Analytical Workload Model for Estimating En Route Sector Capacity in Convective Weather*

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16 June 2011

*This work was sponsored by the Federal Aviation Administration under Air Force Contract No. FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

Issues with Existing Airspace Capacity Models

- Weather-impact models yield flow reduction relative to historical fair-weather traffic (fractional availability)
  - Route blockage model
  - Sector min-cut max-flow approach
  - Directional ray scanning method
- Controller workload, which determines sector capacity, is not taken into account

- Workload-based sector models give absolute capacity values but weather effects not included
  - Detailed simulation models
  - "Macroscopic" analytical models

$\Rightarrow$ Incorporate convective weather effects into analytical sector workload model

Outline

- Motivation
- Sector capacity model without weather
- Sector capacity model with weather
- Results and issues
- Summary

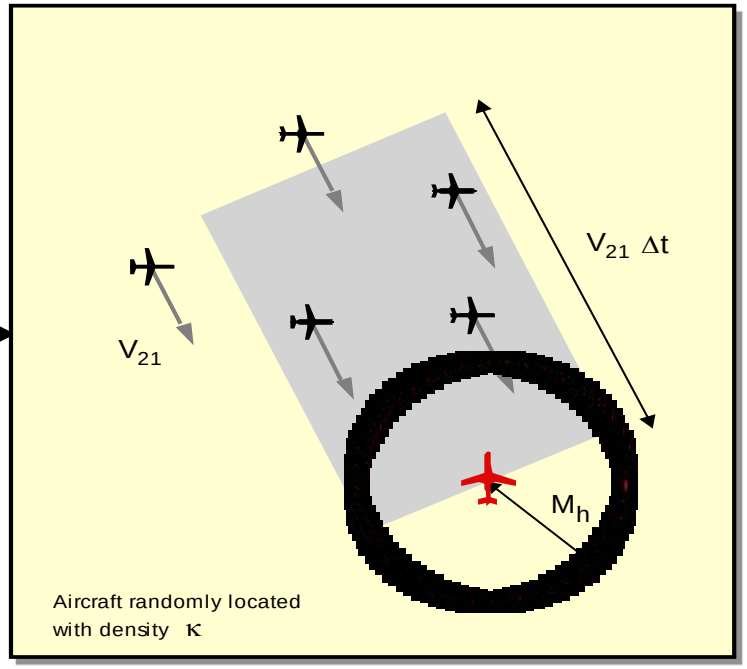
Controller Workload Limits Traffic

- Sector reaches capacity when the controller team is fully occupied
- Queuing grows with three critical traffic-dependent event rates

Conflict rate

$\lambda_c = (2\ N^2/Q)\ M_h\ M_v\ V_{21}$

Sector aircraft count N
Sector airspace volume Q
Miss distances M_h, M_v
Mean closing speed V_{21}



Monitor Alert Parameter (MAP) basis

Transit (boundary crossing) rate

$\lambda_t = N/T$

Sector aircraft count N
Mean sector transit time T

Recurring event (scanning/monitoring) rate

$\lambda_r = N/P$

Sector aircraft count N
Recurrence period P

Task-Based Analytical Sector Workload Model

Sector workload intensity

$$G = G_b + G_c + G_r + G_t$$

Fraction of controller time

Background | Conflict | Recurring | Transition

Service times (*empirical*)

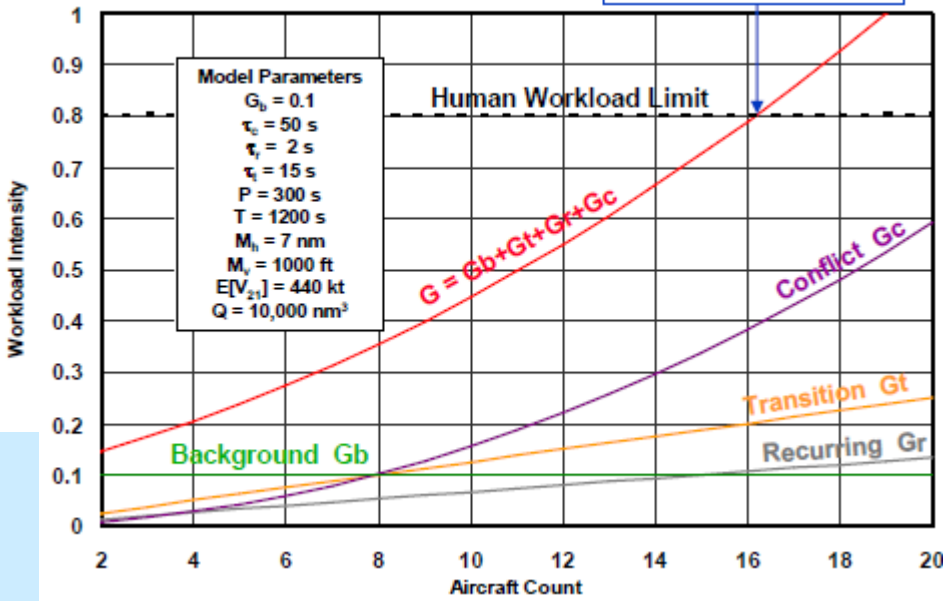
as conflicts arise | periodic | at sector crossings

$$G_c = \tau_c [(2 N^2/Q) M_h M_v V_{21}]$$

$$G_r = \tau_r [N/P]$$

$$G_t = \tau_t [N/T]$$

Occurrence rates (*calculated from airspace parameters*)



- **Determining the unknown service times**
  - **Live approach**
    - Measure controller performance
  - **Regression approach**
    - Observe peak daily counts N_p for many sectors
    - Calculate corresponding model capacities N_m
    - Find service times that best fit N_m to N_p bound

Welch et al., 2007: Macroscopic model for estimating en route sector capacity, 7th USA/Europe ATM R&D Seminar, Barcelona, Spain

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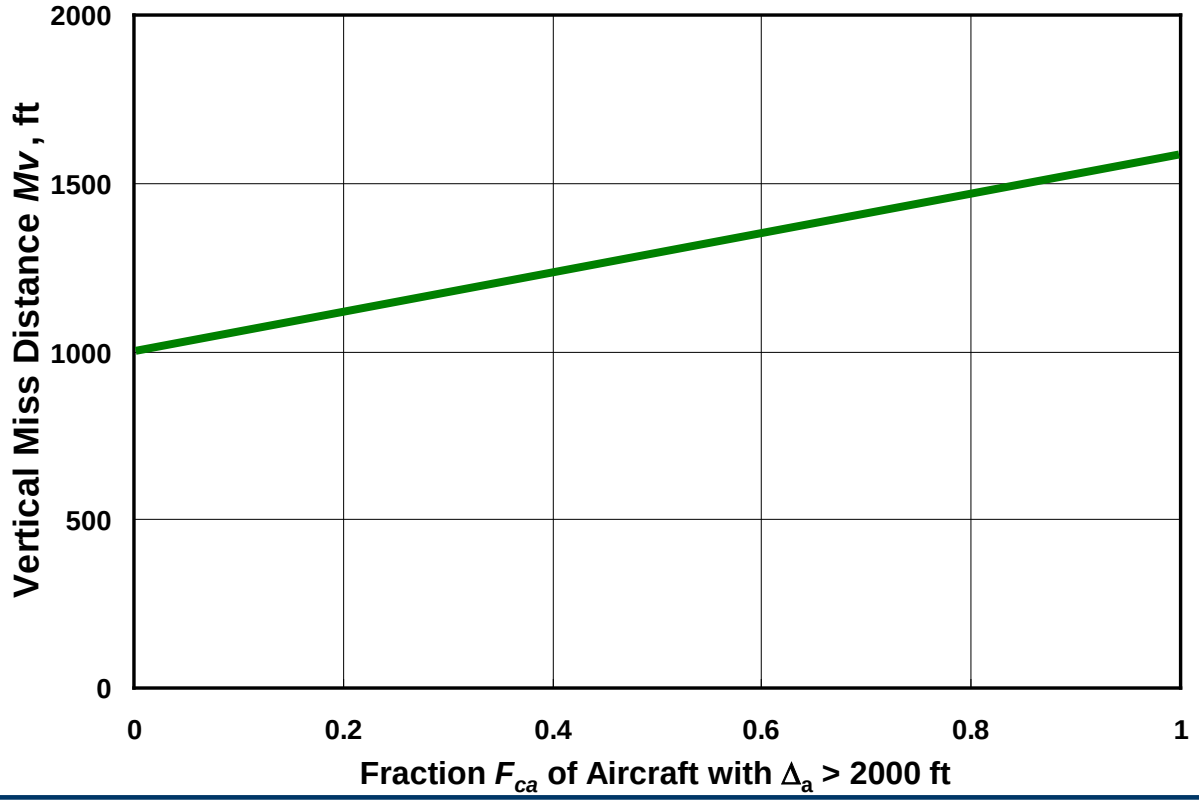
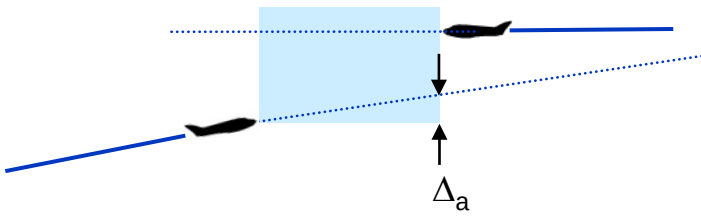
Effect of Altitude Changes

- Aircraft with vertical rates cause increased uncertainty
- Adapt by increasing vertical miss distance M_v
  - Determine fraction F_{ca} of aircraft with ≥ 2000 ft altitude change
  - As F_{ca} grows, increase M_v linearly from 1000 ft to M_{vmax}

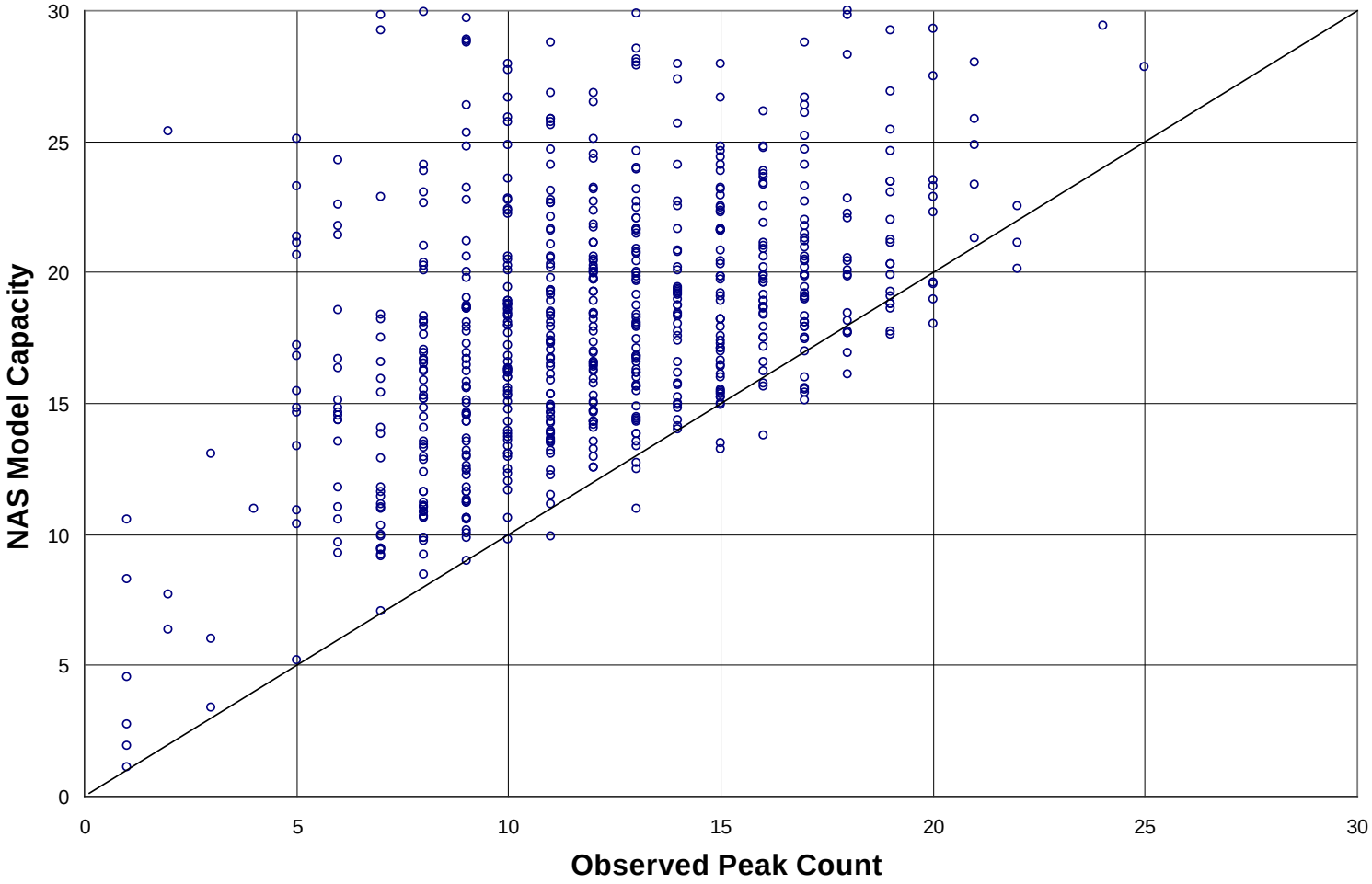


$M_{vmax} \approx$ 1600 ft (for NAS)



Fitted Capacities vs. Peak Counts

(790 NAS Sectors July–August 2007)



Simple analytical model can bound data well and is suitable for real-time application

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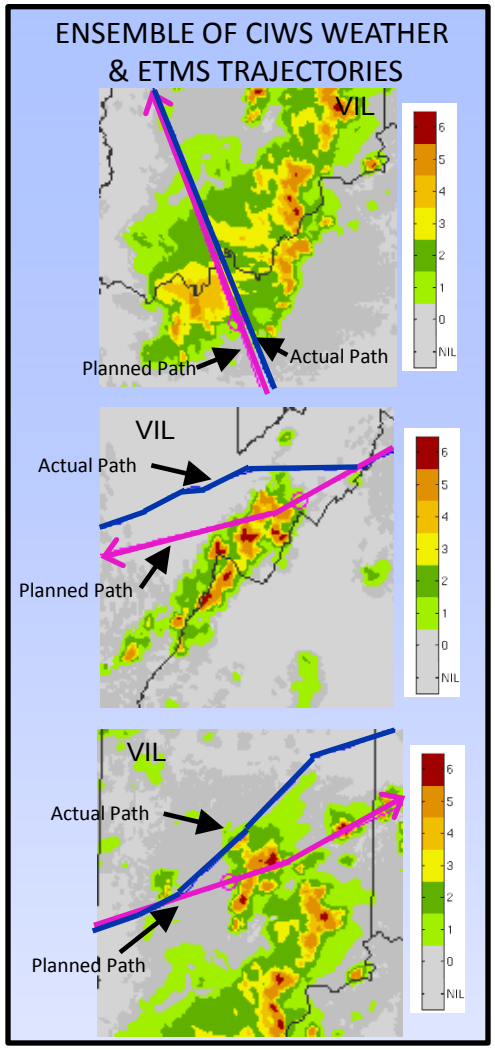
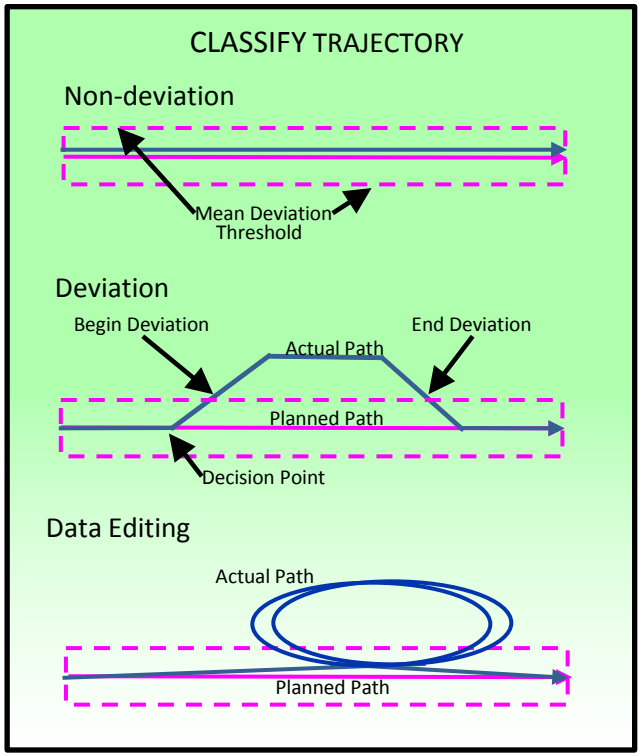
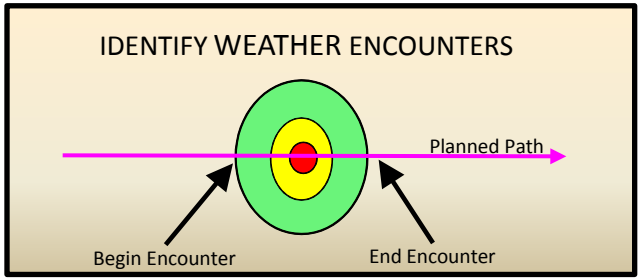
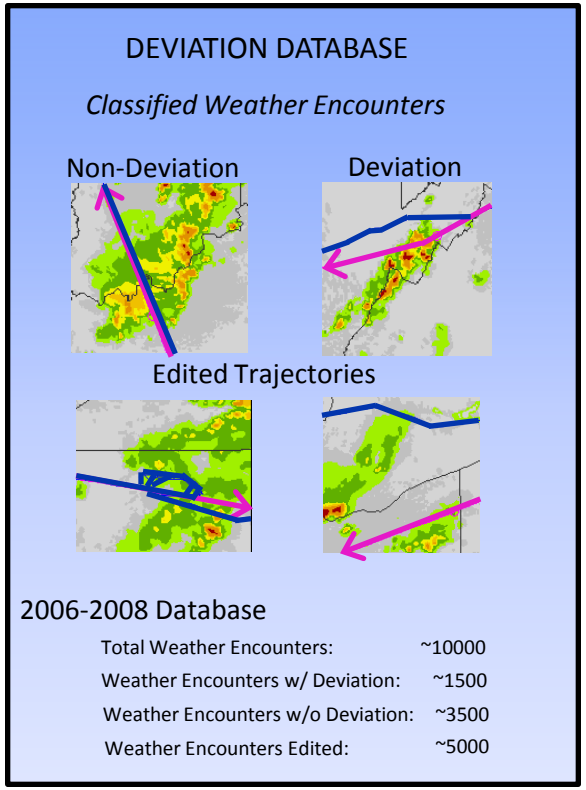
Convective Weather Avoidance Model (CWAM)

Creating the model



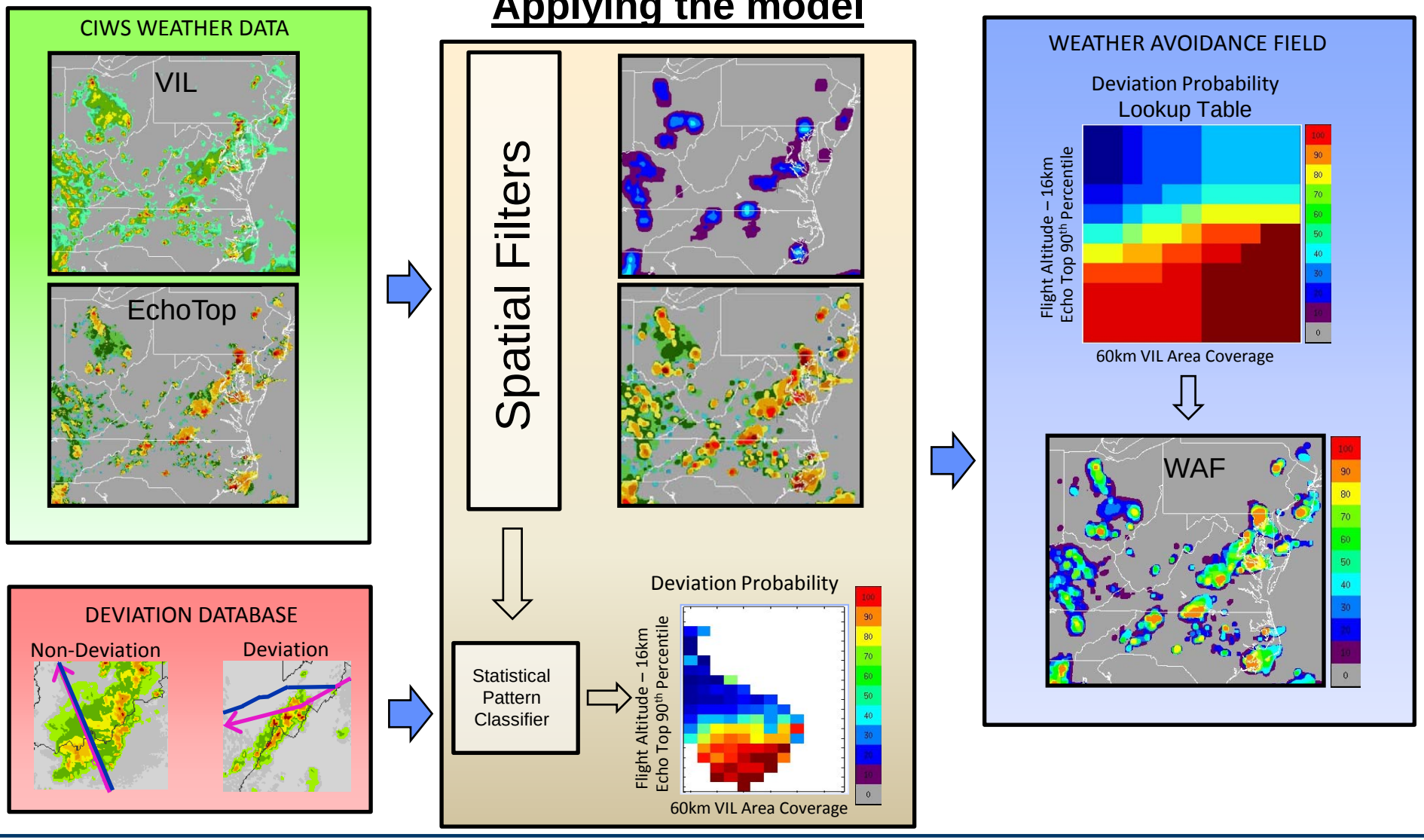






Weather Avoidance Field (WAF)

Applying the model



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Weather Blockage Modification to Sector Workload Model

No Weather

$$G_{\max} = G_b + \frac{\tau_r}{P} N + \frac{\tau_t}{T} N + \frac{\tau_c B N}{Q}(N+1)$$

With Weather

$$G_{\max} = G_b + \frac{(\tau_r + \tau_w F_w) N}{P} + \frac{\tau_t N}{T} + \frac{\tau_c B N (N+1)}{Q(1-F_w)}$$

F_w = fraction of airspace blocked by weather

τ_w = time needed per reroute due to weather blockage

- Compute F_w from WAF data
  - 80% WAF contours
  - Integrate over WAF contours at 2000-ft altitude increments
  - Fractional blockage of 3D sector volume
- Fit to observed sector peak counts during weather to obtain τ_w
  - Compare to τ_w = 45–60 s estimated by experienced air traffic controller

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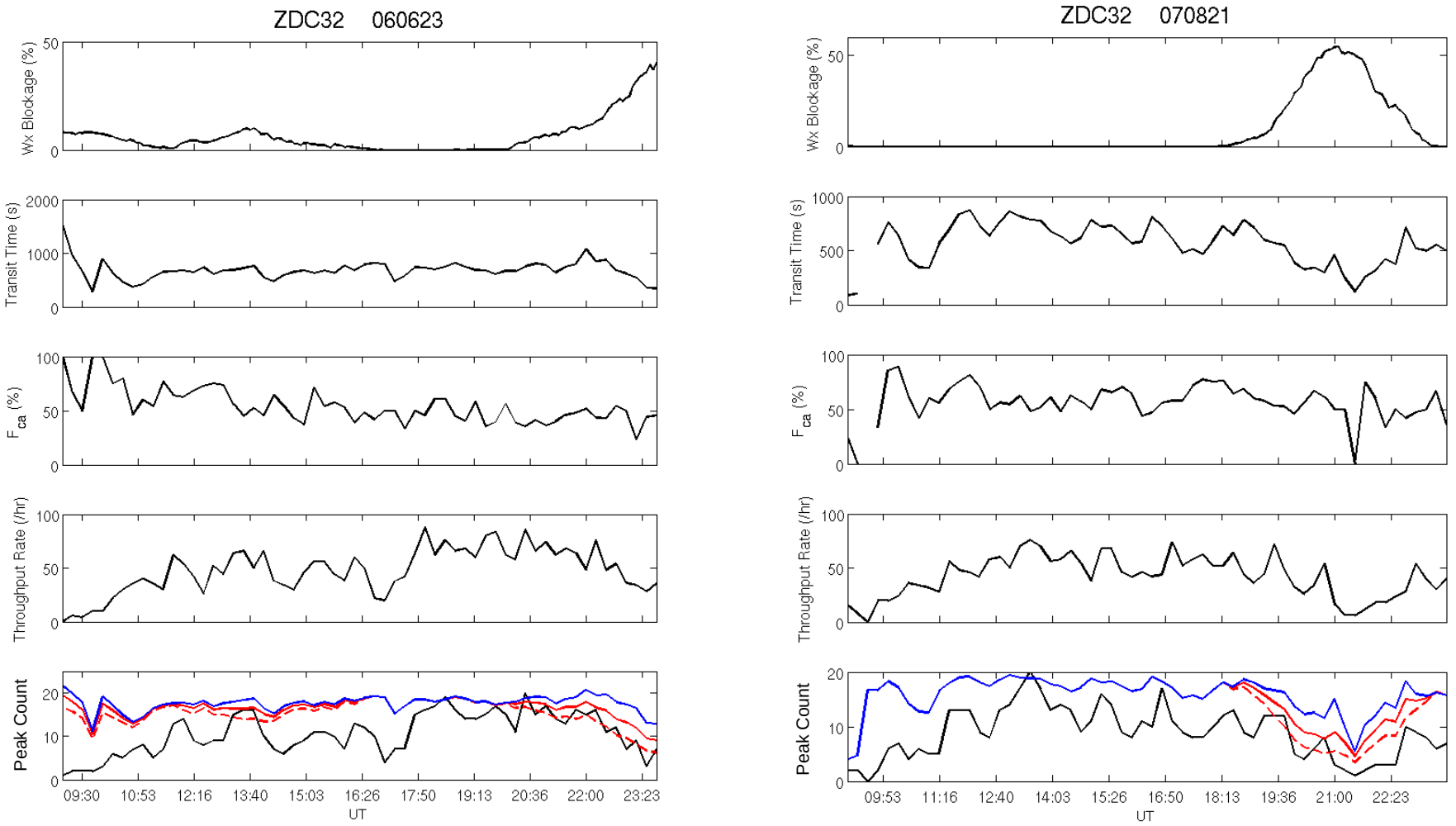
Some Results Using Observed Weather



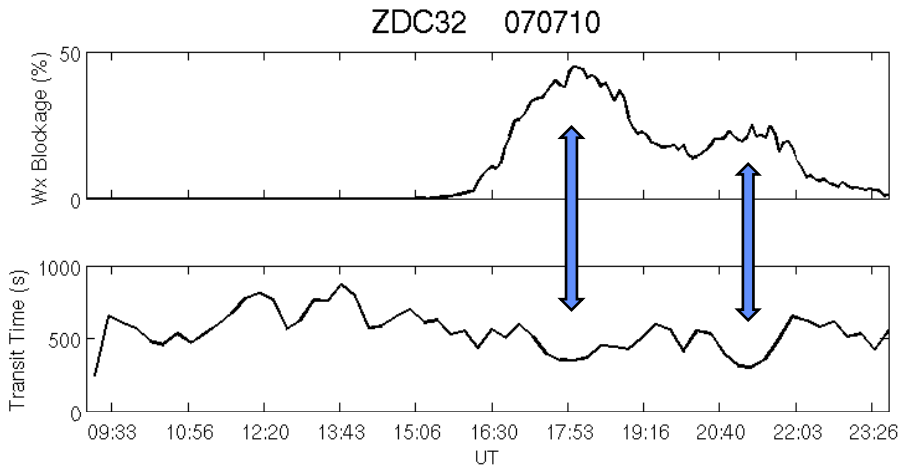
Actual sector peak count

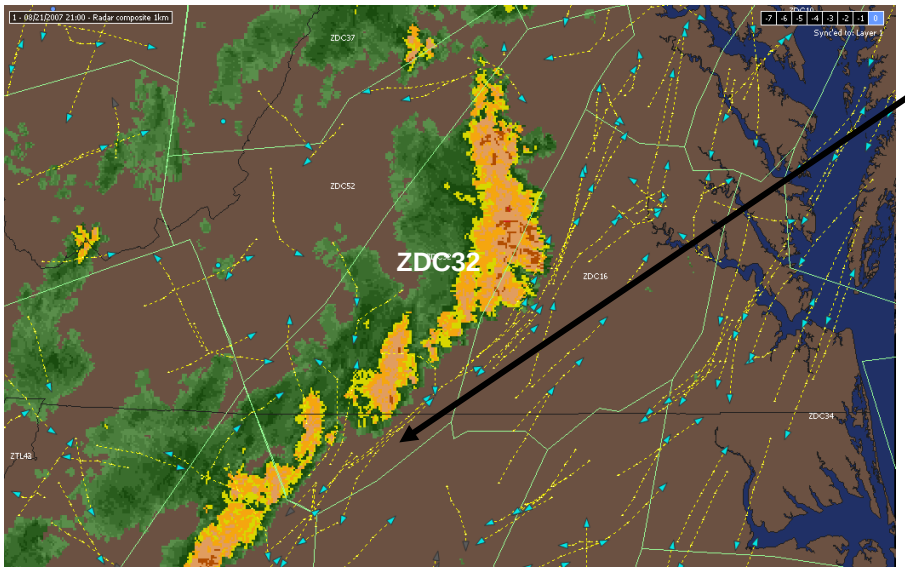
Fair-weather model capacity

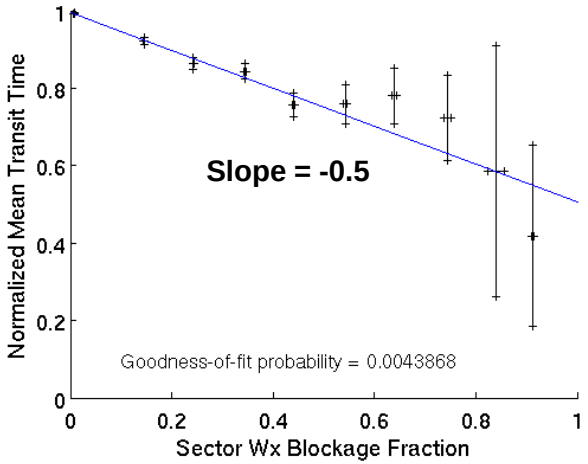
Model capacity with τ_w = 30 s

Model capacity with τ_w = 90 s

Weather Effects on Sector Transit Time

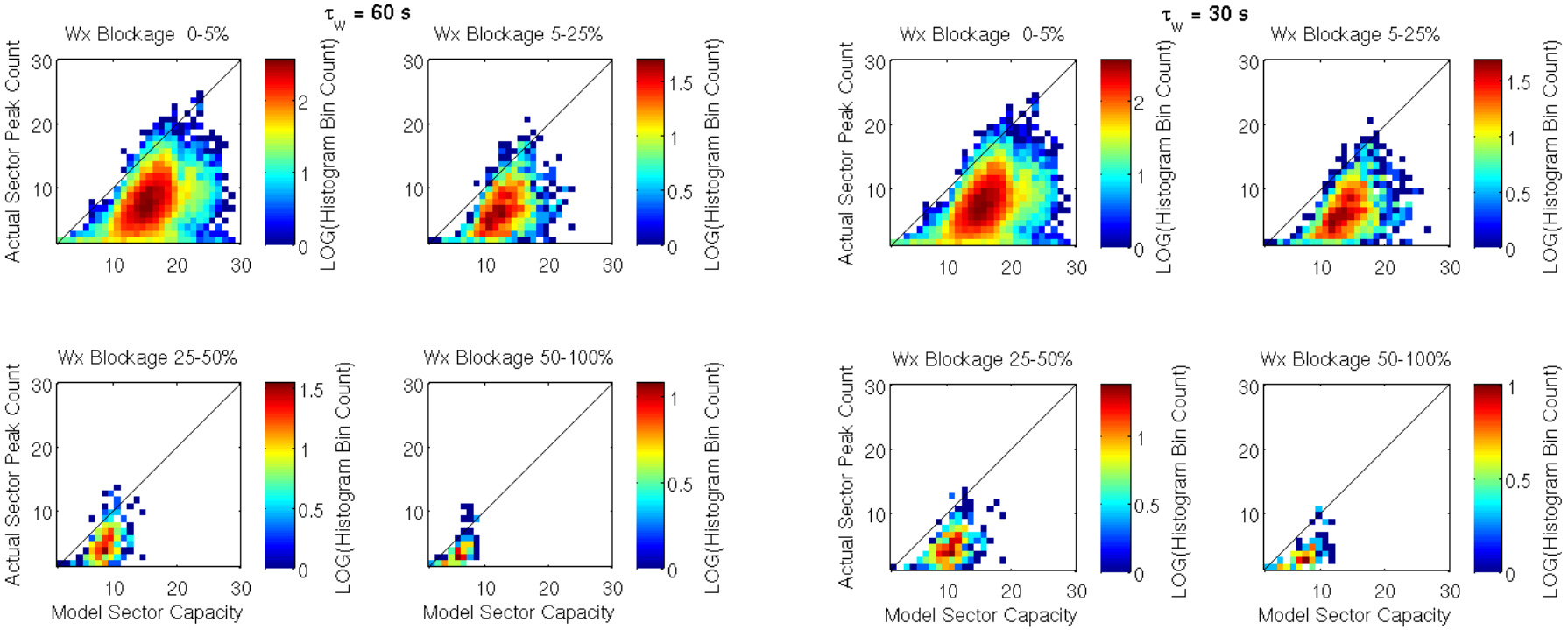






- **"Cutting corners" to avoid weather decrease mean sector transit time**
- **Use fitted wx blockage-transit time relationship to adjust mean transit time in capacity forecast**
- **F_{ca} does not show dependence on weather blockage**

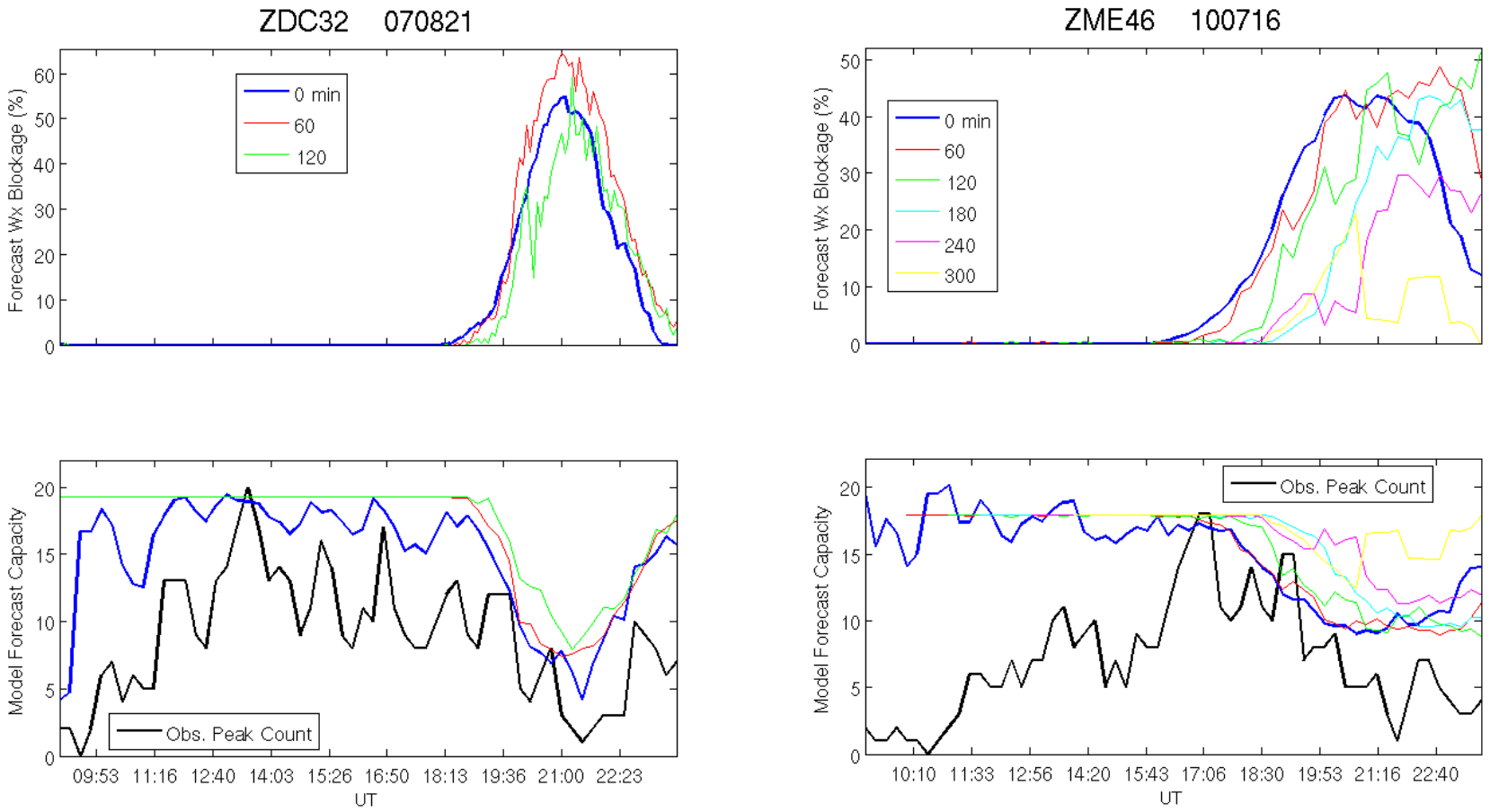
Model vs. Observed Peak Sector Count



- **Capacity model should bound sector peak count data**
- **Still do not have a lot of heavy weather impact cases**
- **For now set τ_w = 45 s (consistent with subject matter expert estimate)**

31 ARTCC-days worth of data used

Some Results with Forecast Weather



- **Historical mean sector transit time and F_{ca} per are used in forecast**
  - **Transit time adjusted for weather blockage**
  - **Better to use time-dependent forecast values of transit time and F_{ca} if available**

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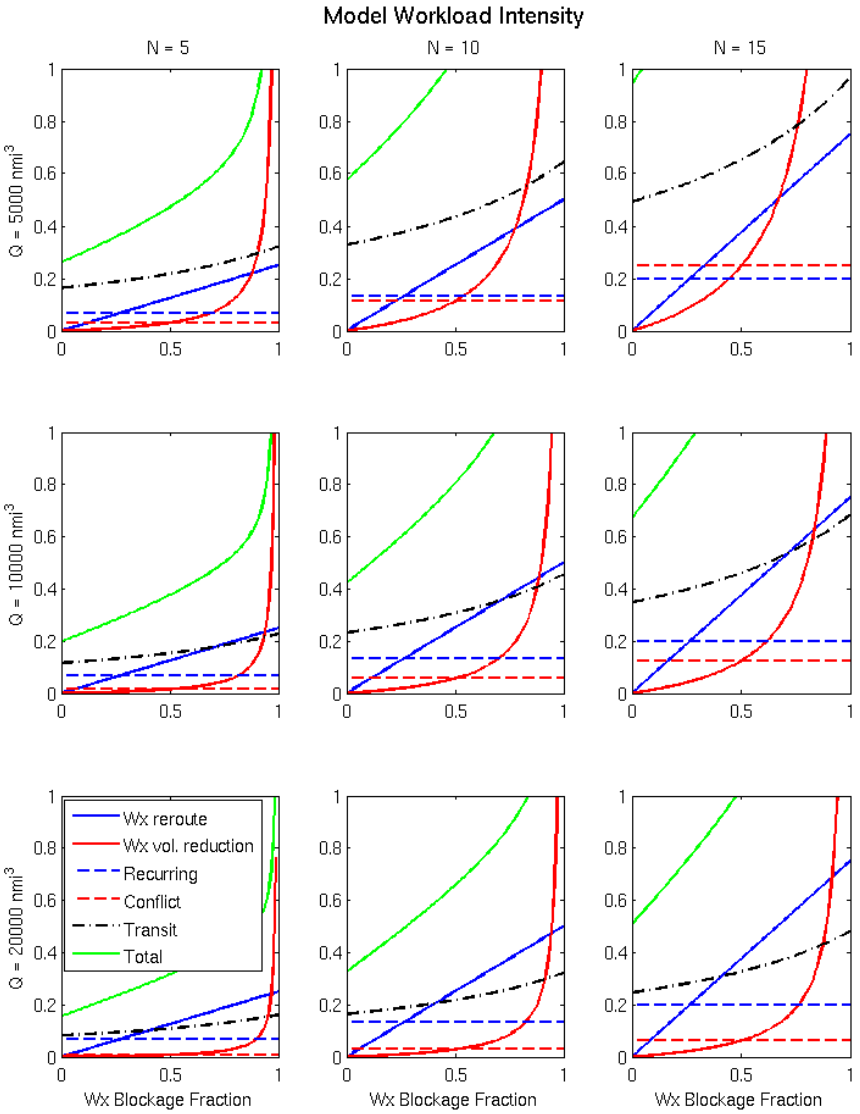
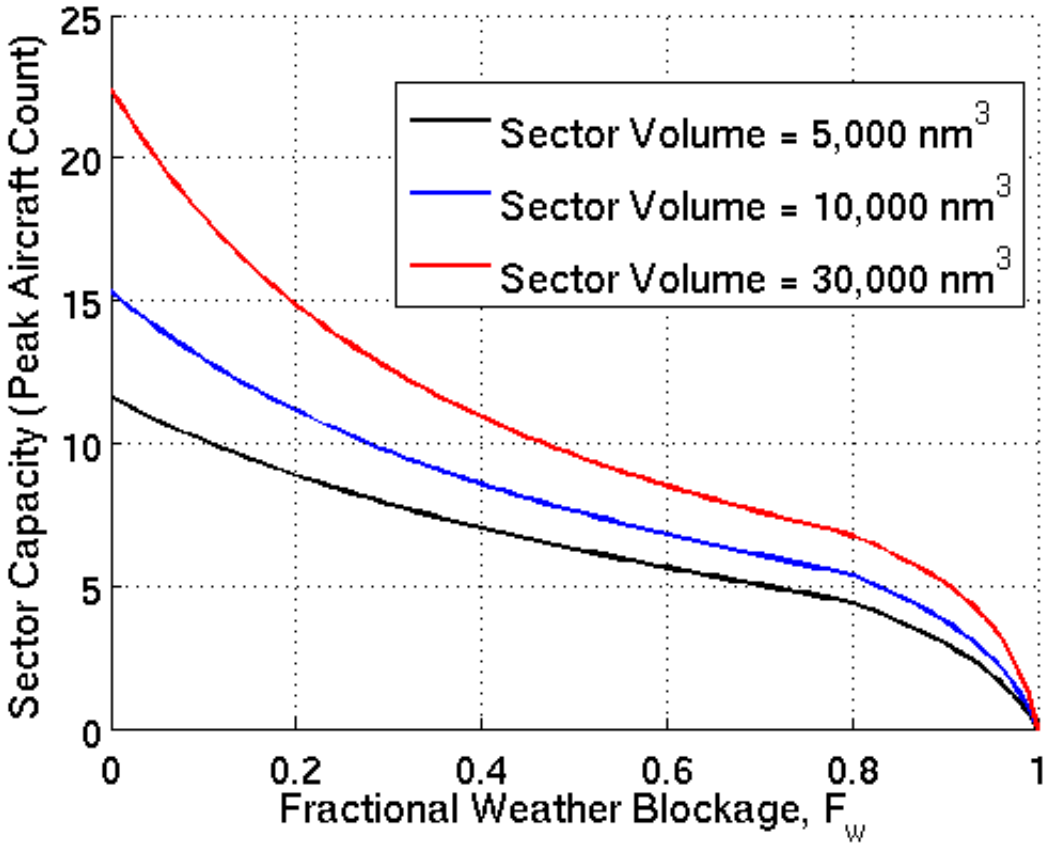
Model Dependencies



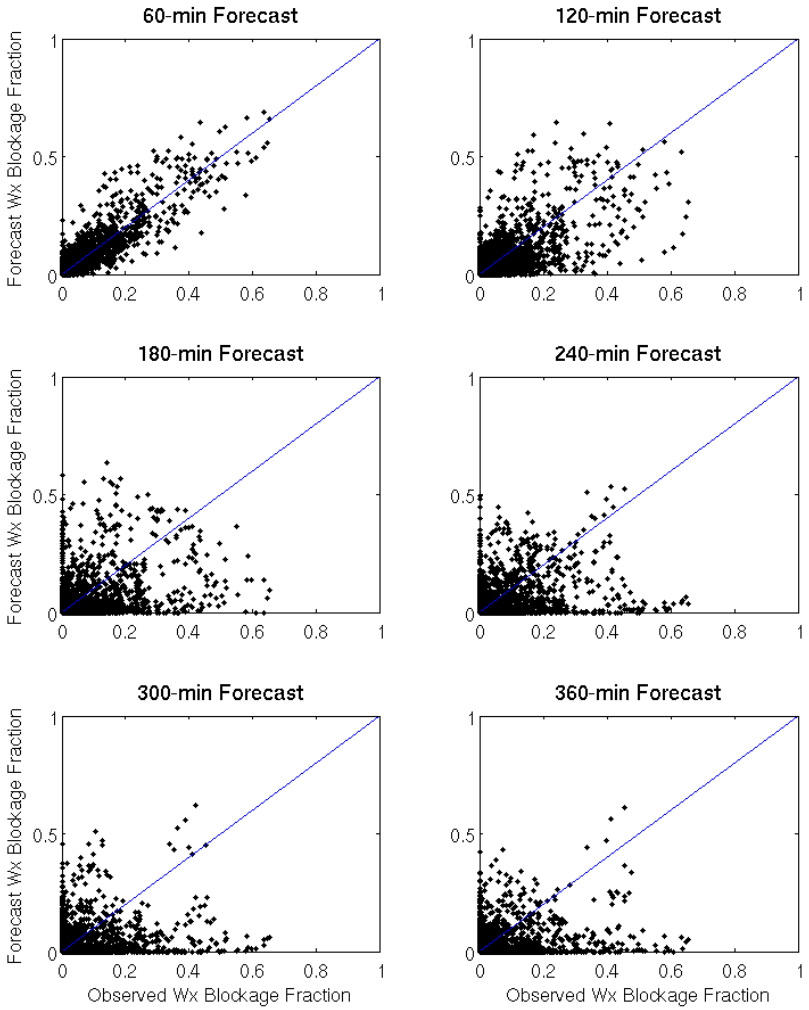
- **Three workload components affected by weather**
  - **Conflict resolution task (via available airspace reduction)**
  - **Weather rerouting task**
  - **Sector hand-off task (via mean transit time reduction)**
- **The rerouting and hand-off tasks dominate the dependence of workload on weather except at very high weather blockages**

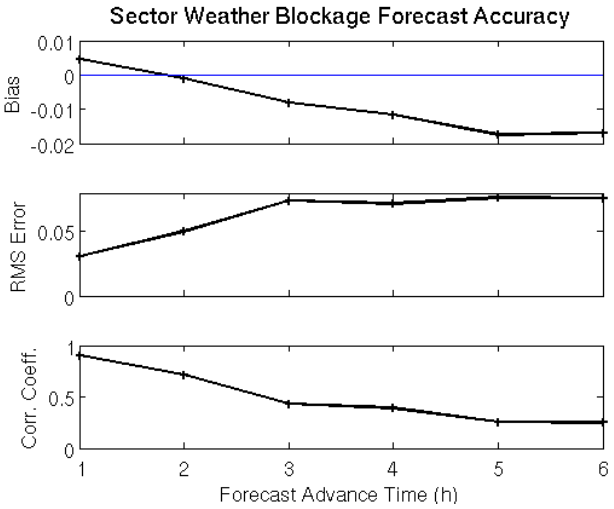
Capacity vs Weather Blockage Fraction



Capacity dependence on weather blockage is nonlinear

Sector Weather Blockage Forecast Errors





- **Sector weather blockage is scalar: Straightforward error analysis**
- **Need to accumulate more data for heavy weather cases**

22 ARTCC-days worth of data used

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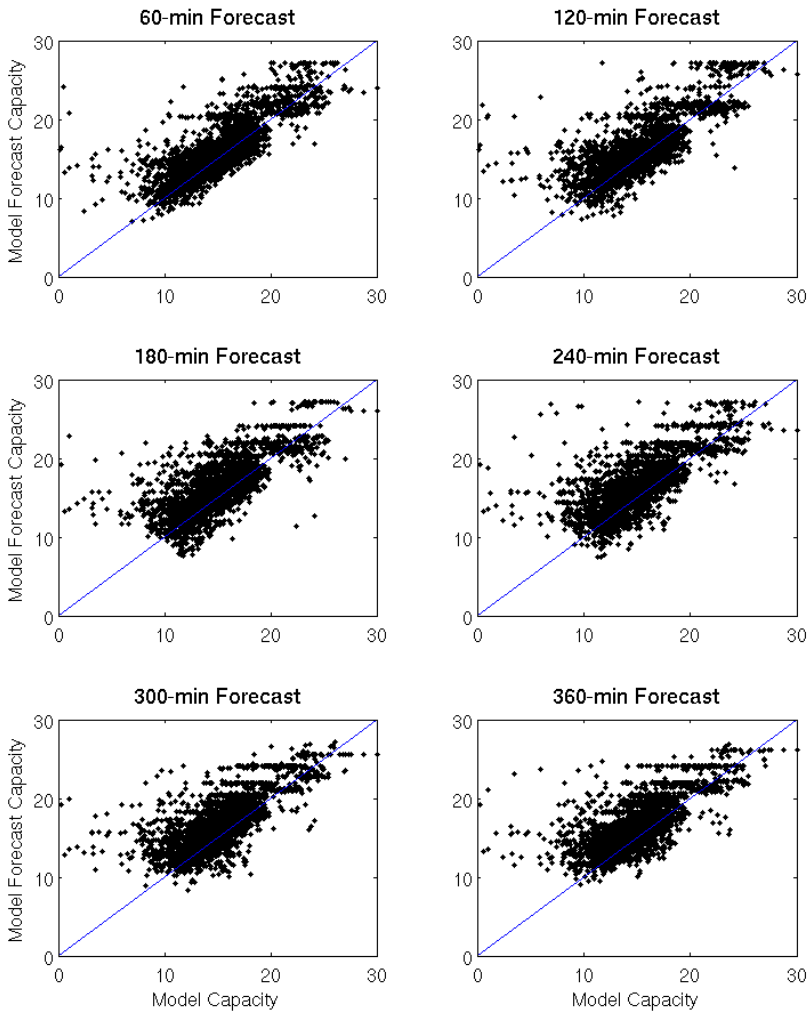
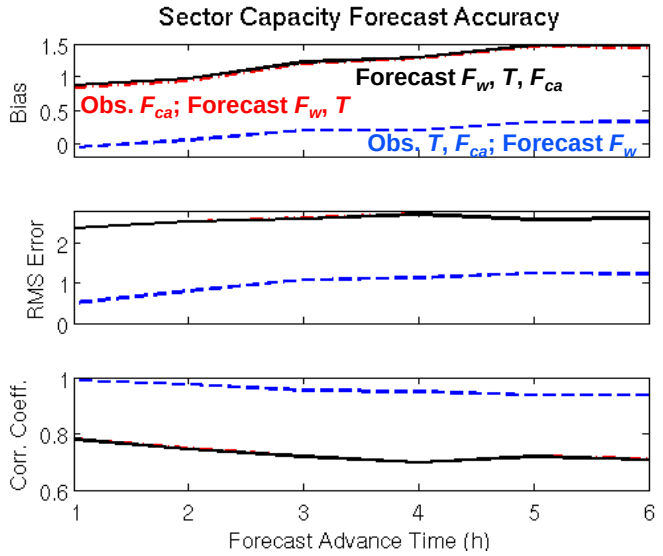
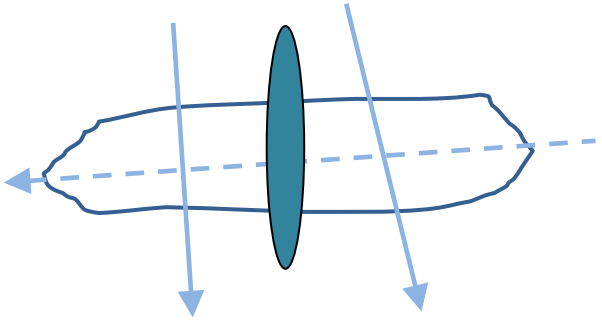
Sector Capacity Forecast Errors





- **No sector capacity truth available**
- **Comparison of model capacity using forecast data vs. observed data**
- **Accurate forecast of sector transit time as important as weather forecast**

Directional Capacity Issue



- Sector capacity (peak traffic count) is scalar—no differentiation based on flow direction
- But flow capacity is directional
  - Sector transit time depends greatly on sector shape and travel direction
  - Weather blockage can be highly directional
- Formulate workload model for directional capacity
  - Replace scalar F_w with directional weather blockage in reroute term
  - Utilize existing directional blockage model
- Scalar capacity depends on directional capacity *and* 4D flight trajectories—a difficult forecast problem

Summary

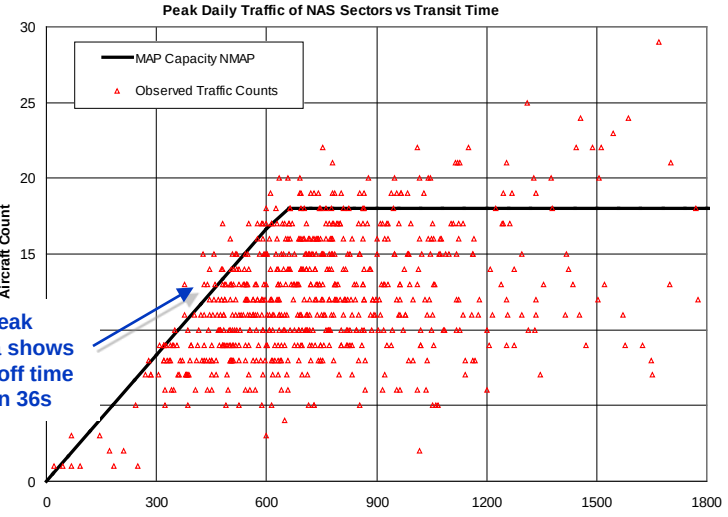
- Sector capacity model based on analytical workload model was modified to include weather effects
- Difficult to validate because “truth” is not available
  - Model as upper bound—use statistics
  - Initial results are promising—need to analyze more data
- Sector capacity forecast uncertainties arise from
  - Sector transit times
  - Weather
- Weather forecast uncertainties are large at several hours in advance
  - Huge effort in developing complicated and ultradetailed capacity model may not be justified
- Need to tackle directional capacity issue
- Collaboration with MIT ORC and Metron to provide sector capacity input to air traffic flow optimization models

Back-up Slides

Monitor Alert Parameter (MAP) Model

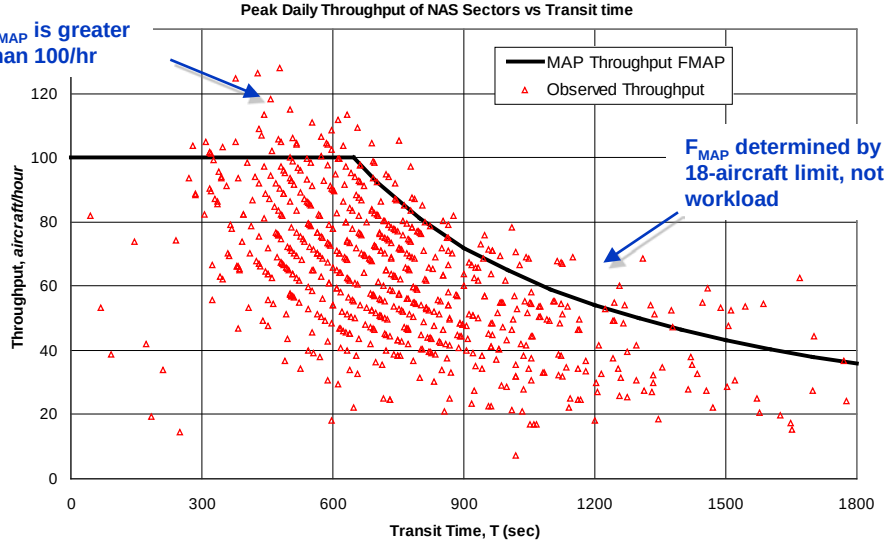
MAP capacity is based on handoff workload, assuming 36-second handoff time per flight

Peak aircraft count, $N_{MAP} = T/36$ (18 aircraft limit)
[T is mean transit time, in seconds]



Slope of peak count data shows that hand-off time is less than 36s

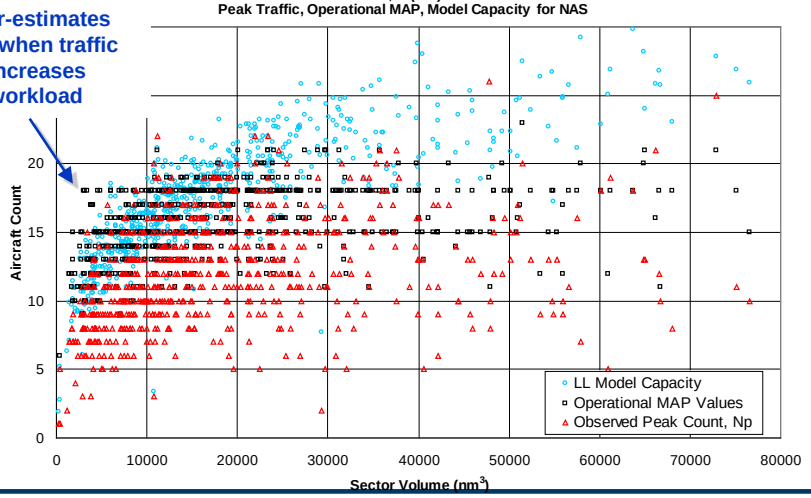
Peak throughput, $F_{MAP} = N_{MAP}/T$
F_{MAP} = 100 aircraft/hour



F_{MAP} is greater than 100/hr

F_{MAP} determined by 18-aircraft limit, not workload

MAP over-estimates capacity when traffic density increases conflict workload



Operational MAP settings:
- over-estimate capacity of small sectors by ignoring conflict workload
- show that workload, not MAP rule, limits small-sector capacity

Lincoln Laboratory model
- accounts for additional workload effects
- extrapolates small sector workload capacity to large sectors
- shows that18-aircraft limit under-estimates capacity in large sectors

Advantages of fitting models to peak count and transit time data:
- simple and inexpensive
- can determine system workload parameters for
  - entire NAS
  - individual centers
- could support automated performance and parameter updates

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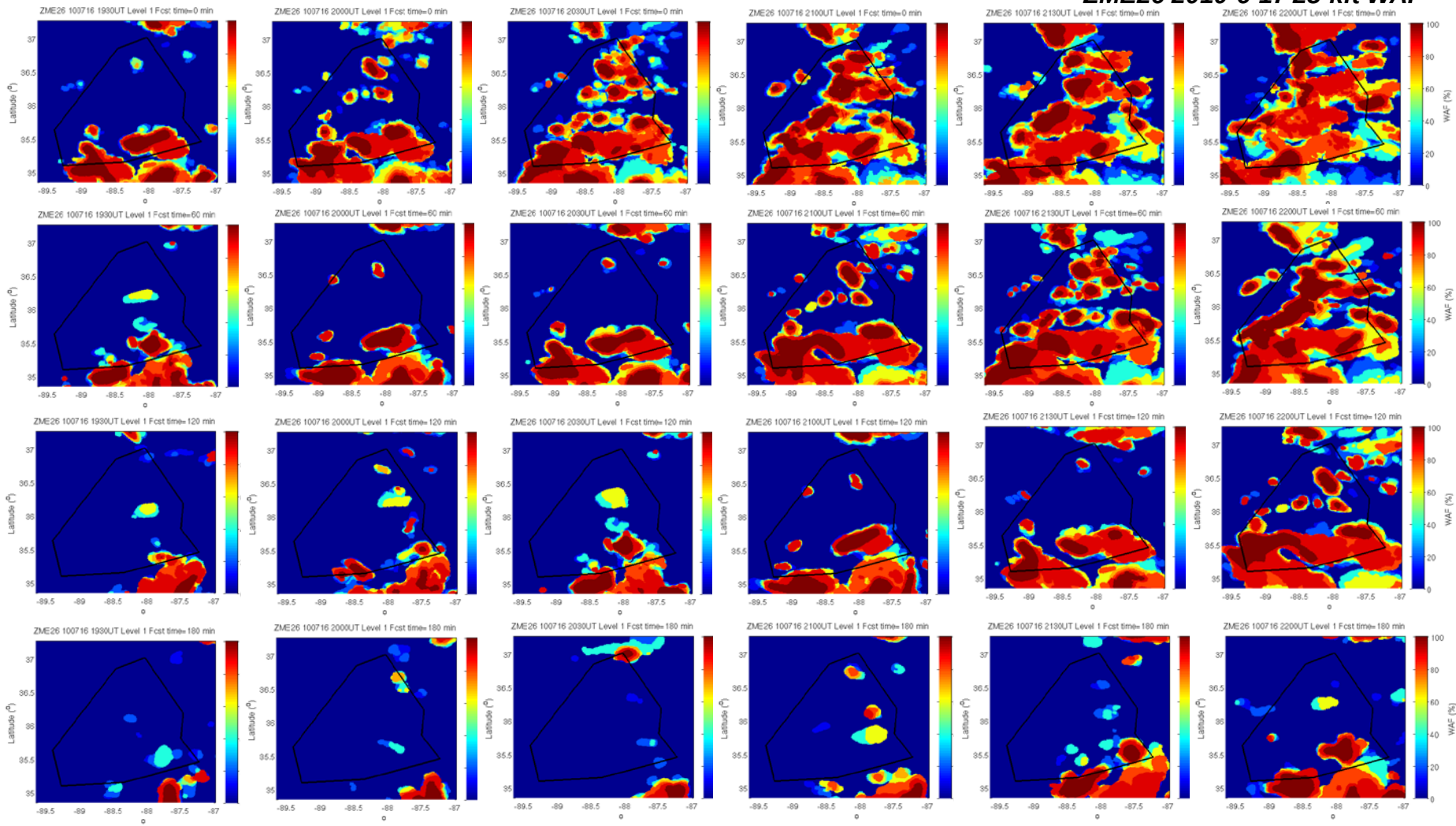
Convective Weather Forecast Issues

ZME26 2010-6-17 25-kft WAF



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