Green Aviation: Review, Aspirations, and Operational Improvements

Dr. Banavar Sridhar

USRA@NASA Ames Research Center

Moffett Field, CA, USA

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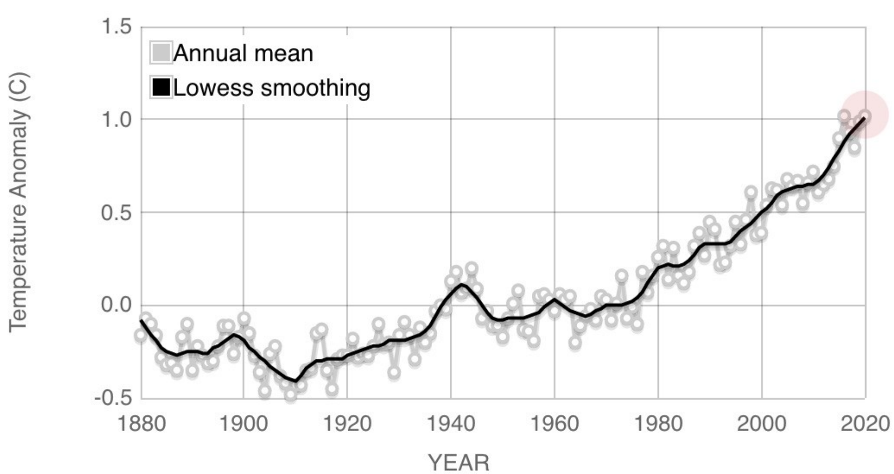
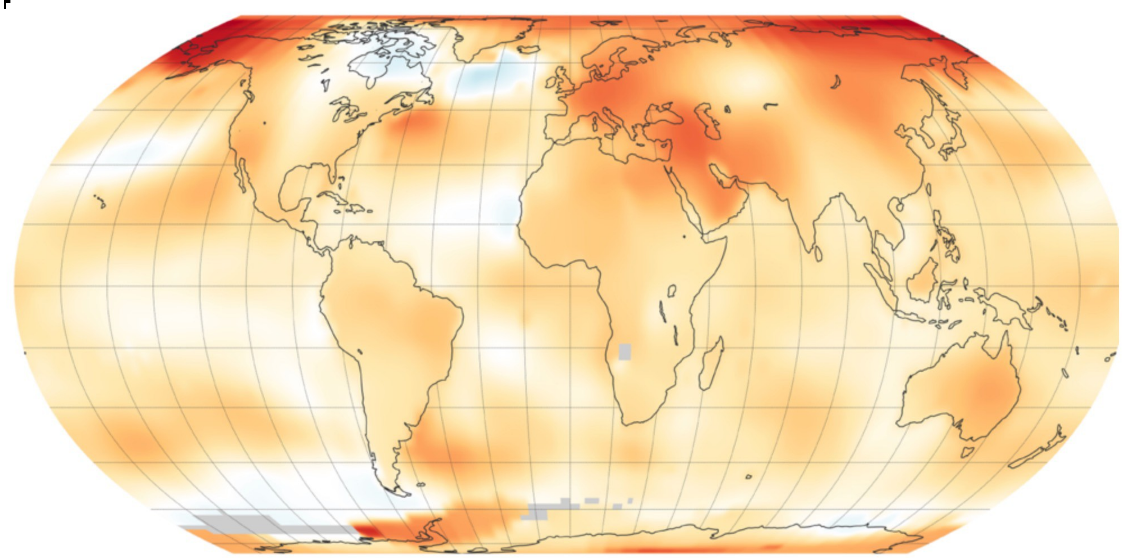
What is Global Warming?

- Earth's surface temperatures has increased by about 2.12 Fahrenheit (1.18 degrees Celsius) since the baseline period of 30 years (1951-80) based on historical observations over oceans and land (NASA and NOAA 2019 Announcement)
- Change driven largely by increased carbon dioxide emissions into the atmosphere and other human activities.



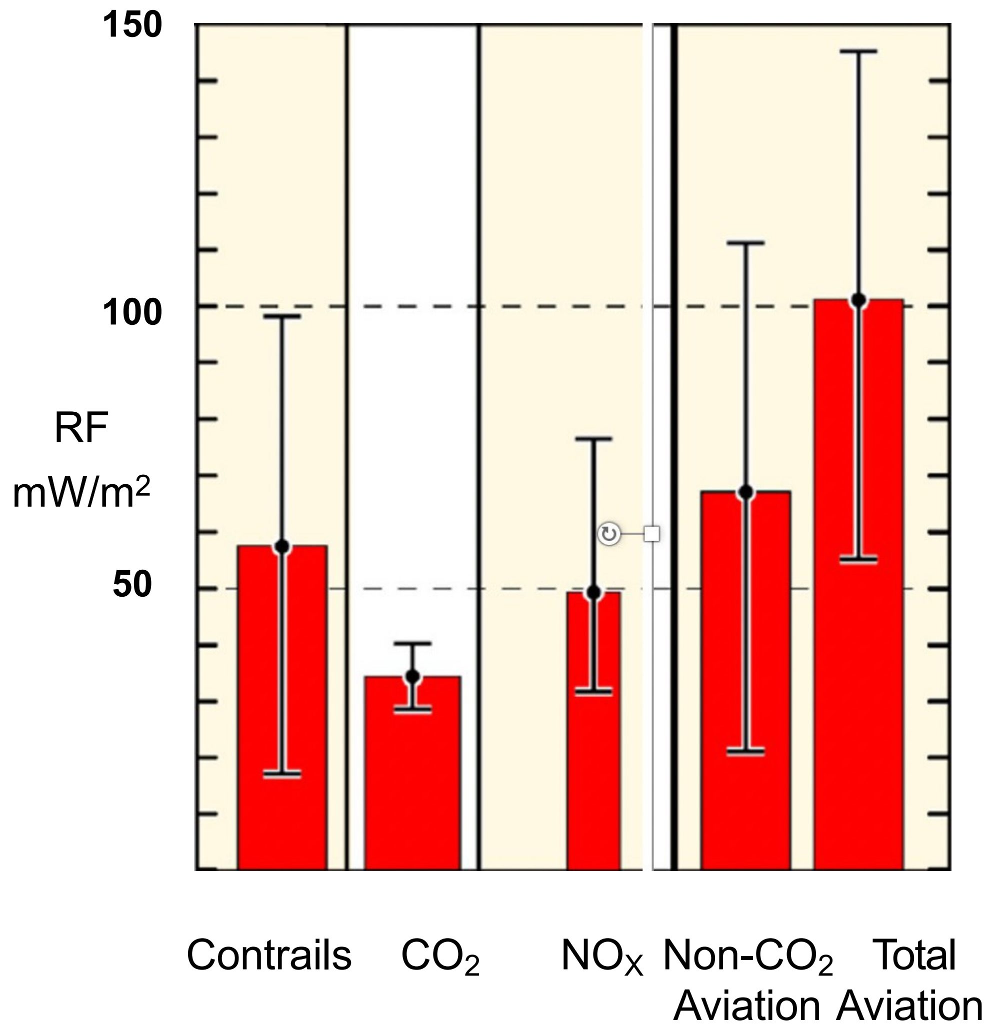
Change in global surface temperature relative to baseline



2018 global temperature data: higher than average (temperatures are shown in red, lower than normal temperatures are in blue.

Impact of Aviation on Climate Change*

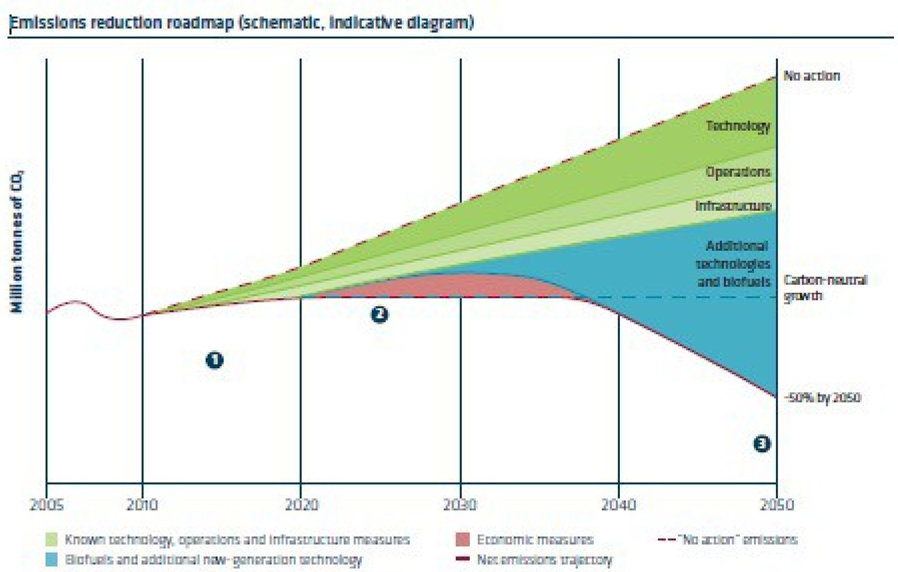
- Aviation responsible for 13% of transportation-related fossil fuel consumption and 2.0% of all anthropogenic CO_2 emissions
  - Direct emissions: CO_2 and water vapor are greenhouse gases (GHG) resulting in a positive Radiative Forcing (RF); Because of its abundance and long lifetime, CO_2 has a long-term effect on climate change
  - Indirect effects: NO_x affecting distributions of Ozone and Methane has a short-term effect on climate change.
  - Condensation trails (Contrails) are clouds that are visible trails of water vapor made by the exhaust of aircraft engines.



*D.S. Lee et al, Atmospheric Environment, 2021

International Civil Aviation Organization (ICAO) Strategies for Reducing Impact

- ICAO established global aspirational goals in 2010
  - 2% annual fuel efficiency improvements through 2050
  - Carbon neutral growth from 2020 onwards.



- Three-pronged approach
  - Improvements in aircraft technology,
  - Improvements in operations and
  - Development and market-based approach to the use of alternative aviation fuels.

Figure Credit: "Beginner's Guide to Aviation Efficiency", Air Transport Action Group, Nov 2010, ATAG_EfficiencyGuide_Reprint_web.pdf

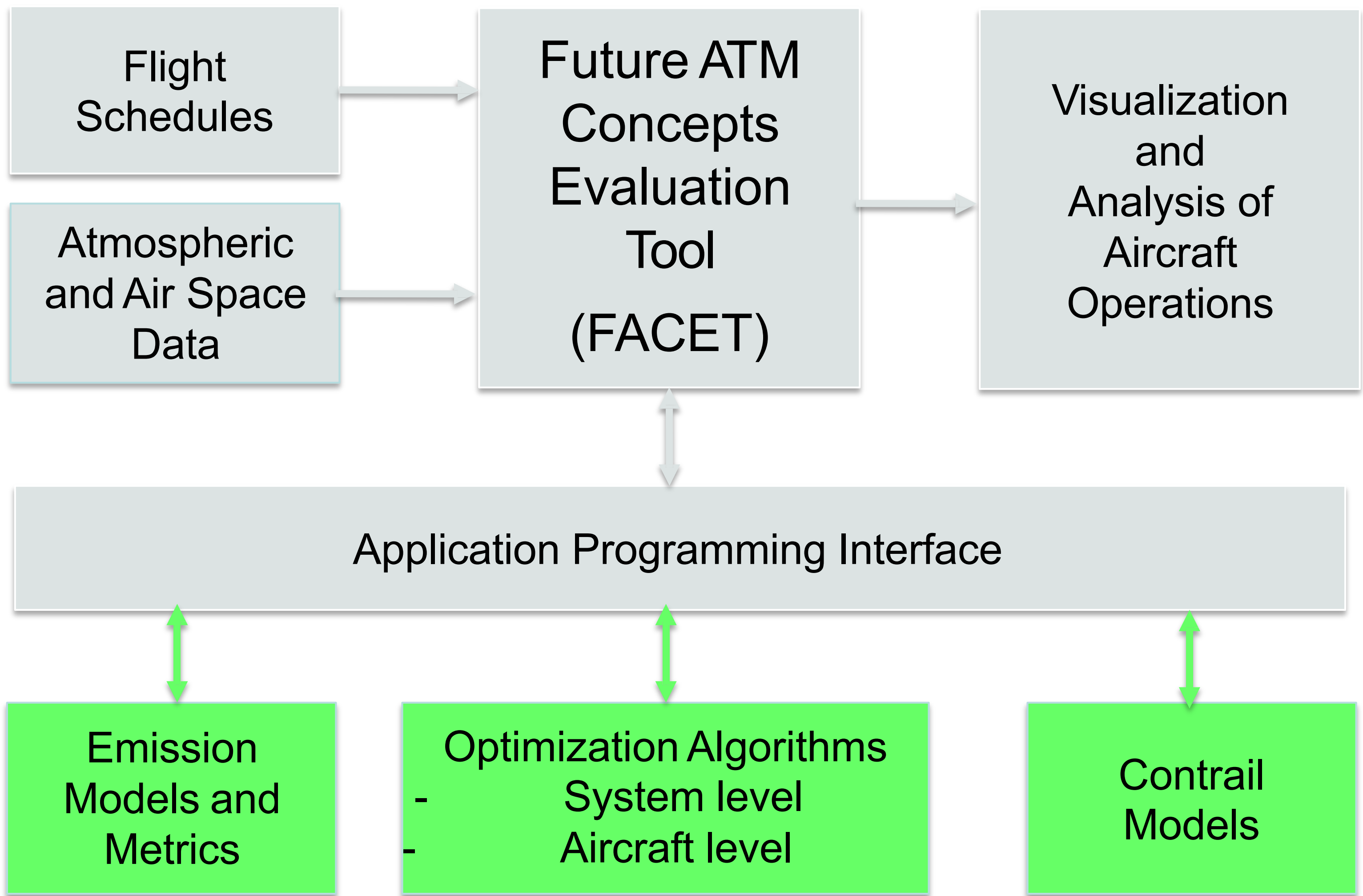
Why is it hard?

- Analysis of concepts to reduce the impact of aviation and climate requires models of aviation operations, emissions, climate models and metrics
  - Time variation from minutes to decades, spatial variation from local to global
  - Uncertainties in climate models and atmospheric variations
  - Appropriate level of modeling and computationally efficient algorithms to support operations and policy
- Review of AF Traffic Flow Management Research (2010-2016) on Green Aviation
  - Efficient aircraft operations under constraints
    - Wind optimal routes for different operating costs including airspace charges for oceanic and intercontinentall flights
  - Development of aircraft trajectory designs minimizing the combined effects CO_2,NO_X and contrails

Outline

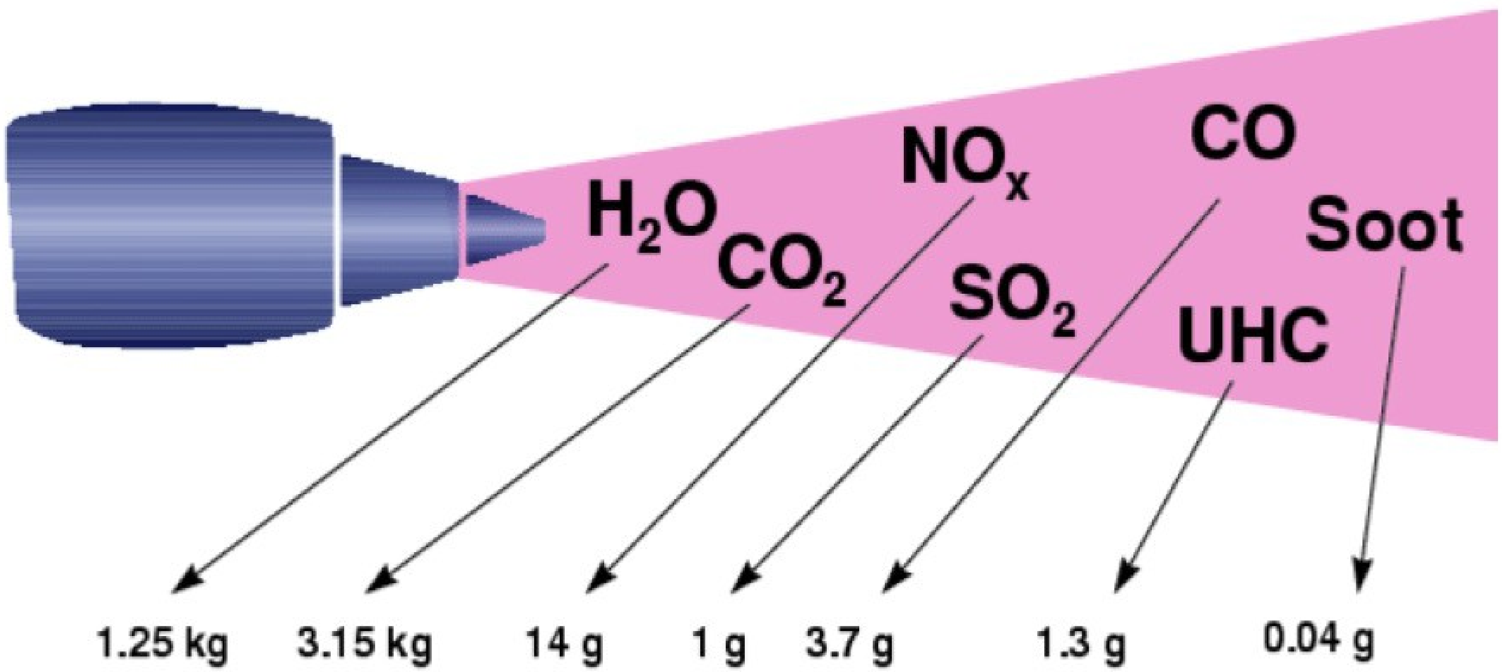
- Method of approach to build a global air traffic and climate impact simulation capability
- Emissions and contrails models
- Strategies for reducing contrail formation
- Aircraft Trajectory Design Based on Reducing the Combined Effects of Carbon-di-oxide, Nitrogen and Contrails
- Lessons learned
- Going forward
- Concluding remarks

Approach


Flight Schedules
Atmospheric and Air Space Data
Future ATM Concepts Evaluation Tool
(FACET)
Visualization and Analysis of Aircraft Operations
Application Programming Interface
Emission Models and Metrics
Optimization Algorithms
- System level
- Aircraft level
Contrail Models

Fuel and Emission Models

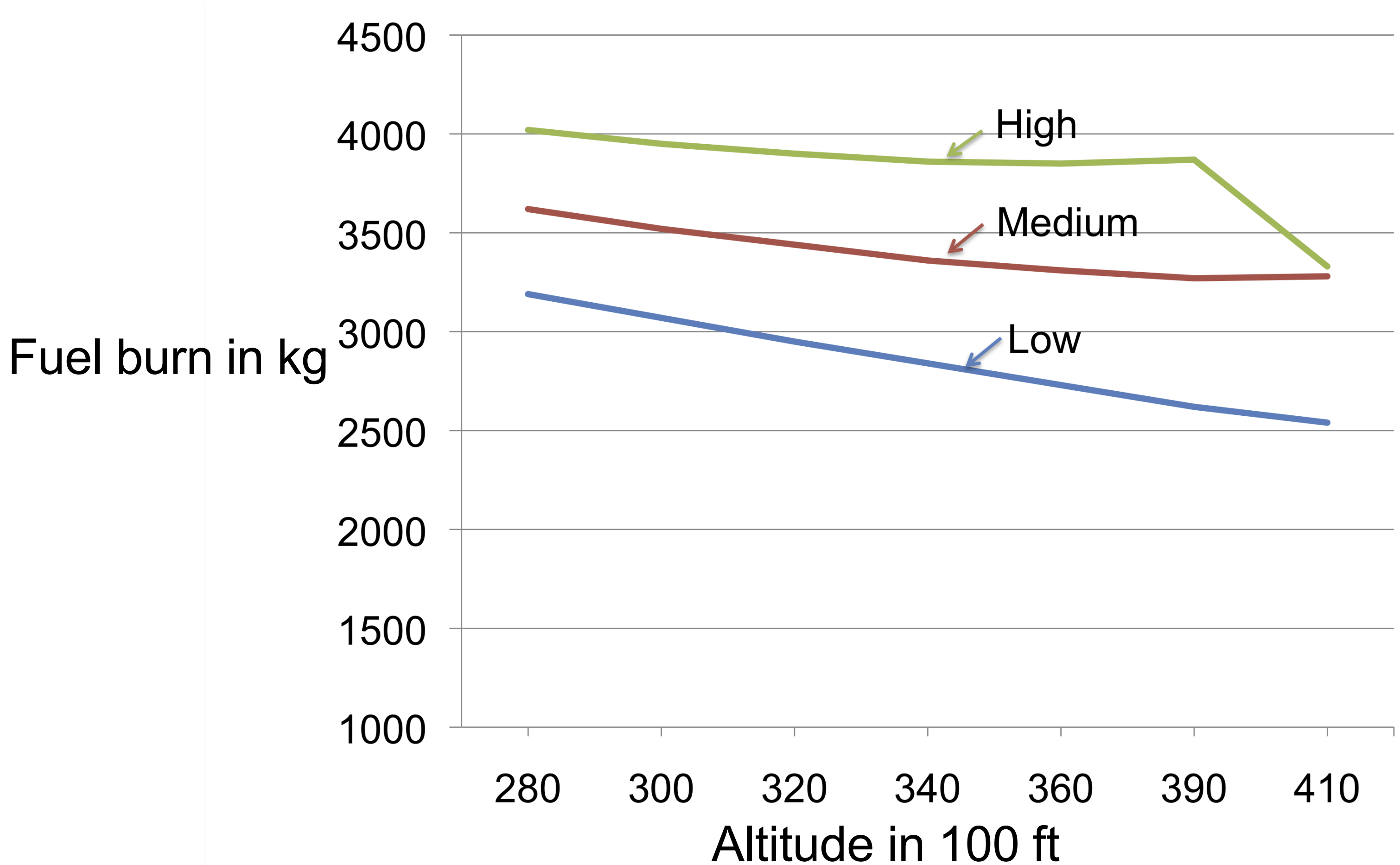
Emissions per kg of aviation fuel



- Eurocontrol's Base of Aircraft Data (BADA)
- FAA Aviation Environmental Design Tool (AEDT)

Fuel Consumption Model (BADA)

- Eurocontrol's Base of Aircraft Data (BADA)
- Fuel burn during cruise: $f_c = t \times SFC \times Th$



Fuel burn for a typical jet from Chicago to Newark

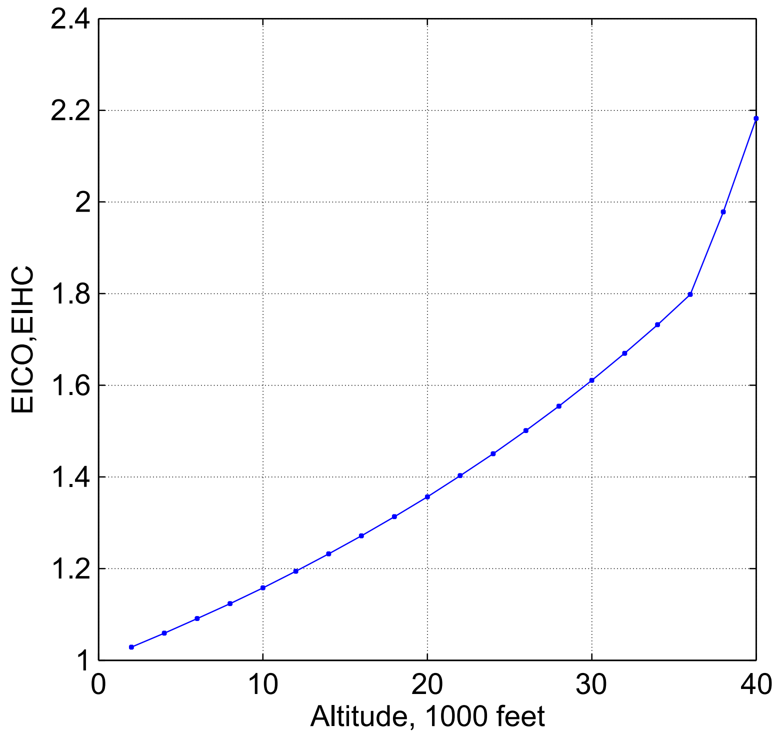
Variation of Emissions with Altitude

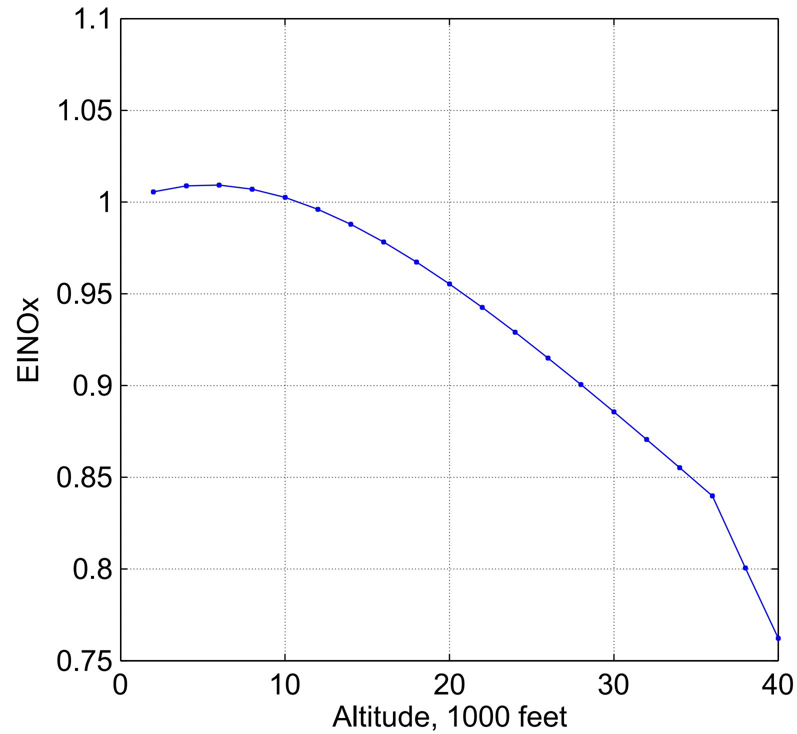
Fuel Burn = FB = σ

Emission is in grams/kg of fuel

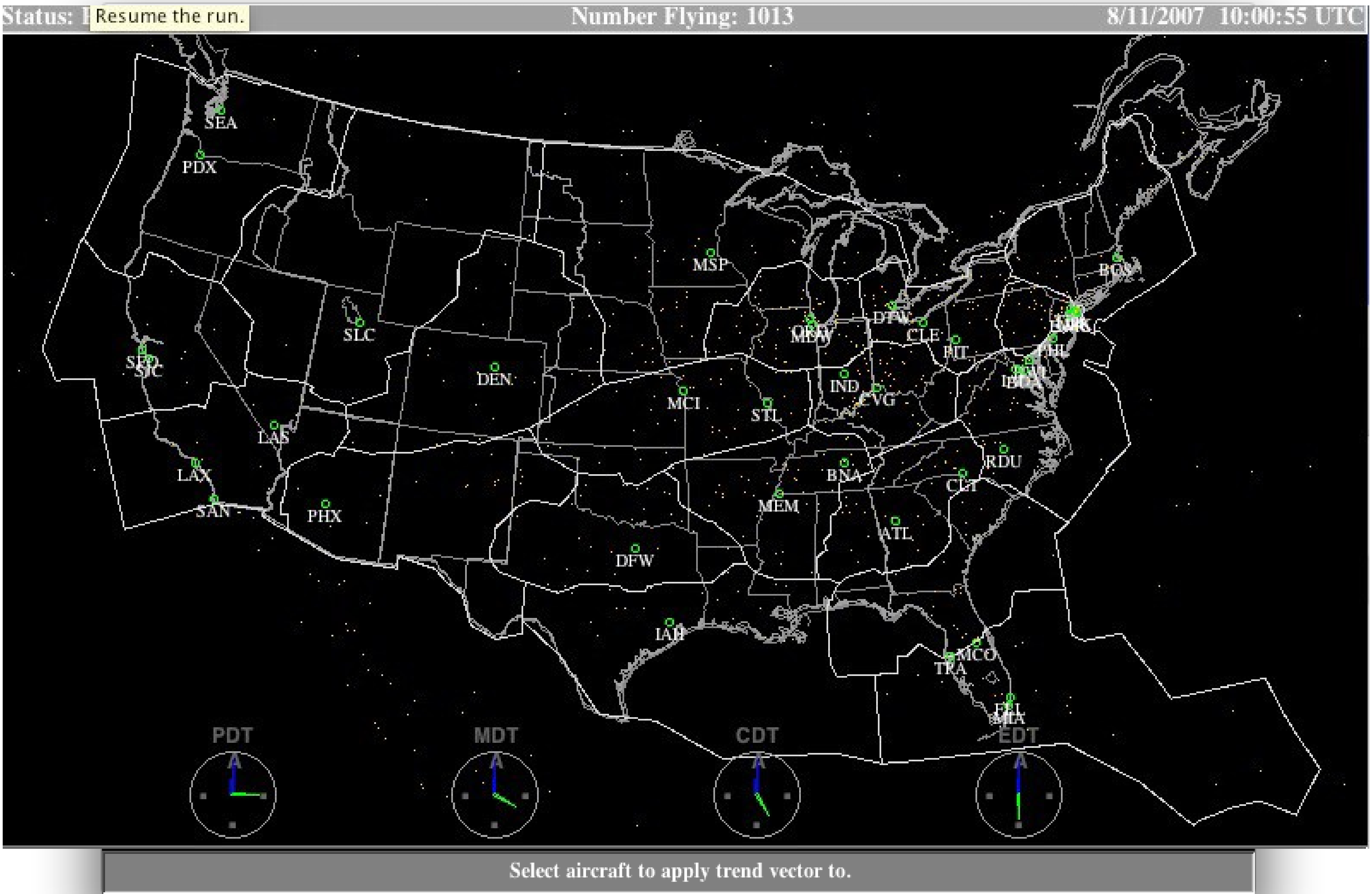
$$e(CO_2) = 3155 \times \sigma$$
$$e(H_2O) = 1237 \times \sigma$$
$$e(SO_2) = 0.8 \times \sigma$$

$$e(HC) = EIHC \times \sigma$$
$$e(CO) = EICO \times \sigma$$
$$e(NO_x) = EINO_x \times \sigma$$





Air Traffic Simulation: CO_2 emissions



Contrails

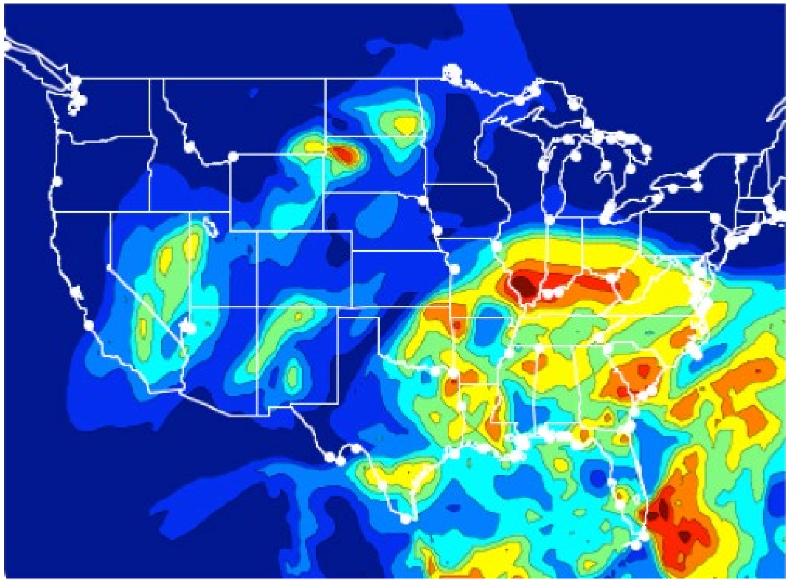
- Occur when warm engine exhaust gases and cold ambient air interact under favorable temperature and humidity conditions

Image Credit: NASA/Eddie Winstead

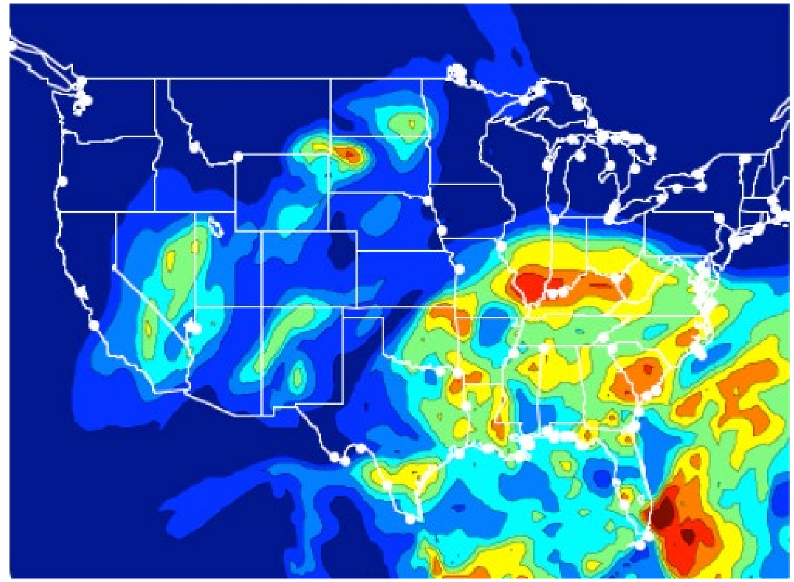
Persistent Contrail Formation Model (PCFM)

- Contribution of contrails to global warming may be larger than contribution from CO_2 emissions
- Contrails form if relative humidity with respect to water (RHw) is greater than a temperature dependent threshold
- In mid-latitudes, Contrails generally occur around 30,000ft,but rarely below 25,000ft
- Contrails persist if the relative humidity with respect to ice (RHi) is high (RHi > 100 %)
- RHi can be calculated from the RHw and the environmental temperature which are provided by the Rapid Update Cycle (RUC)
- Information available to compute PCFM on an aircraft except RHw; some aircraft have humidity sensors

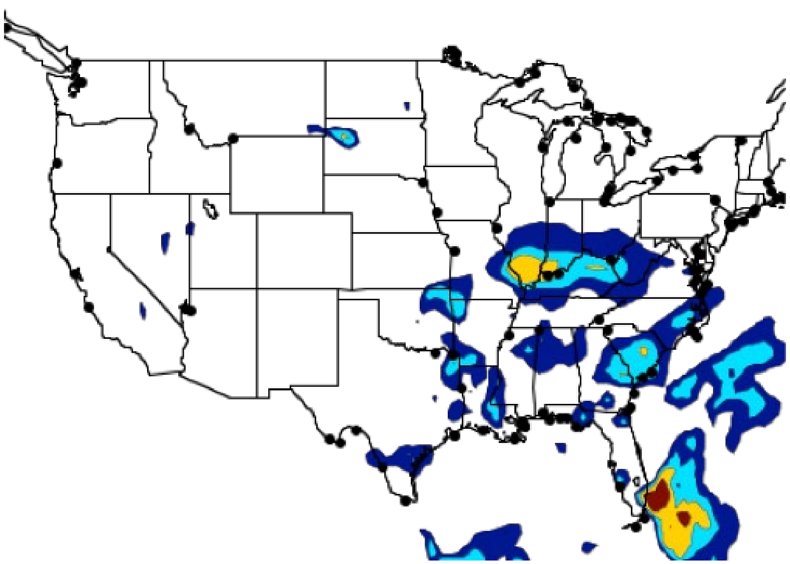
Persistent Contrail Formation Model



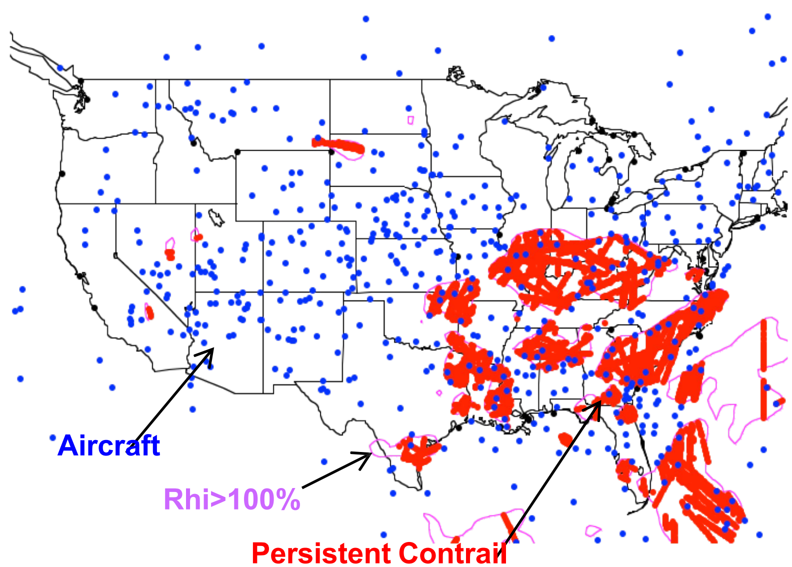
RHW Contours



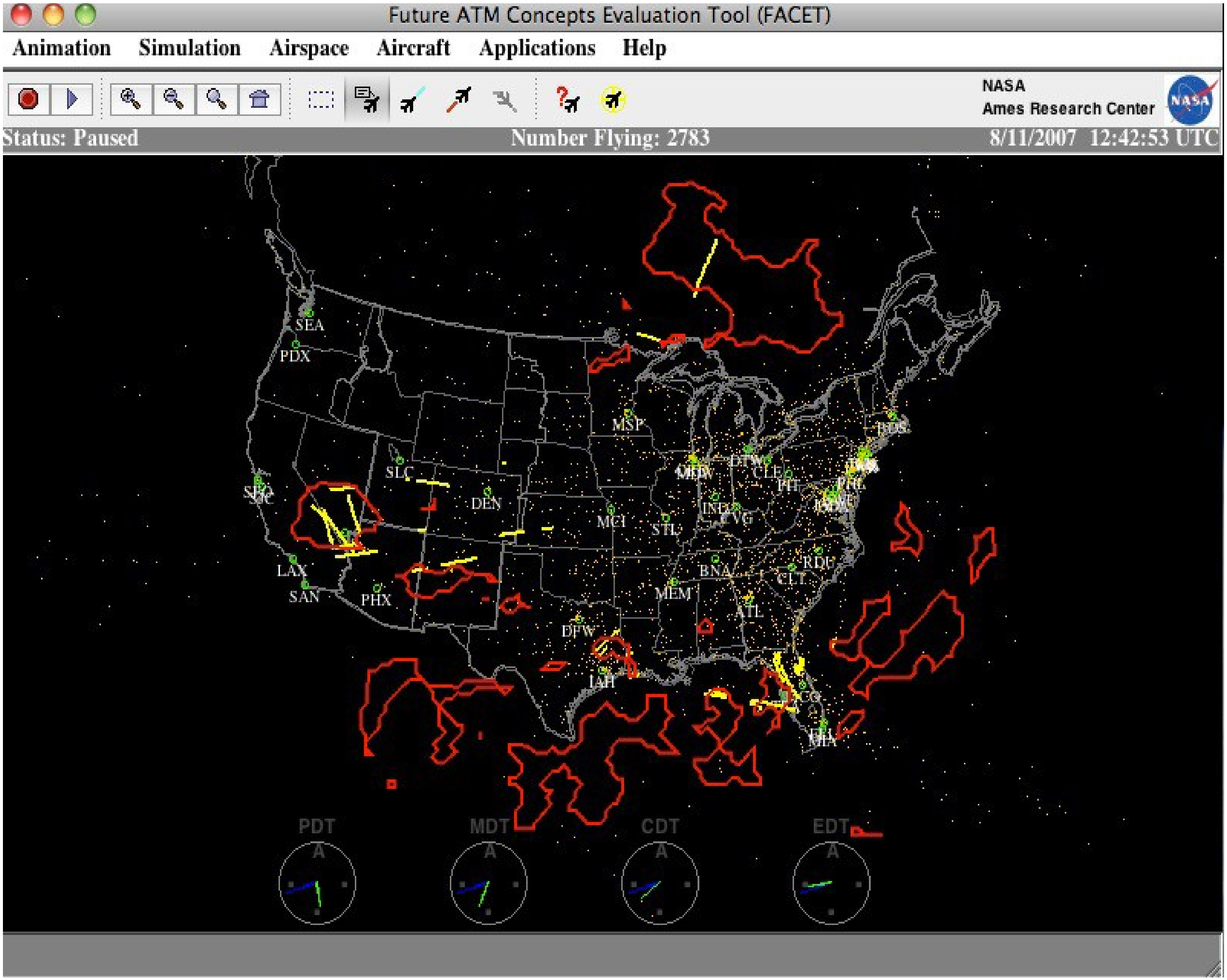
RHI Contours



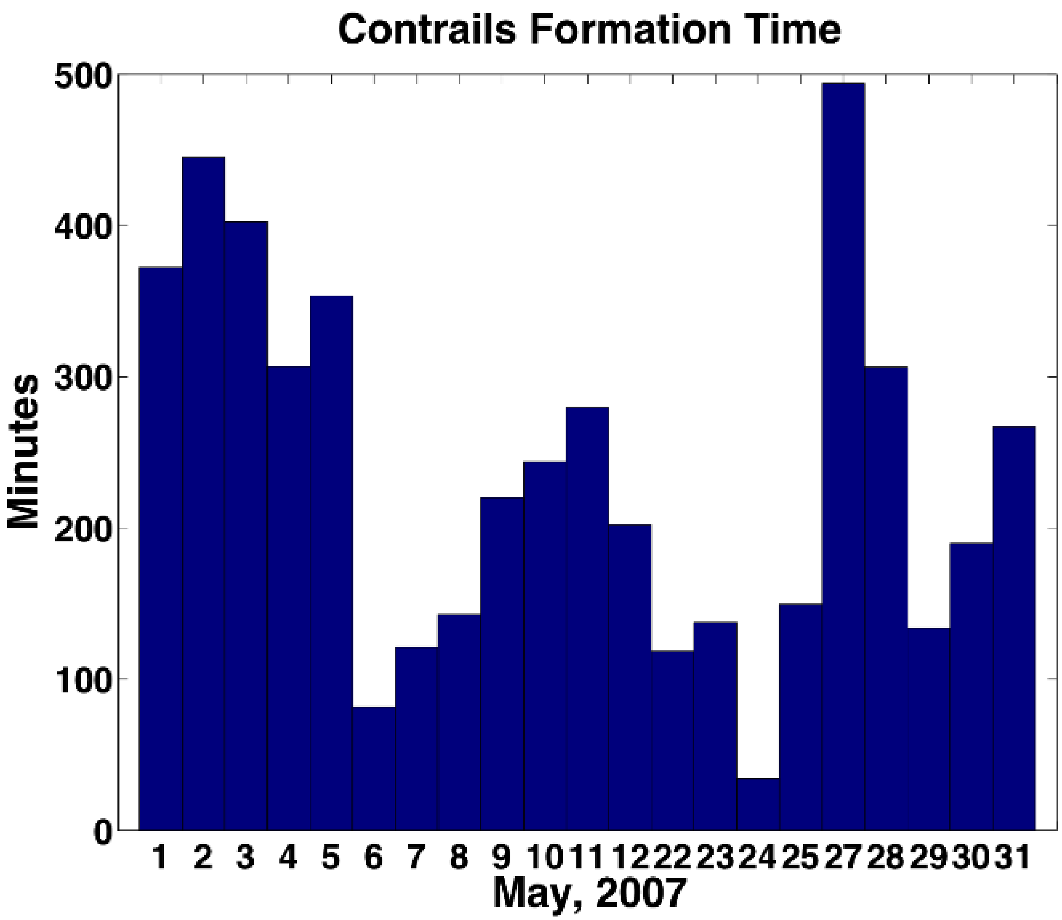
RHI>100% Contours



Potential Contrail Regions at 31,000 Feet



Daily Variation of Contrails

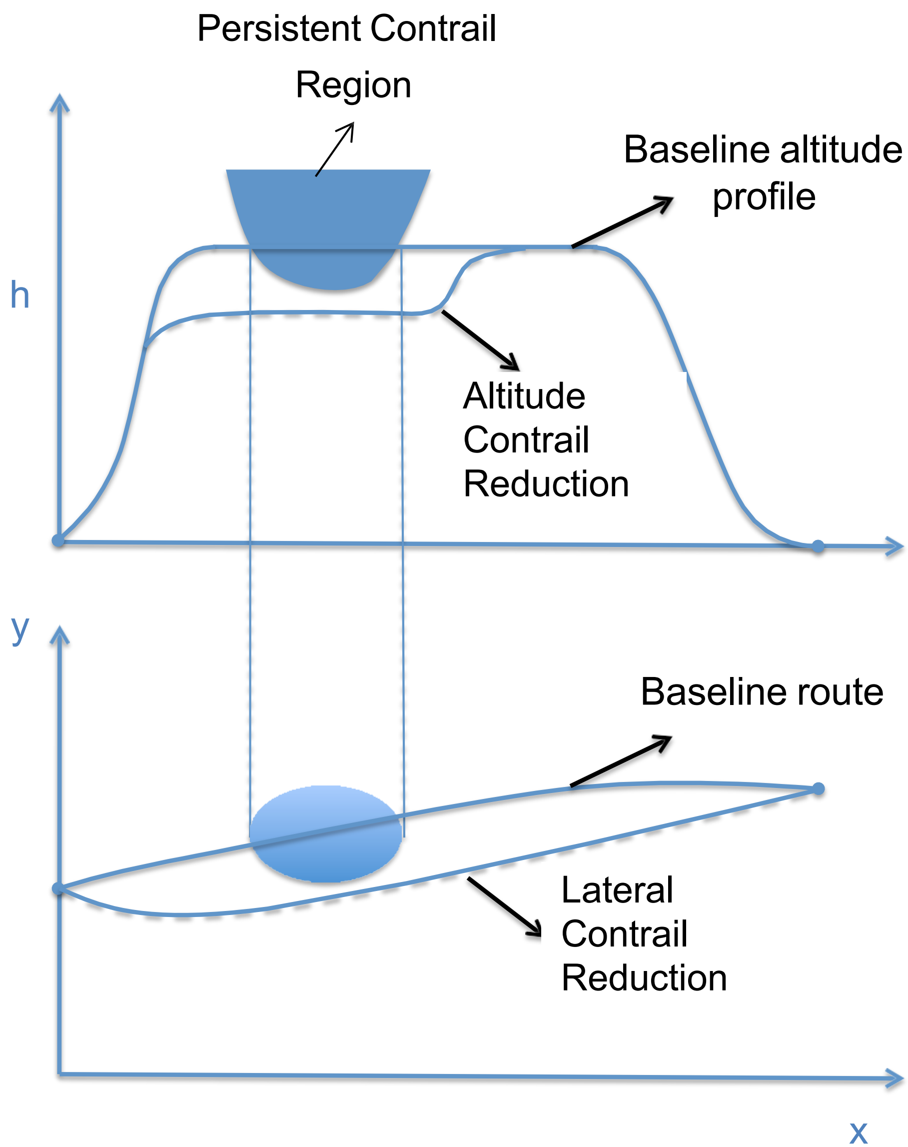


- Mean: 238 minutes
- Standard deviation: 125 minutes
- May 24 – Low (34 minutes)
- May 4 – Medium (307 minutes)
- May 27 – High (494 minutes)

Strategies for Avoiding Contrails

- Strategic
  - Models for predicting contrails
  - How to extend current models?
  - Validation using satellite data
- Tactical
  - Requires on-board sensors to detect super-saturated air
  - Air Traffic Service Provider (ATSP) needs to accommodate changes to the flight plans
- Both strategies may result in extra fuel burn
  - How much extra fuel burn (depends on avoidance technique)
  - Some estimates in Europe put this at 5% (No wind conditions). No US estimates!
- Research question: How to trade off the extra fuel burn with the environmental impact of going through contrails?

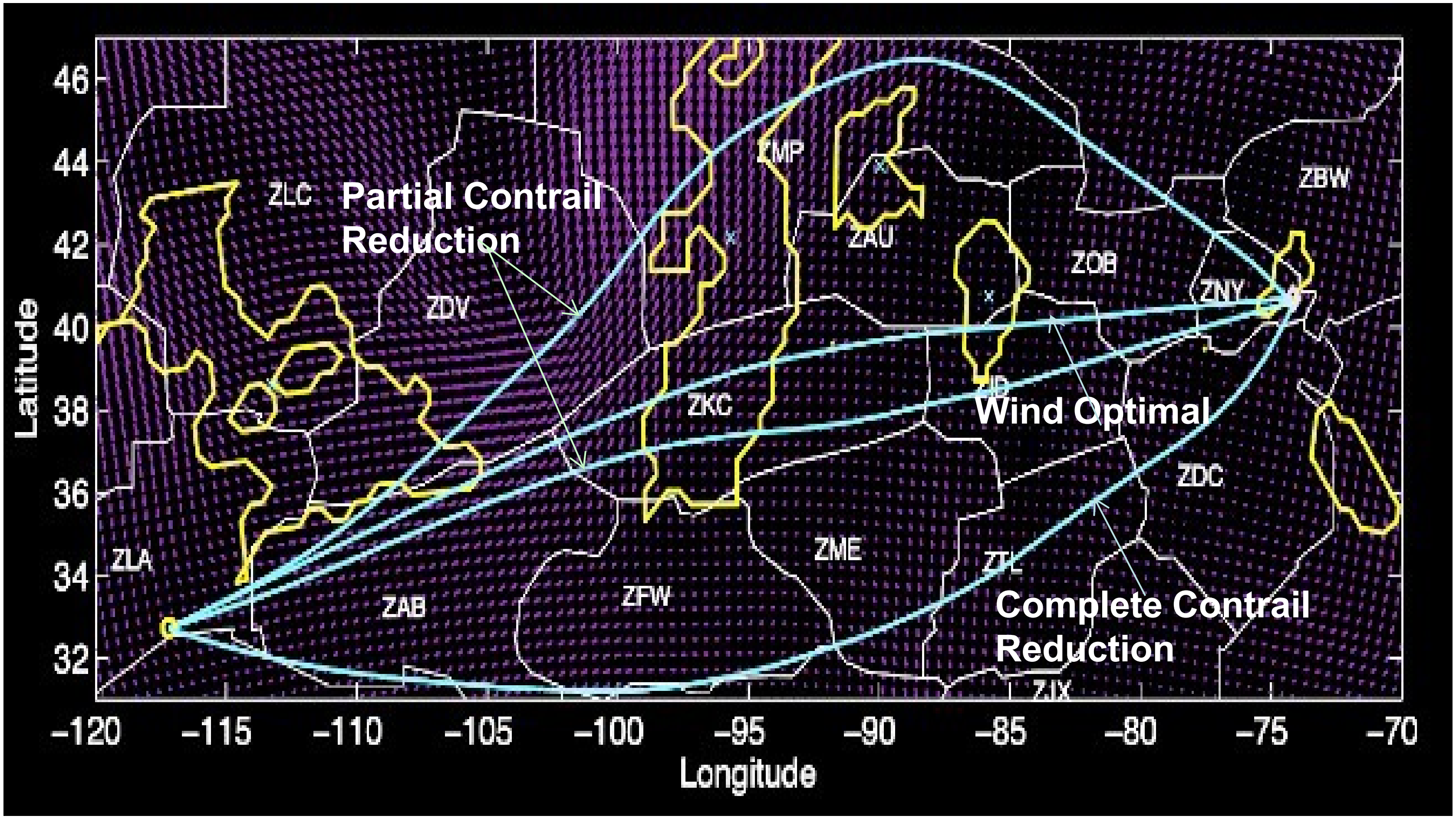
Contrail Reduction Concepts



Contrail reduction using altitude changes is highly effective in reducing climate impact even in the presence of uncertainties*

*Sridhar, B., Chen, N. Y., and Ng, H. K., "Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation," Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), Chicago, IL, June 2013.

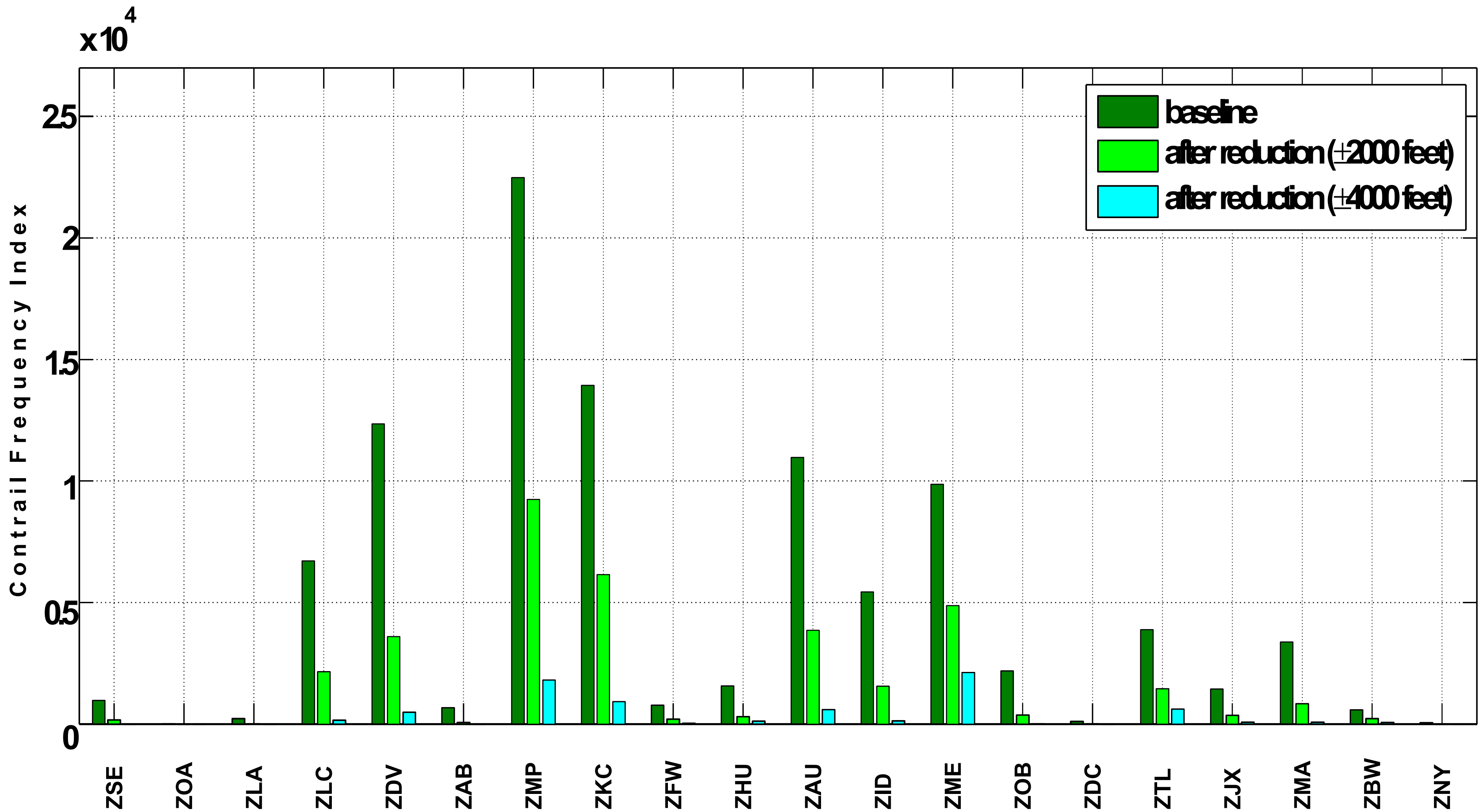
Lateral Contrail Reducing (LCR) Concept



- 3-Dimensional Contrail Reducing (3DR) Concept : Best LCR for a range of altitudes

Reduction of Contrail Formation by Altitude Changes

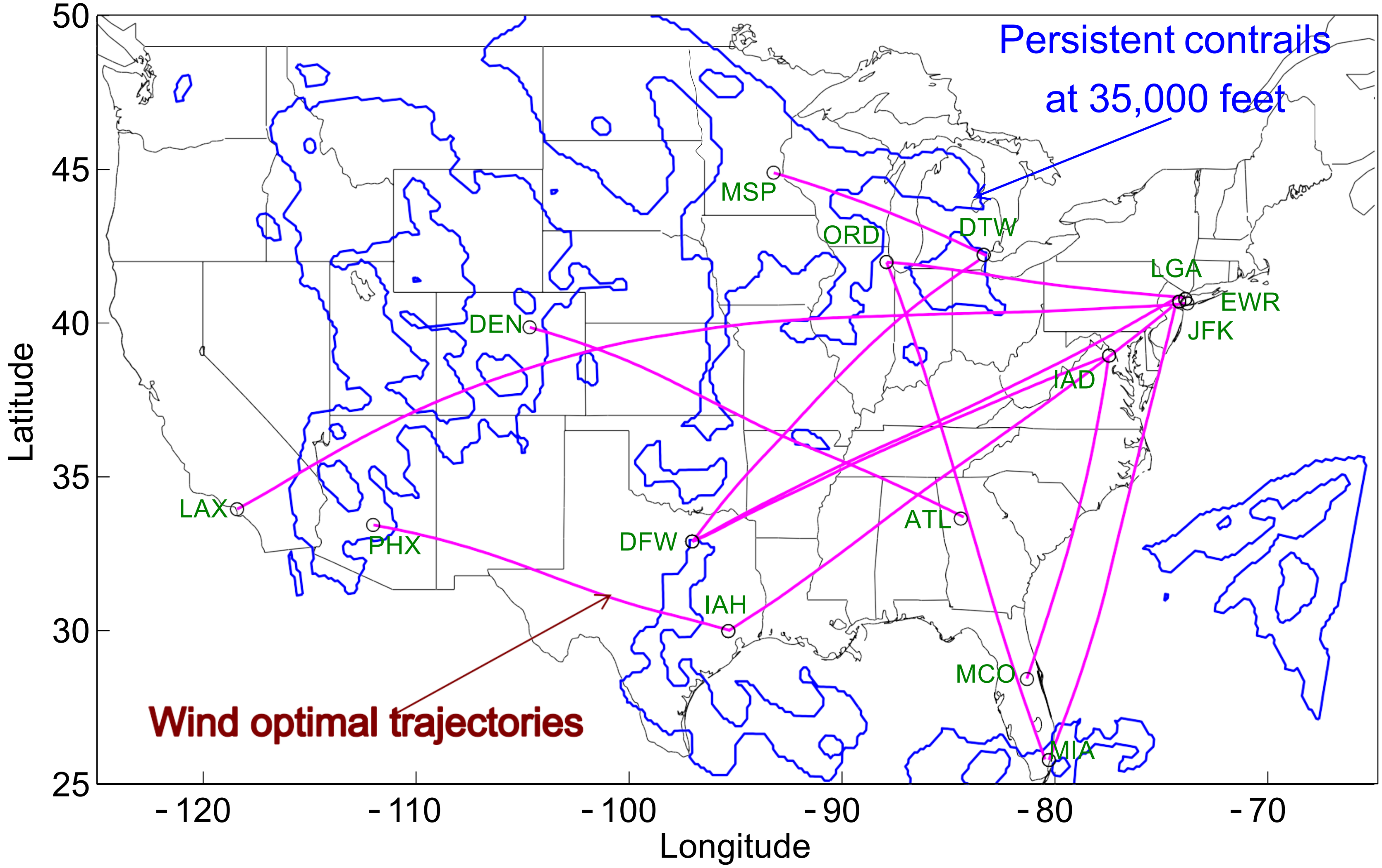
- Baseline: Traffic and weather data at 8.00AM on April 23, 2010



Simulation Details

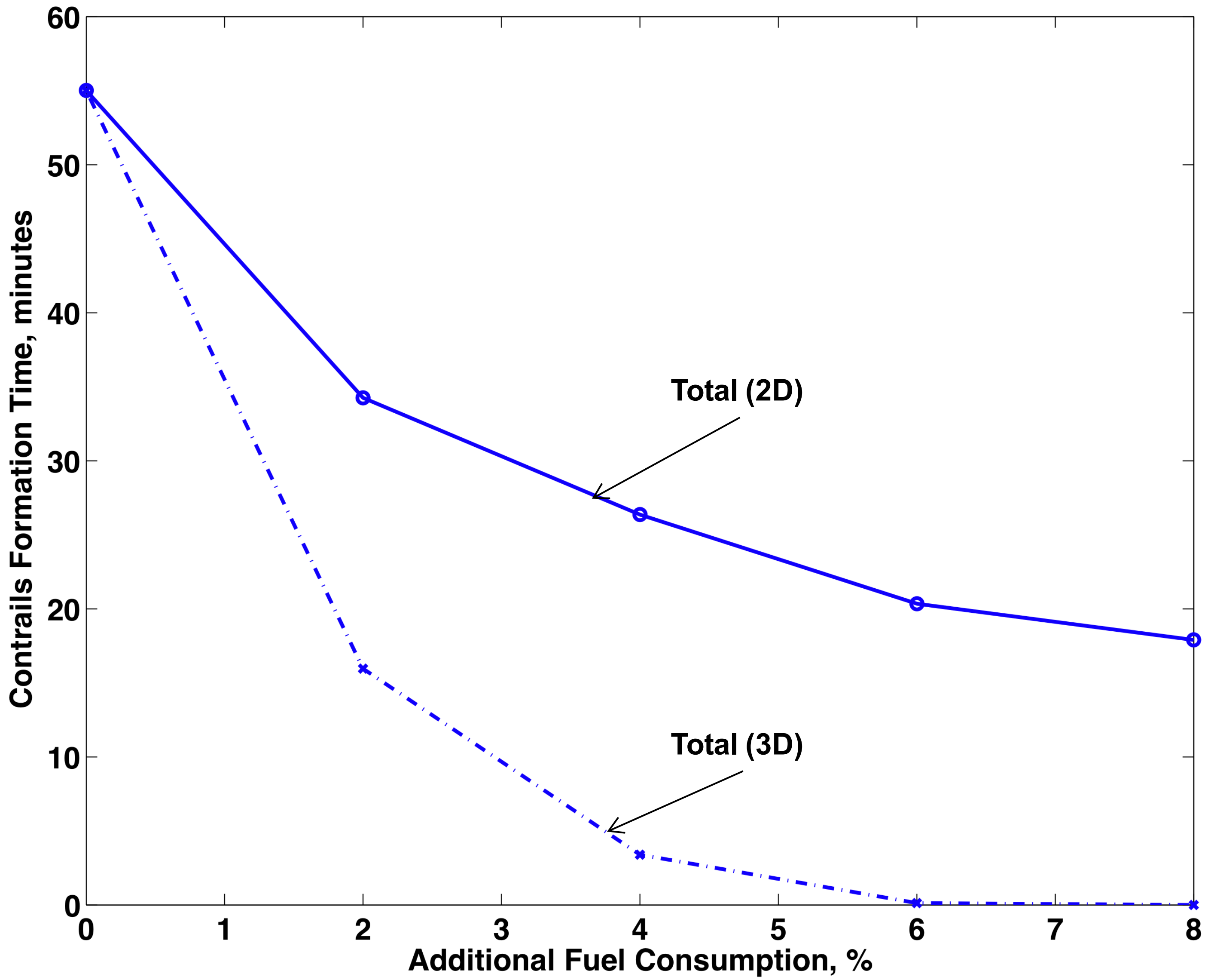
- Baseline Traffic*:* Hourly departure from 12 city-pairs with aircraft flying great circle routes at nominal cruise altitude and cruise speeds
- Generation of family of trajectories for each flight using both 2D and 3D contrail reduction strategies
  - Each trade-off curve requires approximately 73,000 aircraft trajectory calculations
- Atmospheric data for May 2007

Integrated Example: Optimal Trajectories for 12 City Pairs



- April 12, 2010; 287 flights; Cruise altitude 26,000-41,000 feet; Air speed 434-463 knots

Tradeoff between Contrail Reduction and Extra Fuel Consumption: Results for 12 City-pairs



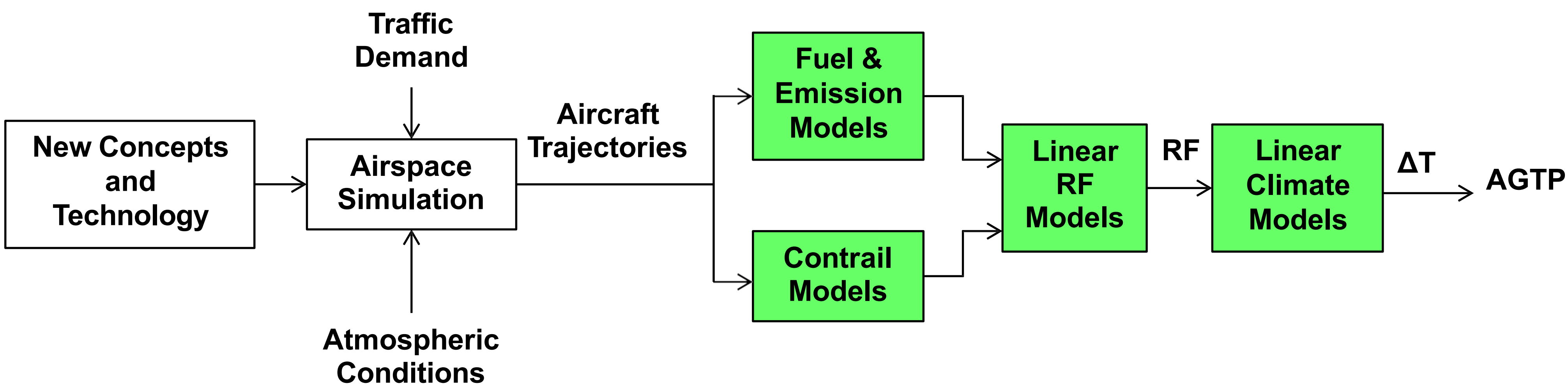
One day's simulation is just the beginning!

Aircraft Trajectory Design Trade-off for Reducing the Combined Effects of Carbon-Dioxide, Oxides of Nitrogen and Contrails

- How are the results influenced by atmospheric variations, unknowns and emission goals?
- Some of the uncertainties
  - Aircraft parameters: thrust, weights (variation of 15%), fuel flow
  - Daily variation of traffic and atmospheric conditions
    - Temperature, relative humidity, winds
  - Quantity, location and lifetime of emissions
  - Climate impact: Large uncertainty over contrail formation regions and the radiative forcing associated with contrails
- Emission goals
  - Decision-making Interval (H):10/20/50/100 years
  - Carbon neutral/reduce?
  - How much can we afford?

Linear Climate Response Models and Metrics

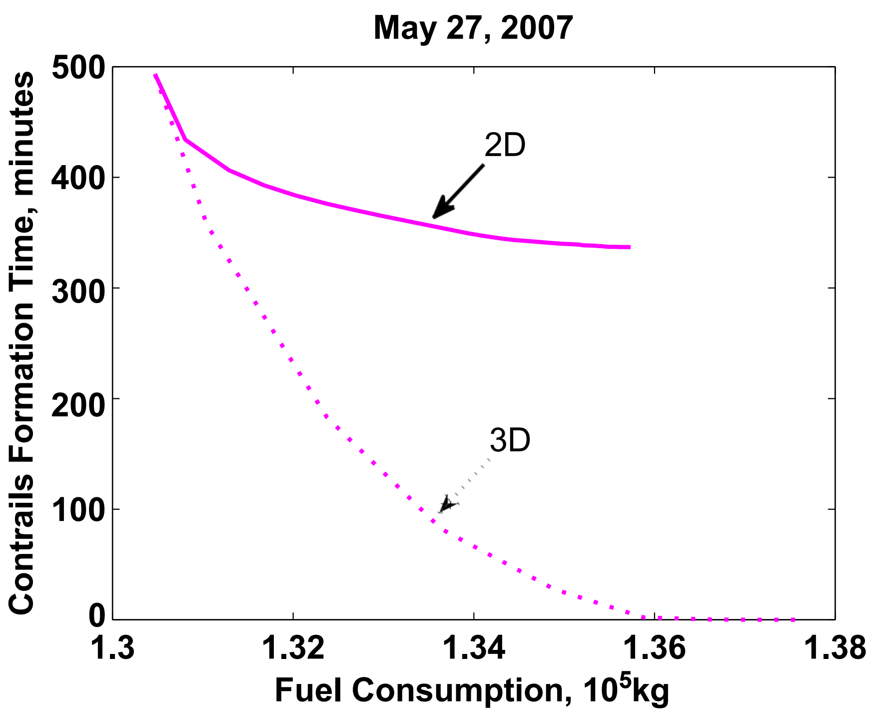
- CO_2 emissions: Most pervasive and best understood
- Radiative Forcing (RF): Radiation flux change induced by the concentration change of a greenhouse gas or an aerosol, or by cloud changes related to human activity
- Absolute Global Change Potential (AGTP): Surface temperature change at the end of H years due to a gas, aerosol or contrails

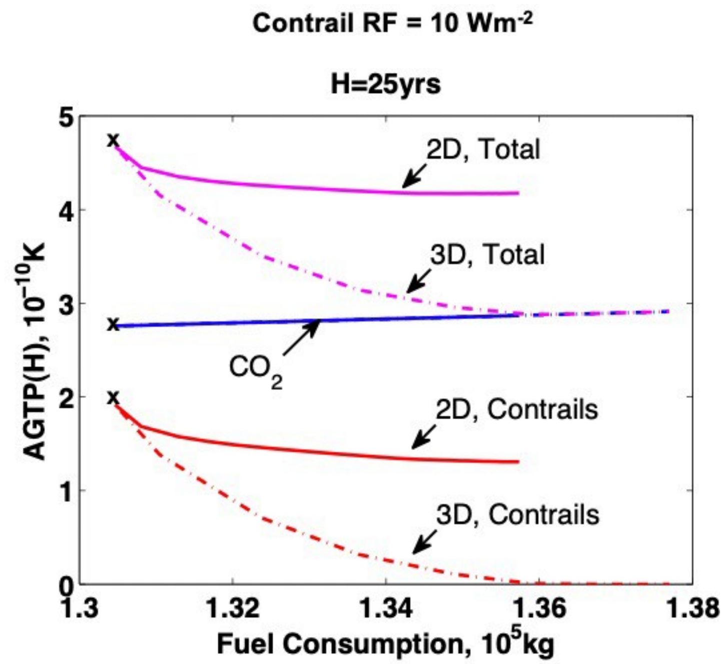


$$\Delta T = \Delta T_{CO_2} + \Delta T_{NO_x} + \Delta T_{Contrails}$$

$$\Delta T = \alpha \Delta_{CO_2} + \gamma \Delta_{NO_x} + \beta \Delta_{Contrails}$$

AGTP: Results for 12 City-pairs



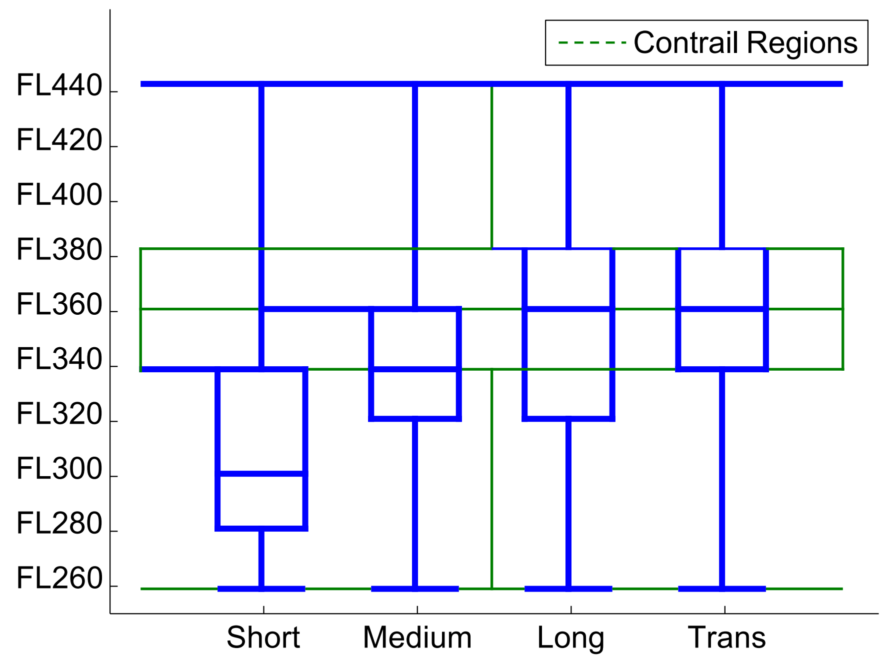


- AGTP due to CO_2 increases linearly with fuel
- AGTP due to contrails shows greater reduction initially
- Combined AGTP shows a minimum and cannot be reduced with more fuel usage
- Contrail reduction by altitude changes is more effective
- 2-3% additional fuel usage over the baseline (X) reduces surface temperature change to its lowest value

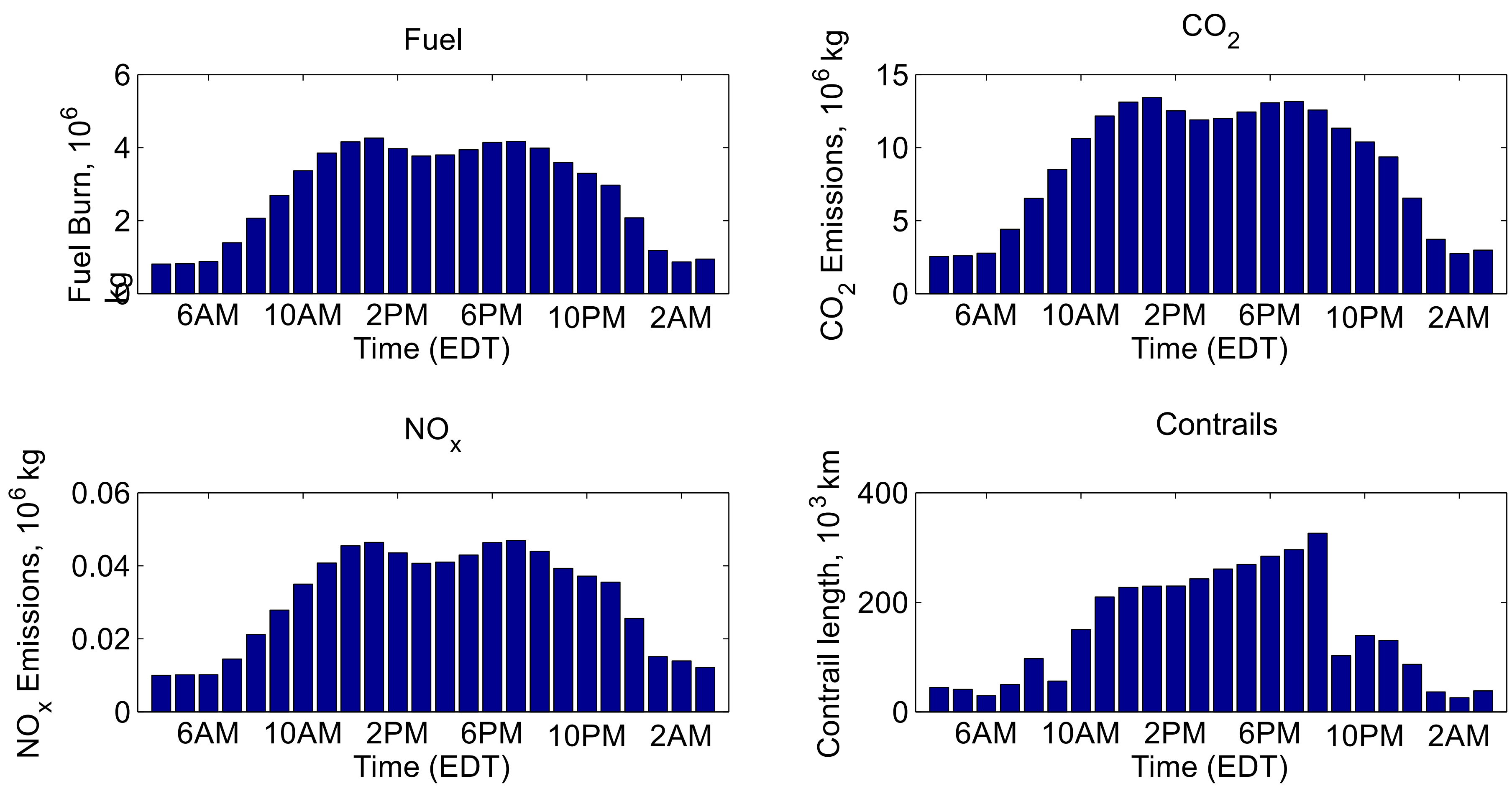
U.S. Airspace Analysis

- 100 times more aircraft than in 12 city-pairs.
- Analysis done by altitude optimization of optimal baseline horizontal route
  - Contrail reduction achieved with significant reduction in computation time

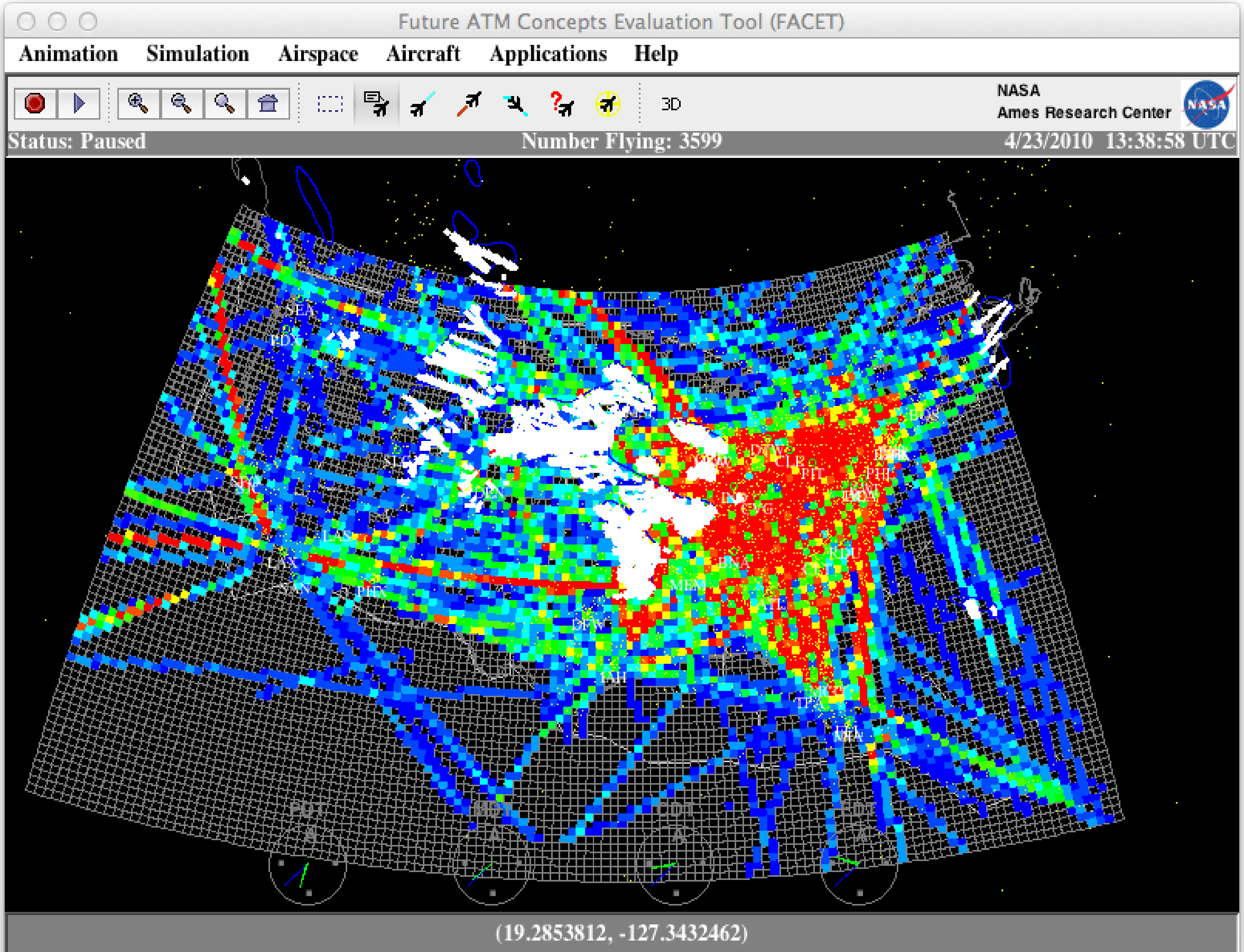
Class	Number of Flights	Contrail Minutes	Total Distance (1000 miles)
Short	13,212	12,796	3,672
Medium	8,096	52,504	5,814
Long	2,864	36,021	3,378
Transcontinental	1,953	67,420	3,378
Total	26,125	168,741	16,242



Typical Daily Aircraft Fuel Consumption and CO_2, NO_X and Contrails Production in US



Contrails and Emissions Distributions

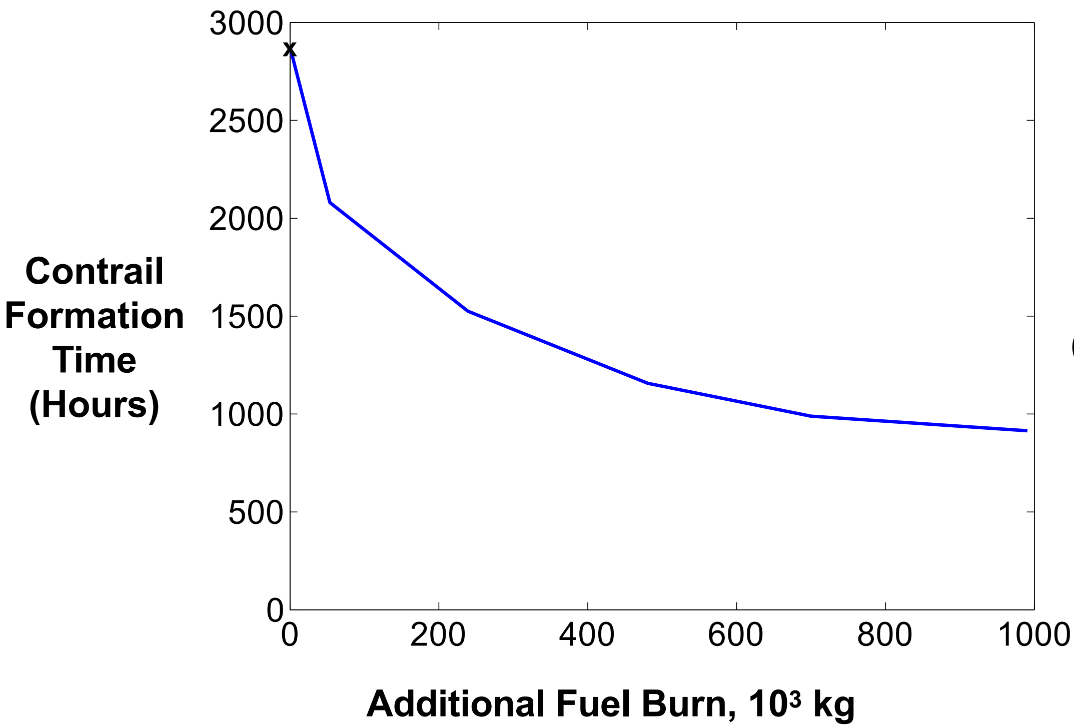


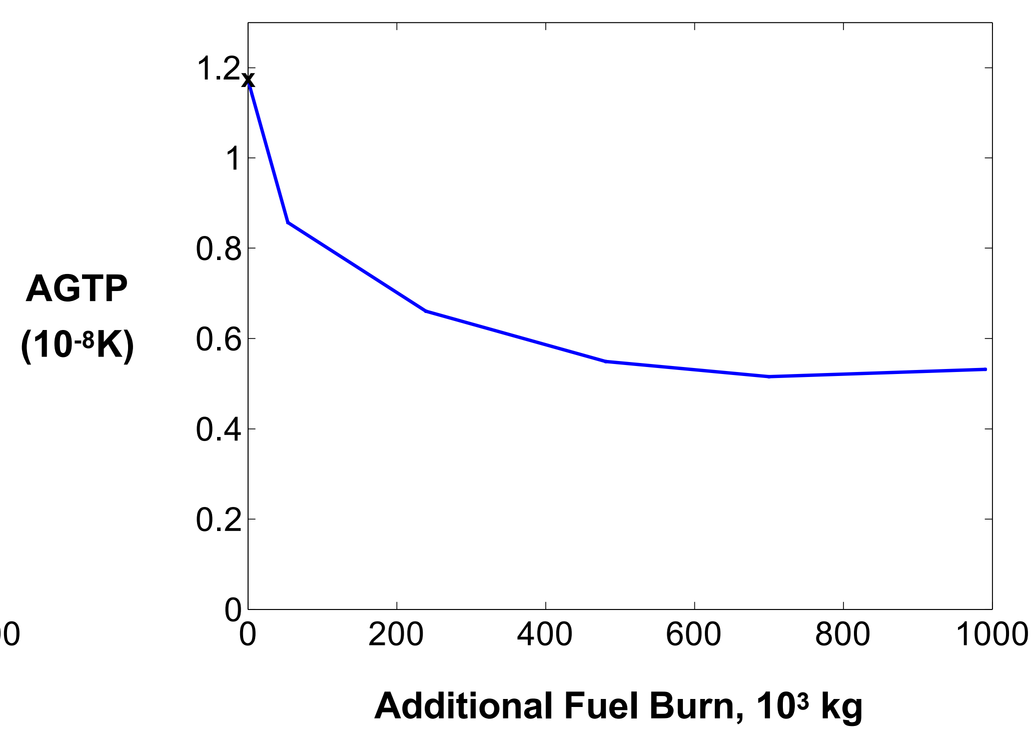
Contrails: white

CO_2 Emissions:

red: > 10000kg
yellow: > 7000kg
green: > 4000kg
blue: > 1000kg

Variation of Fuel and AGTP

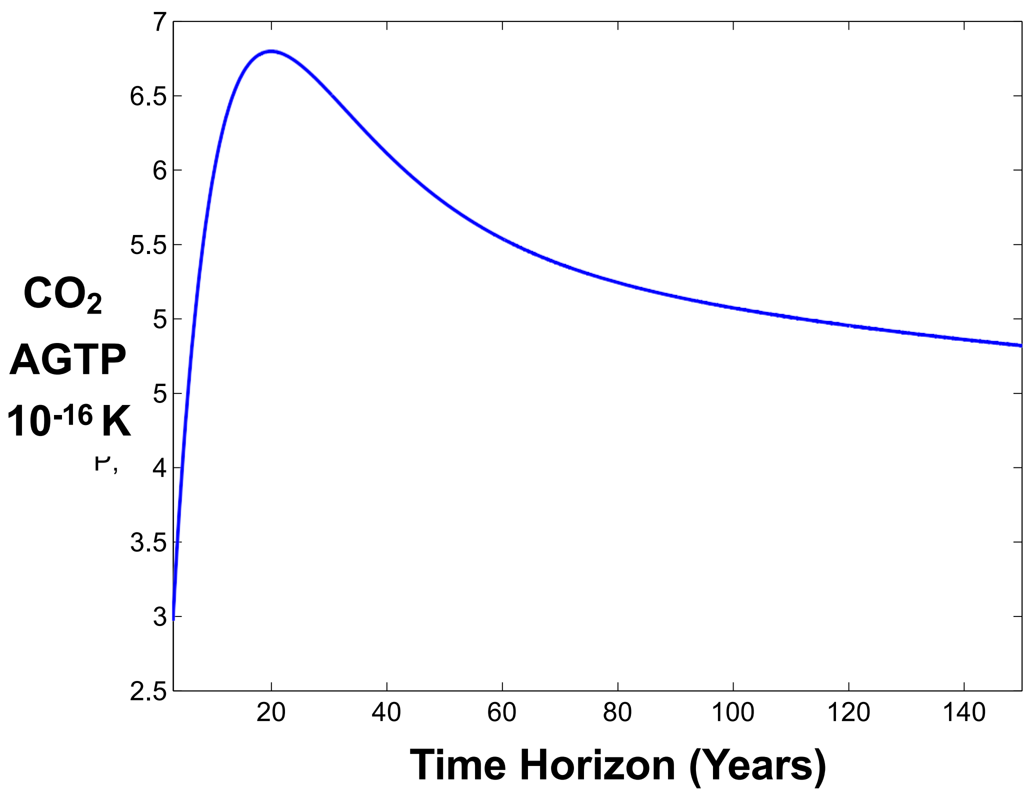


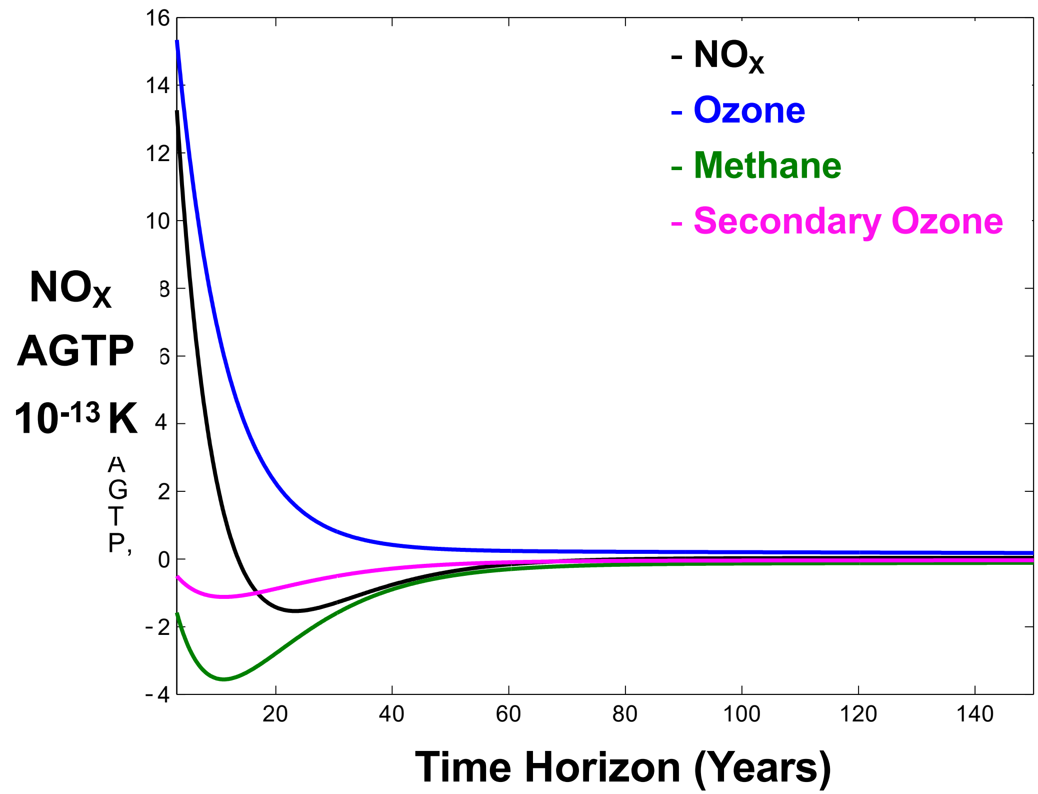


- Baseline (X): 43,215 x 10^3 kg fuel; Contrails 2875 hours
- Contrails reduced to 915 hours using additional 991 x 10^3 kg fuel (68% reduction using additional 2.3% fuel)
- Breakdown of reduction: Short (9.6%), Medium (33.3%), Long (20.8%) and Transcontinental (36.3%)
- Environmental benefit not significant after using 550 x 10^3 kg fuel

AGTP for CO_2 and NO_X

- Three components to the NO_X AGTP
  - Short-lived ozone perturbation
  - Methane perturbation
  - Methane-induced ozone perturbation





Key Findings from the Analysis

- Changing altitude is an efficient way of achieving contrail reduction
- Contrail reduction more efficient on high-contrail days
- Short flights (less than 500 miles), although half the number of flights in the National Air Space, contribute a small amount of contrails (about 7%) due to their altitude profile
- Contrail reduction beyond a certain amount may not be environmentally friendly due to the use of extra fuel and the emission of additional amount of CO_2
- Effect of contrails becomes less important as the decision-making horizon is increased
- Effect of NO_X negligible except for a small impact around 25 years
- Findings true even in the presence of uncertainty relating to contrails

Summary

- Research on environmentally friendly en route traffic flow concepts incorporating models developed by basic climate research
- Integrated linear dynamic emission and climate models in a national level airspace simulation
- Contrail reduction using altitude changes on high contrail days is effective in reducing climate impact even in the presence of uncertainties
- Capability to conduct system level analysis of Air Traffic Management concepts with environmental impact