Weather Impact Modeling

Based on

Joe Mitchell’s slides

Old Paradigm: Human Centric

Weather

Aviation

traffic manager

Forecast Products

ATM Automation

tailored to aviation needs

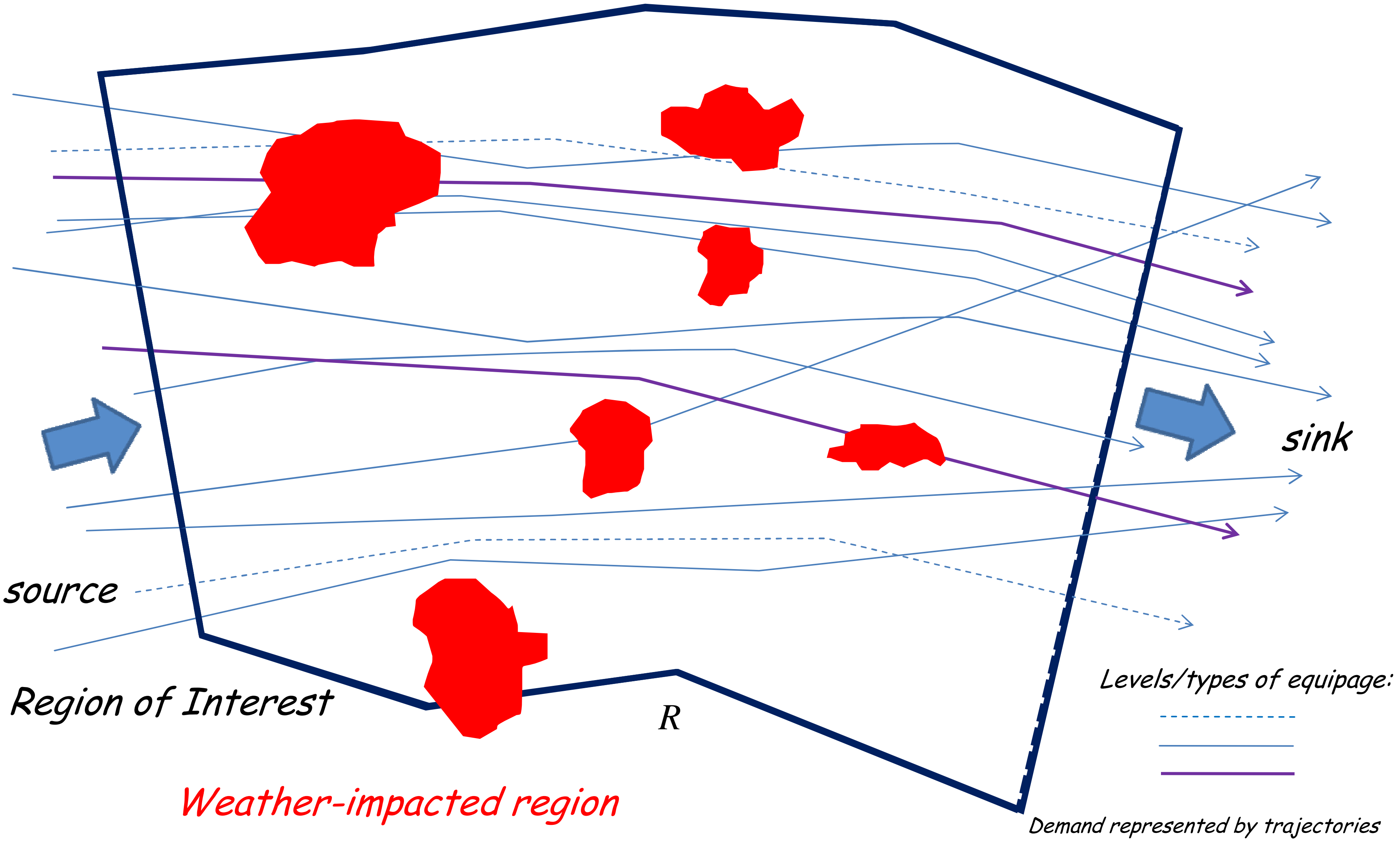
ready for integration

New Paradigm: Automation Ce

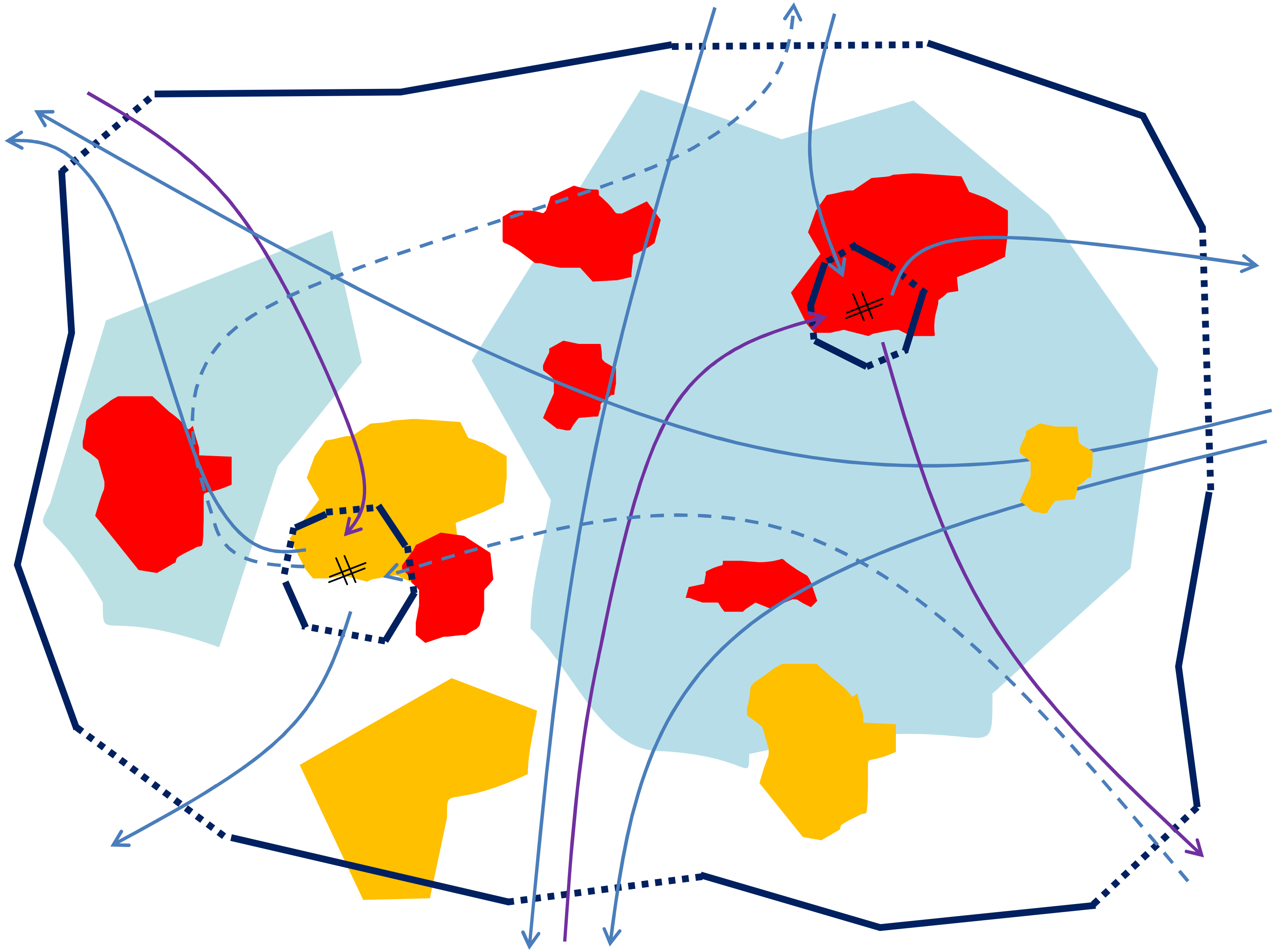
NEXTGEN Next Generation Air Transportation System

Basic En Route Model

Modeling the impact of weather on capacity of airspace

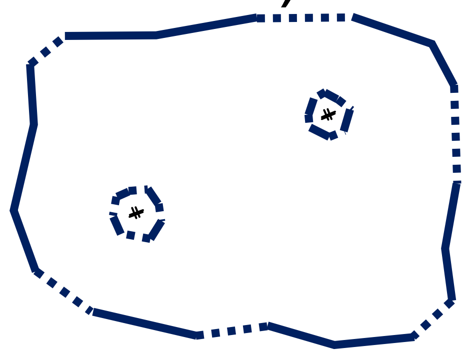


More General Model



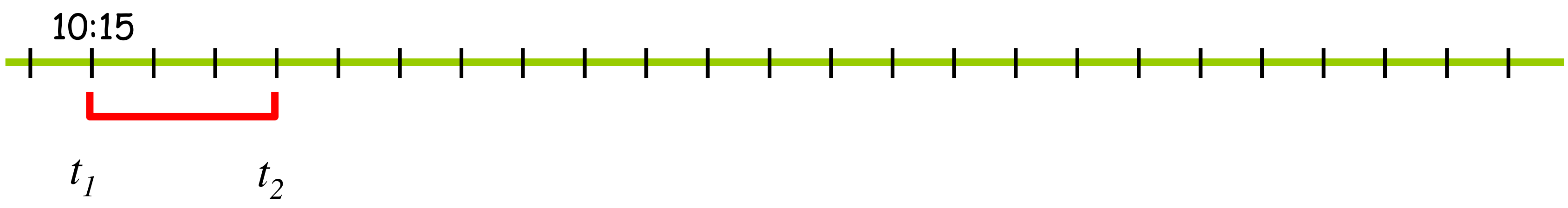
Inputs: Region of Interest

- Region of airspace, R
- Subset of 2D space (polygonal domain)
- Subset of surface of sphere
- Subset of 3D space



Inputs: Time Horizon

- Time window, [$t_{1,}$ t_2], of interest
- Sliding time window [$t_{1,}$ t_2]
- Updates every Δt



Inputs: Demand

- "Demand" given as a set of trajectories (flights) in space-time:

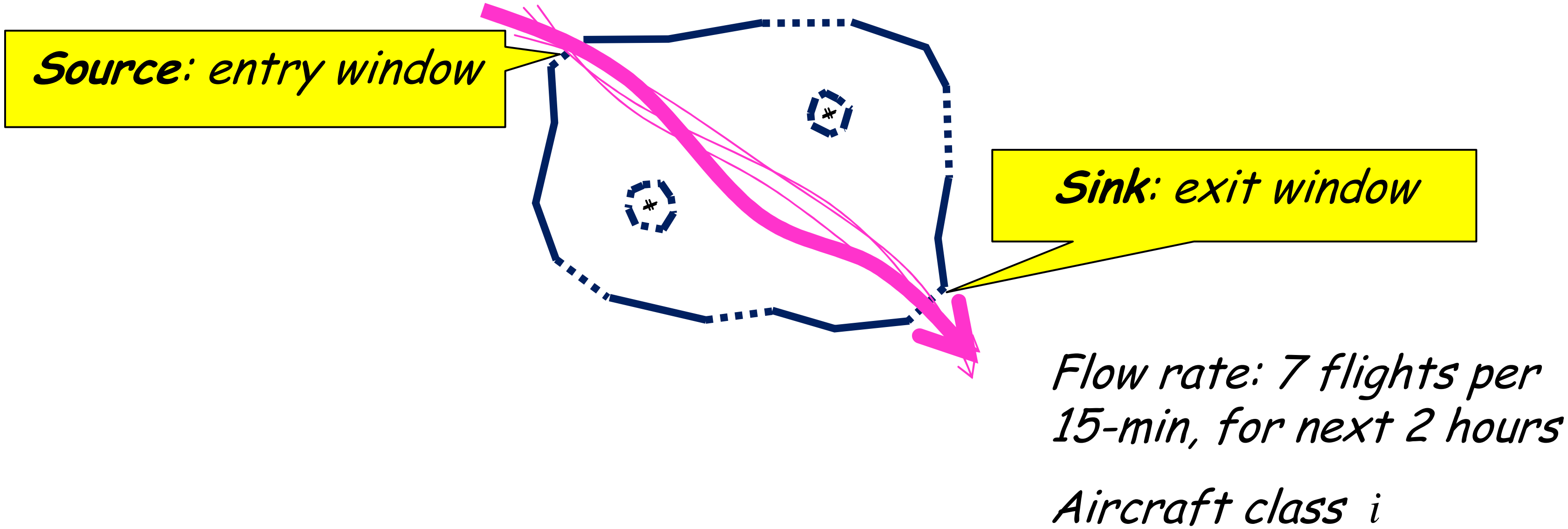
  τ : (x_1,y_1,z_1,t_1), (x_2,y_2,z_2,t_2), (x_3,y_3,z_3,t_3), …

- Each trajectory τ has associated with it
  - Probability distribution of time T_τ when τ enters R
    - Given by ETA estimator
  - Equipage class, i, which includes information about the aircraft, specifying a set Σ_i of preferences and parameters
  - Priority, specified as an integer $\in \{1,2,\ldots,N_P\}$
  - Entrance point (or window), where it enters R
  - Exit point (or window) where it will leave R

More detail below

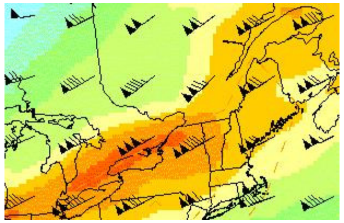
Inputs: Demand

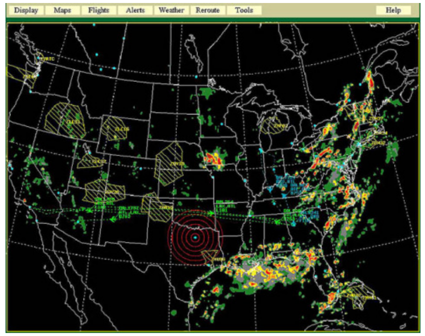
- Demand can be approximated be an aggregation of trajectories into flows, bucketed by time:

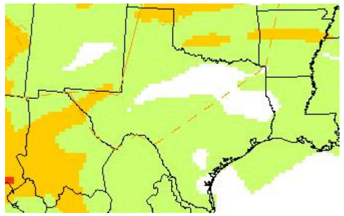


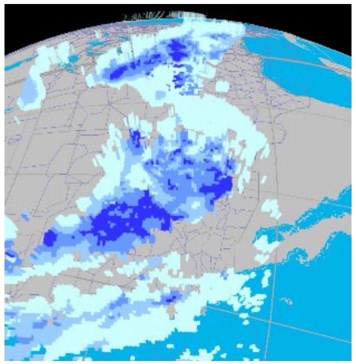
Inputs: Weather

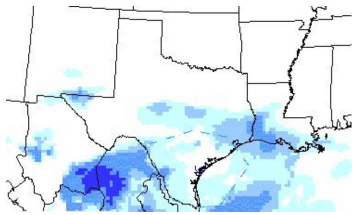
- There are many types of weather events:
  - Convection
  - Icing conditions
  - Turbulence
  - Fog/Impeded visibility
  - Volcanic ash
- Let j indicate the type of weather event









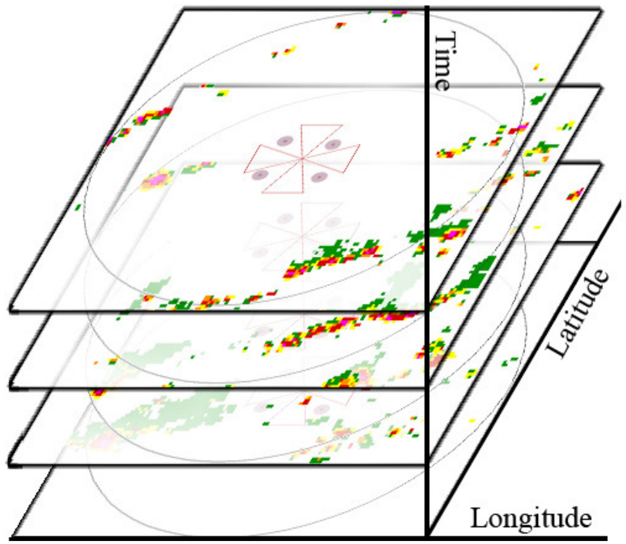


Inputs: Weather

- Each type j of weather event:
  - $W_j(x,y,z,t)$ = intensity at position (x,y,z), time t
  - $W_j(x,y,z,t)$ is not known with certainty, but is given by a probabilistic forecast
  - Binary impacts: $W_j(x,y,z,t) \in \{0,1\}$

The event either exists or it does not

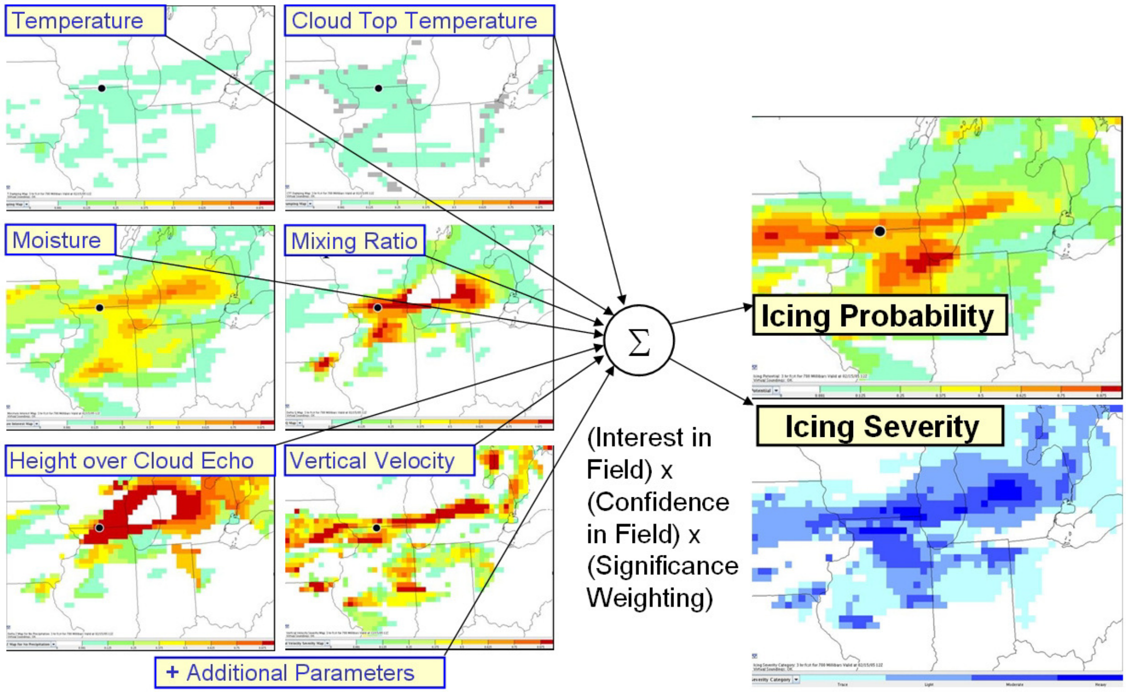
- Impact region of weather event j for class i aircraft:
  - $I_{i,j}(t) = \{ (x,y,z) : W_j(x,y,z,t) \geq \xi_{i,j} \}$
- Since impact regions can vary over time (dynamic weather), it is best to view impact regions as portions of space-time.



Convective example

Inputs: Weather

- Each type j of weather event may have many forms of data input that yield the intensity map, $W_j(x,y,z,t)$
- Example: Icing

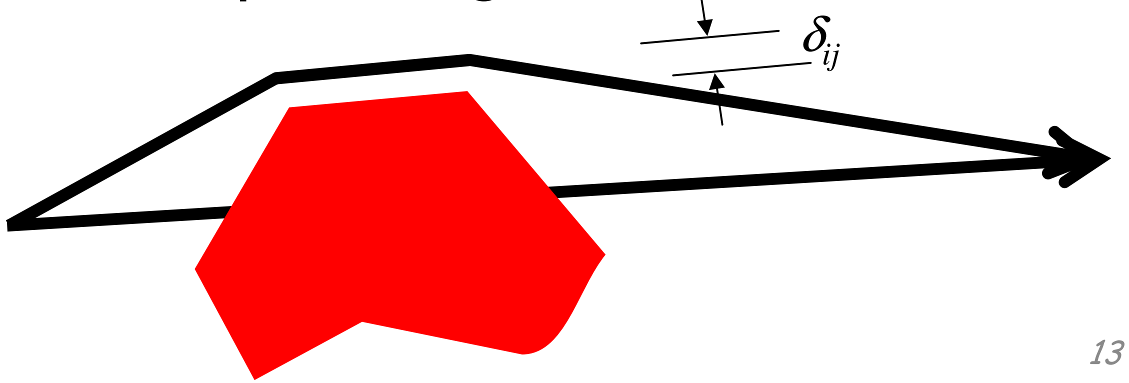


Weather Impacts on Routes

- “No-Go” constraints (avoidance model)
- Cost related to intensity/severity
- Limited total exposure
- Limited exposure bursts

Weather Impacts on Routes: "No-Go" Constraints

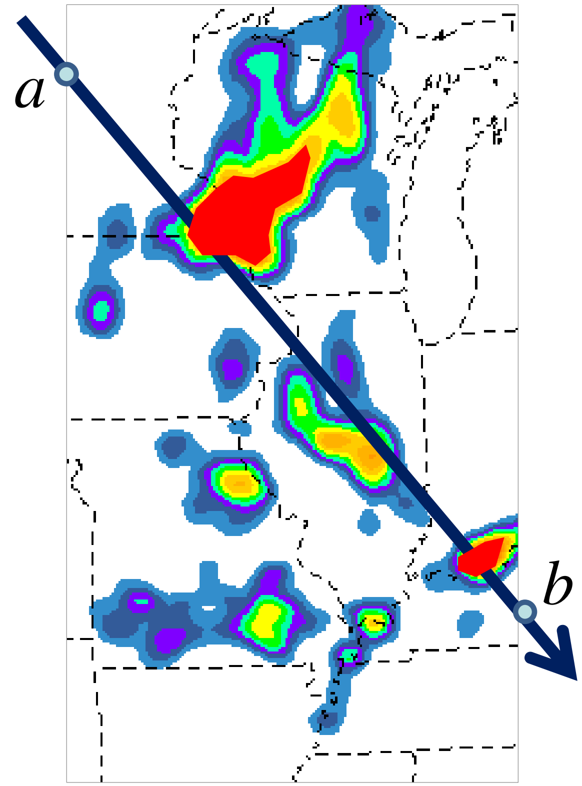
- Impact regions are "no-go" constraints
  - Routes *must* avoid regions whose intensity values are above a specified threshold, $\alpha_{i,j}$.
  - Optionally, there is a weather avoidance threshold, $\delta_{i,j}$, specifying a minimum clearance distance a route of equipage class i should stay from impact regions of weather type j.

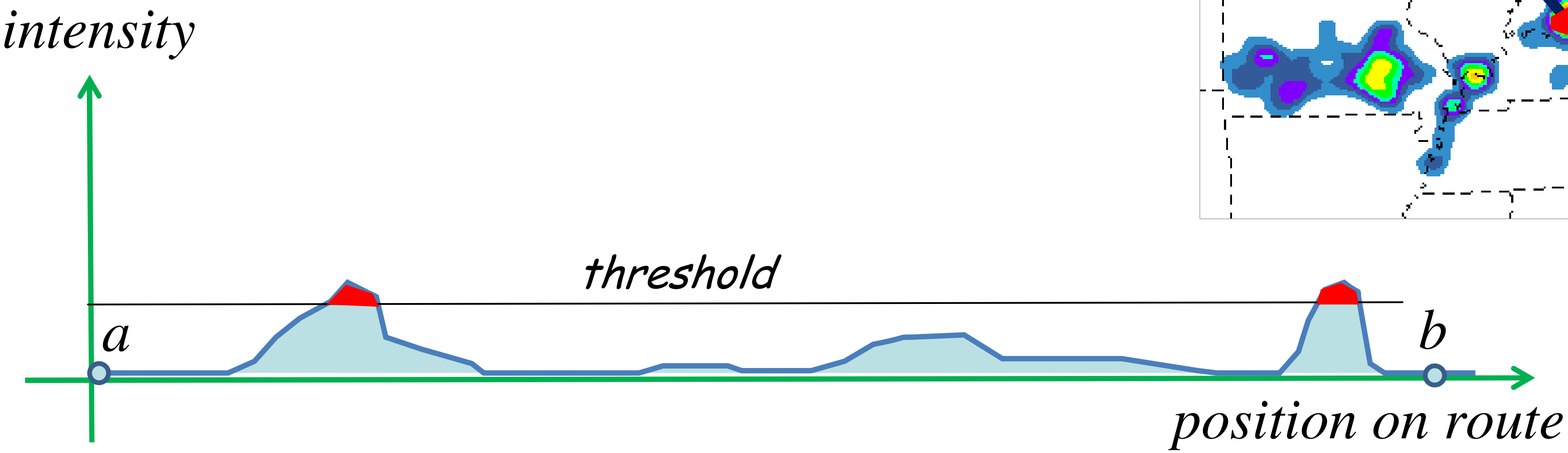


Also: Clearance above (in z) echo top

Hard constraint

Example: No-Go Above a Threshold





Weather Impacts on Routes: Function of Intensity/Severity

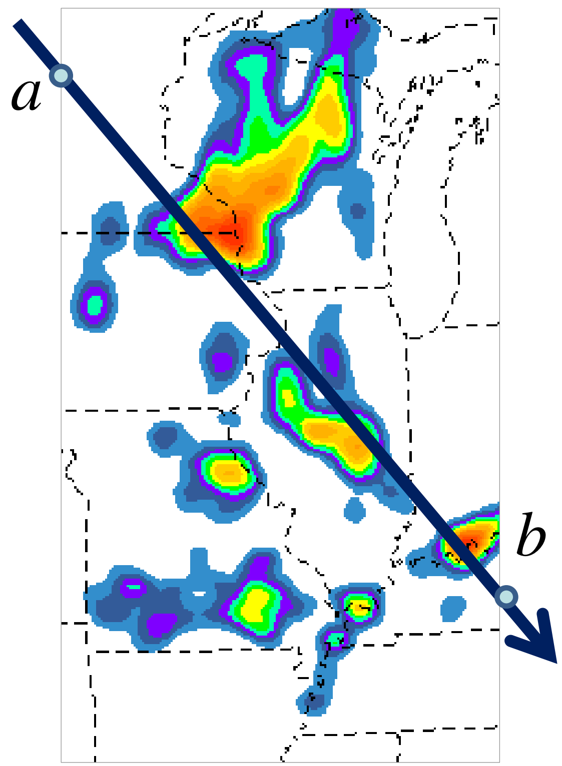
- Impact regions incur cost related to intensity along the route from a to b:
  - Intensity $I_j(x)$ at position x implies cost per unit distance of $g_{ij}(I_j(x))$, for a total cost of

$$\int_a^b g_{ij}(I_j(x))dx$$

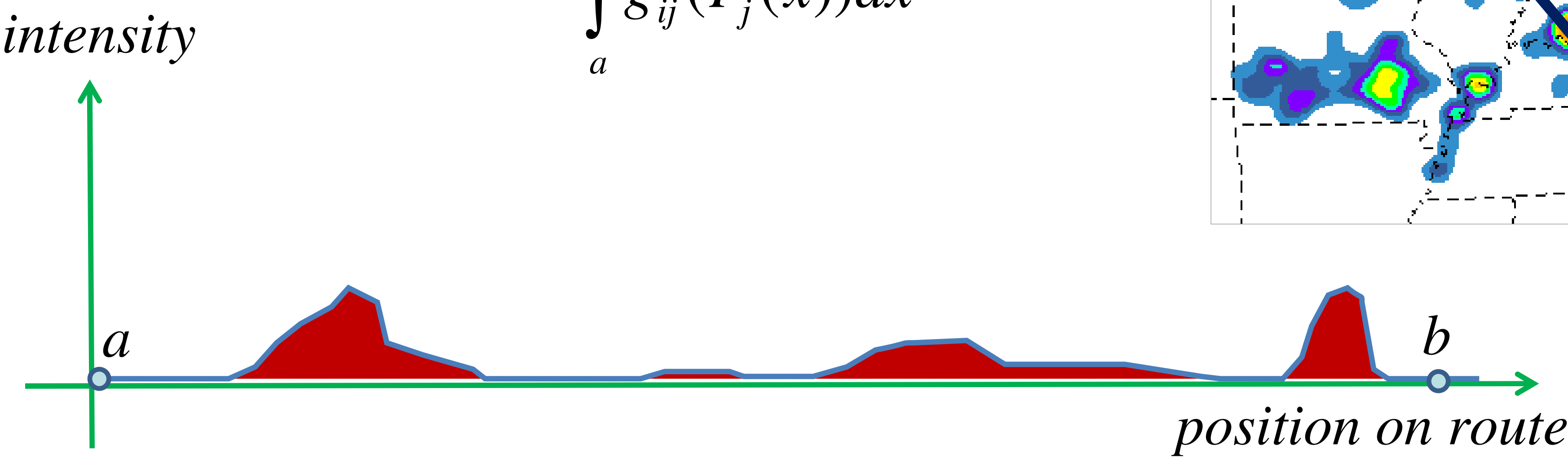
Can also take into account the probabilities associated with the weather event – stochastic model

Example: Weighted Impact Cost

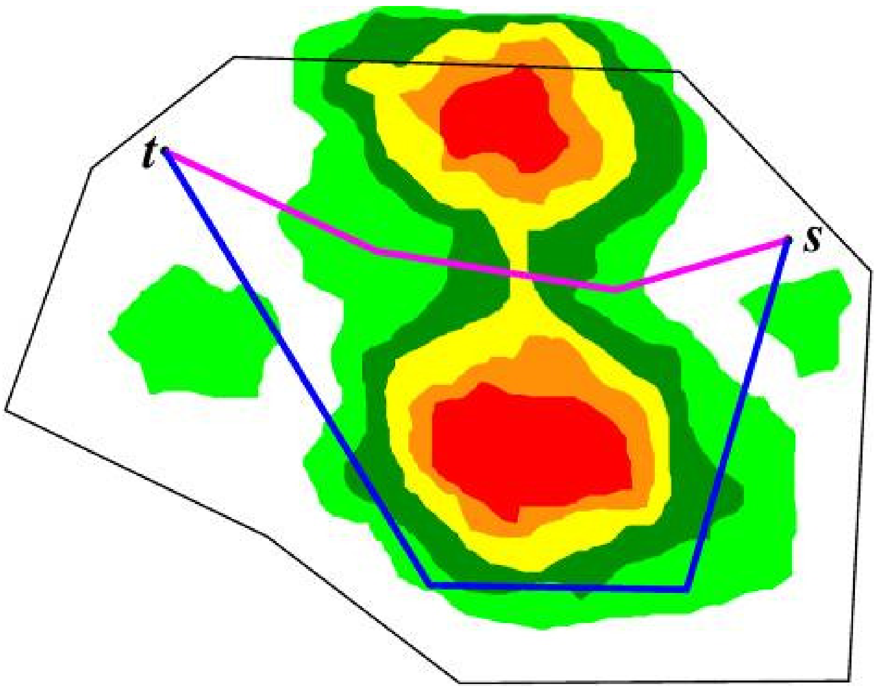
Route is feasible, but incurs a cost related to the integrated intensity along the route

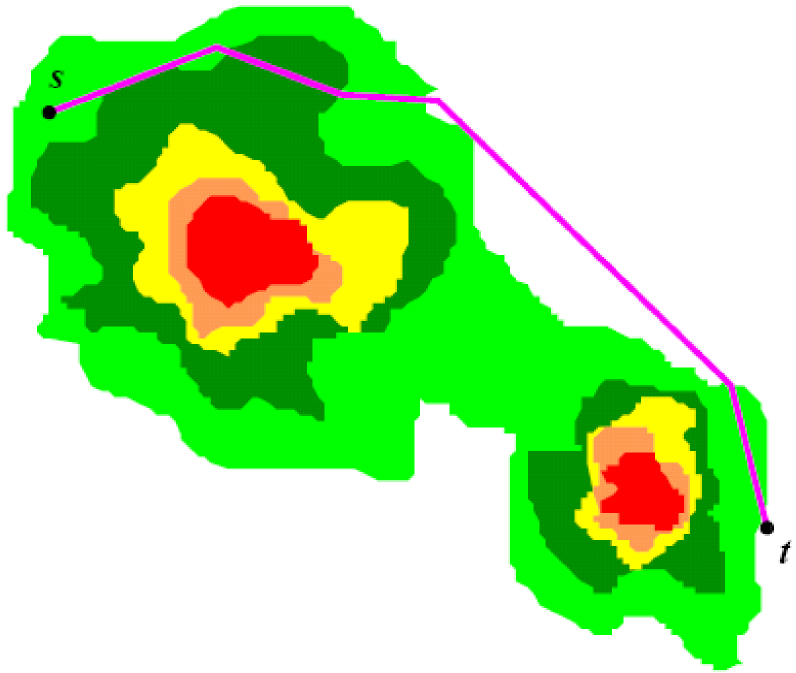


$$\int_a^b g_{ij}(I_j(x))dx$$



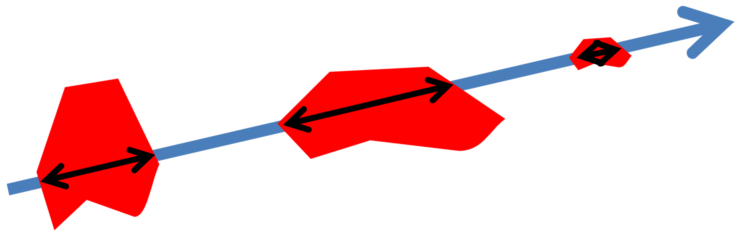
Example: Weighted Impact Costs





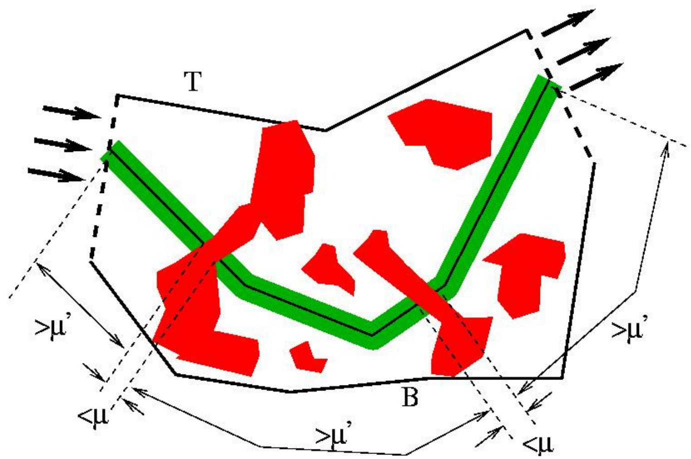
Weather Impacts on Routes: Limited Exposure

- Impact regions incur cost related to intensity along the route from a to b:
  - Total exposure parameter: Total travel (throughout R) cannot exceed $D_{i,j}^{max}$



  - Alternation parameters:
    - Can travel ≤ $d_{i,j}$ in region of type j if followed by travel of ≥ $D_{i,j}$ outside regions of type j

      $\mu = d_{i,j} \quad \mu' = D_{i,j}$



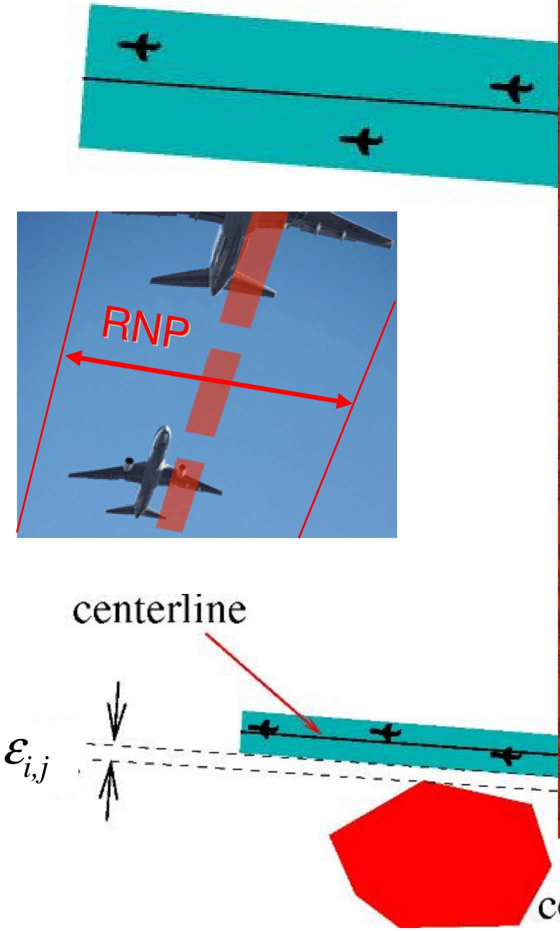
Discussion: Do these limited exposure models reflect any actual aircraft-weather interactions?

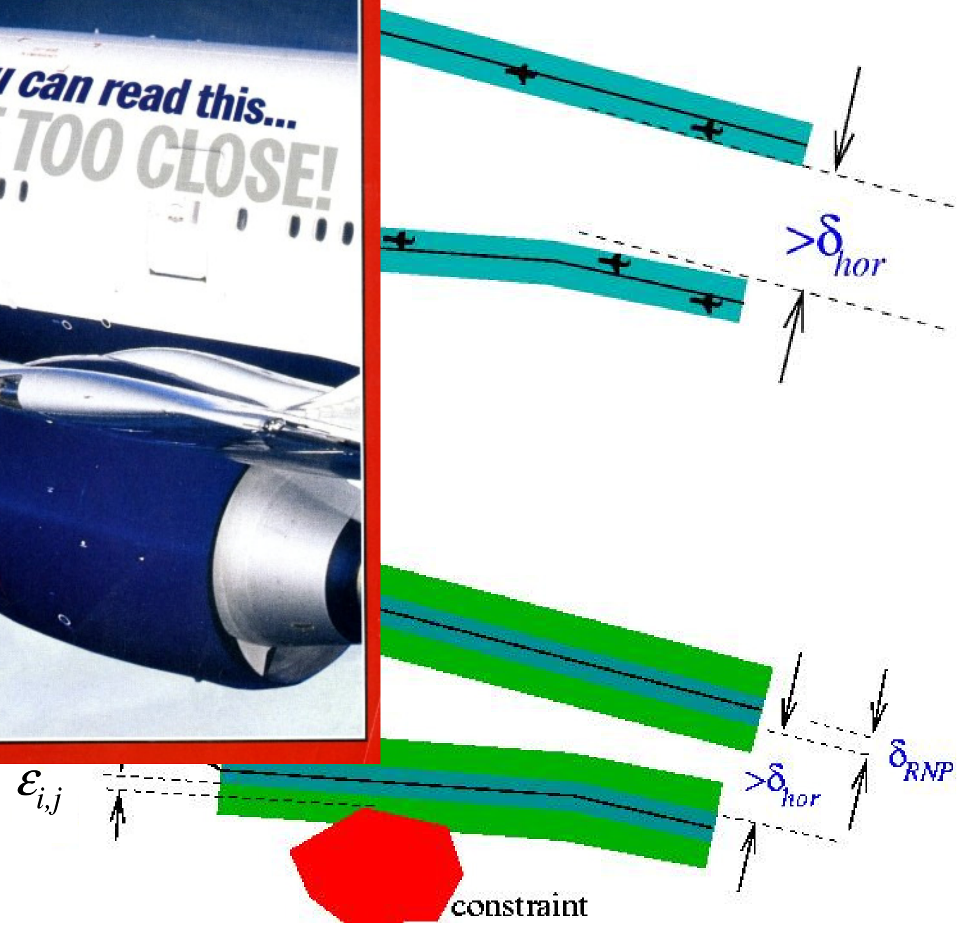
Inputs: Set Σ_i of Preferences/Parameters

- RNP parameter, $\delta_{RNP,i}$, specifying how closely an aircraft of class i can follow a specified route
- For each type j of weather constraint, and for each equipage class i:
  - Offset (clearance) $\varepsilon_{i,j}$ to be applied to type j impact regions to be treated as "no-go" constraints for intensities above a threshold, $\alpha_{i,j}$
  - Cost function $g(I)$, cost per unit distance in type j regions of intensity I.
  - Total exposure parameter: Total travel (throughout R) cannot exceed $D_{i,j}^{max}$
  - Alternation parameters for exposure bursts:
    - Can travel $\leq d_{i,j}$ in region of type j if followed by travel of $\geq D_{i,j}$ outside regions of type j

Flows and Air Lanes:

RNP, Sep … arameters



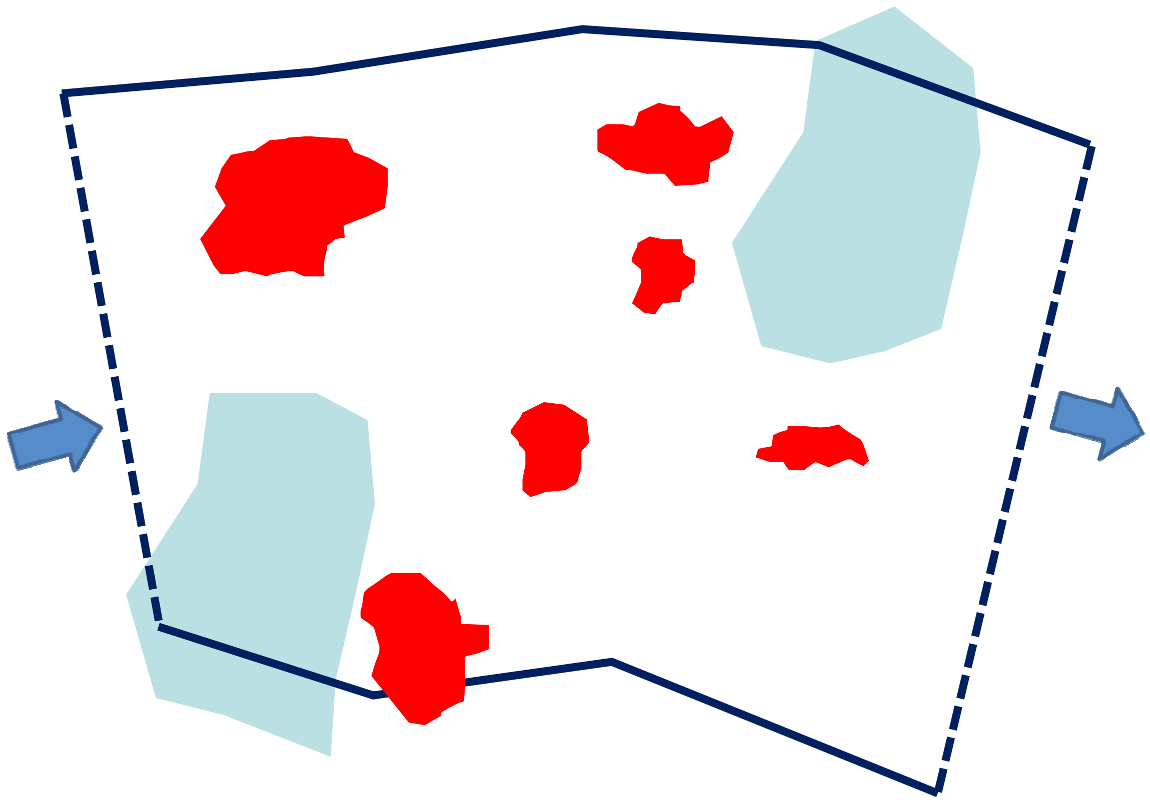


Model of Hard/Soft Constraints

- Hard, soft, and everything in between:
  - Each class i of aircraft (equipage, preferences, etc) has an *interaction profile* with each type j of weather event
- *Weather Impact Interaction Grid*
- Multiclass capacity

Model of Hard/Soft Constraints

- Simple, 2-class, 2-type example:
  - Class 1: Avoid type-1 (red) constraints ("Hard"), but can ignore type-2 (blue) constraints ("Soft")
  - Class 2: Must avoid both type-1 and type-2 constraints (Hard and Soft)



Weather Impact Interaction Grid

Weather event type j

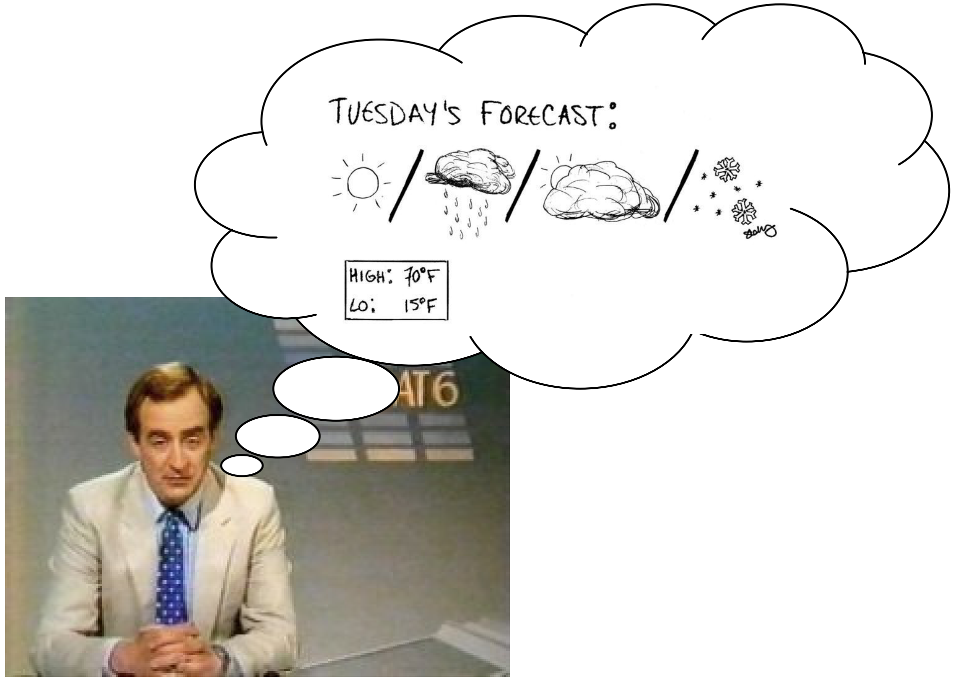
Aircraft class i

	Icing	Turbulence	Fog	Visibility
1	Light OK Moderate: limit total exposure Extreme: no-go			
2	Light: alternation parameters Moderate: No-go			
3				

Stochastic Model of Weather

- The intensity, $W_j(x,y,z,t)$, of weather of type j is not known with certainty, but is given by a probabilistic forecast
- How to model the random function $W_j(x,y,z,t)$?

Probability of What?

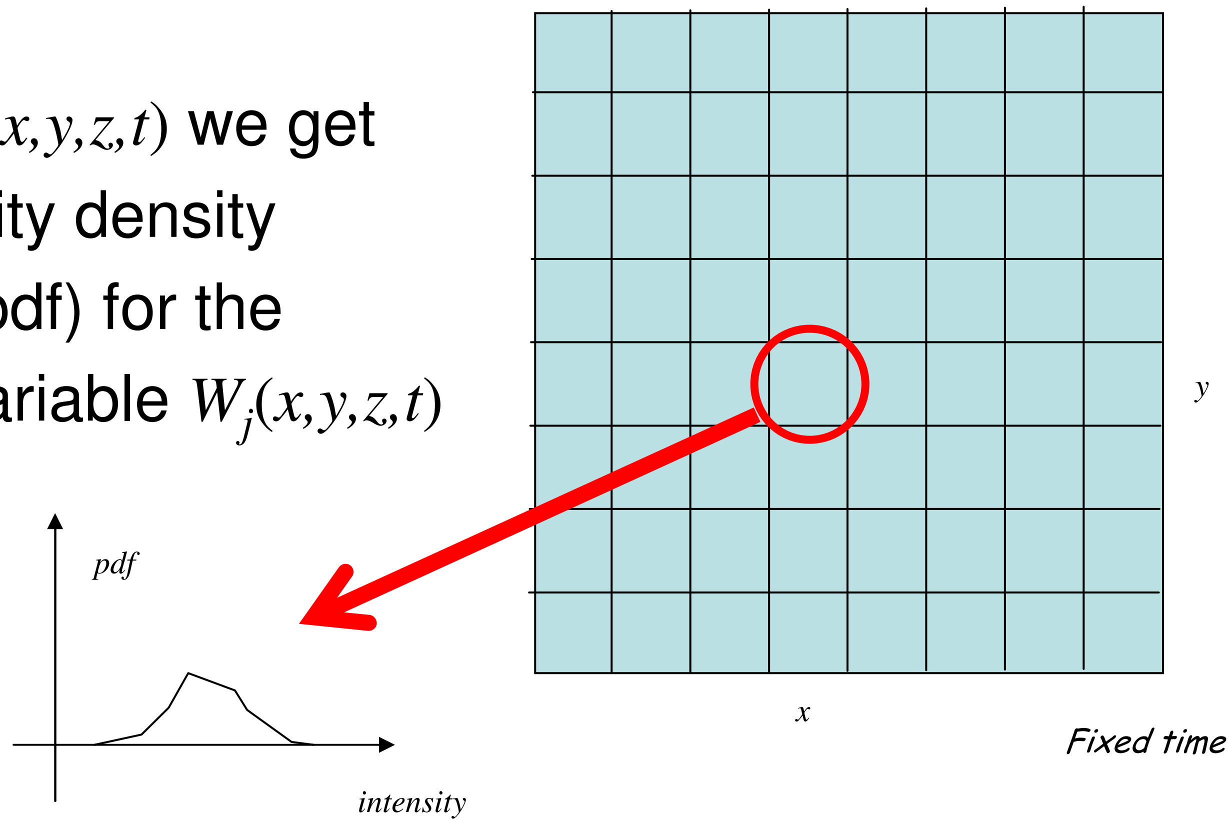


- <u>Ambiguity</u> in
  - timing & location
  - definition of “event”
  - communication
- <u>Probability</u> of
  - presence of weather hazard in space & time
  - hazard exceeding critical threshold intensity
  - structure & organization of weather hazard
- <u>What do aviation users want?</u>

Stochastic Model of Weather

- One method: probabilistic pixel grid (or forecast of gridded pdf's):

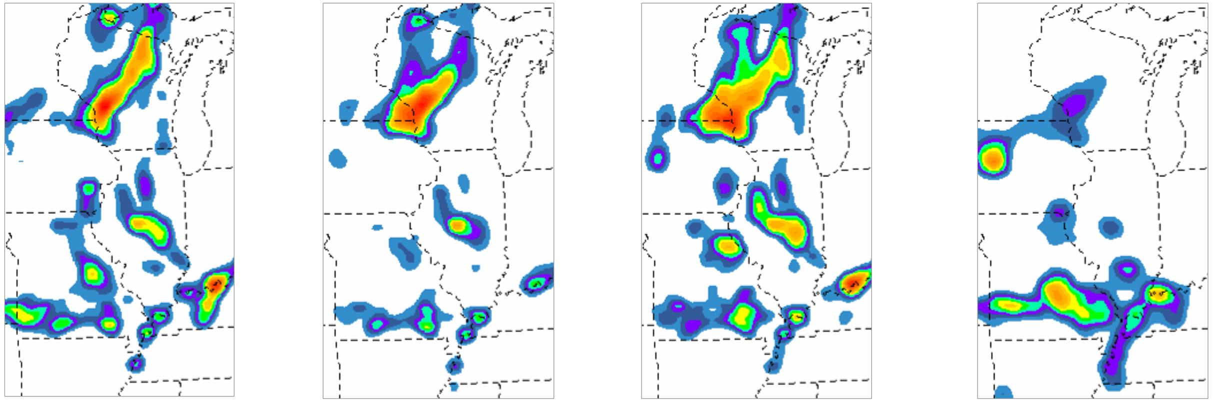
- For each (x,y,z,t) we get a probability density function (pdf) for the random variable $W_j(x,y,z,t)$



Fixed time t, *altitude* z

Stochastic Model of Weather

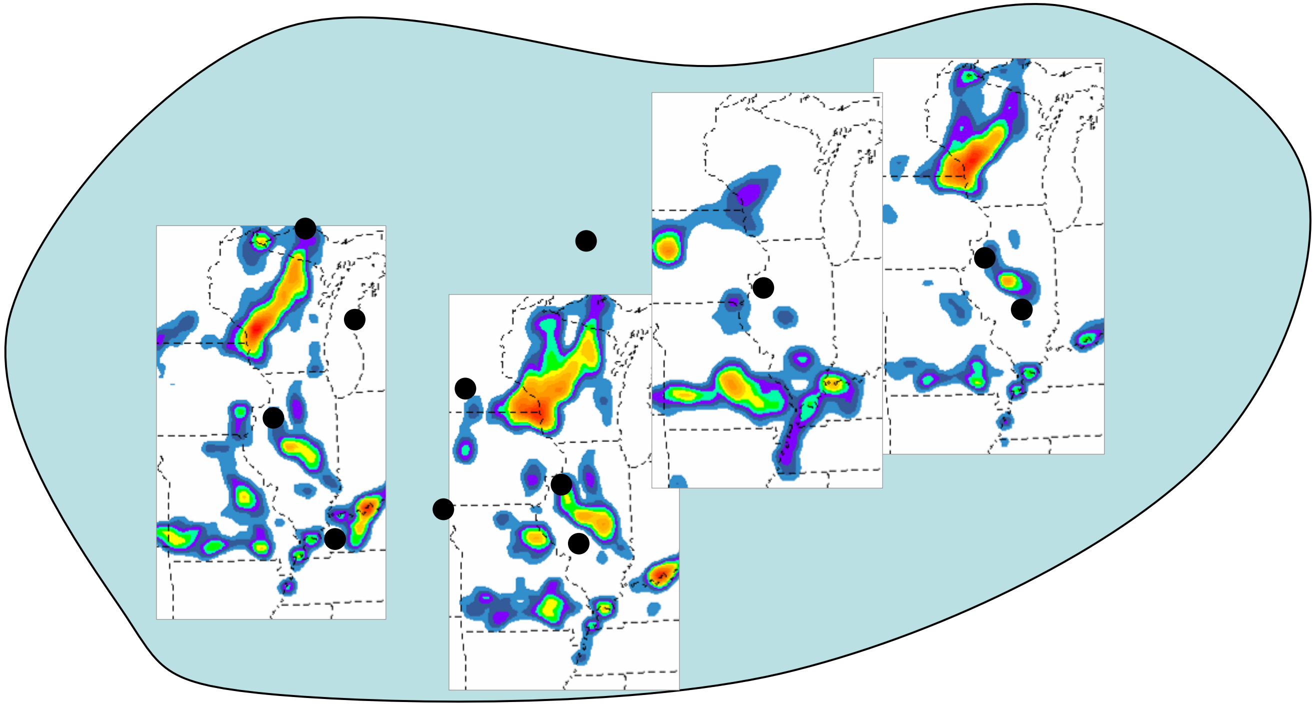
- Another method: Ensemble of forecasts



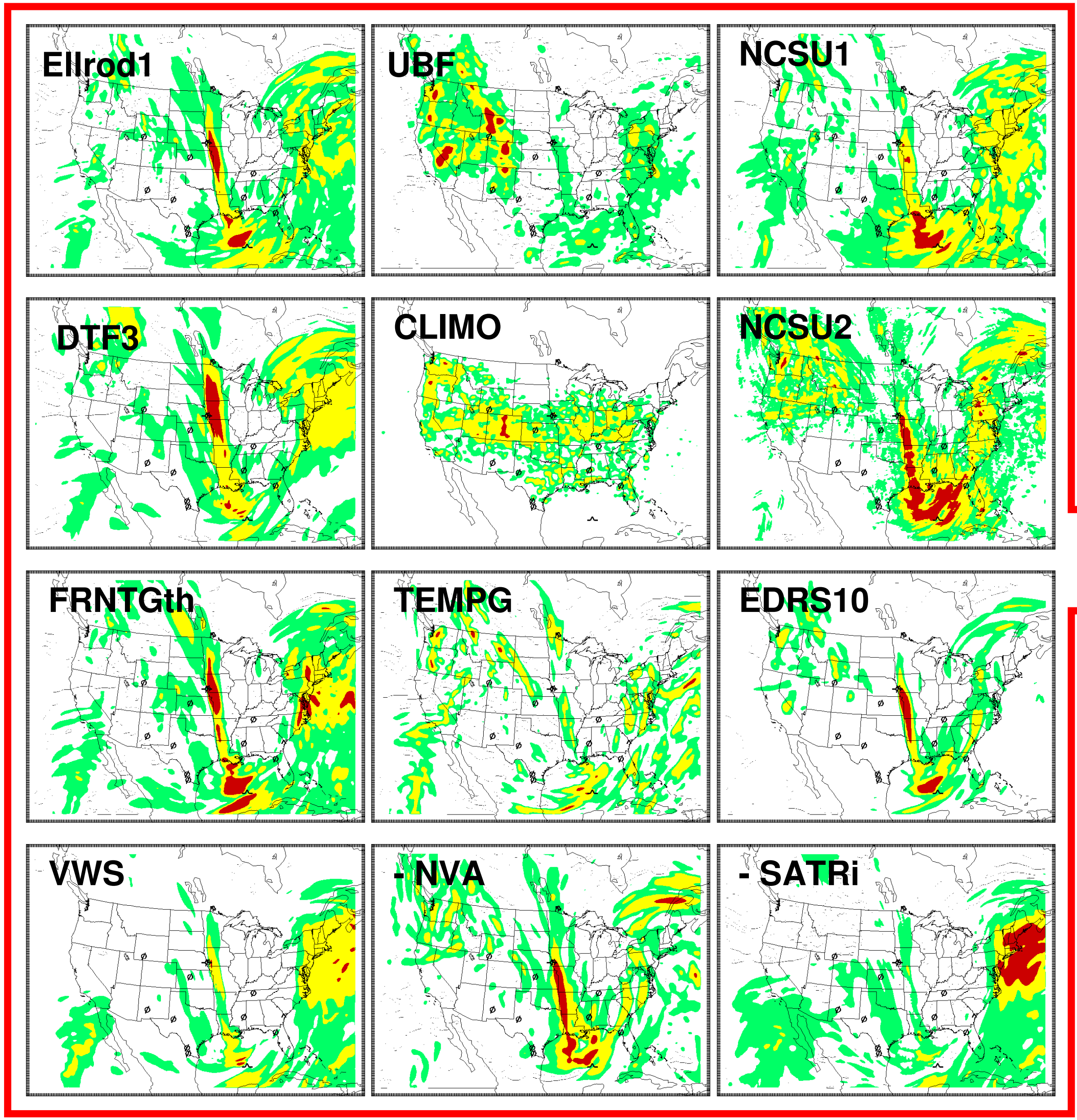
Forecast:	F_1	F_2	F_3	F_4	…
Probability:	p_1	p_2	p_3	p_4	…

Discussion: How many? How to assess prior probabilities?

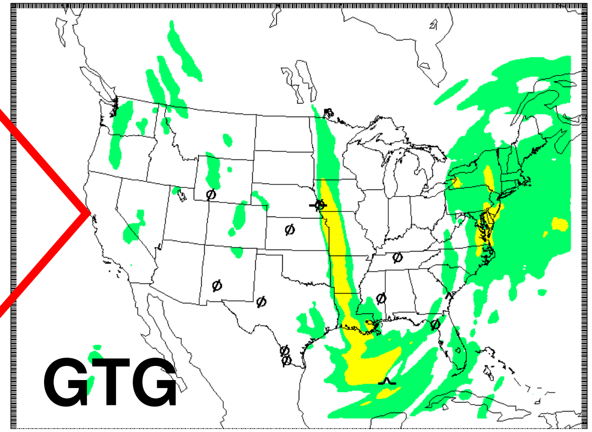
Stochastic Models: Ensembles



Space of all possible forecasts F *: probabilities* $p(F)$



Merging a variety of turbulence diagnostics into GTG

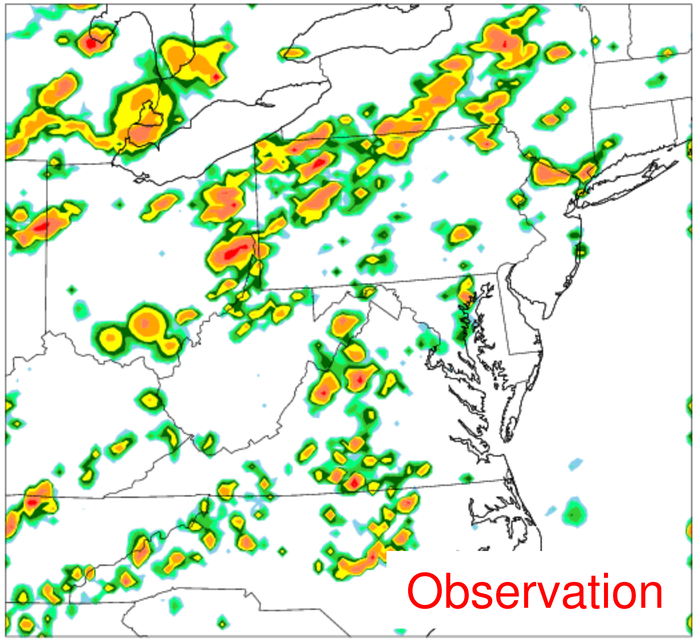


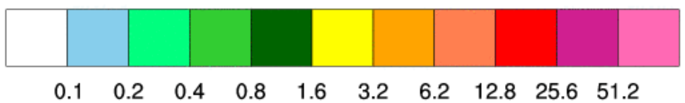
6 h forecast valid at 5 Feb 2006 00Z

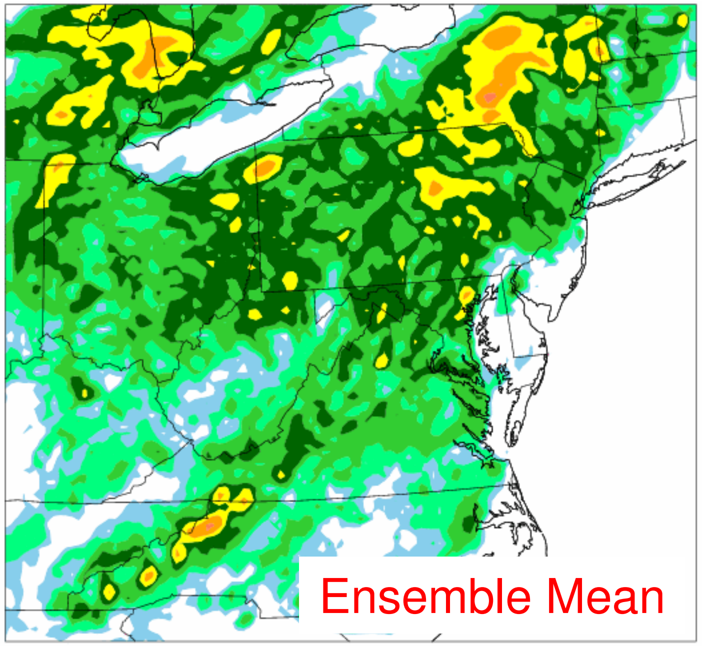
Flight level: 350

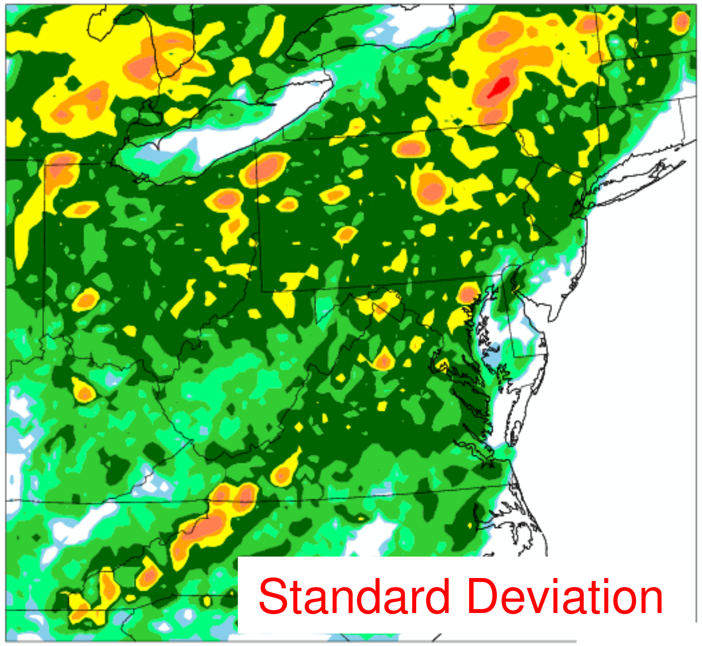
provide a measure of "forecast confidence"

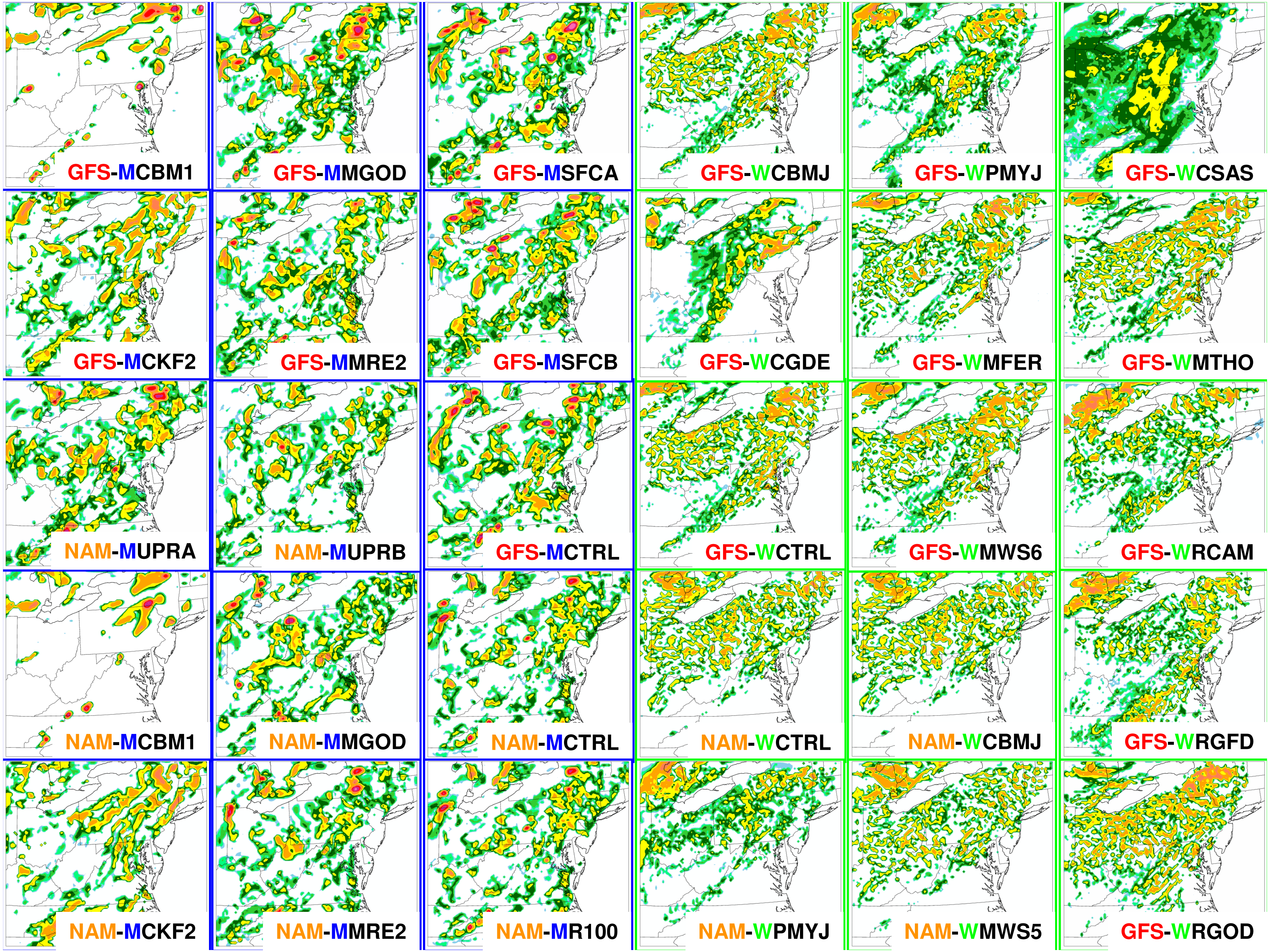
9 h Ensemble Forecast
valid for
27 June 2007 at 21 UTC

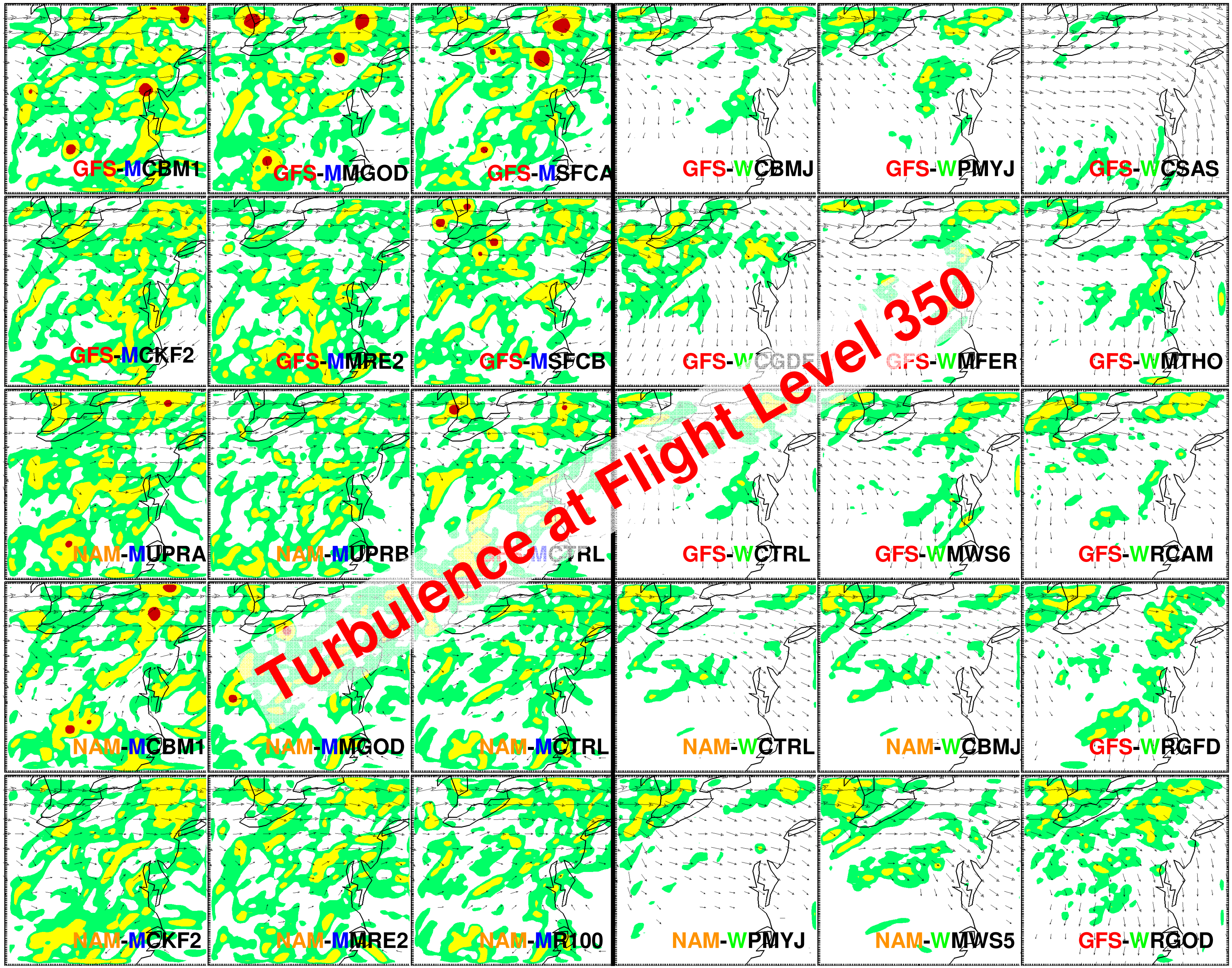




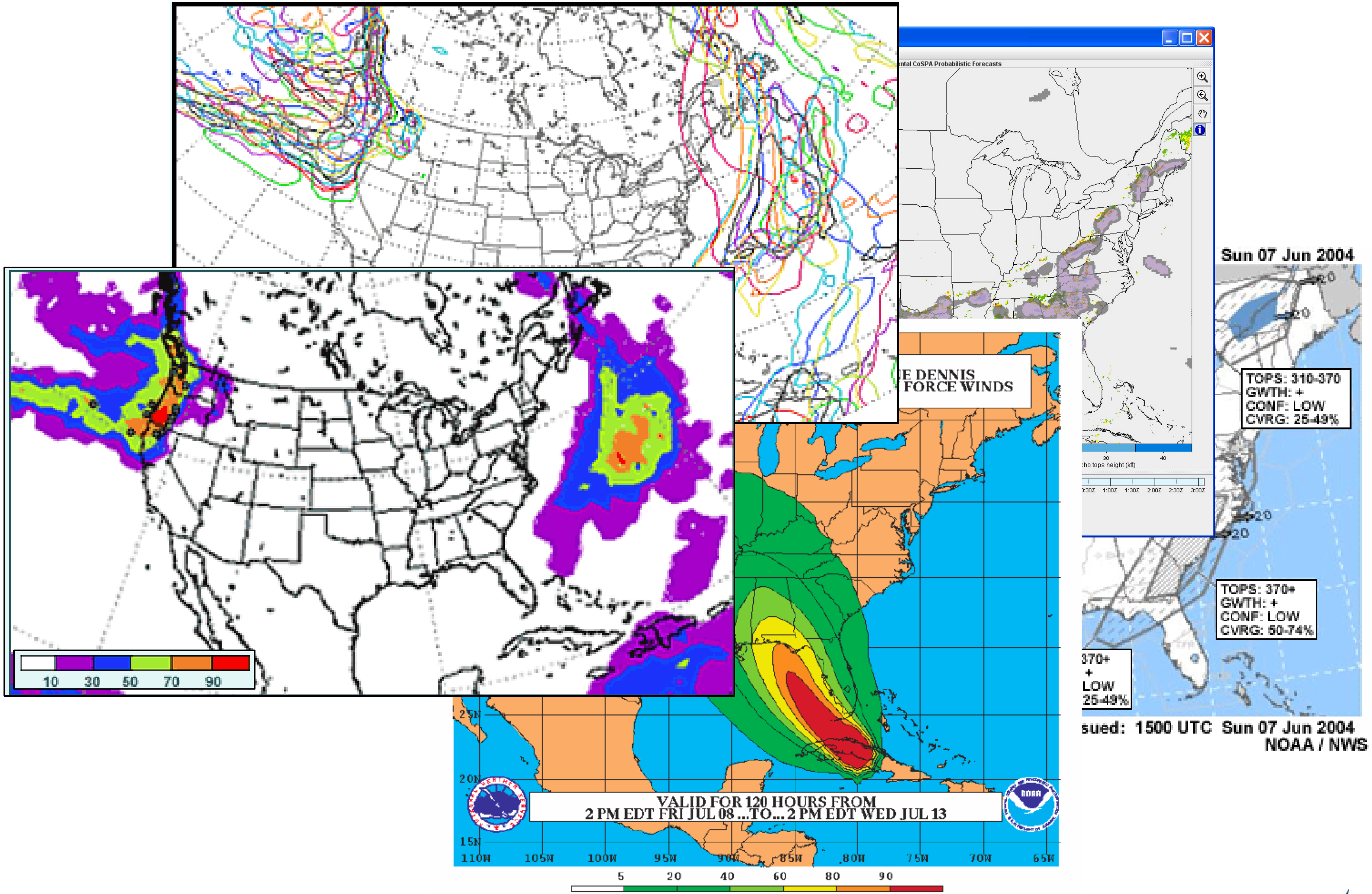





GFS-MCBM1
GFS-MMGOD
GFS-MSFCA
GFS-WCBMJ
GFS-WPMYJ
GFS-WCSAS
GFS-MCKF2
GFS-MMRE2
GFS-MSFCB
GFS-WCGDE
GFS-WMFER
GFS-WMTHO
NAM-MUPRA
NAM-MUPRB
GFS-MCTRL
GFS-WCTRL
GFS-WMWS6
GFS-WRCAM
NAM-MCBM1
NAM-MMGOD
NAM-MCTRL
NAM-WCTRL
NAM-WCBMJ
GFS-WRGFD
NAM-MCKF2
NAM-MMRE2
NAM-MR100
NAM-WPMYJ
NAM-WMWS5
GFS-WRGOD


Turbulence at Flight Level 350
GFS-MCBM1
GFS-MMGOD
GFS-MSFCA
GFS-WCBMJ
GFS-WPMYJ
GFS-WCSAS
GFS-MCKF2
GFS-MMRE2
GFS-MSFCB
GFS-WMFER
GFS-WMTHO
NAM-MUPRA
NAM-MUPRB
GFS-WCTRL
GFS-WMWS6
GFS-WRCAM
NAM-MCBM1
NAM-MMGOD
NAM-MCTRL
NAM-WCTRL
NAM-WCBMJ
GFS-WRGFD
NAM-MCKF2
NAM-MMRE2
NAM-MR100
NAM-WPMYJ
NAM-WMWS5
GFS-WRGOD

Visualization of Ensemble Forecasts



Stochastic Model of Weather

- Issue: Grid does not explicitly model spatial and temporal dependencies/correlations

Forecast F_1 , prob = 0.5

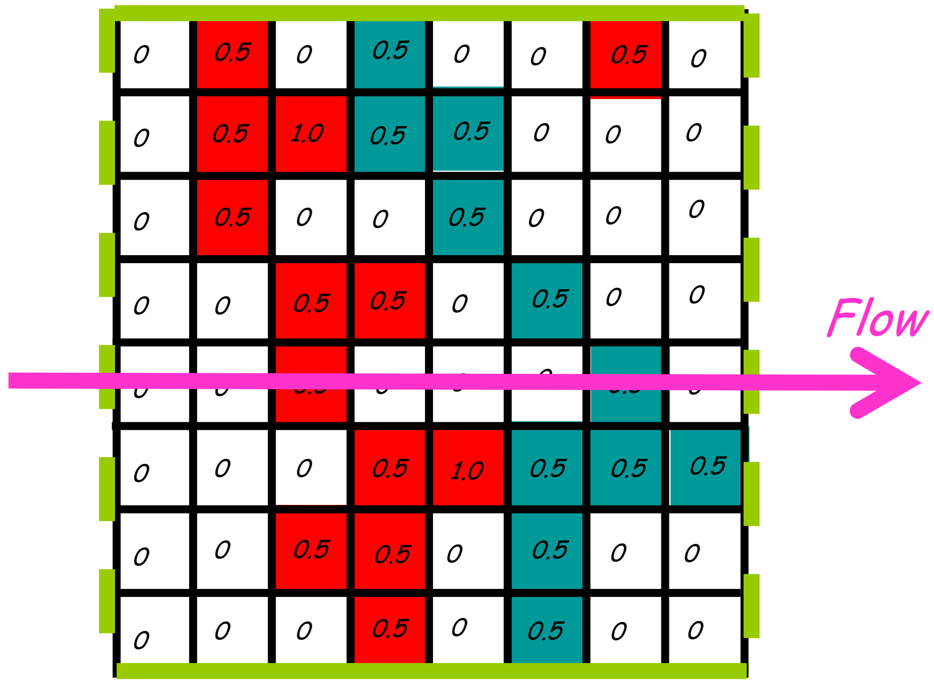
Forecast F_2 , prob = 0.5

Each pixel has a simple Bernoulli distribution, with P(blocked) given by the values (0, 0.5, 1.0) shown

P(flow is feasible) = ?

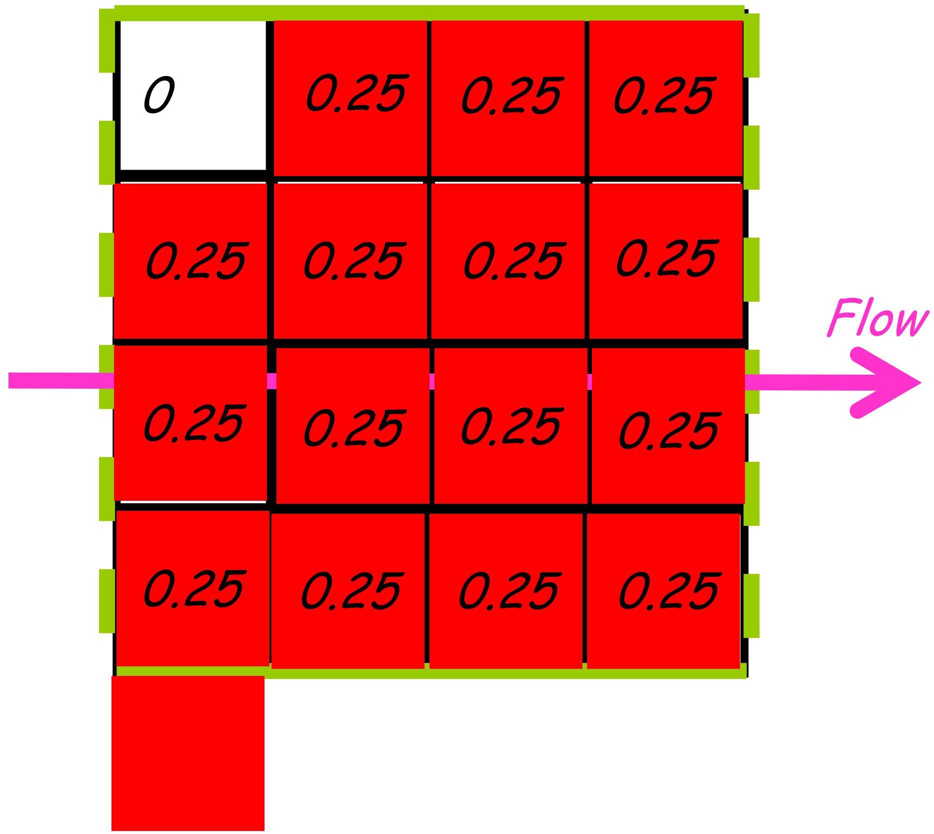
0.5 ? $(0.5)^2$?

Ensemble model: Prob = 0



Variations on a Forecast

- Uncertainty on when exact a weather event impacts and moves through a region:



Probabilities 0.25 each

P(flow is feasible) = ?

$(0.75)^4$? (indep)

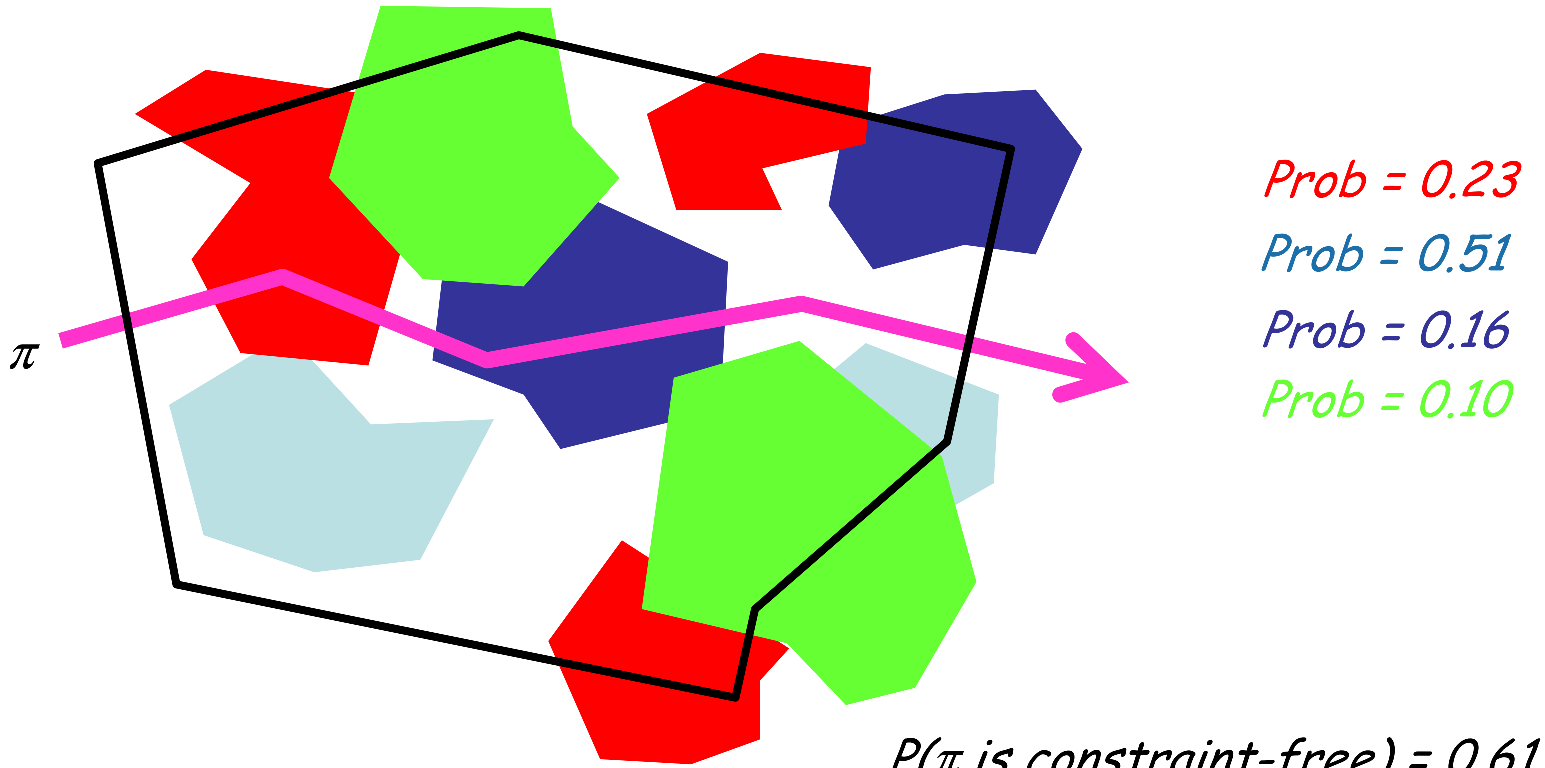
0.25 ?

BUT, P(there is east-west capacity of at least 2 lanes) = 1

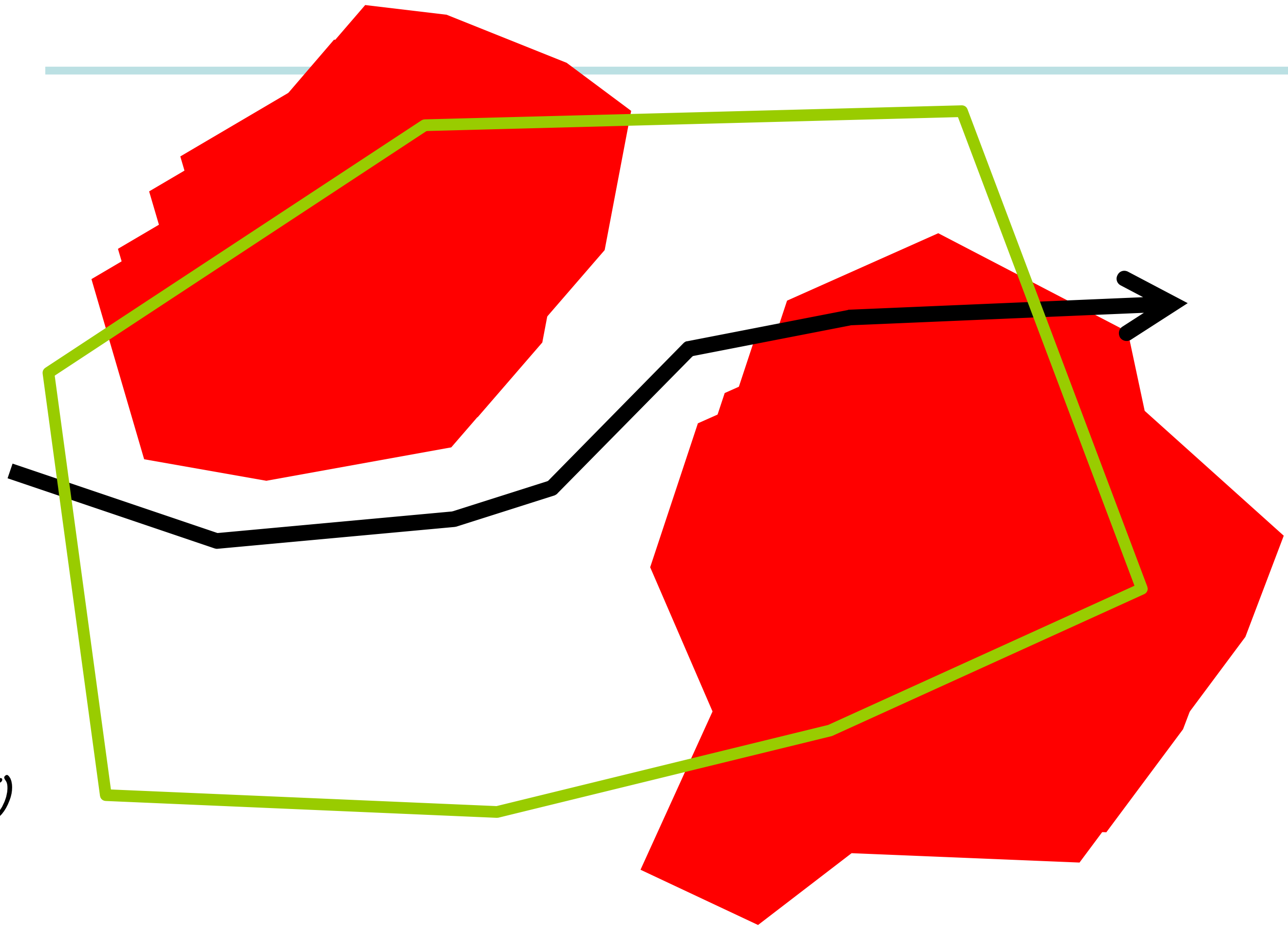
NOTE: P(north-south lane) = 0 !

Interactions with Probabilistic Weather

- What is the probability a route π is feasible with respect to constraints?



Variations on Forecast



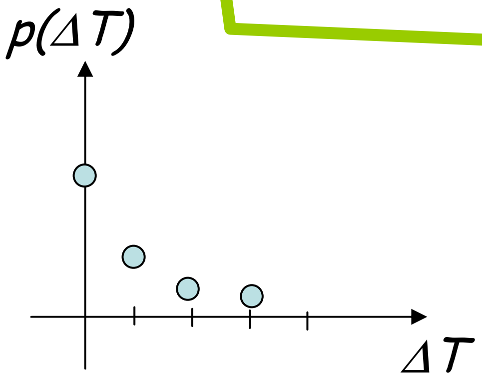
Seed location:

ΔT = 0, p=0.5

ΔT = 1, p=0.2

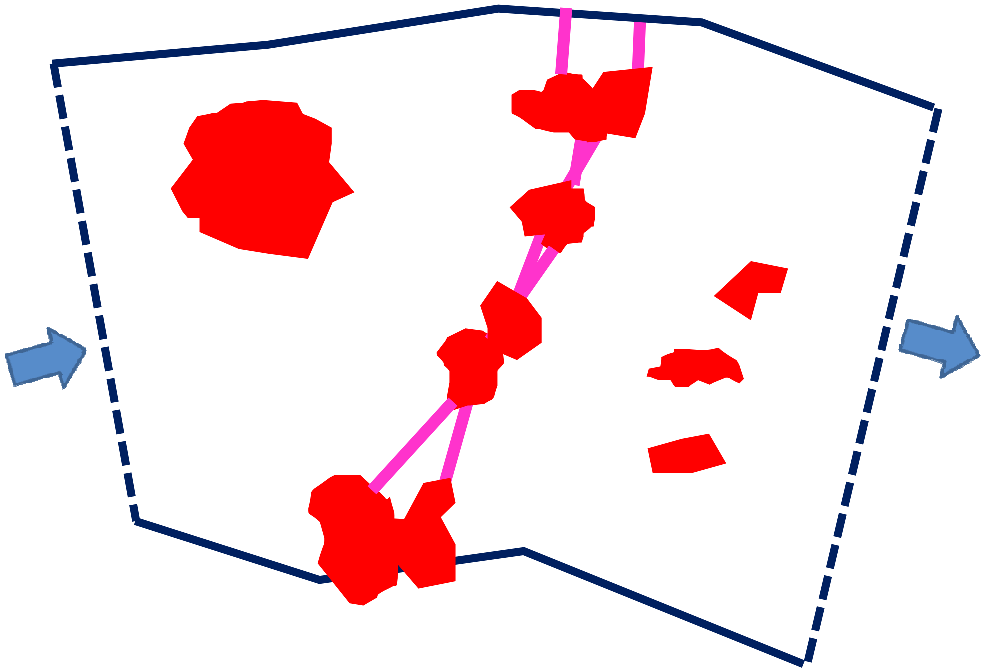
ΔT = 2, p=0.15

ΔT = 3, p=0.15



Capacity Estimation: Probabilistic Weather

- For capacity estimation, exact shape of weather impact region is not as significant as its “porosity”



Clustered Ensemble Models

- Use variations on seed forecasts
- Much fewer seeds
- Each cluster of forecasts is based on a variation model centered on a seed:
  - Vary time (errors in time)
  - Vary intensity map (shift up/down), thereby impacting coverage
  - Vary translation (x, y)
  - Vary echo tops

•What distributions to use for variations on seed forecasts? ΔT, ΔCoverage, ΔTranslation, ΔTops, etc.