Sensitivity Study of Persistent Contrail Development using Large Eddy Simulation

Alexander D. Naiman and Sanjiva K. Lele
Department of Aeronautics and Astronautics
Mark Z. Jacobson
Department of Civil and Environmental Engineering

Stanford University

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Outline

- Project overview
- Description of simulations
- Sensitivity study results
- Comparison to parameterized contrail dynamics model
- Conclusions and future work

Project Overview

Goal: Improve estimates of the climate impact of aviation through better understanding of physical processes

Detailed climate simulations (*Jacobson, et al. 2011*)	⇦	Simple model of contrail dynamics (*Naiman, et al. 2010*)	⇦	Detailed contrail simulations (*Naiman, et al. 2011*)
Large scale transport, model microphysical properties of subgrid clouds, calculate radiative effect of distributions of contrails, scales of years and hundreds of kilometers		Predict contrail volume and coverage based on parameters, individual contrails, scales of hours and kilometers		Resolve turbulence, model water vapor deposition, individual contrails, scales of seconds and meters

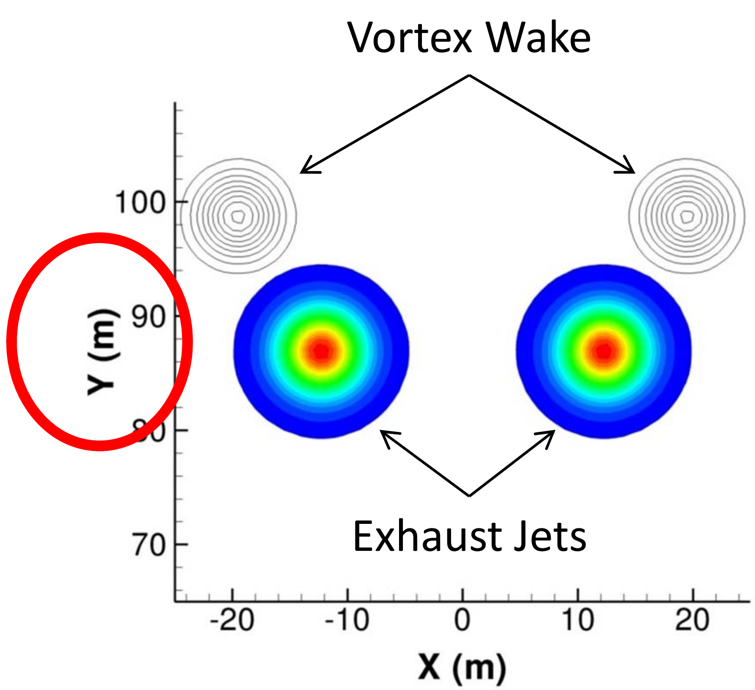
Description of Simulations

- Incompressible 3D LES with Boussinesq approximation (*Mahesh, et al. 2004, Ham, et al. 2007*)
- Lagrangian ice particles with water deposition and sublimation

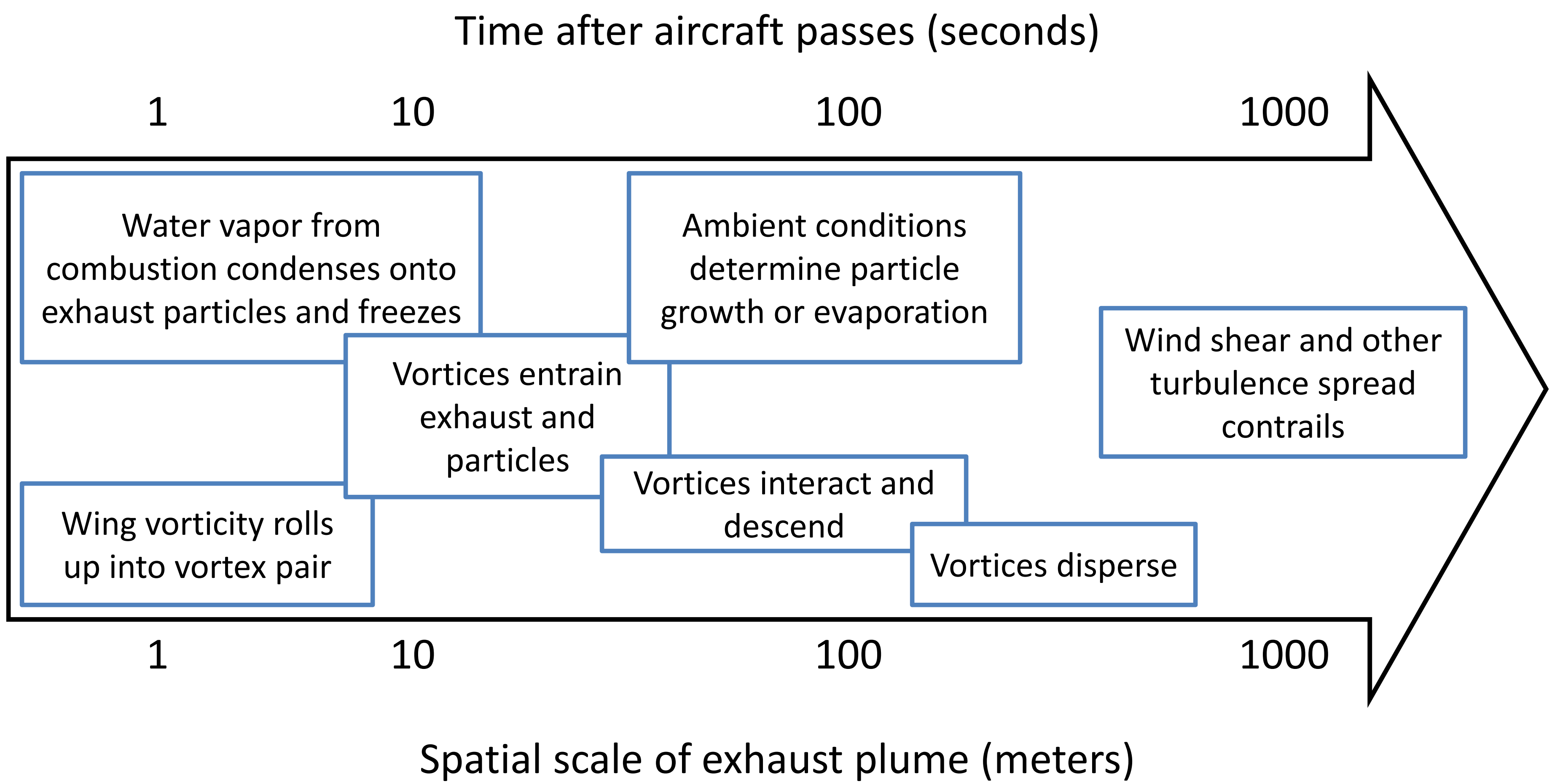
- Twenty minutes simulated from time of emission
- Sensitivity cases vary:
  - Aircraft type (3 cases)
  - Vertical wind shear (2 cases)
  - Ambient relative humidity (2 cases)
- Additional cases vary ice nuclei emission index and atmospheric stability, validation cases include inertial/sedimenting particles and resolution studies (not presented here)

Description of Simulations

- Ambient conditions based on cruising commercial jet
  - 10.5 km altitude
  - Stable temperature gradient
  - Highly supersaturated w.r.t. ice to produce persistent contrails
- 3D Initial Condition uses idealized 2D vortex/jet field plus 3D decaying isotropic turbulence



Description of Simulations



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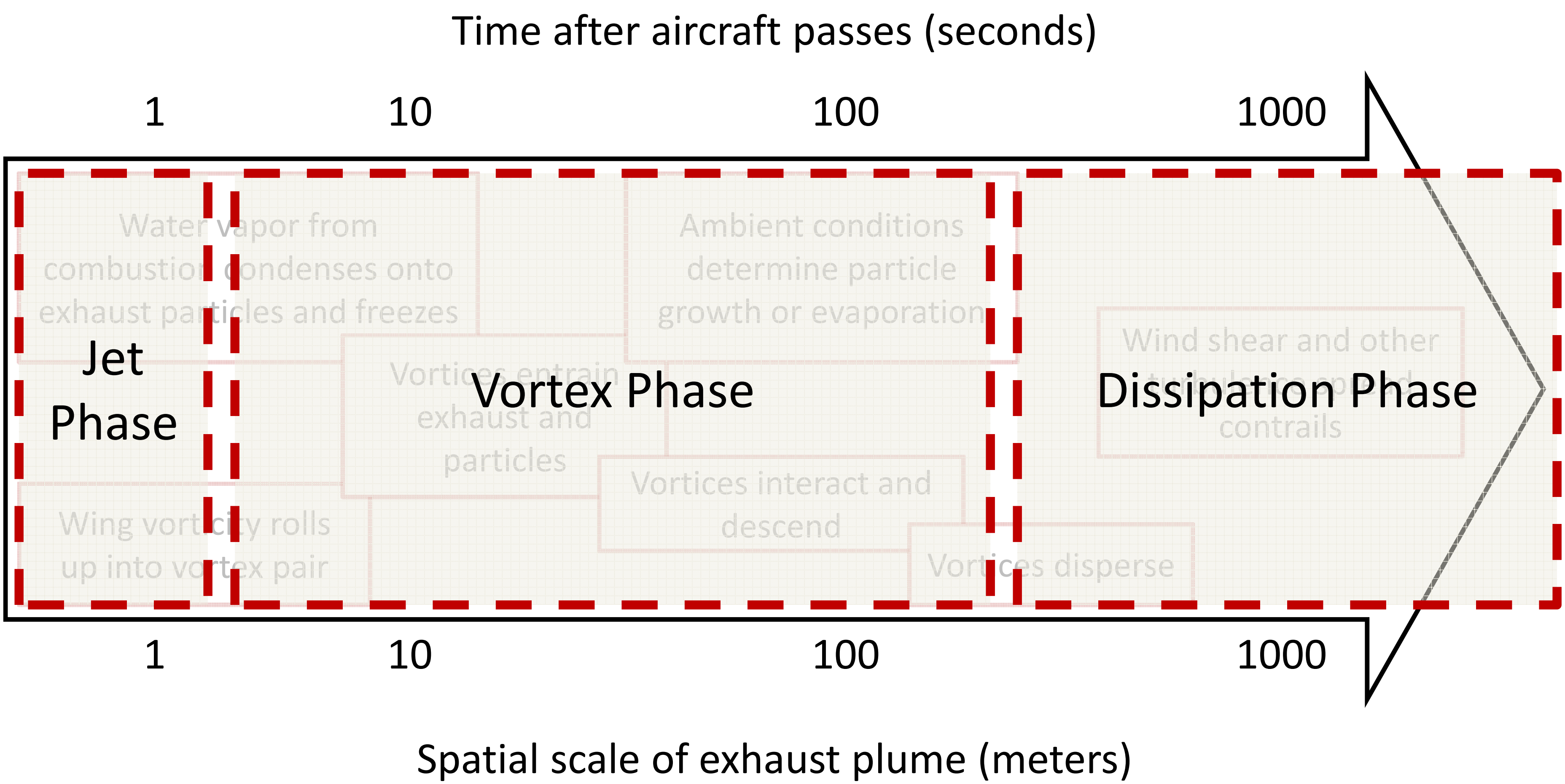

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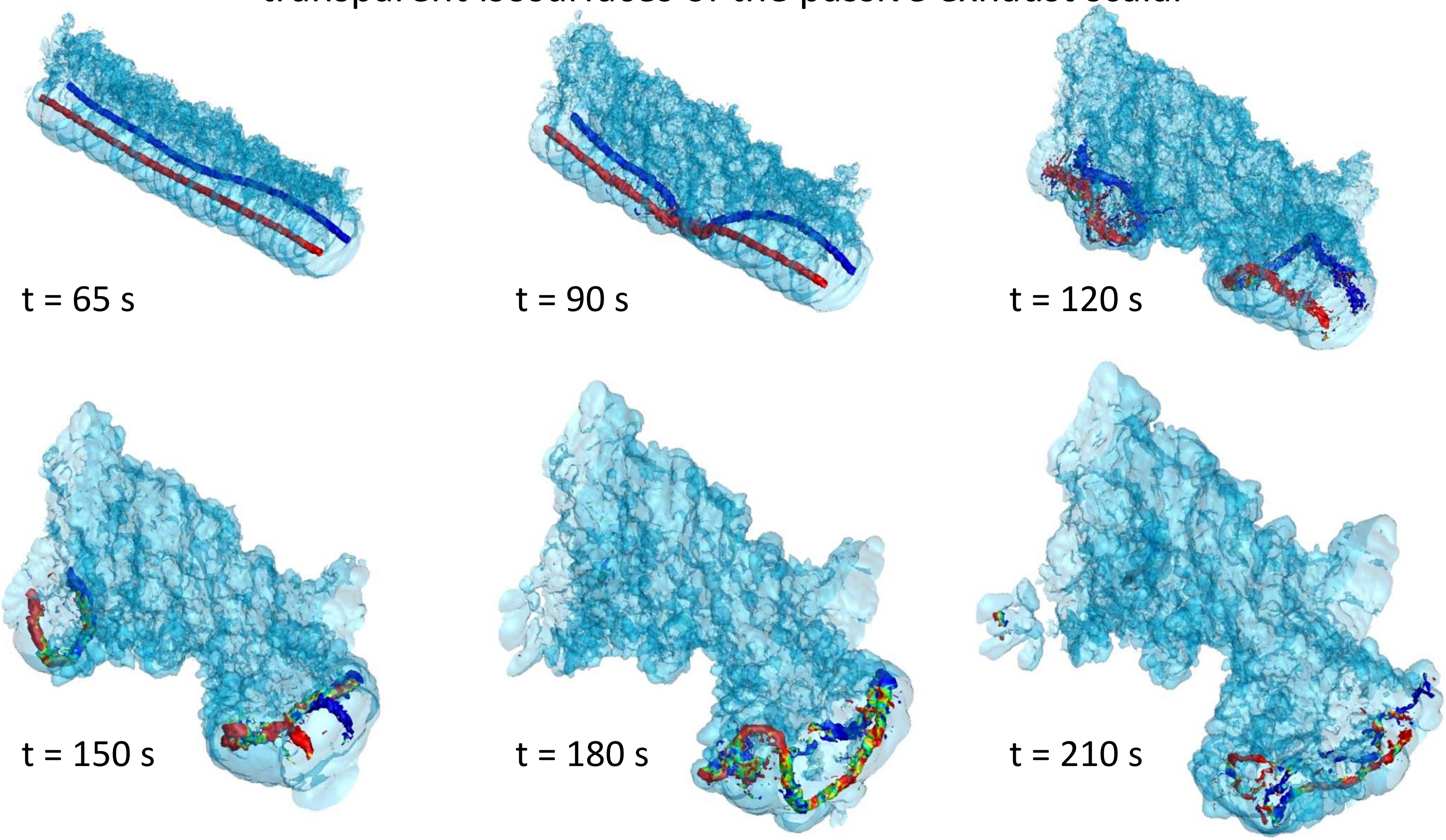
Baseline Case – Crow Instability

Isosurfaces of vorticity magnitude (colored by streamwise vorticity) inside transparent isosurfaces of the passive exhaust scalar



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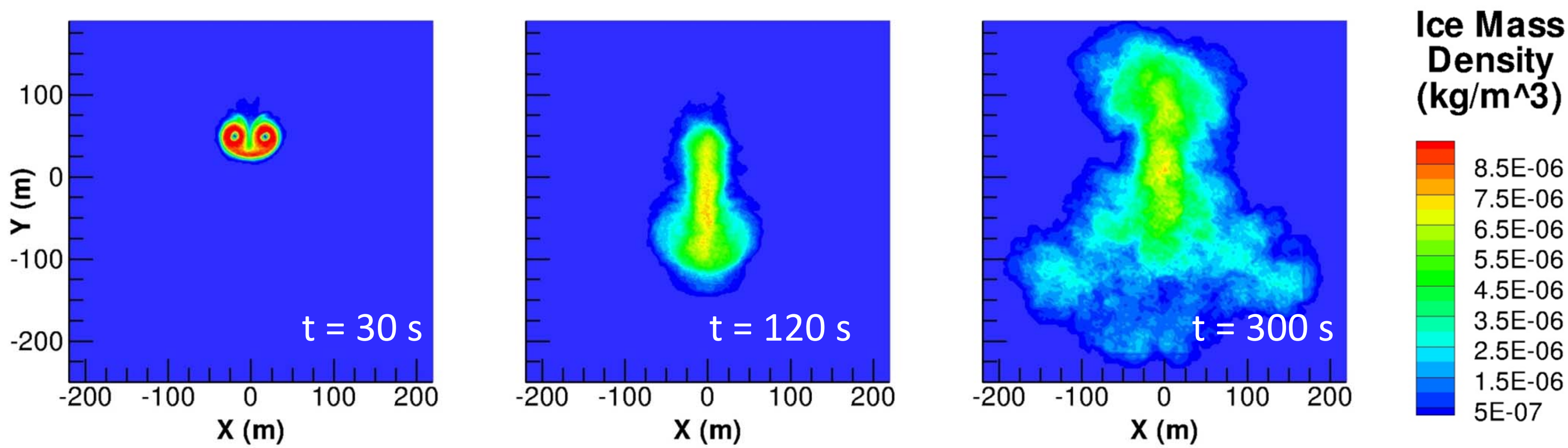
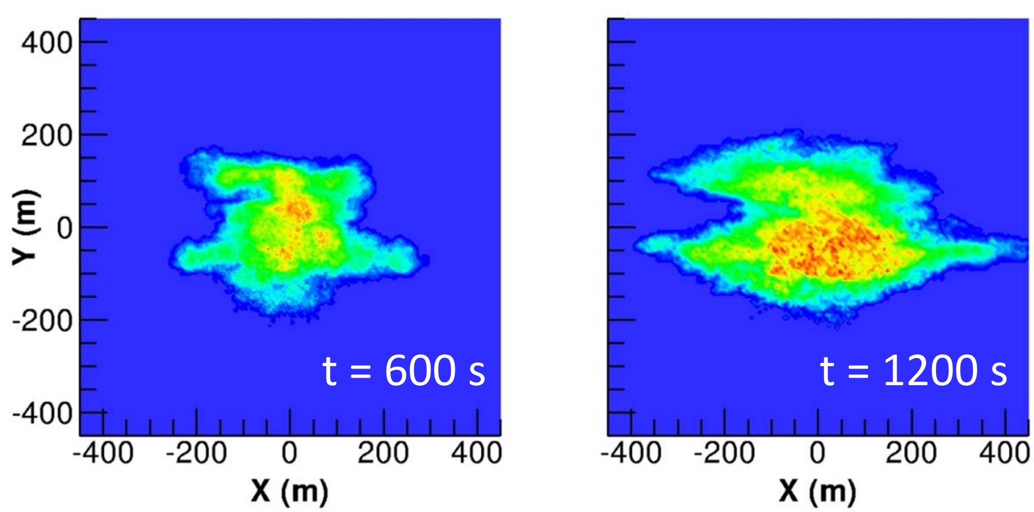
Baseline Case – Ice Density Contours





- Primary wake is spread horizontally after vortex breakdown
- Primary and secondary wake limited in vertical extent by stability

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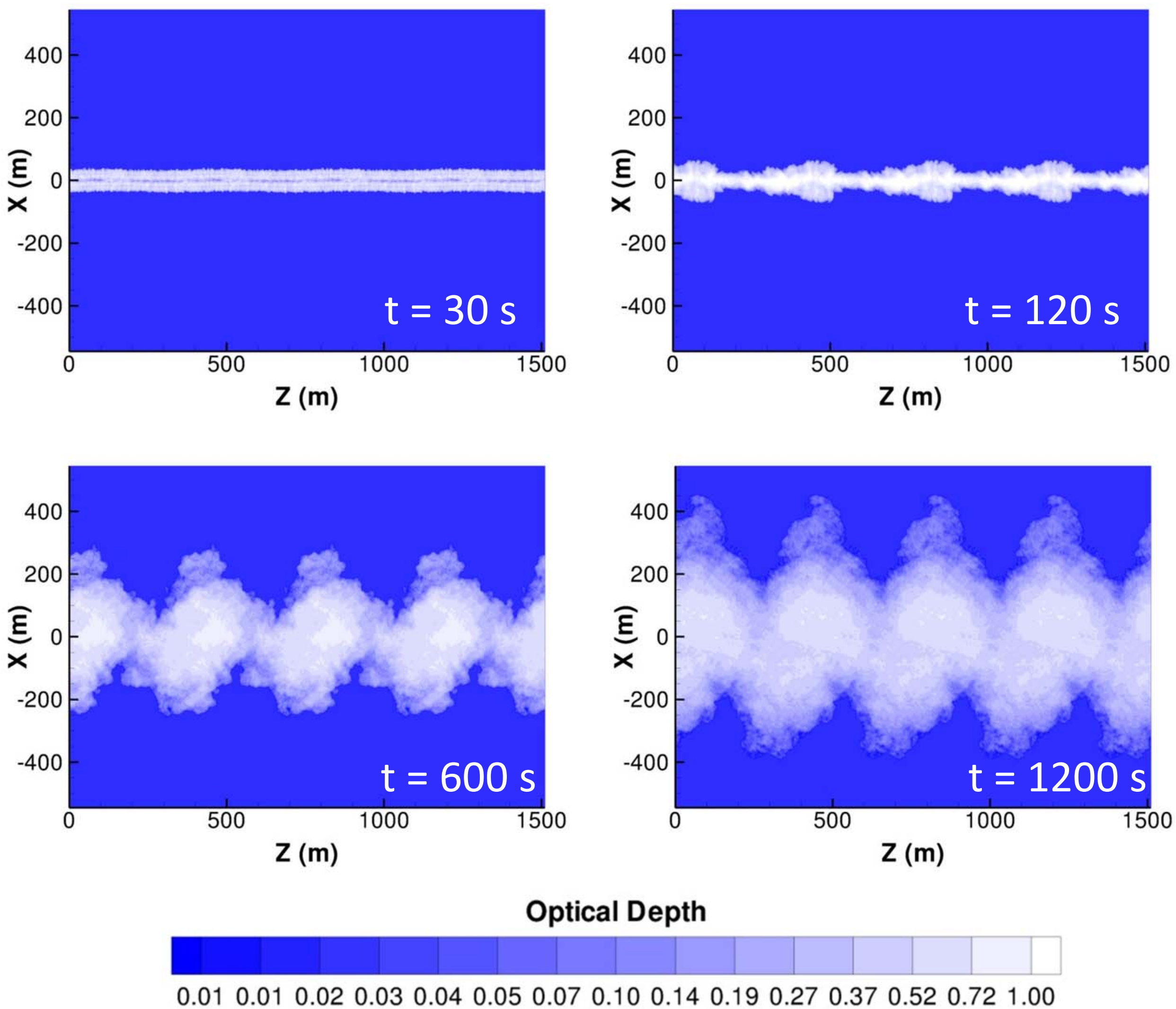
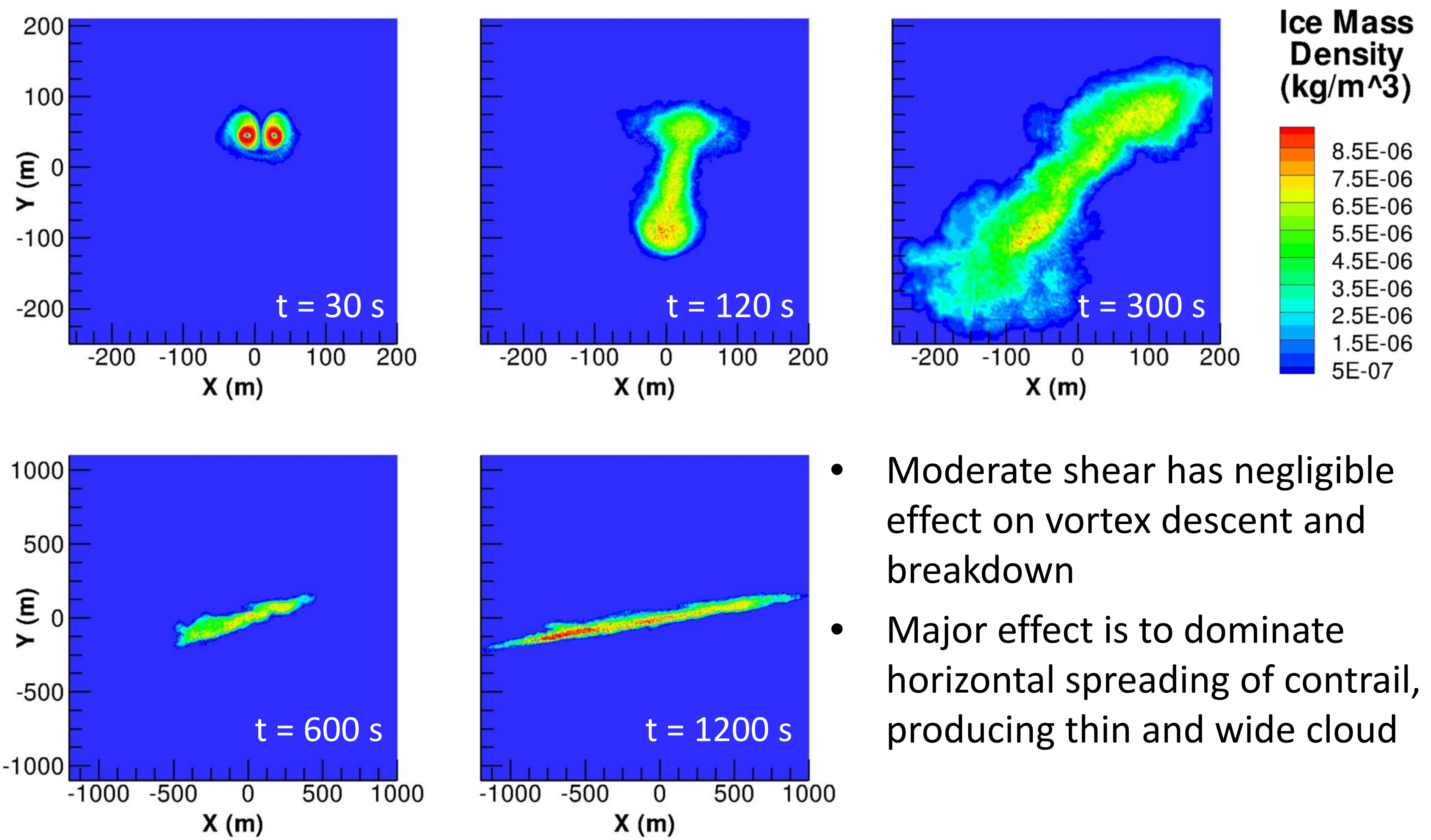
Baseline Case – Optical Properties



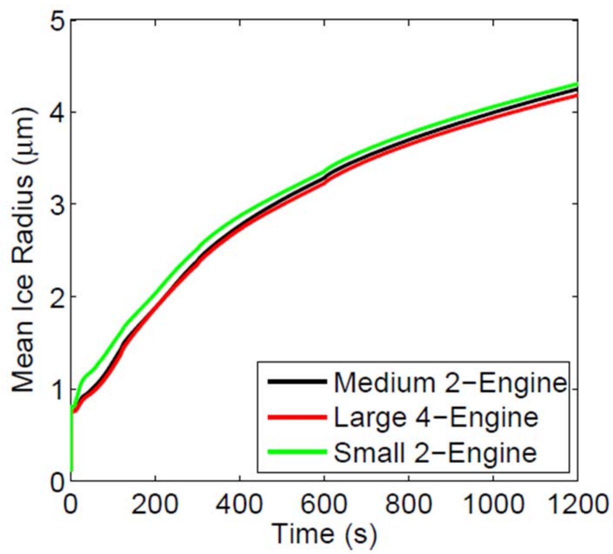
- Periodic domain has been copied in flight-direction to better depict contrail
- During early dispersion phase, spread controlled by vortex breakdown

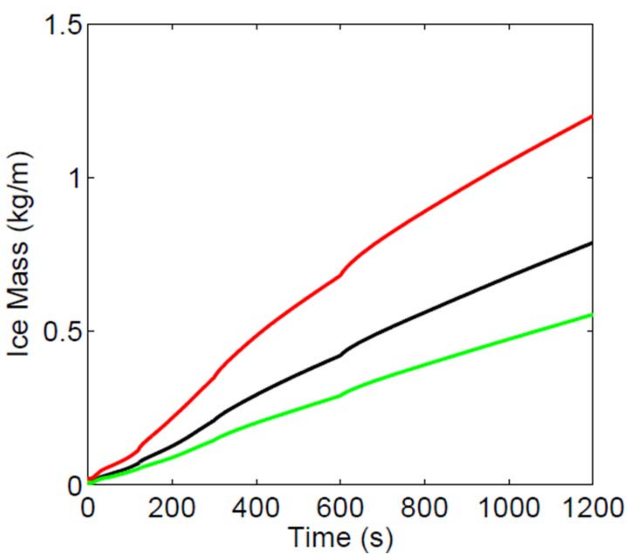
Shear Case – Ice Density Contours



- Moderate shear has negligible effect on vortex descent and breakdown
- Major effect is to dominate horizontal spreading of contrail, producing thin and wide cloud

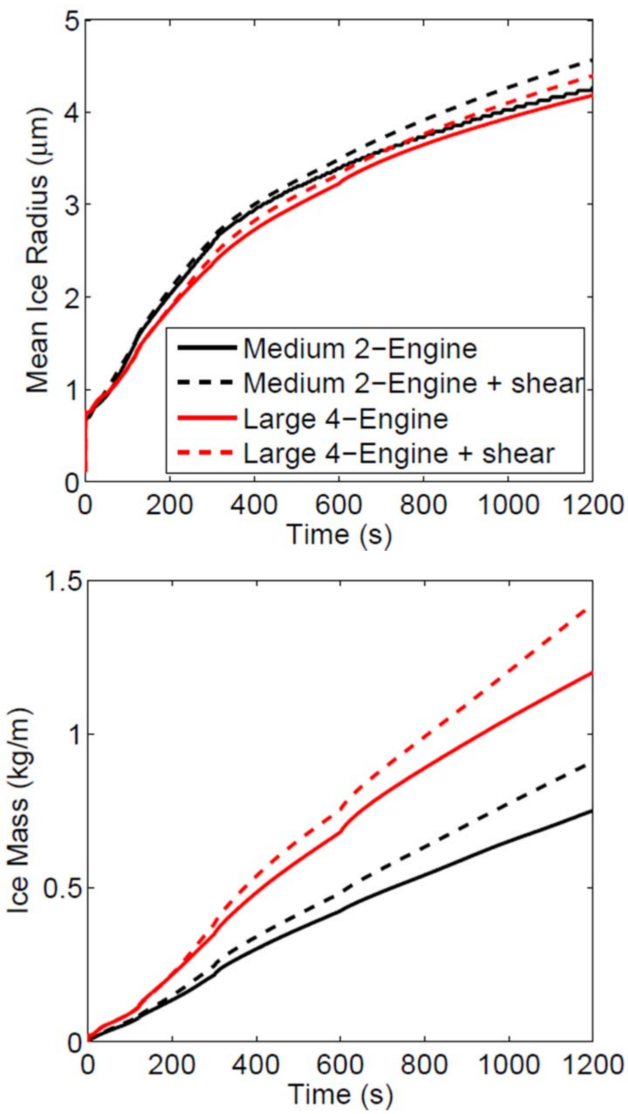
Sensitivity Cases – Ice Statistics





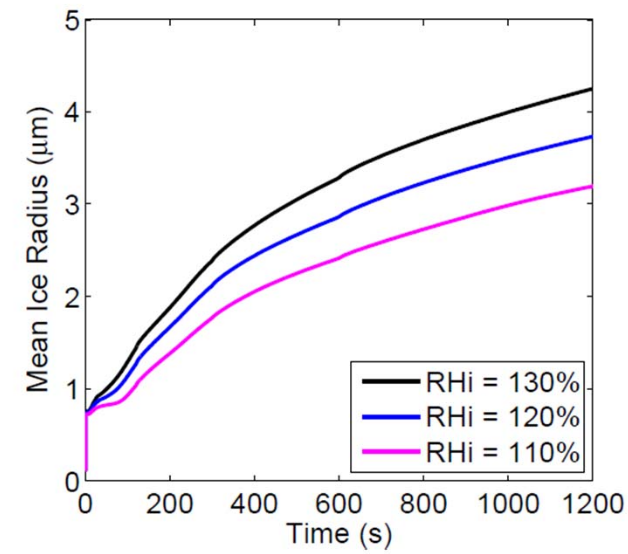
- Aircraft type cases
  - Different initial conditions varied wing span, circulation strength, number of engines, and emissions (scaled by estimated fuel burn)
- Negligible differences in mean size of ice particles produced
- Integrated ice mass increased with aircraft size
  - Larger aircraft emit more ice nuclei and water vapor
  - Larger vortex wakes entrain more ambient water vapor

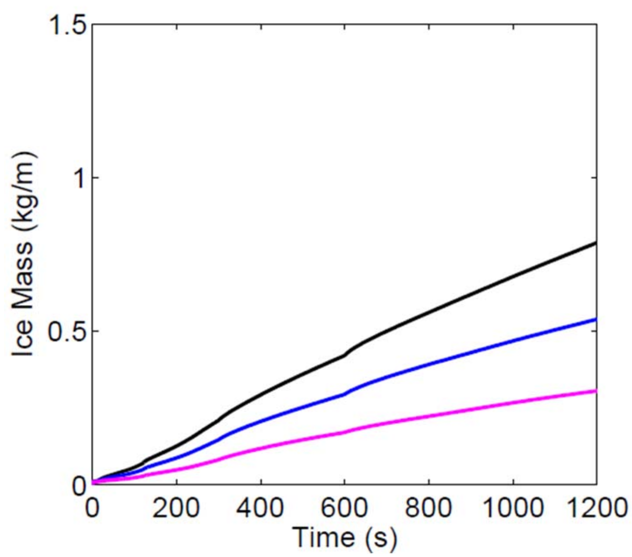
Sensitivity Cases – Ice Statistics



- Vertical shear cases
  - Added moderate wind shear (5 m/s/km) to baseline medium and large aircraft cases
- Slight differences in mean size of ice particles produced
- Integrated ice mass increased with shear
  - Shear promotes entrainment of ambient air in dispersion phase
  - Increased mixing of humid air produces larger particles, more ice mass

Sensitivity Cases – Ice Statistics





- Ambient relative humidity cases
  - Reduced RHi from baseline 130% medium aircraft case
- Higher humidity produced larger ice particles
- Integrated ice mass also increased with humidity
  - Entrainment of ambient water vapor controls ice growth in persistent contrails
  - Higher humidity cases provide more water vapor for deposition to ice

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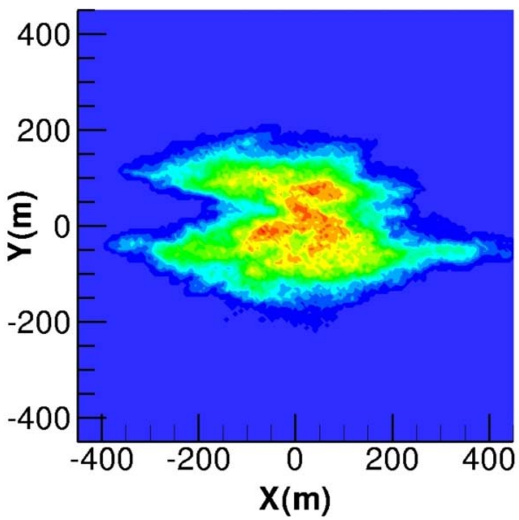
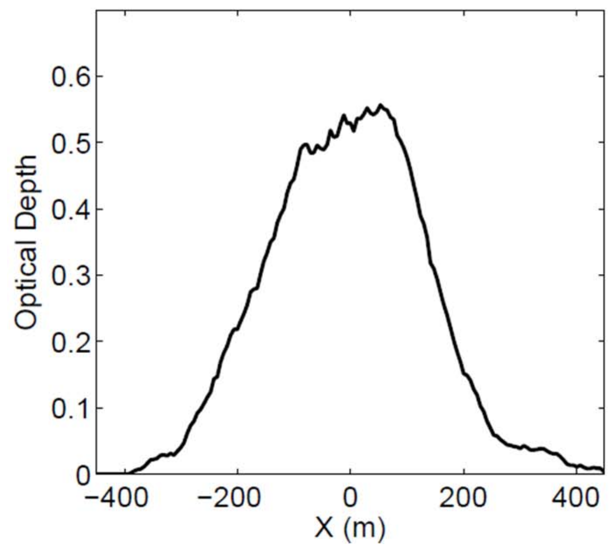
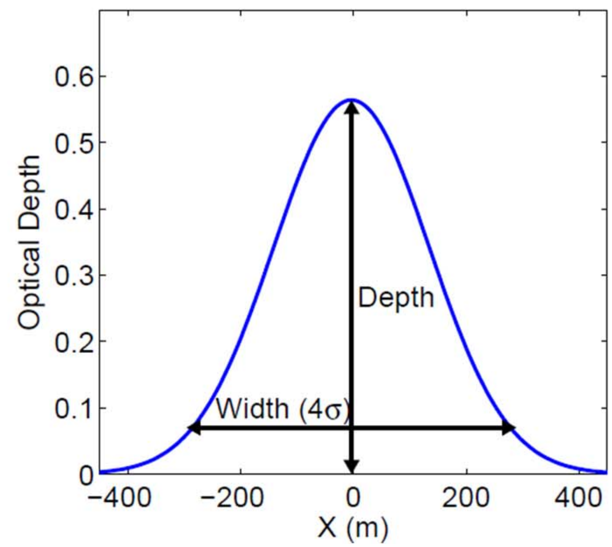
Contrail Optical Calculations



Z-averaged optical extinction



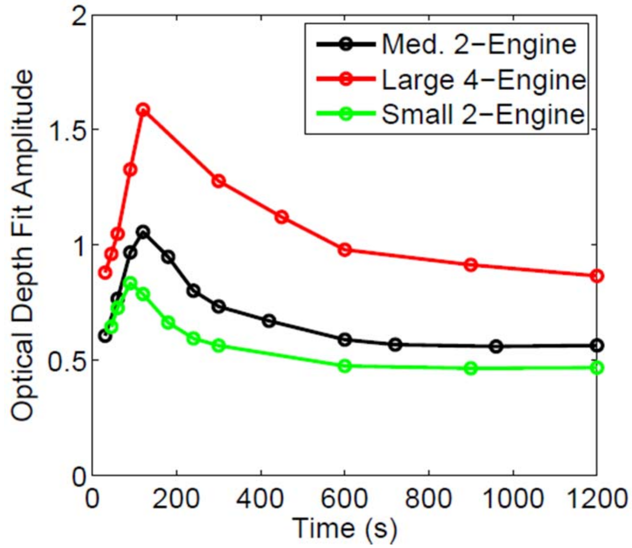
Optical depth

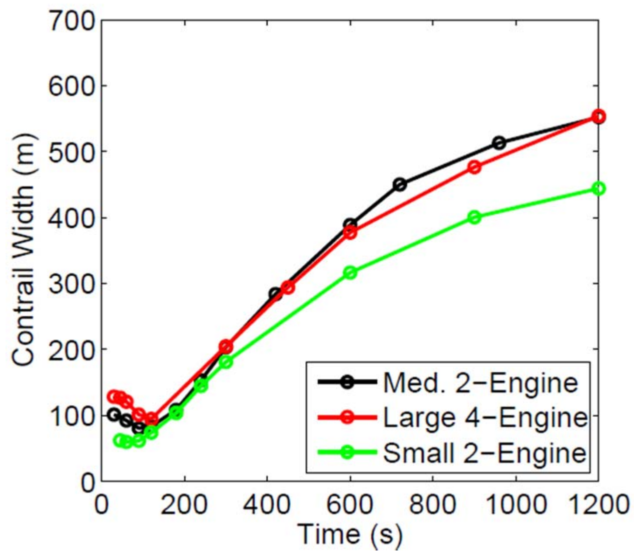


Gaussian fit

Contrail optical depth and width reported from fit of Gaussian to flight-direction averaged optical depth

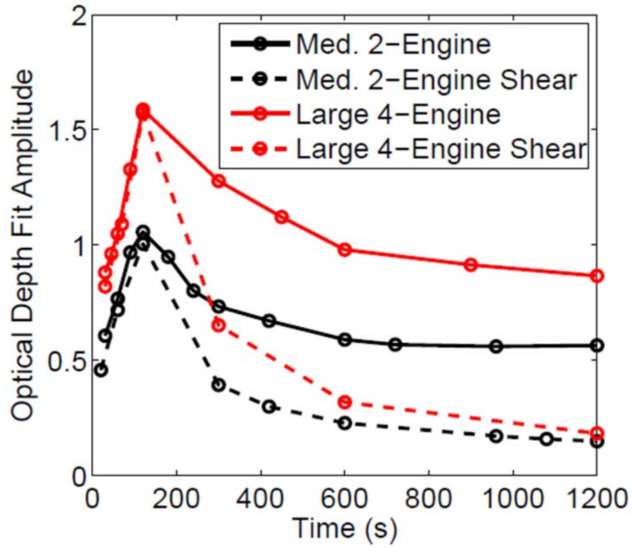
Sensitivity Cases – Optical Properties

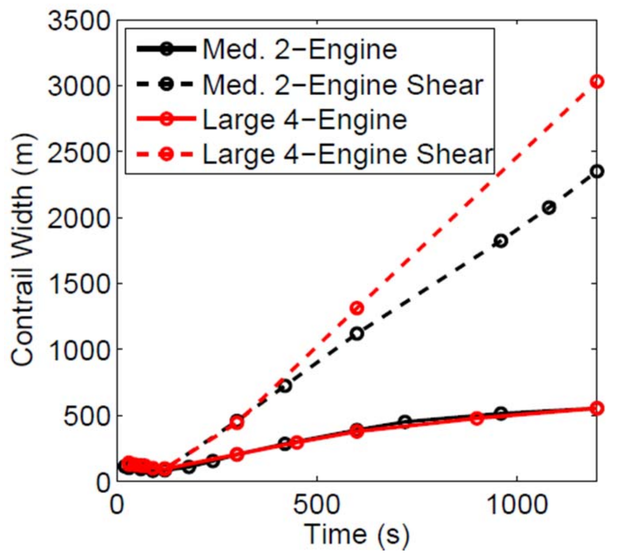




- Aircraft type cases
- Larger aircraft produced optically thicker contrails
  - Higher number density
  - Larger ice surface area
  - Both due to more emitted nuclei
- Larger aircraft initially produced wider contrails
  - Width at early times controlled by wingspan
  - Width at late times controlled by turbulence
  - Long term effect of aircraft size uncertain based on 20-minute results

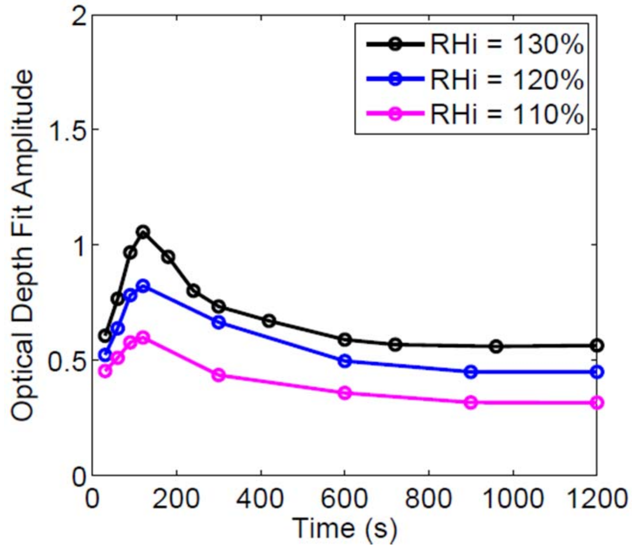
Sensitivity Cases – Optical Properties



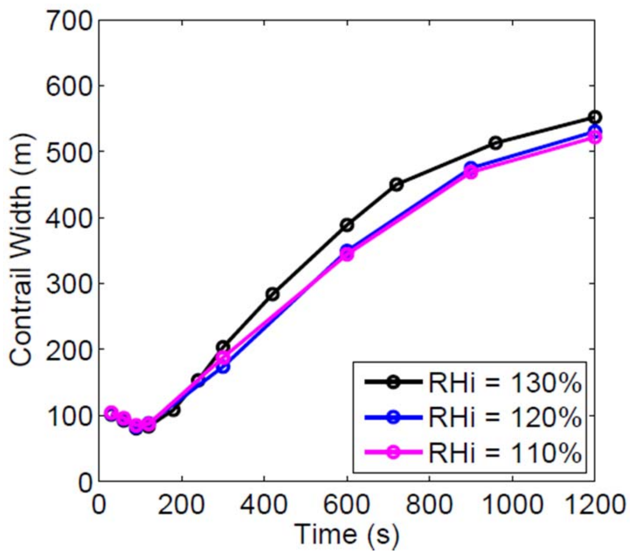


- Vertical shear cases
- Optical depth and contrail width unaffected by shear during vortex phase
- Both properties controlled by shear during dispersion phase
  - Kinematic effect of shear produces thin, wide clouds

Sensitivity Cases – Optical Properties

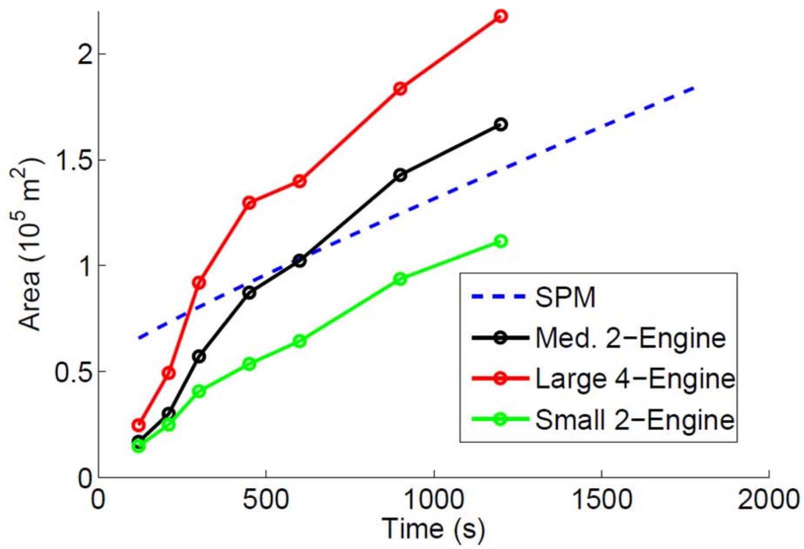


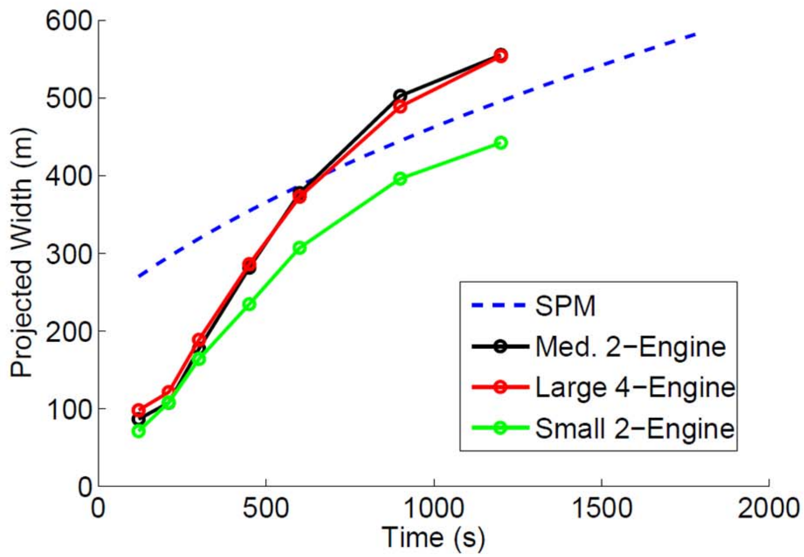
- Ambient relative humidity cases
- Higher humidity produced optically thicker contrails
  - Larger ice surface area due to larger particle sizes



- Negligible effect on contrail width

Parameterized Model – LES Data Comparison

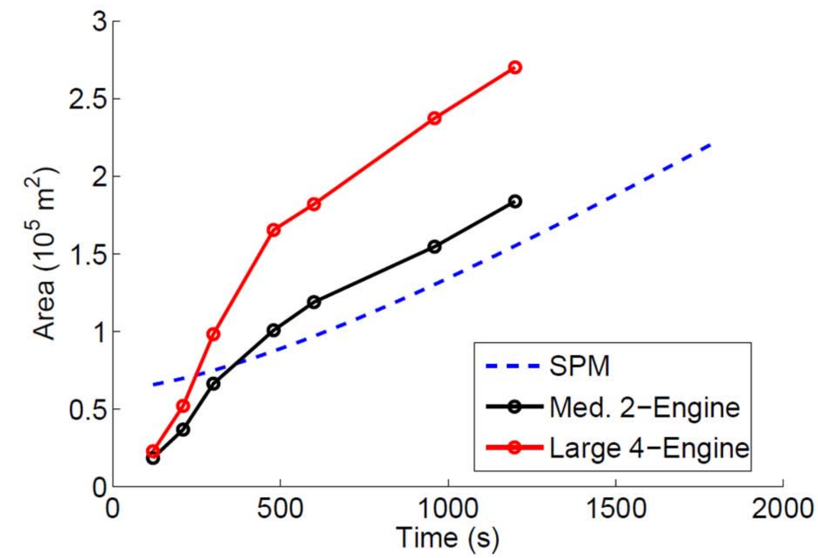


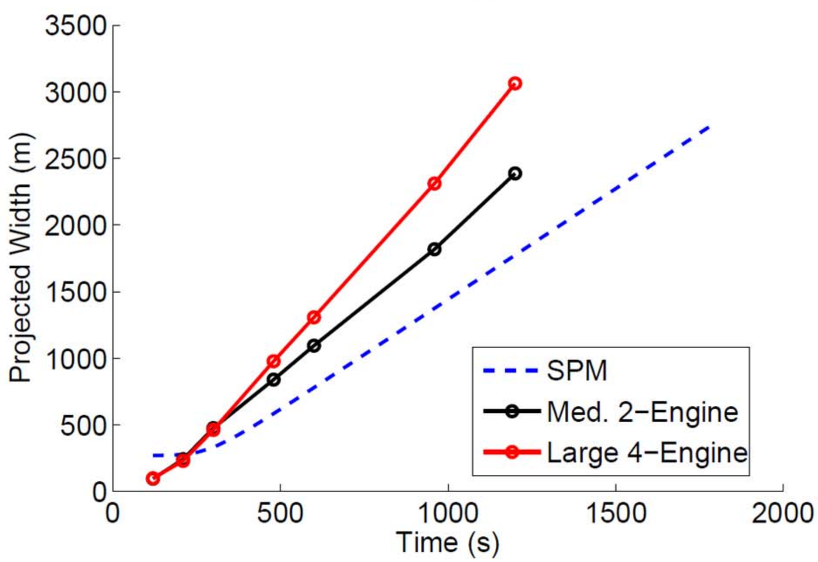


- SPM is the basic parameterized model described in *Naiman, et al. 2010*
- Basic SPM initial condition set to match zero shear, medium aircraft result at t = 10 minutes

- Appears to capture growth rate of area and width, but longer time LES needed for meaningful comparison
- Does not account for variations in initial condition with aircraft type

Parameterized Model – LES Data Comparison





- Basic SPM initial condition set to match zero shear, medium aircraft result at t = 10 minutes
- Similar to comparison with zero shear cases
  - Appears to capture growth rate of area and width, but longer time LES needed for meaningful comparison
  - Does not account for variations in initial condition with aircraft type

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Conclusions

- LES:
  - Optical properties relevant to climate impact strongly sensitive to vertical shear – mostly due to kinematic effect
  - Sensitivity in optical depth to aircraft type and ambient humidity
  - Long term sensitivity in width to aircraft type uncertain
- Parameterized model:
  - Captures growth rates of contrails
  - Lacks sensitivity to aircraft type
  - Longer time LES needed for comparison

Future Work

- LES:
  - Incorporate ice habit parameterization to more realistically model ice crystal growth
  - Implement turbulence forcing for longer time horizon simulations (2-3 hours)
- Improve SPM for global climate modeling
  - Initial condition can be varied with aircraft type based on vortex wake descent parameters
  - Wake descent speed = $\Gamma / (2 \pi b)$
  - Descent time characterized by vortex system lifetime based on turbulence intensity (*Crow and Bate, 1976*)

Acknowledgements

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References

Crow, S.C. and E.R. Bate, Jr. (1976), Lifespan of Trailing Vortices in a Turbulent Atmosphere, *J. of Aircraft*, 13, 476-482.

Ham, F., K. Mattsson, G. Iaccarino, and P. Moin (2007), Towards Time-Stable and Accurate LES on Unstructured Grids, *Complex effects in large eddy simulation*, pp. 235-249, Springer.

Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, and S.K. Lele (2010), The effects of aircraft on climate and pollution. Part I: Numerical methods for treating the subgrid evolution of discrete size- and composition-resolved contrails from all commercial flights worldwide, *J. Comp. Phys.*, (in review).

Naiman, A.D., S.K. Lele, M.Z. Jacobson. (2011), Large Eddy Simulations of Contrail Development: Sensitivity to Initial and Ambient Conditions over Twenty Minutes, *J. Geophys. Res. – Atmos.*, (in review).

Naiman, A. D., S.K. Lele, J.T. Wilkerson, and M.Z. Jacobson. (2010), Parameterization of subgrid plume dilution for use in large-scale atmospheric simulations, *Atmos. Chem. Phys.*, 10, 2551-2560.

Mahesh, K., G. Constantinescu, and P. Moin (2004), A numerical method for large-eddy simulation in complex geometries, *J. Comp. Phys.*, v. 197, pp. 215-240.

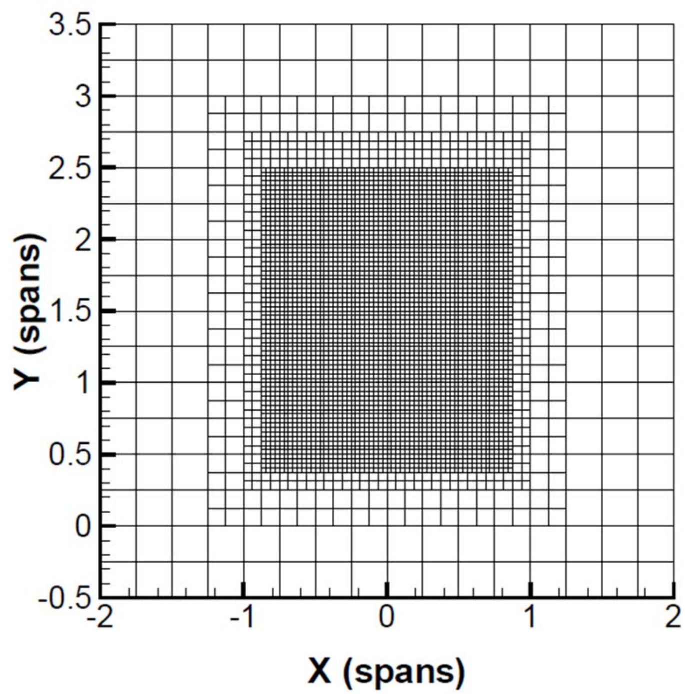
Additional Slides

Case Summary

Sensitivity	Initial Condition	Wind Shear	RHi	EI_{ice}	N_{bv}
A/C Type	Medium 2-Engine	0	130%	10^{15}	0.01 s^{-1}
A/C Type	Large 4-Engine	0	130%	10^{15}	0.01 s^{-1}
A/C Type	Small 2-Engine	0	130%	10^{15}	0.01 s^{-1}
Shear	Medium 2-Engine	0.005 s^{-1}	130%	10^{15}	0.01 s^{-1}
Shear	Large 4-Engine	0.005 s^{-1}	130%	10^{15}	0.01 s^{-1}
RHi	Medium 2-Engine	0	120%	10^{15}	0.01 s^{-1}
RHi	Medium 2-Engine	0	110%	10^{15}	0.01 s^{-1}
EI_{ice}	Medium 2-Engine	0	130%	10^{14}	0.01 s^{-1}
EI_{ice}	Medium 2-Engine	0	110%	10^{14}	0.01 s^{-1}
Stability	Medium 2-Engine	0	130%	10^{15}	0
Stability	Medium 2-Engine	0	130%	10^{15}	0.015 s^{-1}

Grid Example

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	
Simulation Time	0-30	30-60	60-120	120-300	300-600	600-1200	s
Domain Size	8x8x8	8x8x8	8x8x8	16x16x8	24x24x8	32x32x8	b^3
Central Resolution	1/128	1/64	1/64	1/32	1/24	1/16	b
Number of Nodes	$34x10^6$	$18x10^6$	$33x10^6$	$20x10^6$	$17x10^6$	$14x10^6$	



Contrails over Stanford, CA, 3 October 2009