

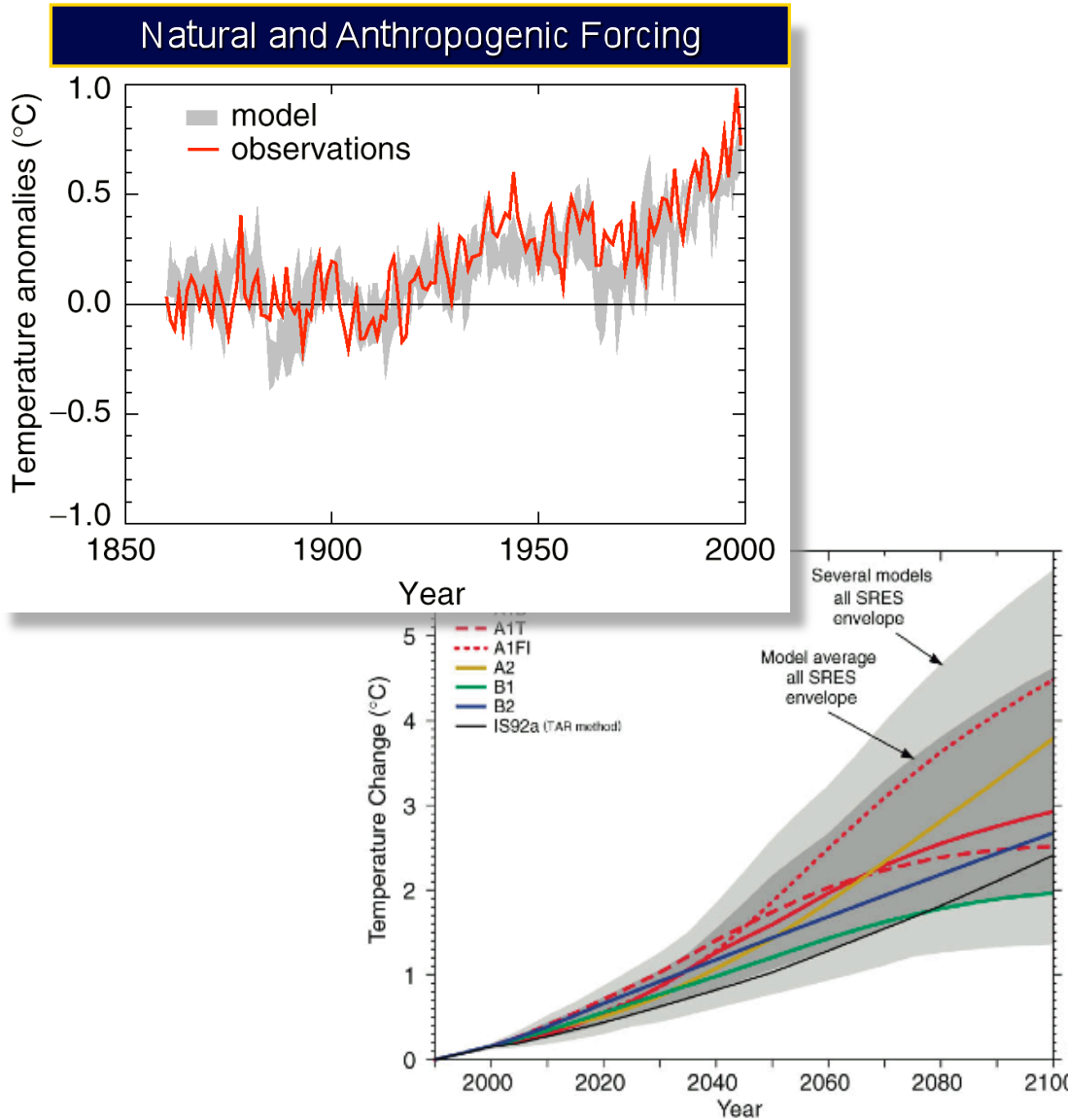
The Impacts of Aviation on Climate: Issues and Uncertainties

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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*
- *Global climate will continue to warm significantly unless we take major actions*

Aviation and Climate

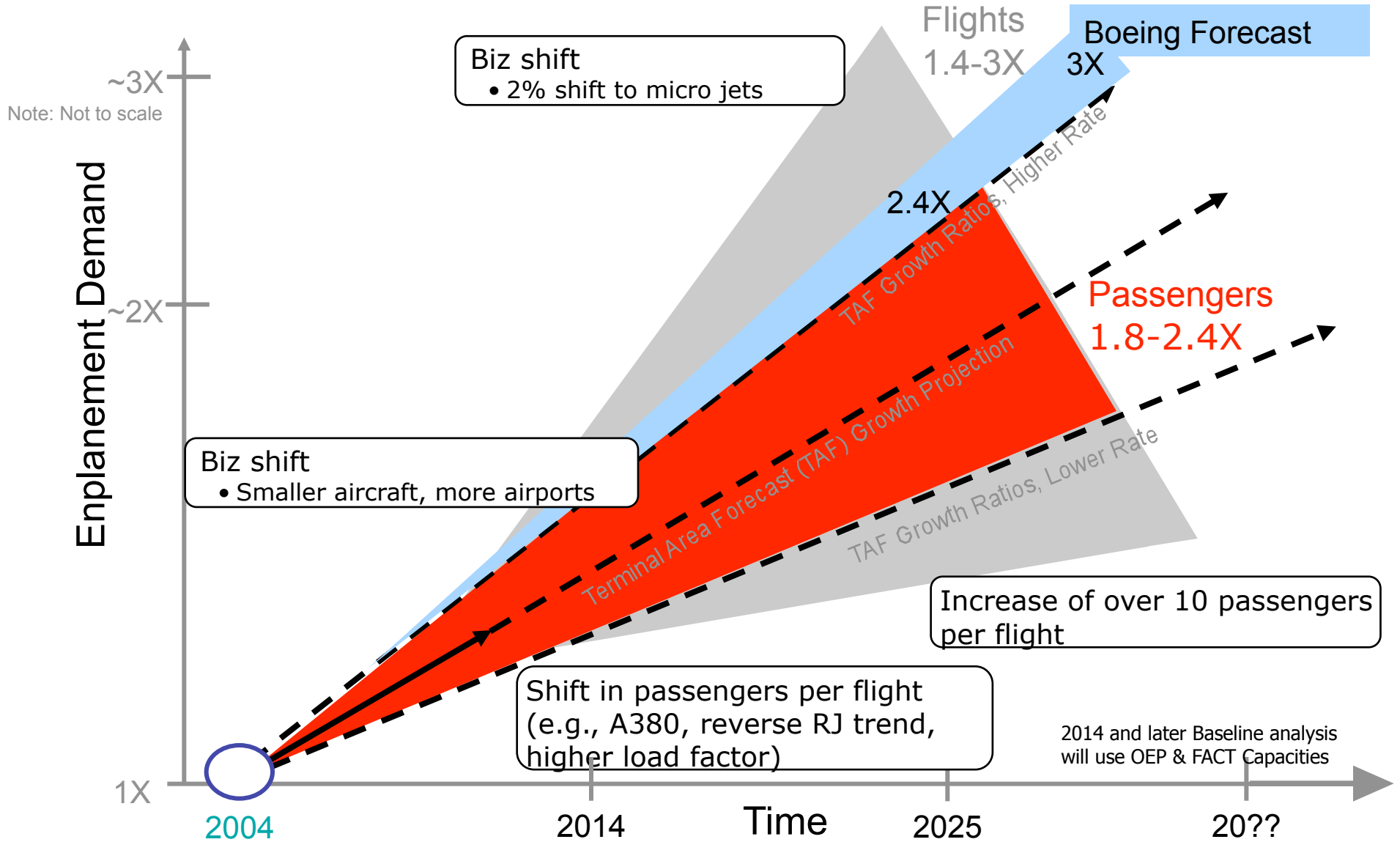


Climate change impact is potentially the most serious long-term issue facing the aviation industry

- Aviation plays a key role in the world economy
 - Aviation supports 8% of global economic activity and carries 40% of the value of freight
 - U.S. has 4% of world's population and 40% of aviation activity
 - Aviation activity outpaces economic growth



Future U.S. Aviation Services Demand



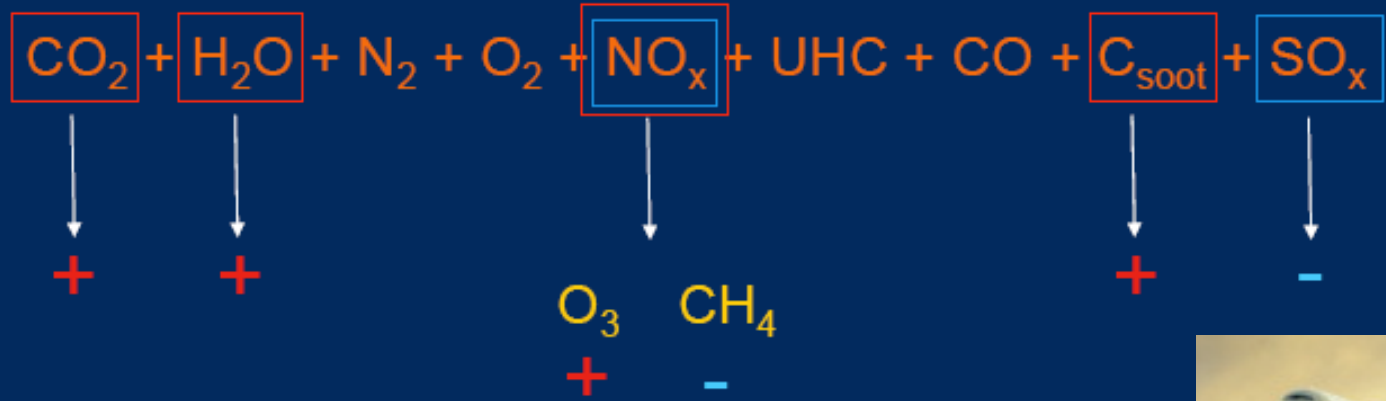
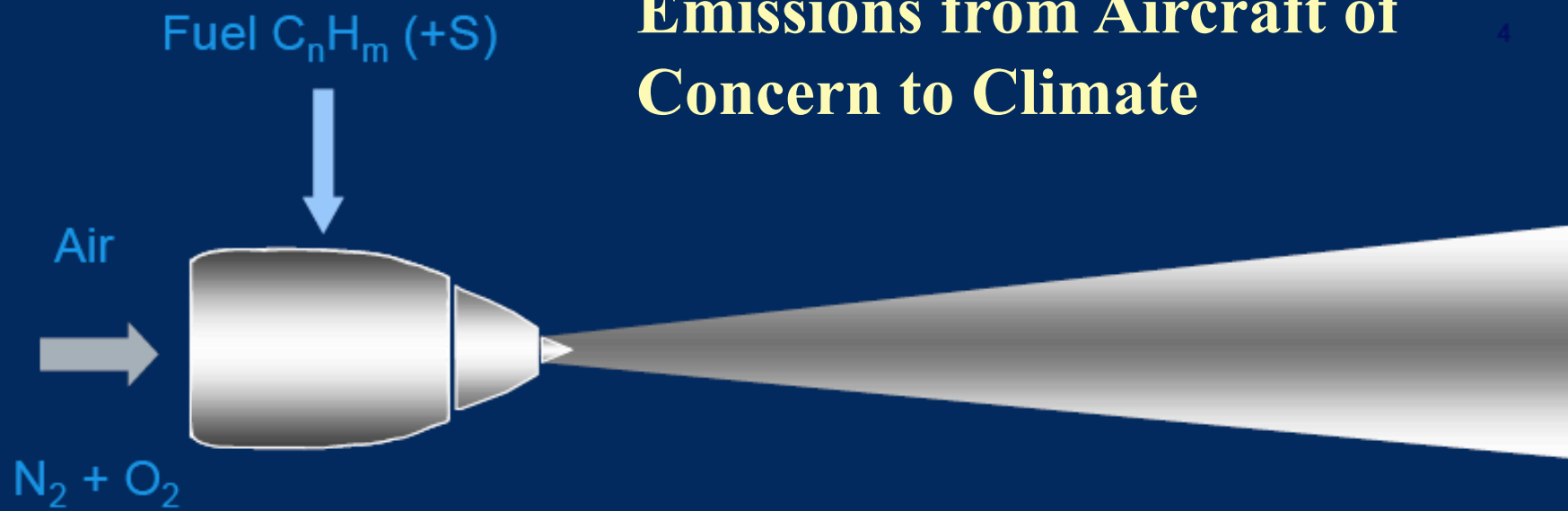
Aviation and Climate



- Aviation ~2% of global emissions of human-related carbon dioxide (CO₂)
- Aviation total climate effect could be more than double the CO₂ 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

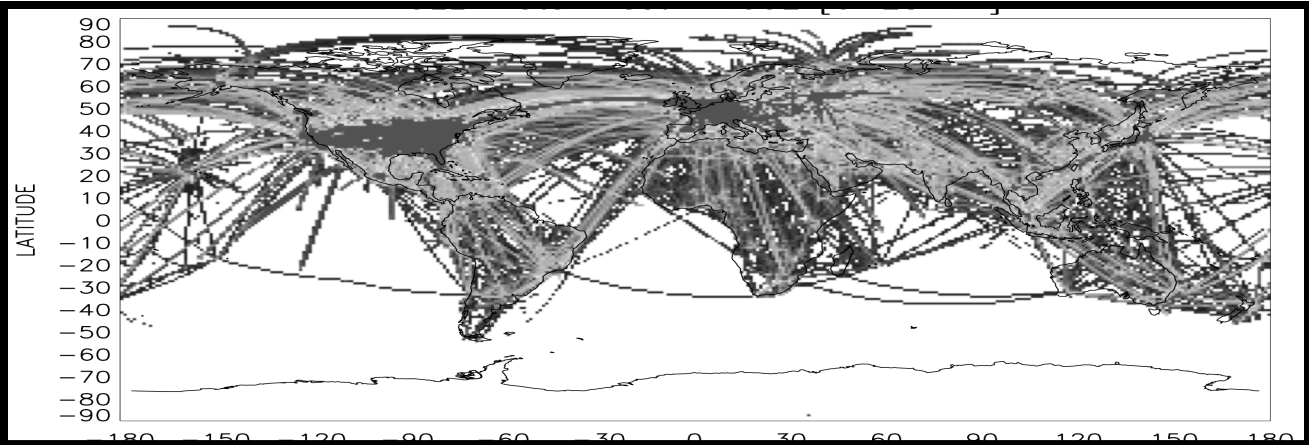
Emissions from Aircraft of Concern to Climate

4



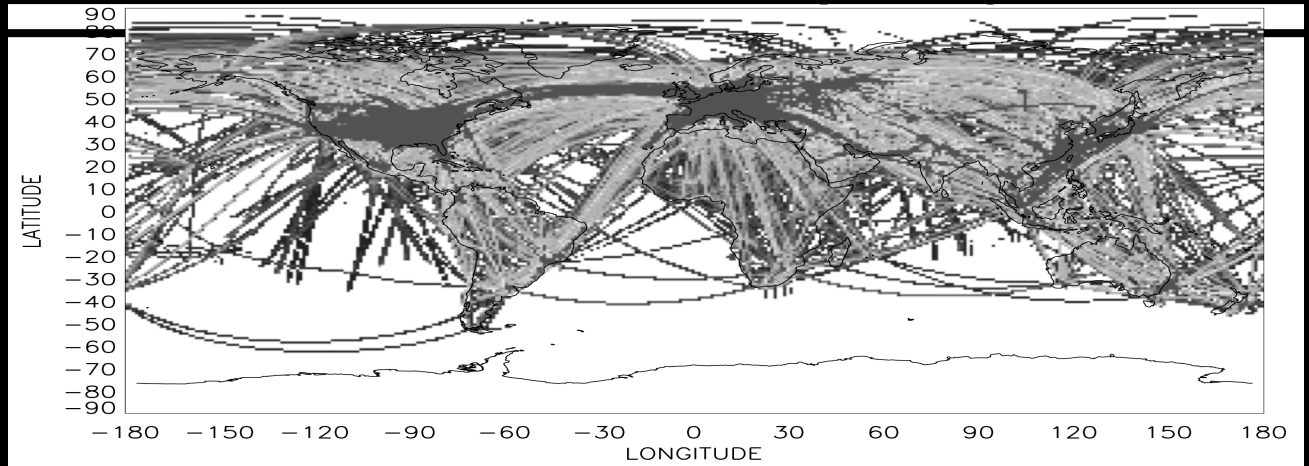
CAEP Focus Has Been on Emission Inventories

1992

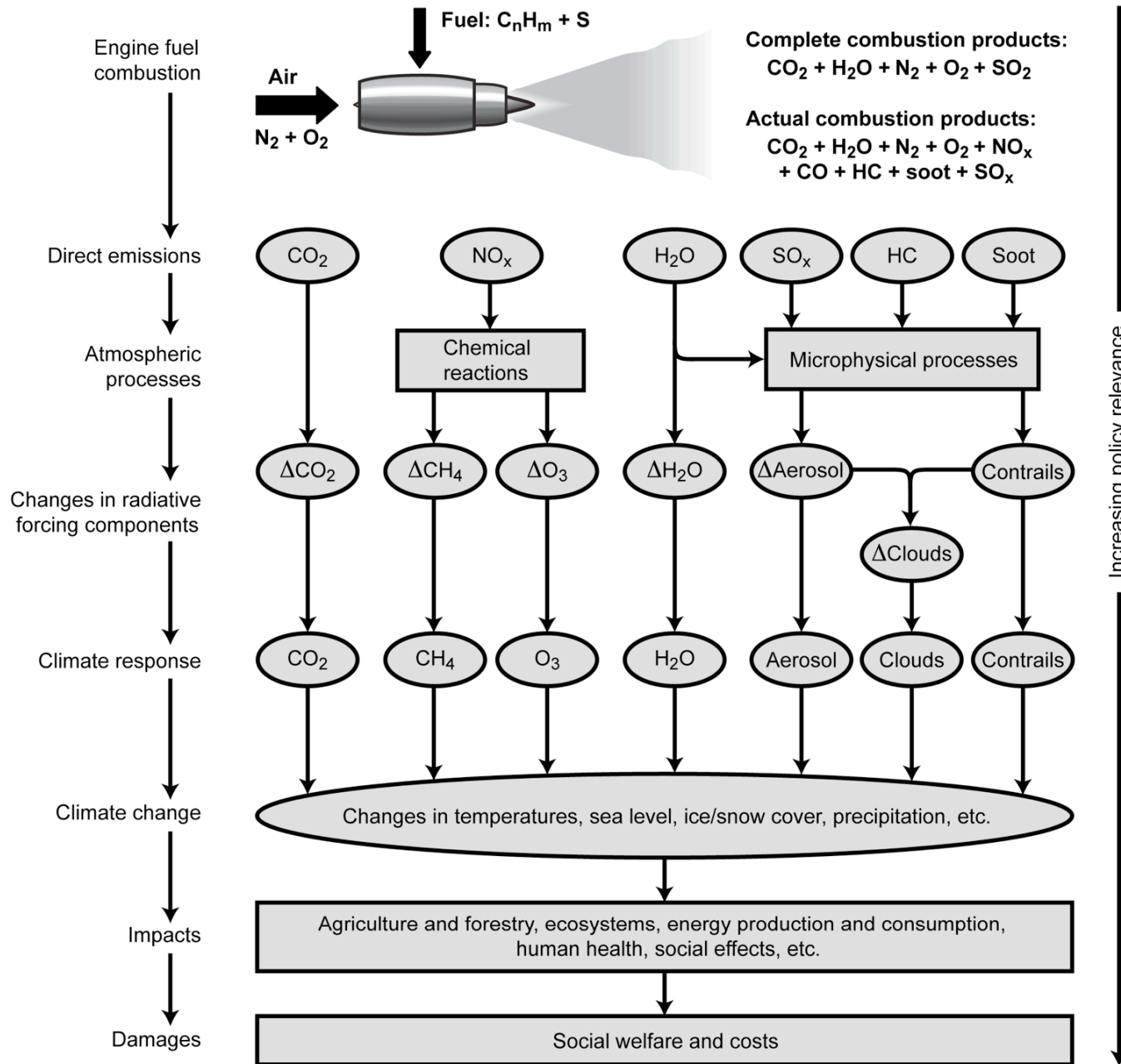


Fuel
Burn

2015

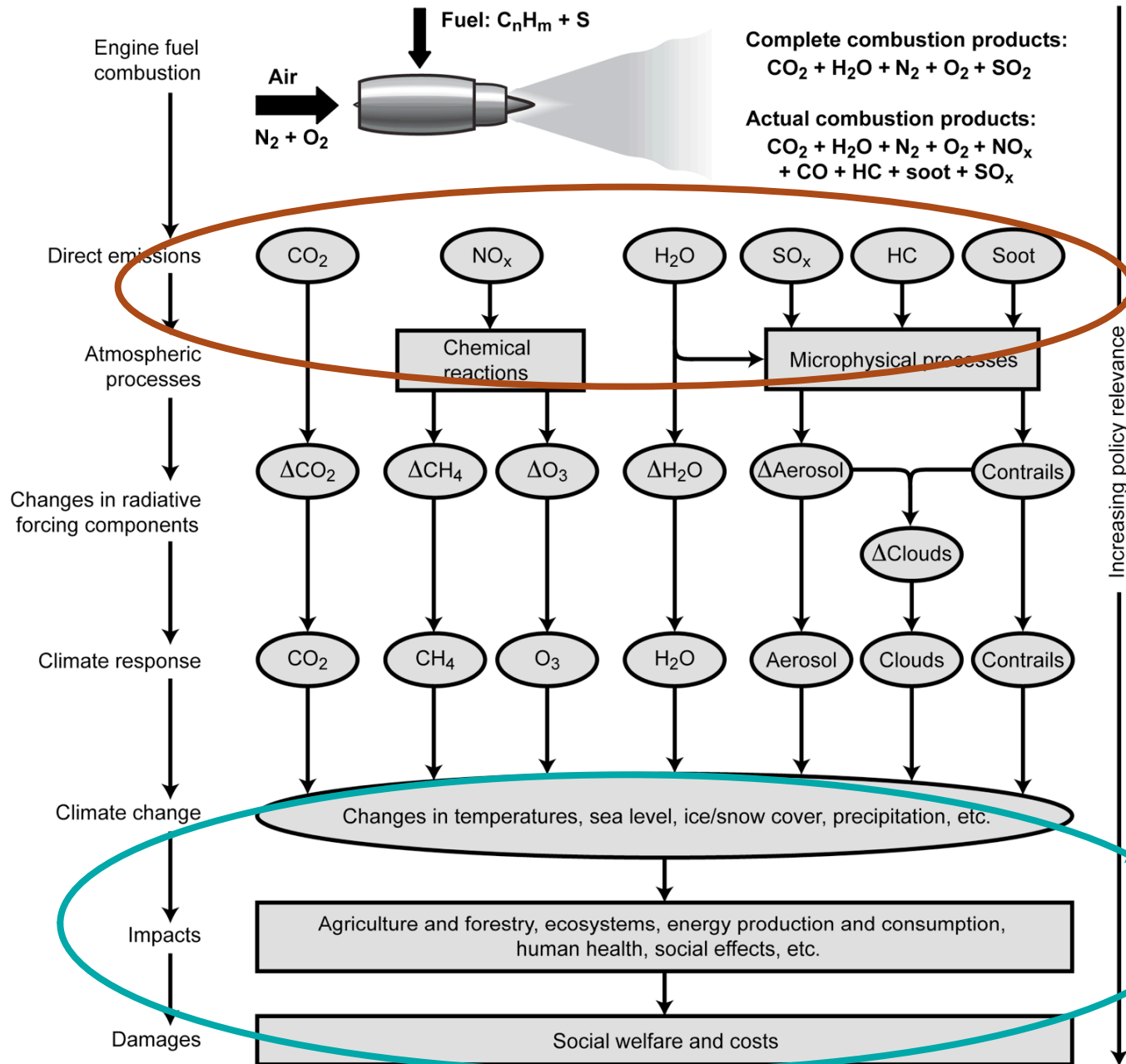


Aircraft emissions and climate change



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

Aircraft emissions and climate change



How do we go from This ...

... to This.

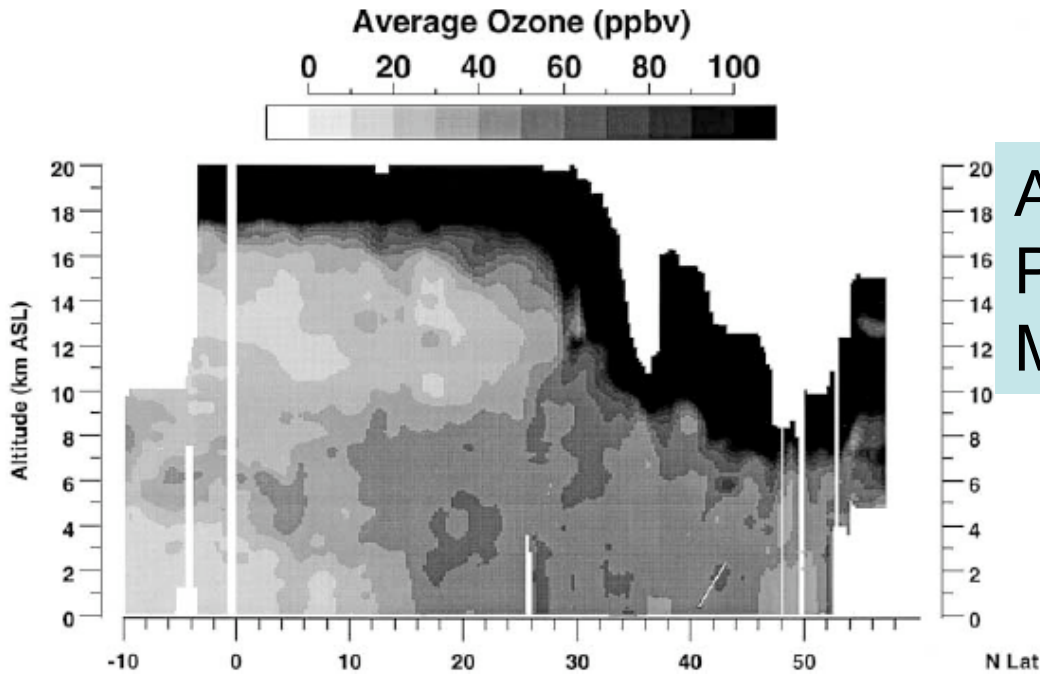
The Challenge: understand and address the effects on climate resulting from aircraft engine emissions

Most emissions occur at cruise altitudes in the UT/LS

- **Direct effects of carbon dioxide (CO₂) emissions**
- **Indirect effects from changes in ozone and methane from NO_x emissions**
 - At these altitudes, NO_x emissions produce O₃
 - Increase in ozone results in increased tropospheric OH and reduced CH₄
- **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**
 - CO₂ effects are for many decades ($\tau \sim 100$ yrs)
 - Other emission effects much shorter
 - O₃ : 1-2 years or less
 - CH₄: ~10-12 years (but only get full effect if NO_x 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 CO₂ effects**, large uncertainties remain

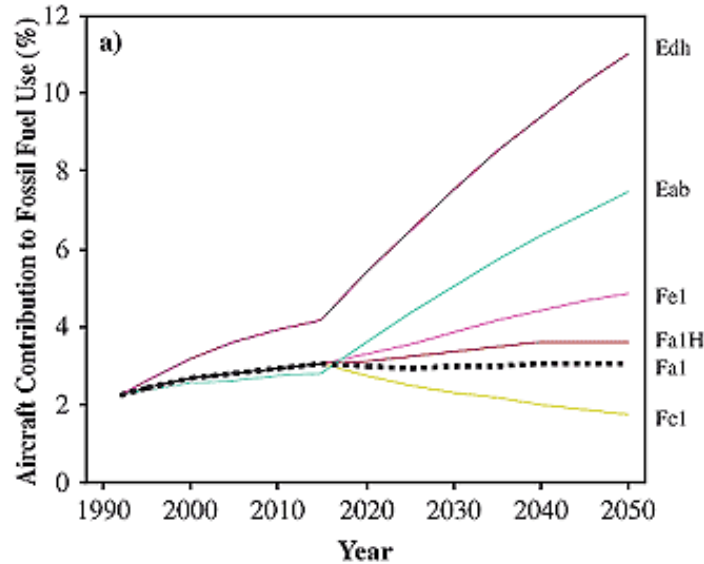


Airborne lidar during NASA PEM-Tropics, February–March 1994.

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

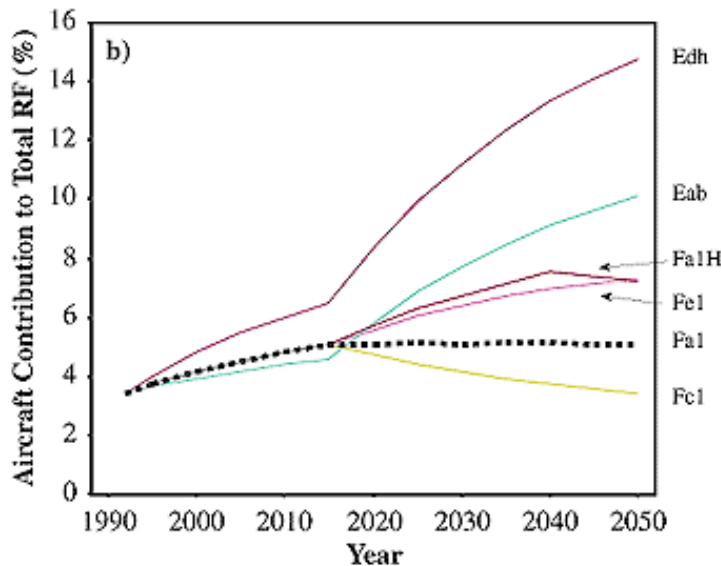
How determine aviation effects on climate?



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

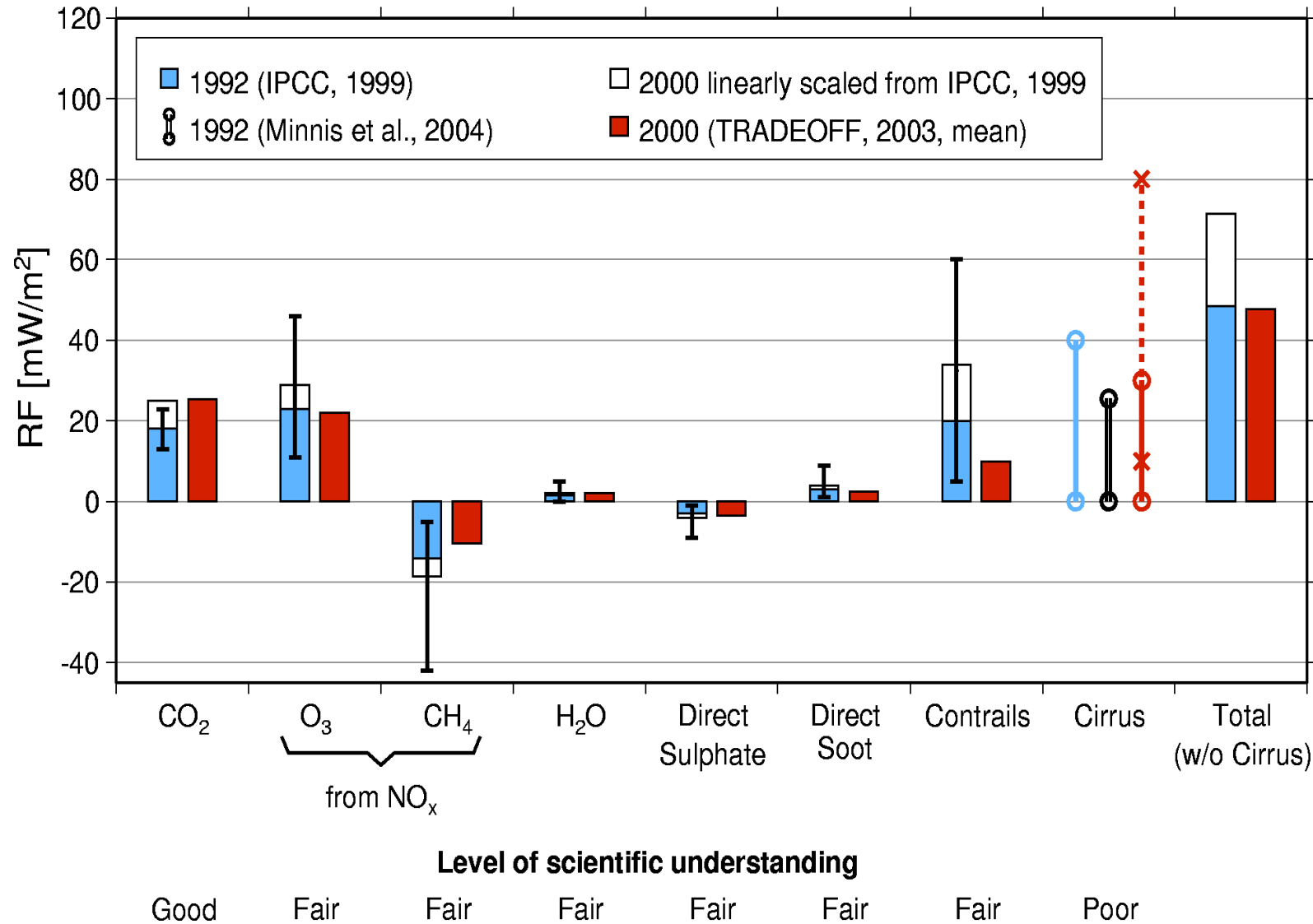
$$\Delta T_{surface} = \lambda RF_{trop}$$

- 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

Aircraft RF

From Sausen et al. (2005)

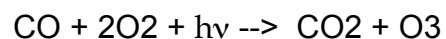
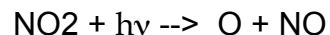
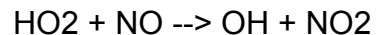
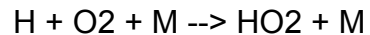
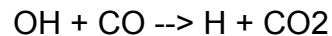
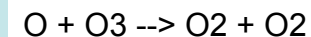
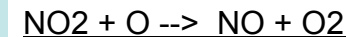
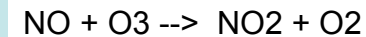
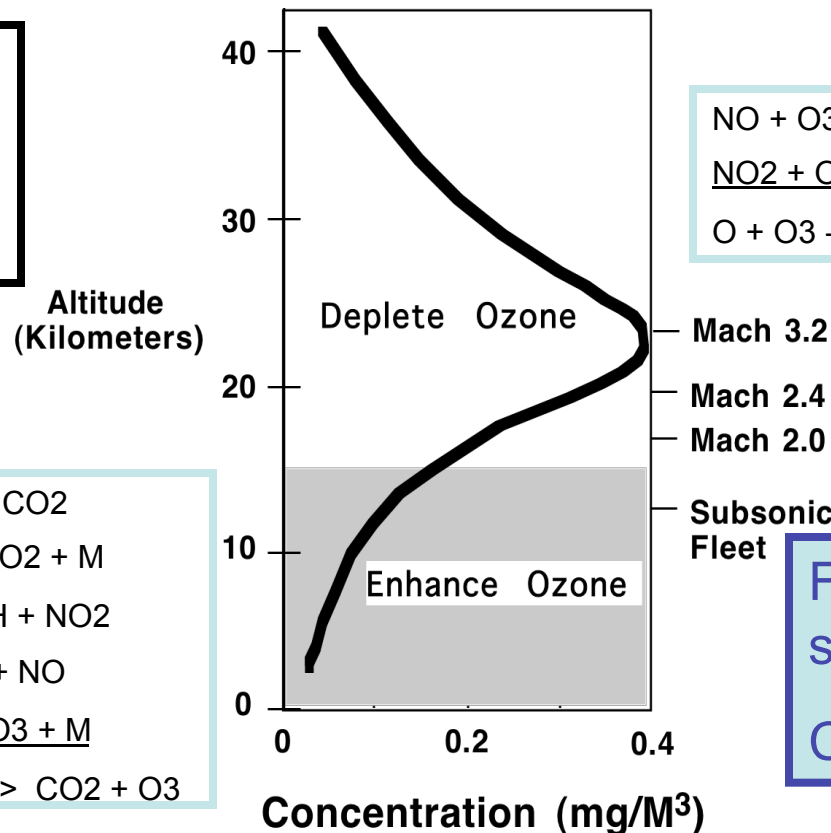


Effect of Aviation on Ozone (and Methane) Depends on Where Emissions Occur

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

NO_x emissions and stratospheric H₂O emissions are important to O₃

Midlatitude Model



Focus is on subsonic aircraft

Cruise: 8-13 km

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

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):

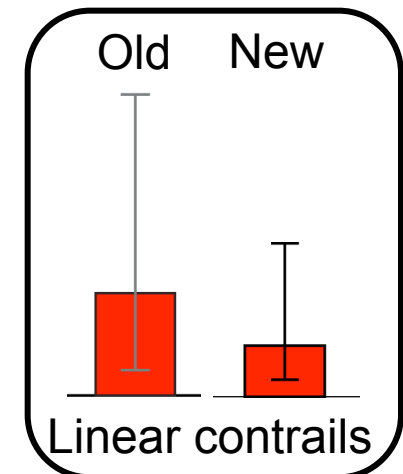
- contrail cover
- contrail optical properties

} *NOT understood*

Linear contrail radiative forcing estimates:

- 1992 subsonic fleet 0.02 W/m² (0.005 - 0.06) (IPCC)
- 2005 subsonic fleet **0.01 W/m² (0.003 - 0.03 W/m²)****

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

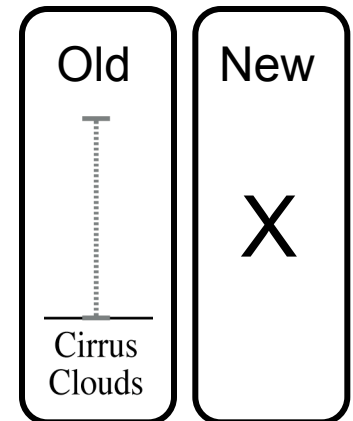
Caveat: Some fraction of induced cirrus indistinguishable from background cirrus clouds

Old estimate (IPCC, 1999):

- for 1992 subsonic fleet: **0 to 0.04 W/m²**
- **no best estimate** of contrail cirrus

New estimates:

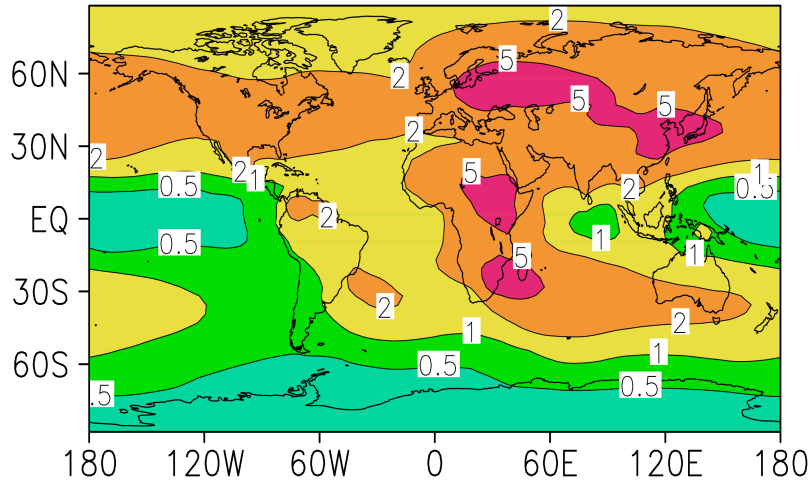
- **no best estimate** of contrail cirrus



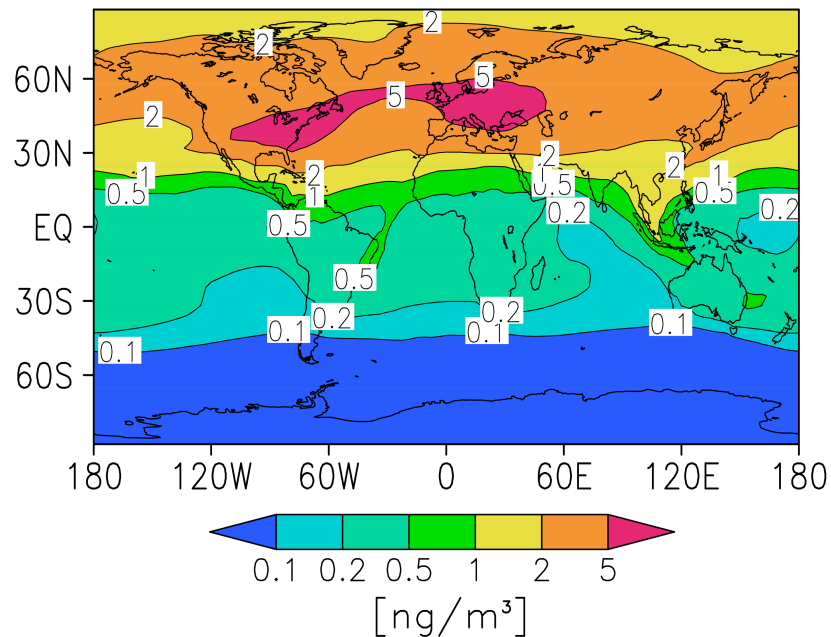
- ratio of contrail cirrus to linear contrail cover in 2005: **1.8 - 10**
- total aviation cloudiness in 2005: **0.030 W/m²** (0.01 - 0.08 W/m²)

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**

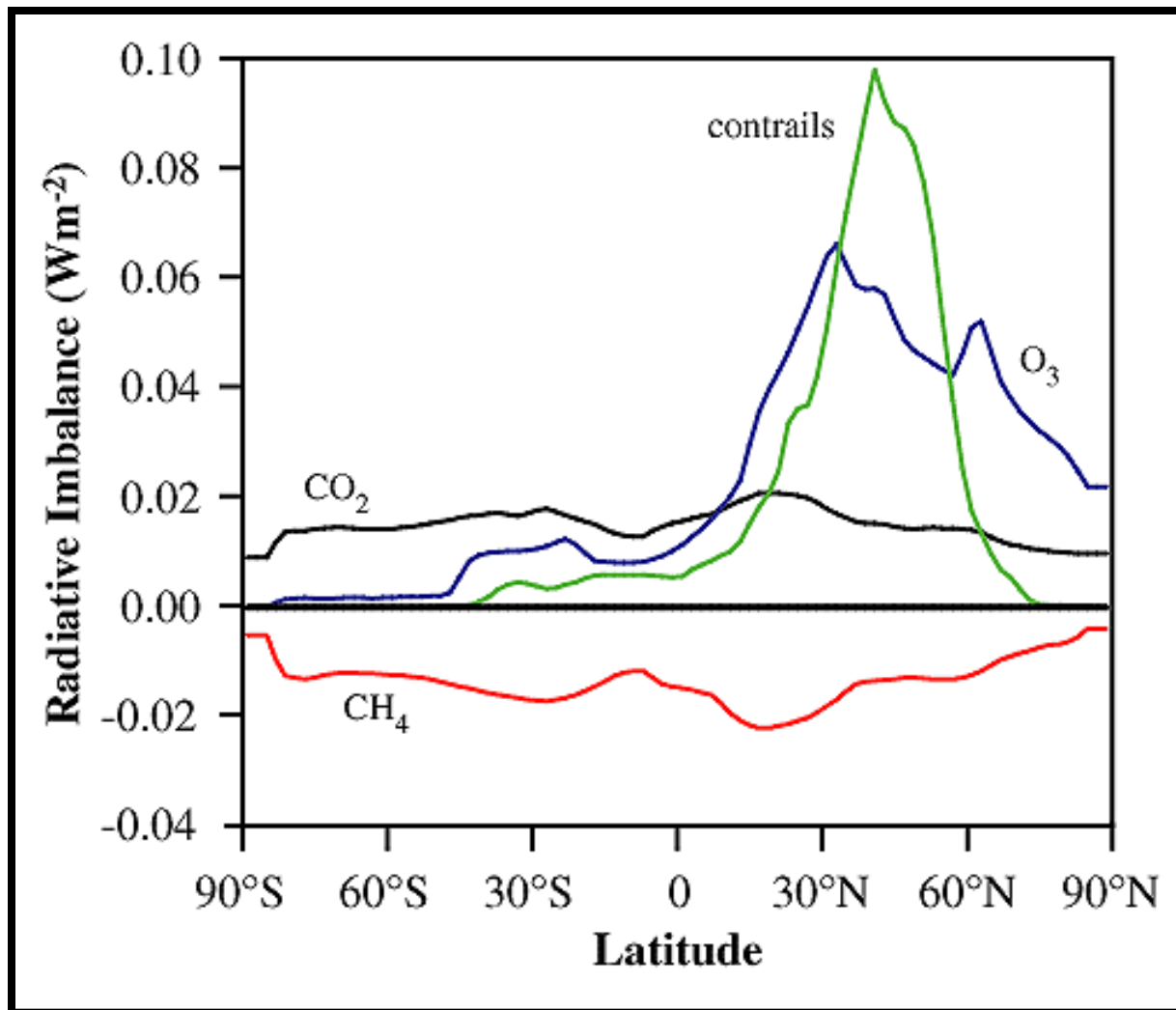
Key Research Needs

- 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

Metrics for Aviation Analyses

- **Special considerations**
 - Aviation emissions occur mostly in specific regions (UT/LS, flight corridors)
 - Aircraft emissions not large compared to other human emissions (scaling and nonlinearities)
 - Many of the emissions are short-lived
 - Some effects not only dependent on the emissions (supersaturation and the formation of contrails)
 - Some indirect effects depend on atmospheric chemistry while others depend on aerosol processes and microphysics

For Some Aviation Emissions, Radiative Forcing has Strong Location Dependence



Are efficacies an adequate correction?

IPCC 1999

Aviation and Climate Metrics

- **A number of metrics have been proposed.**
- **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 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.

Metrics: Establishing Research Priorities

Some Considerations ...

- **It is not at all clear which metrics will be most suitable for addressing the questions of aviation impacts on climate.**
- **The suite of possible metrics need to be tested, evaluated, and prodded.**
 - Right now, it appears most effort likely should go into Equivalent RF, GWPs, GTPs, and Simple Models metrics
- **Different scientists have different experiences with different metrics → may be worthwhile to form a working group that together would evaluate the different metrics and their value for addressing different policy questions.**

Consideration of Environmental and Other Trade-offs

Continuous Descent Approach

- Reduced Noise impact
- *Reduced Fuel Burn/CO₂*

Reduce cruise altitude

- *Increased fuel burn, CO₂*
- *Increased NO_x*
- *Less increase O₃*
- **Reduced contrails**

Operations changes

- *Reduce contrails*
- *More fuel burn, CO₂*

Nacelle Modifications

- Reduced Noise
- *Increased Fuel Burn/CO₂*

Improved aerodynamic efficiency and reduced weight

- Reduced CO₂
- Reduced Noise
- *Reduced NO_x*

Reduced polar flights

- *Less effects on stratosphere*
- *More fuel burn, CO₂*

Increased Engine Pressure Ratio & Temperatures

- *Reduced Fuel Burn / CO₂*
- Reduced HC and CO
- *Increased NO_x*

Steep climb

- Reduce noise impact
- *More fuel burn, CO₂*

Increased engine bypass ratio

- *Reduced Fuel Burn / CO₂*
- Reduced Noise
- *Increased NO_x*

Using Current Tools

Policymakers May Face Decisions Before Metrics Research is Completed

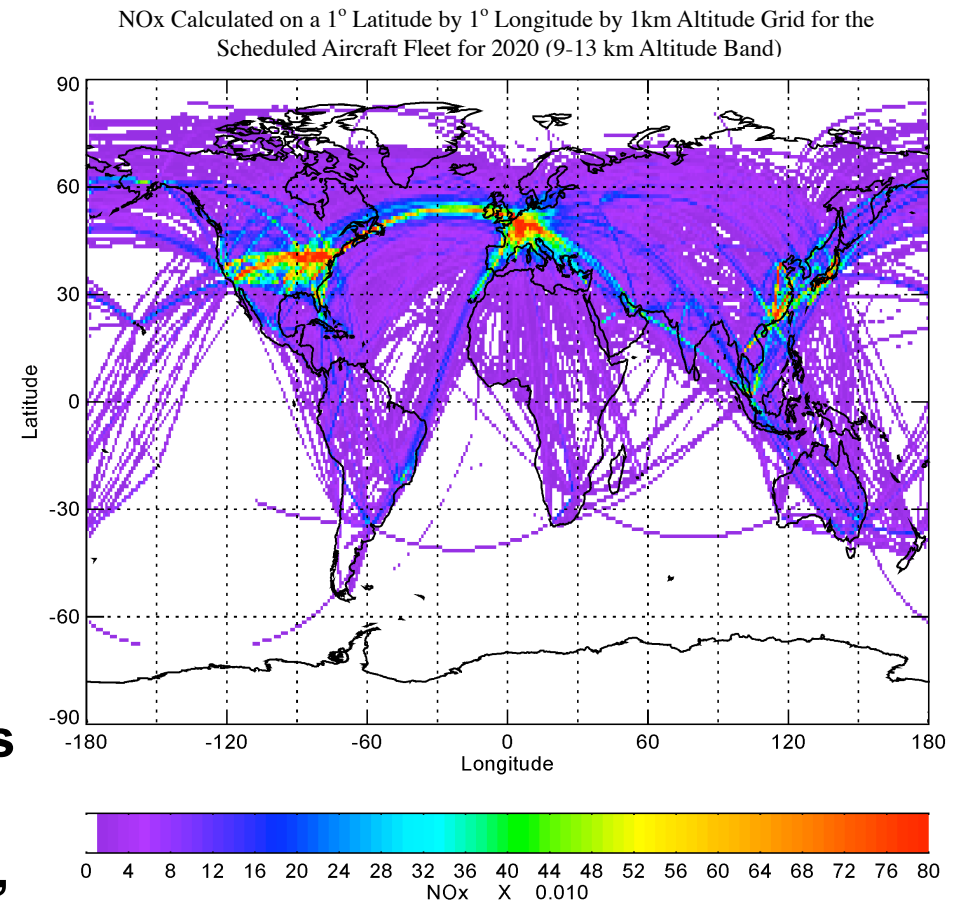
- **Need to take a systems point of view in any new study using existing metrics to evaluate the climate impacts from aviation.**
 - Consider all of the uncertainties associated with current understanding of the effects of aviation emissions on climate.
- **For perspective relative to prior assessments, examine Radiative Forcing first, including efficacies to the degree possible -- Current time plus future scenarios**
- **Use emissions-based metrics to degree possible, but depends on state of further development of GWPs, GTPs, and SM for aviation at the time.**
 - Get science community agreement on the metrics applications.
- **It will be difficult to make useful policy decisions involving many of the tradeoffs at this time.**



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