Common Methodology for Efficient Airspace Operations

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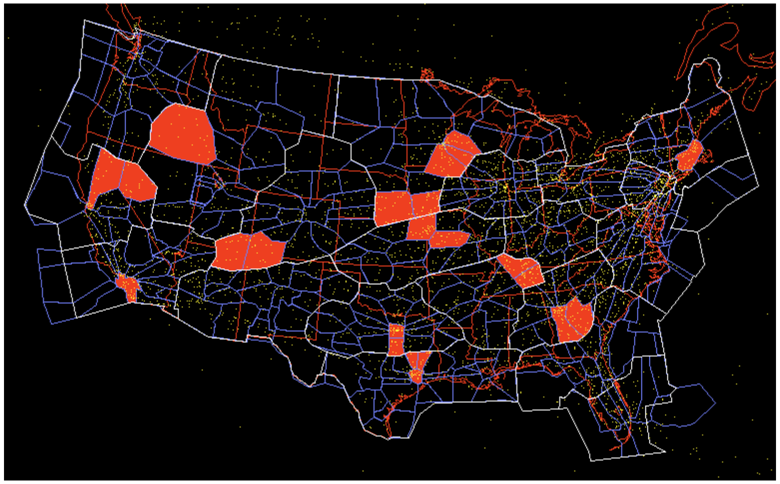
Efficient Airspace Operations Under All Conditions

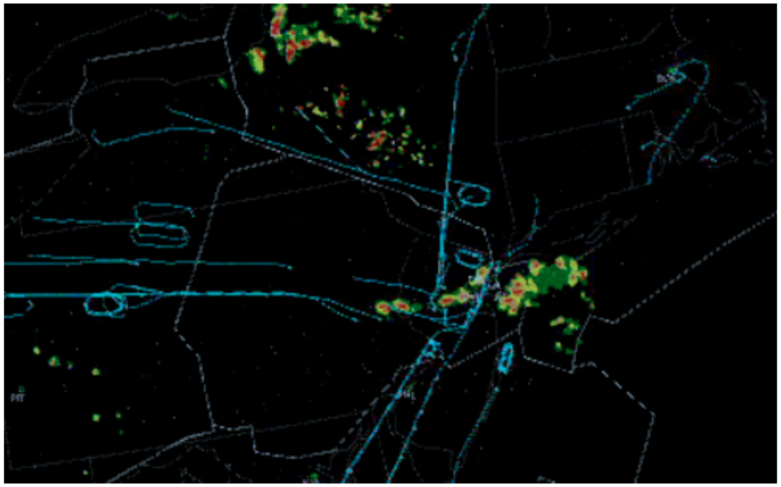
- Airspace operations is a trade-off balancing safety, capacity, efficiency and environmental considerations
- Ideal flight: Unimpeded wind optimal route with optimal climb and descent
- Operations degraded due to reduction in airport and airspace capacity caused by inefficient procedures and disturbances
  - Runway and airport constraints (fog, visibility, winds, noise)
  - Terminal area constraints (procedures, wake vortex, noise)
  - En Route Airspace Constraints
    - Congestion
    - Turbulence and Convective weather
    - Contrails
    - Volcanic Ash

En Route Airspace Constraints

Congestion



Convective weather

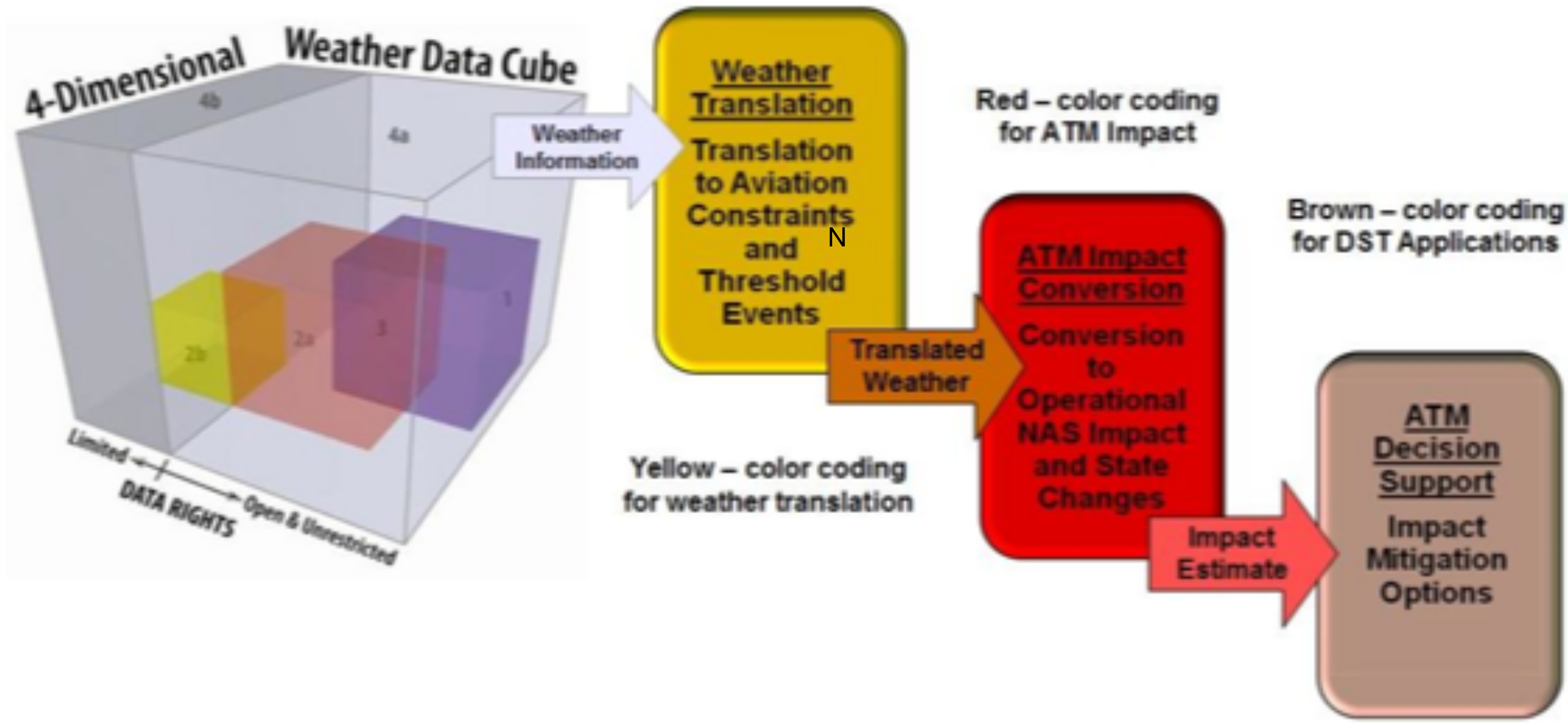


Volcanic ash

Contrails

- Frequency and the cause of the constraint/disturbance varies

NextGen Weather-ATM Integration Concepts



National Weather Service FAA Meteorology FAA ATM Operations

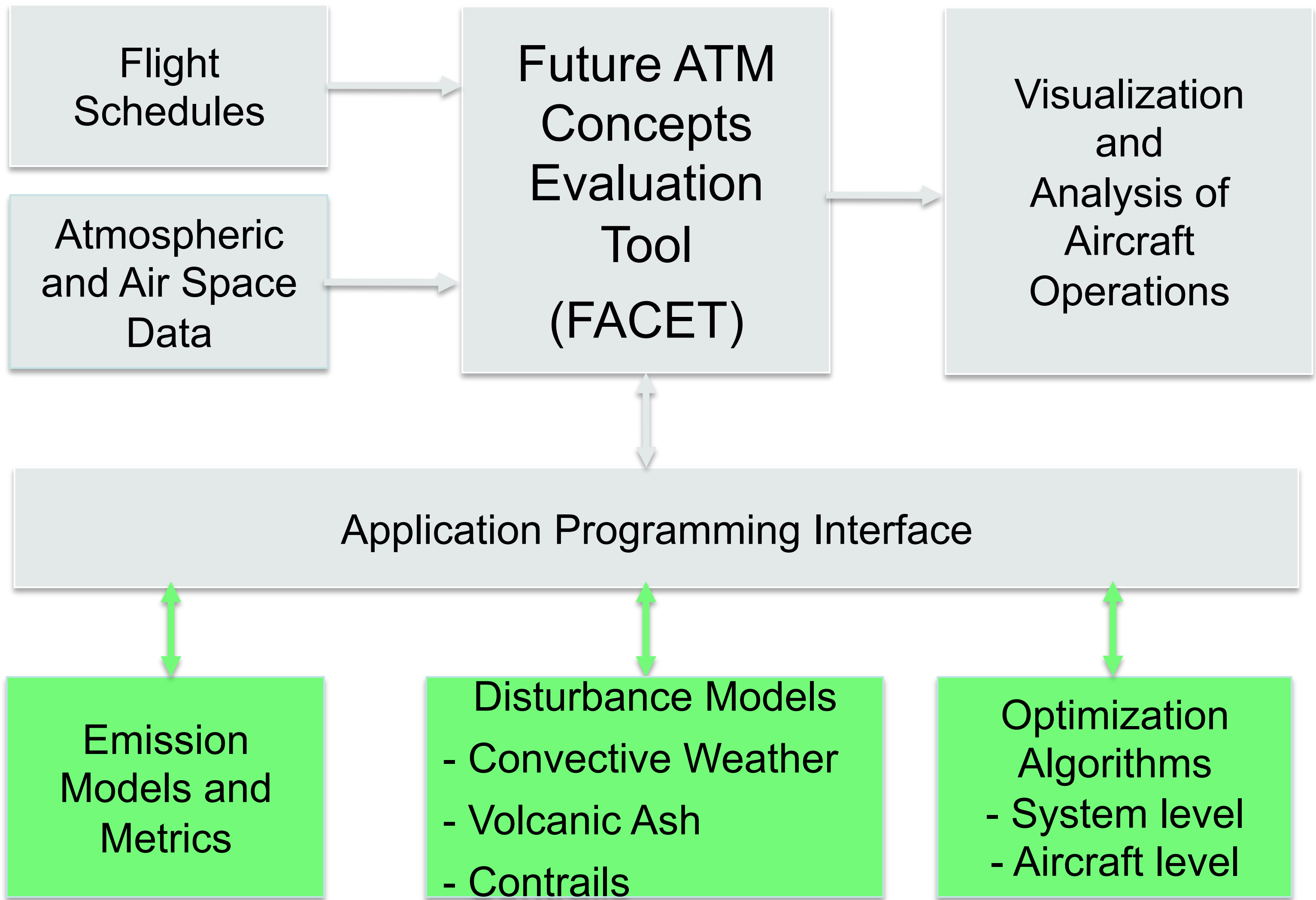
Research Goal

- Characterize and predict disturbance using a combination of models, satellite observations and aircraft based sensors
  - Adapt from atmospheric sciences and weather research
- Develop methodology to design fuel efficient trajectories in the presence of disturbances
- Integrate environmental factors and new fuel and vehicle technologies in airspace simulations to evaluate alternate concepts and policies for sustainable aviation

Outline

- Modeling approach
- Models
  - Emissions
  - Contrails formation
  - Volcanic ash
- Efficient aircraft trajectories
- Integrated example
- 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
Disturbance Models
- Convective Weather
- Volcanic Ash
- Contrails
Optimization Algorithms
- System level
- Aircraft level

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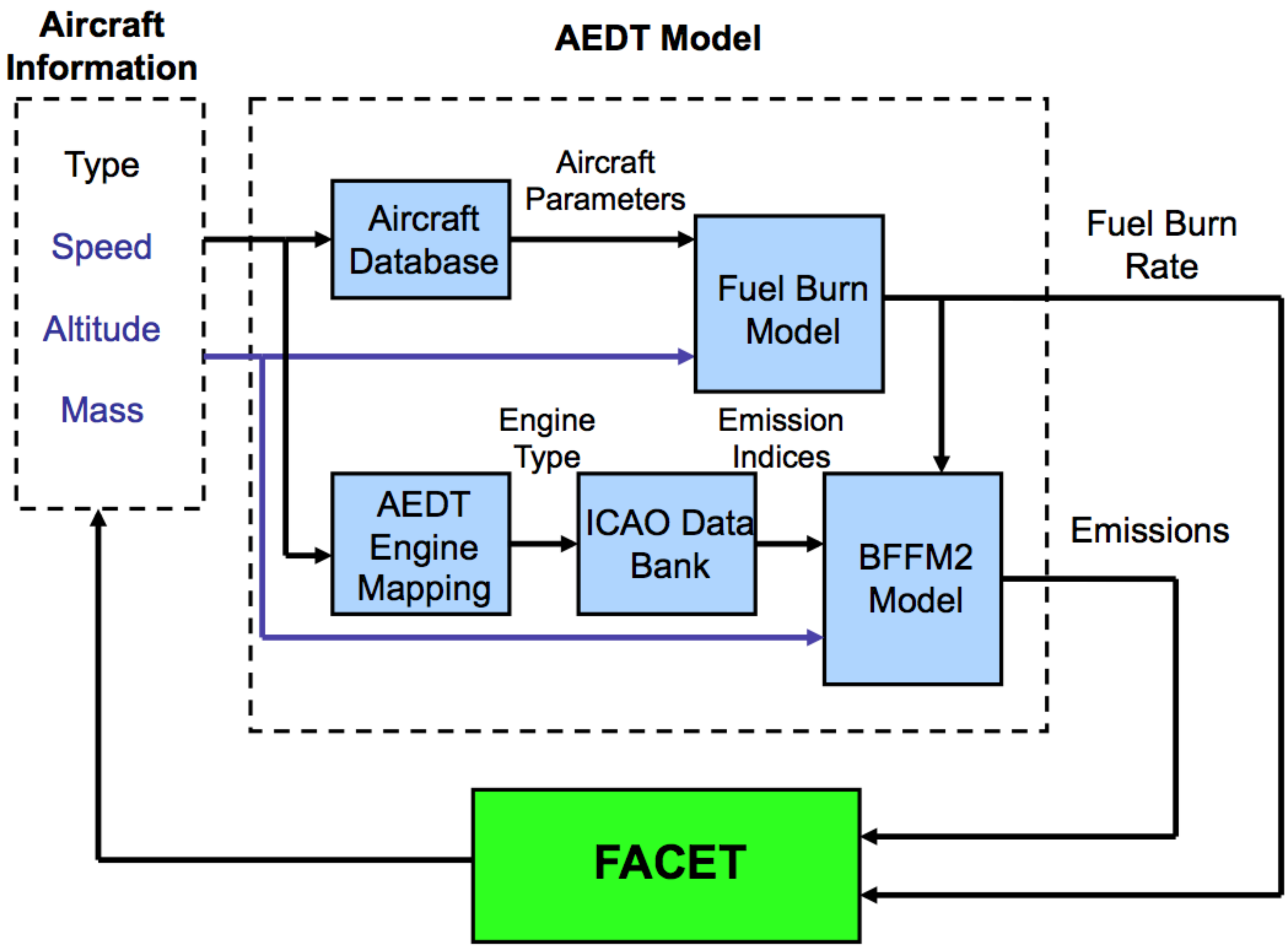
Fuel and Emission Models



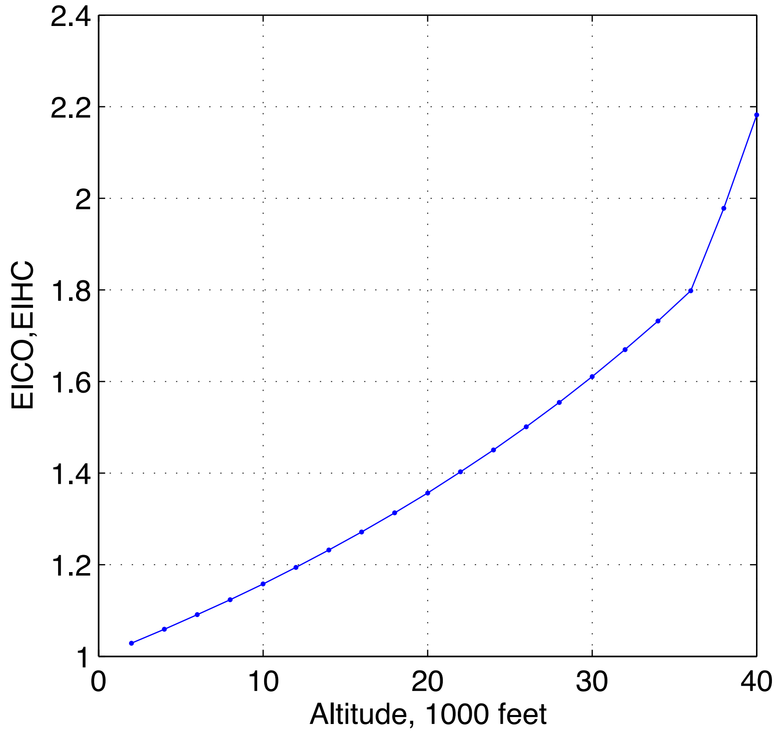
Aviation Environmental Design Tool (AEDT)
Eurocontrol's Base of Aircraft Data (BADA)

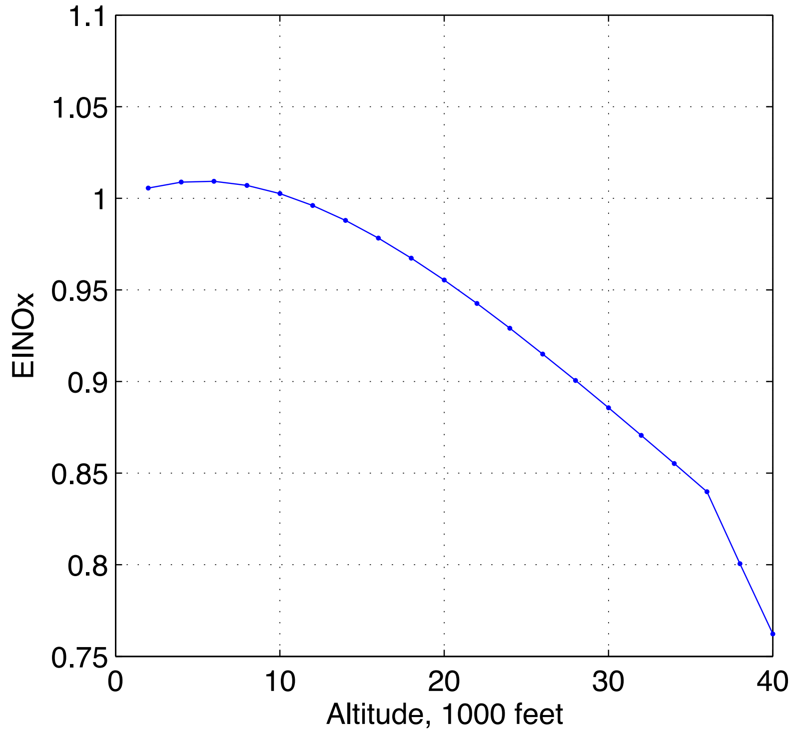
Variation of Emissions with Altitude

$$e(CO_2) = 3155 \times \sigma \qquad e(HC) = EIHC \times \sigma$$

$$e(H_2O) = 1237 \times \sigma \qquad e(CO) = EICO \times \sigma$$

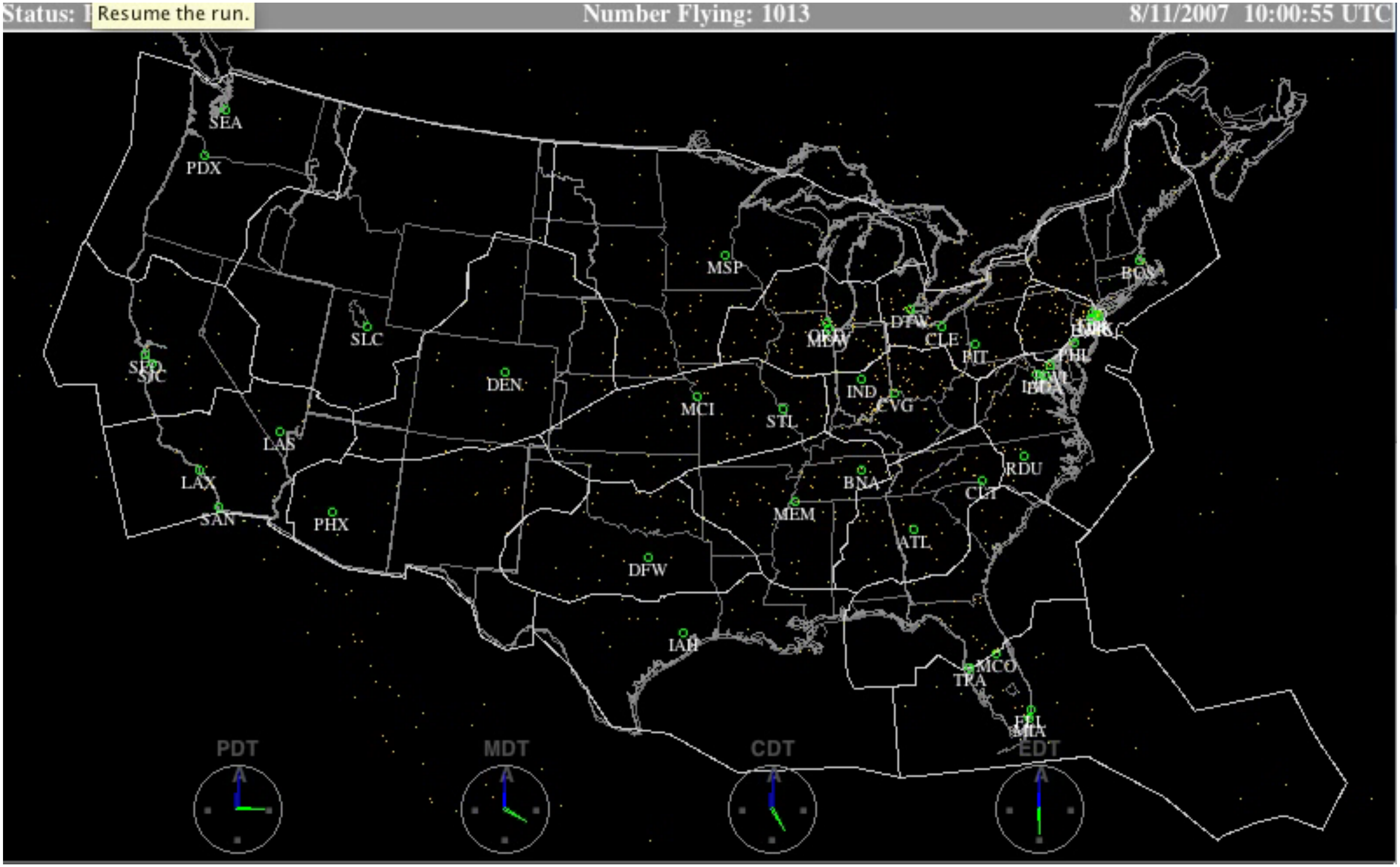
$$e(SO_2) = 0.8 \times \sigma \qquad e(NO_x) = EINO_x \times \sigma$$





- Fuel and emission models undergoing additional verification using AEDT (Collaboration with Volpe National Transportation Systems Center)

CO_2 Emissions (Boeing 737-300)

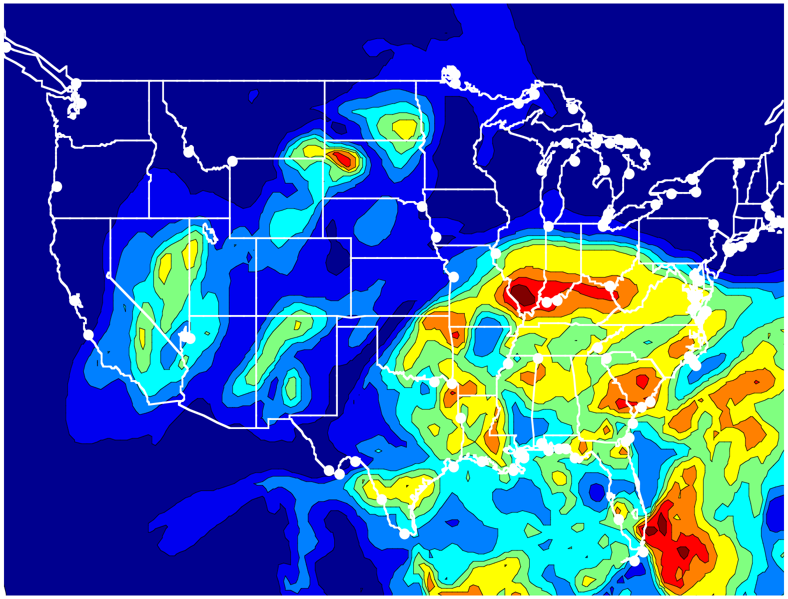


Contrails

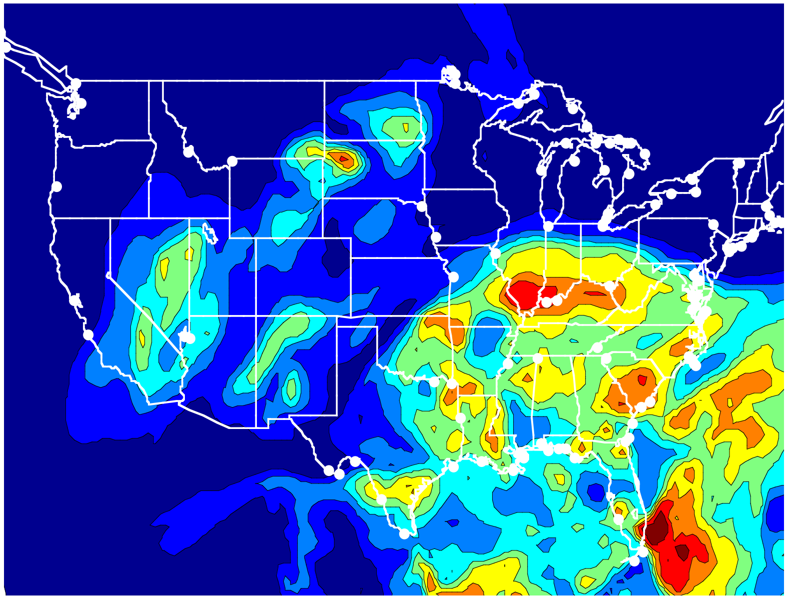
- Aircraft condensation trails occur when warm engine exhaust gases and cold ambient air interact
  - Contrails form when Relative Humidity with respect to Water (RHW) > Temperature dependent threshold
  - Persist when Relative Humidity with respect to Ice (RHI) >100%
- Contribution of contrails to global warming may be larger than contribution from CO_2 emissions

http://www.nature.com/nclimate/journal/v1/n1/full/nclimate1078.html

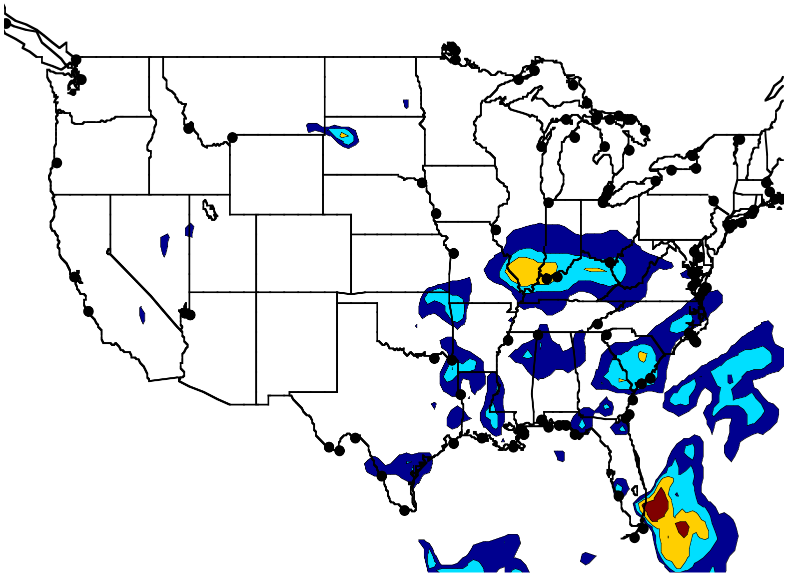
Persistent Contrail Formation Model



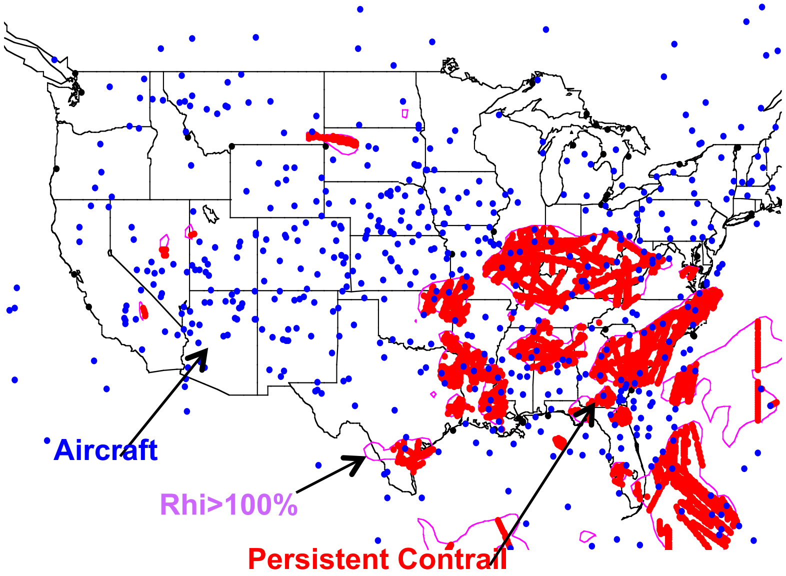
RHW Contours



RHI Contours

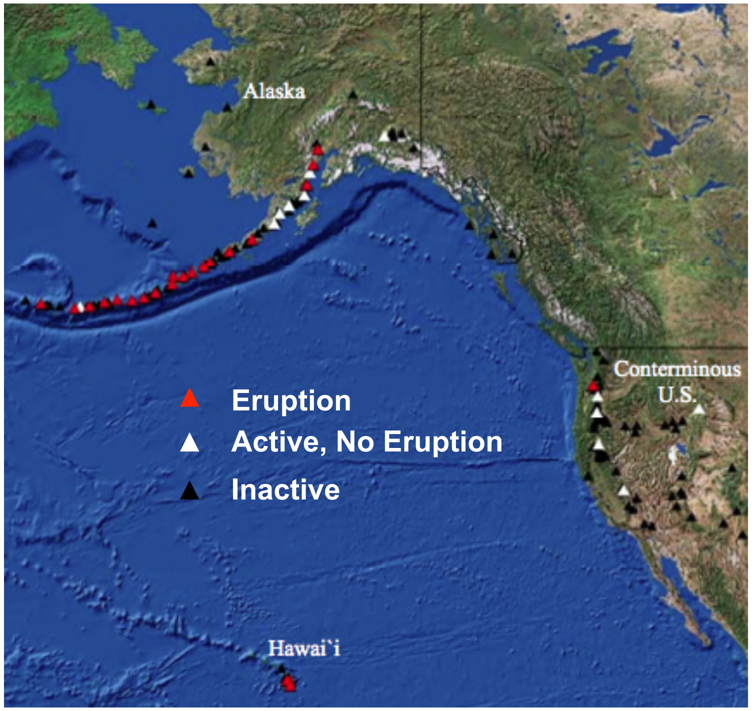


RHI>100% Contours



Volcanic Activity*

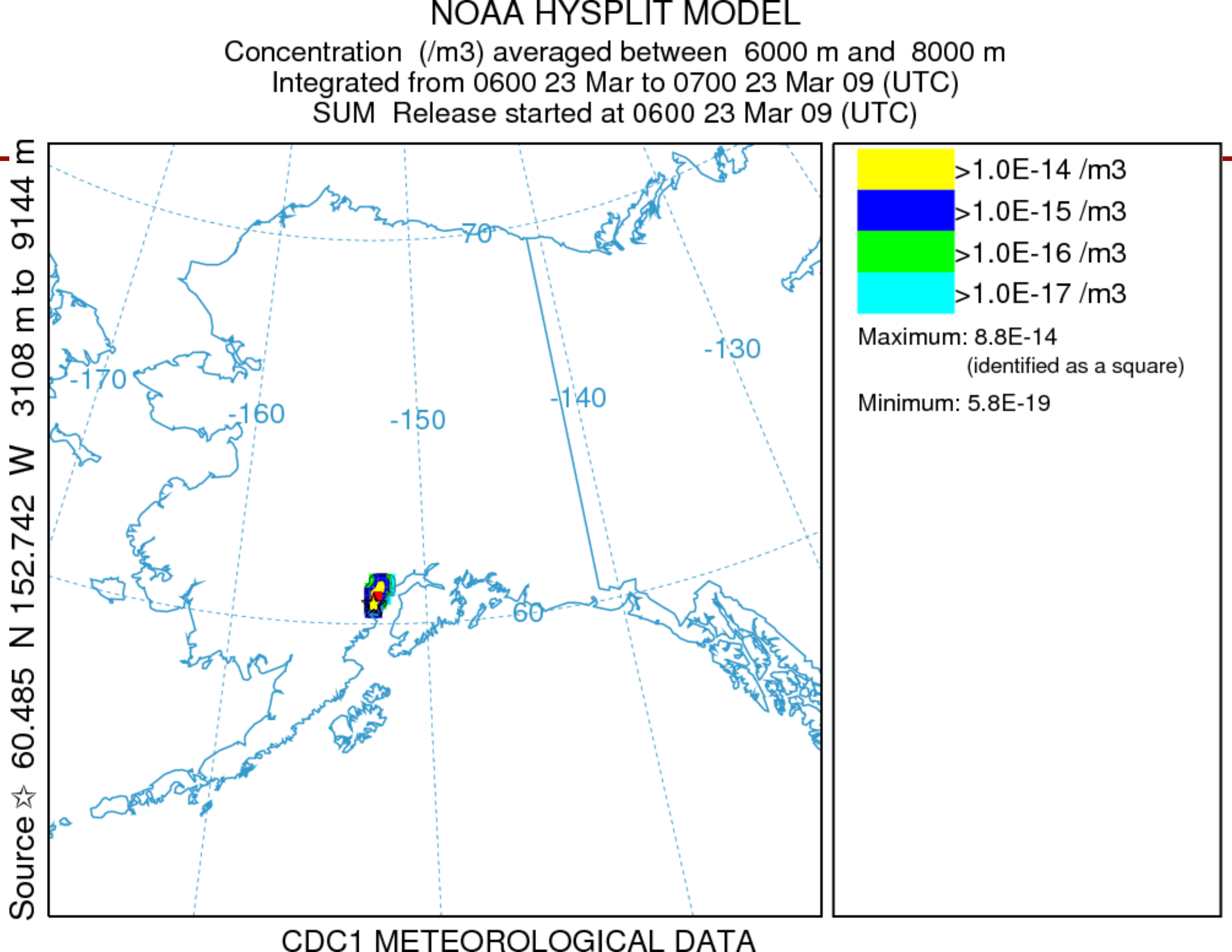
- Air traffic during April-May, 2010 Iceland (Eyjafjallajokull) volcanic eruption
- Major volcanic eruptions in US
  - Mount St. Helens (1980, Portland, OR airport)
  - Mount Redoubt (1989-90, Anchorage, AK airport; 2009, Anchorage and Fairbanks, AK airports)
- Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)
  - Developed by NOAA Air Resources Laboratory for predictions of volcanic plume locations



US volcanic activity 1980-2008

- Accuracy of dispersion models depends on eruption height and strength
- Integration of plume locations with FACET and evaluate concepts for plume refinement using observations

* Angela K. Diefenbach, Marianne Guffanti, and John W. Ewert , "Chronology and References of Volcanic Eruptions and Selected Unrest in the United States, 1980- 2008, USGS Report 2009-1118, 2009


NOAA HYSPLIT MODEL
Concentration (/m3) averaged between 6000 m and 8000 m
Integrated from 0600 23 Mar to 0700 23 Mar 09 (UTC)
SUM Release started at 0600 23 Mar 09 (UTC)
Source ☆ 60.485 N 152.742 W 3108 m to 9144 m
70
60
-170
-160
-150
-140
-130
>1.0E-14 /m3
>1.0E-15 /m3
>1.0E-16 /m3
>1.0E-17 /m3
Maximum: 8.8E-14
(identified as a square)
Minimum: 5.8E-19
CDC1 METEOROLOGICAL DATA

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Optimal Trajectory on Horizontal Plane

- Find the optimal trajectory given the arrival and departure airports, cruise speed and winds subject to environmental constraints

- Aircraft equations of motion in the horizontal plane are

$$\dot{x} = V\cos\theta + u(x,y)$$

$$\dot{y} = V\sin\theta + v(x,y) \quad \text{subject to}$$

$$Th = D$$

$$L = W$$

$$\dot{m} = -f$$

Optimization Subject to Environmental Constraints

- Optimize horizontal trajectory by determining the heading angle that minimizes the cost function

$$J = 1/2X^T(t_f)MX(t_f) + \int_{t_0}^{t_f} [\underbrace{C_t}_{\text{Time cost}} + \underbrace{C_f}_{\text{Fuel cost}} f + \underbrace{C_r}_{\text{Contrails penalty cost}} \cdot r(x,y)]dt$$

- Solution reduces to solving

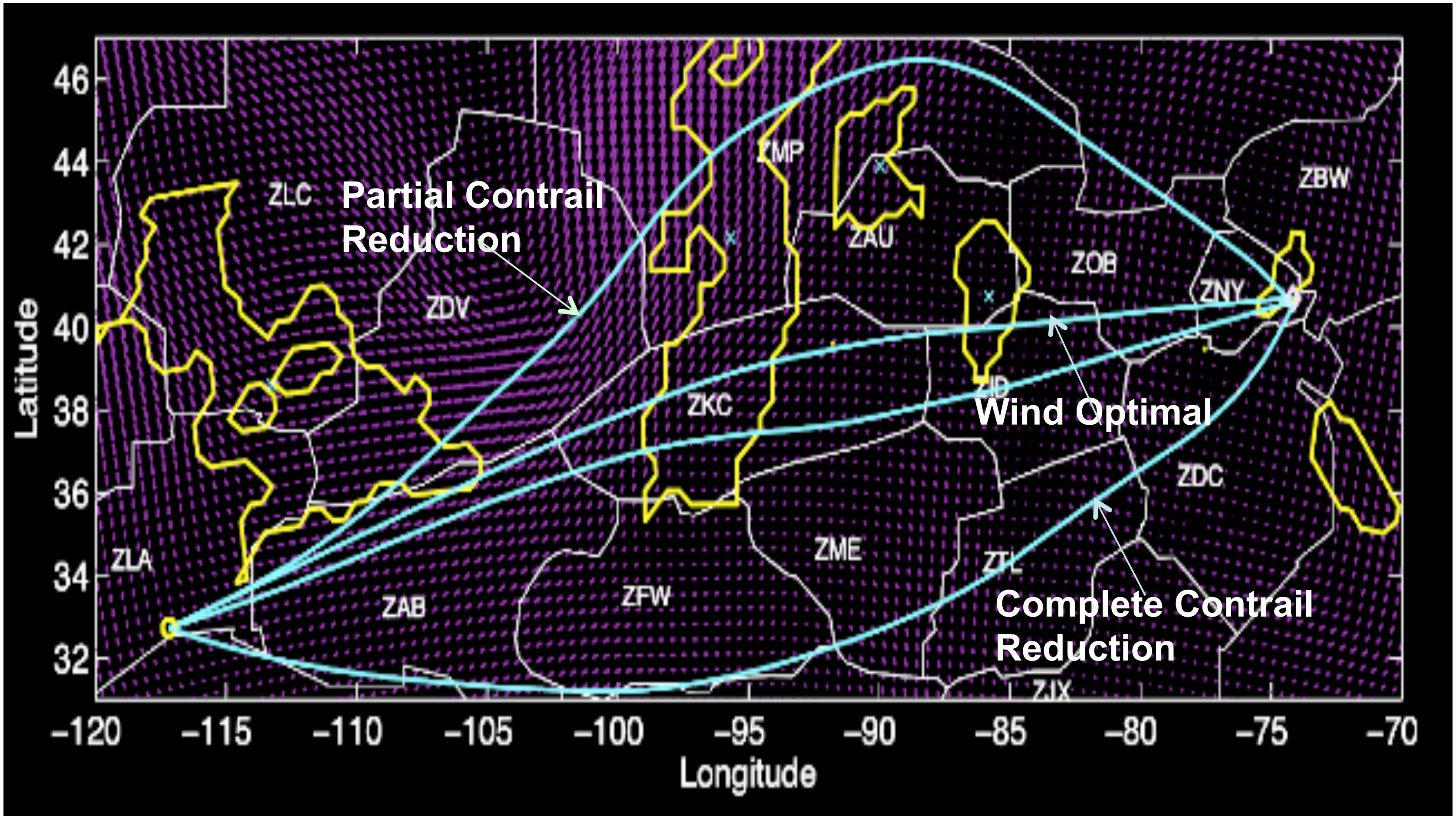
$$\dot{x} = V\cos\theta + u(x,y)$$

$$\dot{y} = V\sin\theta + v(x,y)$$

$$\dot{\theta} = \frac{(V + u(x,y)\cos\theta + v(x,y)\sin\theta)}{(C_t + C_f f + C_r r(x,y))}(-C_r \sin\theta \frac{\partial r(x,y)}{\partial x} + C_r \cos\theta \frac{\partial r(x,y)}{\partial y})$$

$$+\sin^2\theta(\frac{\partial v(x,y)}{\partial x}) + \sin\theta\cos\theta(\frac{\partial u(x,y)}{\partial x} - \frac{\partial v(x,y)}{\partial y}) - \cos^2\theta(\frac{\partial u(x,y)}{\partial y})$$

Contrail Reducing Optimal Aircraft Trajectories



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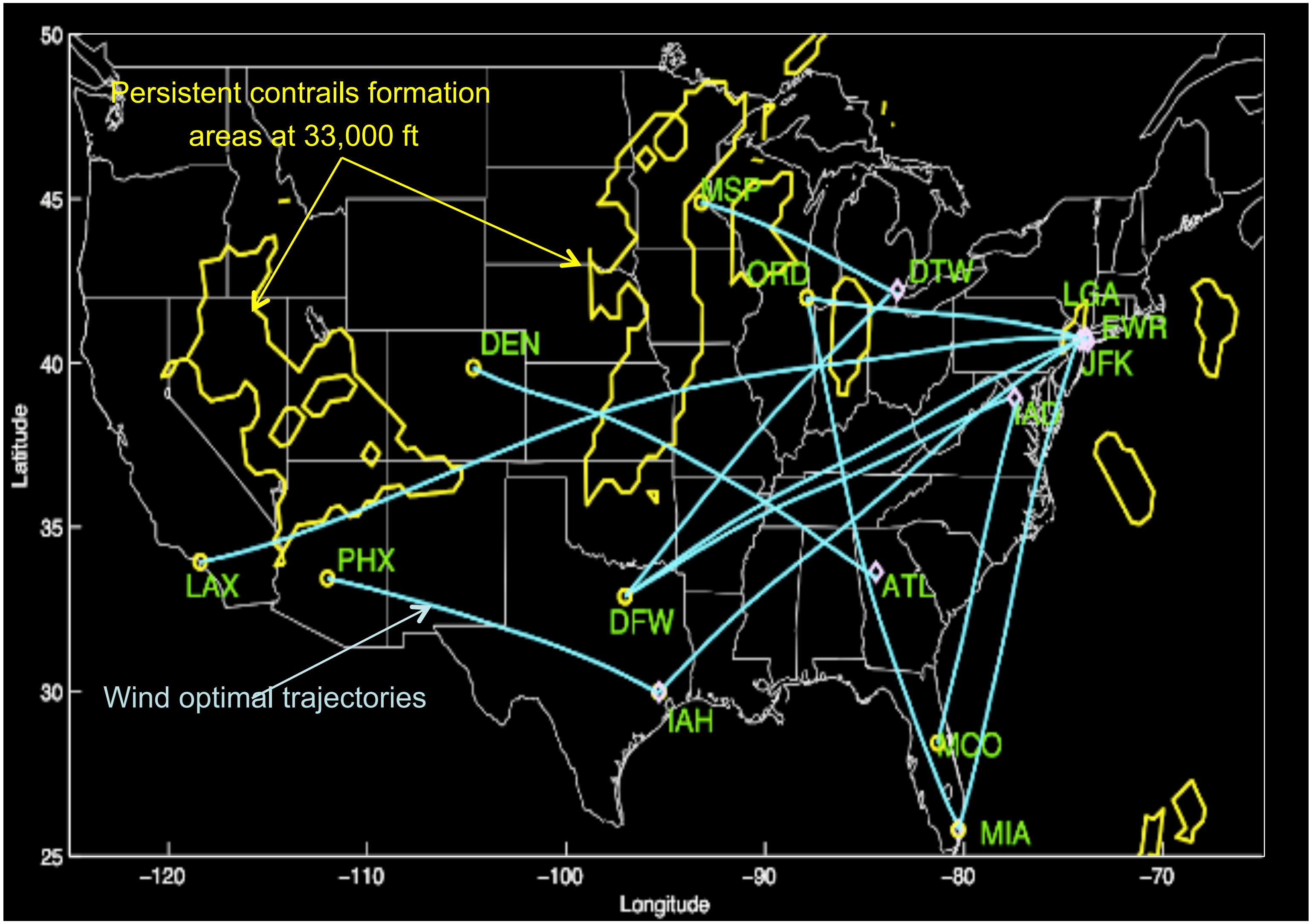
Optimal trajectories between 12 City-pairs

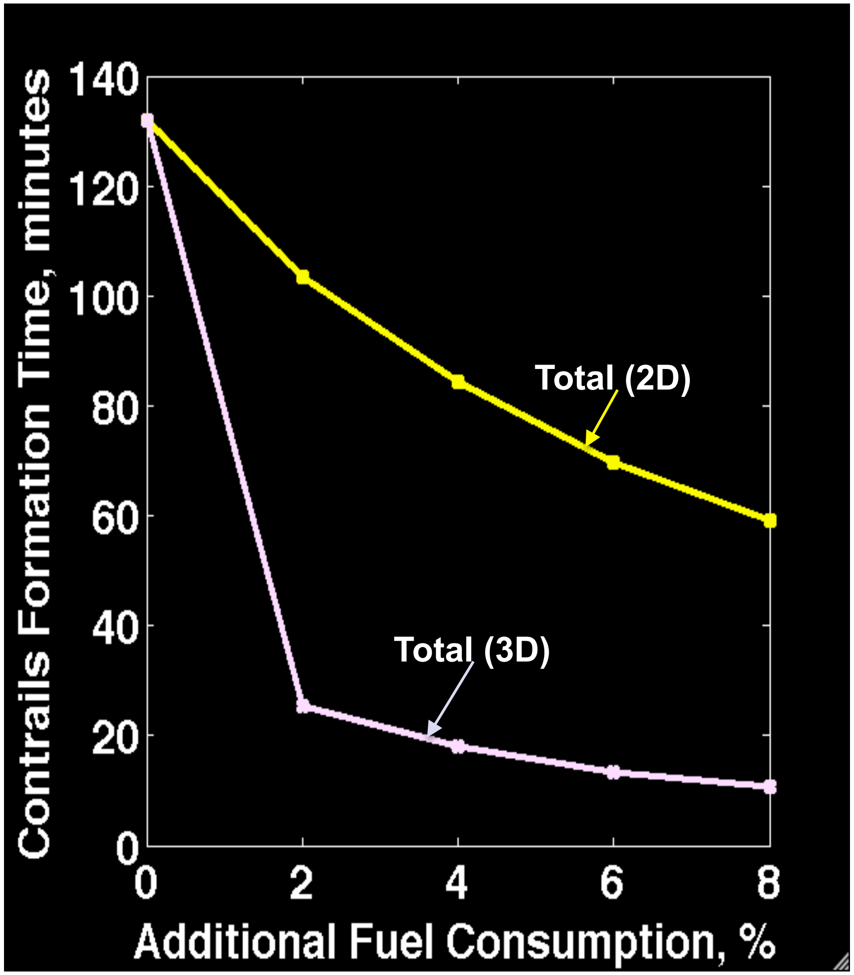


Optimal Trajectories for 12 City Pairs

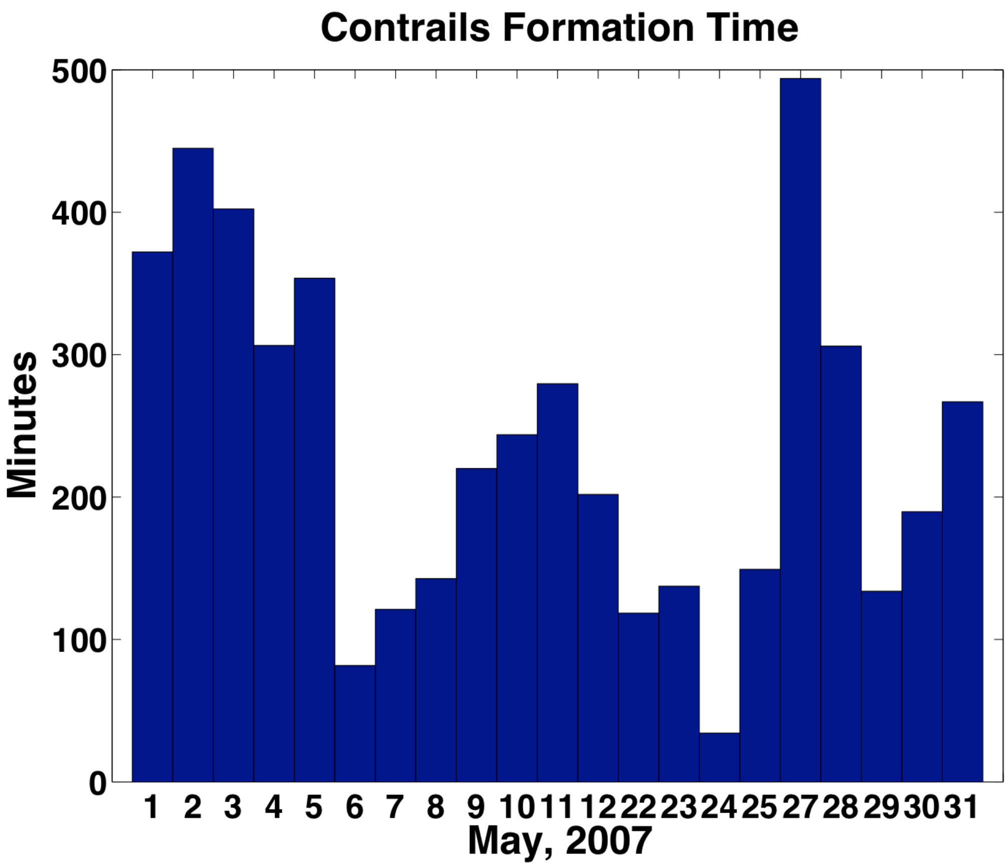
- Investigate the tradeoff between persistent contrails formation and additional fuel burn, with and without altitude optimization, for 12 city-pairs in the continental United States for a period of 24 hours starting from 6 a.m. EDT on May 24, 2007

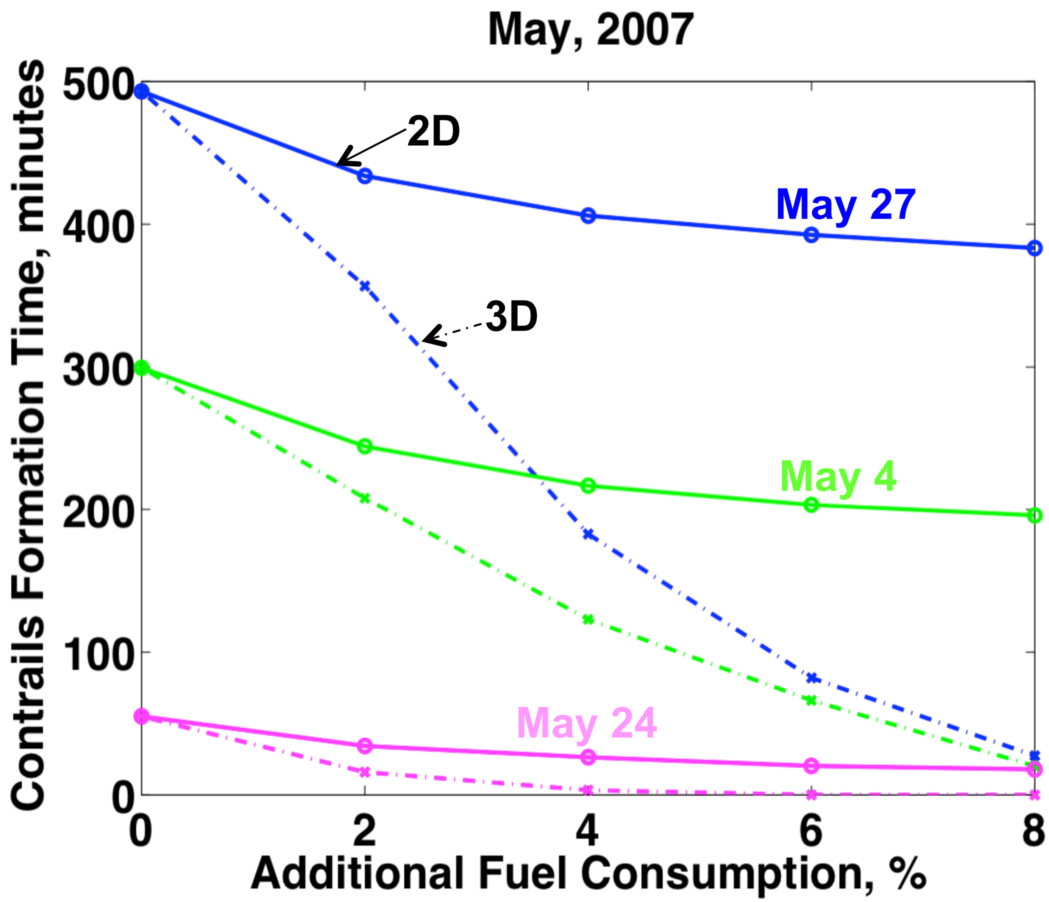
- For each hour (24 hours in total)
    - For each city pair and direction (12 pairs, 2 directions)
        - For each possible flight level (6 levels between 290 – 400)
            - Compute 1 wind-optimal trajectory
            - Compute 20 wind-optimal contrails-avoidance trajectories
            - Compute fuel burn for each of the 21 trajectories
            - Compute persistent contrails formation time for each of the 21 trajectories

Results for 12 City-pairs

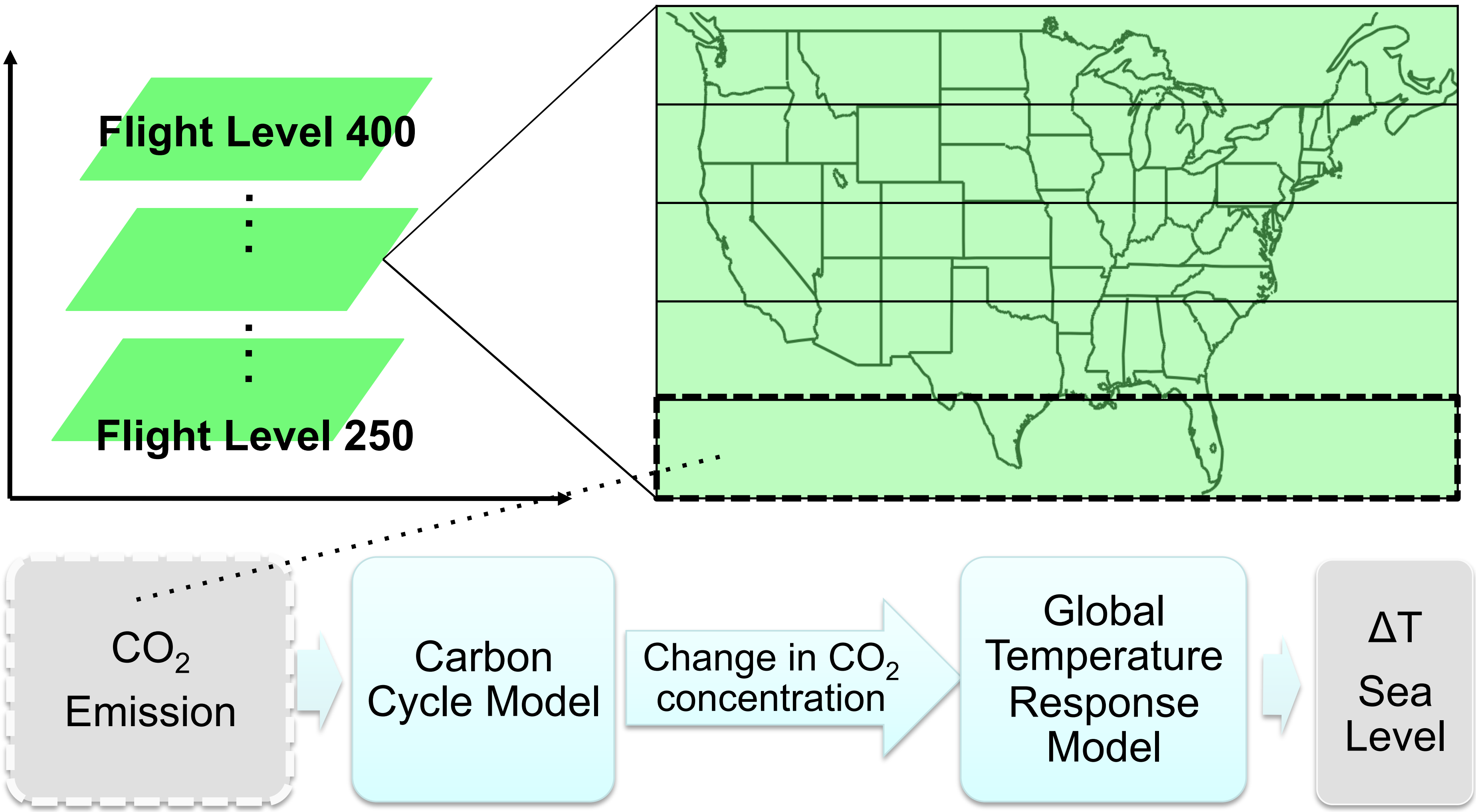


Daily variations in the trade-off of emissions



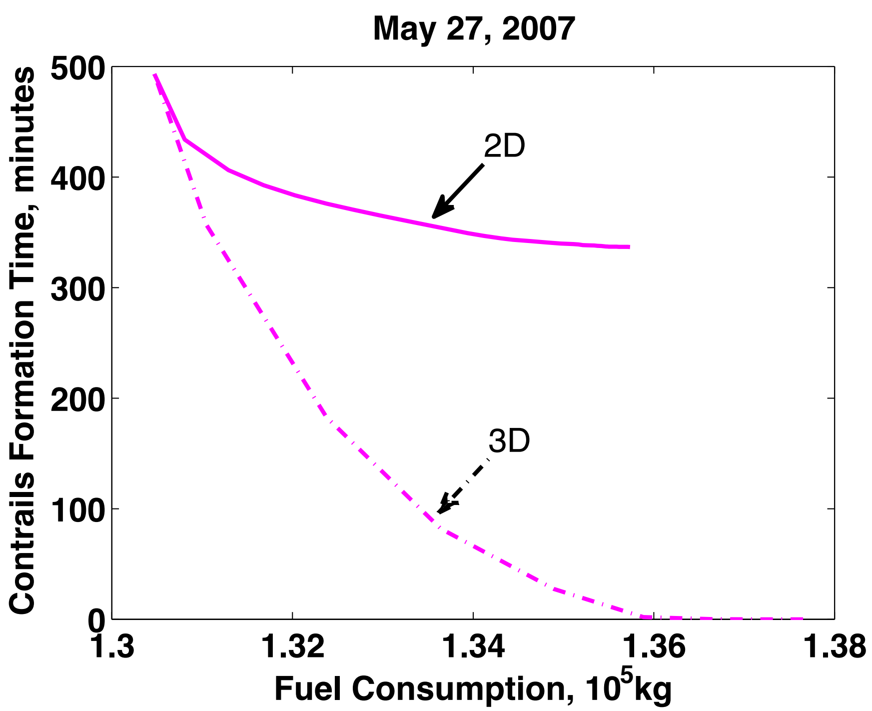


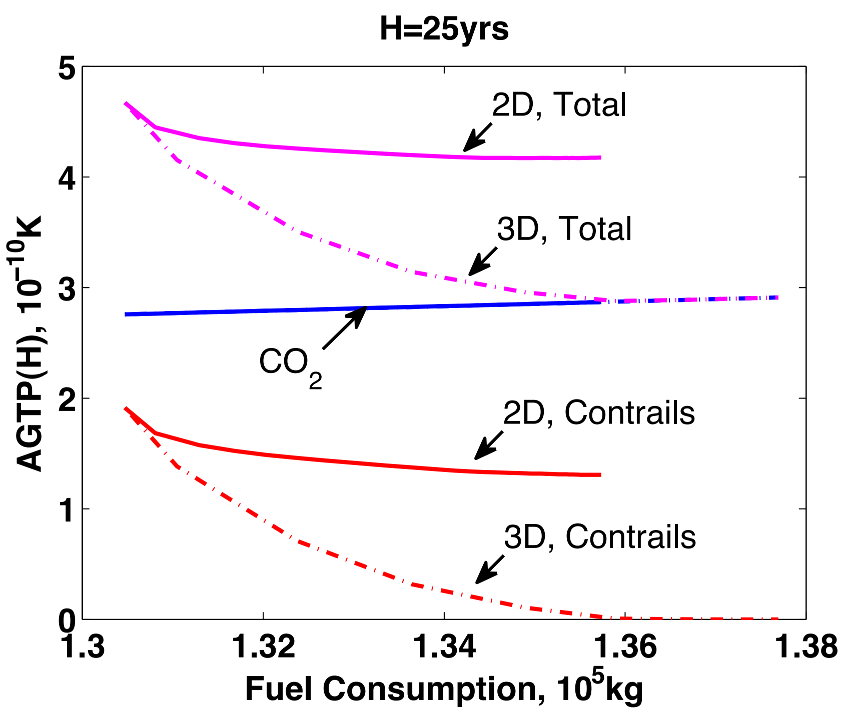
Climate Impact of Emissions: Linear Climate Models



$$E(t) \longrightarrow \boxed{\begin{aligned} \dot{x}_1 &= A_1 x_1 + B_1 E(t) \\ y_1 &= C_1 x_1 \end{aligned}} \xrightarrow{\;y_1\;} \boxed{\begin{aligned} \dot{x}_2 &= A_2 x_2 + B_2 y_1 \\ y_2 &= C_2 x_2 \end{aligned}} \longrightarrow y_2$$

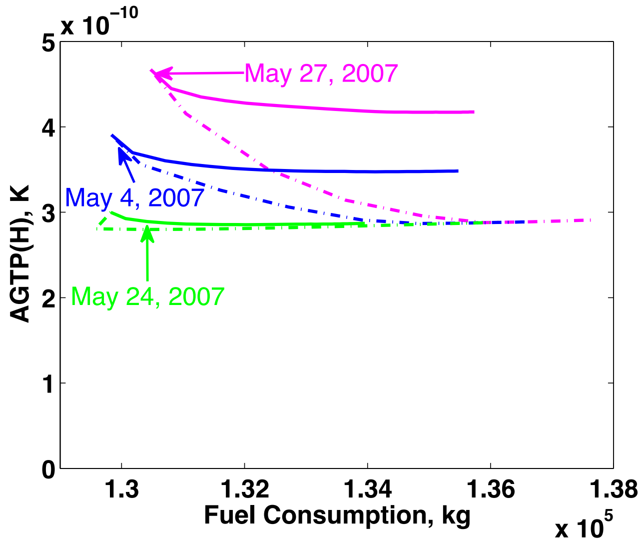
Results for 12 City-pairs



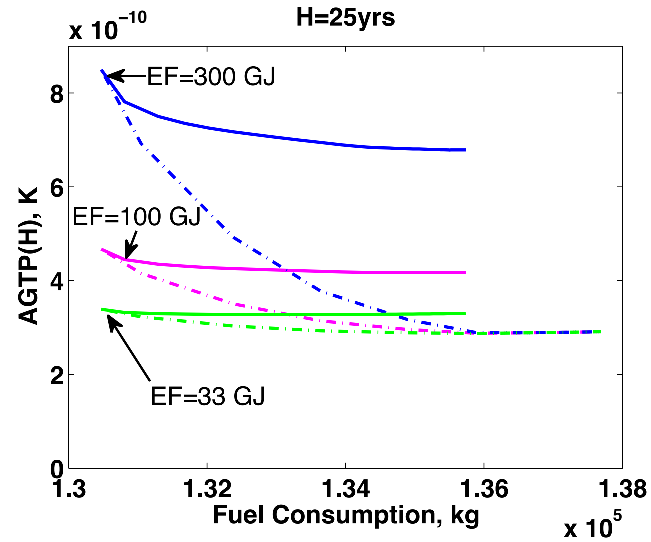


- 2-3% additional fuel usage reduces surface temperature change to its lowest value

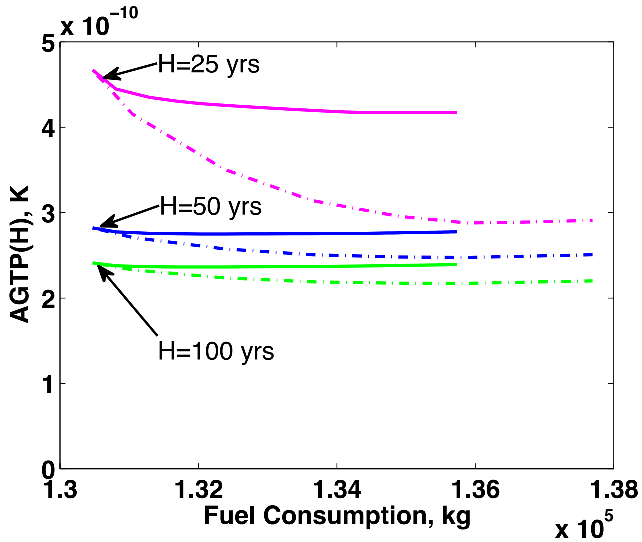
Parameter Variation of AGTP



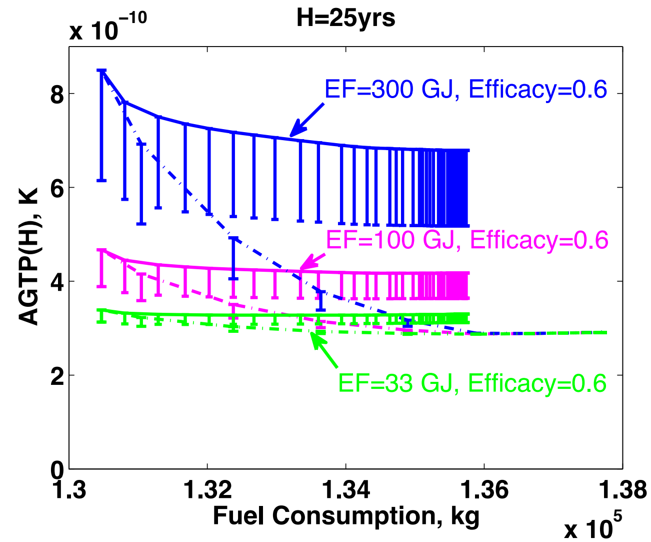
Daily Variation



Variation (Contrail RF)



Variation (End Time)



Variation (Efficacy)

Concluding Remarks

- Developing a common methodology to model and avoid disturbances affecting airspace
- Integrated contrails and emission models to a national level airspace simulation
- Developed capability to visualize, evaluate technology and alternate operational concepts and provide inputs for policy-analysis tools to reduce the impact of aviation on the environment
- Collaborating with Volpe Research Center, NOAA and DLR to leverage expertise and tools in aircraft emissions and weather/climate modeling.