Evaluating the Impacts of Aviation on Climate

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

“Further work is required to reduce scientific and other uncertainties, to understand better the options for reducing emissions, to better inform decision-makers, and to improve the understanding of the social and economic issues associated with the demand for air transport.”

Aviation and the Global Atmosphere, IPCC (1999)

“The (environmental) topic of greatest uncertainty and contention is the climate impact of aircraft.”

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

New aircraft are a long-term (~30 year) investment
• 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
Future U.S. Aviation Services Demand

Note: Not to scale

Flights
1.4-3X

Passengers
1.8-2.4X

2004
2025
1X ~3X

~2X

Enplanement Demand

Biz shift
- 2% shift to micro jets

Shift in passengers per flight
(e.g., A380, reverse RJ trend, higher load factor)

2014 and later Baseline analysis will use OEP & FACT Capacities

Boeing Forecast
3X

Passengers
1.8-2.4X

2014
Biz shift
- Smaller aircraft, more airports

Increase of over 10 passengers per flight

Time

Terminal Area Forecast (TAF) Growth Projection

TAF Growth Ratios, Lower Rate

TAF Growth Ratios, Higher Rate
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
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 NOx emissions
  - At these altitudes, NOx 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
Emissions from Aircraft of Concern to Climate

Fuel $C_nH_m (+S)$

Air

$N_2 + O_2$

$CO_2 + H_2O + N_2 + O_2 + NO_x + UHC + CO + C_{soot} + SO_x$

$O_3 + CH_4$

$+$ $+$ $+$

$+$ $-$
Radiative Forcing as a Metric of Climate Change
The Greenhouse Effect

Net incoming solar radiation
343 W m⁻²

Some solar radiation is reflected by the earth’s surface and the atmosphere

103 W m⁻²

Solar radiation passes through the clear atmosphere

ATMOSPHERE

Some of the infrared radiation is absorbed and re-emitted by the greenhouse gases. The effect of this is to warm the surface and the troposphere

EARTH

Most solar radiation is absorbed by the surface and warms it

Infrared radiation is emitted from the earth’s surface

Net outgoing infrared radiation
240 W m⁻²
Radiative forcing – a climate metric

- Radiative forcing is an index of the importance of a factor as a potential climate change mechanism
- It is expressed in Watts per square metre ($W \, m^{-2}$)

\[
\Delta T_{surface} = \lambda \, RF_{trop}
\]
Radiative Forcing quantifies the change in global radiative energy balance attributable to each emission.
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Analyses of Radiative Forcing from Subsonic Aircraft

Many uncertainties remain in quantifying impacts of aviation emissions on climate.

Radiative Forcing quantifies the change in global radiative energy balance attributable to each emission.
IPCC (1999): Climate Effects from Subsonic Aircraft

Radiative Forcing from Aircraft in 2050

- Much higher radiative forcing,
- And uncertainties also very large,
- But is this analysis even thought to still be robust?
Radiative Forcing has Strong Location Dependence
Other Important Factors

- **Time scales** of climate effects after emission
  - CO$_2$ effects are for many decades ($\tau \sim 100$ 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
  - Indirect effects may dominate

- Except for the CO$_2$ effect, **large uncertainties remain**
Workshop on Impacts of Aviation on Climate Change

- June 7-9, 2006
- Sponsors: FAA, NASA, PARTNER Center of Excellence, JPDO
- Workshop chaired by Prof. Donald Wuebbles (UIUC)
- About 35 international science experts from the U.S., Europe (UK, Norway and Germany) and Canada
- Federal research, university and industry representation
- Three science focus groups
- Participant authored workshop report; externally reviewed

This report can be downloaded at:
or
http://climate.volpe.dot.gov/docs/aviationclimwkshp.pdf
Workshop Objectives

• To assess and document
  • The current state of knowledge
  • Uncertainties and gaps

• To identify
  • Ongoing research to constrain the uncertainties and fill the gaps

• To recommend
  • Prioritized short- and long-term future research needs

• To help focus the scientific community on aviation-climate change research needs

This workshop is the first such U.S. (and even international) effort since the IPCC 1999 report on Aviation and the Global Atmosphere
Subgroup 1: Emissions in the UT/LS region and resulting chemistry effects

Subgroup 2: Contrails and induced cirrus clouds

Subgroup 3: Climate impacts and climate metrics

Everyone: Climate impact tradeoffs
Effect of Aircraft Emissions on Ozone Depends on Altitude of the Emissions

Only NOx emissions and stratospheric H$_2$O emissions are important to O$_3$

\[
\begin{align*}
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2 + \text{O}_2 \\
\text{NO}_2 + \text{O} & \rightarrow \text{NO} + \text{O}_2 \\
\text{O} + \text{O}_3 & \rightarrow \text{O}_2 + \text{O}_2
\end{align*}
\]

Our focus is on subsonic aircraft

Cruise: 8-13 km
Key Findings and Research Needs – Subgroup 1

- 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
Key Findings – Subgroup 2

• 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 poorly understood.
Contrails develop if air is colder and moister than a threshold caused by air traffic.
Contrail-cirrus
persistent: lifetime can be many hours

spreading due to wind shear in combination with ice supersaturation increases the contrail coverage
Contrails and High Clouds

- Aircraft influence high clouds **directly** by producing line-shaped contrails that can persist and spread in ice-supersaturated air.

- The resulting clusters of **contrail-cirrus** can be observed on regional scales, sometimes also in regions without significant air traffic, because they are advected with the wind field over large distances.

- Aircraft influence high clouds **indirectly** by injecting aerosol particles that may act as heterogeneous ice nuclei at some point after emission, without contrail-cirrus being involved. In the absence of aircraft emissions, a cirrus cloud would not have formed or the resulting cirrus would have different properties.

- It is conceivable that the **indirect effect occurs along with contrail-cirrus**, because ice supersaturation required for persistence facilitates ice formation at low supersaturations.

- If that occurs, **contrail-cirrus can exert an indirect effect on their own**. Cirrus may have different properties because they nucleate in regions with preexisting ice and share the available water.
Particles and the Discrepancy of Scale

Modeled distributions of soot and sulfate aerosols show strong variations between models.

- Includes uncertainties in treatment of microphysics

Measurements since IPCC (1999) indicate most sulfates (\(~97\%) produced after aircraft emission of SO$_2$.

Not enough measurements of soot in the UT/LS to characterize the distribution.

Effect of aerosols as condensation nuclei for formation and persistence of contrails and formation of cirrus clouds is highly uncertain.

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

- Advanced plume and contrail models needed
• Important parameters (e.g., temperature, humidity in UT) in real atmosphere remain uncertain.

• Contrail time scales and frequency of occurrence -- many uncertainties
Surface observations suggest a significant trend in contrails and cirrus since early 1970s.

MOZAIC suggests more supersaturation in UT than predicted by weather and climate models (What about 2020? 2050?)

Global modeling of contrails remain highly uncertain -- given scale issues and their inability to represent some key processes, do they have any validity at all?

Deriving radiative effects of contrails are another problem of scale.
Does Aviation Affect Cirrus?

Roughly 30% of the Earth is covered by cirrus clouds.

Aviation-induced persistent contrails and aerosols may be affecting cirrus.

Some studies suggest a growing trend in cirrus related to aviation.

However, uncertainties remain very large.
• 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
Why do we need metrics for climate change?

**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 climate model) -- the signal not big enough relative to natural variability.
• Climate impacts and climate metrics
  • Some metrics for aviation effects on climate are being used.
  • 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,
  • But RF is not an emissions based metric. Need emission based metrics (e.g., GWPs)
  • Identify, develop and evaluate metrics for climate impact assessments and examine scientific basis;
  • Quantify the uncertainties in proposed metrics;
Emissions Based Metrics

- **Global Warming Potentials (GWPs)**
  - IPCC
  - Metric often used in existing climate policy

- **Global Temperature Potentials (GTPs)**
  - Shine et al., 2005
  - Assumes sustained emissions

- **Linearized Temperature response (LTR)**
  - Waitz et al. (2007)
  - Assumes one year emissions “pulse”
No Simple Solutions: Consideration of Trade-offs

**Continuous Descent Approach**
- Reduced **Noise**
- Reduced **Fuel Burn/CO₂**

**Nacelle Modifications**
- Reduced **Noise**
- Increased **Fuel Burn/CO₂**

**Increased Engine Pressure Ratio & Temperatures**
- Reduced **Fuel Burn / CO₂**
- Reduced **HC and CO**
- Increased **NOₓ**

**Reduce cruise altitude**
- Increased fuel burn, **CO₂**
- Increased **NOₓ**
- Less increase **O₃**
- Reduced **contrails**

**Improved aerodynamic efficiency and reduced weight**
- Reduced **CO₂**
- Reduced **Noise**
- Reduced **NOₓ**

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

**Reduced polar flights**
- Less effects on stratosphere
- More **fuel burn, CO₂**

**Steep climb**
- Reduce **noise**
- More **fuel burn, CO₂**

**Increased engine bypass ratio**
- Reduced **Fuel Burn / CO₂**
- Reduced **Noise**
- Increased **NOₓ**
Key Research Needs – Aviation Tradeoffs

- Aviation emissions tradeoffs (within climate impacts)
  - Need sensitivity analyses for various trade-offs
    - Emission reduction vs. fuel technology
    - Flights re-routing (altitude as well as latitude)
    - Geographical distribution of aviation
    - Differential impact of day/night operations
  - Co-dependence of physical impacts – how future climate change may alter aviation impacts

Trades between noise vs. emissions impacts (and amongst emissions) also part of tradeoffs but workshop participants not charged to address – however, FAA and the international community must address these issues.
Avoiding contrails by altitude changes or 'active flight routing'

Active flight routing seems most efficient, but requires sophisticated air traffic management and high skill in near live-prediction of ice-supersaturated regions

ISSR = Ice SuperSaturated Regions

Mannstein et al., 2005
Conclusions

• Many uncertainties remain in determining the role of aviation on climate change

• Existing metrics are either inadequate or not adequately tested for policy considerations related to aviation

• Premature to develop meaningful climate policy for aviation.
Workshop Recommendations

“... the need for focused research efforts in the U.S. specifically to address the uncertainties and gaps in our understanding of current and projected impacts of aviation on climate and to develop metrics to characterize these impacts.”

“... coordination and expansion of existing and planned atmospheric and climate research programs or development and implementation of new aviation focused research activities.”

“... a strong interaction between science and aviation communities while undertaking such initiatives.”

FAA and other agencies are working with the science community to prioritize research needs and in establishing research support.
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, turnaround time)
- Number of operational aircraft and their usage characteristics
- Flight characteristics (City pairs criteria, route diversions, supersonic over land?)

From S. Baughcum