LS region and resulting chemistry effects
  - Models have improved representation of chemical and physical processes since IPCC (1999)
  - Need models and measurements intercomparison to evaluate uncertainties;
  - Need new measurements and data analyses to improve understanding of troposphere and UT/LS processes
  - Need new evaluations of emissions
    - Better account for real flight characteristics
  - Re-examine the impacts of aviation using improved models

Under right conditions, emissions of water vapor from aircraft can create contrails

Contrails and Induced Cirrus Clouds

- **Basic physics of contrail formation reasonably well understood, but important parameters (e.g., temperature, humidity in UT, optical properties) remain uncertain.**

- **There remain significant issues with the scale of climate models versus the size of the plume**

- **Aviation-induced persistent contrails and aerosols may affect cirrus, but this is poorly understood.**

Persistent Linear Contrails

Linear contrail formation depends on:
- engine and aircraft parameters
- high relative humidity in exhaust plume and surrounding atmosphere

} *Well understood*

Linear contrail geographic coverage depends on:
- contrail formation conditions
- air traffic and traffic patterns
- relative humidity distribution in atmosphere

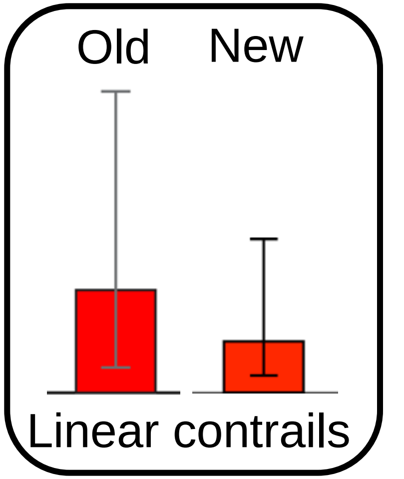
} *NOT well understood*

Linear contrail climate impact (radiative forcing):
- contrail cover
- contrail optical properties

} *NOT understood*

Linear contrail radiative forcing estimates:
- 1992 subsonic fleet 0.02 W/m^2 (0.005 - 0.06) (*IPCC*)
- 2005 subsonic fleet 0.01 W/m^2 (0.003 - 0.03 W/m^2)**

** Downward adjustment due to refined estimates of contrail cover and cloud optical properties



Aviation-Induced Cirrus

Induced cirrus formation and cover depends on:

- linear contrail formation } *Well understood*
- wind shear conditions
- high relative humidity in the atmosphere } *NOT well understood*

Induced cirrus climate impact (radiative forcing) depends on:

- additional cirrus cover
- cirrus optical properties } *NOT well understood*

Caveat: Some fraction of induced cirrus indistinguishable from background cirrus clouds

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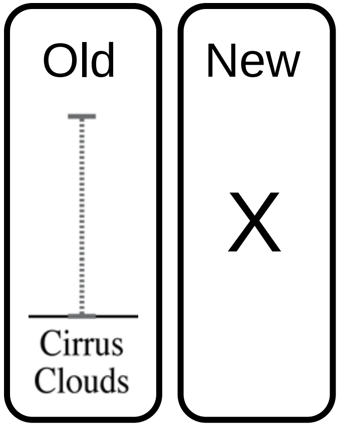
Old estimate (IPCC, 1999):
- for 1992 subsonic fleet: 0 to 0.04 W/m^2
- no best estimate of contrail cirrus

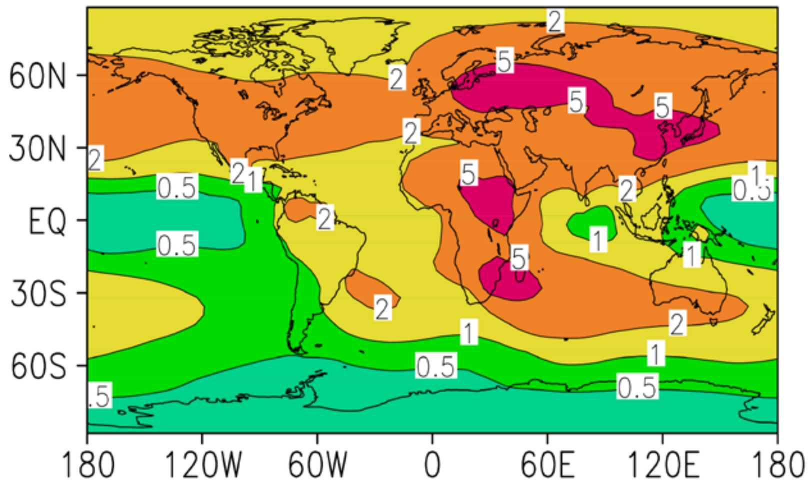
New estimates:
- no best estimate of contrail cirrus



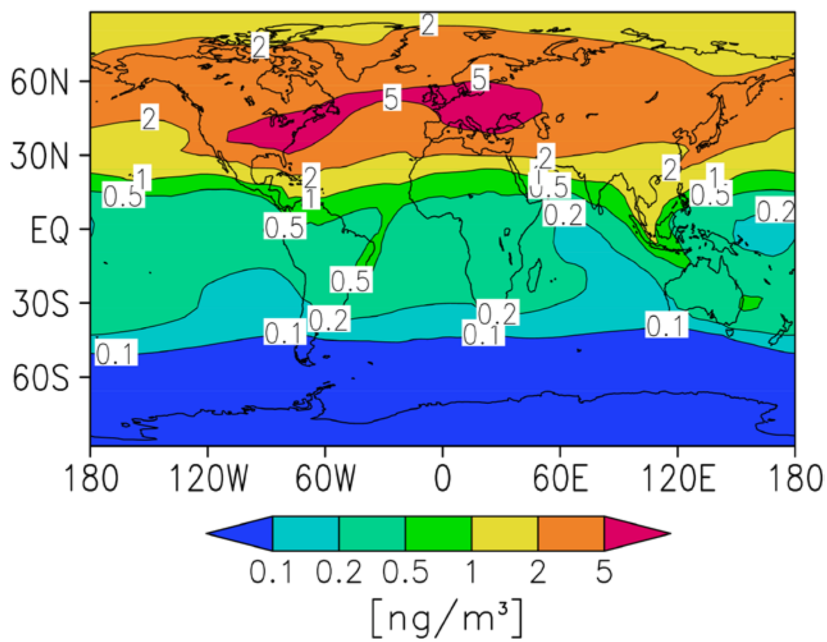
- ratio of contrail cirrus to linear contrail cover in 2005: 1.8 - 10
- total aviation cloudiness in 2005: 0.030 W/m^2 (0.01 - 0.08 W/m^2)

Aviation sulfate and black carbon (soot) aerosols

Black carbon mass from all sources



100 x Black carbon mass from aviation



Accumulation of aviation aerosol mass calculated with atmospheric models, emission indices, and traffic scenarios

Aviation source is small in mass units in comparison to other natural and human sources: small direct climate forcings

Aviation source of black carbon is large in the increase of the number of particles:
Potential cloud effects are important, but currently unknown

Key Research Needs

- Contrails and induced cirrus clouds -- Research
  - Regional studies of supersaturation and contrails using measurements and weather forecast models;
  - *Need In situ* probing and remote sensing of aging contrail-cirrus and aircraft plumes;
  - Global model studies addressing direct and indirect effects of contrails and effects on cirrus;
  - Enhanced analysis of existing or upcoming information from space-borne sensors;
  - Process studies of plume and contrail development;
  - Laboratory measurements of ice nucleation

Aviation and Climate Metrics

- **Radiative forcing has traditionally been the metric for climate analyses**
- **Radiative forcing (RF) not adequate -- at minimum needs to include efficacy for various climate effects**
- **A refined RF may be still be useful, but also need emissions based metrics**
  - **Emissions based metric are used in assessing other energy / transportation/ industry sources of concern to climate.**
- **There likely is no single perfect metric -- the specific metric needed likely depends on the questions being asked.**

Emissions Based Metrics

- Global Warming Potentials (GWPs)
  - IPCC
  - Metric often used in existing climate policy
- Global Temperature Potentials (GTPs)
  - Shine et al., 2005
  - Assumes pulse or sustained emissions
- Simple Models
  - Linearized Temperature Response (LTR)
    - Marais et al. (2007); Grewe and Stenke (2007)
  - Other simplified climate models

The problem is that none of them has been adequately tested for aviation studies.

Consideration of Environmental and Other Trade-offs

Continuous Descent Approach
- Reduced **Noise** impact
- *Reduced* **Fuel Burn/CO_2**

Reduce cruise altitude
- *Increased fuel burn,* **CO_2**
- *Increased* **NO_x**
- *Less increase* **O_3**
- *Reduced* **contrails**

Operations changes
- *Reduce* **contrails**
- *More* **fuel burn, CO_2**

Nacelle Modifications
- Reduced **Noise**
- *Increased* **Fuel Burn/CO_2**

Improved aerodynamic efficiency and reduced weight
- Reduced **CO_2**
- Reduced **Noise**
- *Reduced* **NO_x**

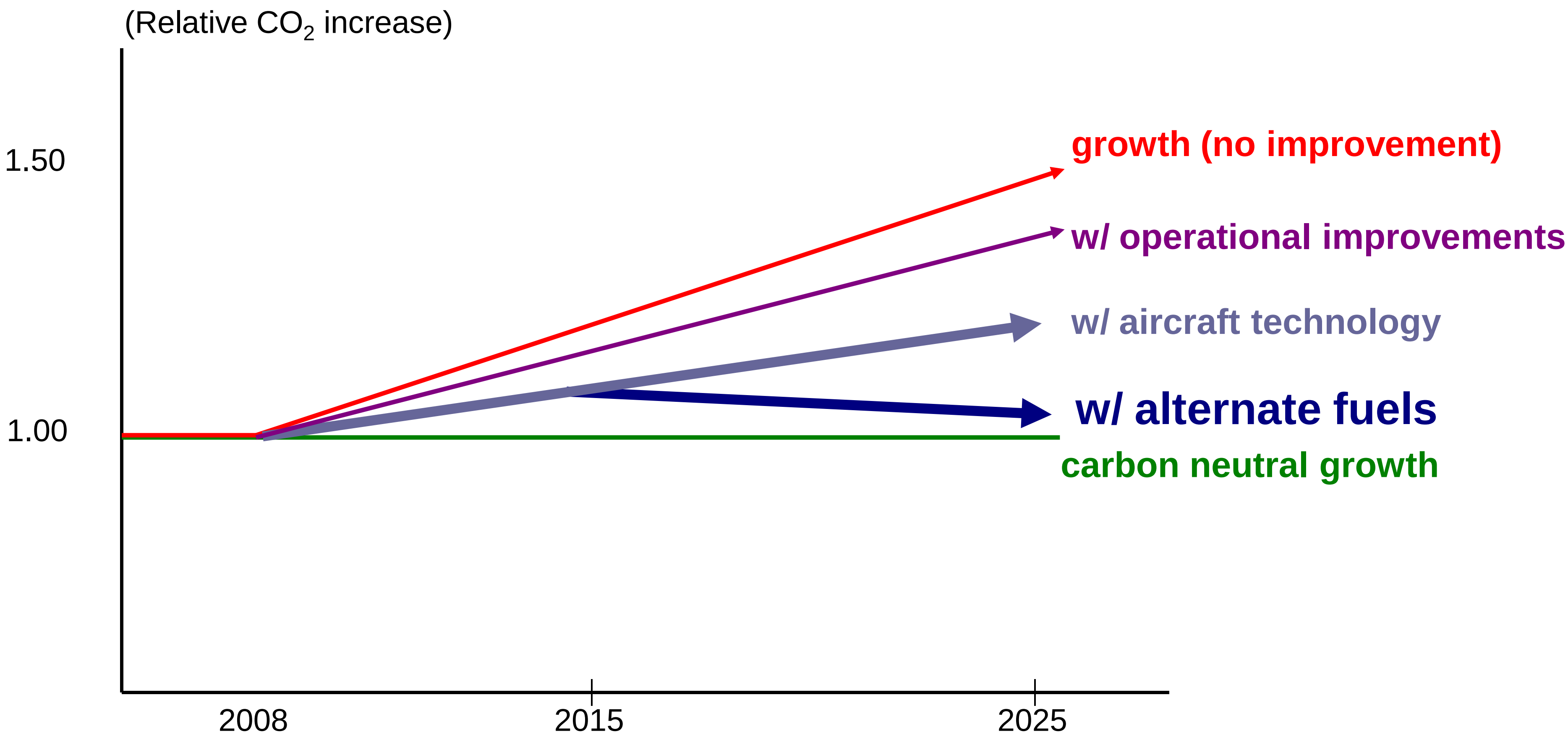
Reduced polar flights
- *Less effects on stratosphere*
- *More* **fuel burn, CO_2**

Increased Engine Pressure Ratio & Temperatures
- *Reduced* **Fuel Burn / CO_2**
- Reduced **HC** and **CO**
- *Increased* **NO_x**

Steep climb
- Reduce **noise** impact
- *More* **fuel burn, CO_2**

Increased engine bypass ratio
- *Reduced* **Fuel Burn / CO_2**
- Reduced **Noise**
- *Increased* **NO_x**

FAA: Contributions to Reducing Environmental Footprint



Alternative Jet Fuels

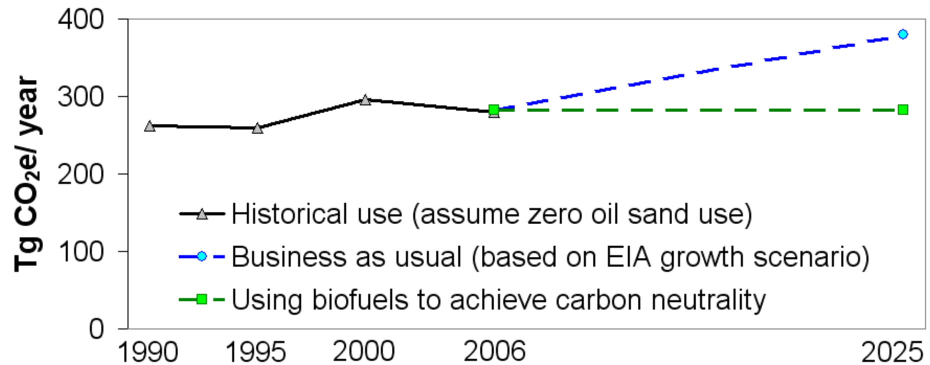
- **FAA looking at alternative fuels**
  - Reduce emissions that impact global climate change and air quality thus improving the environment
  - Expand and diversify energy supplies beyond conventional petroleum to reduce price volatility.
  - Be produced in large quantities without adverse impacts on our land and water resources.
  - Fuel needs to be compatible with existing infrastructure.

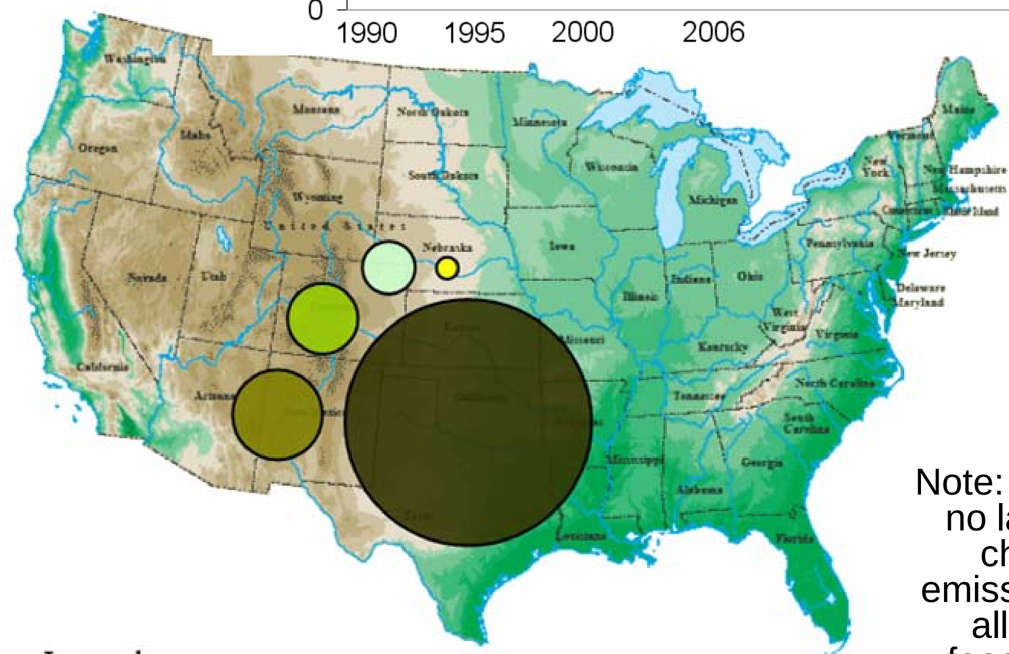
Alternatives to Existing Jet Fuel

- **Ultra Low Sulfur (ULS) jet fuel**
  - Created from conventional petroleum
  - Processed to under 15 ppm sulfur content
  - Reduced impact on air quality, increased GHG impact
- **Synthetic Paraffinic Kerosene (SPK) jet fuel**
  - Functionally similar to Jet A except contains little to zero aromatic compounds and no sulfur
  - Can be created from varied feedstocks (e.g., biomass, renewable waste oils, vegetable oil, coal, natural gas)

Enabling Carbon Neutral U.S. Aviation Growth

- **Assessed potential for carbon neutral growth from 2006 to 2025.**
- **Analysis used biofuel life-cycle GHG emissions and yield per hectare.**
- **Circles show land area requirements for three existing and two hypothetical feedstocks.**
- **Soybean and palm requirements both exceed current production levels.**
- **Analysis looked at single feedstock solutions – practical approach is to consider multiple feedstock solutions.**
- *Need feedstocks with high yield and low life-cycle emissions that do not require arable land.*





Legend:
- Soy oil (oil yield~550L/ha)
- Herbaceous biomass (using F-T process with ~11,000 kg biomass/ha)
- Palm oil (oil yield ~5600 L/ha)
- Feedstock B (oil yield~10,000L/ha)
- Feedstock D (oil yield~50,000L/ha)

Note: Assumed no land use change emissions with all of the feedstocks.

Results from H.M. Wong S.M. Thesis (2008)


Thank You