An Econometric Model of Flight En Route Inefficiency

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Outline

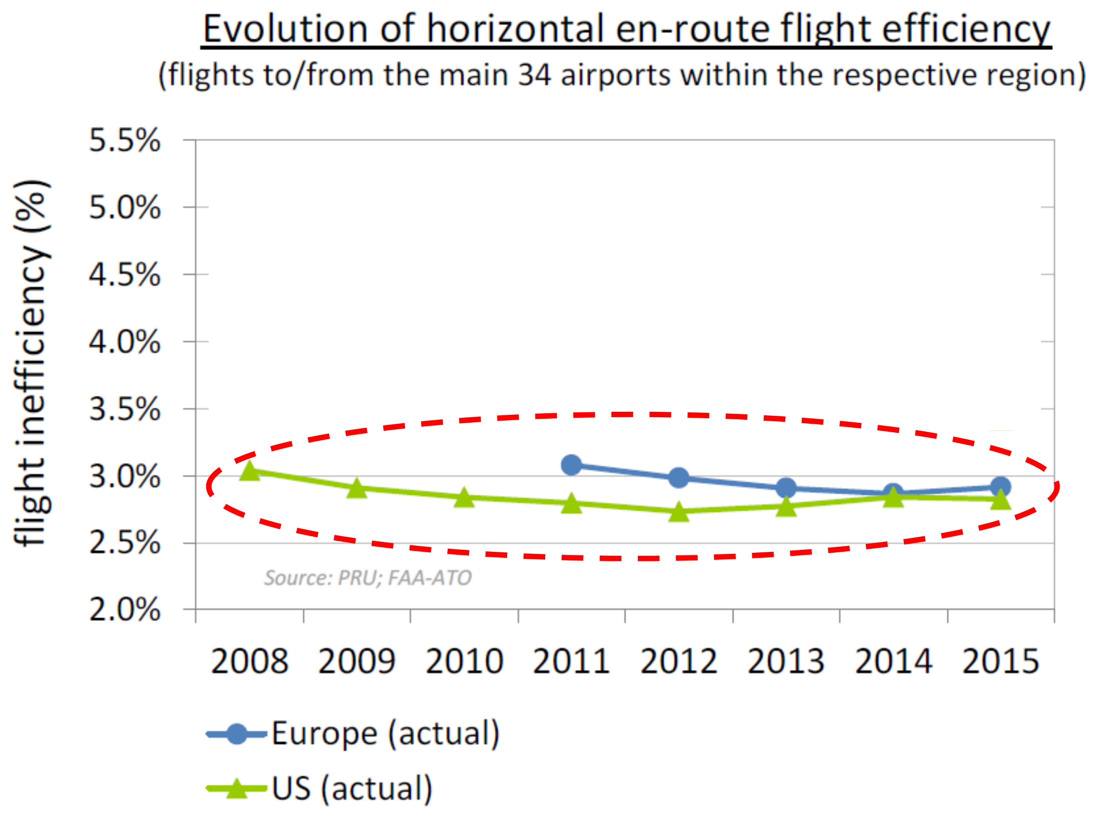
- Introduction
- Data Sources and Data Exploration
- Methodology
- Contributions and Ongoing Research

Motivations (I)

- FAA and Eurocontrol have published metrics to evaluate flight en route performance.
- It is central to many benefit in aviation community
  - Fuel efficiency
  - Environmental assessment
  - Workload evaluation

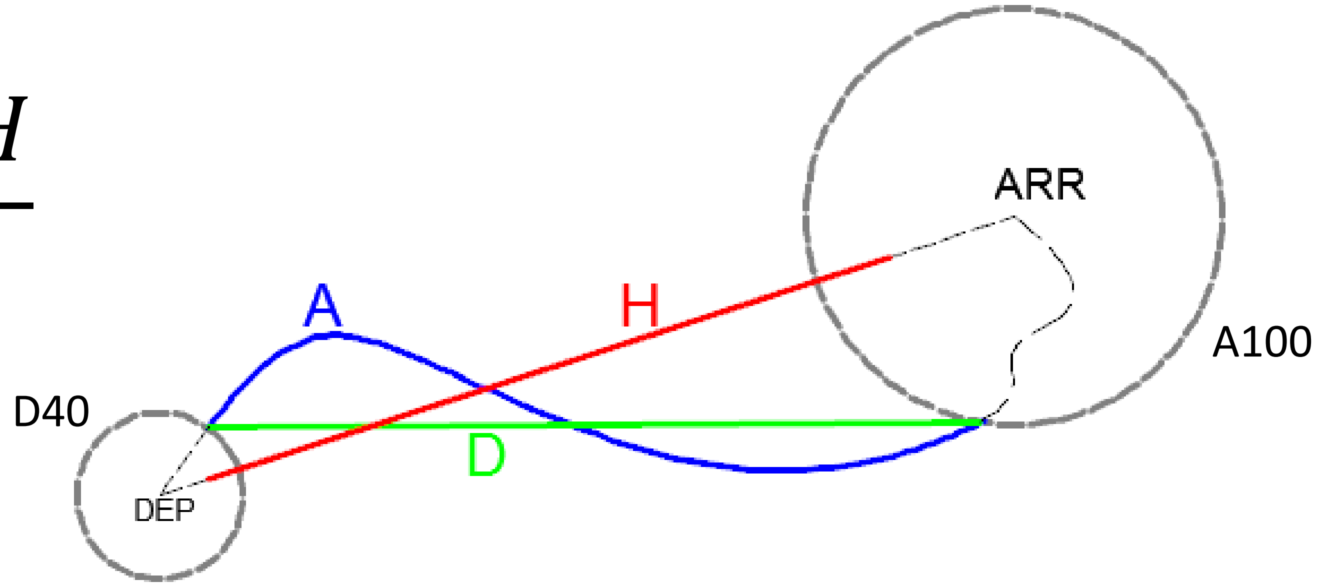
Motivations (II)

- Limited understanding of the causalities behind the inefficiency.
- Evolution of en route inefficiency – what/who accounts for the change?
  - ANSP
  - Airline
  - Adverse weather
- Can we do something to mitigate the inefficiency?



Background – En Route Inefficiency

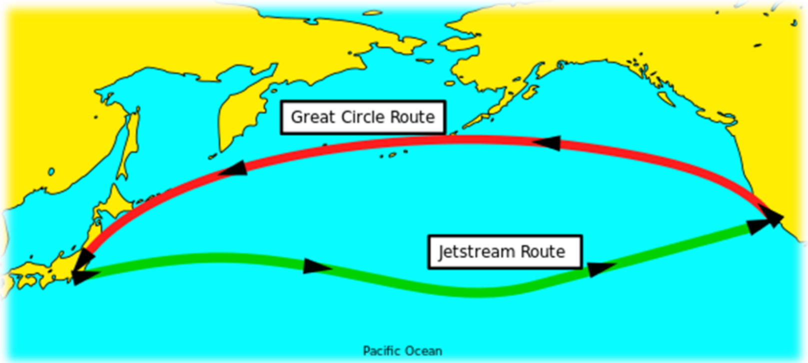
$$Inefficiency = \frac{A - H}{H}$$

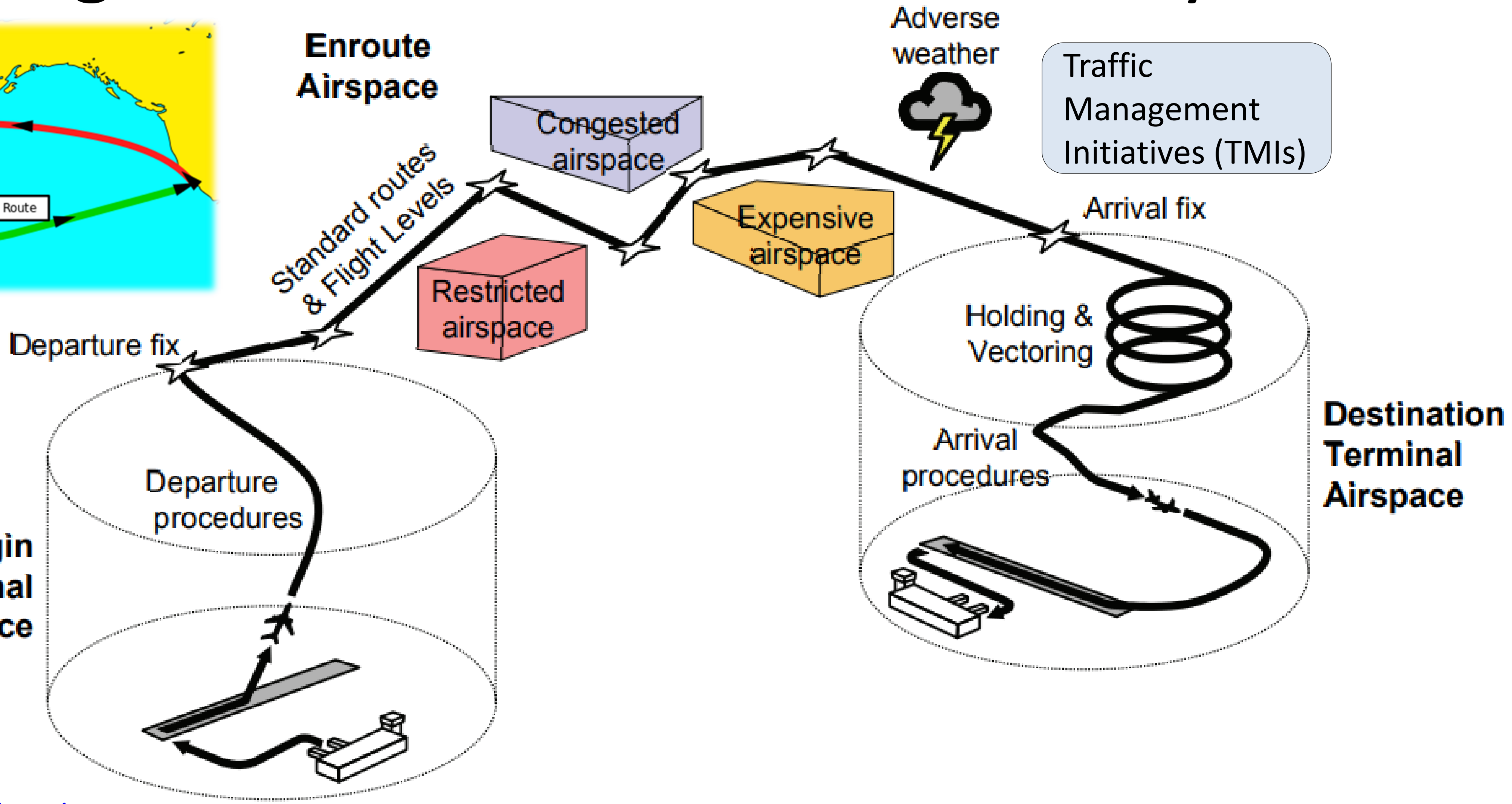


- A: Actual flown distance from exit point to entry point.
- D: Great circle distance between terminal entry and exit point.
- H: Achieved distance — "projection" of D onto great circle route between departure and arrival airport.

Sources:
https://www.faa.gov/air_traffic/publications/media/us_eu_comparison_2013.pdf
https://www.eurocontrol.int/sites/default/files/content/documents/single-sky/pru/news-related/2013-05-08-slides-workshop-achieved-distance.pdf

Background – Sources of Inefficiency

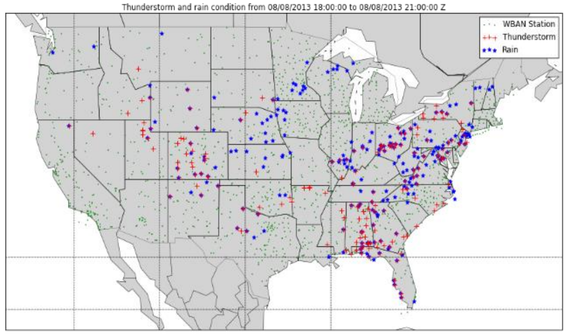


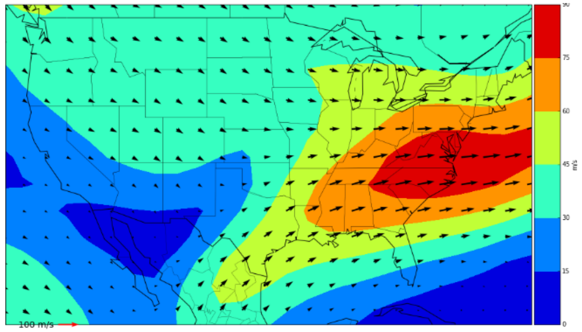


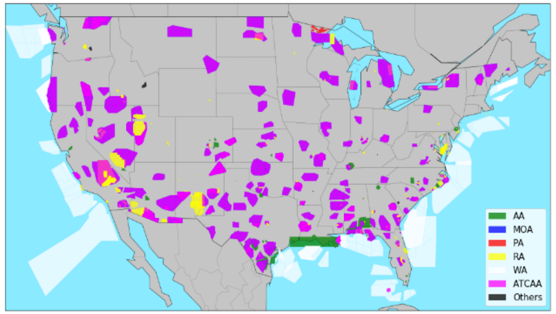
Source:
https://en.wikipedia.org/wiki/Jet_stream
Reynolds, T. G. (2008, September). Analysis of lateral flight inefficiency in global air traffic management. In 8th AIAA Aviation Technology, Integration and Operations Conference, Anchorage, Alaska, US.

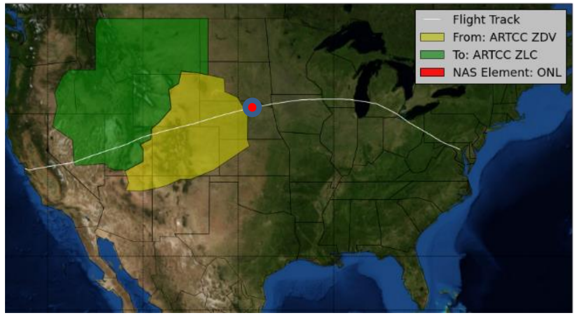
Background – Sources of Inefficiency

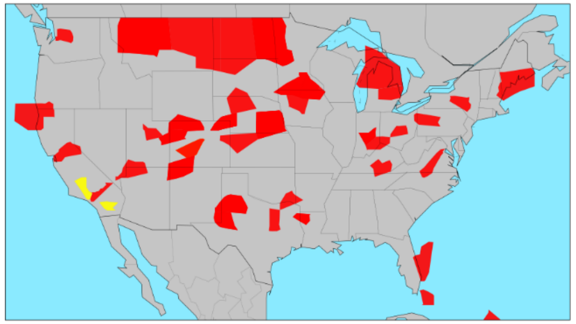
- Sources of Interest
  - Meteorological conditions
    - Convective weather
    - Wind
  - Controlled inputs
    - Special Activity Airspace (SAA)
    - Miles-In-Trail (MIT)
    - Airspace Flow Program (AFP)
    - Monitor Alert (MA)



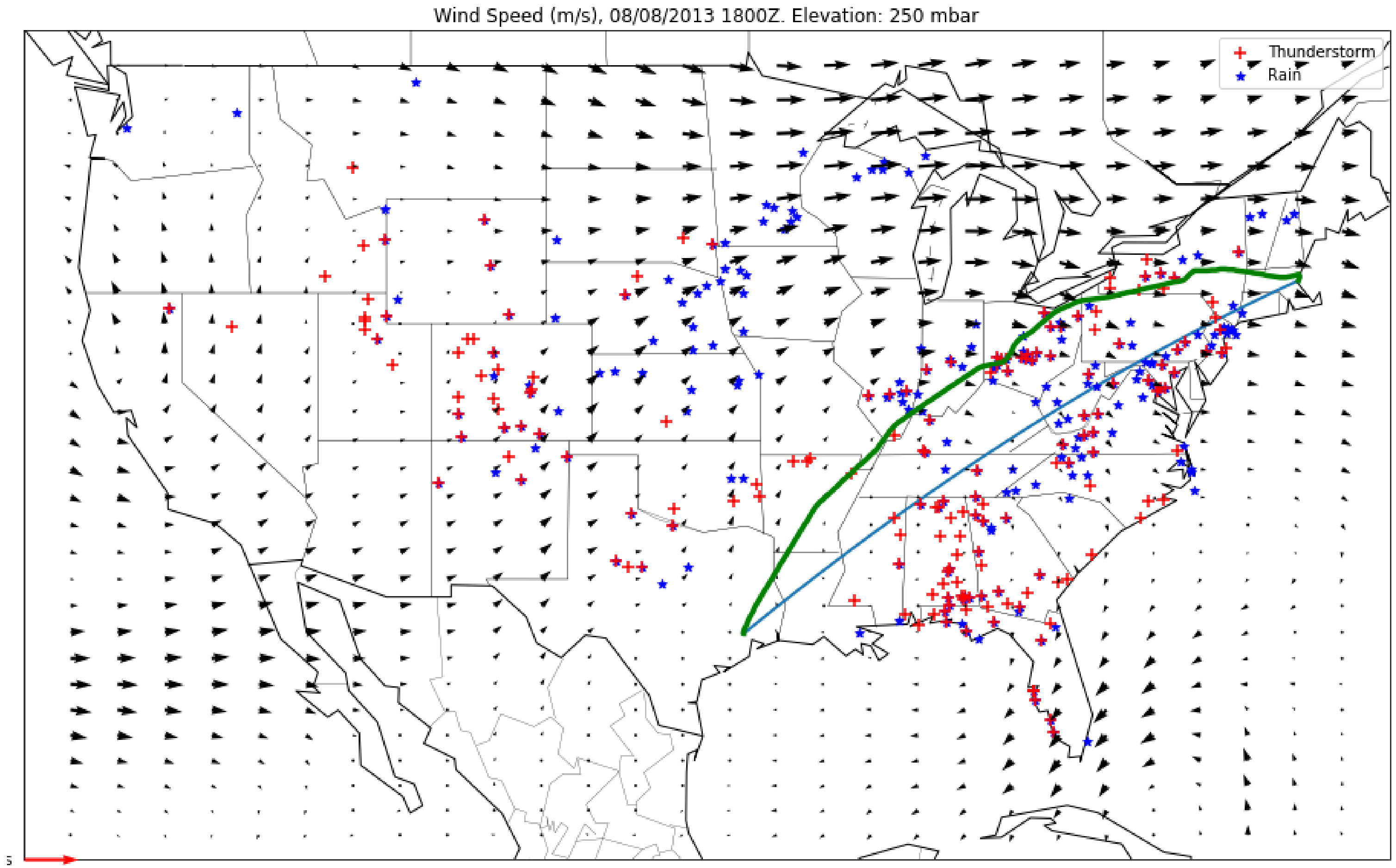








Research Goal



Overview

- Propose a **trajectory synthesis algorithm** to create nominal route.
- Offer a **tree-based matching algorithm** to efficiently match flight trajectories with high-fidelity spatiotemporal data.
- Estimate an **econometric model** to quantitatively understand how different factors affect flight en route inefficiency, with an emphasis of cross-sectional effect.

Outline

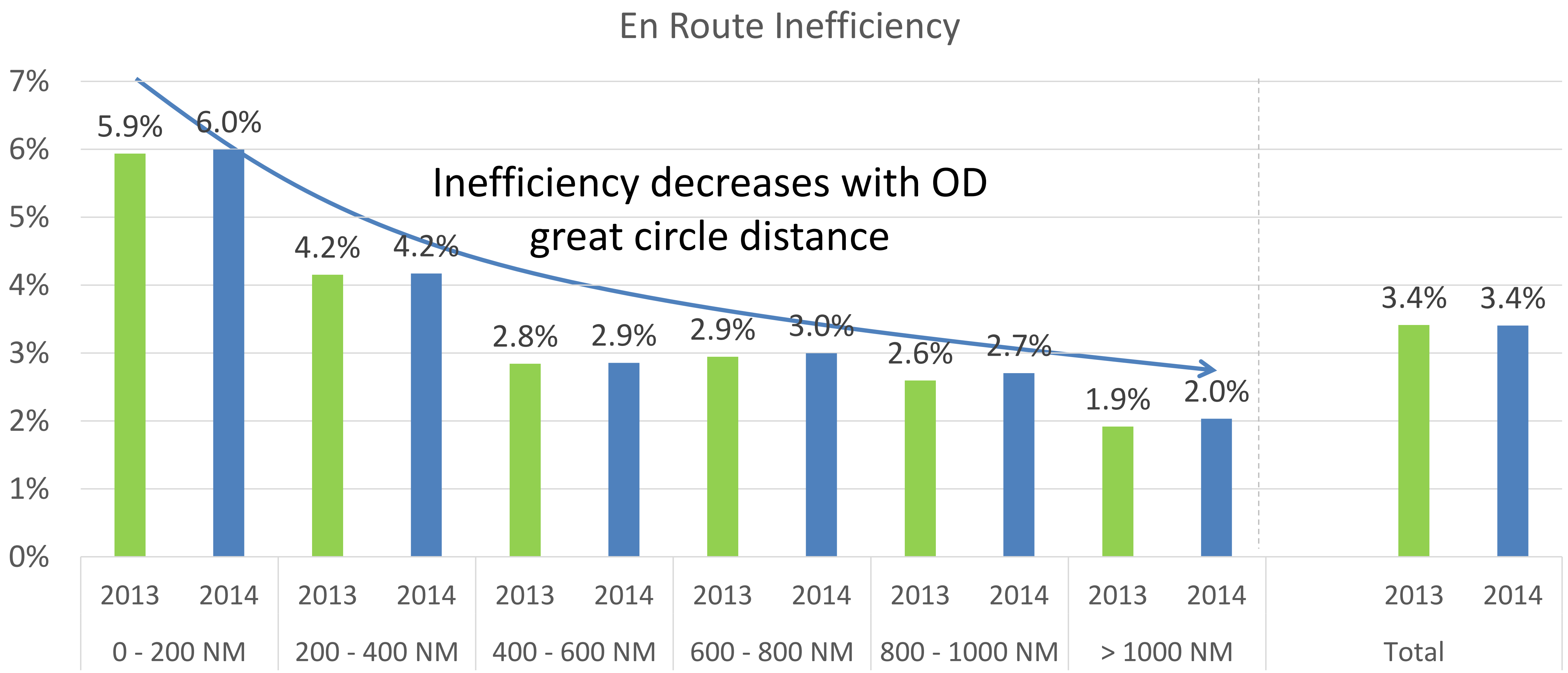
- Introduction
- Data Sources and Summary Statistics
- Aggregate Model
- Flight Level Model
- Contributions and Ongoing Research

Data Sources

- FAA Traffic Flow Management System (TFMS)
  - Inefficiency dataset: flight inefficiency records.
  - Flight track dataset: flight track records.
- FAA National Traffic Management Log (NTML)
  - Miles-In-Trail (MIT) dataset
  - Airspace Flow Program (AFP) dataset
  - Monitor Alert (MA) dataset

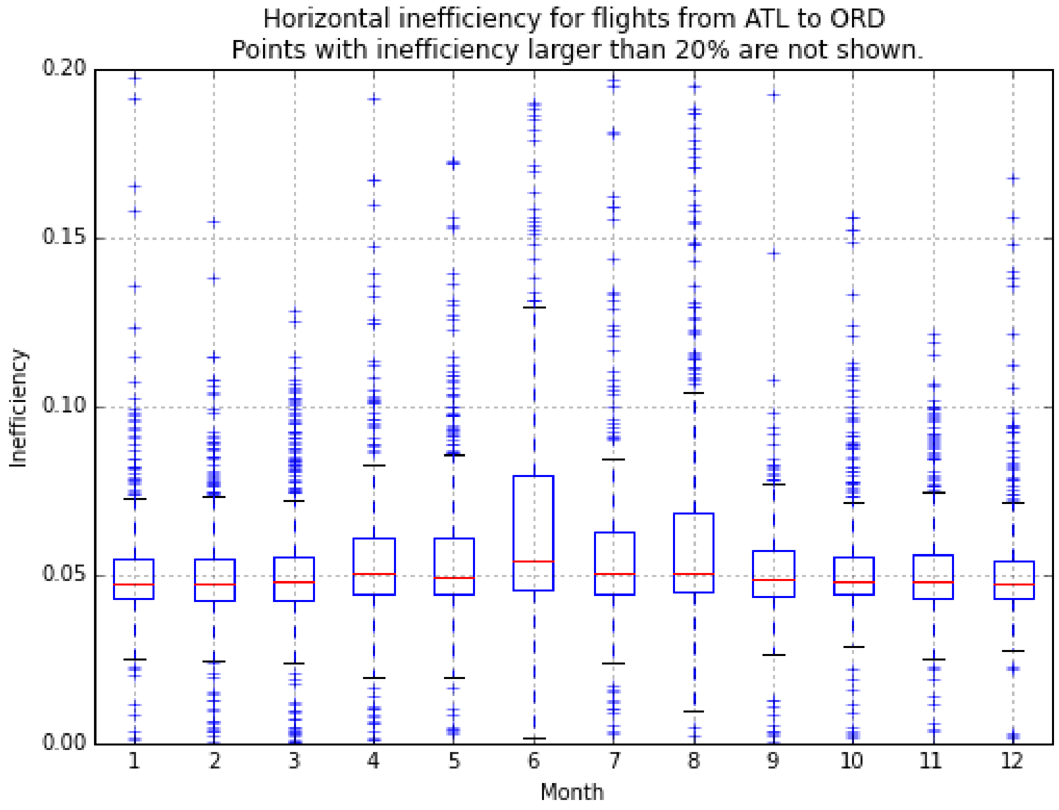
  Where, when, how those "initiatives" were "implemented"
- NASA Sherlock Data Warehouse
  - Special Activity Airspace (SAA) dataset: SAA start/stop time
- National Oceanic and Atmospheric Administration (NOAA)
  - Convective weather dataset: ground based observations
  - Forecast wind dataset: raster wind data with fixed geospatial grids.

En Route Inefficiency vs Great Circle Distance

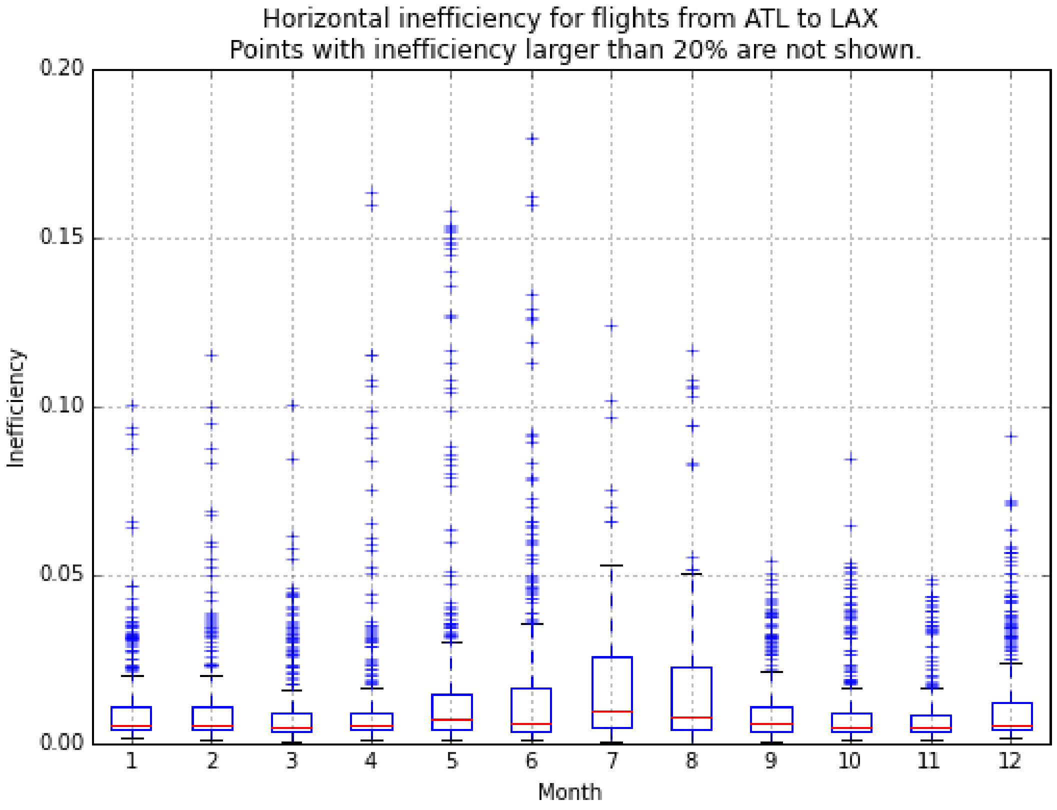


Inefficiencies for Representative Airport Pairs (2013)

ATL to ORD (6.86%)

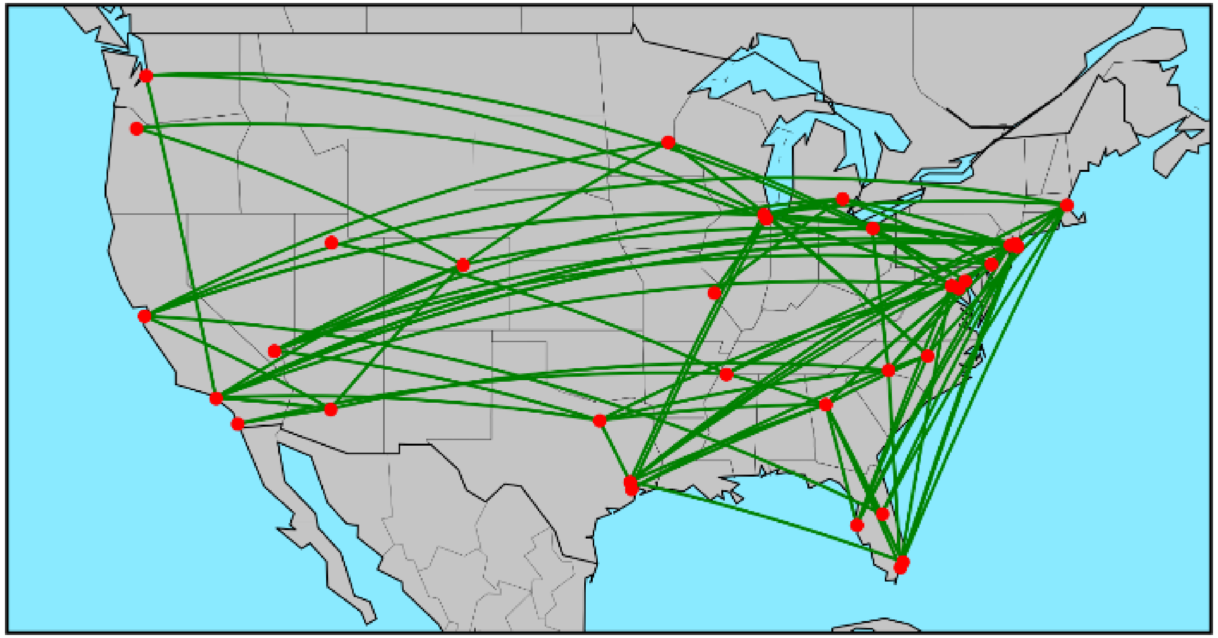


ATL to LAX (1.28%)

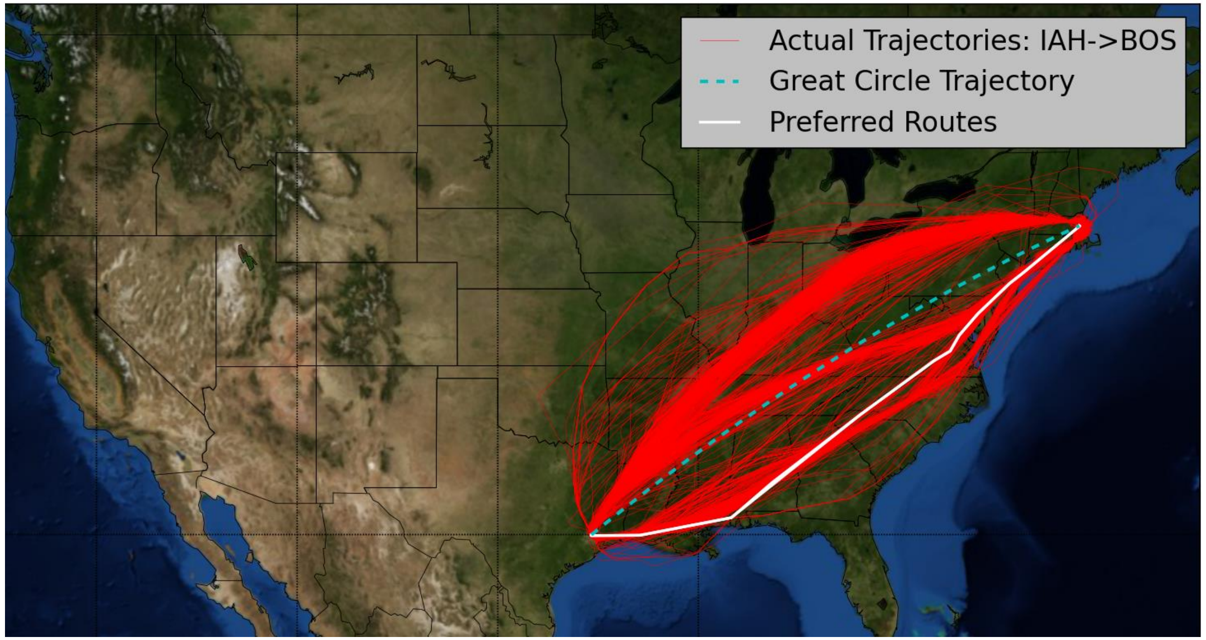


Flight Track Data

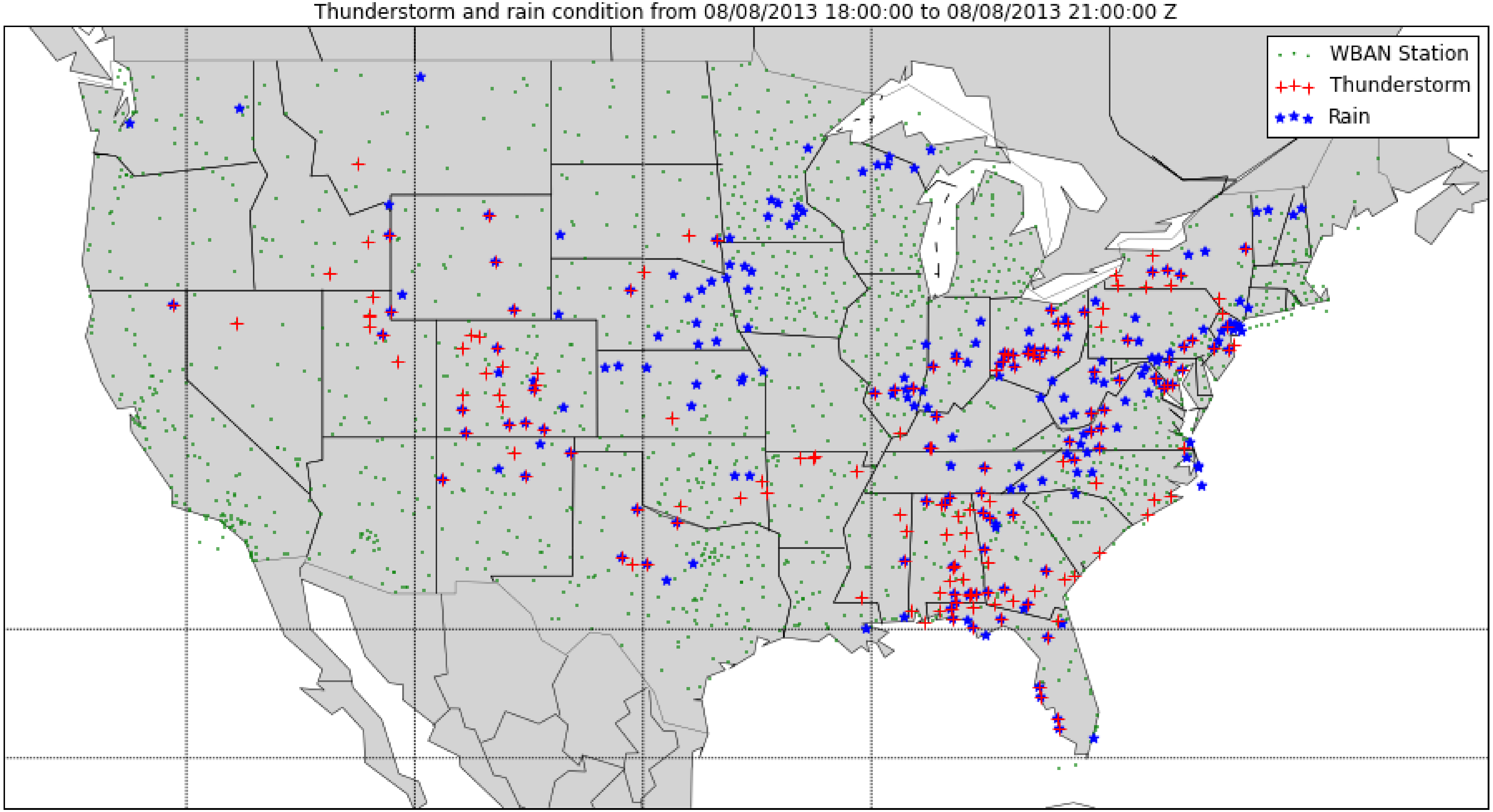
97 US Major Airport Pairs, 436830 flights



IAH → BOS (2013)

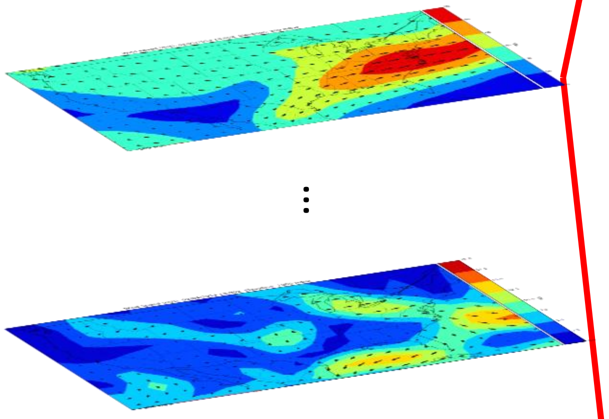


Convective Weather Data

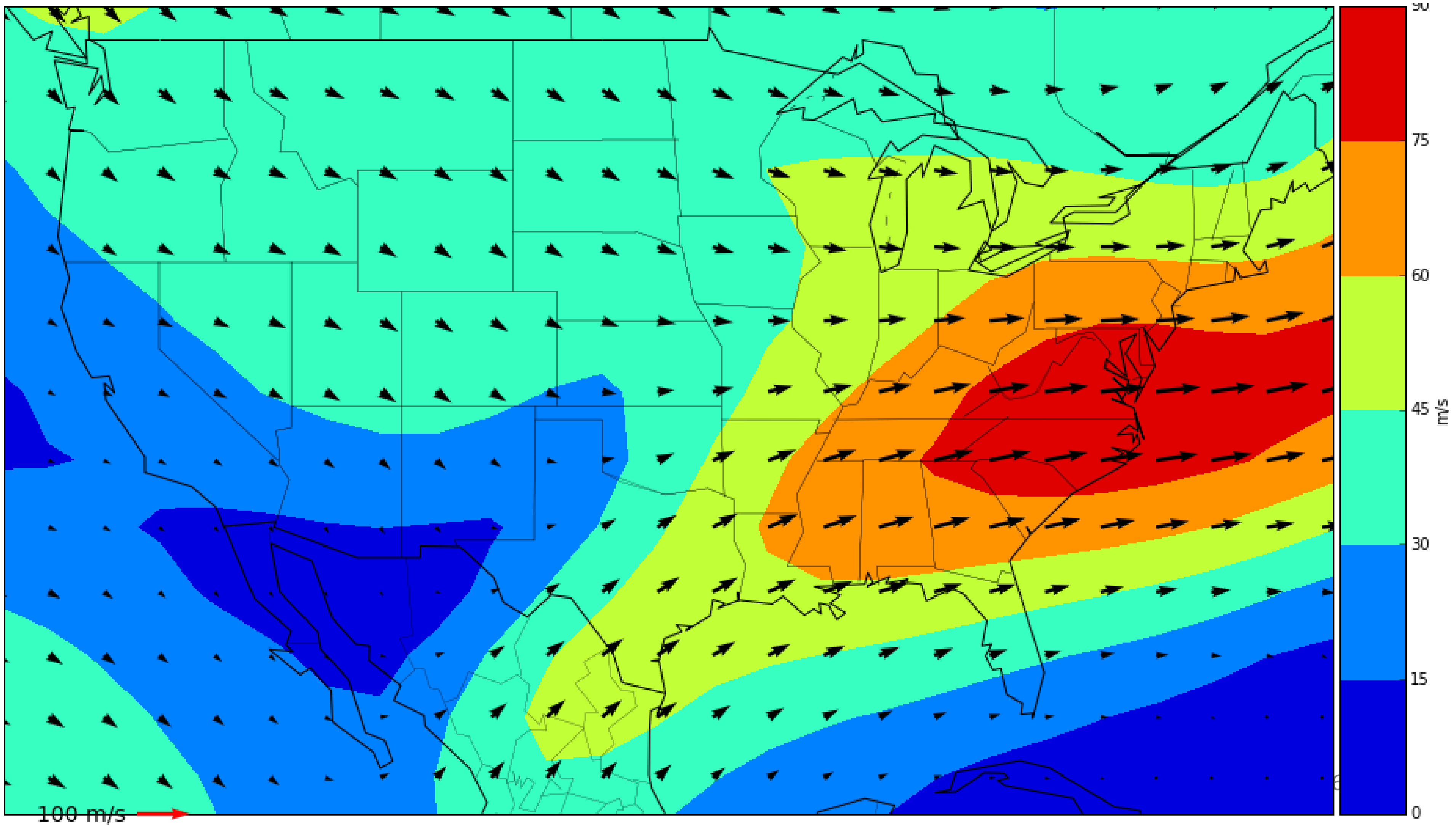


Forecast Wind Data

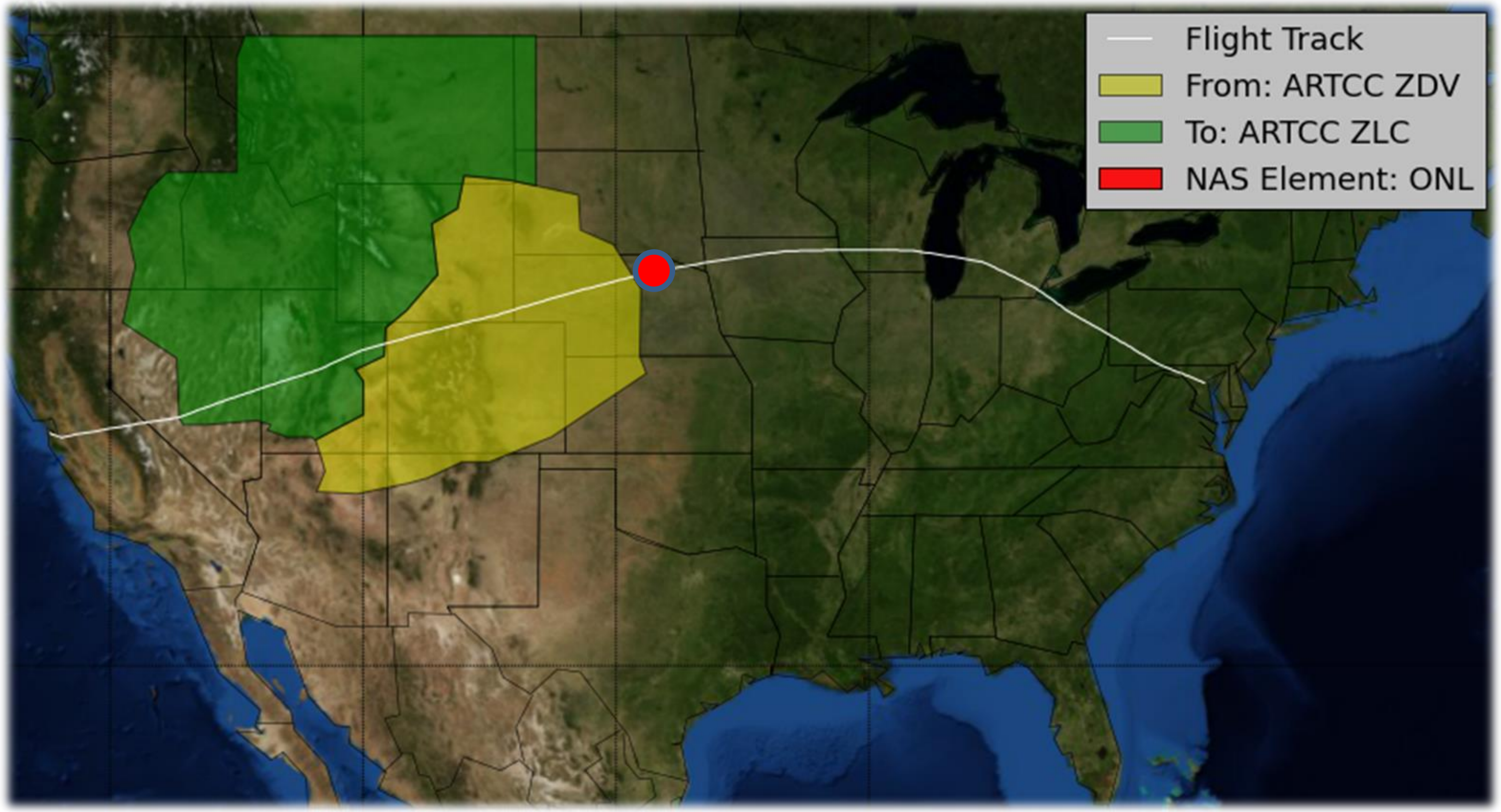
17 isobaric pressure levels
For each level, the resolution is 2.5° by 2.5° lat/lon.



Wind Field Diagram (m/s) @ 200 mbar (~ 38,000 ft.); 02/04/2013 18:00 Zulu



Miles-In-Trail (MIT) Data



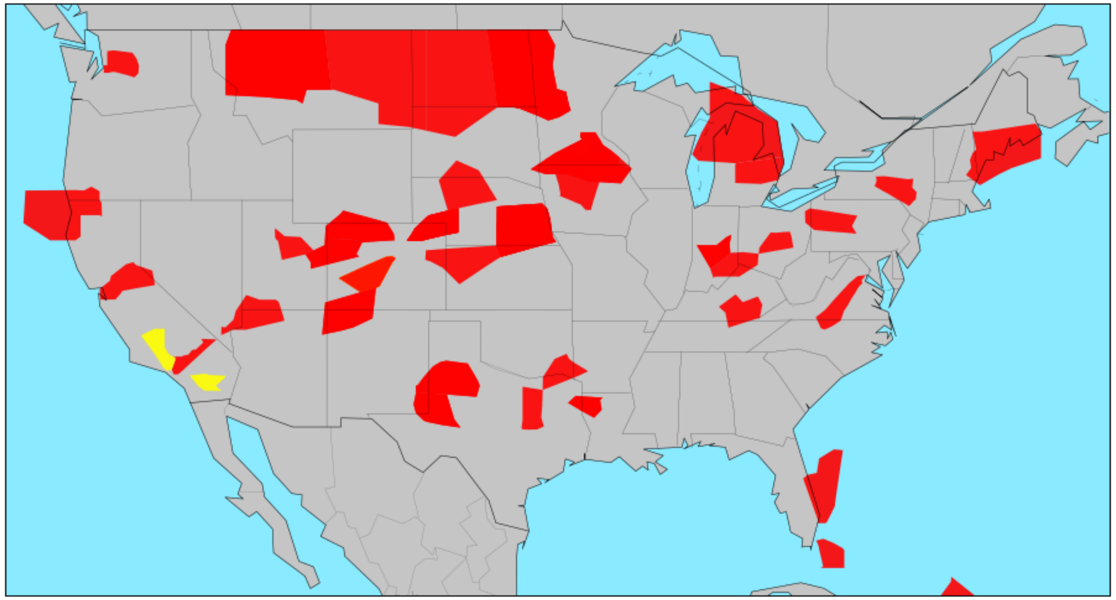
- Miles-in-trail specifies the minimal required distance between two consecutive aircrafts.
- Apportion traffic into a manageable flow.

ZDV is trying to protect ***ZLC***, which is overloaded, by providing a MIT (e.g., 15 miles) to separate aircrafts through the Navaid ***ONL***.

Airspace Flow Program (AFP) Data

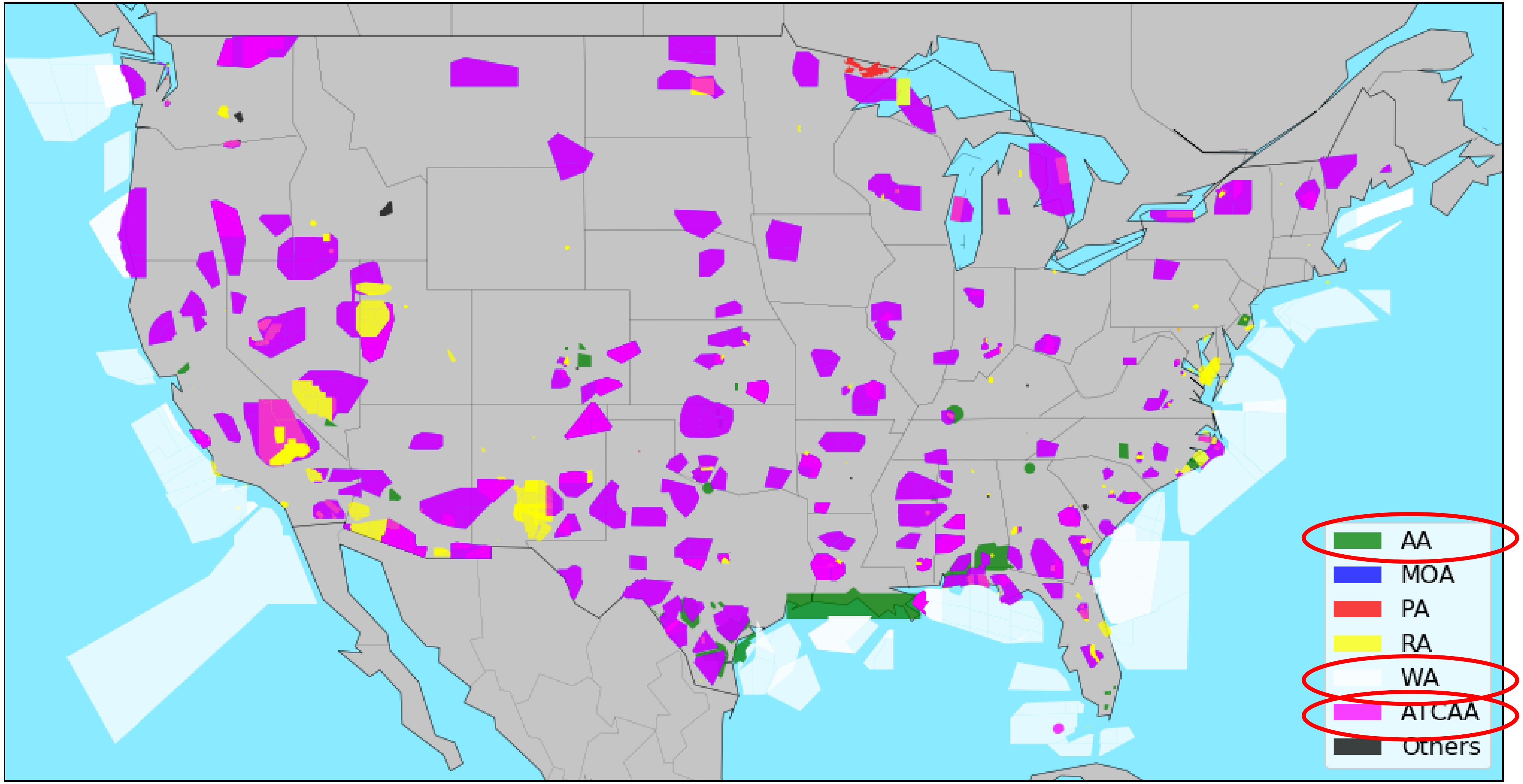
- AFP identifies constrained areas and assigns expected departure time (EDT) for flights entering the area.
- Flights could either route out of the constrained area or accept the EDT and its attendant ground delay.

Monitor Alert (MA) Data



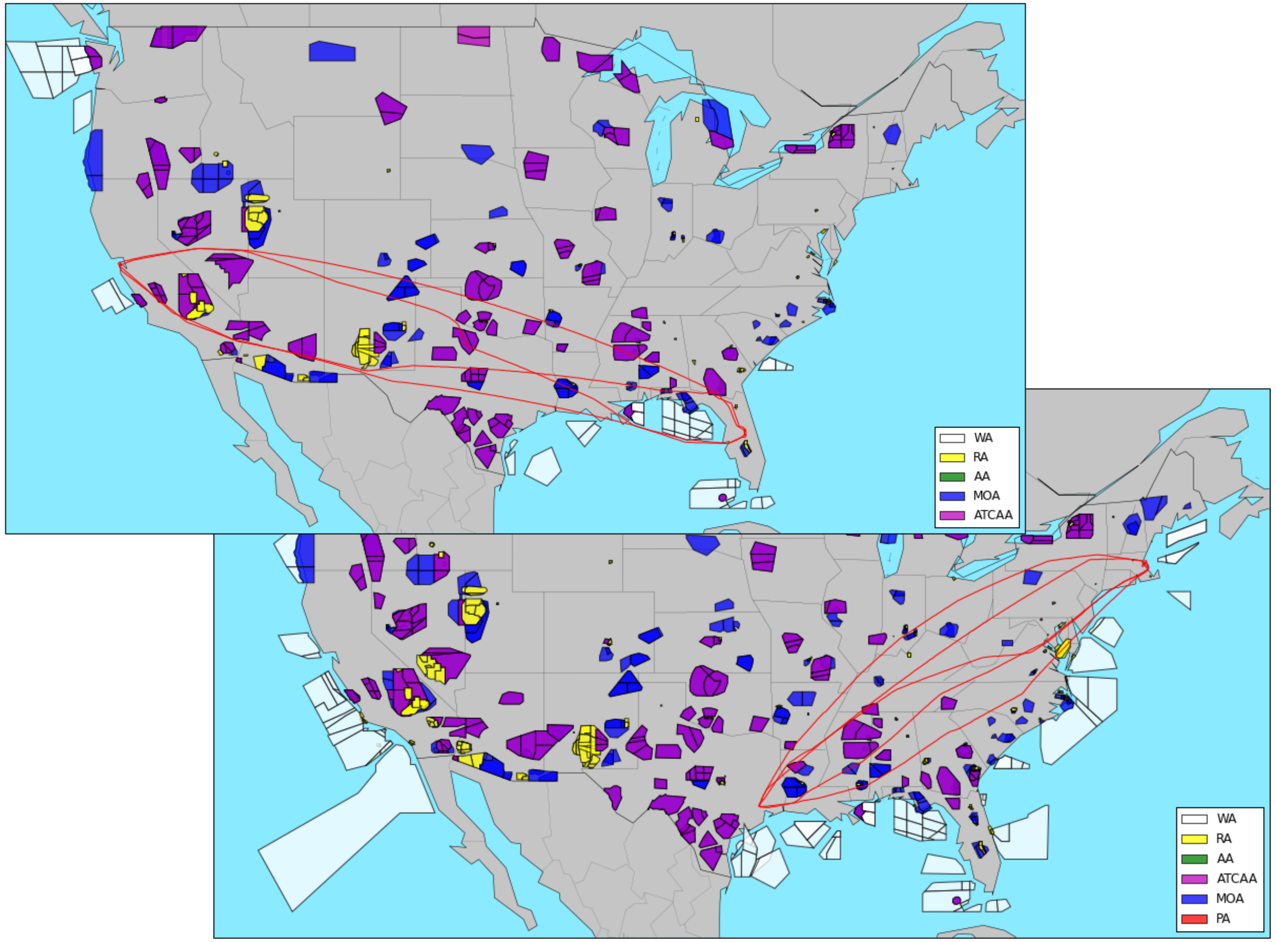
- MA alerts sector personnel when the forecast flight demand exceeds a pre-defined value.
- Red: demand exceeds the capacity.
- Yellow: demand approaches the capacity.

Special Activity Area (SAA) Data

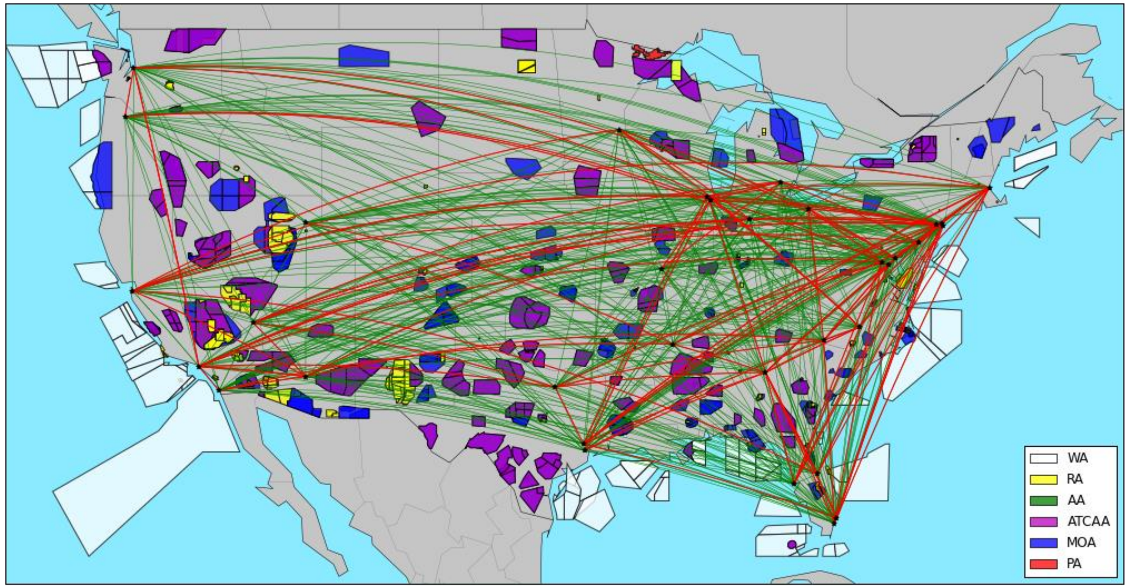


Special Activity Area Data (cont.)

Flights barely cross the SAA



Direct routes crosses the SAA frequently

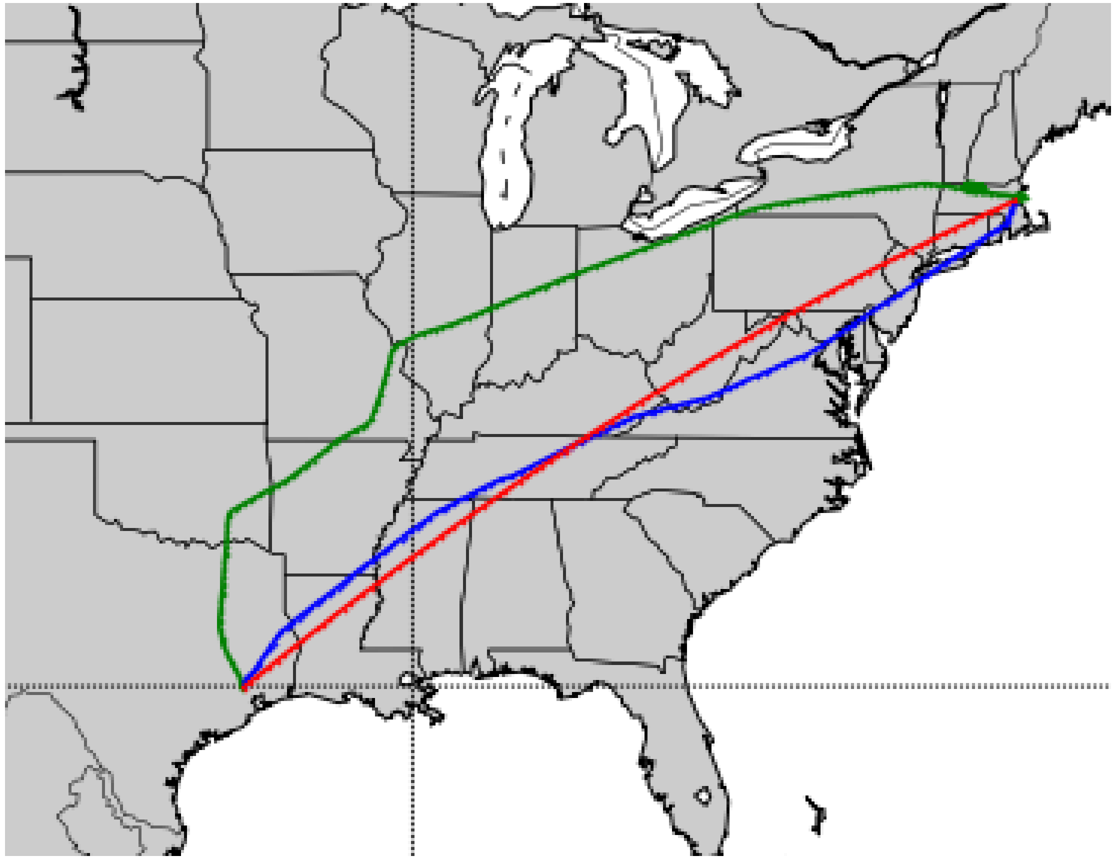


Methodology

- Inefficiency is measured by the ground distance of a flight trajectory relative to the "great circle distance".
- However the realized flight trajectory and the corresponding inefficiency are the results of weather and air traffic control.
- In other word, it is the weather/air traffic control/other inputs on the most efficient route that "causes" the actual flight route and inefficiency.
- Thus, to quantitatively understand how those factors affect inefficiency, we need to match them with some synthetic, yet representative, routes.

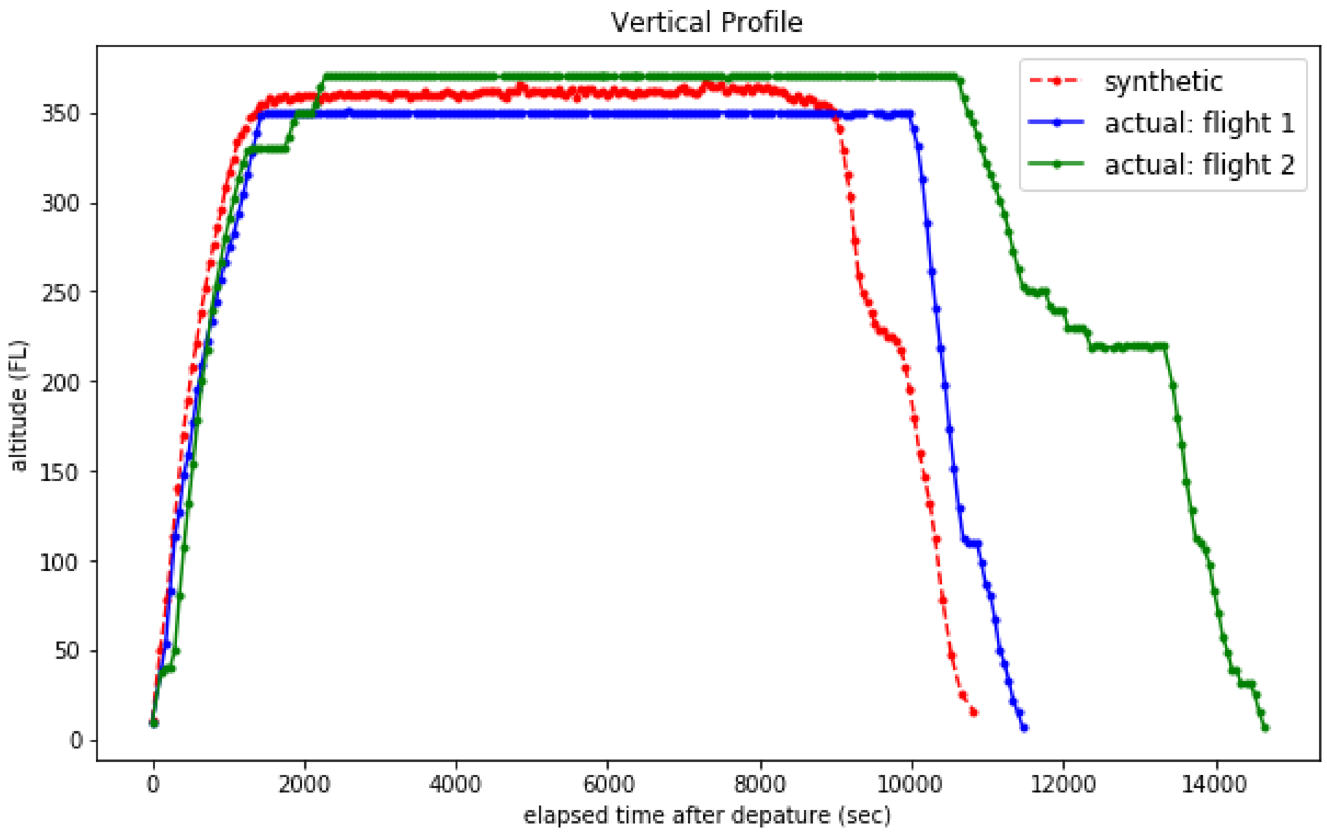
Generating Synthetic Great Circle Route

- Synthetic Great Circle Route
  - Easy to handle.
  - Computational tractable in large scale analysis.
- Horizontal Profile
  - Equally spaced waypoints
- Vertical and Time Profile
  - How to ensure an reasonable altitude and time profile so that they won't violate the basic law of kinematics?



Generating Synthetic Great Circle Route

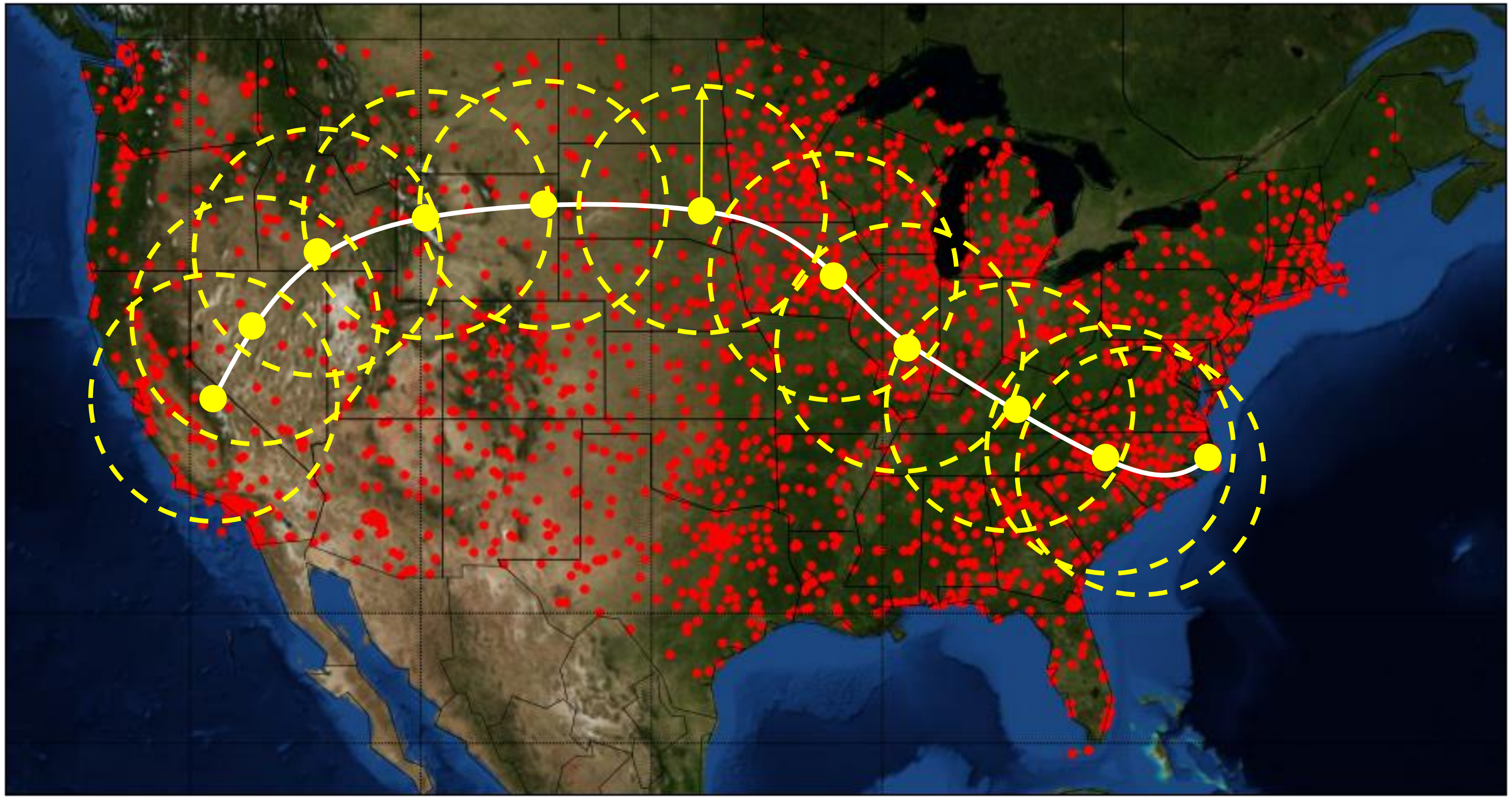
- Vertical and Time Profile
  - Flight-track-based approximation.
  - Nearest neighbor and weighted average.



Matching Algorithm

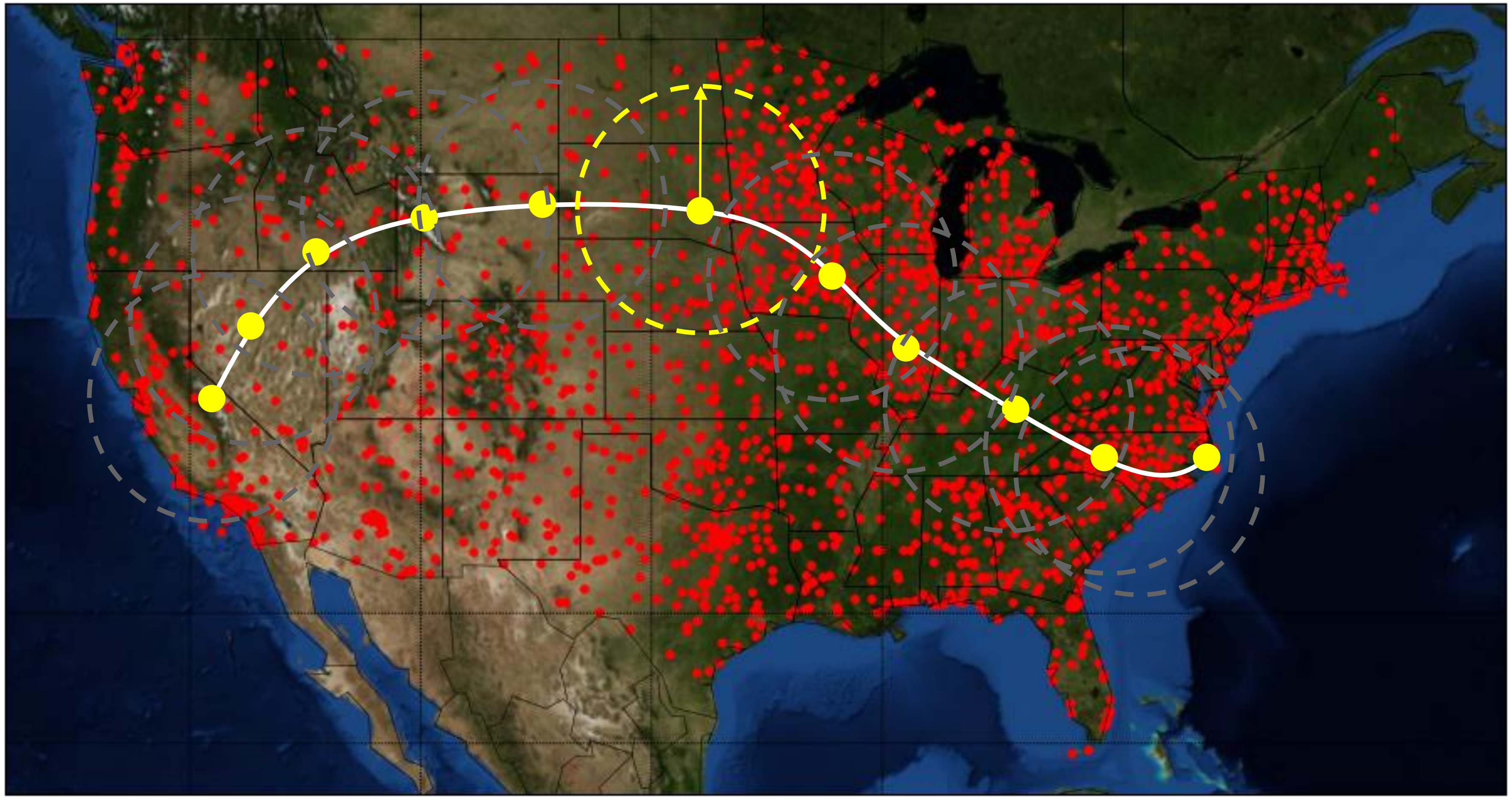
- We use the **nominal route**, or the synthetic great circle route, as the basis to match with different factors – weather, wind, MIT, AFP, MA, SAA.
- For each flight, we assume it will fly the nominal route, which is the hypothetical shortest route. Thus, we characterize the conditions a given flight **would have** encountered if it had flown the nominal route, assuming its **actual departure time**.

Matching – Convective Weather



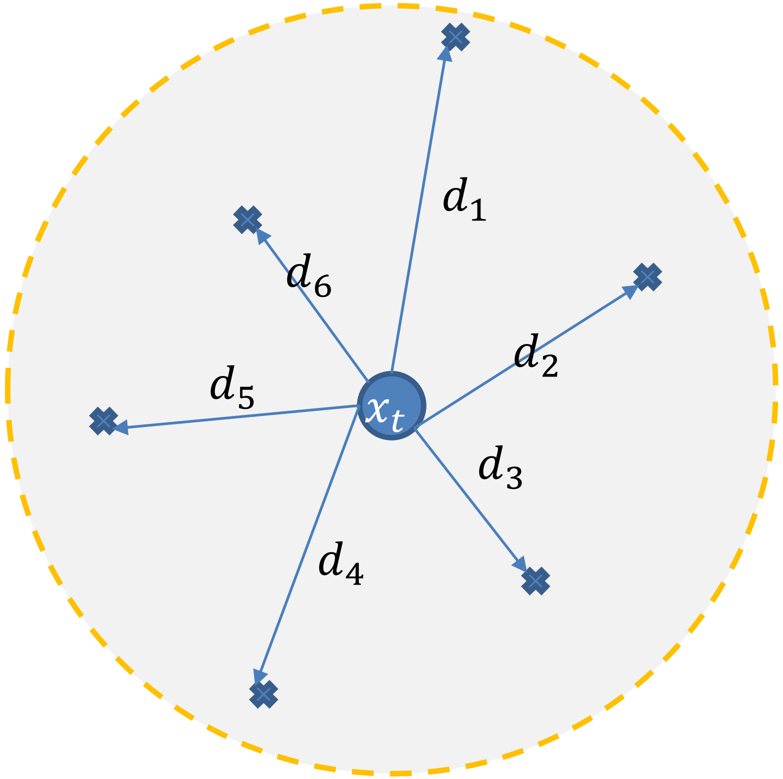
- For each track point on the trajectory, find all the stations within a circle with radius r (150 nmi).

Matching – Convective Weather



- Weighted average the weather variable (binary) for stations within the circle, and the weight is the proportional to the inverse of the distance.
- Metric: average of the weather exposure for all track points along the route.

Matching – Convective Weather



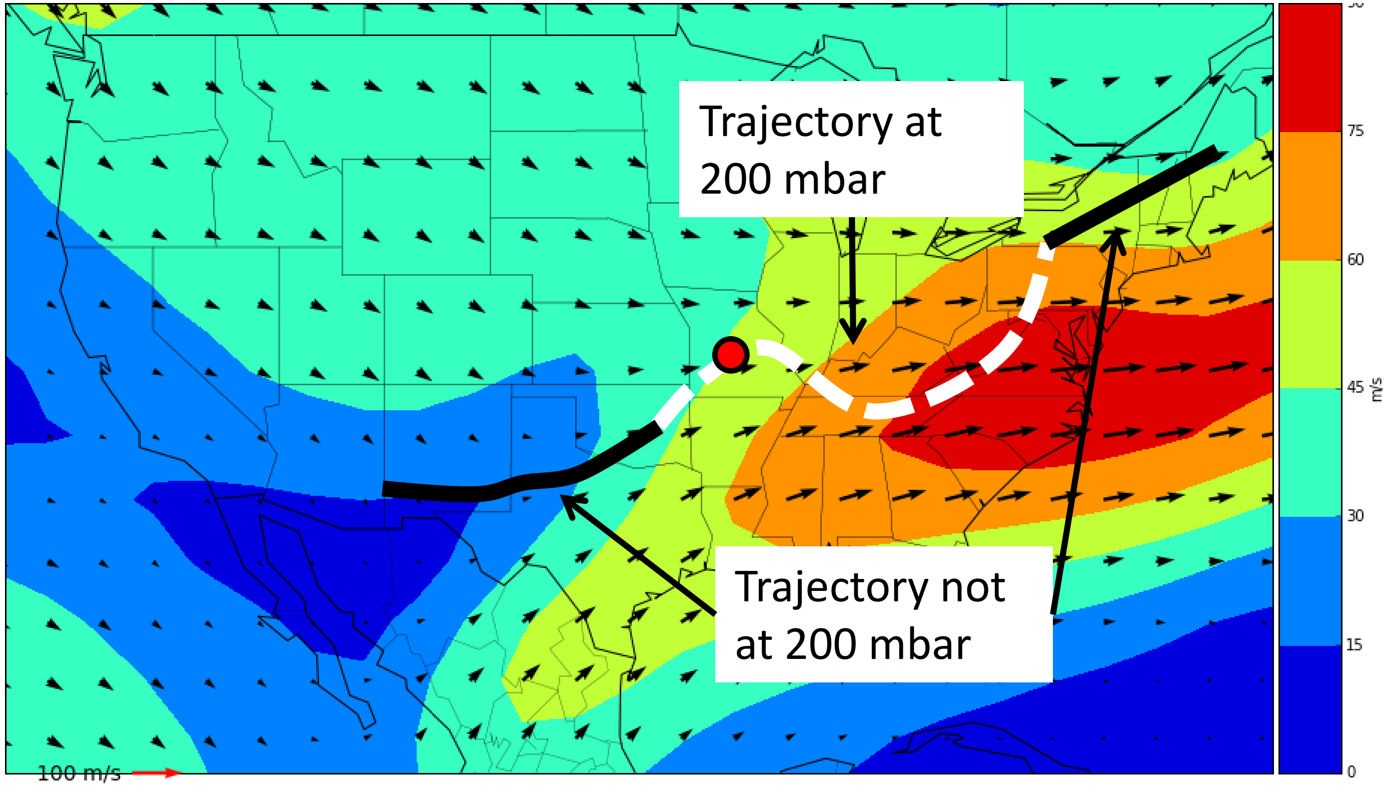
$$Wx_t = \sum_i I_i \cdot \frac{d_i}{\sum_j d_j}$$

$$Wx = \frac{1}{T} \cdot \sum_t Wx_t$$

- Weighted average the weather variable (binary) for stations within the circle, and the weight is the proportional to the inverse of the distance.
- Metric: average of the weather exposure for all track points along the route.

Matching – Wind

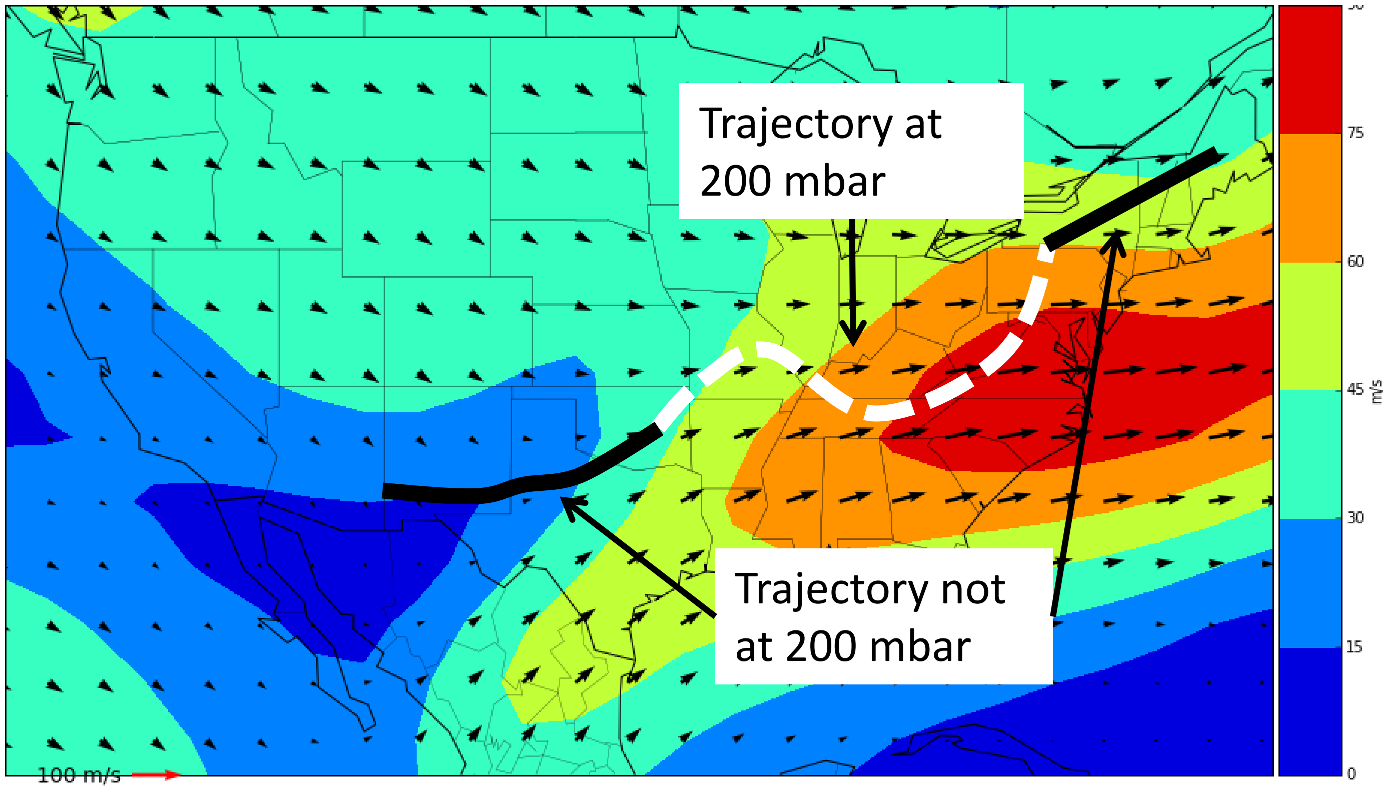
Wind Field Diagram (m/s) @ 200 mbar (~ 38,000 ft.)
02/04/2013 18:00 Zulu

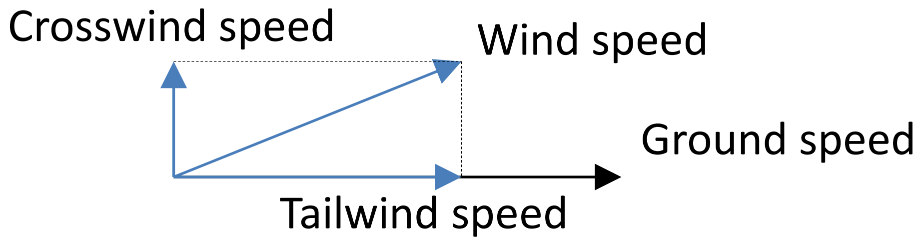


- For each track point, find the nearest 4d reference point of the wind data file
- Assign the wind speed (vertical and horizontal) of the nearest grid to the track point

Matching – Wind

Wind Field Diagram (m/s) @ 200 mbar (~ 38,000 ft.)
02/04/2013 18:00 Zulu



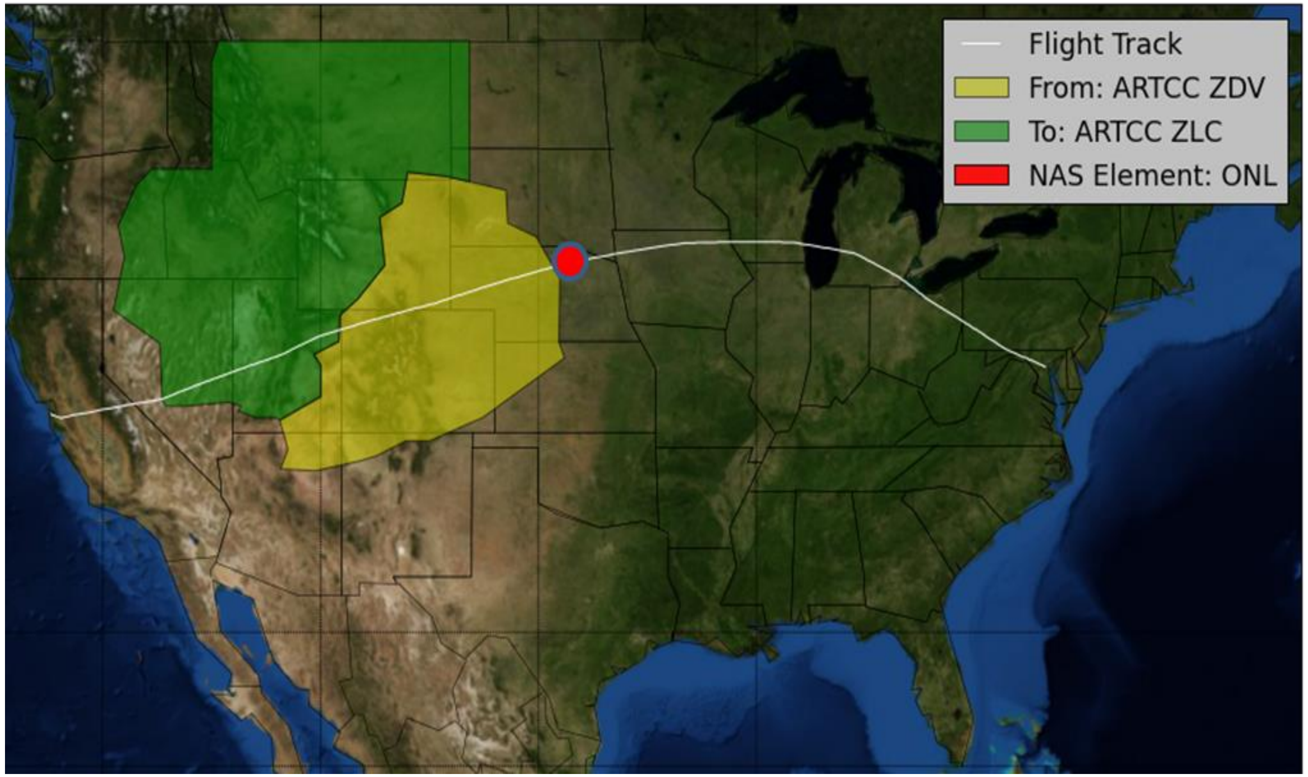


- Calculate the headwind/tailwind speed for each track point, based on heading derived from previous track point
- Metrics
  - Equivalent still air distance
  - Average wind speed along the route.

Matching – Trick of Trees

- Weather and wind datasets
  - High-dimension spatiotemporal raster
  - Fixed temporal resolution
  - Fixed geospatial grids
- Static spatial and temporal k-d trees
  - Query and vectorization
  - Batch-mode operation

Matching – MIT/AFP/MA/SAA



- A given nominal route, with adjusted departure time, is assumed to be affected by a MIT/AFP/MA/SAA if:
  - It crosses the facilities
  - Its crossing time is within the time of effect
  - Its crossing altitude is covered by the restriction

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Matching – Summary of Metrics

Metric	Description
TS	Thunderstorm exposure (in percentage)
Squall	Squall exposure (in percentage)
AvgWindSpd	Average wind speed (positive if tailwind and negative if headwind) along the great circle route (in 100 m/s)
WindDist	Distance traveled with respect to air (equivalent still air distance, in 1000 nmi)
NumMIT	Number of MIT crossed
MaxMITSTR	Maximal MIT stringency among all crossed MITs (in 100 $mile \cdot hr$)
NumAFP	Number of AFP crossed
MaxAFPDly	Maximal AFP assigned delay among all crossed AFP (in hours)
MaxAFPArr	Maximal AFP acceptance rate among all crossed AFP (in 100 per hour)
NumSAA	Number of SAA crossed
MaxSAAT	Maximal transverse time within crossed SAA (in hours)
NumMARed	Number of red MA crossed
NumMAYel	Number of yellow MA crossed
MaxMAT	Maximal transverse time within crossed MA (in hours)

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NEXTOR II

Matching – Summary of Metrics

Metric	Description
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AvgWindSpd	Average wind speed (positive if tailwind and negative if headwind) along the great circle route (in 100 m/s)
WindDist	Distance traveled with respect to air (equivalent still air distance, in 1000 nmi)
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NumSAA	Number of SAA crossed
MaxSAAT	Maximal transverse time within crossed SAA (in hours)
NumMARed	Number of red MA crossed
NumMAYel	Number of yellow MA crossed
MaxMAT	Maximal transverse time within crossed MA (in hours)

Matching – Summary of Metrics

Metric	Description	sign
TS	Thunderstorm exposure (in percentage)	+
Squall	Squall exposure (in percentage)	+
AvgWindSpd	Average wind speed (positive if tailwind and negative if headwind) along the great circle route (in 100 m/s)	-
WindDist	Distance traveled with respect to air (equivalent still air distance, in 1000 nmi)	+
NumMIT	Number of MIT crossed	+
MaxMITSTR	Maximal MIT stringency among all crossed MITs (in 100 $mile \cdot hr$)	+
NumAFP	Number of AFP crossed	+
MaxAFPDly	Maximal AFP assigned delay among all crossed AFP (in hours)	+
MaxAFPArr	Maximal AFP acceptance rate among all crossed AFP (in 100 per hour)	-
NumSAA	Number of SAA crossed	+
MaxSAAT	Maximal transverse time within crossed SAA (in hours)	+
NumMARed	Number of red MA crossed	+
NumMAYel	Number of yellow MA crossed	+
MaxMAT	Maximal transverse time within crossed MA (in hours)	+

Model Specifications

Metric	sign
TS	+
Squall	+
AvgWindSpd	-
WindDist	+
NumMIT	+
MaxMITSTR	+
NumAFP	+
MaxAFPDly	+
MaxAFPArr	-
NumSAA	+
MaxSAAT	+
NumMARed	+
NumMAYel	+
MaxMAT	+

- Dependent variable: flight en route inefficiency
- Additional explanatory variables
  - Achieved distance (benchmark distance) $\frac{A - H}{H}$
  - Airport-pair fixed effect
- Specifications
  - Model I: full model
  - Model II: reduced model
  - Model III: omit achieved distance effect
  - Model IV: omit airport-pair fixed effect

Estimation Results – Weather

Variable	Models Est. / (Std.)			
	Model I	Model II	Model III	Model IV
constant	-	-	-	3.410*** (0.027)
TS	0.103*** (0.023)	0.109*** (0.021)	0.253*** (0.030)	0.819*** (0.030)
Squall	1.823 (1.377)	-	-	-
AvgWindSpd	-1.877*** (0.441)	-1.880*** (0.433)	-1.945*** (0.596)	-0.168 (0.113)
WindDist	6.775*** (1.415)	6.817*** (1.390)	6.247*** (1.872)	1.195*** (0.170)

- Positive *TS* → flights take detour to avoid weather incidences.
- Model II and III report smaller estimates of *TS* – some airport pairs inherently have more convections.
- Higher average tailwind speed and shorter wind distance reduce the inefficiency – flights tend to “chase” a more favorable wind condition.

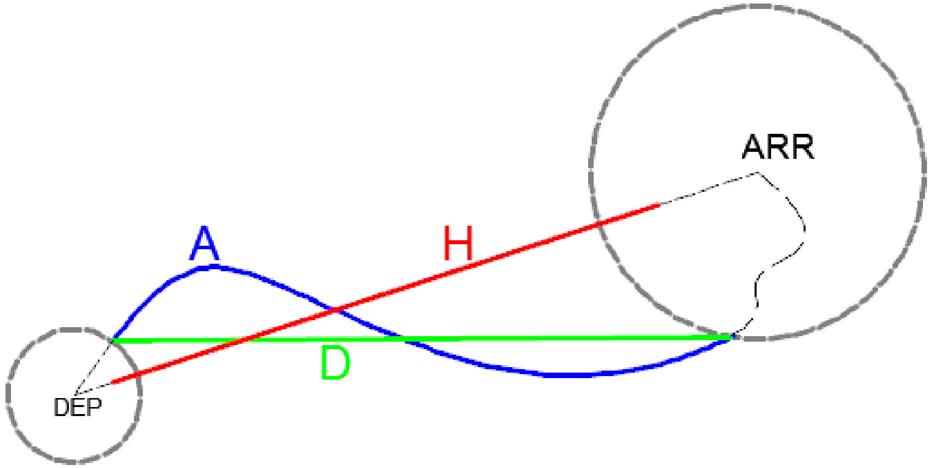
Estimation Results – ATC

Variable	Models Est. / (Std.)			
	Model I	Model II	Model III	Model IV
NumMIT	0.148*** (0.016)	0.148*** (0.016)	0.314*** (0.027)	0.185*** (0.026)
MaxMITSTR	0.110*** (0.024)	0.110*** (0.024)	0.239*** (0.038)	0.244*** (0.040)
NumAFP	0.232 (2.004)	0.394*** (0.112)	1.078*** (0.224)	1.121*** (0.230)
NumSAA	-0.003 (0.010)	-	-	-
MaxSAAT	2.666*** (0.271)	2.587*** (0.183)	2.816*** (0.242)	2.981*** (0.134)
NumMARed	-0.025 (0.018)	-	-	-
NumMAYel	-0.022 (0.028)	-	-	-
MaxMAT	0.086 (0.091)	-	-	-

- Flights whose great circle routes have stronger MIT restrictions, AFP delays, and traverse time in the SAA areas are less efficient.
- Monitor Alert not significant: MA not affect inefficiency per se, but may result in MIT or AFP.

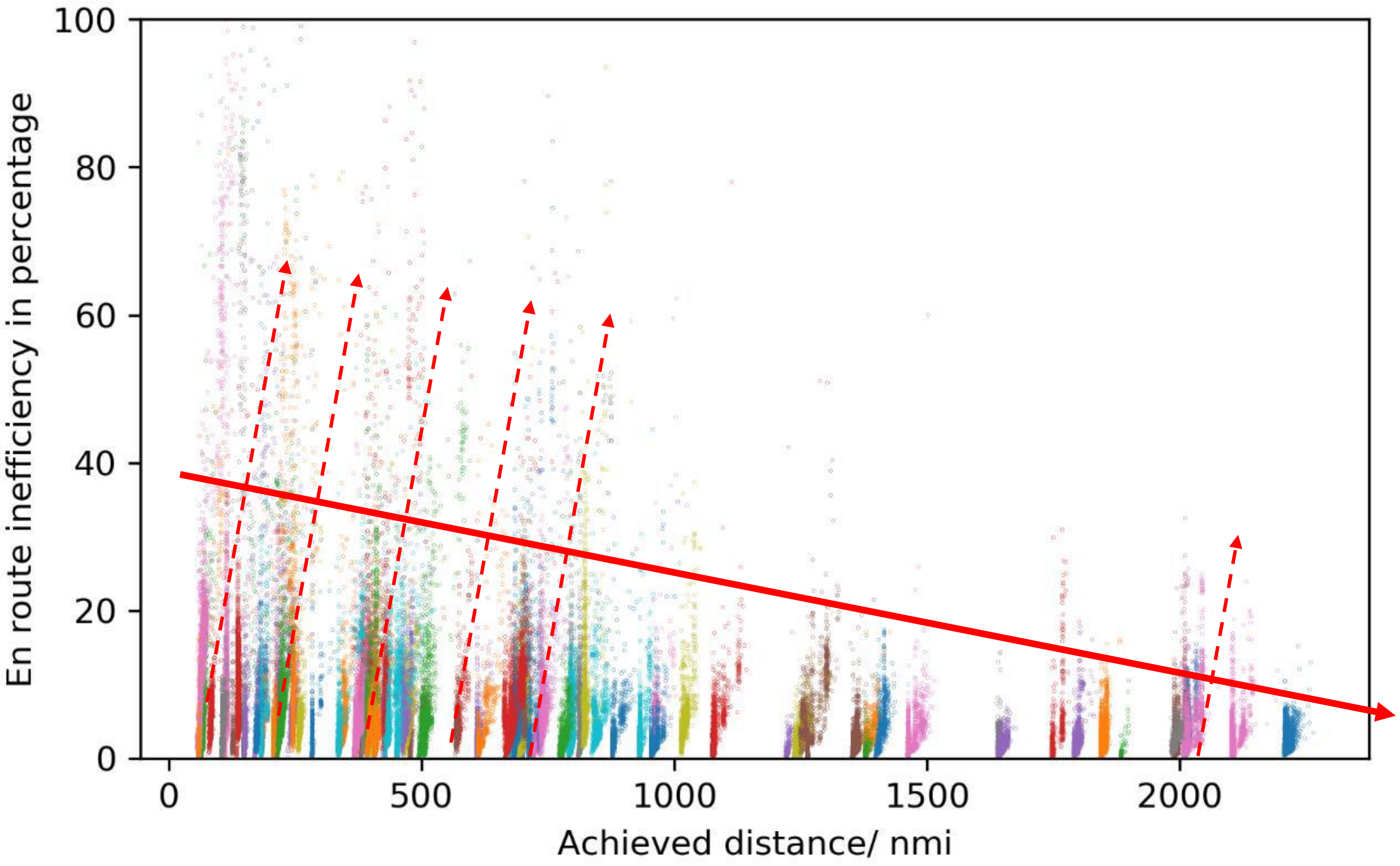
Estimation Results – Cross Sectional

Variable	Models Est. / (Std.)			
	Model I	Model II	Model III	Model IV
AchDist	53.9478*** (1.871)	53.955*** (1.830)	-	-0.109*** (0.002)
Airport-pair fixed effect	…	…	…	-
Obs.	436,830	436,830	436,830	436,830
Adjusted R^2	0.654	0.654	0.445	0.040



- Model II (airport-pair fixed effect controlled): *AchDist* mainly derives from flights within the same OD pairs → less efficient departure/arrival procedures result in higher en route inefficiency.
- Model IV: *AchDist* mainly captures the cross sectional variations → long haul flights are in general more efficient.

Estimation Results – Cross Sectional

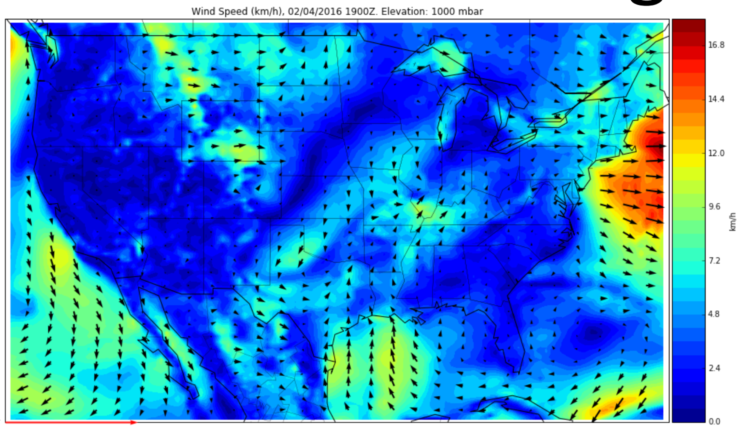


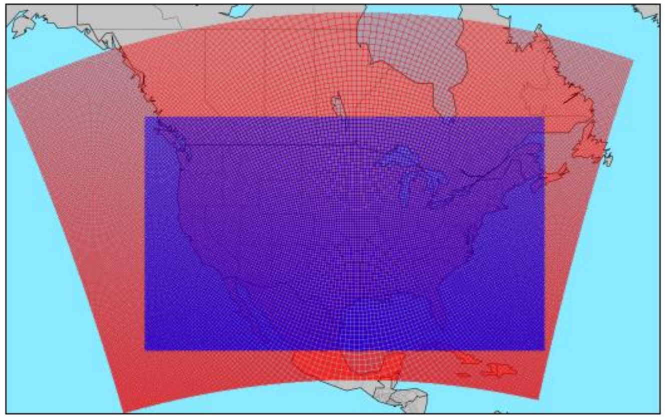
Summaries

- Trajectory Synthetic Algorithm
- Tree-based Matching Algorithm
- Econometric Models
  - Worst case: headwind, convective weather activity, TMIs, and SAAs.
  - Inefficient terminal procedure → reduce en route inefficiency.

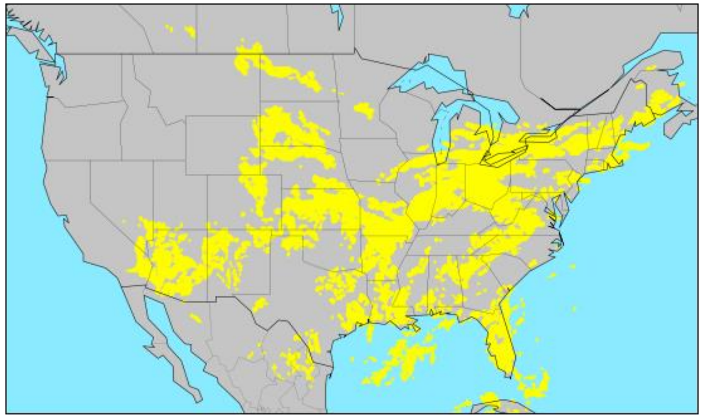
Ongoing Work

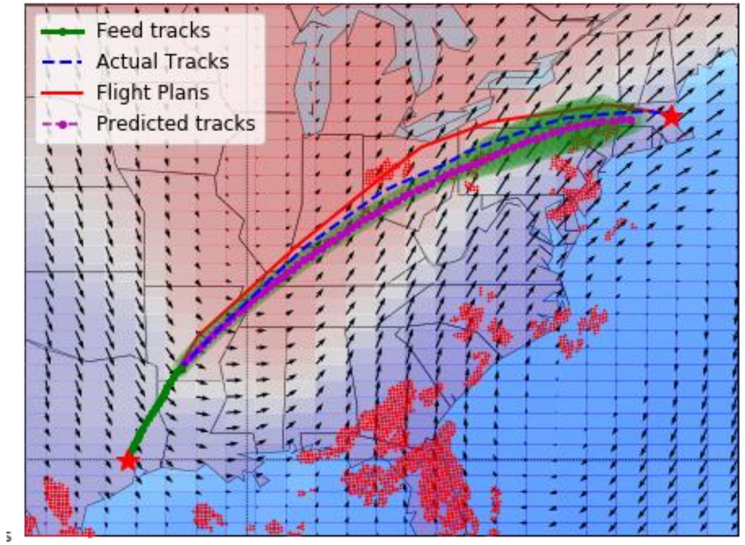
- Data with (even) higher fidelity
- Individual flight trajectory prediction model

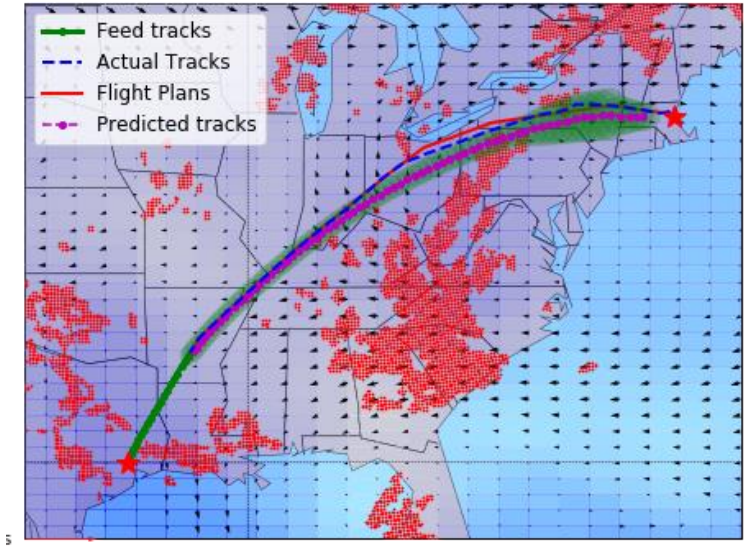




NCWF convective weather polygon







Thank you!

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