Global Oceanic Model Analysis to Support FAA Business Case for Satellite-based ADSB

Virginia Tech, FAA Contractors (GRA, CSSI, Boeing) and MIT Modeling Team

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Presentation Outline

- Modeling tool and assumptions
  - Oceanic areas considered
  - GO model technical assumptions
- Reporting benefits
- Modeling results
  - Fuel and travel time benefits
  - Tactical conflict results
  - Potential conflict events requiring monitoring
- Conclusions and Recommendations

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The modeling work presented here involves individuals at Virginia Tech, MIT and several FAA contractors

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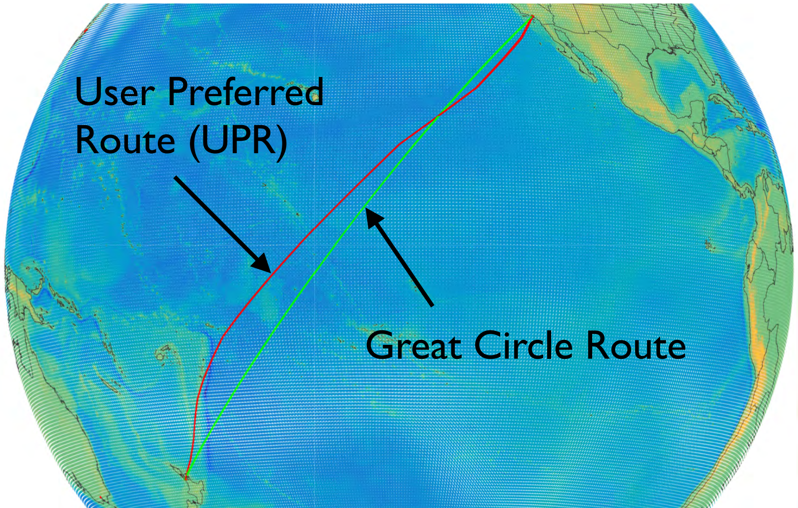
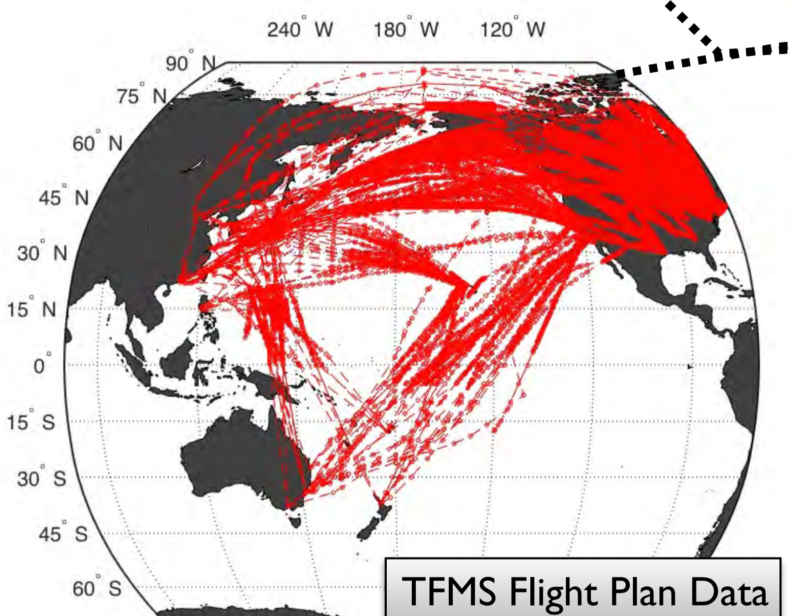
Global Oceanic Model Information

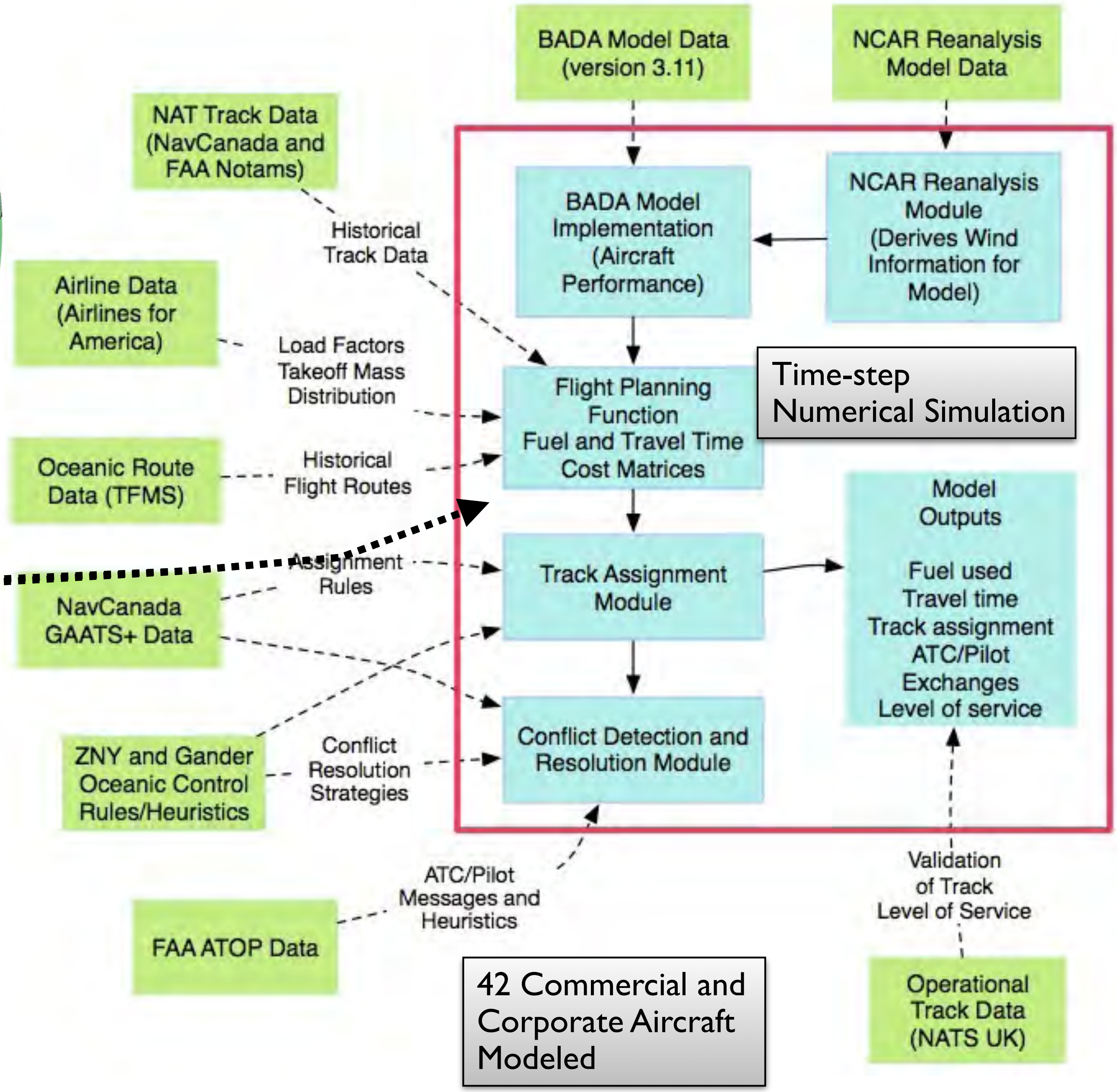
Global Oceanic Model

Los Angeles - Auckland



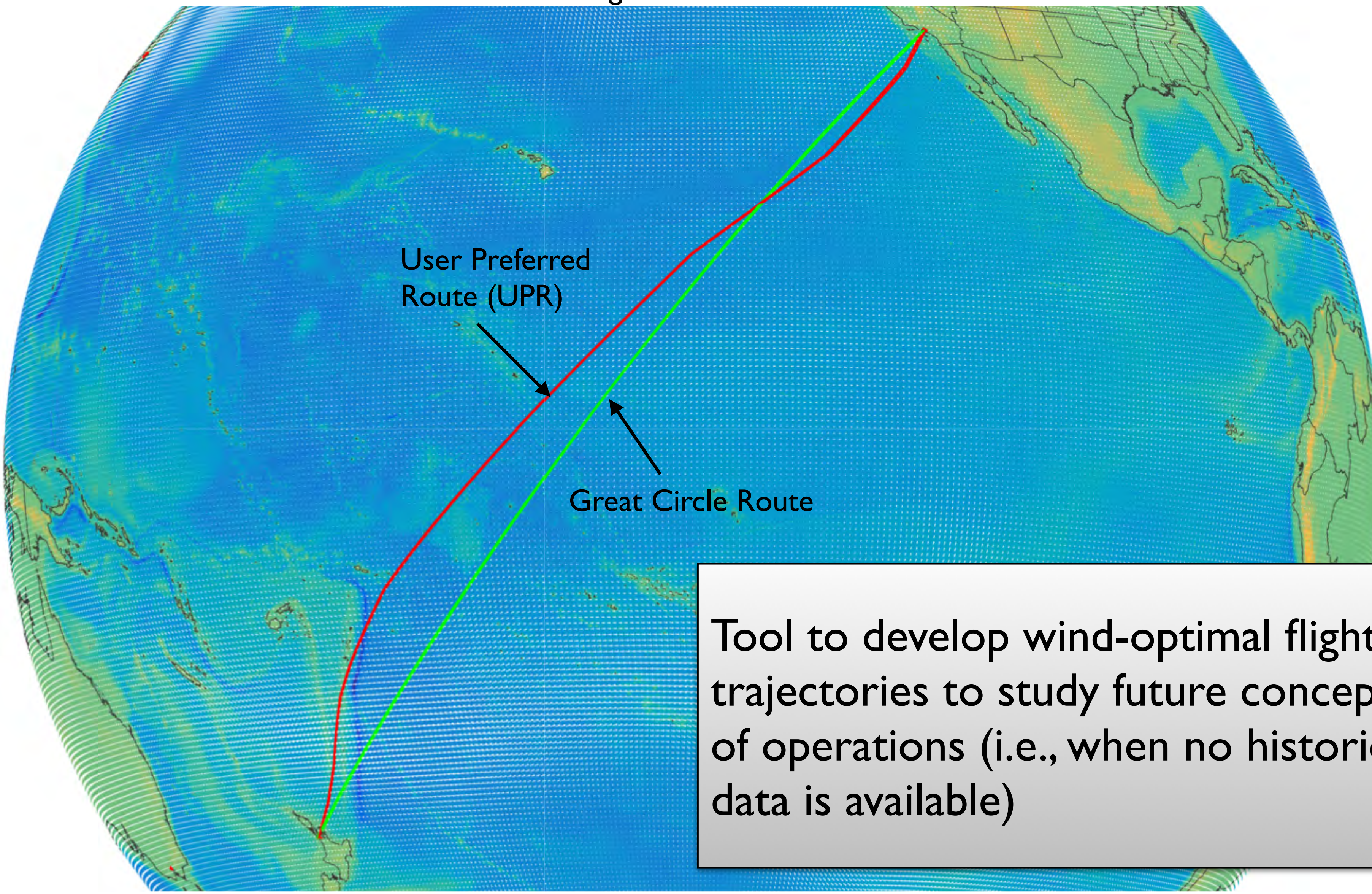
Flight Planning Module





Global Oceanic Model : Flight Planning Tool

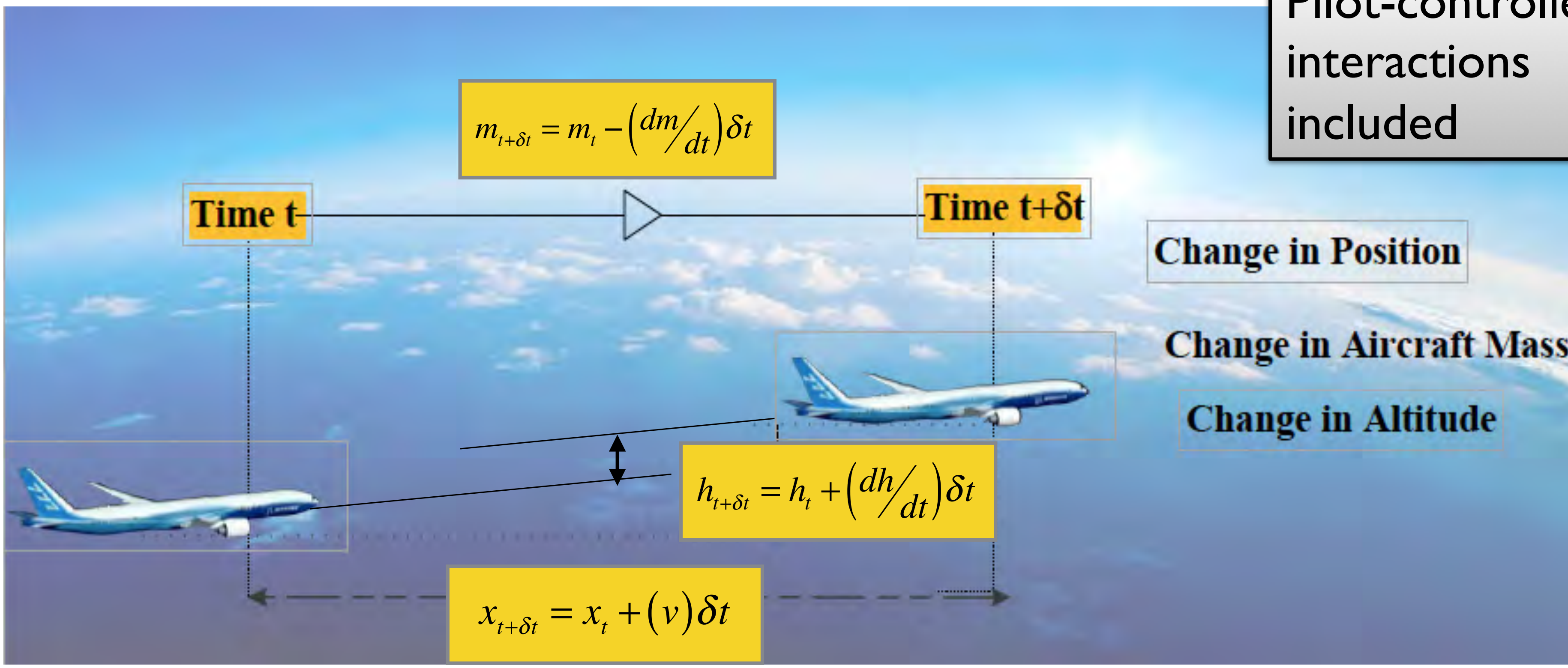
Los Angeles - Auckland



Tool to develop wind-optimal flight trajectories to study future concepts of operations (i.e., when no historical data is available)

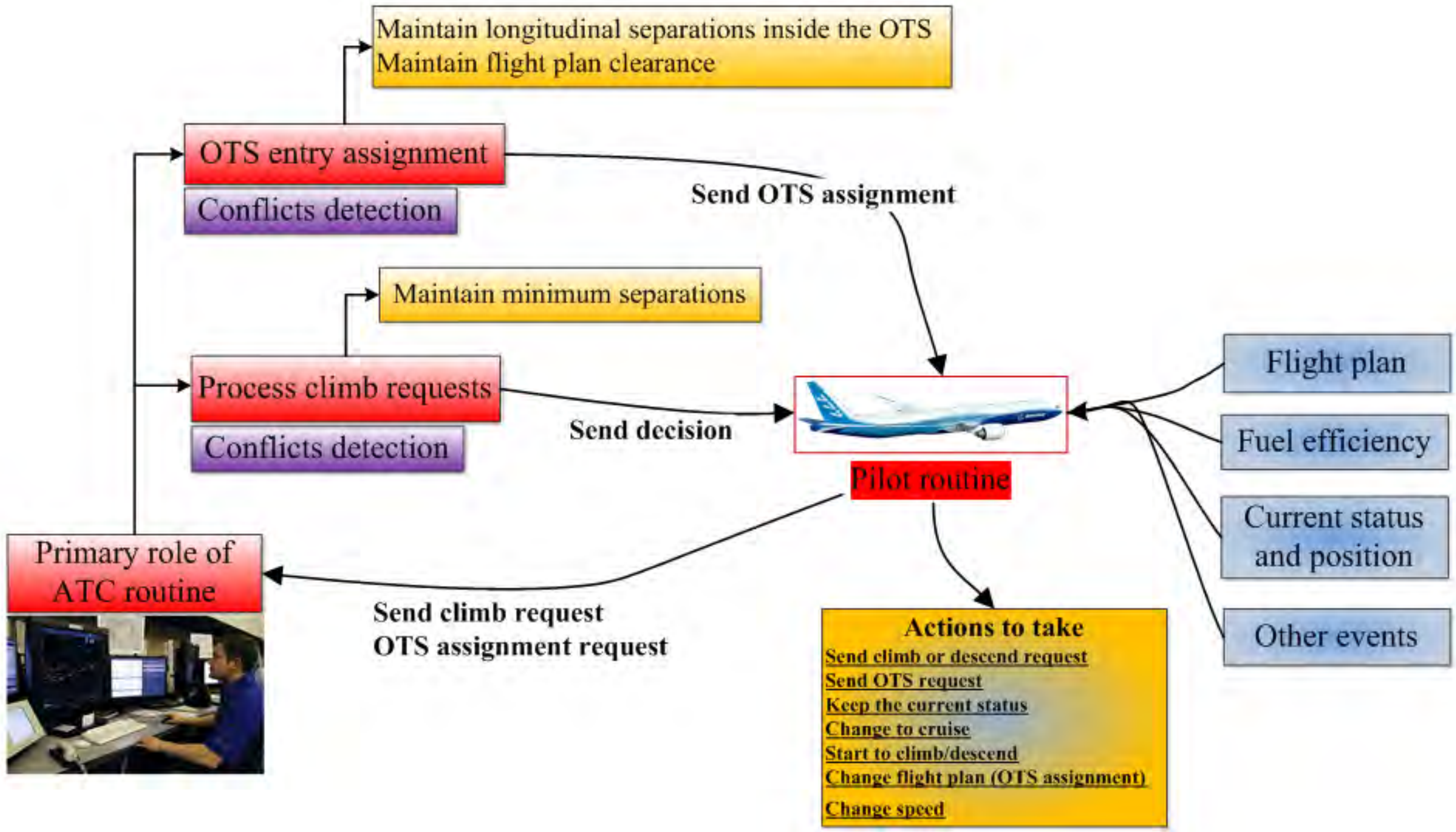
Simulation Model Paradigm

Pilot-controller interactions included



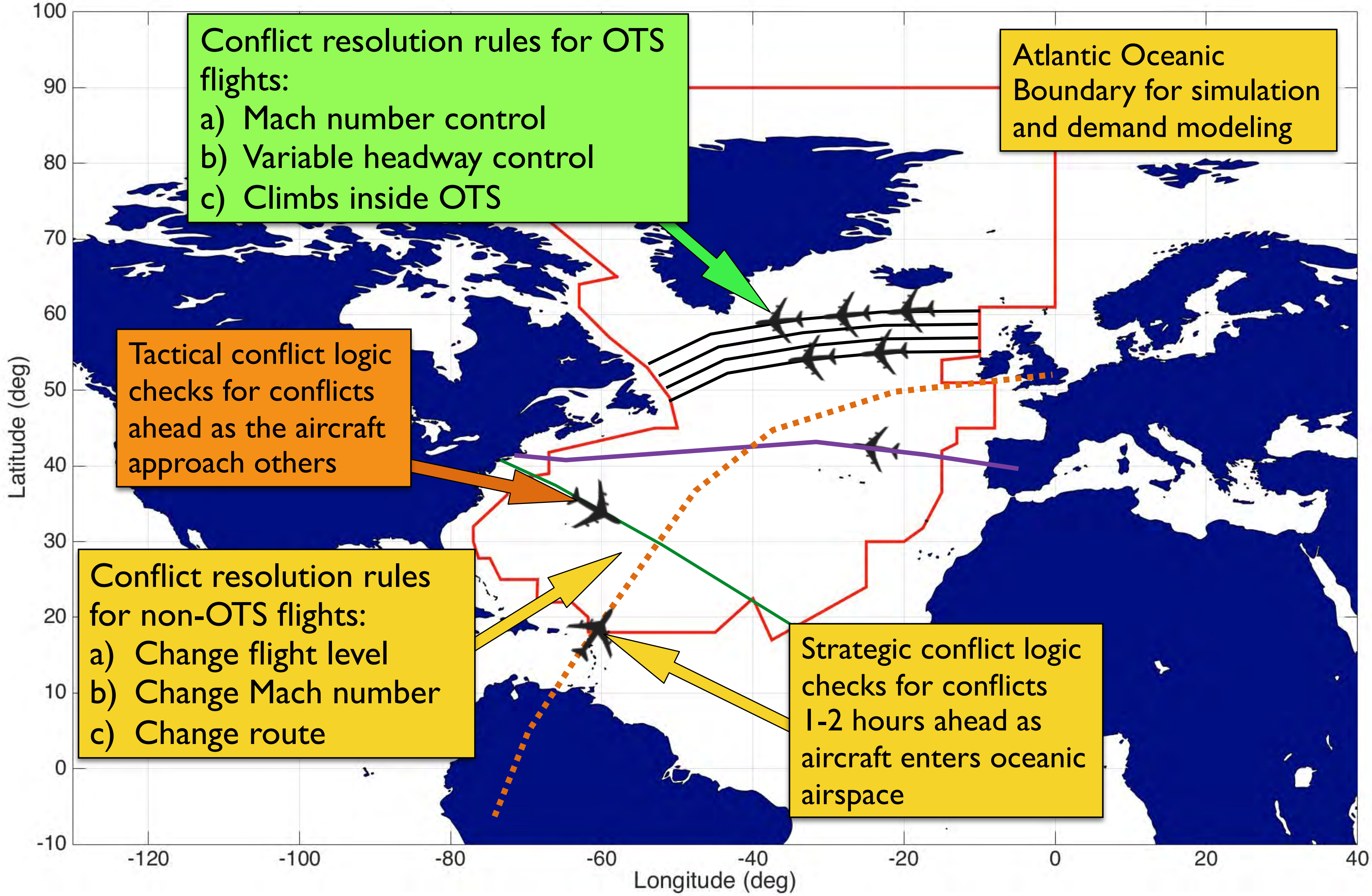
- Aircraft states are evaluated every 5 seconds (sampling rate)
- Model solves the aircraft equations of motion numerically
- BADA aerodynamic model (version 3.13.1)
- Distance traveled, mass and altitude are aircraft state variables tracked
- NCAR Reanalysis wind model developed by NOAA
- Pilot and controller interactions modeled

Modeling Pilot and ATC Interactions



- The pilot routine and ATC routine control aircraft together
- The pilot routine controls an individual aircraft
- The ATC routine controls all the aircraft within a certain airspace

Strategic and Tactical Conflict Algorithms in the Model



OTS Track Assignment Logic

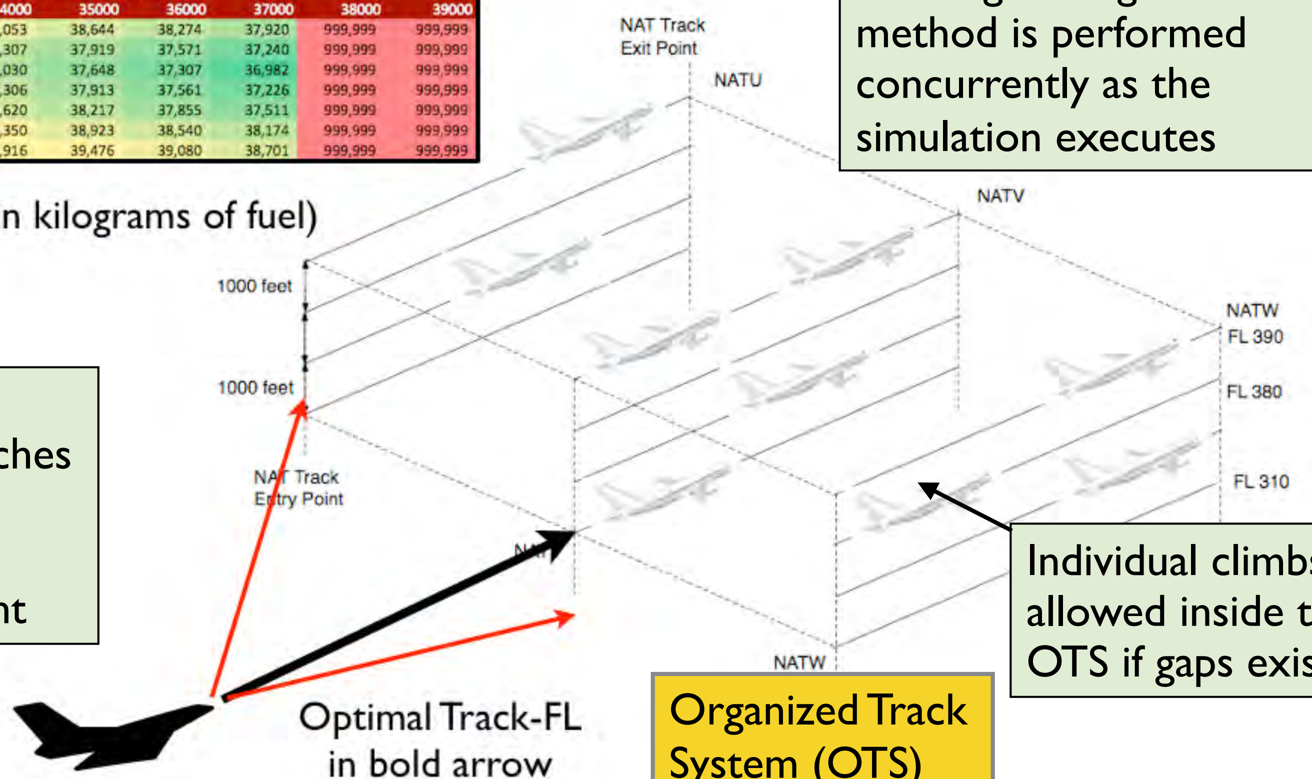
- The track assignment module assigns flights to NAT OTS and random tracks based on their relative costs compared to an optimal track selected as preferred alternative

- Flights are assigned to a track considering competing flights requesting the same track

Track	31000	32000	33000	34000	35000	36000	37000	38000	39000
	Cruise Altitude (feet)								
NATT	40,912	40,246	39,625	39,053	38,644	38,274	37,920	999,999	999,999
NATU	40,264	39,563	38,910	38,307	37,919	37,571	37,240	999,999	999,999
NATV	40,041	39,321	38,650	38,030	37,648	37,307	36,982	999,999	999,999
NATW	40,325	39,602	38,928	38,306	37,913	37,561	37,226	999,999	999,999
NATX	40,662	39,931	39,249	38,620	38,217	37,855	37,511	999,999	999,999
NATY	41,384	40,655	39,976	39,350	38,923	38,540	38,174	999,999	999,999
NATZ	41,984	41,243	40,553	39,916	39,476	39,080	38,701	999,999	999,999

Fuel Cost Matrix (in kilograms of fuel)

OTS flight assignment method is performed concurrently as the simulation executes

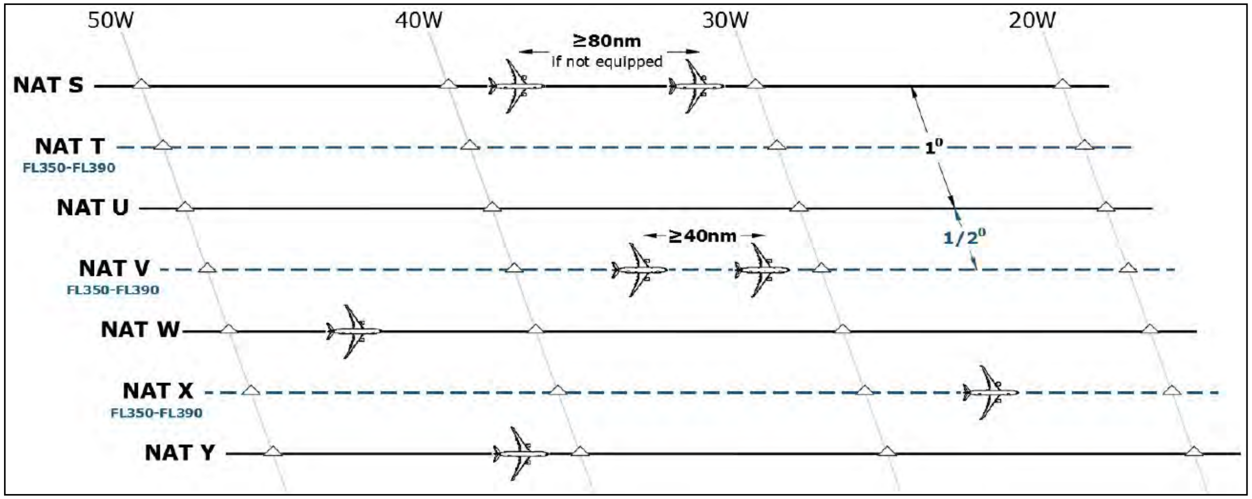


Flight Plan Changes
Necessary when a flight approaches the OTS entry point
Use of variable Mach number headway rules in OTS assignment

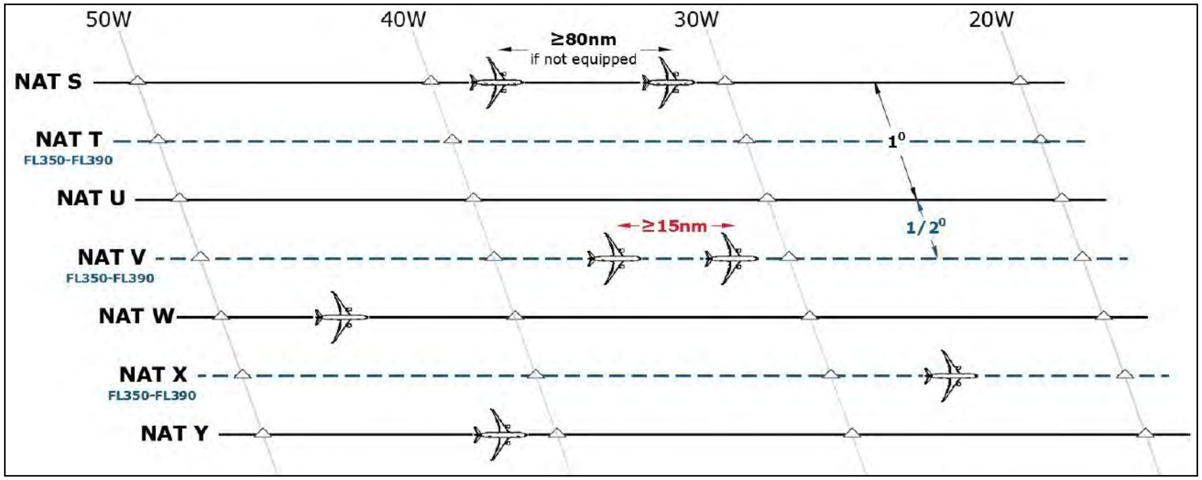
Individual climbs allowed inside the OTS if gaps exists

Organized Track System (OTS)

Model Can Study Many Variations of OTS Track System



2013 Time Frame



Mid-Future State

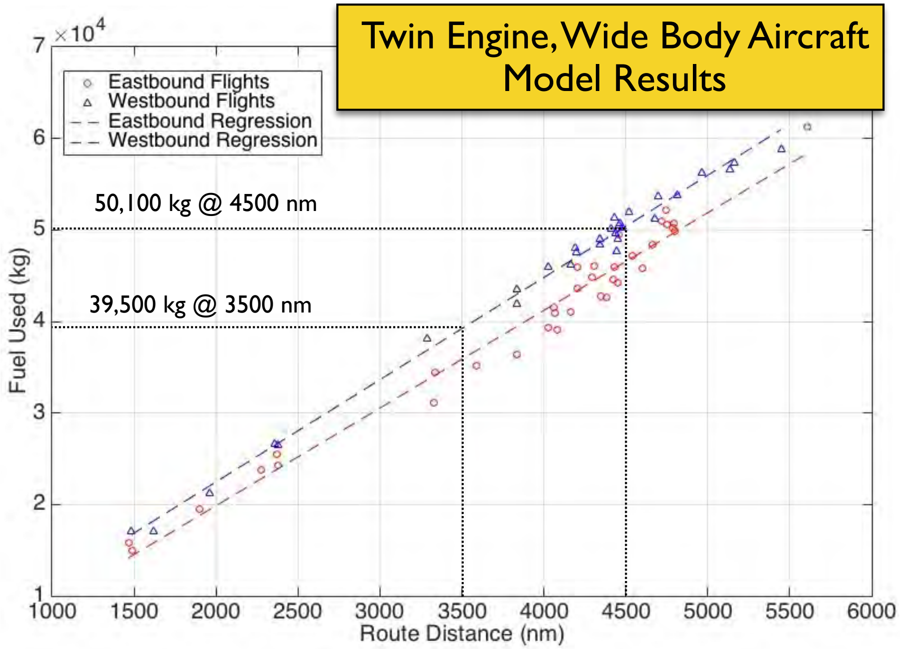
Far-Future State (no tracks)

OTS Track configuration specified via an Excel input file

Global Oceanic Model Outputs

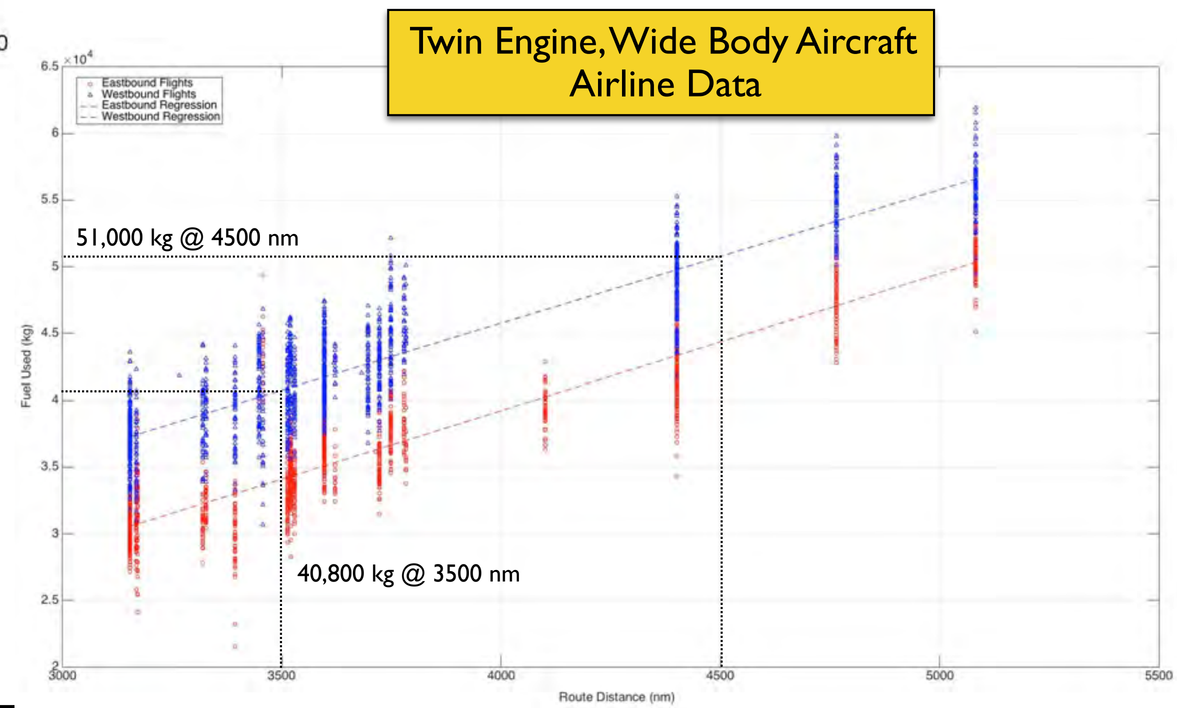
Model Output	Remarks
Fuel consumption	Total fuel used for all flights (NAT OTS and non-OTS) from origin to destination
Travel time	Total travel time for all flights (non-OTS and NAT OTS) from origin to destination
Emissions (GHG)	Reported as a multiplier to fuel consumption
Percent of non-OTS flights flown with tactical conflict resolution changes	Level of service indicator for OTS flights Reports the number of tactical conflicts detected and resolved
Percent of non-OTS flights flown with strategic conflict resolution changes	Level of service indicator for on-nOTS flights Reports number of strategic conflicts
Percent of OTS flights accommodated in desired NAT track and cruise altitude (both)	Level of service indicator for OTS flights Reports the percent of flights assigned to their requested NAT track and cruise altitude in the NAT region
Pilot and ATC Exchanges	Number of requests for cruise flight level changes
Aircraft trajectory details	5-second interval flight trajectory

Model Validation



Airline data supplied by Airlines for America

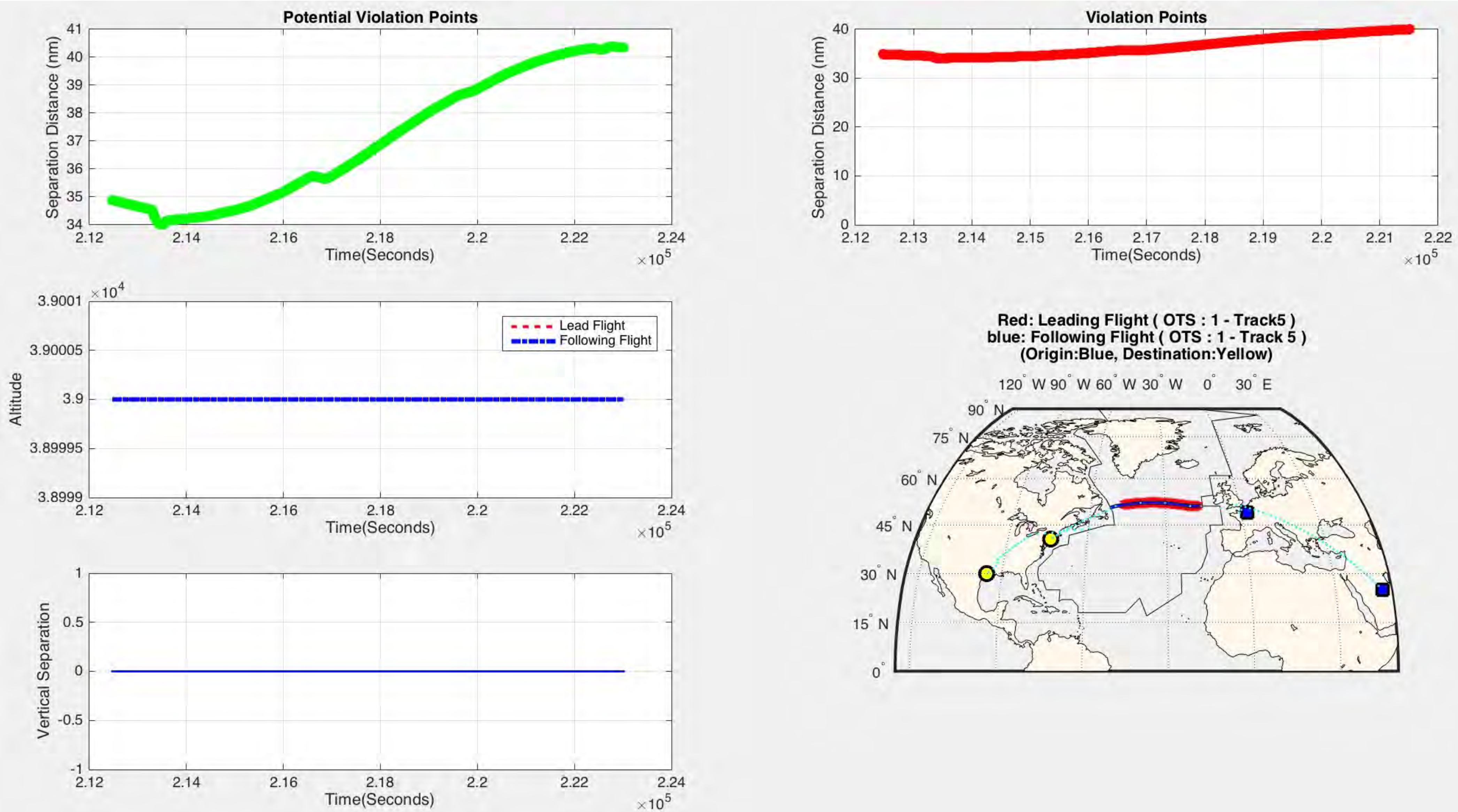
For most aircraft the model replicates within 2-3% accuracy the observed fuel trends derived from airline data (A4A)



Airline data has much wider variability in fuel used because the data is taken from 79 distinct days

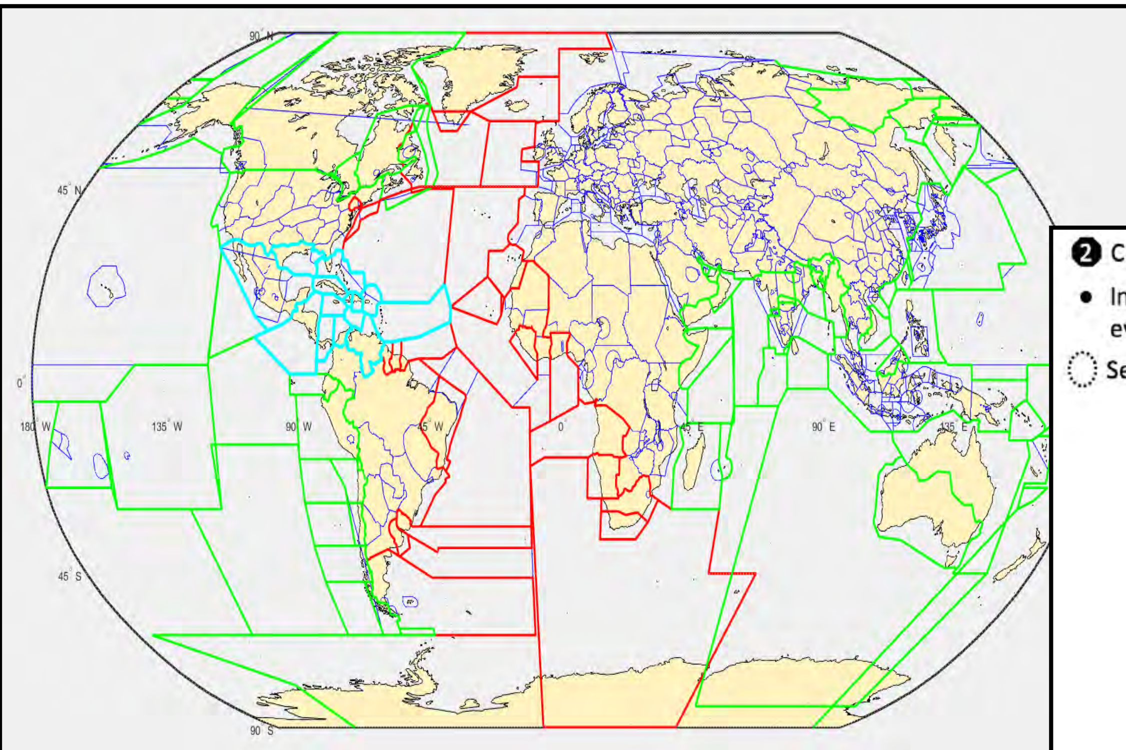
Thanks to A4A and IATA airlines for providing the data

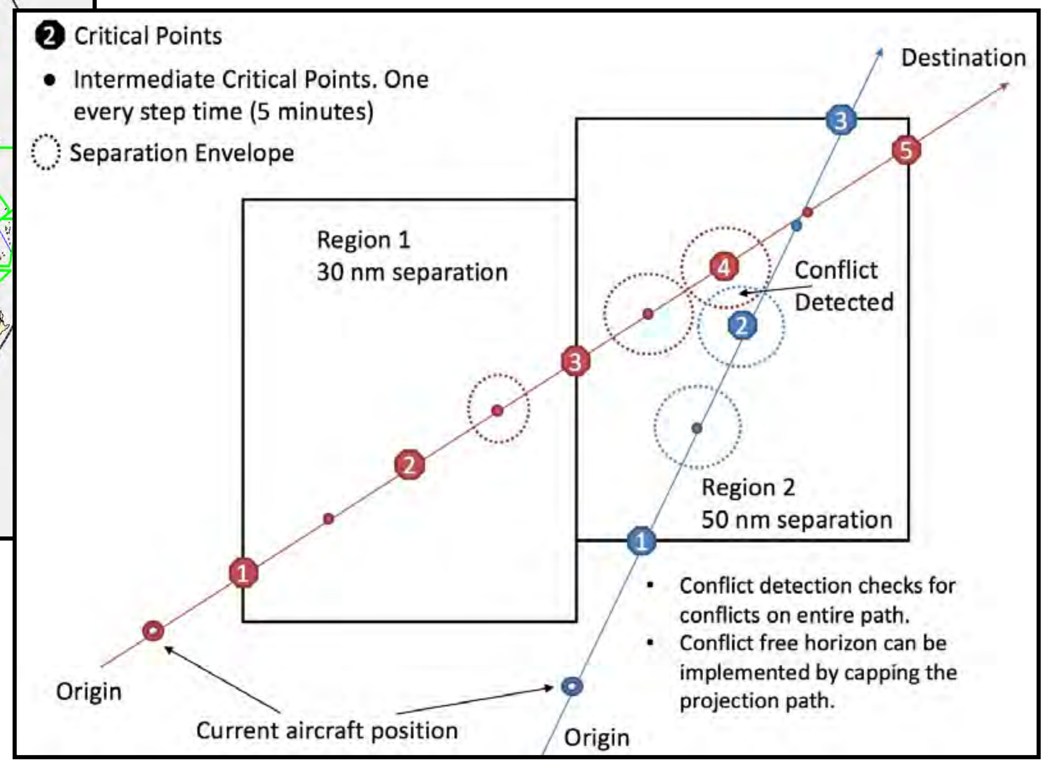
Global Oceanic Model: Conflict Analysis Post-processor



Global Oceanic Model: Multi-Region Simulation

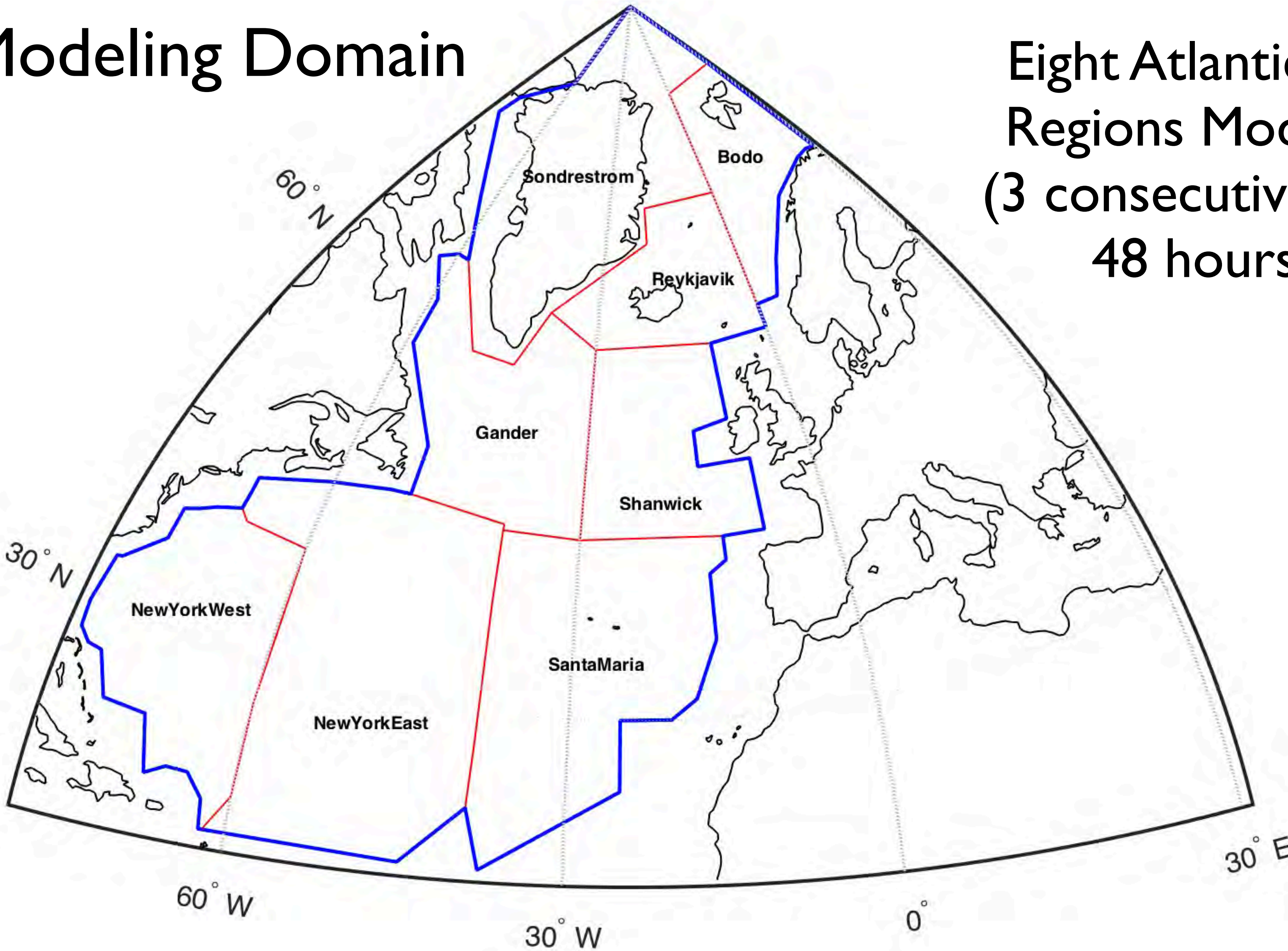
- Model can accommodate "local" FIR separation rules
  - Aircraft equipage levels defined via input demand file





Application of the GO Model to Support Satellite ADS-B Benefits Analysis

Modeling Domain



Eight Atlantic FIR Regions Modeled (3 consecutive days 48 hours)

Other Model Assumptions

Traffic Sample Days (up to 8)	June 24/25/26, 2016 seed day (3 days simulated) October 31, November 1-2, 2016 seed day (3 days simulated)	
Traffic Growth Rate	3.4% annual growth to 2018/2020; Based on approved NAT EFFG Traffic Forecast (2016)	
OTS Track Structures	2016 OTS track data from NavCanada based on the 8 sample days (24 days including 3 day blocks)	
Aircraft Types	42 Aircraft types in the simulation	
BADA Aircraft performance model	3.13 and 4.0	MIT Optimal CI ~ 65 Tables
NOAA NCAR wind model	Re-analysis 2	
Hemispherical Rules	Applied (1000 feet)	
AC simulation step size	10 seconds	
Climb Check Interval	30 mins	
Conflict envelope	Asymmetrical Envelope	

Modeled Scenarios

Case	Separation Criteria	Remarks
Scenario 1 * **Fixed Mach Baseline Separation**	23/40 nm **	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path
Scenario 2 * **Fixed Mach Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path
Scenario 3 * **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path

Note:

* All runs using MIT tables at Cost Index ~ 65

** New York and Santa Maria at 30/30 nm

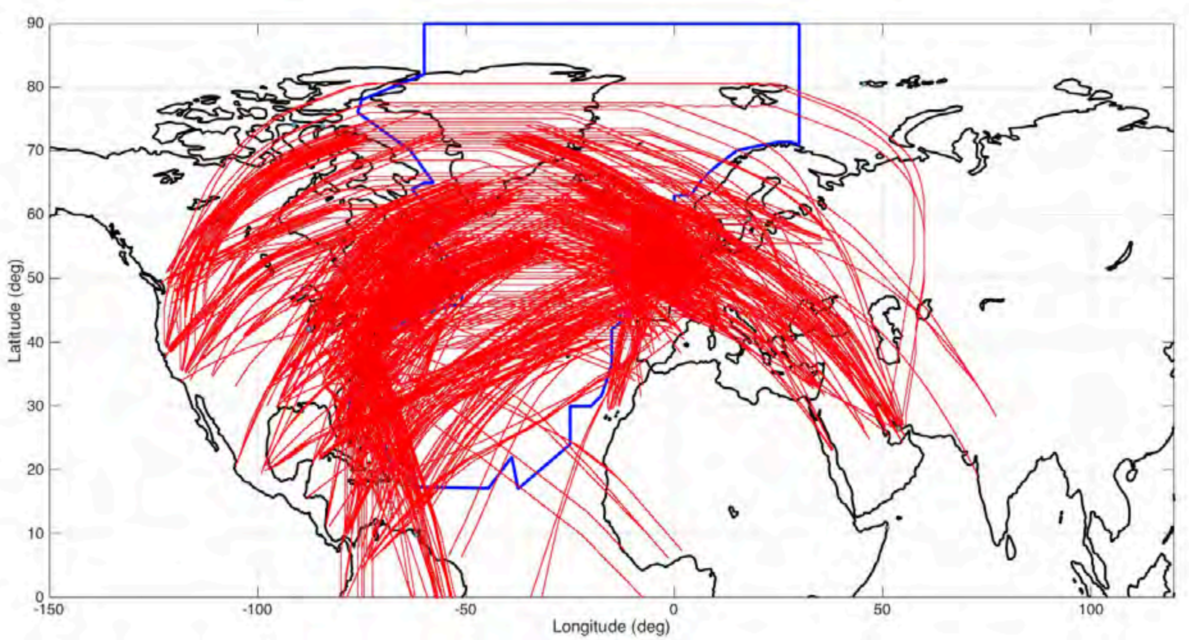
Modeled Scenarios

Case	Separation Criteria	Remarks
Scenario 4.1 **User Preferred Routes and Fixed Mach Number**	15/15 nm	No OTS Track System Climbs allowed everywhere Fixed Mach number Model creates wind-optimal flight plans for each flight Aircraft flies the wind-optimal route (UPR)
Scenario 4.2 **User Preferred Routes and Variable Mach Number**	15/15 nm	No OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Aircraft flies the wind-optimal route (UPR)

Note:
a) All runs using MIT tables at Cost Index ~ 65

Reporting Flight Benefits

- Two sets of flights reported:
  - **Organized Traffic System** (OTS) flights
  - **All North Atlantic flights** whose flight path meets the following criteria:
    - Extends above 20 degree North of Latitude
    - 1,800 nm or more route length

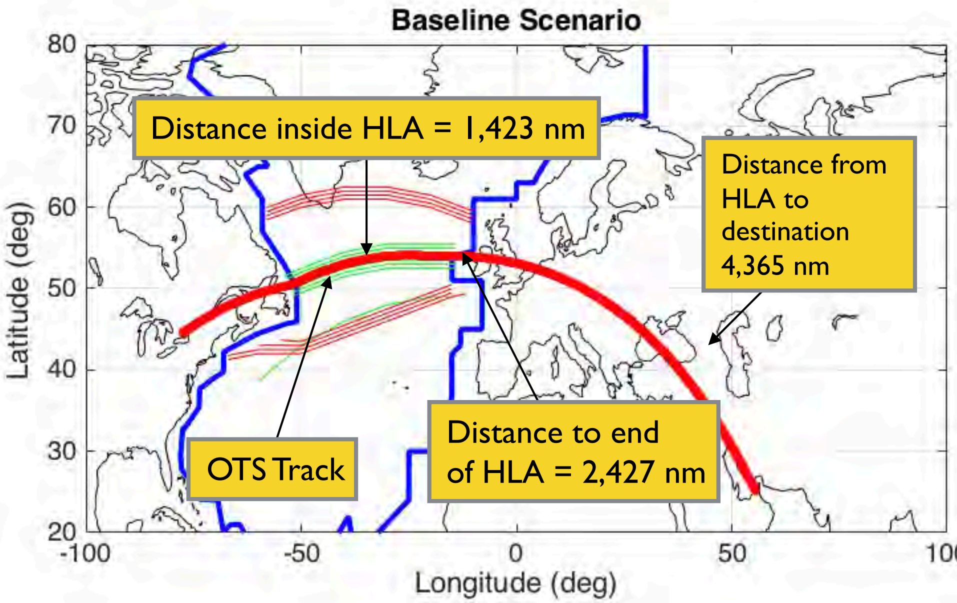


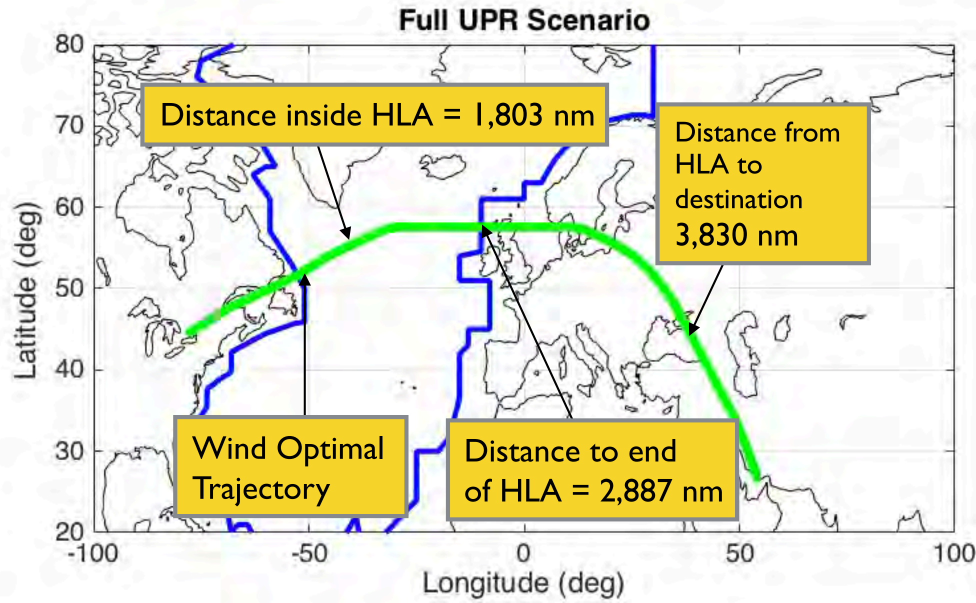
Typical flights included in the all North Atlantic flights report

Reporting Flight Benefits (2)

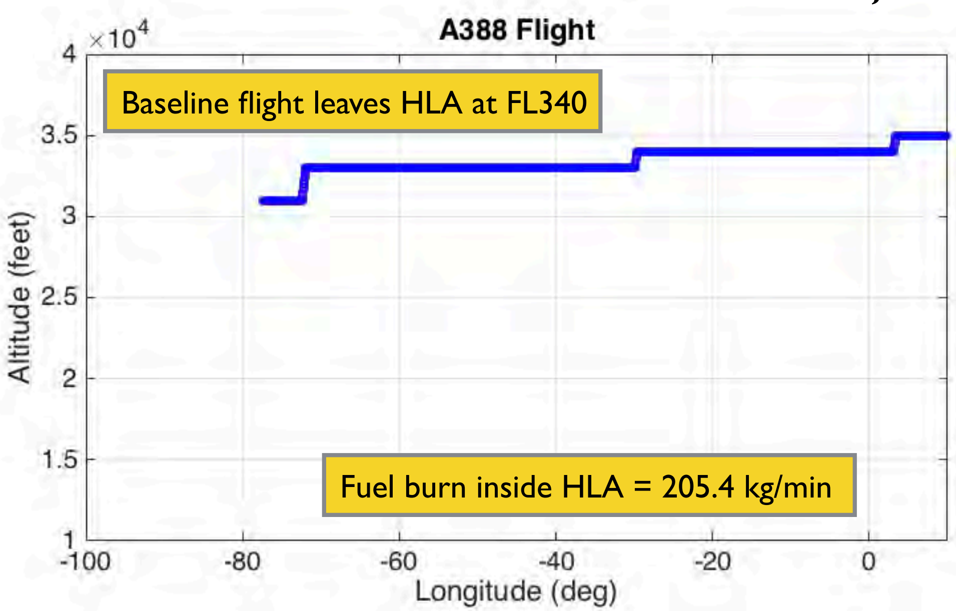
- In a complex system, benefits are not additive
  - Percent aircraft that climb, variable Mach and travel time savings are all inter-related
- Flight benefits are reported for the complete flight path and for the HLA portion of the flight
- Benefits in the HLA airspace **enable** aircraft to reach more fuel efficient altitudes altitudes after leaving the HLA airspace
- For advanced concepts of operations (~User Preferred Routes), many flights spend more time inside HLA airspace
  - This could create the false impression of additional fuel and travel time inside HLA boundaries
  - Reporting fuel and travel time results to the end of the HLA has also its own set of complications (see example in the next page)

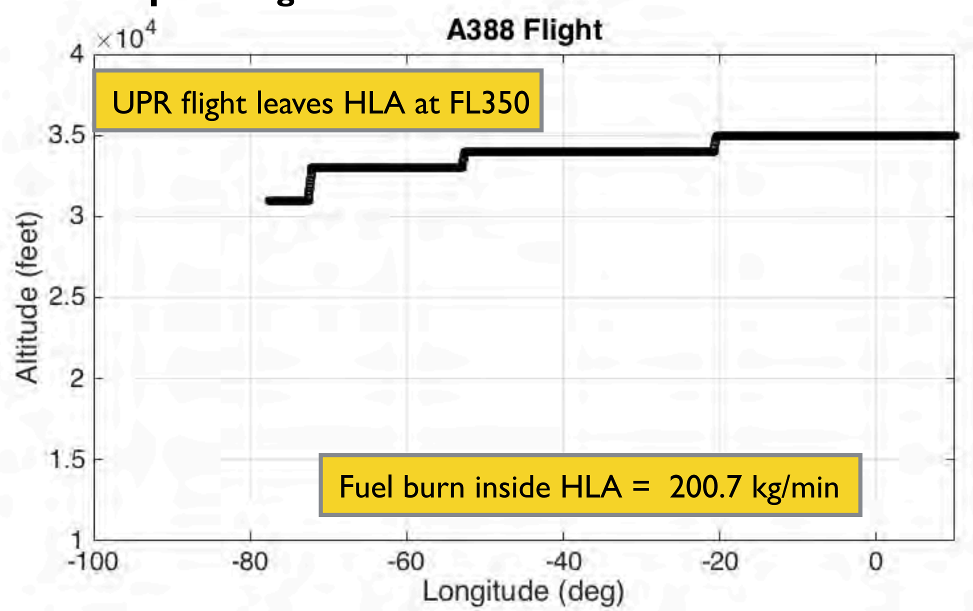
Reporting Flight Benefits (3)





Full UPR flight burns more fuel to reach the end of the HLA boundary
Nevertheless, it saves fuel in the complete flight





Other Scenario Technical Assumptions

Parameter	Baseline 23/40 nm Separation Scenario	15/15 nm Separation Scenarios	UPR Scenarios 15/15 nm Separation
OTS flight delivery technical allowance	2 minutes additional headway above minimum (5 minutes)	20 second additional headway above minimum (5 minutes)	20 second additional headway above minimum (5 minutes)
Climb-through spacing for OTS flights	4 minutes additional headway above minimum (5 minutes)	Minimum in-trail separation (15 nm) for lead and following aircraft	Minimum in-trail separation (15/15 nm)
Pilot climb request interval	40 minutes *	20 minutes	20 minutes
Pilot request “cool-down” interval	90 minutes *	20 minutes	20 minutes

* Technical parameters used to replicate New York Oceanic climb requests and climb approval metrics (0.78 requests per flight observed vs 0.85 requests in model)

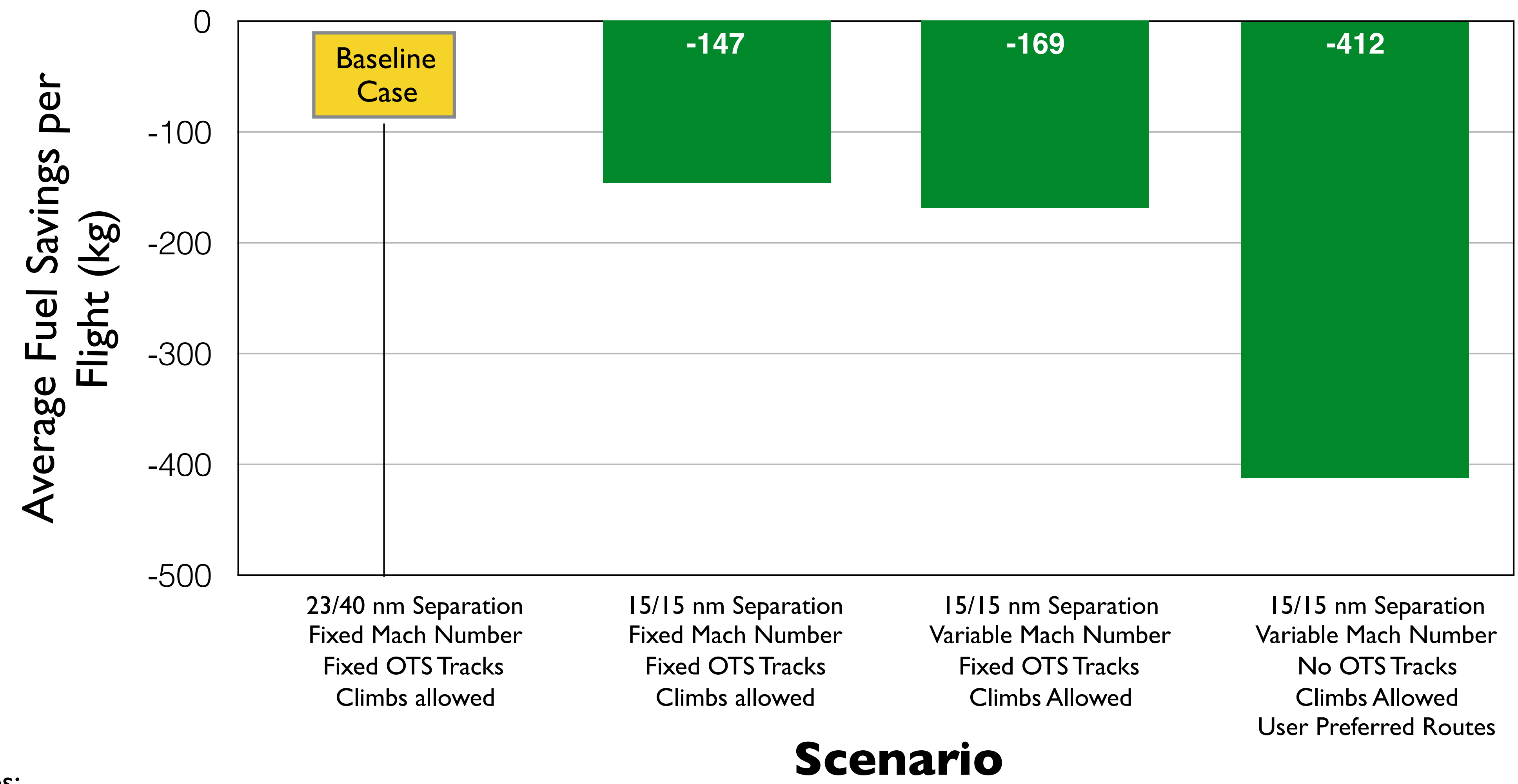
Other Scenario Technical Assumptions (2)

Parameter	Baseline 23/40 nm Separation Scenario	15/15 nm Separation Scenarios	UPR Scenarios 15/15 nm Separation
Aircraft climb allowance	Dictated by aircraft mass at climb request point (500 ft/minute minimum)	Dictated by aircraft mass at climb request point (500 ft/minute minimum)	Dictated by aircraft mass at climb request point (500 ft/minute minimum)
Aircraft assignment rule while entering OTS boundary	Up to three cruise flights level changes, then switch track	Up to three cruise flights level changes, then switch track	Not applicable (no OTS)

* Original heuristic rule provided by NATS UK in discussion with FAA and Virginia Tech in 2014

Complete Flight Benefits

Potential Fuel Benefits for Complete Flights



Notes:
a) **Includes All Atlantic traffic above 20 degrees North**
b) All 2220 flights typical (in 24 hour period)
c) Projected year 2020 traffic
d) Aircraft enter HLA at optimal Mach Numbers
e) All flight plans designed using wind-optimal trajectories

- **Contribution of Variable Mach Number to fuel benefit is 22 kilograms per flight**
- **OTS flights save on average 184 kilograms of fuel per flight**

Simulation Model Benefits (**All North Atlantic Flights**)

Case	Separation Criteria	Remarks	Benefits
Scenario 1 * **Fixed Mach Baseline Separation**	23/40 nm **	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**Baseline case**
Scenario 2 * **Fixed Mach Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**147 kilograms of fuel saved** **0.2 minute reduction in travel time**
Scenario 3 * **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**169 kilograms of fuel saved** **0.3 minute reduction in travel time**

Note:
* All runs using MIT tables at Cost Index ~ 65
** New York and Santa Maria at 30/30 nm

Simulation Model Benefits (**All North Atlantic Flights**)

Case	Separation Criteria	Remarks	Benefits
Scenario 1 **Fixed Mach Baseline Separation**	23/40 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**Baseline case**
Scenario 4.1 **User Preferred Routes and Fixed Mach Number**	15/15 nm	No OTS Track System Climbs allowed everywhere Fixed Mach number Model creates wind-optimal flight plans for each flight Aircraft flies the wind-optimal route (UPR)	**388 kilograms of fuel saved** **1.9 minutes reduction in travel time**
Scenario 4.2 **User Preferred Routes and Variable Mach Number**	15/15 nm	No OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Aircraft flies the wind-optimal route (UPR)	**412 kilograms of fuel saved** **2.4 minutes reduction in travel time**

Note:
a) All runs using MIT tables at Cost Index ~ 65

Simulation Model Benefits (**Organized Track System Flights**)

Case	Separation Criteria	Remarks	Benefits
Scenario 1 **Fixed Mach Baseline Separation**	23/40 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**Baseline case** **32% of the flights can execute a climb maneuver**
Scenario 3 **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**184 kilograms of fuel saved** **0.3 minutes of travel time saved** **64% of the flights execute at least one climb maneuver**

Notes:
a) Contribution to fuel benefit due to climbs for OTS flights is estimated at 184 kilogram

Conclusions (1)

- There are fuel and travel time benefits to be obtained from reduced separation criteria for Atlantic flights
  - 169 kilograms of fuel savings and 0.3 minute reduction in travel time is estimated for the average North Atlantic flight
  - 184 kilograms of fuel savings and 0.3 minutes of travel time saved are estimated for OTS flights
- Additional benefits (412 kilograms per flight and 2.4 minutes in travel time savings) would be possible with the implementation of User Preferred Routes (UPRs)
- Implementation of UPRs would require a substantial change in the concept of operations in the North Atlantic
- The fuel and travel time benefits due to climbs, variable Mach speed (i.e., optimization) and wind optimal routes derived from reductions in separation minima are **not mutually exclusive**

Conclusions (2)

- Reduction in separation minima from 23/40 nm to 15/15 nm would allow:
    - Doubling the number of climbs in the Organized Track System from 32% to 64% **
    - More fuel efficiency for flights beyond the HLA boundary
- Our simulations do not support the finding that all flights will be able to climb inside the OTS

** The improved climb rate estimate assumes climb through procedures using minimum 15 nm in-trail separation between leading and following aircraft (without additional technical in-trail allowance)

Oceanic Benefits

Simulation Model Benefits in HLA
(**All North Atlantic Flights**)

Case	Separation Criteria	Remarks	Benefits
Scenario 1 **Fixed Mach Baseline Separation**	23/40 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**Baseline case**
Scenario 3 **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**99 kilograms of fuel saved inside the HLA boundary** **0.18 minutes of saving in travel time** **64% more flights climb to better cruise flight levels**

Notes:
1) All runs using MIT tables at Cost Index ~ 65 to assign optimal Mach numbers at HLA entry point
2) 59% of the complete flight fuel savings attributed to HLA

Conclusions (3)

- Reduction in separation minima from 23/40 nm to 15/15 nm would allow:
  - Savings 99 kilograms for fuel inside the HLA (59% of the benefit estimated inside the HLA)
  - 65% more flights would be able to climb at some point in their journey
  - More fuel efficiency for flights beyond the HLA boundary
- Our simulations do not support the notion that all flights will be able to climb inside the OTS

** The improved climb rate estimate assumes climb through procedures using minimum 15 nm in-trail separation between leading and following aircraft (without additional technical in-trail allowance)

Potential Additional Savings for OTS Flights

- Remove "legacy" OTS track and cruise flight level assignment rule:
  - Assign flight up to three cruise flight levels down on the same track before moving to an adjacent track
  - Rule was justified to reduce navigation operational errors
- With Reduced Lateral Separation (RLat) in place for all OTS tracks, flying an adjacent track is more cost effective than flying at a less than optimal cruise altitude

Example of Fuel Savings Removing Cruise Altitude Assignment Legacy Rule

Consider a Boeing 747-400 flying from EGLL to JFK (Westbound flight)

- Optimal track is G and optimal cruise altitude 37,000 feet
- Cruise altitudes of 36,000 ft. and 35,000 have large fuel penalties

Additional Fuel Used (kg)

Track E	Track F	Track G	Track H	Cruise Altitude (ft)
				40,000
veight limitation				39,000
				38,000
452.8	175.0	0.0	35.9	37,000
1036.2	754.3	565.1	622.2	36,000
1637.6	1352.8	1149.2	1229.2	35,000
ra-flow flights				34,000
3044.0	2763.6	2551.6	2690.3	33,000
3889.1	3614.4	3406.4	3581.9	32,000
4819.4	4554.1	4348.6	4565.9	31,000

Table contains additional fuel used if a non-optimal track and flight level are selected

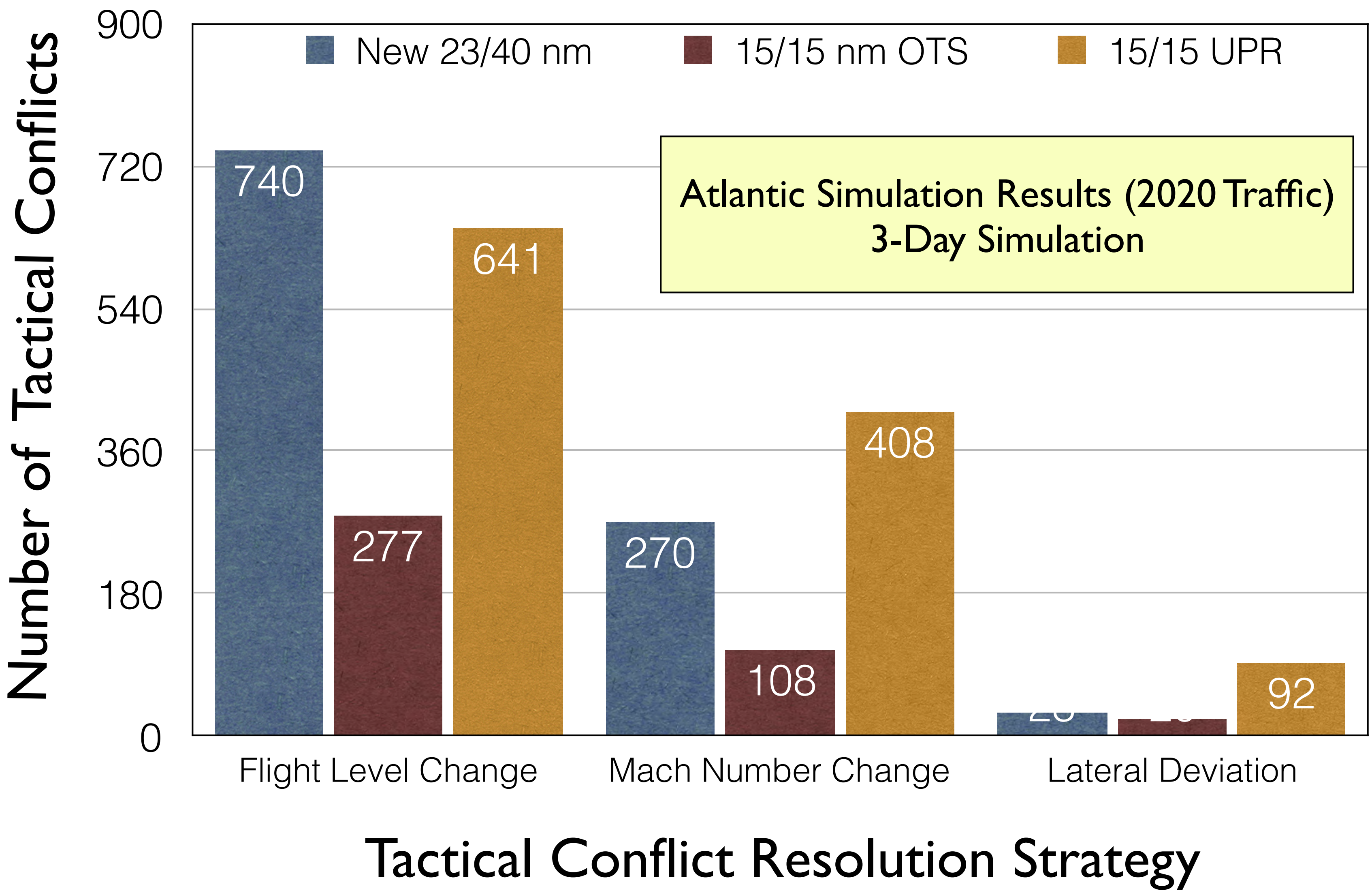
Conclusion: Under RLat conditions, shifting to adjacent tracks saves fuel

Simulation Model Benefits in HLA (**Organized Track System Flights**)

Case	Separation Criteria	Remarks	Benefits
Scenario 1 **Fixed Mach Baseline Separation**	23/40 nm	Fixed OTS Track System Climbs allowed everywhere Fixed Mach number in cruise Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path	**Baseline case**
Scenario 3 **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path **Maximum of three cruise flight level change in OTS assignment before moving to adjacent track**	**99 kilograms of fuel saved inside the HLA boundary** **0.18 minutes of saving in travel time** **64% more flights climb to better cruise flight levels**
Scenario 3.2 **Variable Mach Number Reduced Separation**	15/15 nm	Fixed OTS Track System Climbs allowed everywhere Mach number changes allowed Model creates wind-optimal flight plans for each flight Model Assigns OTS Tracks based on Wind-Optimal Flight Path **Maximum of two cruise flight level change in OTS assignment before moving to adjacent track**	**135 kilograms of fuel saved inside the HLA boundary** **0.30 minutes of saving in travel time** **60% more flights climb to better cruise flight levels**

Tactical Conflicts

Tactical Conflict Resolution Maneuvers
Heavy Traffic Day



Observations: Tactical Conflicts (1)

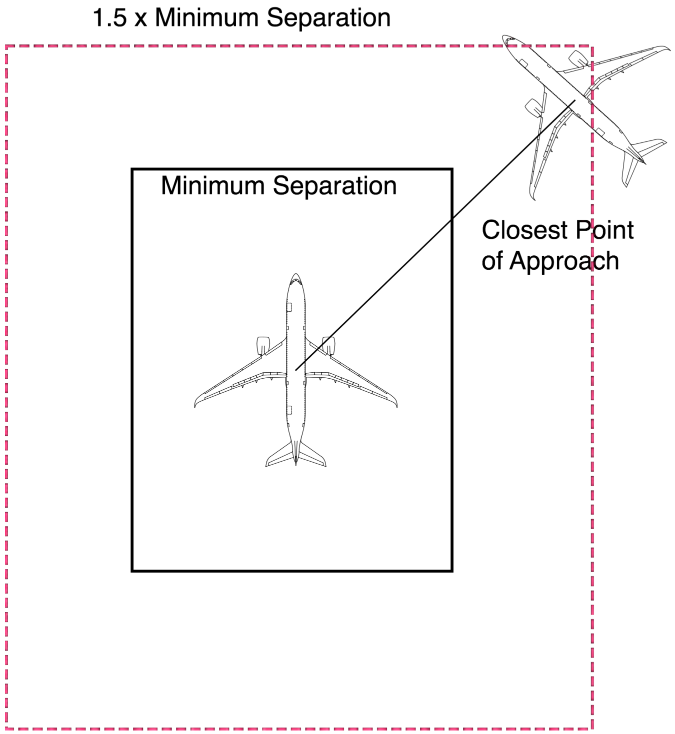
- With:
  - Reduced separations to 15/15 nm,
  - Forecasts traffic levels in year 2020, and
  - Maintaining the organized track system
- *The total number of tactical conflicts for non-OTS flights could decrease by 61% compared to the tactical conflicts estimated for the baseline scenario (23/40 nm) in a heavy traffic day*
- Removing the organized track system and reducing separation minima to 15/15 nm,
  - *The total number of conflicts for non-OTS flights will increase 181% compared to a scenario with 15/15nm separation minima and with the OTS track system in place*
  - *The total number of tactical conflicts will be about 10% higher than baseline scenario (applicable to non-OTS flights)*

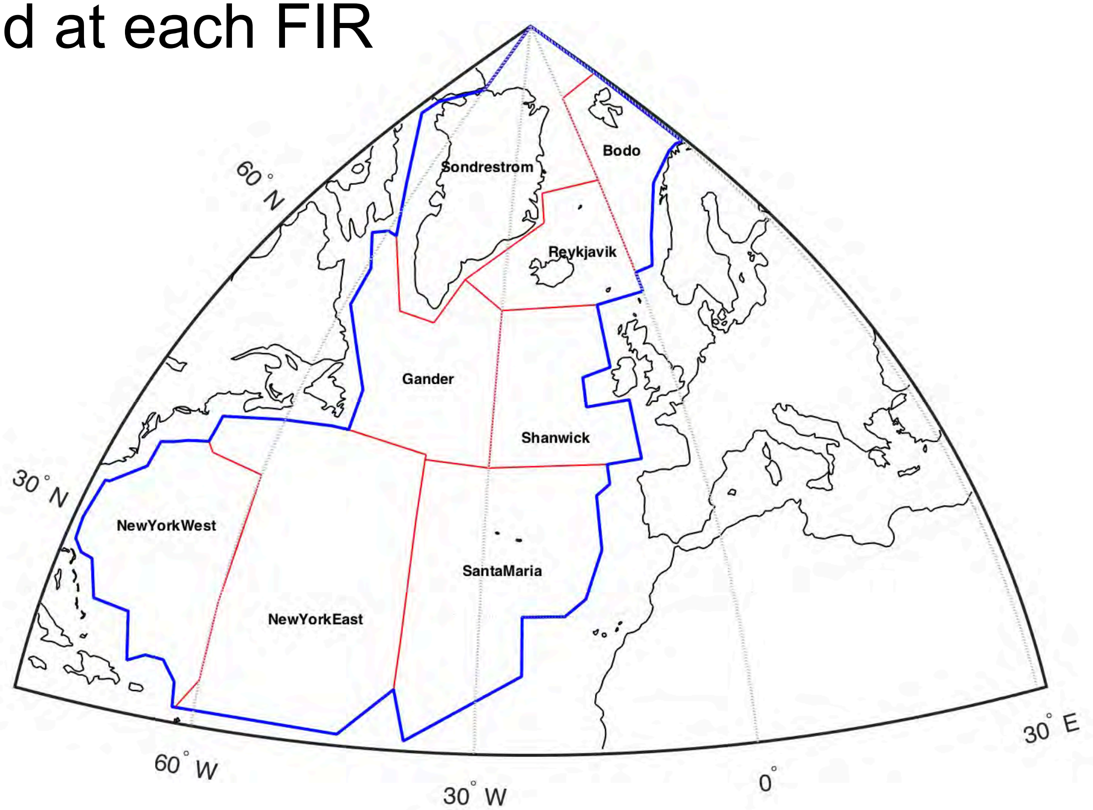
Observations: Tactical Conflicts (2)

- Enabling airlines to fly User Preferred Routes (UPRs):
  - The total number of conflicts for non-OTS flights will increase 181% compared to 15/15 separation and maintaining the OTS tracks
  - *The predicted spatial distribution of the tactical conflicts will be more narrowly located in three bands across the Atlantic*
  - *It is expected that some FIRs (i.e., Gander and Shanwick) will experience more tactical conflicts per square mile compared to today's scenario*
- The UPR trajectories offer substantial fuel and travel time benefits but may require more decision support tools beyond those contained in ICAO document *"NAT EFFG Phase 1 Space-Based ADS-B Business Case Analysis for Implementation in the Gander and Shanwick Oceanic Control Areas within the ICAO North Atlantic Region"*

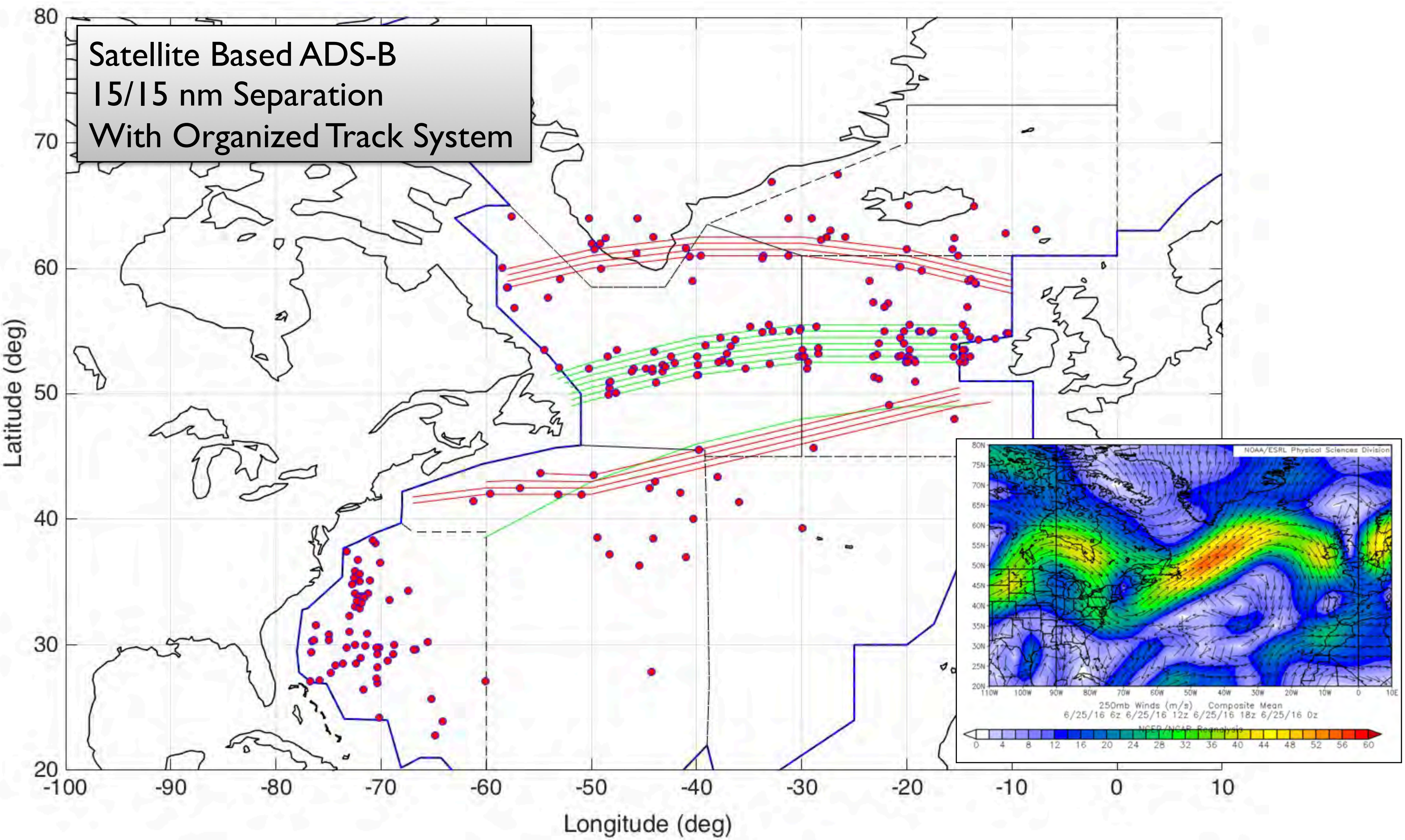
Analysis of Potential Workload Issues in Advanced Oceanic Scenarios

- The simulation results provide insight on the distribution of potential aircraft conflict events that may require close ATC monitoring
- We compared the number and spatial distribution of potential conflicts events detected at each FIR

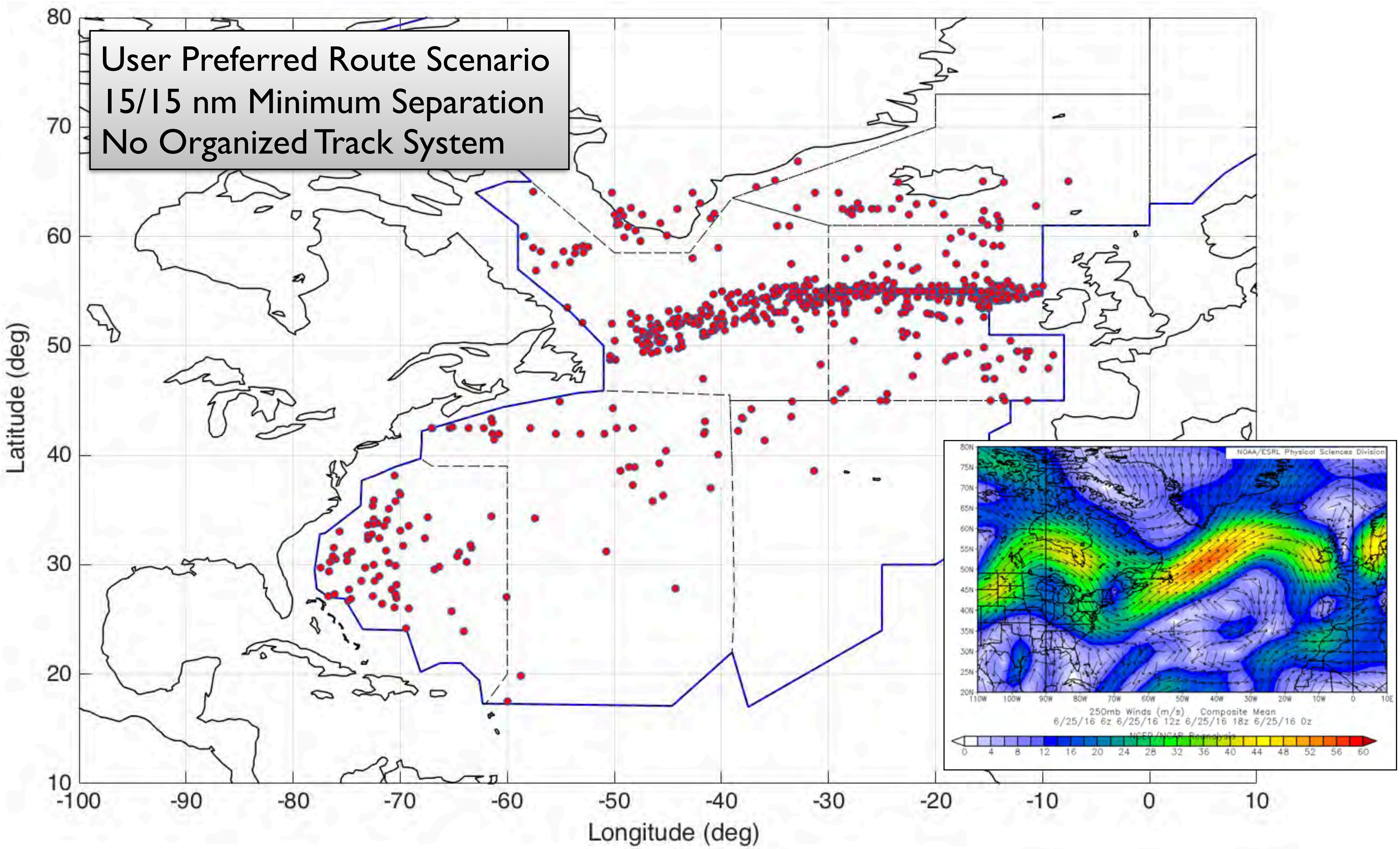




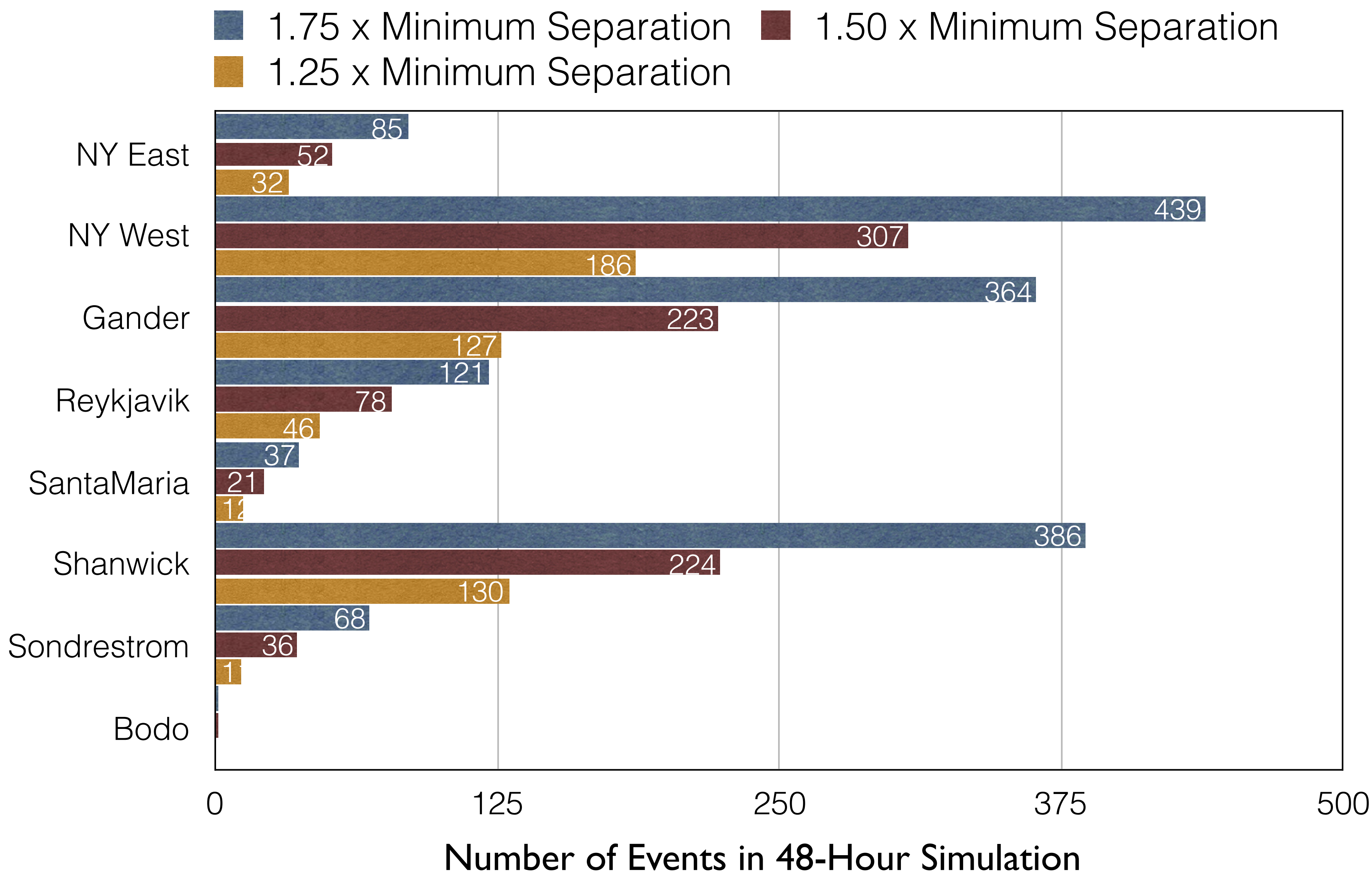
Potential Conflict Events with Closest Point of Approach 150% or less than the Minimum Separation



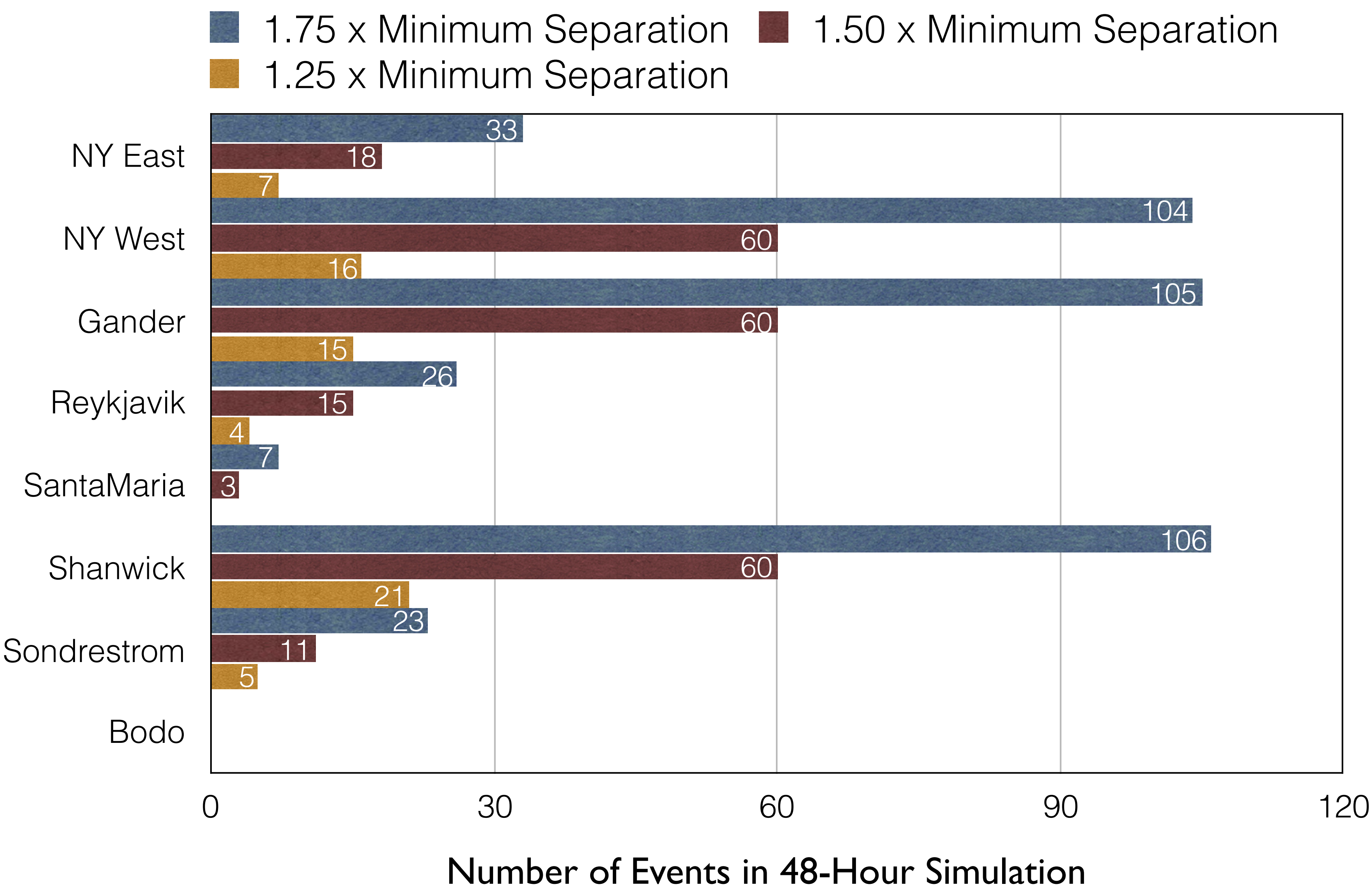
Potential Conflict Events Requiring ATC Monitoring Could Increase Dramatically in Gander and Shanwick



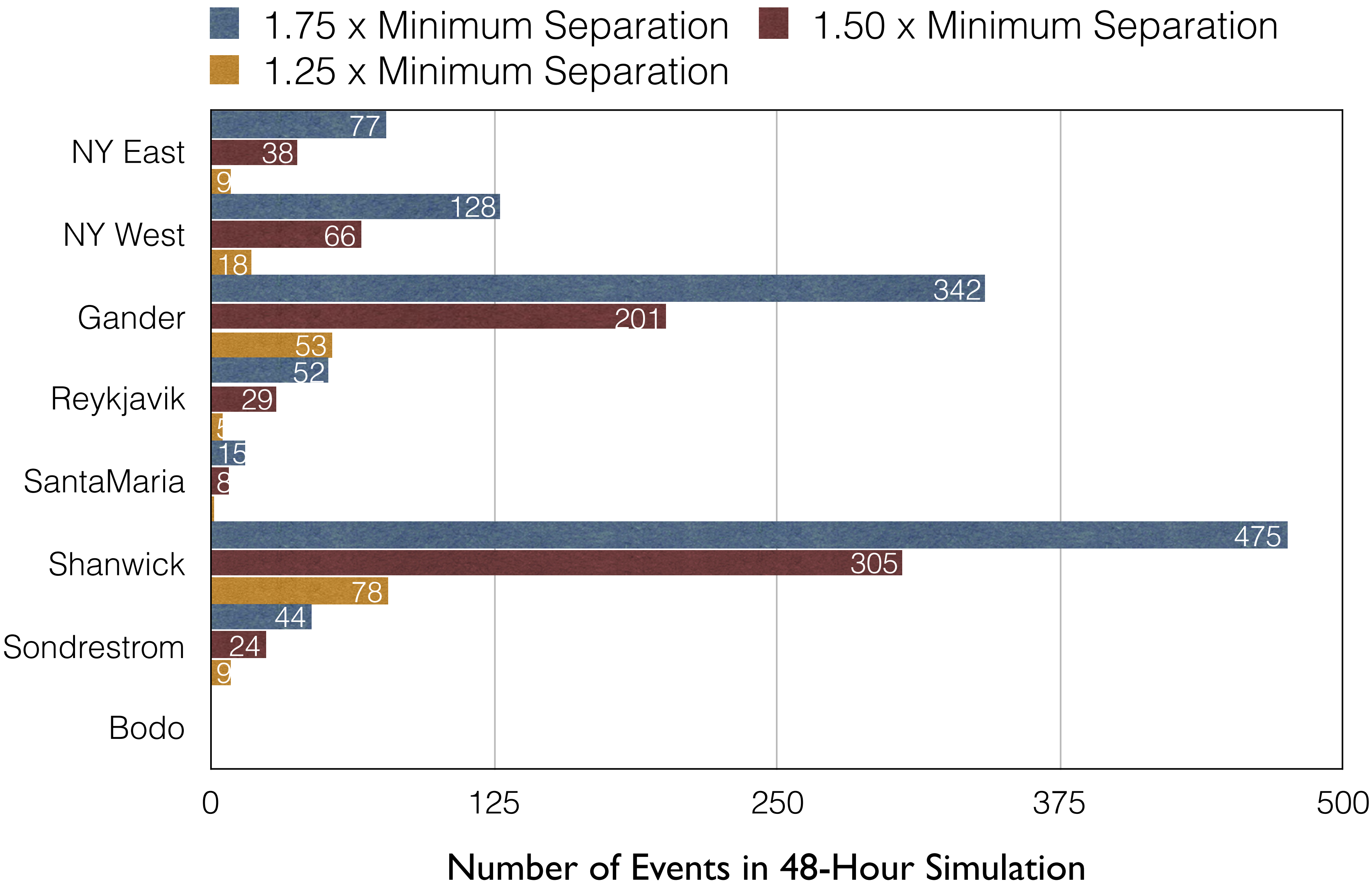
Potential Conflict Events Requiring Close Monitoring (Scenario 1: Baseline Separation 23/40 nm)



Potential Conflict Events Requiring Close Monitoring (Scenario 3: Reduced Separation 15/15 nm with OTS)



Potential Conflict Events Requiring Close Monitoring (Scenario 5: Reduced Separation 15/15 nm and UPRs)



Observations: Potential Conflict Events Requiring Monitoring

- Enabling airlines to fly User Preferred Routes (UPRs) as modeled in Scenario 5:
  - The total number of potential conflict events requiring ATC monitoring **could increase by 185% compared** to and ADS-B scenario with15/15 nm separation and maintaining the OTS track system
  - *It is expected that some FIRs (i.e., Gander and Shanwick) could experience **a three to four-fold increase** in the number of potential conflict events requiring close monitoring compared to the reduced separation scenario*
- The User Preferred Route scenarios modeled offer substantial fuel and travel time benefits but may require better decision support tools than those available today
- The complexity of potential conflicts under UPR should be studied in more detail to understand additional DSS and training costs.

General Recommendations

- When comparing scenarios:
- It is difficult to estimate benefits in a given region without considering the objectives of the complete flight plan (i.e., reduce fuel, travel time, costs for the complete flight)
- EFG could consider measuring benefits for the complete flights because:
    - Reduced separation scenarios and improved airspace capacity, enables flights to reach better cruise altitudes at the end of the HLA boundary
    - Future advanced concept of operation scenarios (i.e., UPR) would enable flights to plan different routes compared to a fixed OTS track system