Climate Impacts of Aviation Emissions

Post-ACCRI FAA Activities

By: Dr. Mohan Gupta
Office of Environment and Energy
Federal Aviation Administration

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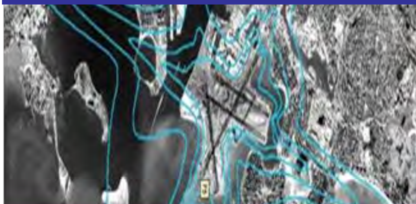
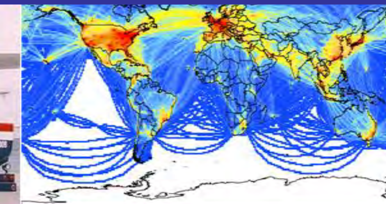
Aviation Environmental Challenges

NOISE | AIR QUALITY | WATER QUALITY | ENERGY | GLOBAL CLIMATE







- Aviation impacts community noise, air quality, water quality, energy usage, and climate change
- Environmental impacts from aviation could pose a critical constraint on capacity growth

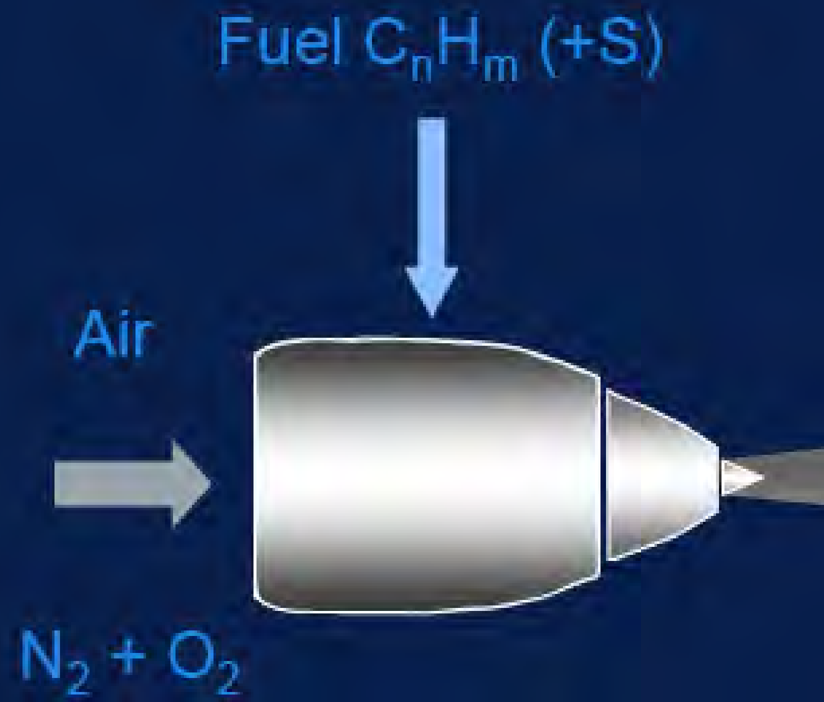
Challenge

Want increased mobility with reduced environmental impacts and enhanced energy availability and sustainability.

FAA Environmental and Energy Strategy and Plan

https://www.faa.gov/about/office_org/headquarters_offices/apl/environ_policy_guidance/policy
http://www.icao.int/environmental-protection/Pages/ClimateChange_ActionPlan.aspx

Aircraft Combustion Emissions



Combustion by-products:
- CO_2
- Water Vapor
- NOx
- SOx
- CO
- Unburned hydrocarbons (UHC) including HAPs
- Non-volatile particulate matter

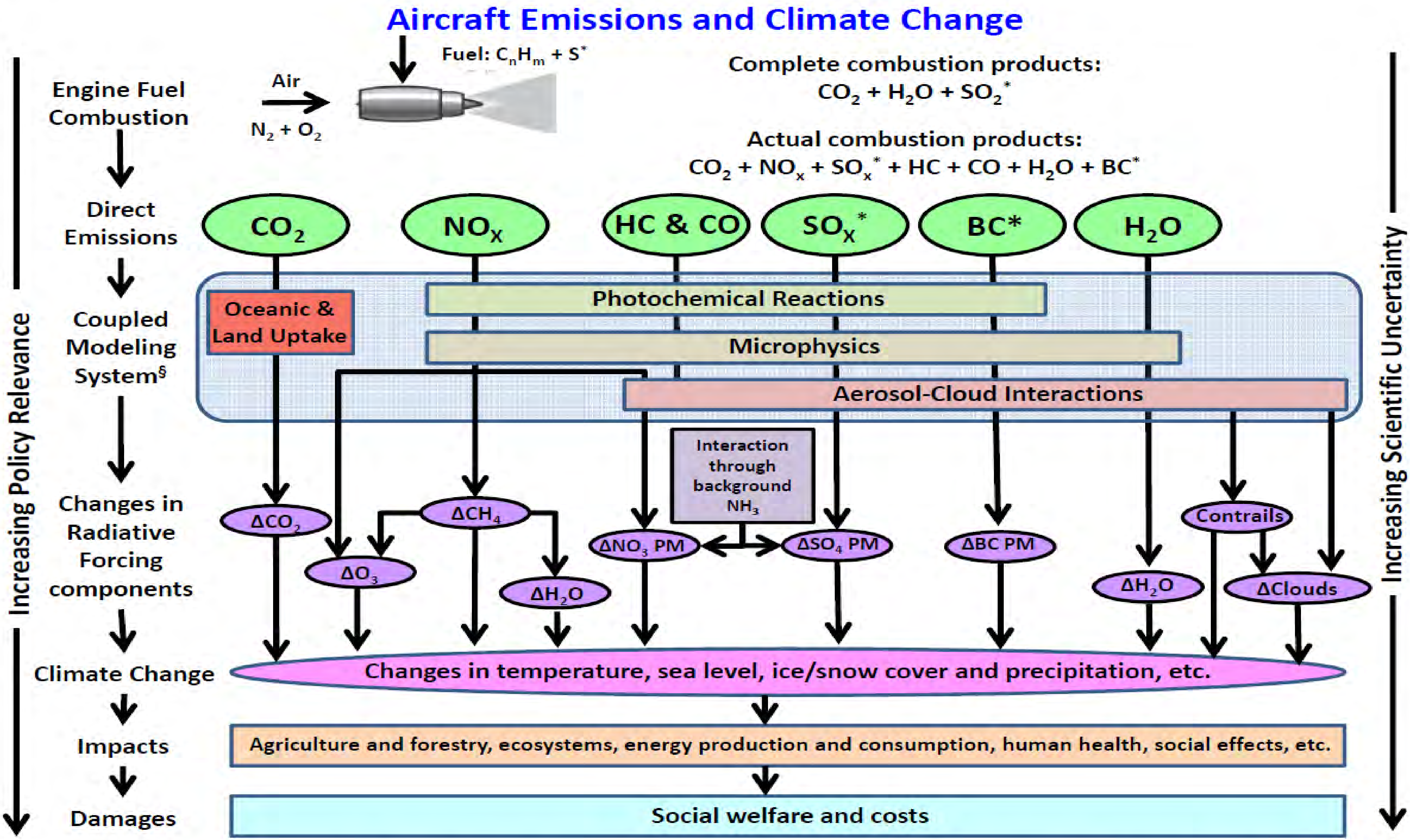
Some key points:

- Aircraft emissions are inherently four-dimensional (space & time) in nature
- Vertical extent of aviation emissions ranges from surface to cruise altitude
- Connect international boundaries with local, regional and global issues
- Emissions evolution from plume to global scale
- Environmental impacts: Air quality, climate change and public health
- Aircraft non-CO_2 emissions are increasing while background emissions are decreasing
  - Aviation demand is projected to increase at the rate of 4.3%/year over the next 20 years (ATAG Forecast, 2016)

ACCRI: Key Questions

- **Magnitude** of non-CO_2 climate impacts of aviation emissions
  current (2006) and future (2050)
- **Interactions** and **feedback** among aviation emissions
  changing background atmosphere
- **Benefits** of emissions miti gation optio ns
  technological advances and use of alternative jet fuels
- **Metric(s)** to properly characterize aviation climate impacts
- **Regional** and **global** climate impacts of aviation

Aviation Climate Impacts – A Schematic Diagram



*100% Alternative Jet fuels will have no sulfur related emissions and have lower black carbon (BC) emissions; other emissions could be lower (e.g., NO_X)

§Account for radiative, chemical, microphysical and dynamical couplings along with dependence on changing climatic conditions and background atmosphere

Developed by Mohan Gupta (Brasseur et al., BAMS, 97, 561-583, 2016)

ACCRI: Key Contributions

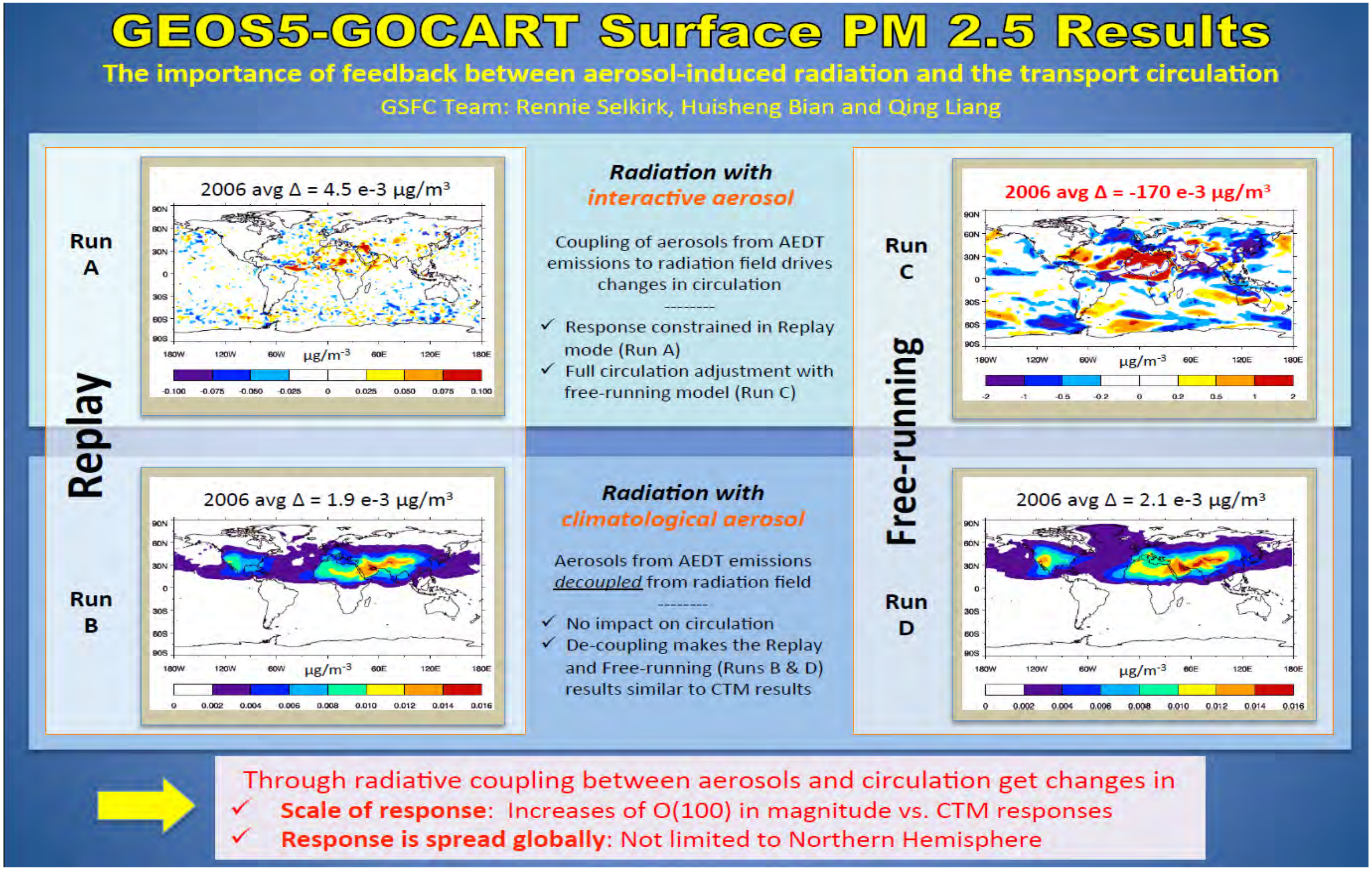
- Isolated/identified some components of aviation radiative forcing (RF)
- Accounted for interactions and feedbacks among aviation emissions and with background atmosphere for current and future conditions
- Narrowed the range of RF estimates for individual components
- Evaluated, for the first time, global RF of contrails and contrail-cirrus solely on the basis of satellite observations
- Increased Level of Scientific Understanding for contrails-cirrus from ‘Very Low’ to ‘Low’
- Estimated climate benefits of emissions reduction due to assumed use of advanced aircraft technologies, efficient operational procedures and alternative jet fuels

A number of papers on ACCRI contributions have been published various journals (e.g. JGR, GRL, ACP etc.). Refer to Brasseur et al. (BAMS, 97, 561-583, 2016) for an overview.

ACCRI: Lessons Learned and Future Direction

- Complex NOx-O3-CH4 interactions and role of background atmosphere
- Role of Vertical transport of emissions and global distribution of short-lived trace species, including that of ammonia and aerosol precursors
- Studies of climate system feedback in single modeling framework
  - Need to develop better estimates of direct and indirect climate impacts of aviation emissions
  - Large uncertainty in indirect effects of aerosols of clouds
- Further studies are warranted to investigate the full range of climate impacts benefits of the uses of alternative jet fuels in relation to conventional fossil-based fuels
- Flight and emissions distributions: Need to quantify geographical disparity in regional climate impacts of aviation emissions
- RF-Temperature (T) relationship for aviation emissions
  - On global and regional basis
  - Use in simplified climate models
- Linear additivity of climate forcing (e.g. RF) vs. climate response (e.g. T)

Effects of Atmospheric Interactions



Couplings and feedbacks are inherent to the Earth System.

CTM results are remarkably different from CRM results

CTM: Chemical Transport Model

CRM: Climate Response Model

Results provided by Rennie Selkirk (NASA GSFC), 2015.

Reduced Contrails Persistence in 2050 relative to 2006

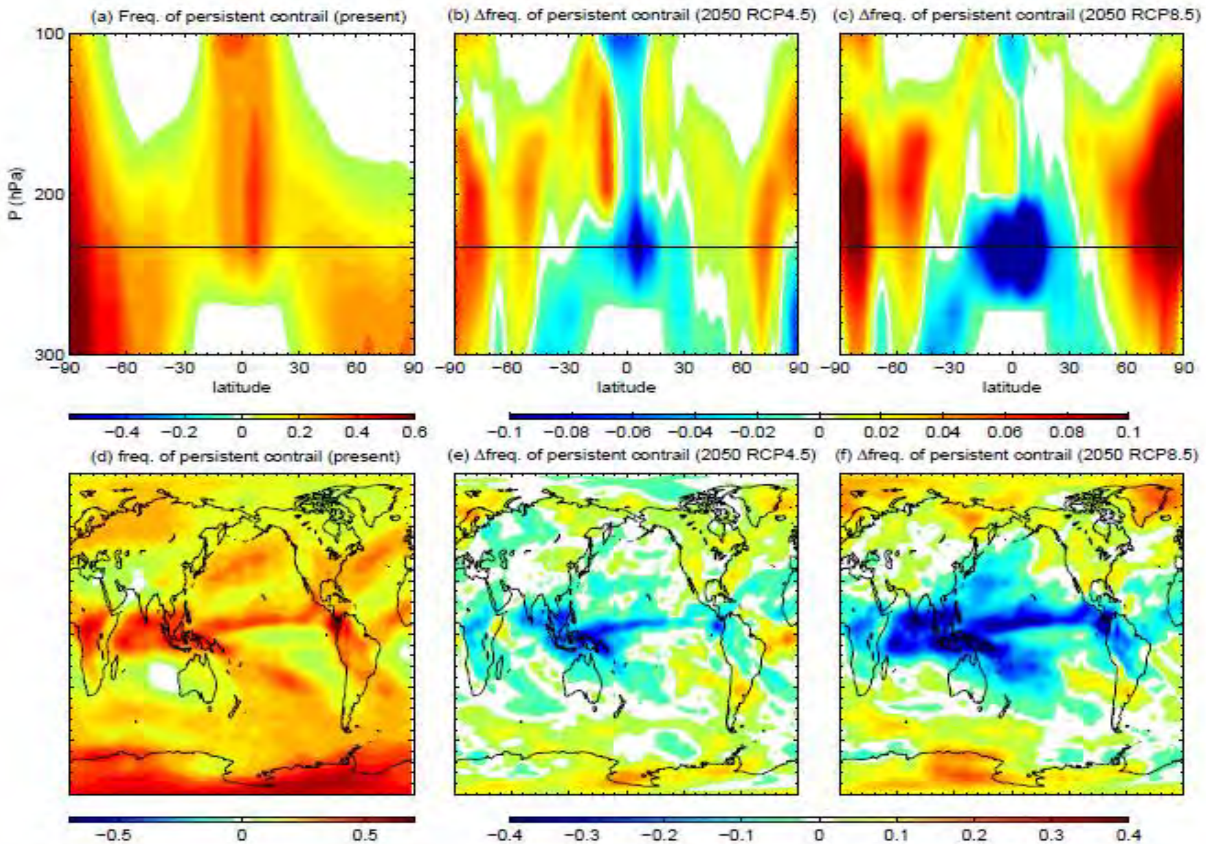


Figure 2. Frequency of persistent contrail based on present and future (RCP4.5 in 2050 and RCP8.5 in 2050) meteorologies: **(a)** zonal average between 100 and 300 hPa, **(b)** zonal difference between 2050 of RCP4.5 and present, **(c)** zonal difference between 2050 of RCP8.5 and present, **(d)** the present condition at $P = 232$ hPa, **(e)** difference between 2050 of RCP4.5 and present at $P = 232$ hPa and **(f)** difference between 2050 of RCP8.5 and present.

Chen and Gettelman, Atmos. Chem. Phys., 16, 7317–7333, 2016

RCP: Representative Concentration Pathways

Radiative Forcing Estimates – 2006 *vs* 2050: Impact of Alternative Jet Fuels

Scenario	Description
2006-Base	Based on actual 2006 flight operations
2050-Base	Baseline Fuel Burn (assumes a technology freeze with no operational improvements, i.e., improvements are limited to those associated with a fleet refresh resulting from retirement and introduction of currently in-production aircraft (as of 2006))
2050-S1	Assumes 2%/year improvement in fuel efficiency (includes technology improvements and operational benefits) with NASA NO_X emissions reduction goal
2050-S2	Alternative Fuel scenario with reduced fuel burn, no sulfur and 50% reduction in black carbon (BC) emissions

Analysis:

S1: Significant benefits of improvement in fuel efficiency and assumed reduction in NOx emissions

S2: Reduction in direct RF estimates for BC and SO4

S2: Need further analysis for indirect RF estimates.

Scenario	Fuel burn (Tg)	NO_x (Tg N)	O_3-S	CH_4	Long Term O_3	Water Vapor	Contrails	Aerosols
			UIUC CAM5*	UIUC CAM5*	UIUC CAM5	UIUC CAM5	NCAR CAM5	NCAR CAM5
2006 -Base	188.1	0.812	36.5	-12.3	-4.5	-2.6	17	-38
2050-Base	902.8	3.950	143	-59.7	-20.3	-12.5	**83**	**-160**
2050-S1	514.4	1.570	70.5	-28.3	-9.4	-5.9	**72**	**-107**
2050-S2	514.4	1.570	**58.5**	**-25.6**	**-8.8**	**-5.4**	**72**	**0**

Updates to ACCRI values are given in **BOLD.**

Gettelman et al., Submitted to Atmos. Environ., 2016

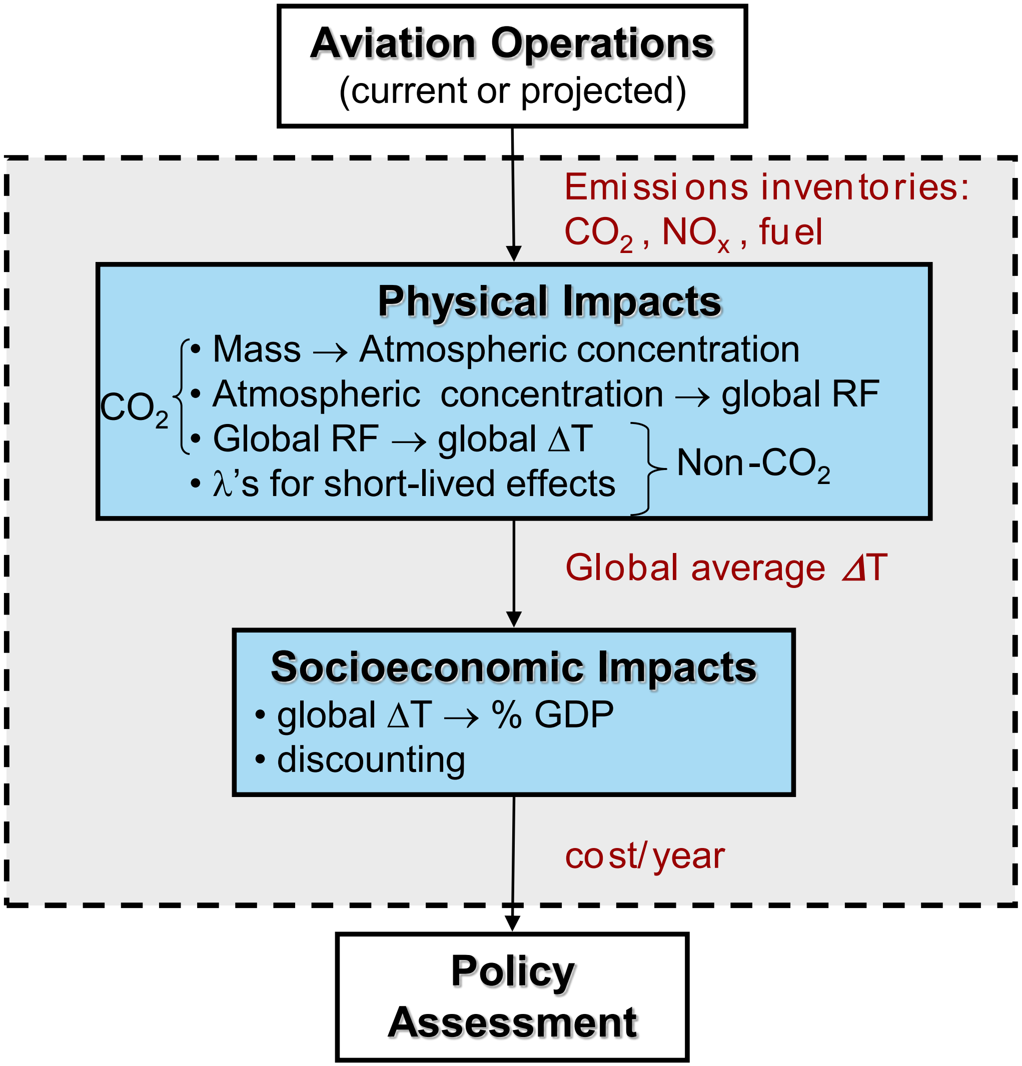
Development of FAA Climate Impacts Analysis Tool

- Fast, efficient, and up-to-date tools are needed to model the expected impact of aviation on the climate for a variety of future technology and operational scenarios.

- This work looks to improve modeling techniques for long- and short-lived aviation emission species on the global climate to support climate and policy analyses leading to sustainable aviation growth.

- Continue development of a rapid reduced-order climate models for policy analysis consistent with the latest literature and scientific understanding

APMT-Impacts Climate Module



APMT: Aviation environmental Portfolio Management Tool

APMT-Impacts Climate module is a simplified model that provides:

– estimates of aviation induced impacts through a portfolio of physical and monetary units

– quantified uncertainties in the estimated climate impacts

Model has been used to:

– Support cost benefit analyses for ICAO CAEP standard setting

– Support evaluation of alternative jet fuel environmental impacts

APMT-Impacts Climate Module

- **Continuously updated to implement up to date scientific understanding**
  - Current Code version 23
  - APMT uses as a baseline an impulse-response function carbon model, updated to a parameterization of the Bern Carbon Cycle from Joos et. Al. 2013. This is the IRF used in the IPCC AR5
  - Non-CO_2 RF from ACCRI
  - Latest version of Dynamic Integrated Climate-Economy Model (DICE2013)
  - Life cycle Emissions and Alt Fuel Impacts
- **Used to inform International Aircraft CO_2 standard**

APMT-I Climate Impacts: Current FAA Activities

CICERO:

- Develop estimates of Regional Temperature Potential for aviation
- Quantify impacts of regional aviation activity changes on global mean temperature for short lived climate forcers

NASA:

- Develop estimates of contrail climate impacts using satellite-observed contrails for 2012

ASCENT Project 21*:

- Implementation of APMT-I Global v23 to APMT-I Global v24
- Include climate impacts of short lived forcers such as Nitrates, Stratospheric Water Vapor etc.

ASCENT Project 22*:

- Review of Requirements Document of APMT-I Climate v24
- Review of CICERO RTP (Regional Temperature Potential) functions
- Evaluation and intercomparison of results from complex three dimensional climate models
- Non-linearity of climate impacts in APMT vs in complex models

*ascent.aero

APMT-Impacts Climate: Future Outlook

- **Develop updated version (v24) of APMT-I Climate**
- **Will include:**
  - Implementation of Interagency Working Group on Social Cost of Carbon Method for monetizing CO_2 impacts
  - Two additional short lived forcers
    - Stratospheric Water Vapor
    - Nitrate Particulate Matter
  - Improved Contrail Impacts Representation

Aviation Climate Impacts: Non-linearity and Simplified Models

Climate Impacts:

- Linear additivity of individual RF Components?
- Linear additivity of change in (global/regional) temperature after RF to T conversion?
- Linear extrapolation of RF for future conditions

Table 1. 2050 RFs calculated from APMT

	APMT calculated 2050 RF (mW/m^2)		
RF Terms	If the used reference RF is from the year 2006 (ACCRI)	If the used reference RF is from the year 2050 (ACCRI)	Difference(%)
H20	-6.8	-4.9	-27.94
Sulfates	-13.7	-15	9.49
Soot	2.2	0.6	-72.73
Contrails	87.1	72	-17.34
CH4	-19.4	-25.9	33.51
O3-short	43.3	42	-3.00
O3-long	-8.7	-8.1	-6.90

Table 2. Exploring the non-linearity of short-lived forcings in the background atmosphere

	APMT calculated 2050 temperature change (10^{-3} K)		
Short-lived Forcings	If the used RFs are linearly scaled from the year 2006 (ACCRI)	If the used RFs are the simulated RFs from the year 2050 (ACCRI)	Difference (%)
H20	-0.7	-0.5	-40.00
Sulfates	-1.4	-1.6	12.50
Soot	0.2	0.06	233.33
Contrails	9.1	7.5	21.33
O3-short	4.5	4.4	2.27

From Don Wuebbles, ASCENT Meeting, 2016

Summary

- FAA has made significant contributions to understand and estimates aviation contribution to climate change through ACCRI program
- Under post-ACCRI activities, FAA has funded research efforts to
  - Estimate climate benefits of sustainable alternative jet fuels
  - Examine the role of cruise aviation emissions on aviation atmospheric impacts
  - Estimate aviation climate impacts under the future aviation growth, mitigation and atmospheric background conditions
  - Estimate contrail radiative forcing for 2012 aviation activities
- FAA continues to improve simplified aviation climate impacts analysis tool (APMT-I Climate)