NWRA *NorthWest Research Associates, Inc.*

Redmond, WA

Development of a New Probabilistic Wake Vortex Prediction Model

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"Operational Wake Vortex Models"

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Acknowledgments

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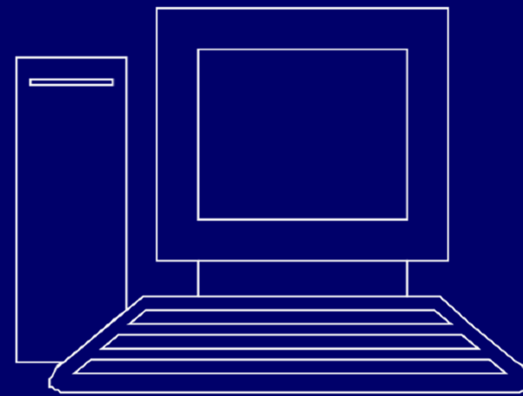
- The work was performed under the NASA NRA “Enabling Super-Dense Operations by Advancing the State of the Art of Fast-Time Wake Vortex Modeling”
- The lidar data shown in this study was provided by NASA
- The Federal Aviation Administration (FAA) has also provided lidar data to use in comparison studies and also provided funding for several of the models that have been incorporated in the new probabilistic model
- Current funding for this work is under the NASA NRA “Wake Vortex Data Collection for Robust Modeling Validation to Enable Advanced, NextGen, Wake-Conscious, Capacity-Enhancing Concepts”
- Neil O’Connor and Dr. Fred Proctor are the technical monitors

Motivation



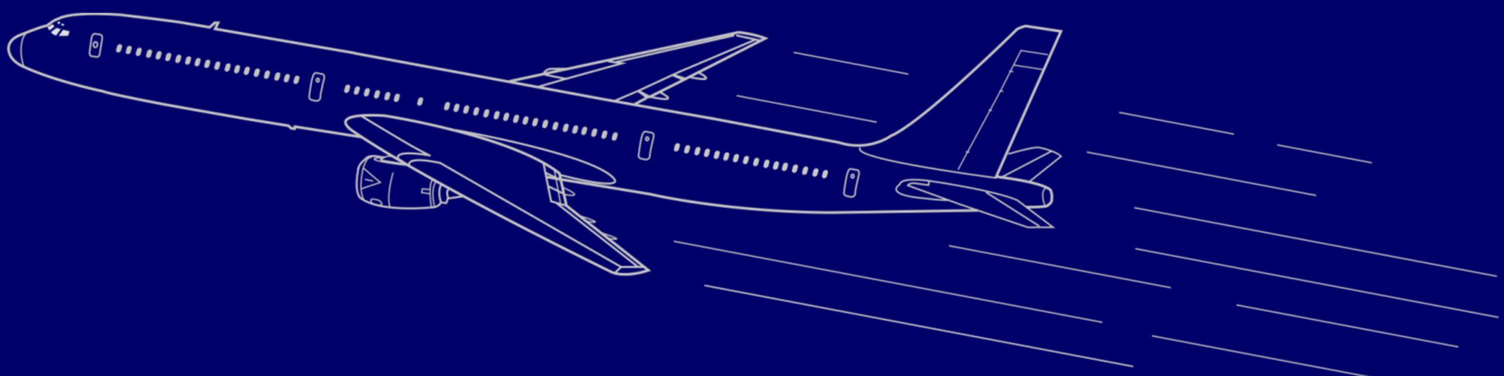
What did we do?
and
What did we find out?

Next Steps

Discussion on related scientific questions, and the feasibility and priorities of different methods with respect to future research

Goal of NASA Probabilistic Model

Quantify the probability of finding a vortex at a specified location at a specified time after passage of a known aircraft in a known atmosphere, where the vortex is of a specified strength or greater

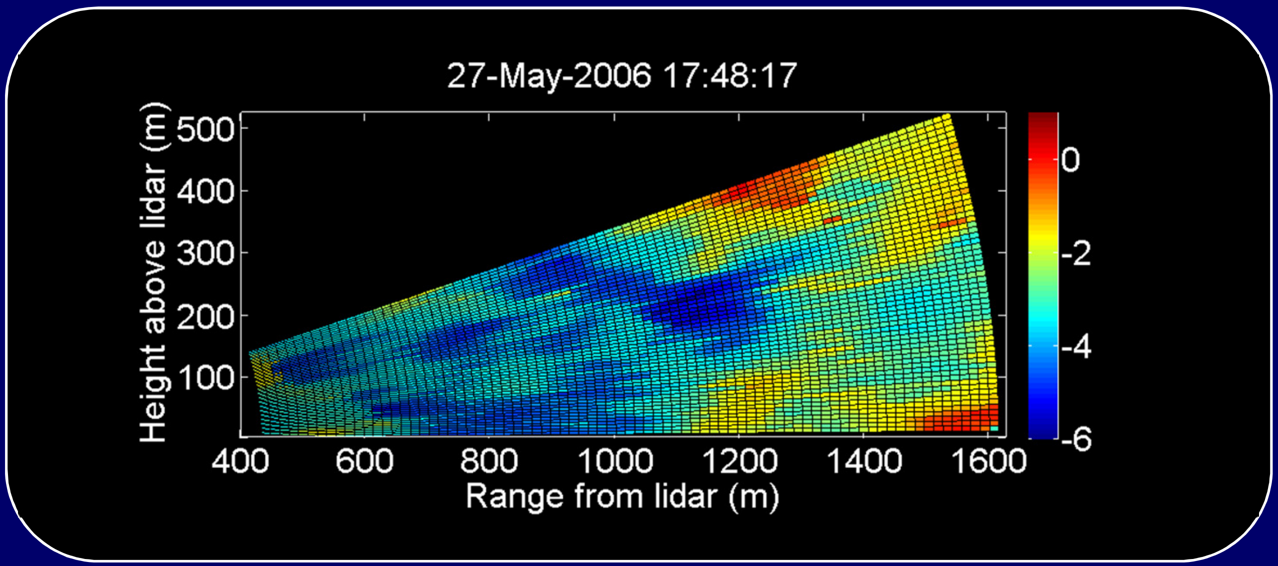


Why is a Fast-time Probabilistic Model Needed?

- Large number of model inputs
  - All model inputs have uncertainties
    - Interaction of these uncertainties and affect of uncertainties on the model predictions is not obvious
- Not clear there is a “best” deterministic fast-time wake vortex prediction model
- Uncertainties in observations are poorly quantified

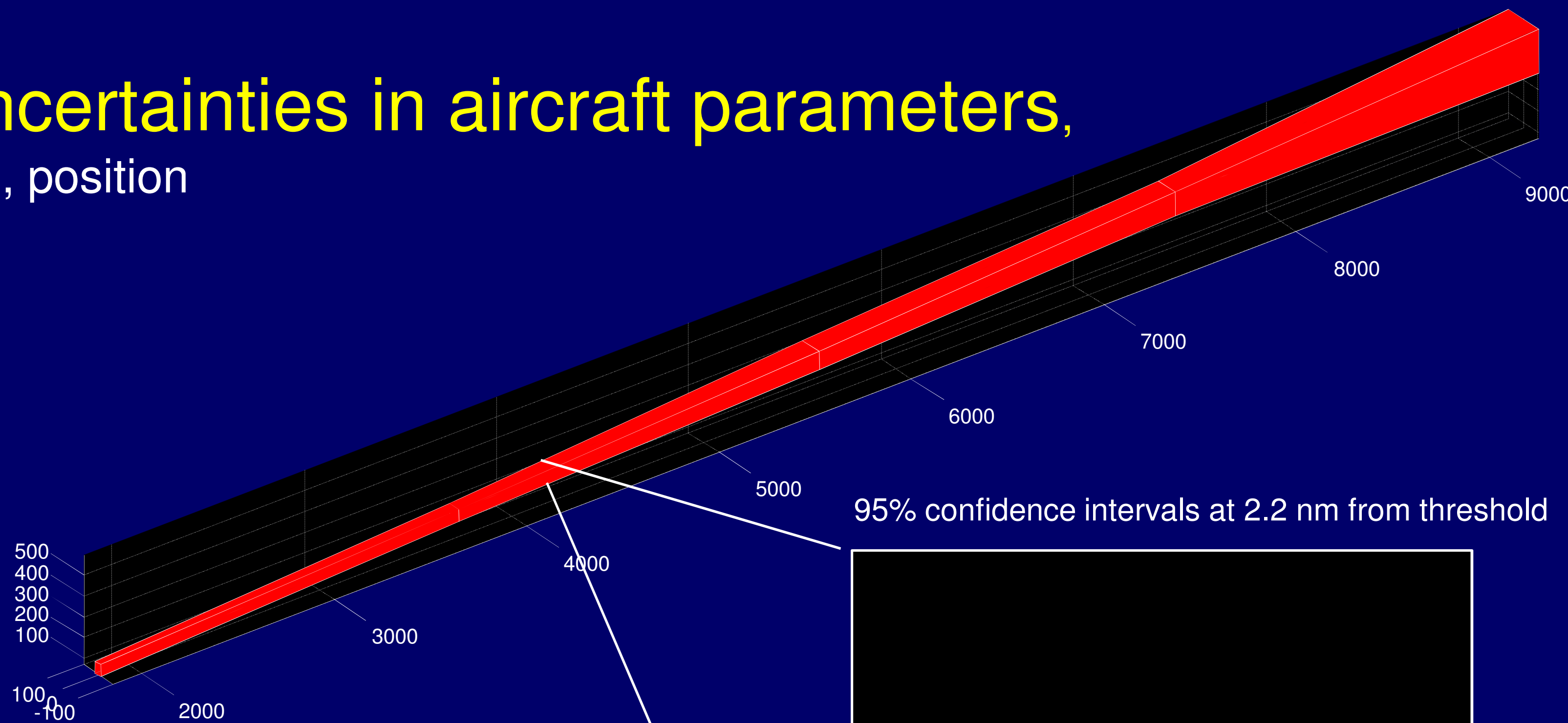
Suboptimum weather information

a) Uncertainties in meteorological sensing
b) Nonhomogeneity of weather conditions
c) Changes in weather since time of last observation



Uncertainties in aircraft parameters,

e.g., position



95% confidence intervals at 2.2 nm from threshold

Approximate dimensions of B752 shown for scale

Also,

- aircraft weight
- true air speed
- initial vortex spacing
- time of overflight

Shown is the 95% confidence intervals estimated from the maximum standard deviations for each distance from the threshold reported in

[1] Zhang Y, Shortle J, Sherry L., 2010. Comparison of Arrival Tracks at Different Airports. In: *Proceedings of 4th International Conference on Research in Air Transportation*. Budapest, Hungary.

[2] Hall, T., M. Soares. 2008. Analysis of localizer and glide slope flight technical error. *27th Digital Avionics Systems Conference*, St. Paul, MN.

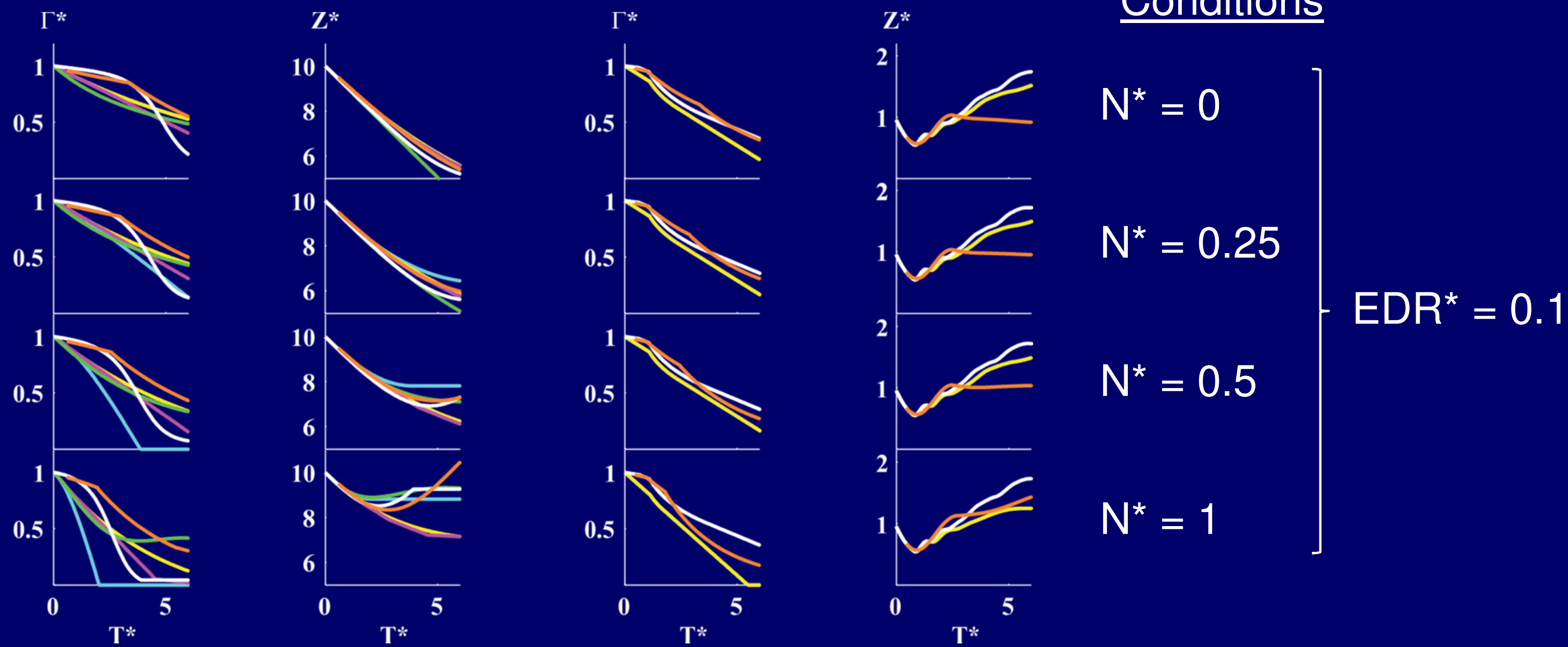
Ambiguities due to model assumptions, simplifications, and parameterizations

APA v3.3 APA v3.4 STL v4.0 TDP v2.1 VPR v1.0 DVM v4.3

Out-of-Ground Effect

In-Ground Effect

Environmental Conditions



Uncertainties in the observation of wakes

- Mean biases of the wake observations with LCMT pulsed lidar are
  - 2-4 m in vertical
  - 4-8 m in horizontal

Lai and Delisi, 2010. **Assessment of Pulsed Lidar Measurements of Aircraft Wake Vortex Positions Using a Lidar Simulator,** AIAA-2010-7988, AIAA Atmospheric and Space Environments Conference, Toronto, Ontario, Aug. 2-5.

Deterministic Fast-time Wake Vortex Prediction Model

Environmental Parameters

- air density(z)
- crosswind(z)
- headwind(z)
- EDR(z)
- potential temperature(z)

Used for Model Assessment
and
Calibration (Model Improvement)

Fast-time Wake Vortex Prediction Models →

Estimates of Wake Vortex Transport and Decay

↕

Observations

Aircraft Parameters:

- aircraft weight
- air speed
- initial vortex spacing
- initial lateral position
- initial vertical position

Wake Research And Prediction System (WRAPS)

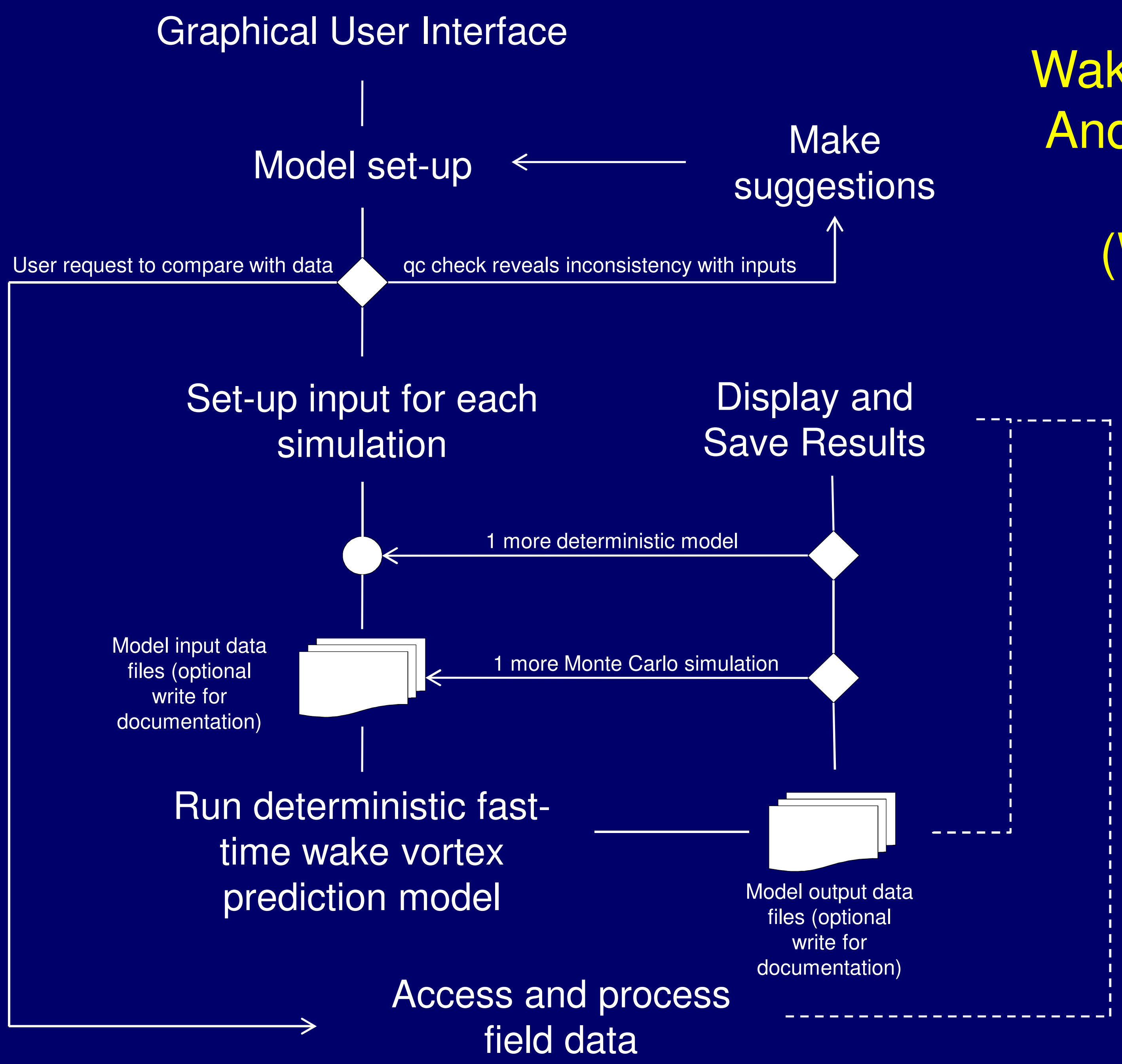
- Ensemble of deterministic, fast-time wake vortex prediction models
- Input uncertainties (i.e., a/c position and speed, weather) are included using a Monte-Carlo approach
- Allows user to compare with wake data that was obtained under similar conditions

Pruis and Delisi, 2011. Comparison of Ensemble Predictions of a New Probabilistic Fast-Time Wake Vortex Model and Lidar Observed Vortex Circulation Intensities and Trajectories, AIAA-2011-3036, 3rd AIAA Atmospheric Space Environments Conference, Honolulu, Hawaii, June 27-30.

How is this model different?

- Principal difference between the new NASA probabilistic model and other probabilistic models is that it is an ensemble of many deterministic fast-time wake vortex prediction models

Wake Research And Prediction System (WRAPS)

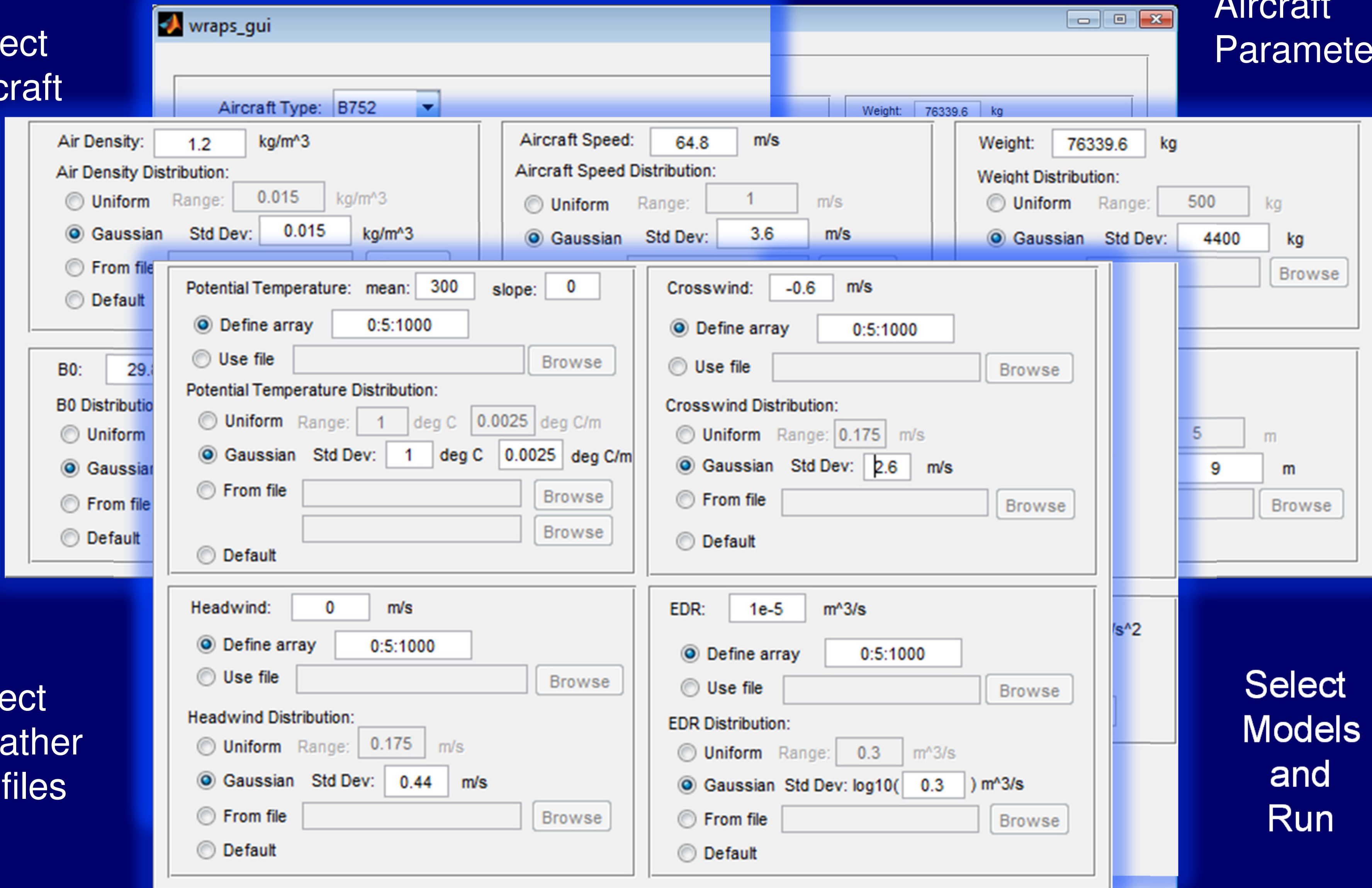


<u>Fast-time models</u>

1. APA v3.2
2. APA v3.3
3. APA v3.4
4. D2P v1.0 (NWRA)
5. Linear v1.0
6. STL v3.0
7. STL v4.0
8. STL v5.0
9. STL v6.0
10. STL v7.0
11. TDAWP v1.0
12. TDAWP v2.1
13. TDAWP v2.2
14. VIPER v1.0
15. VIPER v2.0

Select Aircraft

Select Aircraft Parameters



Select Weather Profiles

Select Models and Run

But what estimates for the uncertainties are appropriate?

Aircraft parameters
1) Time of overflight
2) Vertical position
3) Lateral position
4) Air speed
5) Weight of aircraft
6) Initial vortex separation distance
7) Pilot adjustments

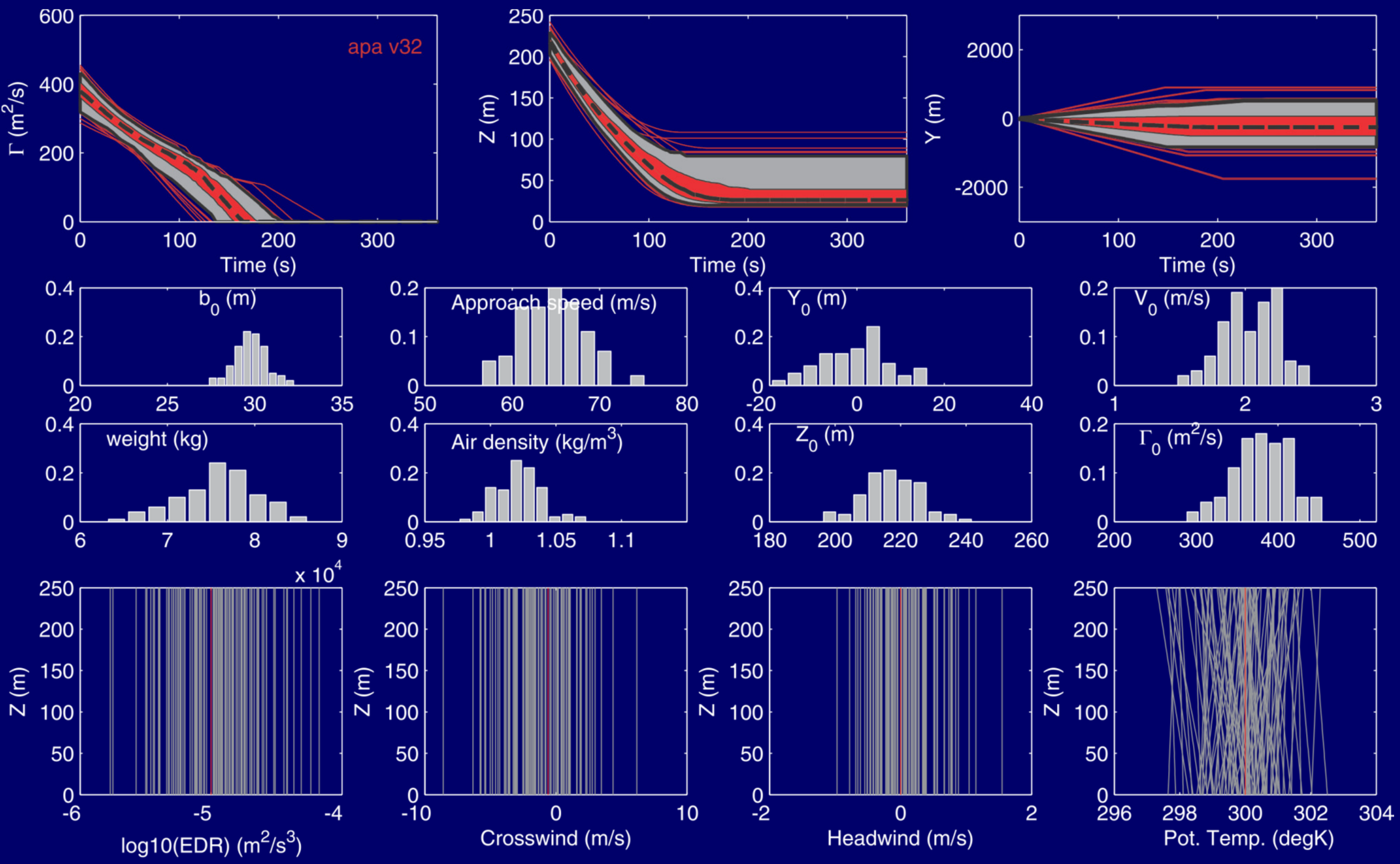
Environmental parameters
1) Air density
2) Ambient turbulence
3) Stratification
4) Crosswind
5) Crosswind shear gradient
6) Headwind

Models
1) Parameterizations
2) Assumptions
3) Simplifications

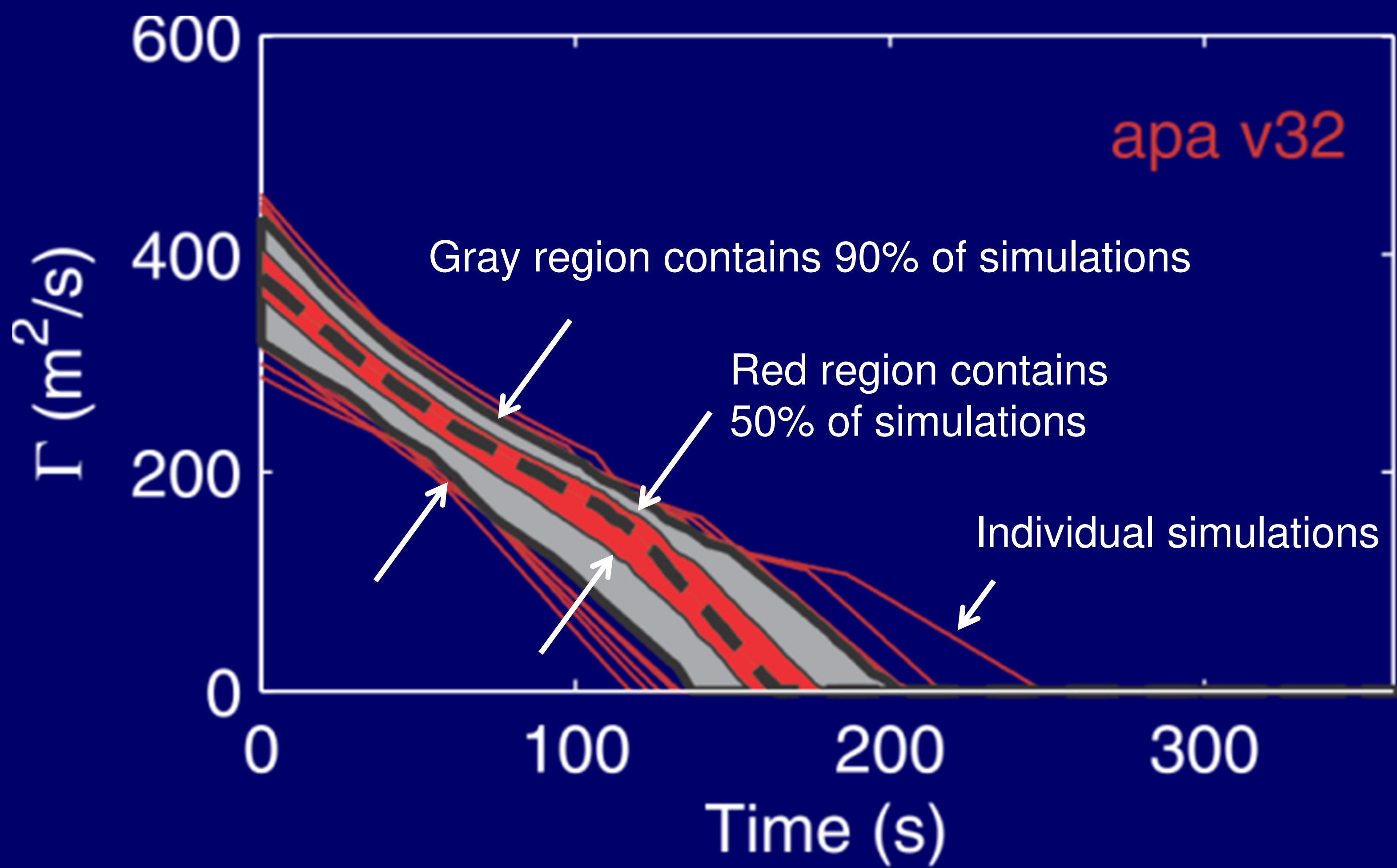
"Example" Estimates of Uncertainties for B752 That is ~2.2 nm From Threshold

	Mean	Standard Deviation
Air density at initial height of vortex	1.02 kg/m^3	0.02
crosswind	-0.6 m/s	2.6
headwind	0 m/s	0.44
EDR	1×10^{-5} m^2/s^3	Factor of 2
Potential temperature	300 °K	1
Potential Temperature Gradient	0 °C/m	0.0025
Aircraft weight	76340 kg	4400
Approach speed	64.8 m/s	3.6
Initial vortex spacing	29.8 m	1
Initial lateral position	0 m	9
Initial vertical position	217 m	9

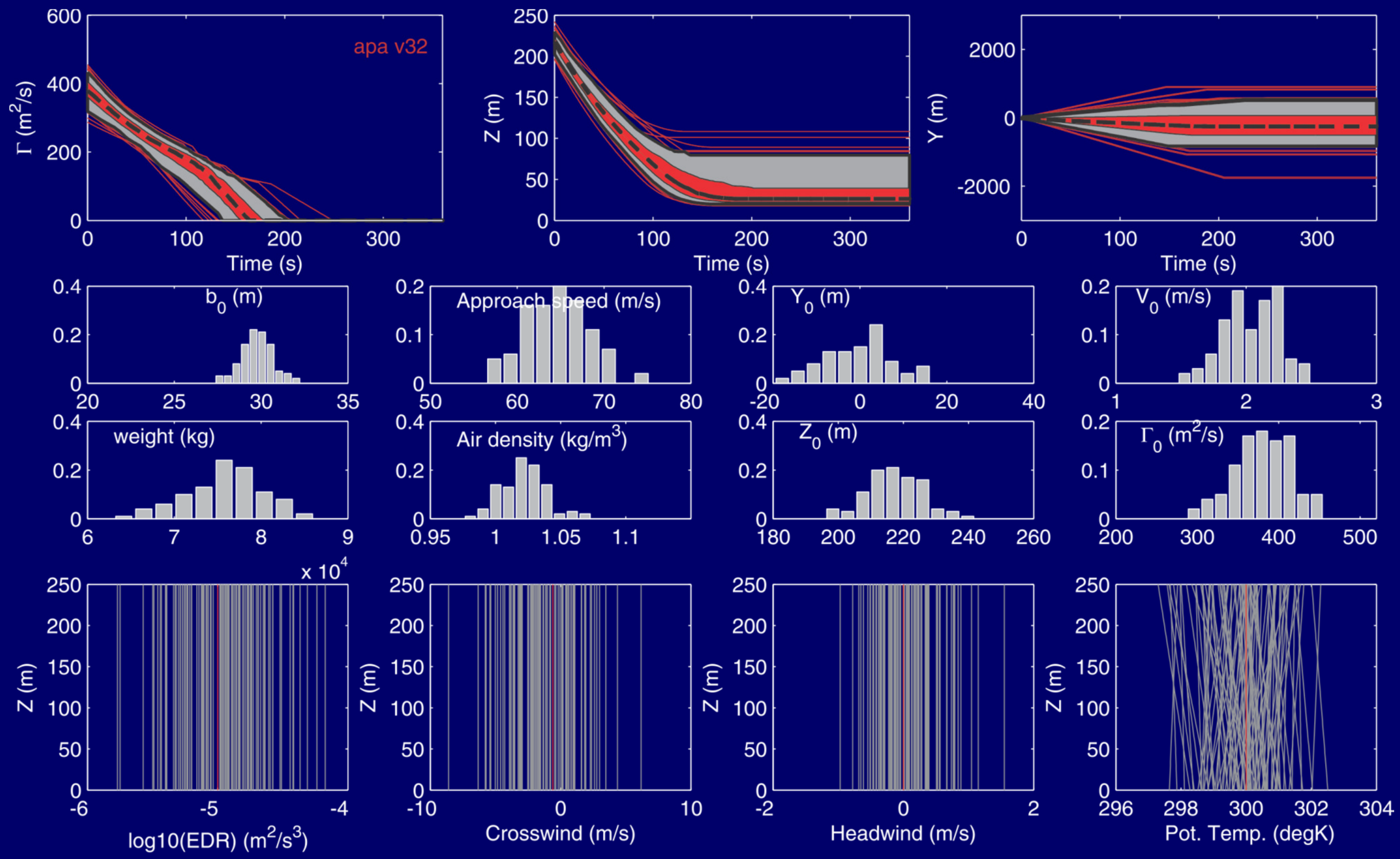
WRAPS Simulation With One Model (APA v3.2)



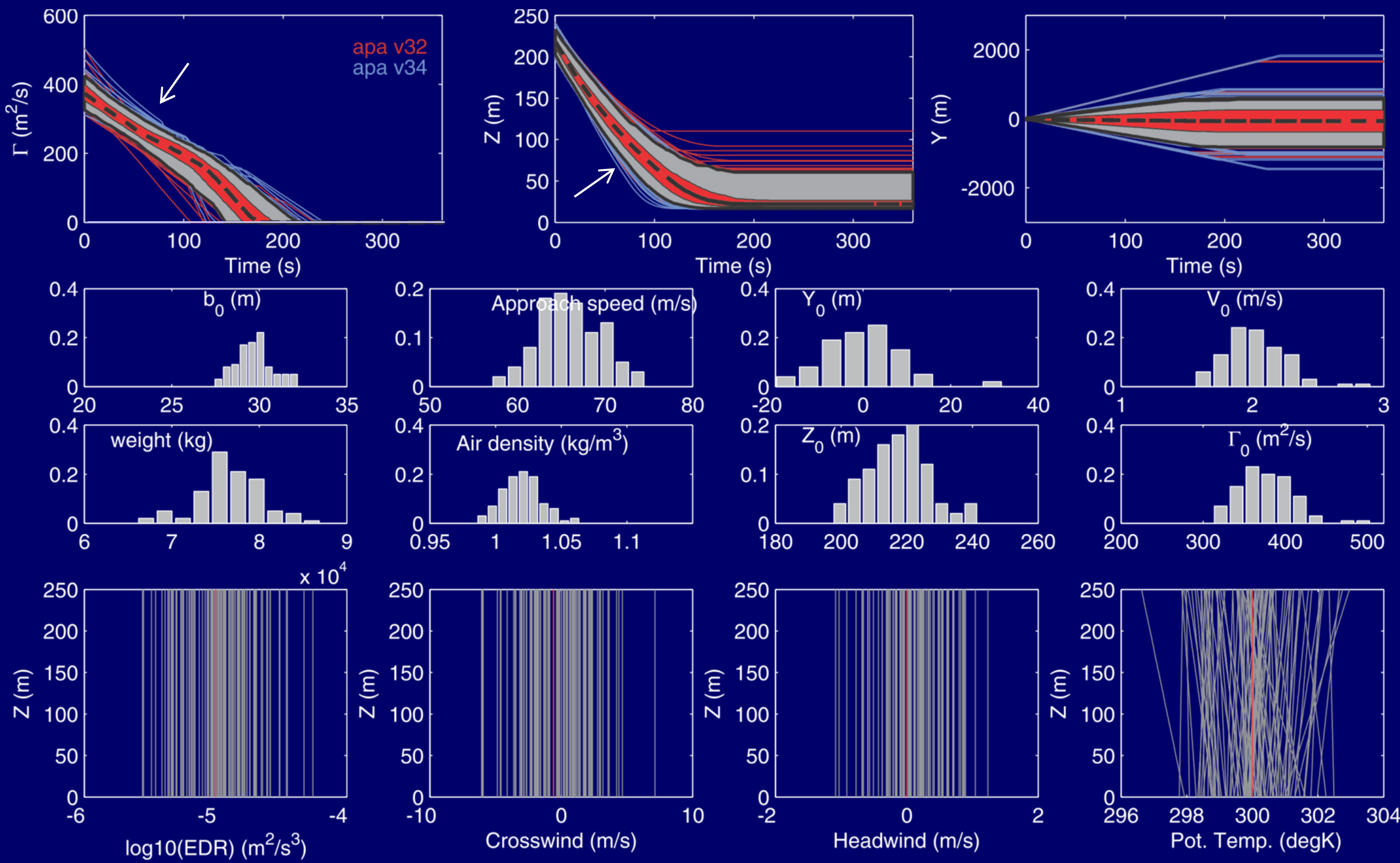
Explanation of Simulation Results With One Model (APA v3.2)



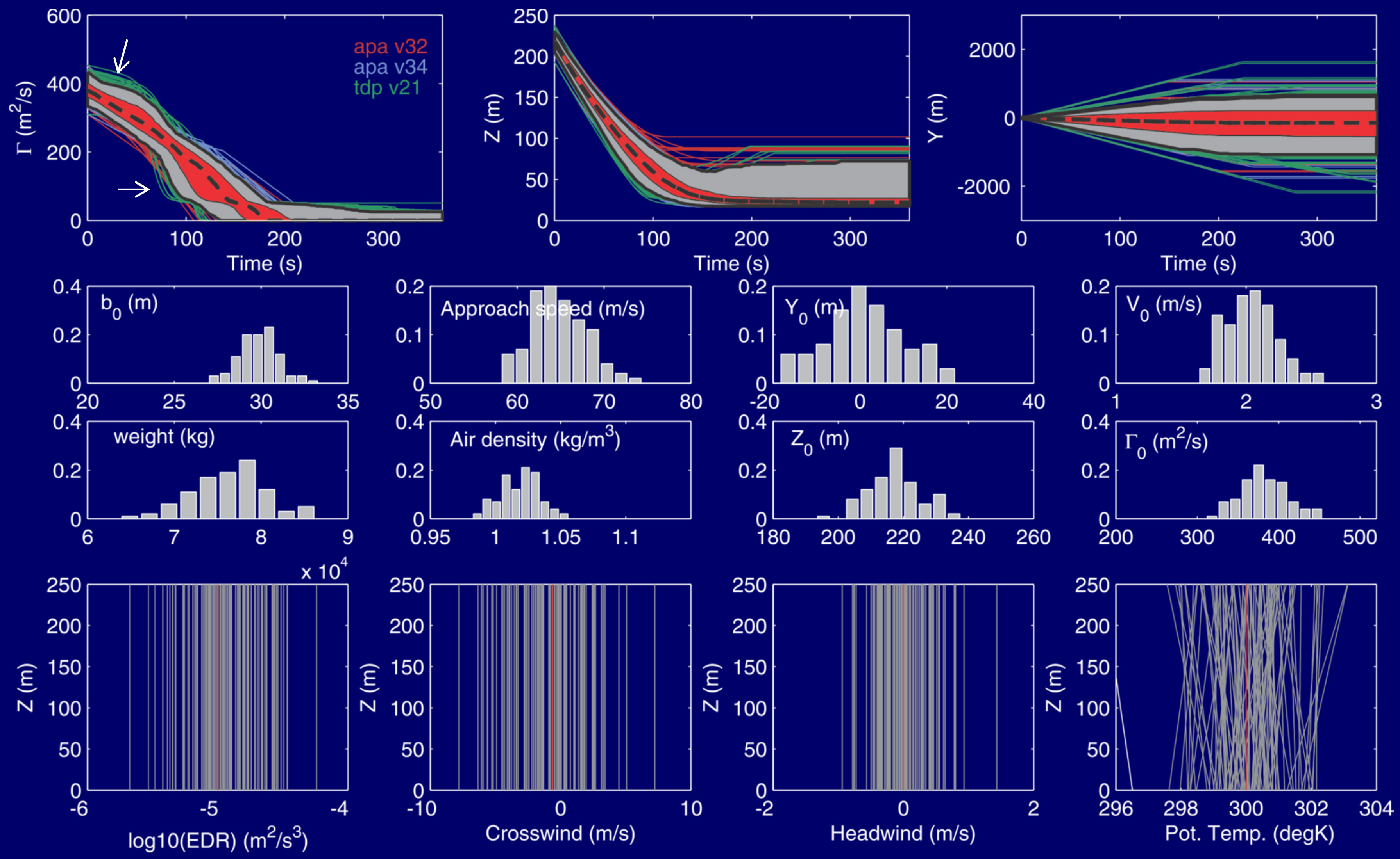
WRAPS Simulation With One Model (APA v3.2)



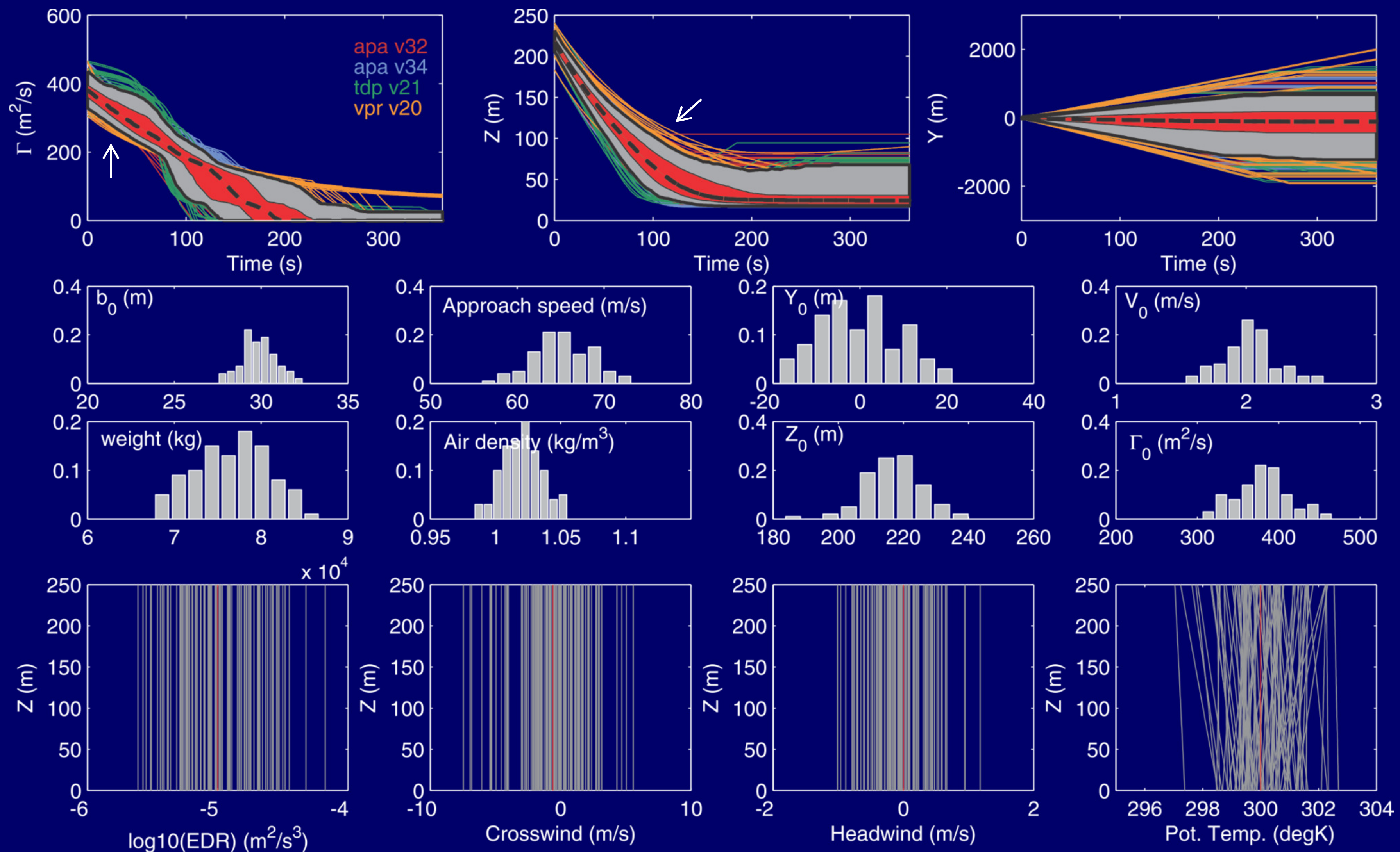
WRAPS Simulation With Two Models (APA v3.2 and APA v3.4)



WRAPS Simulation With Three Models (APA v3.2, APA v3.4, TDP v2.1)



WRAPS Simulation With Four Models (APA v3.2, APA v3.4, TDP v2.1, and VPR v2.0)



Adding Additional Models to Ensemble Tends to Increase Model Spread Slightly and Modifies the Ensemble Mean Only Slightly

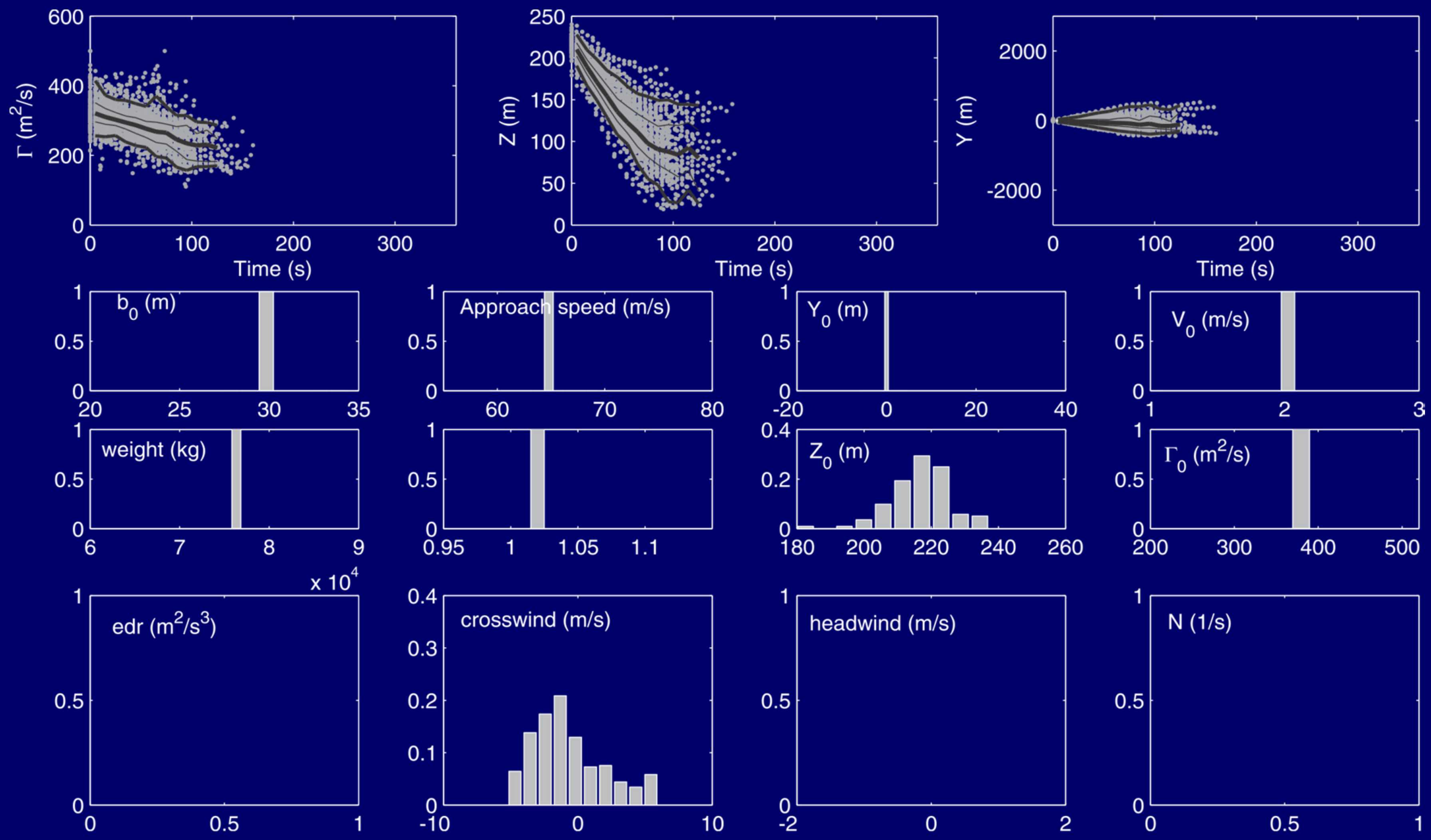
Comparison with data

A comparable data set of LMCT lidar observations of wake vortex circulation intensity and trajectories is 87 B752 landings at Denver airport in 2003 (T_{Last} > 80 seconds)

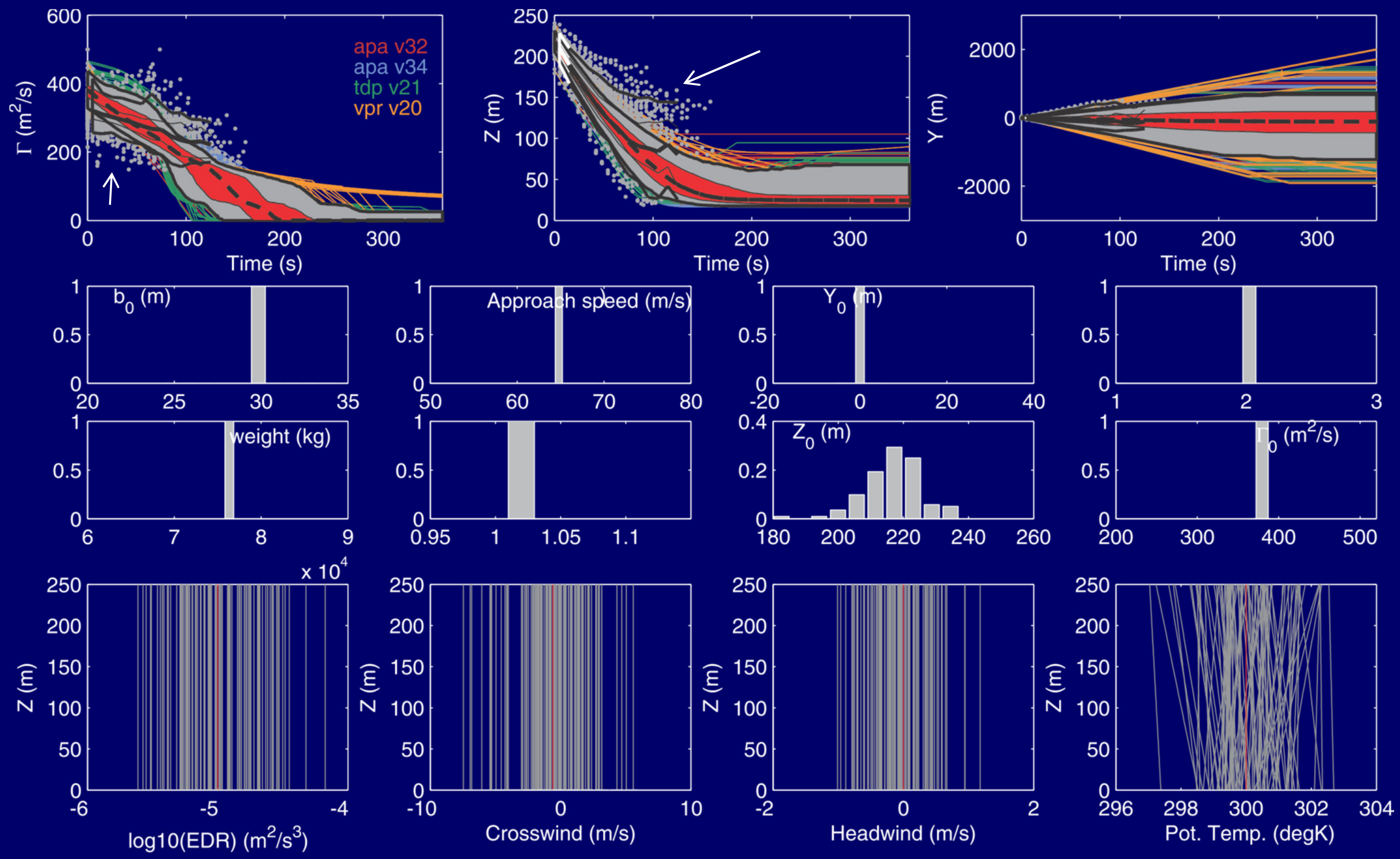
↑

Should correspond to low turbulence conditions

87 landings of a B752 at DEN 2003



Overlay of the Model Predictions and Similar Wake Observations

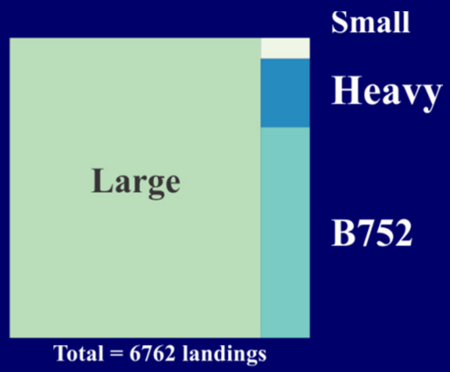


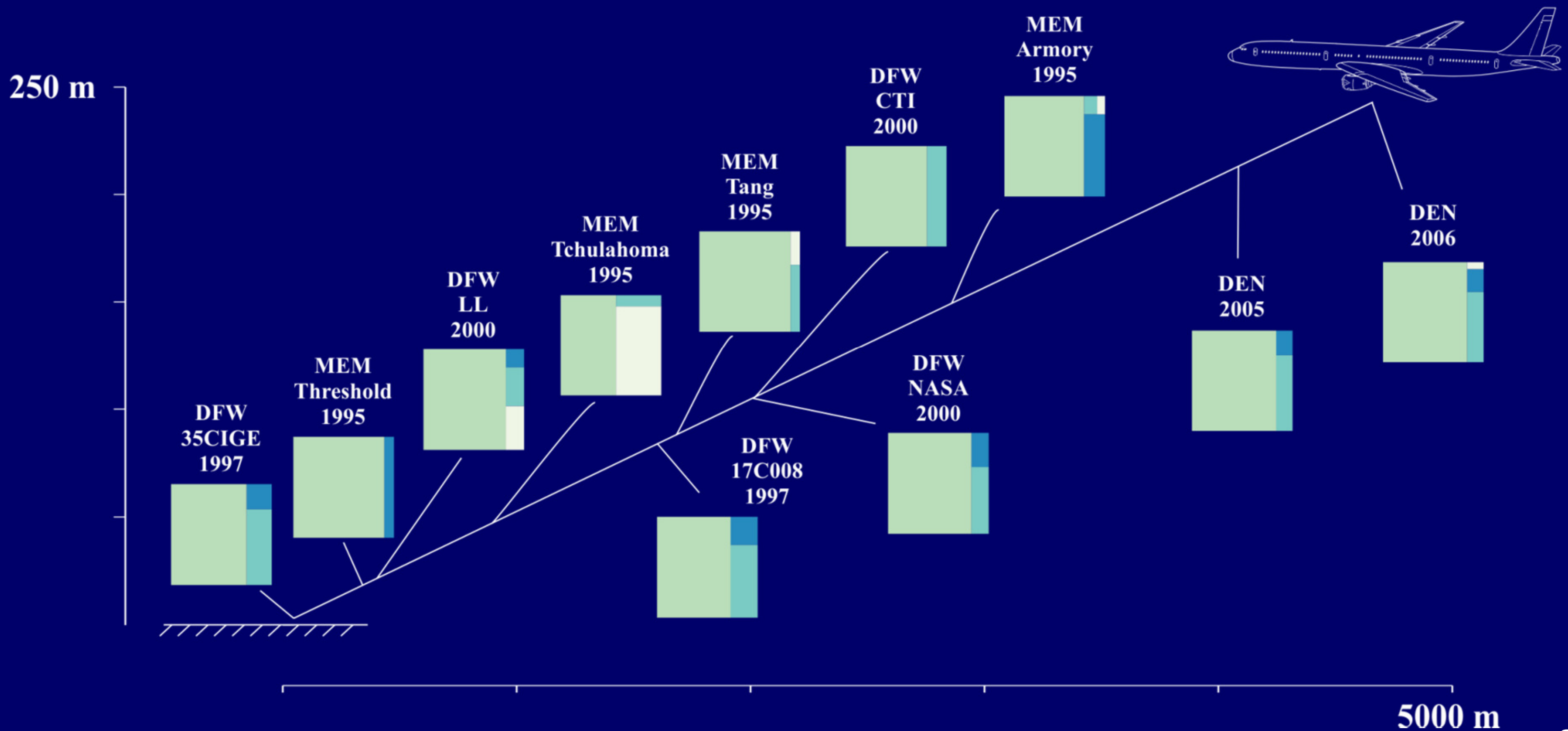
What did we find out?

- » Spread between different deterministic models overlaps when small, plausible uncertainties in aircraft and environmental conditions are used
- » Model reproduces observed vortex behavior and predicts approximately the same mean and spread as the observations

Next Step(s)

- Collect more high quality wake observations, with good weather and aircraft observations





Next Step(s)

- Better estimates of uncertainties (or expected variability) in aircraft and weather inputs

How much do aircraft weights vary? How do the weights vary, is it predictable?

How much variance is there on the aircraft position relative to the glide slope path? How does it vary? Can we use ADS-B to get a better estimate?

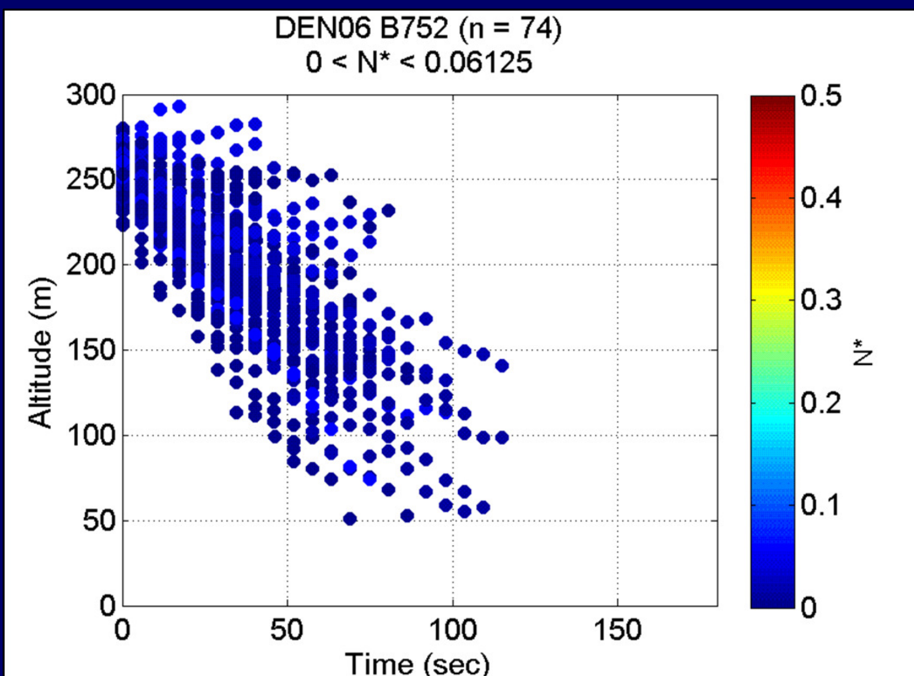
What is the relevant timescale to estimate turbulence for aircraft wakes?

What are the errors associated with using weather observations obtained in different locations then where the wake is observed and modeled, and observations obtained at different times or averaged over the wake lifetime?

What are the errors in weather sensing? How do we estimate this?

Next Step(s)

- Model Improvements
  - Wake observation lifetimes
  - High stratification
  - Low turbulence, weak stable stratification



Observation Lifetime of Wakes, by EDR*

T* of last observation

EDR* (Lidar)	1	2	3	4	5	6	7	8	9	10	n
0.025	100	94	79	74	59	38	38	24	21	3	34
0.075	100	94	79	53	30	11	6	2	2		47
0.125	100	96	70	34	11	3	1				73
0.175	100	75	38	10	5	3					60
0.225	100	74	26	3							35
0.275	100	73	40	13							15
0.325	100	75	13								8
0.375	100	50									2

Pruis and Delisi, 2011. Correlation of the Temporal Variability in the Crosswind and the Observation Lifetime of Vortices Measured with a Pulsed Lidar, AIAA-2011-3199, 3rd AIAA Atmospheric Space Environments Conference, Honolulu, Hawaii, June 27-30.

← Descent of Wakes modified by stratification

Pruis and Delisi, 2011. Assessment of Fast-Time Wake Vortex Prediction Models using Pulsed and Continuous Wave Lidar Observations at Several Different Airports, AIAA-2011-3035, 3rd AIAA Atmospheric Space Environments Conference, Honolulu, Hawaii, June 27-30.

NASA has Funded a New Project

- Lack of data was impetus for a new NASA NRA entitled “Wake Vortex Data Collection for Robust Modeling Validation to Enable Advanced, NextGen, Wake-Conscious, Capacity-Enhancing Concepts”

Overview of New NASA NRA (1 of 2)

- Characterize existing sensors and sensing capabilities
- Establish full set of wake vortex, meteorological, aircraft, and air traffic operational parameters required to be measured and test conditions for several test scenarios
- Develop a ground-based, terminal-area, data collection test program to collect data that can be used to validate existing wake vortex prediction tools

Overview of New NASA NRA (2 of 2)

- Collect meteorological and wake vortex position and strength data
- Conduct a robust validation of wake vortex models. Enhance, as required, existing fast-time wake vortex prediction tools using the new data. This includes both deterministic and probabilistic tools that can:
  - Predict the probability of wake location
  - Predict the probability of wake location *and* strength

Final Questions

- How well do we need to know the weather, and how well can we quantify the uncertainties?
- Can we decrease the probabilistic model uncertainty to a level that is operationally useful? What is that level?
- What is the most critical parameter (or set of parameters) to improve our modeling capabilities? What should the priorities be?