Applied Research Laboratory
Computational Mechanics Div.

PSU Applied Research Laboratory Assimilation Projects

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Presented at: NOAA Center for Satellite Applications and Research

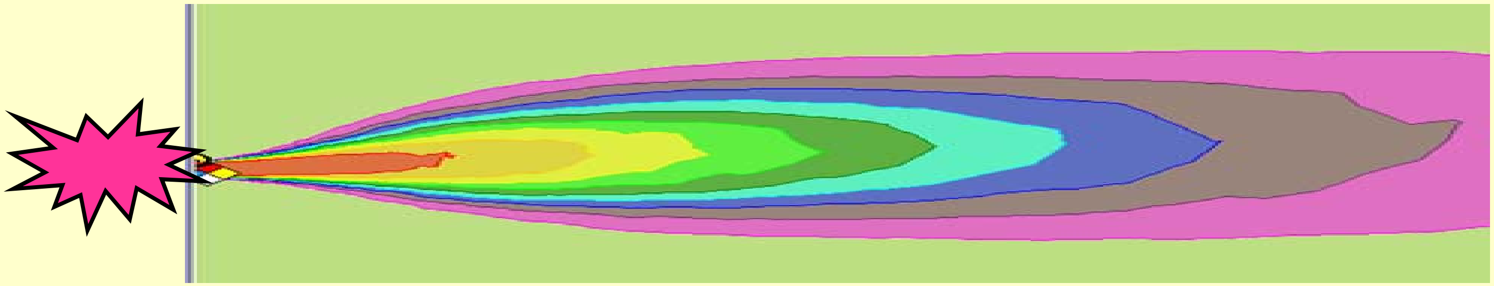
April 15, 2009

Outline

1. Assimilation for contaminant transport
   a. Meandering puff
   b. Technique comparison for a Shallow Water Model
2. Source term estimation
3. Modeling contaminant transport
4. Assimilation for downscaling
5. Modeling volcano emissions
6. Smoke Plume Visualization

DTRA Motivation: CBRN Defense

Chemical, biological, radiological, or nuclear (CBRN) release



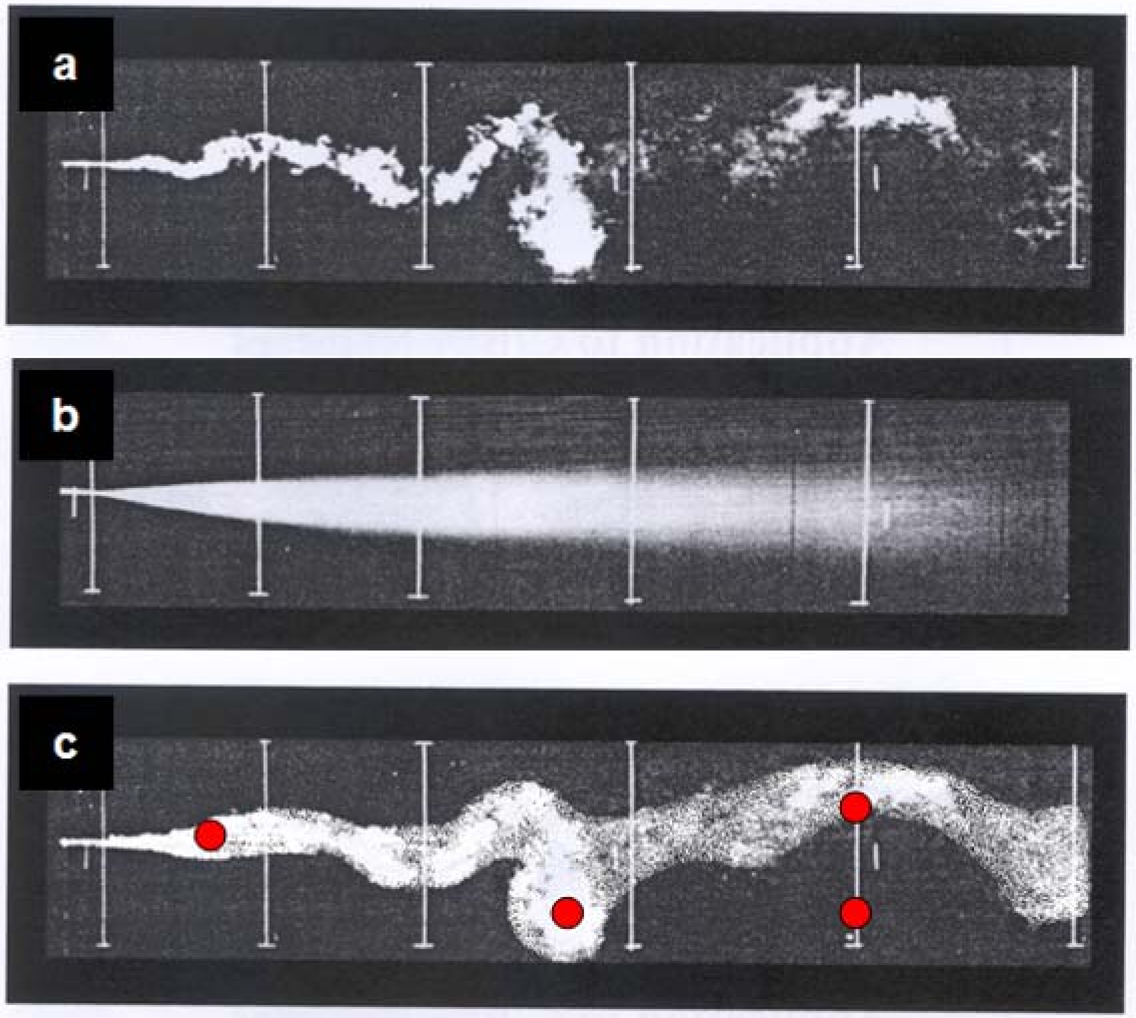
Predict transport and Dispersion
Plan Appropriate Response

Goal: Minimize effects on Humans, Infrastructure, and Equipment

PSU ARL projects funded by DTRA:

- Applied meteorology – estimate model uncertainty
- Meteorology for Dispersion – construct best methods
- Sensor Data Fusion – assimilate data into models
- Estimate unknown source terms via assimilation

1. Assimilation for Dispersion

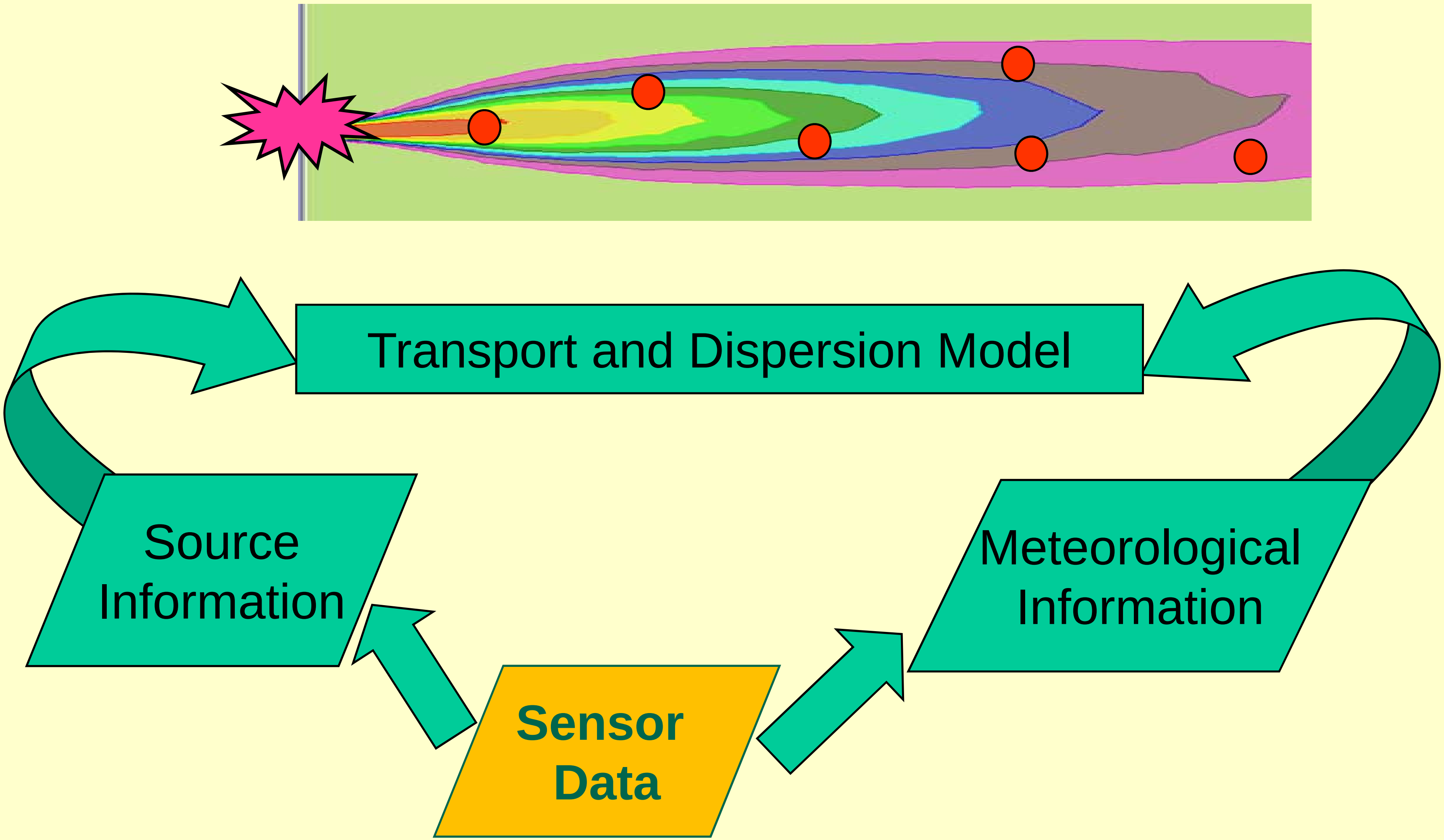


Instantaneous Realization

Ensemble Average

Data Assimilation

Sensor Data Fusion / Data Assimilation



Assimilation Theory

Dynamical Prediction System: $$\frac{\partial \mathbf{x}}{\partial t} = \mathbf{M}\mathbf{x} + \boldsymbol{\eta}$$

Assimilation Process: $$\frac{\partial \mathbf{x}}{\partial t} = \mathbf{M}\mathbf{x} + \boldsymbol{\eta} + G(\mathbf{x}^{\mathbf{0}}, \mathbf{x}^{\mathbf{f}})$$

Objectives:

1. **Determine realization characteristics**
2. **Assimilate data into forecast**

Can separate into wind and concentration equations

$$\frac{\partial \vec{\mathbf{v}}}{\partial t} = \mathbf{M}_{\mathbf{v}}(\vec{\mathbf{v}})\vec{\mathbf{v}} + \boldsymbol{\eta}_{\mathbf{v}} + G_{v}(\vec{\mathbf{v}}^{\mathbf{o}}, \vec{\mathbf{v}}^{\mathbf{f}}, C^{o}, C^{f})$$

$$\frac{\partial C}{\partial t} = \mathbf{M}_{\mathbf{C}}(\vec{\mathbf{v}})C + \boldsymbol{\eta}_{\mathbf{C}} + G_{C}(\vec{\mathbf{v}}^{\mathbf{o}}, \vec{\mathbf{v}}^{\mathbf{f}}, C^{o}, C^{f})$$

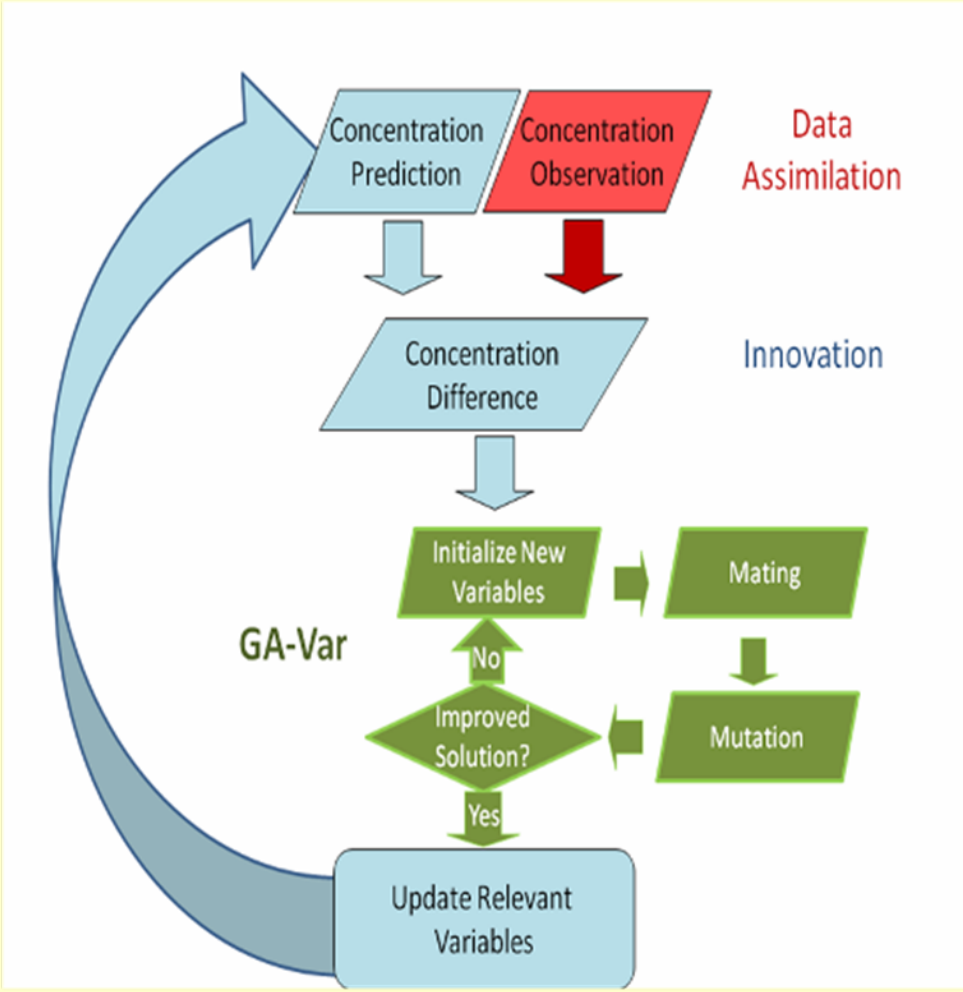
GA-Var Assimilation Procedure

Concentration Assimilation

1. Use "guessed" wind and source data to predict concentration.
2. Compute difference (innovation) between concentration prediction and observation.
3. Use GA-Var to update wind and source variables.

Repeat until converged

➡ dynamically assimilate one time before going on to next time



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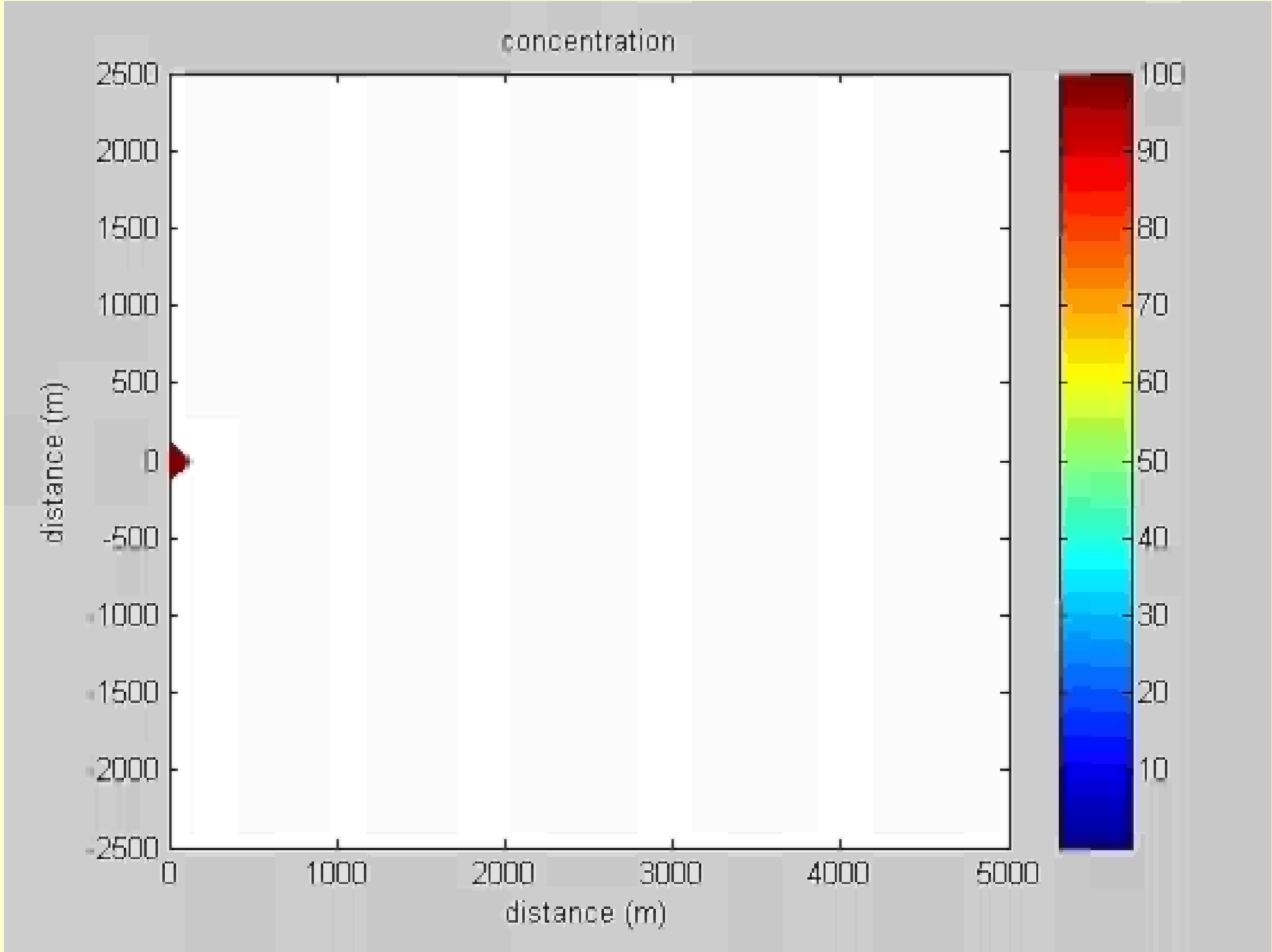
1 a. Meandering Puff



We wish to assimilate a puff in a meandering wind field to reconstruct time dependent wind by assimilating observations of dispersed contaminant concentrations

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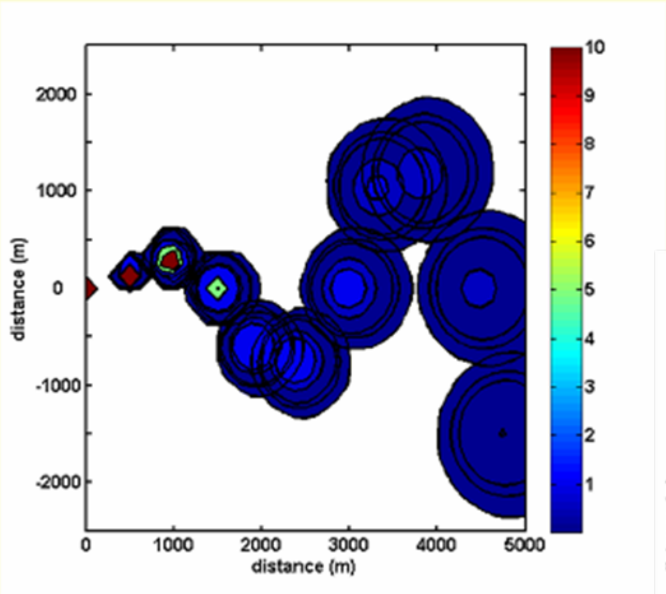
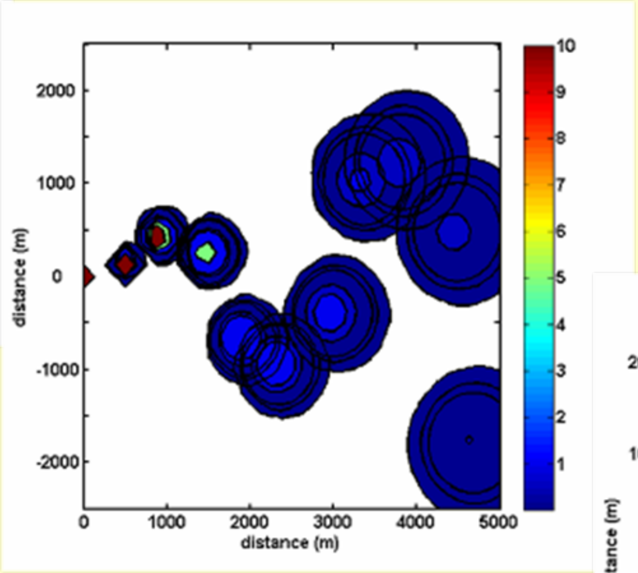
a. Assimilate Puffs in Meandering Wind Field

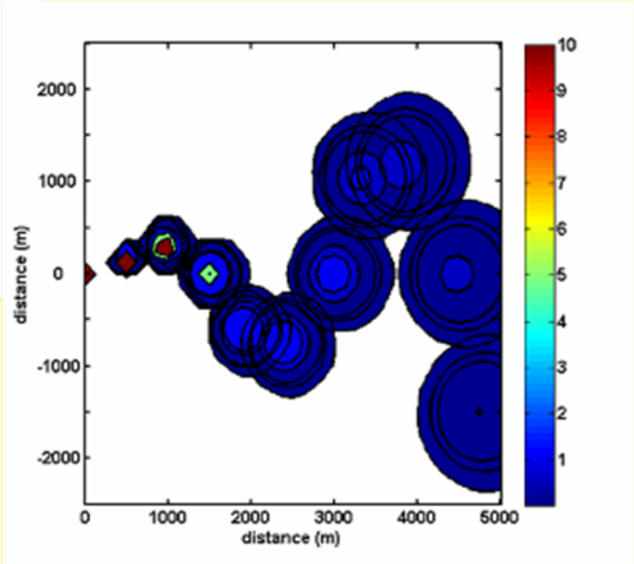
Exact Solution



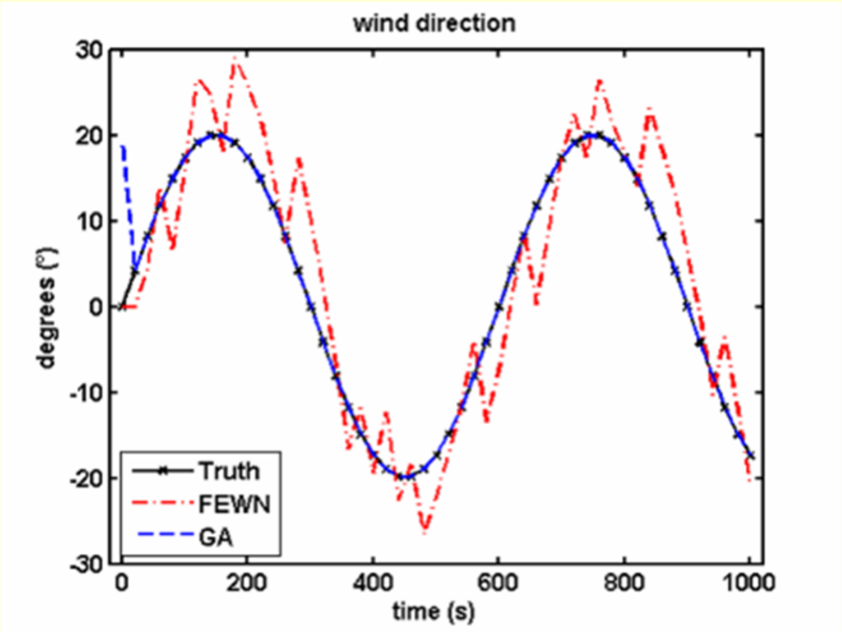
FEWN



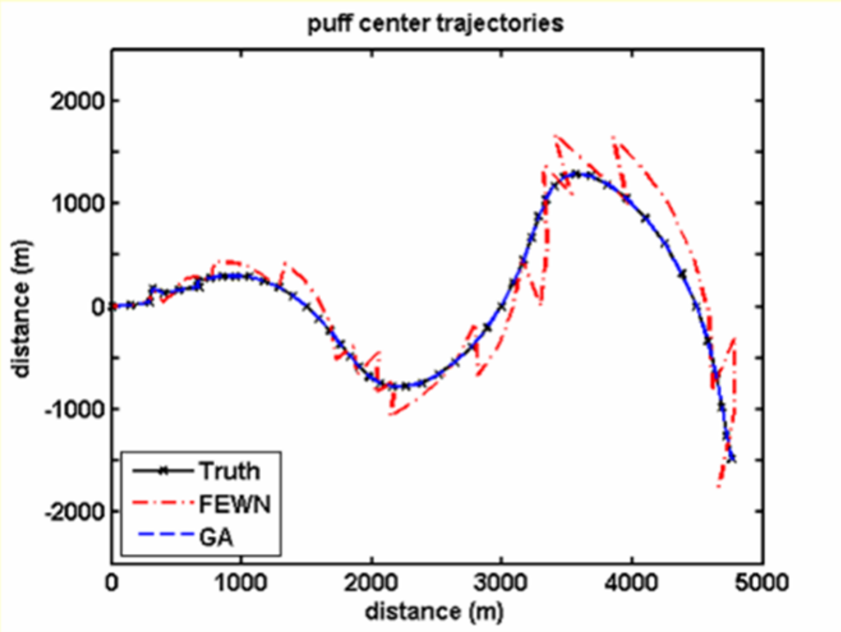
GA-Var



b. The Shallow Water Assimilation: TusseyPuf



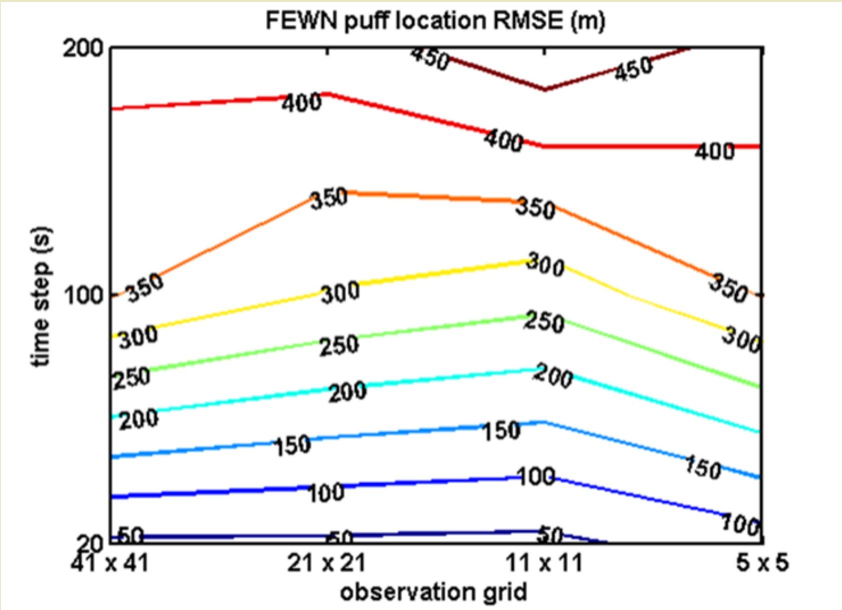
Wind Direction



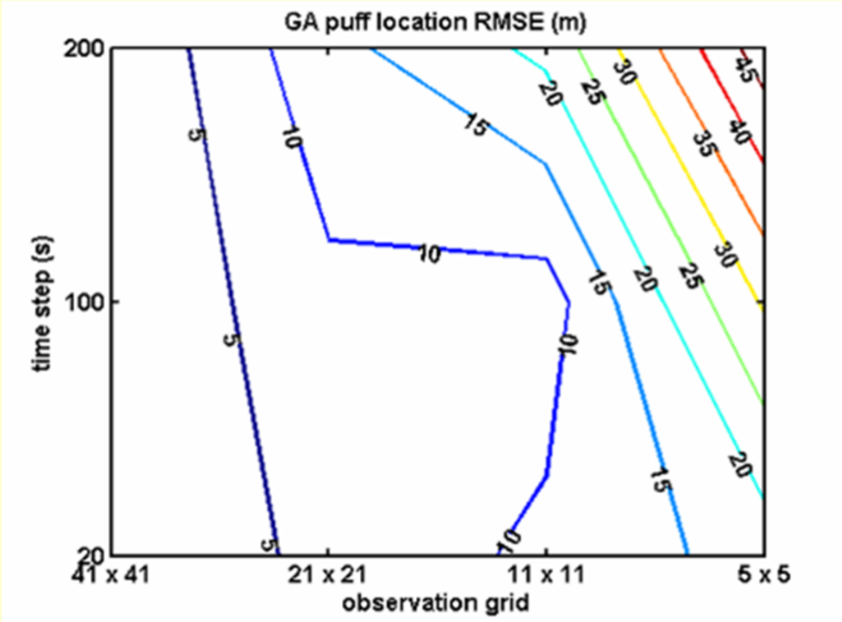
Puff Centroid

Sensitivity to Resolution

FEWN



GA-Var



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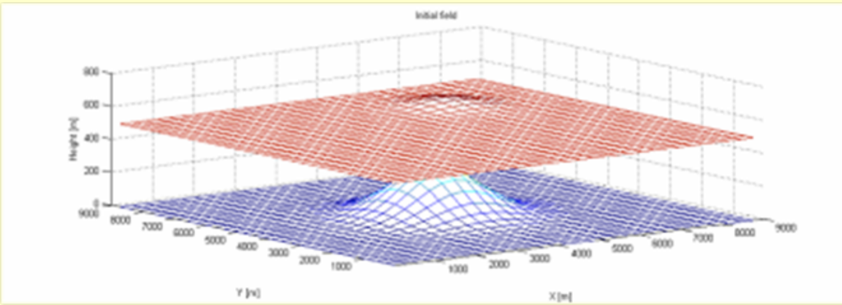
1 b. TusseyPuff Assimilation

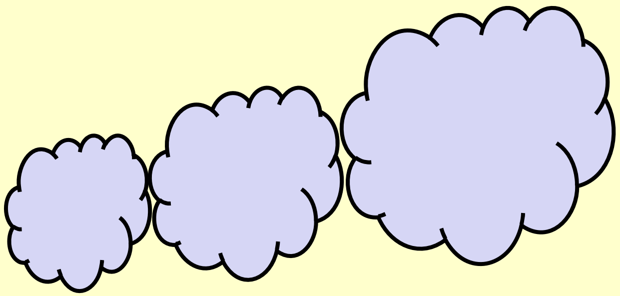
Shallow Water Model



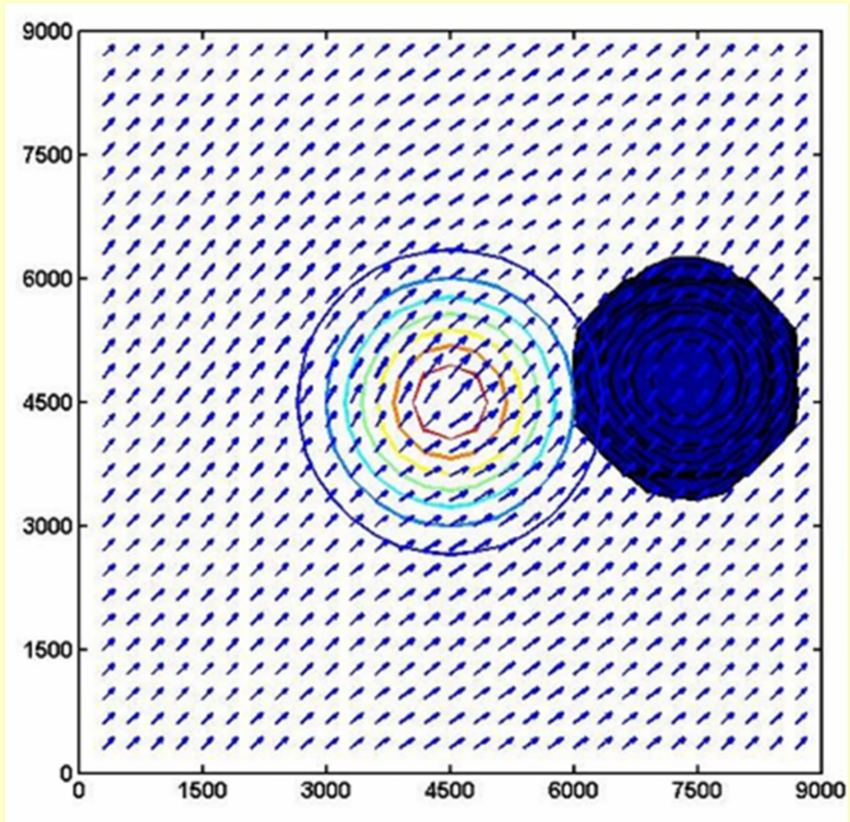
Wind Field

+

Concentration Field



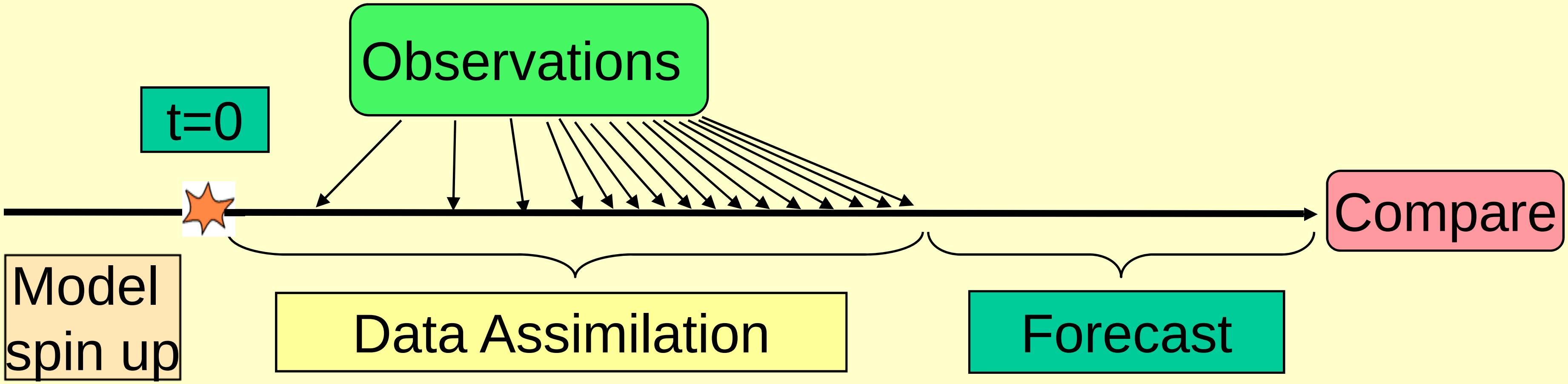
Puff Dispersion



TusseyPUFF

Anke Beyer-Lout

Experimental Setup



- Assess performance via RMSE:
  - Puff trajectories: $RP = \sqrt{\frac{1}{T}\sum_{\tau=1}^{T}[(\bar{x}_{\tau}^{t} - \bar{x}_{\tau}^{f})^2 + (\bar{y}_{\tau}^{t} - \bar{y}_{\tau}^{f})^2]}$
  - Resulting wind field: $RW = \sqrt{\frac{1}{N}\sum_{n=1}^{N}[(u_{n}^{t} - u_{n}^{f})^2 + (v_{n}^{t} - v_{n}^{f})^2]}$

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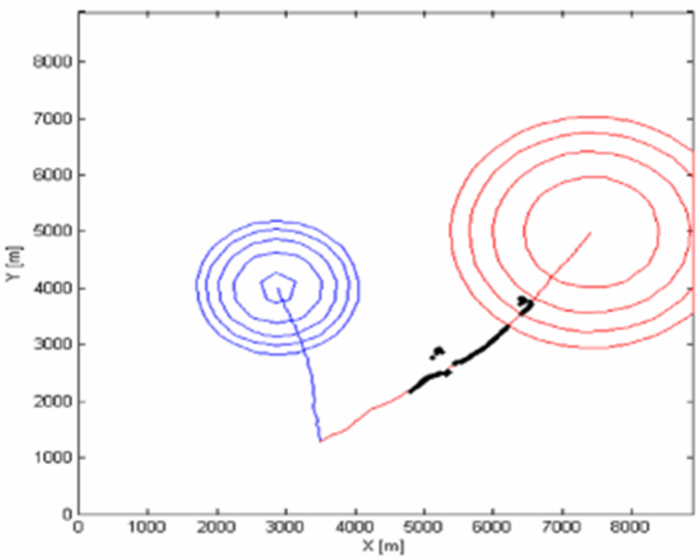
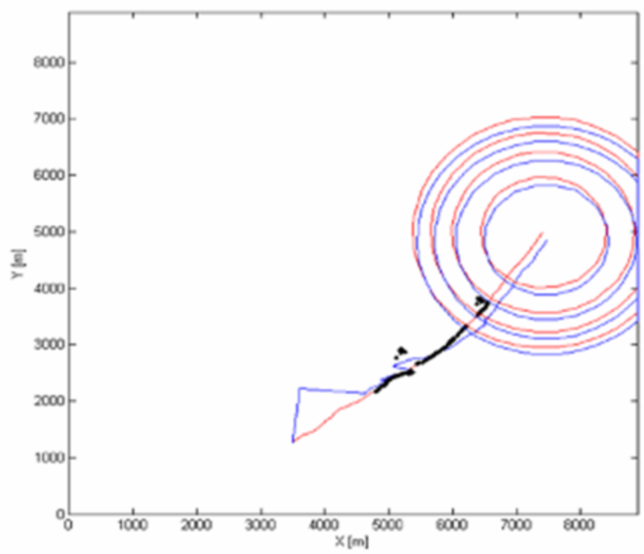
Sensor Data Fusion/Data Assimilation

Assimilate field sensor data to improve transport and dispersion estimate in real time





– Truth
– No data assimilation
• observations

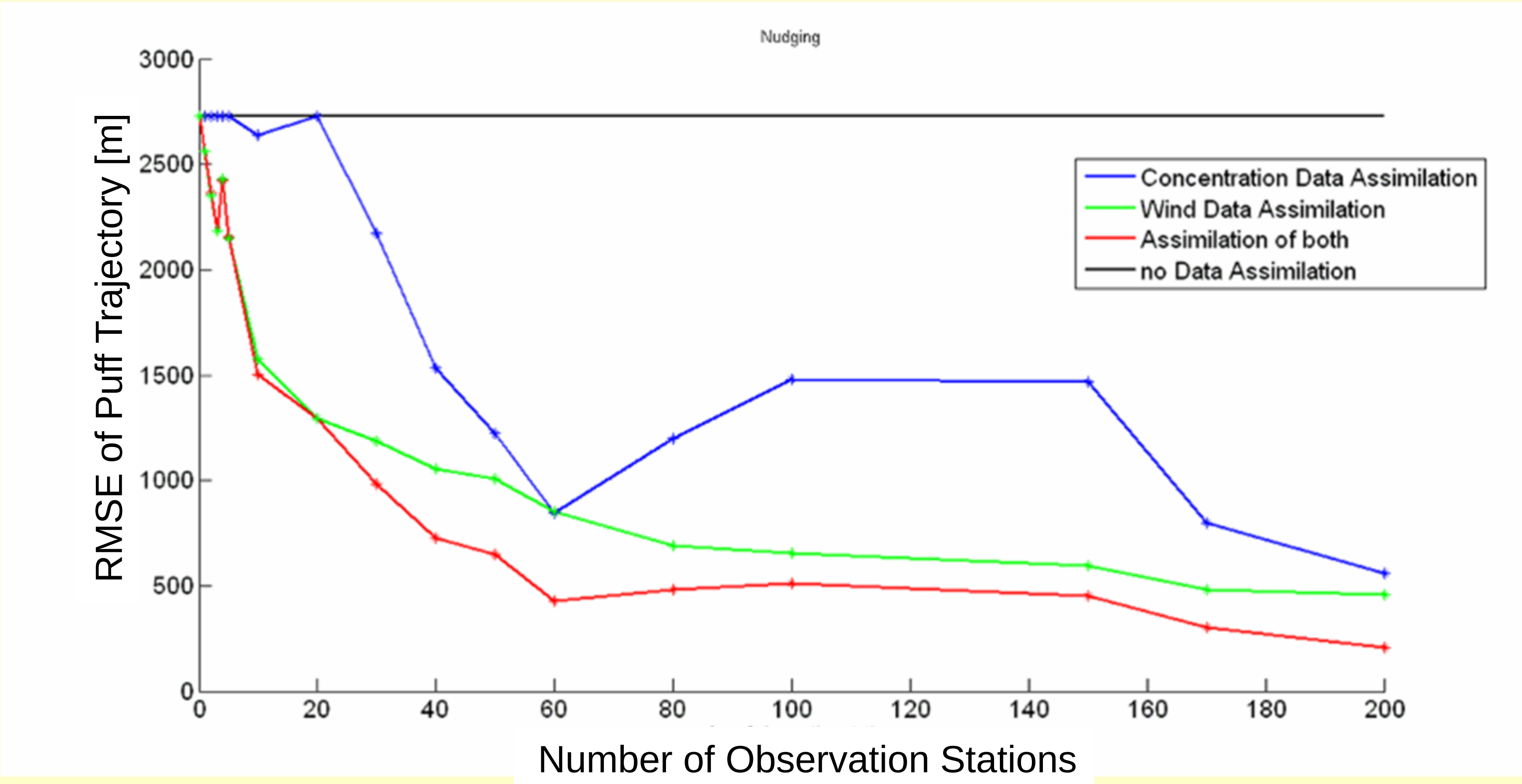
– Truth
– With ensemble Kalman Filter data assimilation
• observations

Much better prediction with assimilation

Anke Beyer-Lout

Results

Newtonian Relaxation



Sensor data fusion improves dispersion prediction

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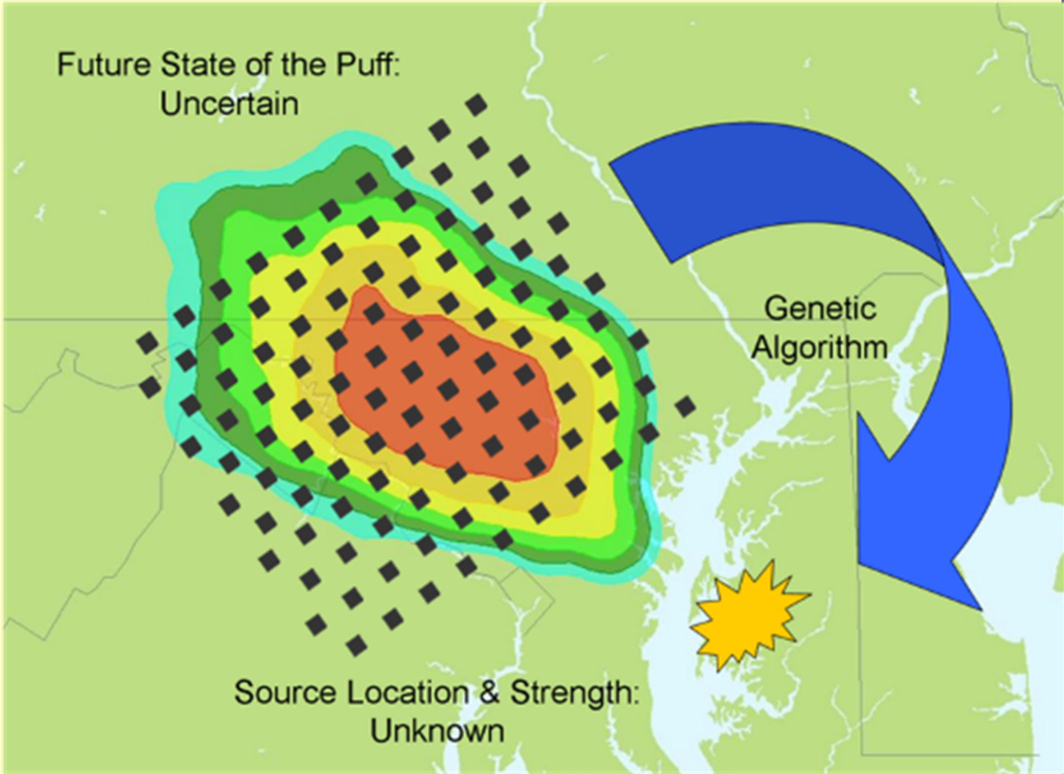
2. Source and Meteorology Inversion

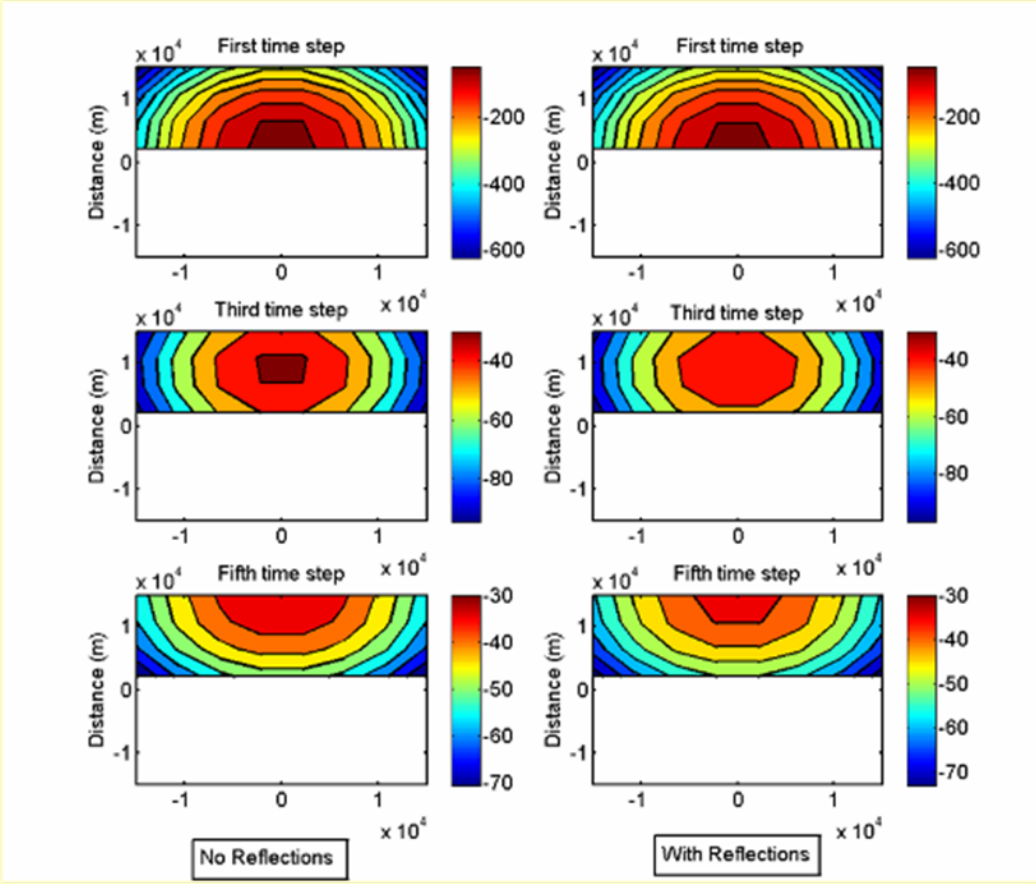
- **May not have required source information in the case of a terrorist release**
- **Can reconstruct that information (and unknown met. data) using Genetic Algorithm**
- **Characterize source and meteorological data given field sensor measurements (6 journal articles)**



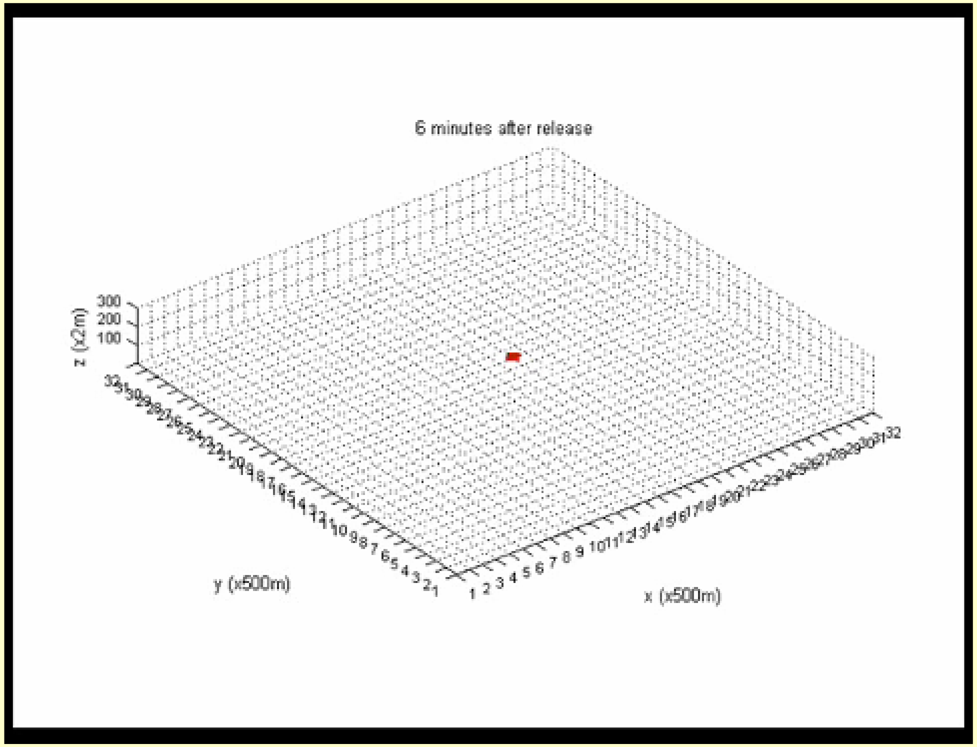
Parameters Estimated

Parameters required to Predict Transport and Dispersion:

- **Source parameters**
  - **2D location (x,y)**
  - **Height**
  - **Strength**
  - **Time of Release**
- **Meteorological modeling parameters**
  - **Wind direction**
  - **Wind speed**
  - **Stability class**
  - **Boundary Layer Depth**
- **Sensor Characteristics**



Use time varying measurements



Grid Size	Grid Spacing
2 x 2	8000 m
4 x 4	4000 m
6 x 6	2667 m
8 x 8	2000 m
16 x 16	1000 m
32 x 32	**500 m**
64 x 64	250 m

Given these puff locations, where is the source?

What meteorological conditions exist?

Kerrie Long

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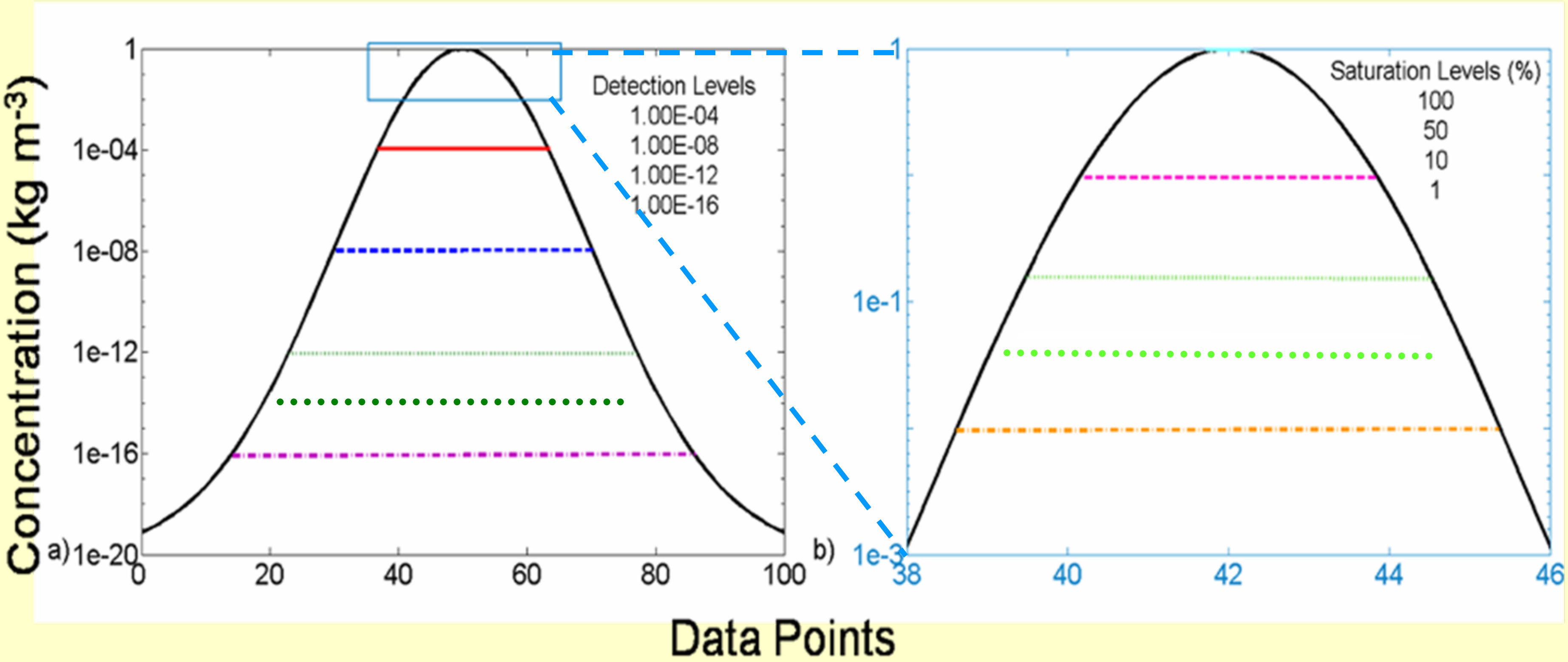
Noiseless Model Results

	Grid Size	Found θ (°)	Strength (Kg s^{-1})	(x,y) (m,m)	Release Time (s)	Speed (m s^{-1})	Cost Function
Actual Solution		180.00	1.00	(0,0)	0	5.0	1.0e-3
GA Alone	2x2	179.12	2.94	(120,-730)	172	7.6	2.0e-1
Hybrid GA	2x2	178.10	5.05	(290,-760)	184	7.9	1.0e-1
GA Alone	4x4	179.69	1.30	(40,-40)	26	5.2	4.1e-3
Hybrid GA	4x4	180.00	1.00	(0,-20)	0	5.0	2.0e-9
GA Alone	6x6	179.91	1.69	(10,80)	28	5.0	2.2e-3
Hybrid GA	6x6	180.00	1.00	(0,0)	0	5.0	3.2e-9
GA Alone	8x8	179.18	1.90	(80,170)	39	5.0	6.0e-3
Hybrid GA	8x8	180.00	1.00	(0,0)	0	5.0	3.1e-9
GA Alone	16x16	179.96	1.35	(0,40)	13	5.0	1.6e-3
Hybrid GA	16x16	180.00	1.00	(0,0)	0	5.0	3.4e-9
GA Alone	32x32	180.07	1.39	(-10,40)	13	5.0	1.8e-3
Hybrid GA	32x32	180.00	1.00	(0,0)	0	5.0	3.6e-8
GA Alone	64x64	179.96	1.45	(0,80)	18	5.0	2.1e-3
Hybrid GA	64x64	180.00	1.00	(0,0)	0	5.0	3.0e-9

Sensor Constraints

Detection Levels

Saturation Levels



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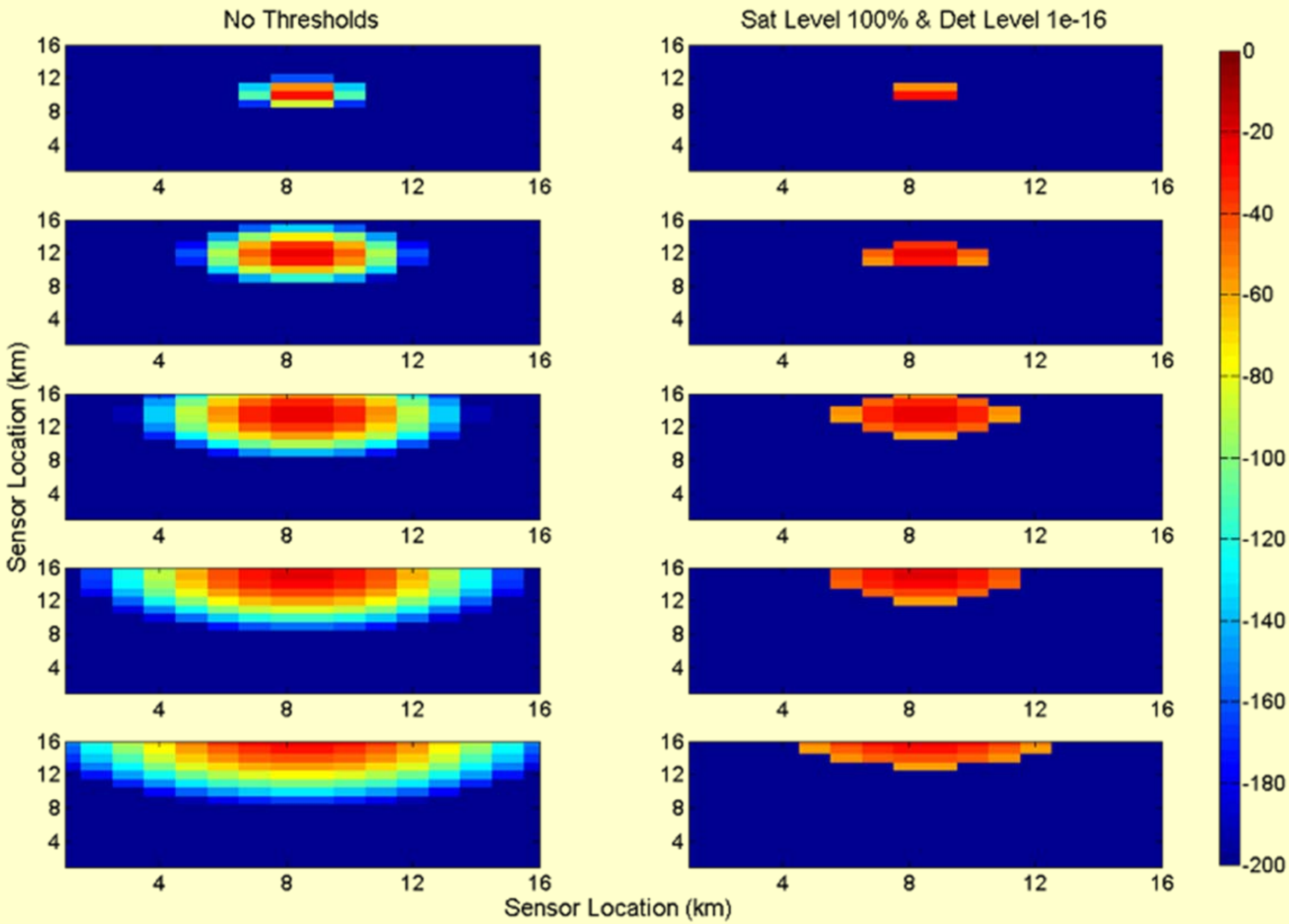
Gaussian Puff with Thresholds



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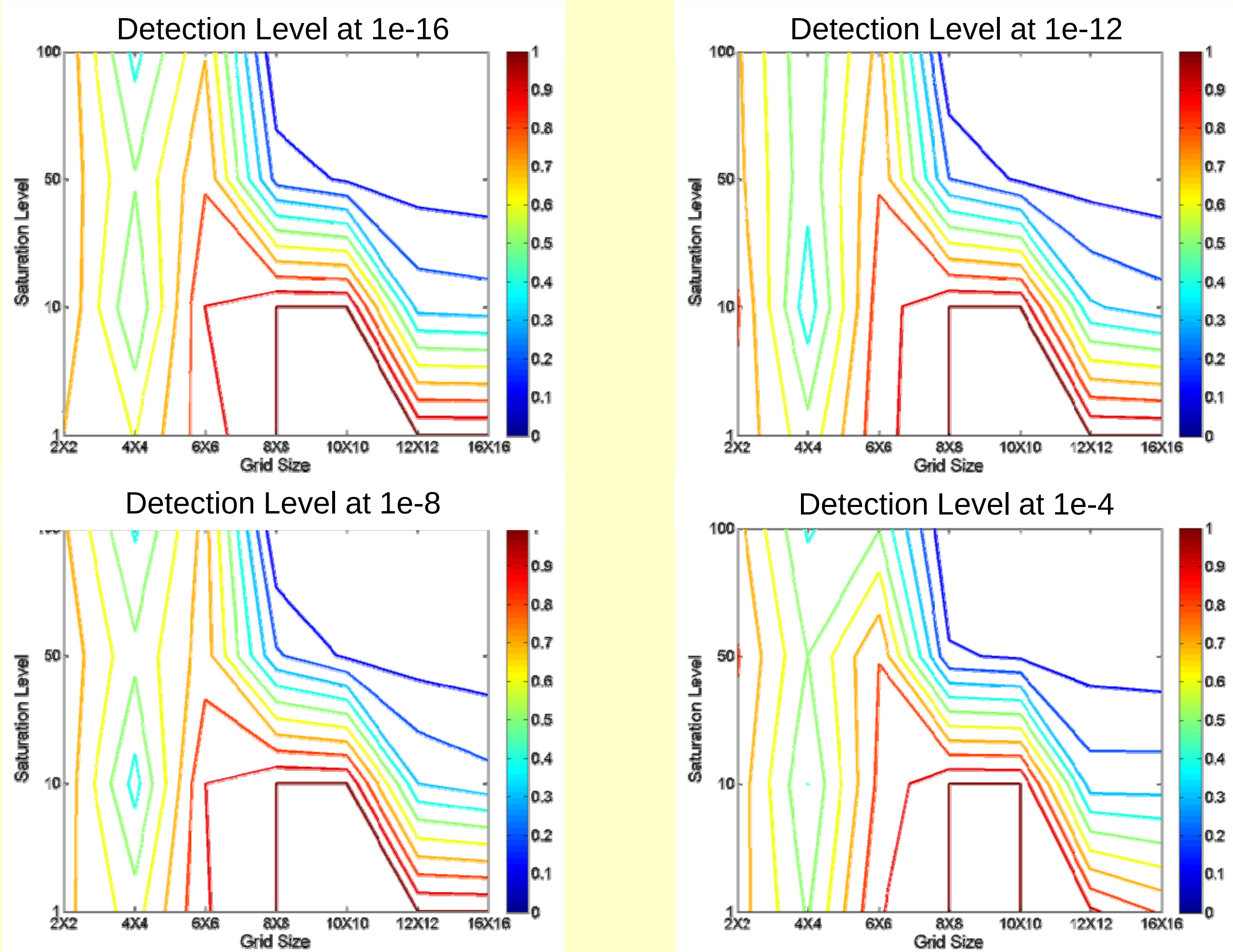
Skill Score Results



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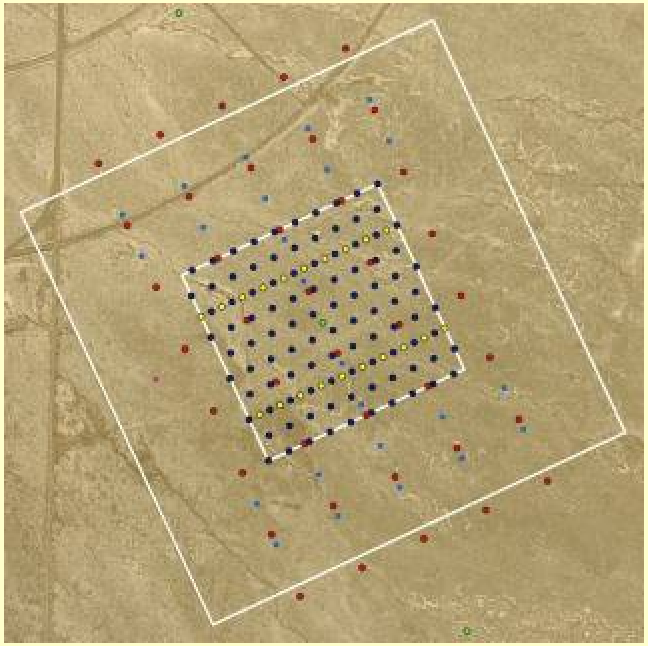
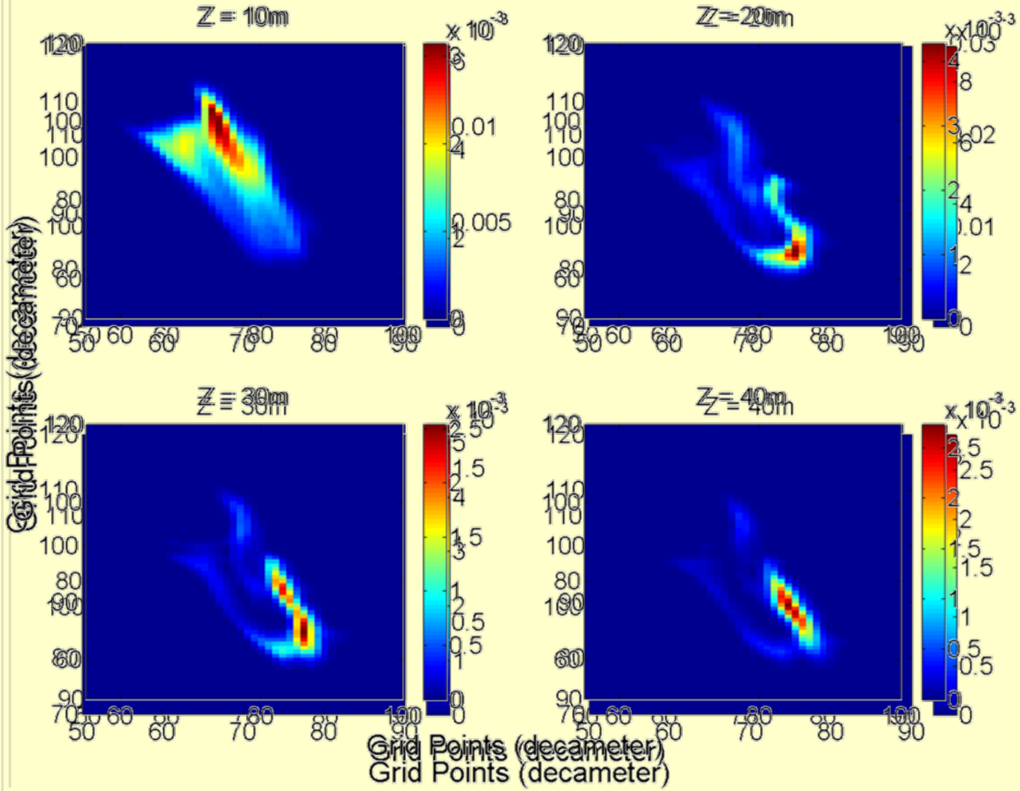
FUSION Field Trial 2007 (FFT 2007)



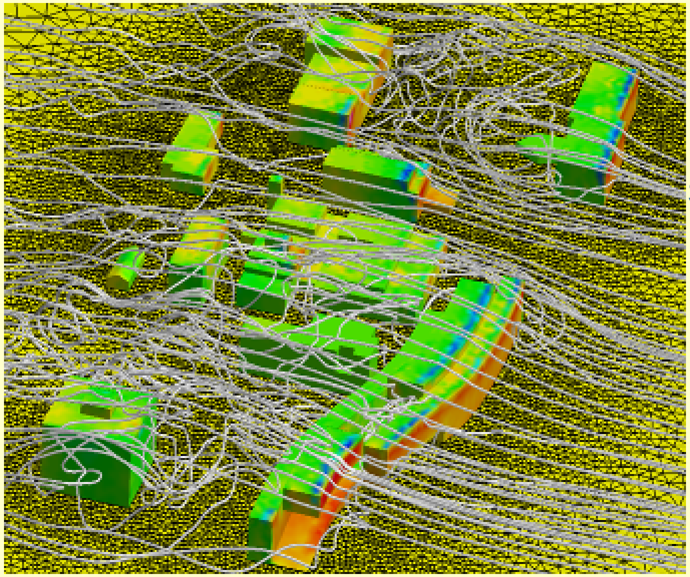


Currently modeling actual DTRA field data – reconstruct source information

3. Modeling Contaminant Transport

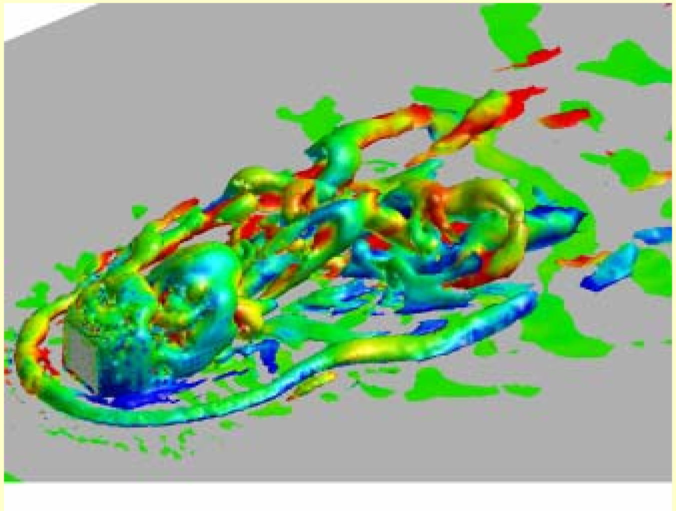
PSU/ARL Computational Mechanics Division has high fidelity tools for CFD modeling and dispersion computation

- **Unsteady Reynolds averaged Navier Stokes**
- **Detached Eddy Simulation**
- **Large Eddy Simulation**
- **Particle Trajectory Models**



Flow streamlines about PSU West Campus Buildings

Joel Peltier

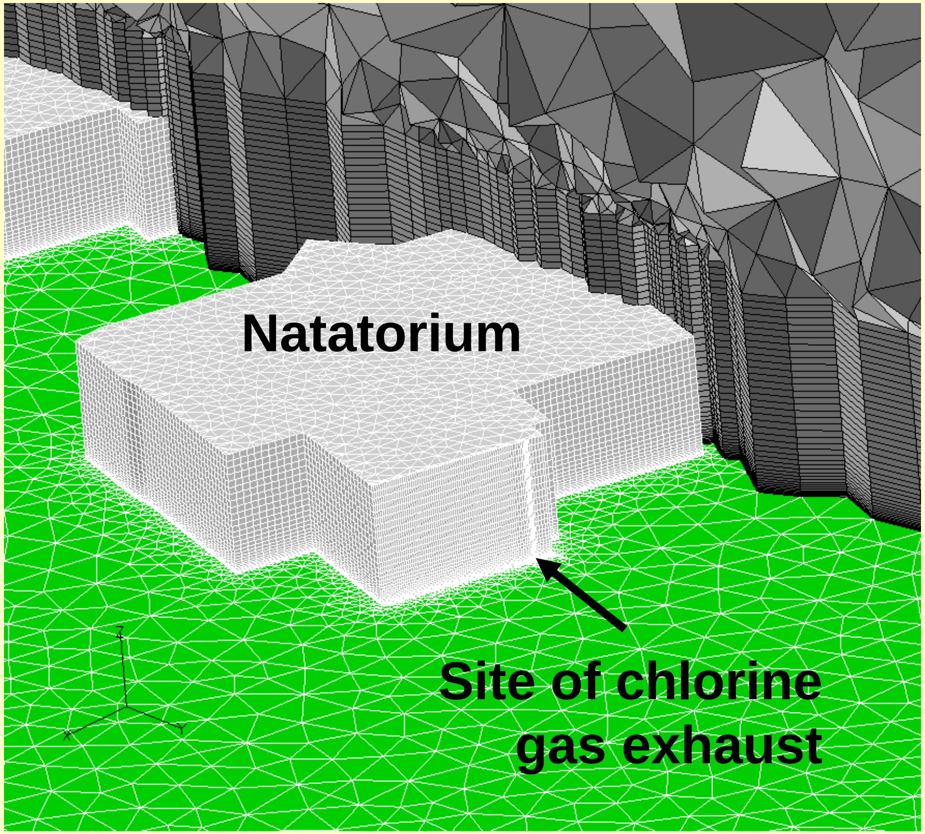


Predicted dispersion about cube agrees well with measure-ments

Robert Wilson

Application of CFD – Hypothetical Chlorine Release

- Model chlorine gas source as exhaust at ground level
- Exhaust port modeled as .3 m x .3 m fan
- Exhaust fan flow rate is ~60 m/s.
- Wall-functions are used at solid boundaries
- Wedge elements are used for z<40 m to control mesh resolution near surface
- Tetrahedral elements are used for >40m to minimize grid overhead in the outer flow



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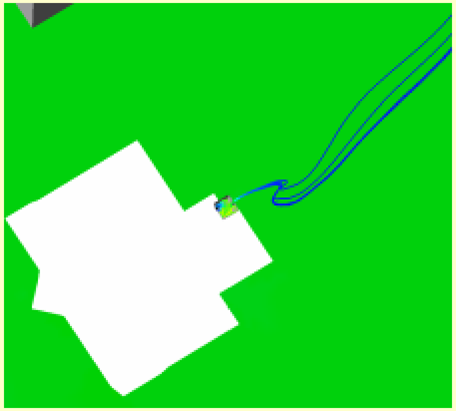
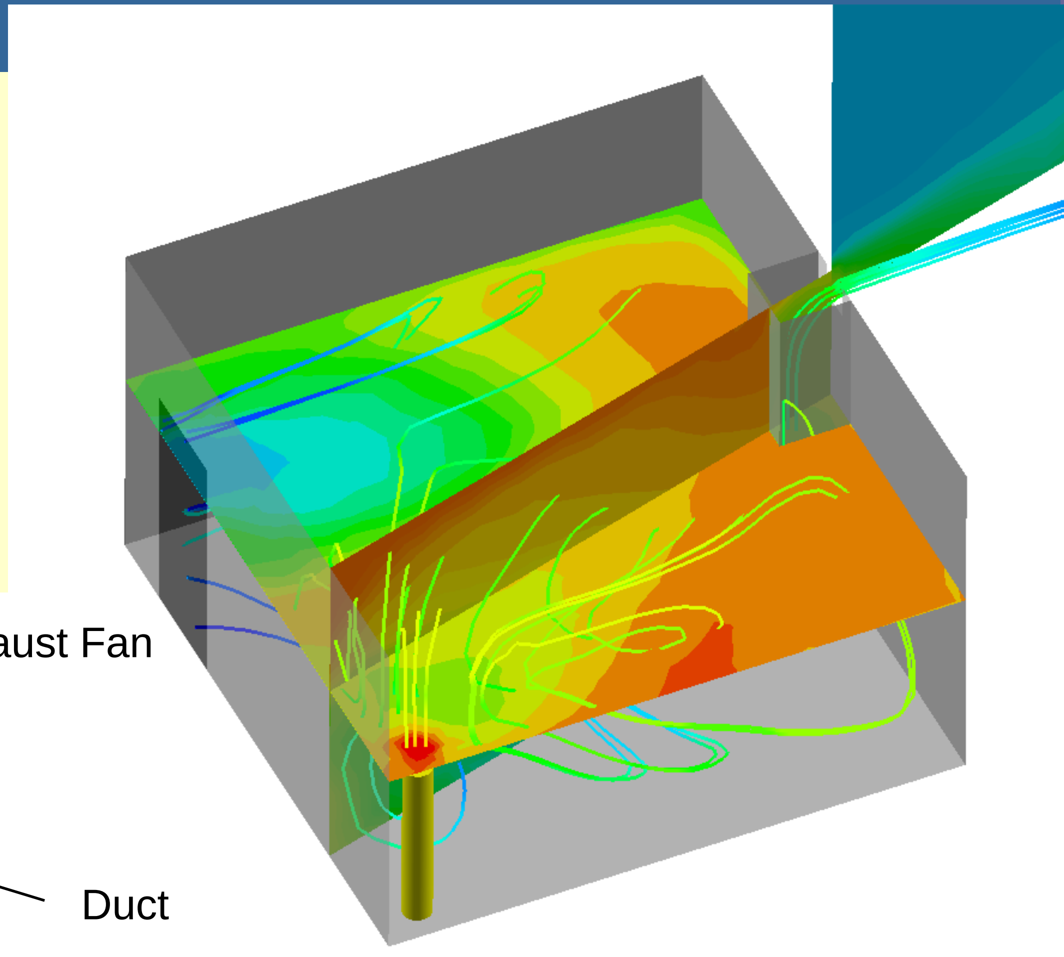
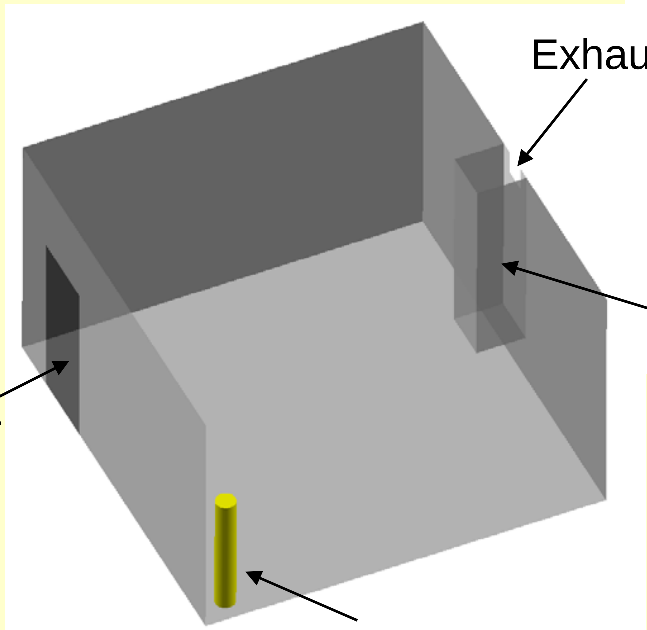
High Fidelity Model of Chlorine Release



Natatorium Footprint





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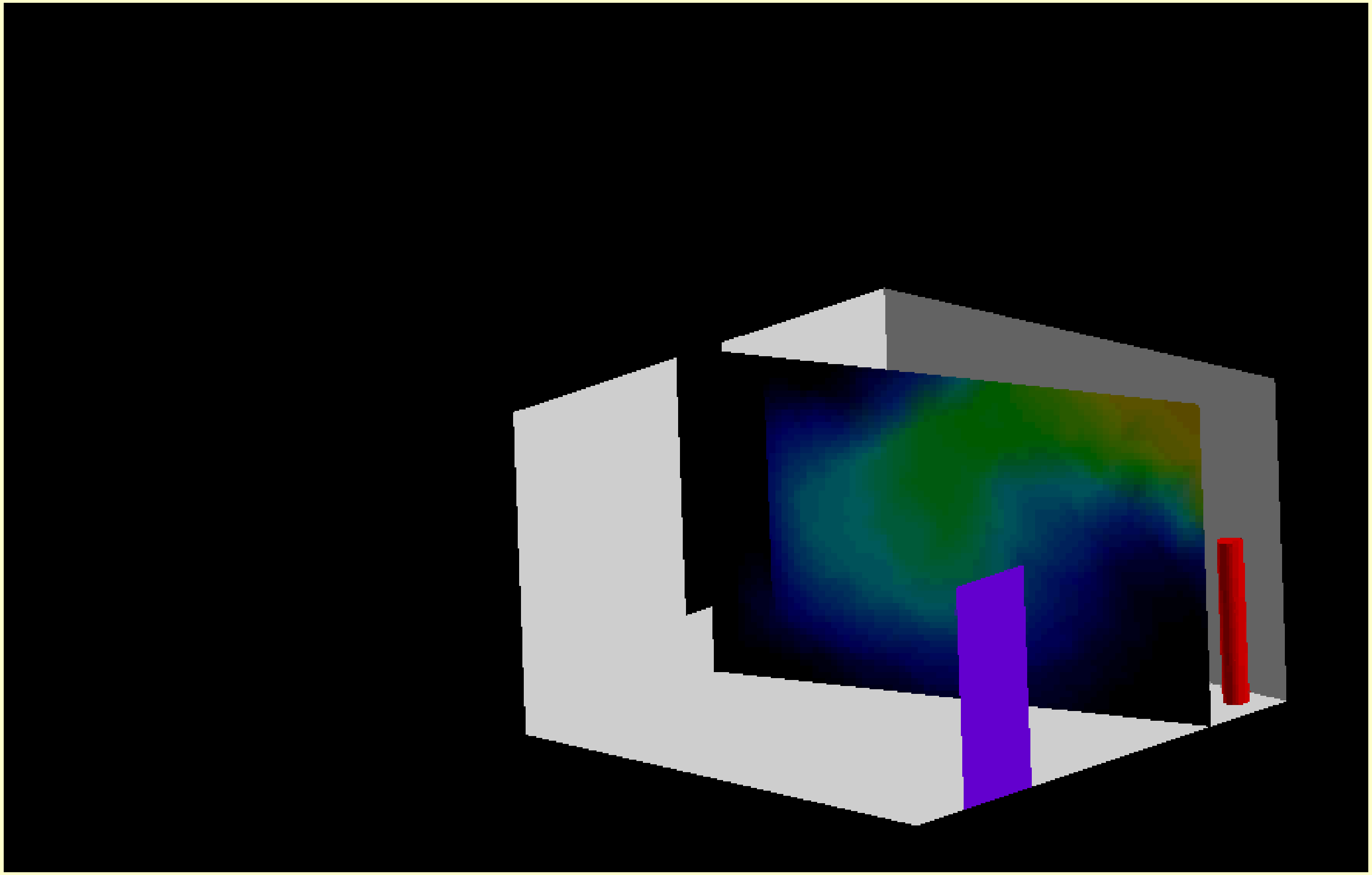
Chlorine release from container



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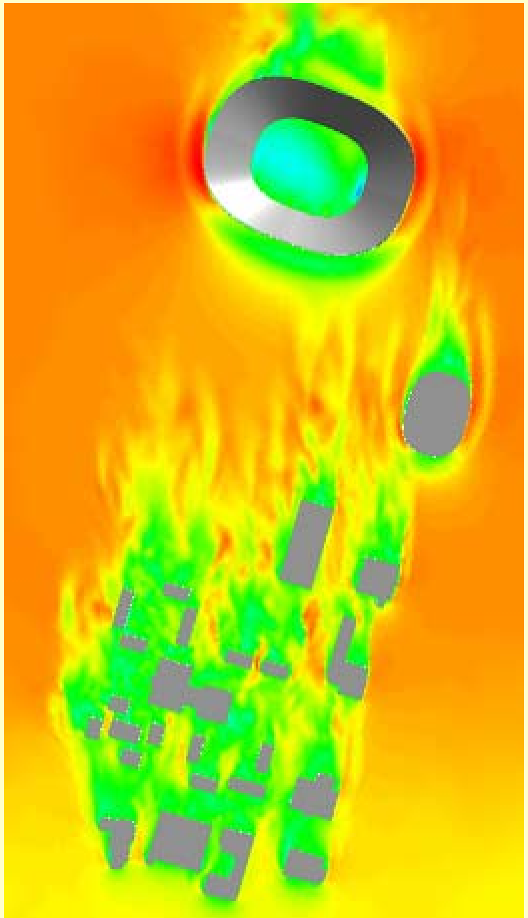
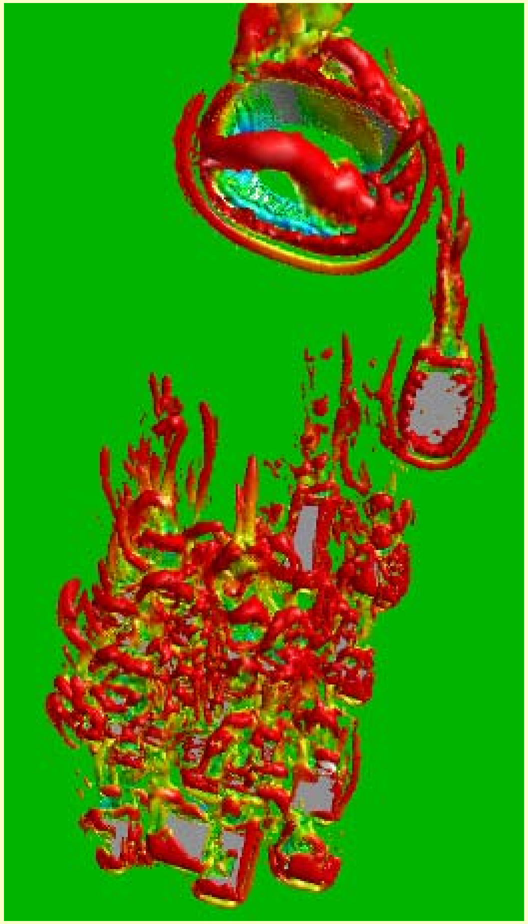
Hypothetical Chlorine Release

Used flow solver AcuSolve™

Surface contours of streamwise velocity at 5 m above the ground



Isosurfaces of Q-Criterion colored by streamwise velocity showing turbulence structures



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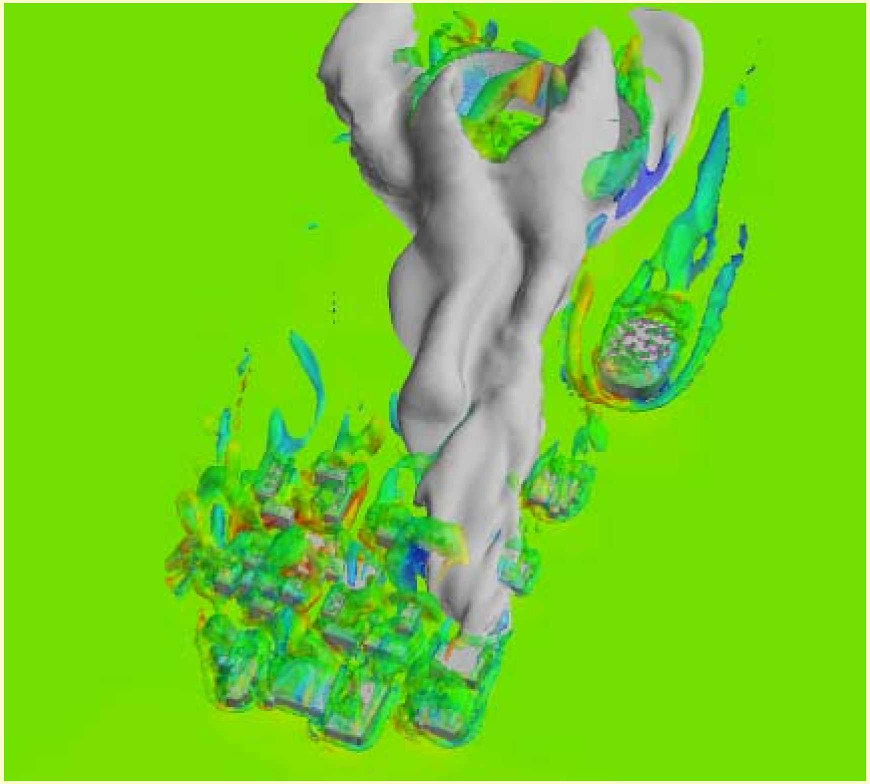
Chlorine Dispersion – CFD



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Chlorine Spread through campus

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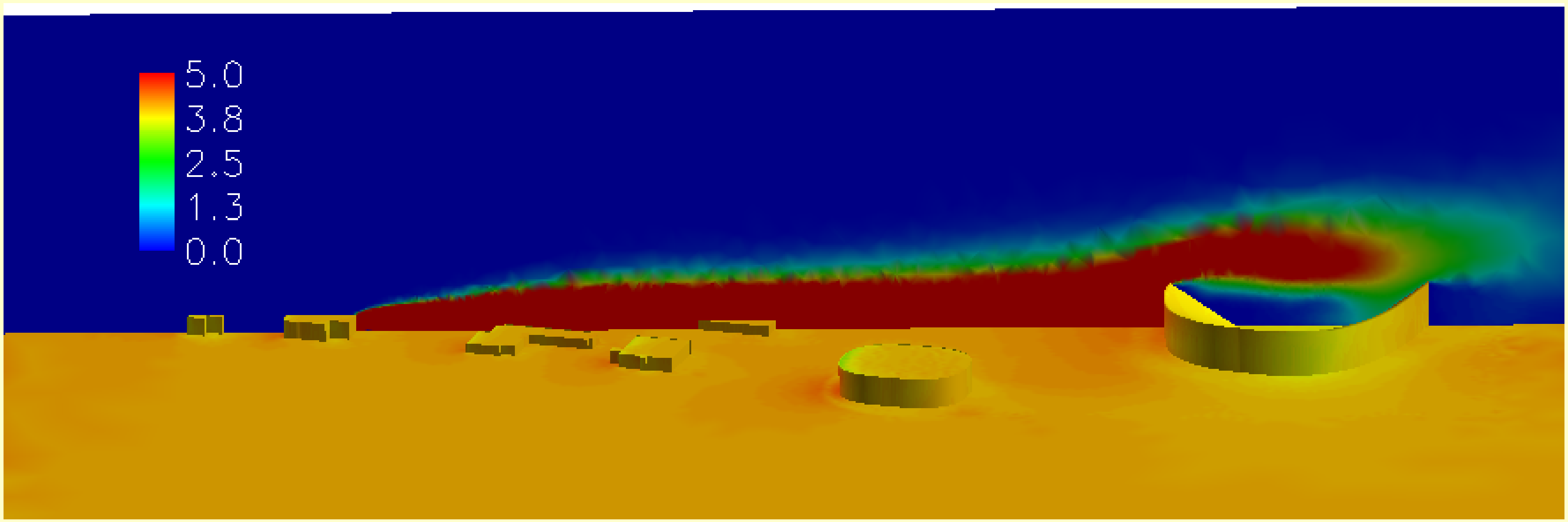
Hypothetical Chlorine Release

Cross-Sectional Concentration (ppm)
Time ~ 6 min from release



Predicted levels of chlorine exposure in the stadium small

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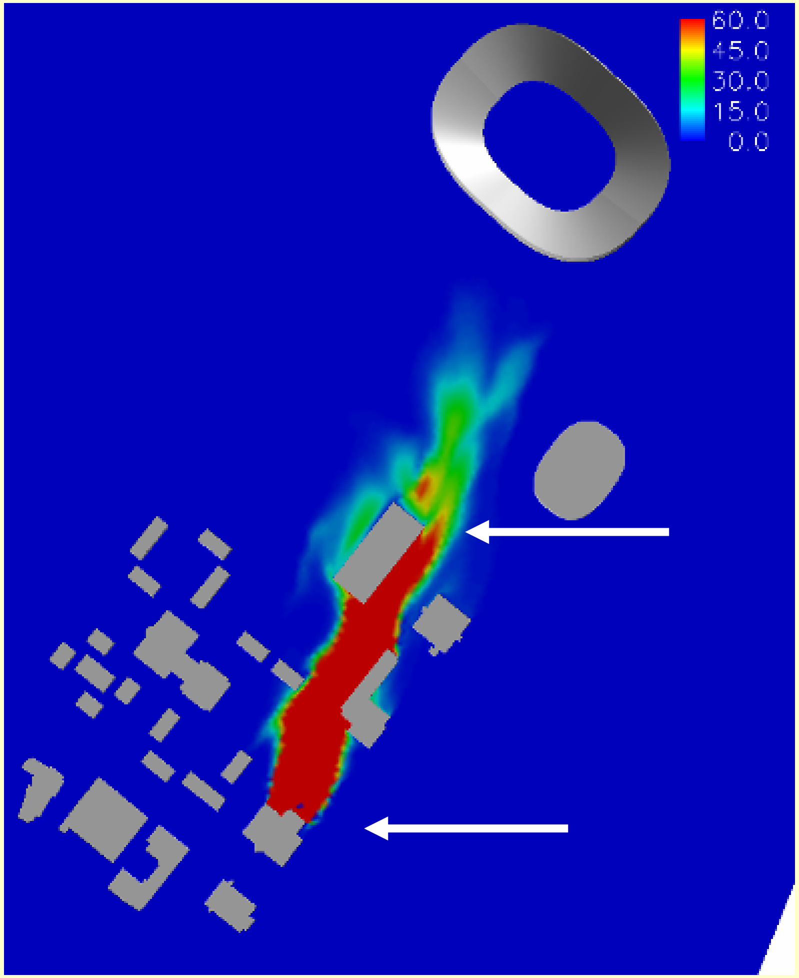
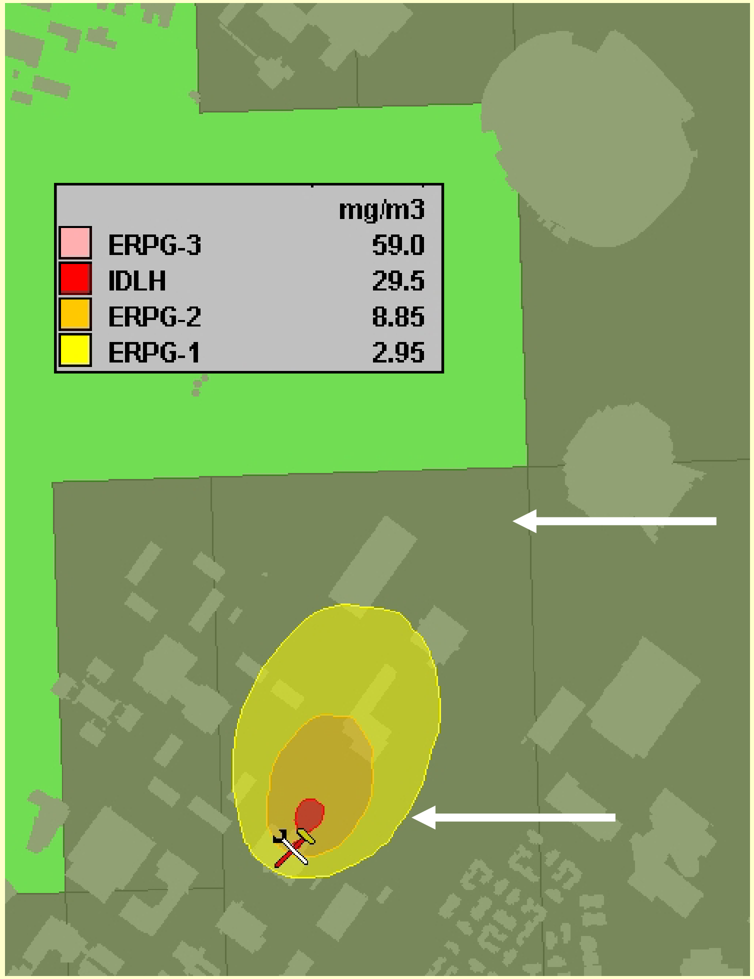
Hypothetical Chlorine Release

CFD



HPAC



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Chlorine Dispersion - HPAC

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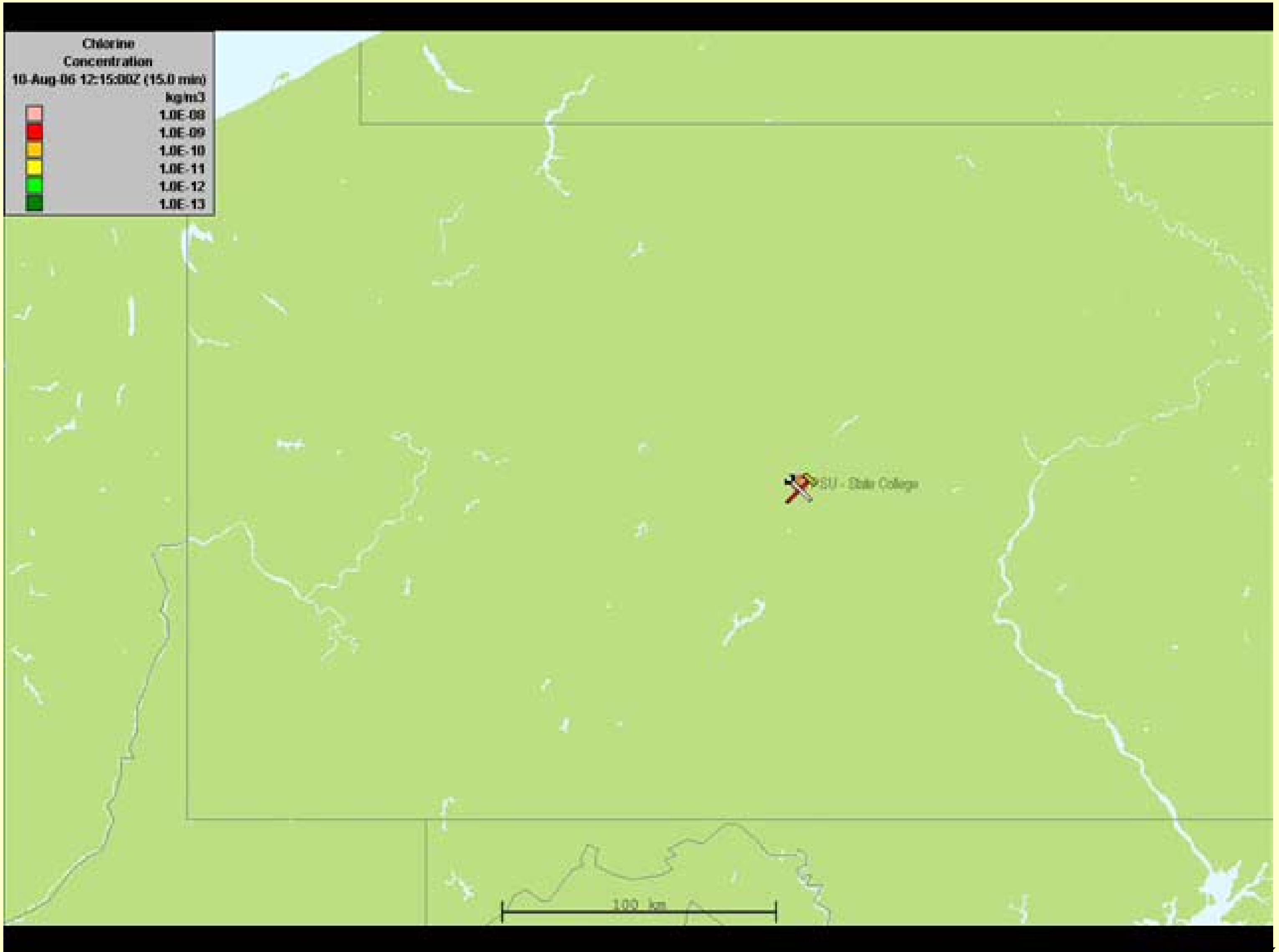
Regional Chlorine Dispersion - HPAC



Kerrie Long

4. Assimilation for Downscaling

- **Need for fine-scale modeling for a locale with specific characteristics of the realization**
  - **Defense applications**
  - **Wind energy**
  - **FAA**
- **Use data from mesoscale model (and/or observations) to initialize a CFD Model simulation**

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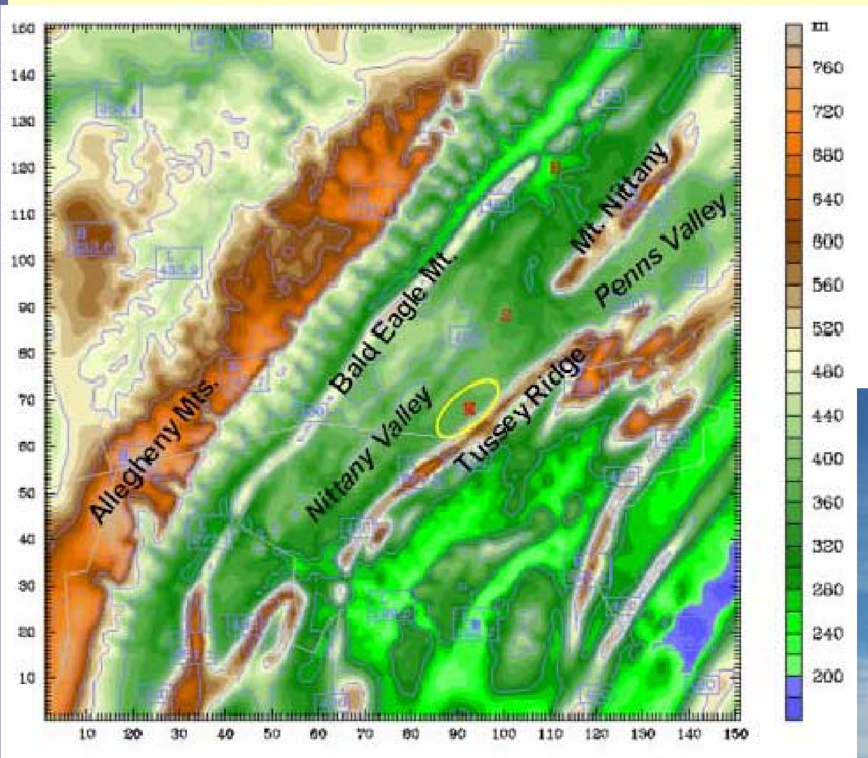
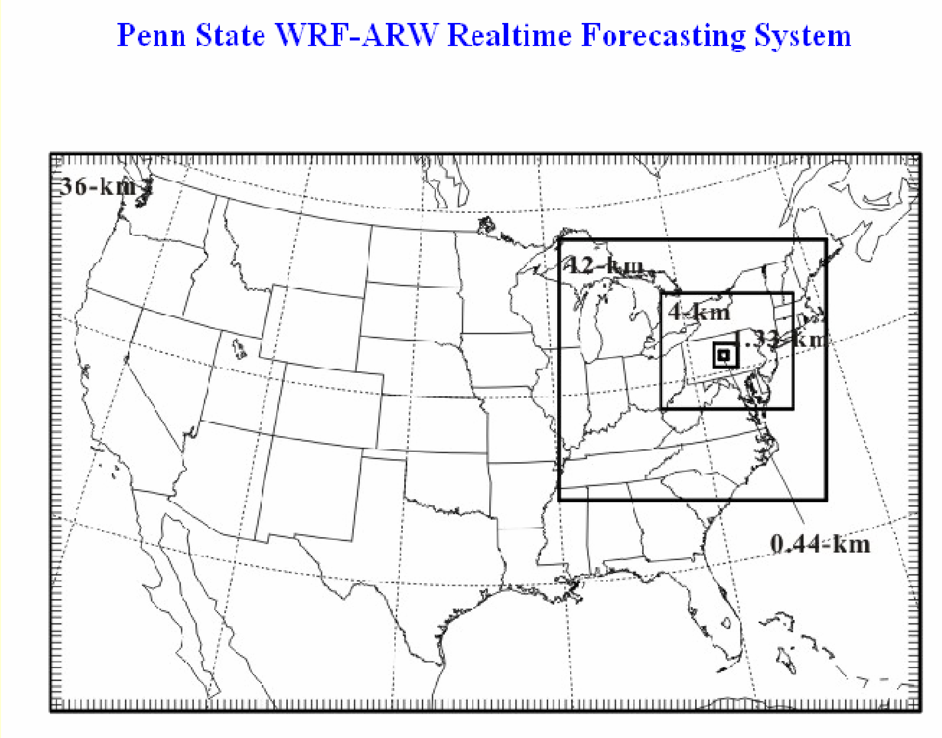
Site Description



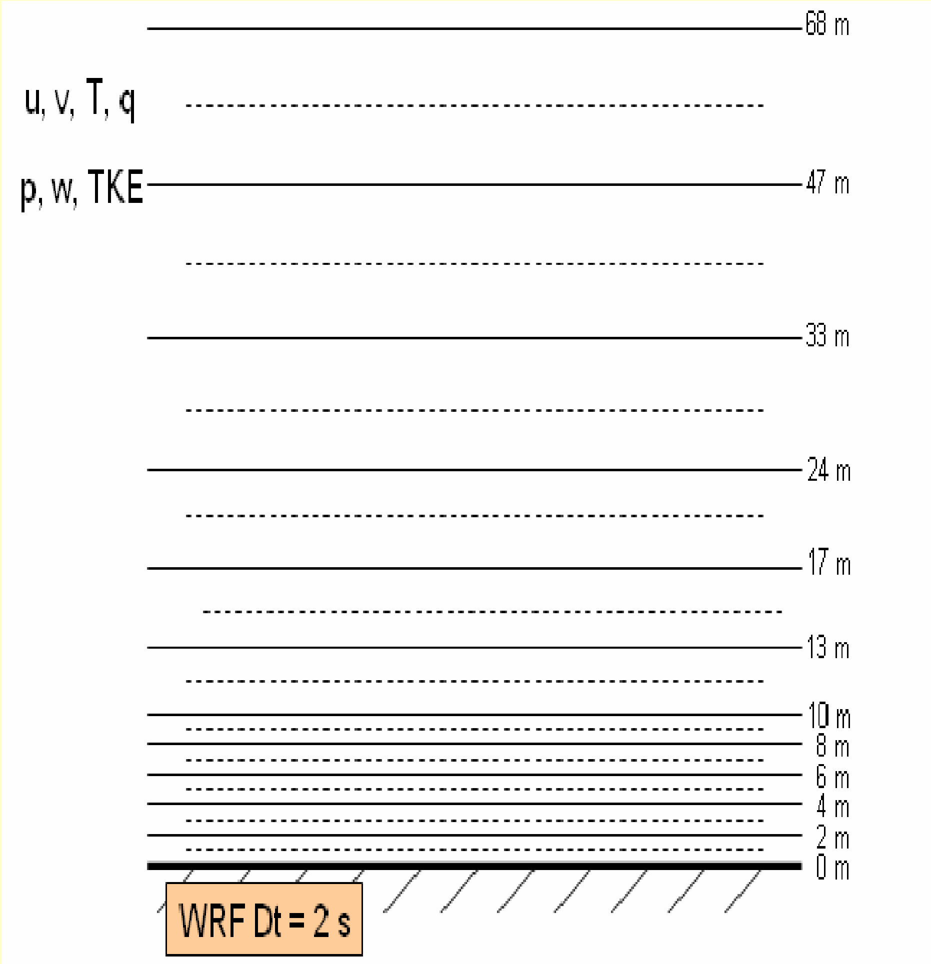
WRF-ARW Setup

- **Five grid nests**
  - **36 km**
  - **12 km**
  - **4 km**
  - **1.33 km**
  - **444 m**
- **One-way interface from coarse to fine**

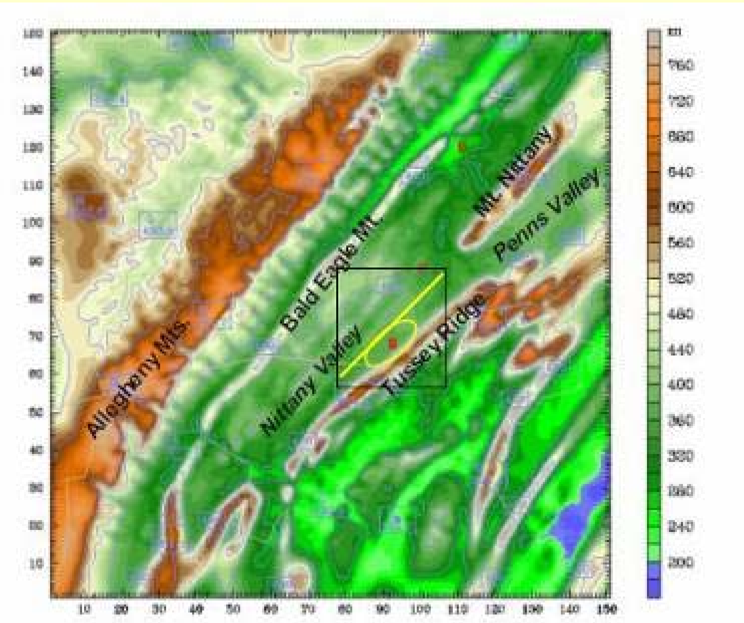


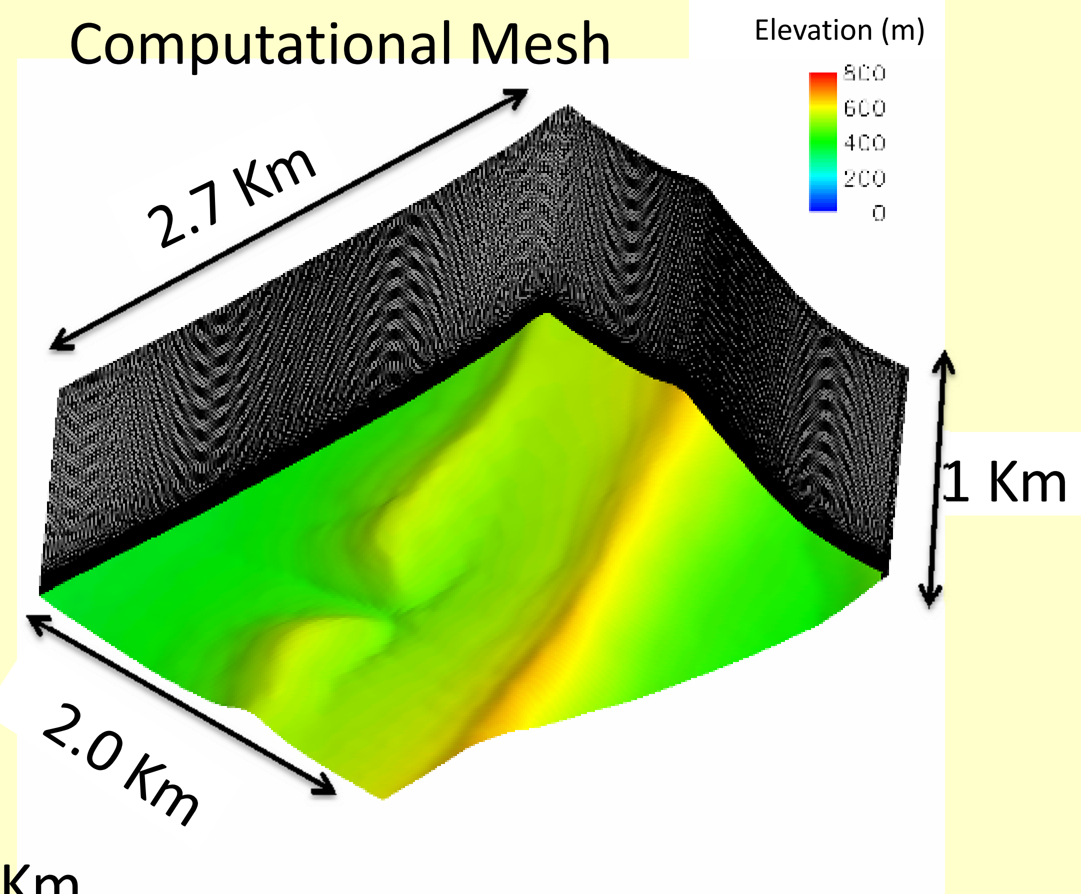
WRF-ARW Setup

- **43 Vertical layers**
- **5 layers in lowest 10 m with 2 m spacing**
- **FDDA**
- **http://www.meteo.psu.edu/~wrfrt/**



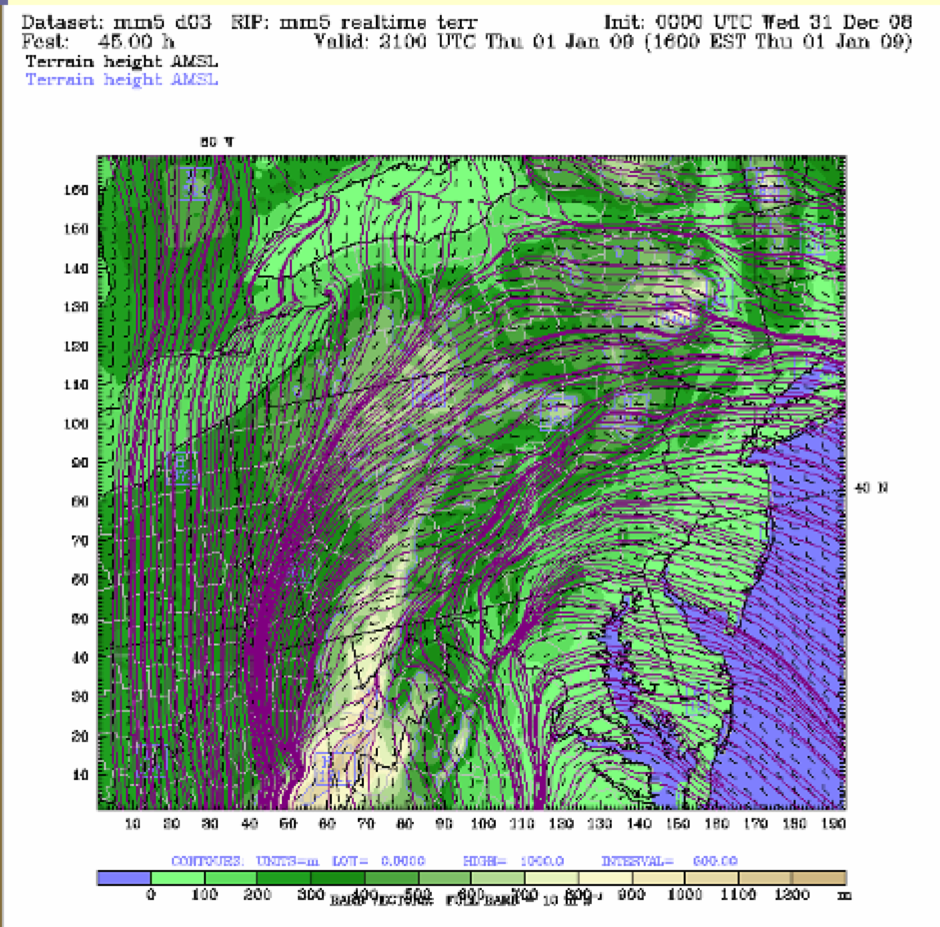
Acusolve Setup





- Domain: 2.7Km x 2Km by 1Km
- Mesh size: 200x200x100 = 4e6 nodes
- Spatial resolution: 1.5 m in the transverse directions
  1 m near wall spacing

Case Description



- 01 January 2009
  1600 EST for data assimilation
- Cold snap in eastern US over PA
- Flow from SSW in western PA to W in central and eastern PA
- Gusty

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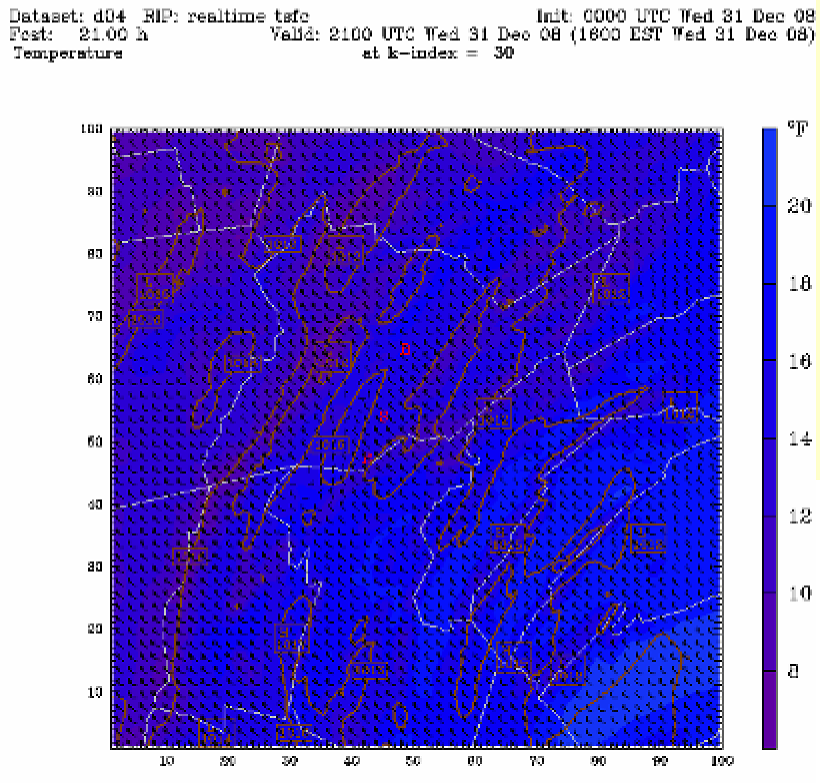
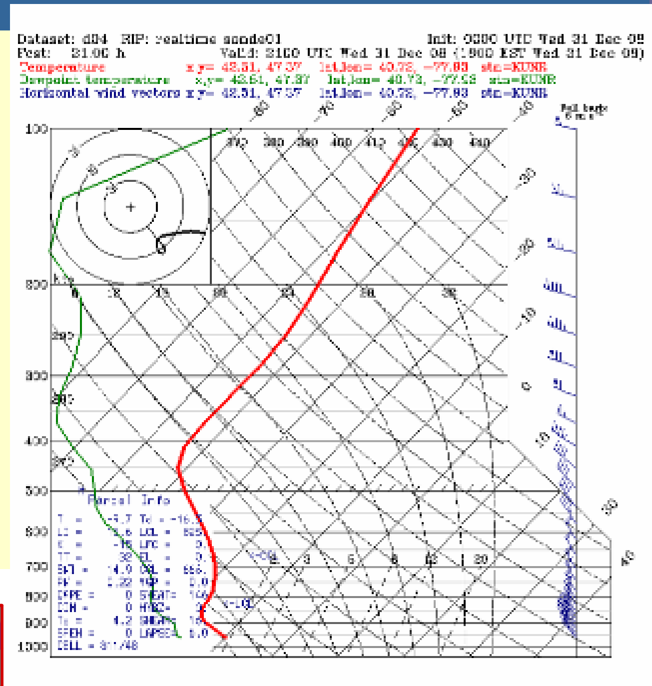
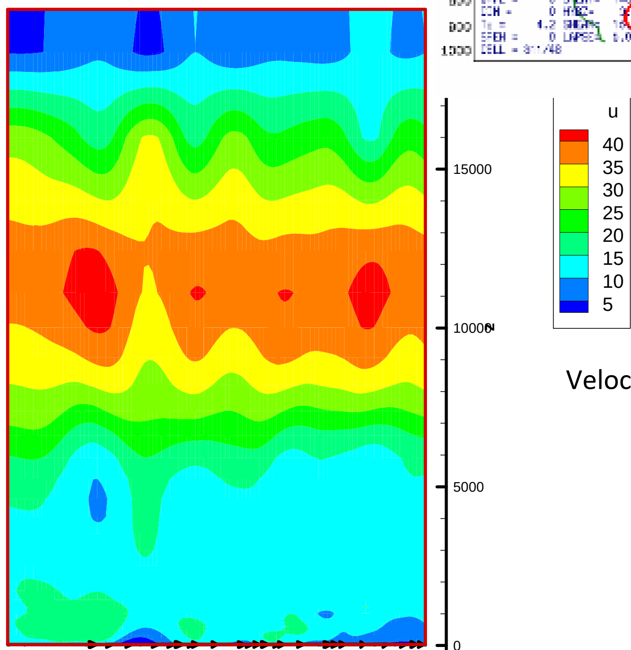
Case – Rock Springs

1.33 km grid



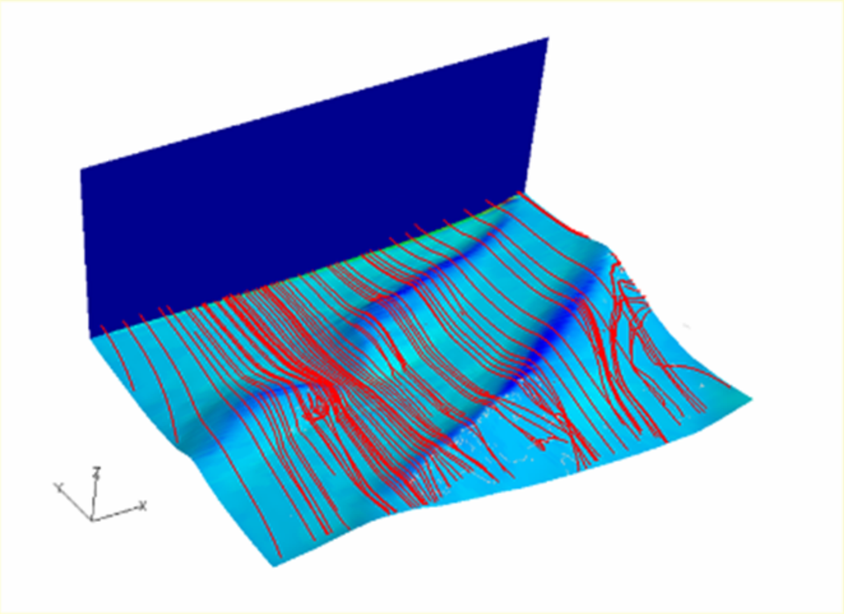




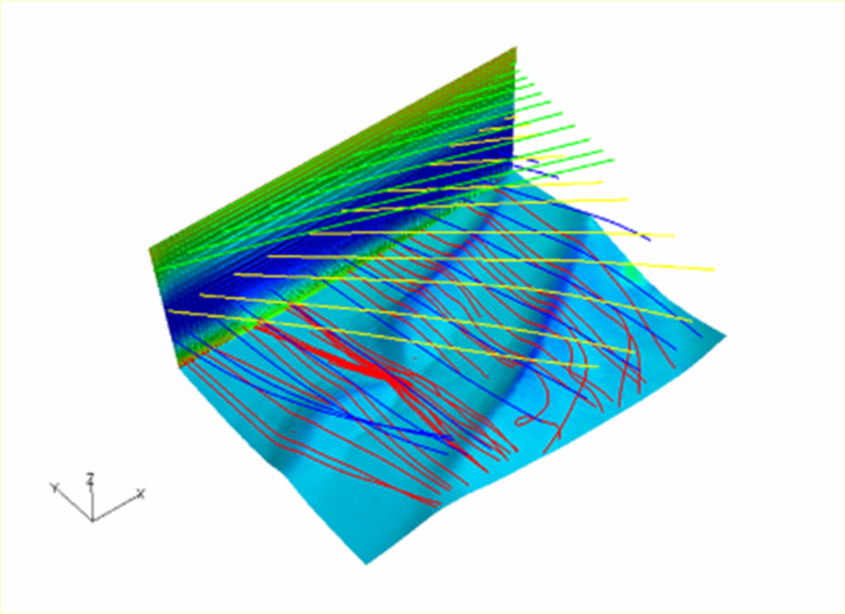
Velocity m/s

Effect of Including Mesoscale Model Data

Constant Inflow

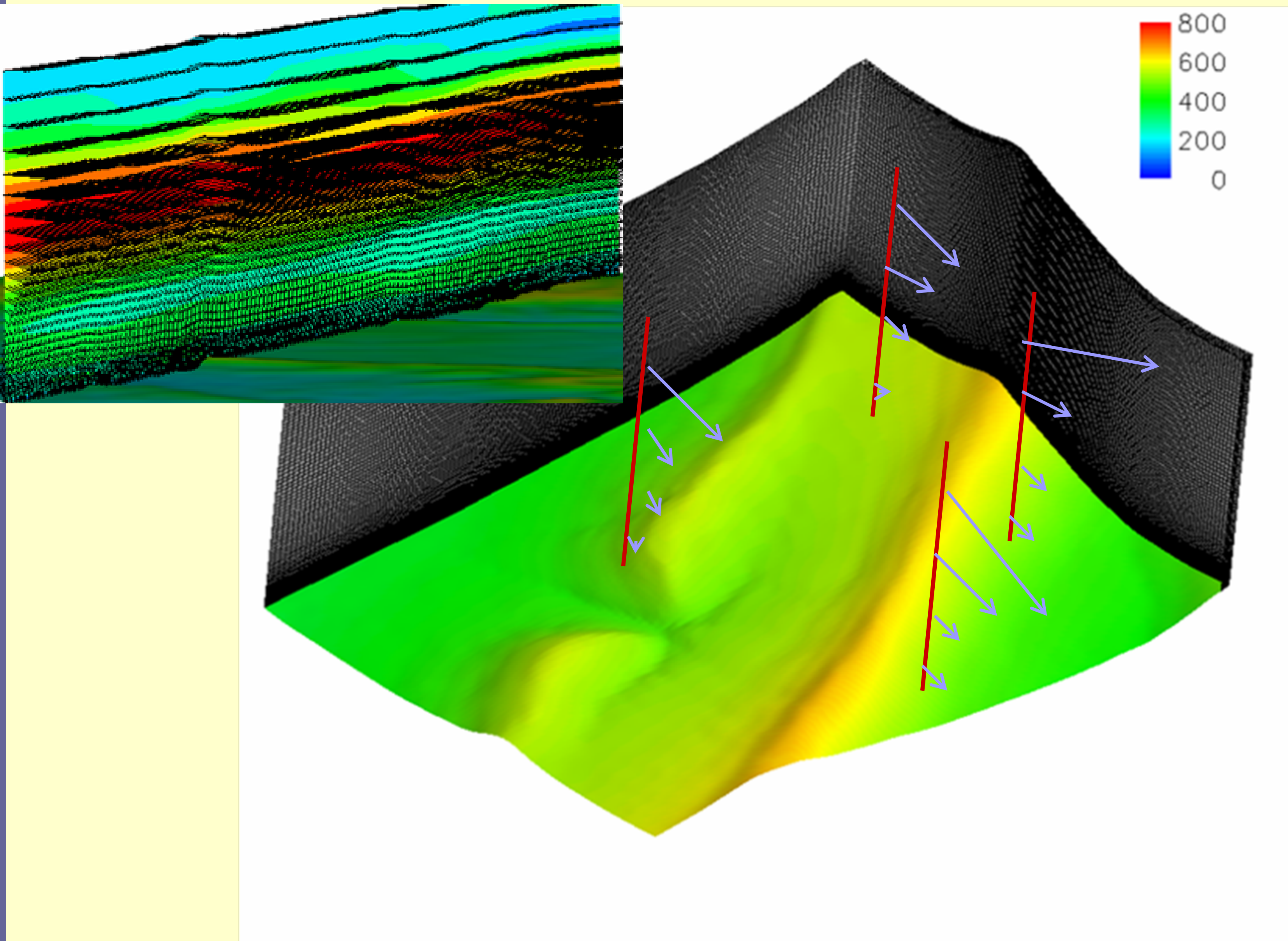


Mesoscale Inflow



Frank Zajaczkowski & Kerrie Long

Plans



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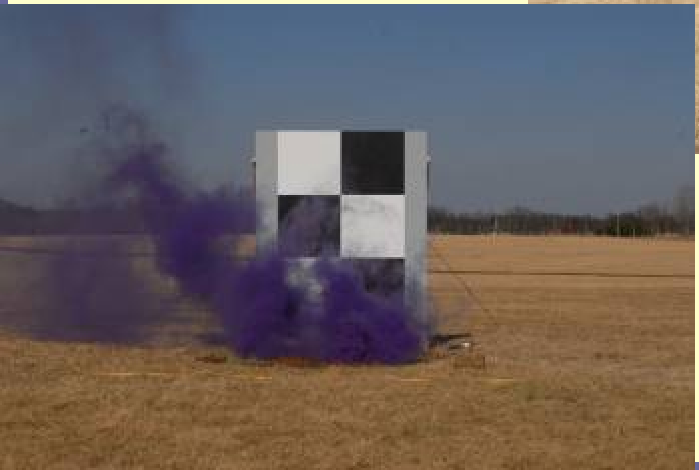
5. Smoke Plume Visualization

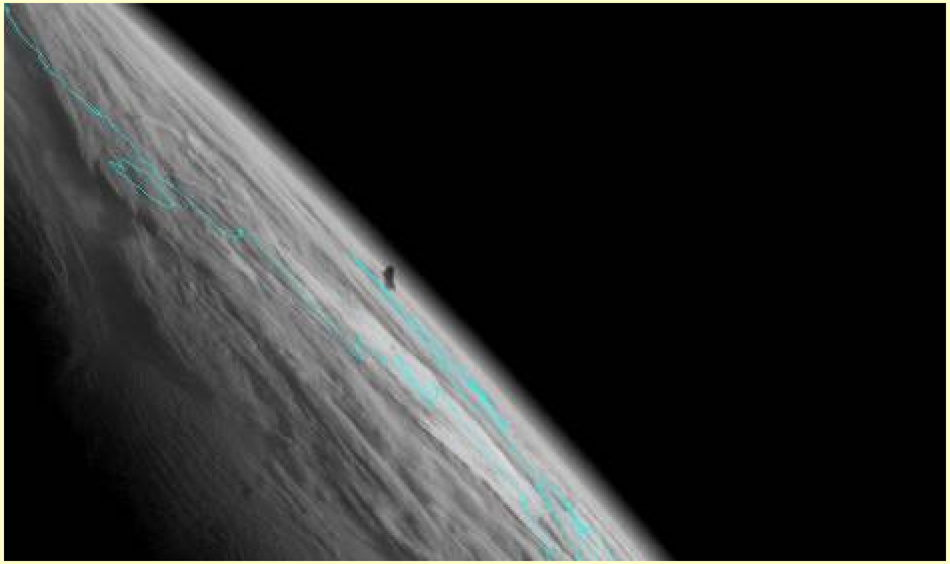


6. Modeling Volcano Emissions

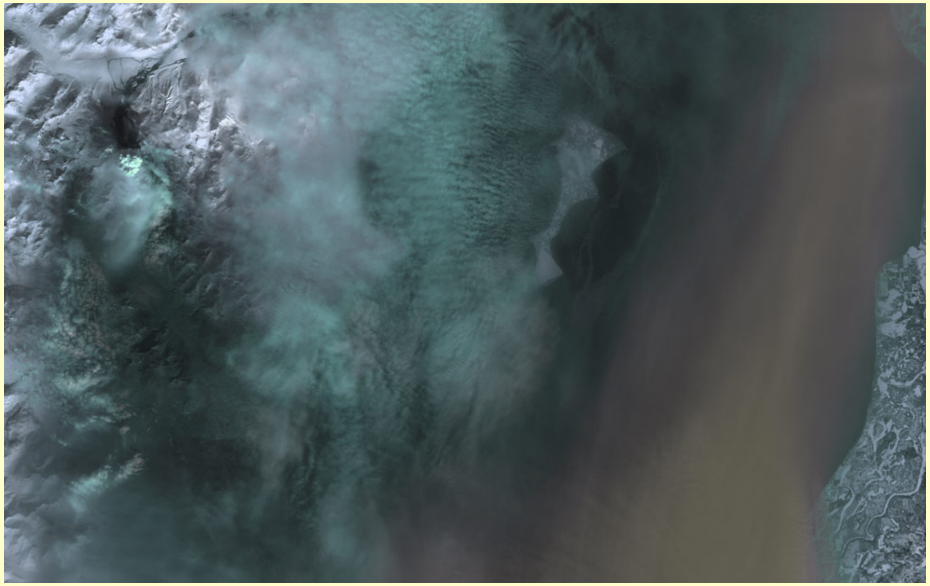
- **FAA must understand volcano paths for routing airplanes**
- **Modeling ash plumes requires good estimate of source term as well as upper level winds**
- **Can our GA-Var technique provide better modeling parameters?**

http://www.boston.com/bigpicture/2009/04/alaskas_mount_redoubt.html

From NSF Daily Briefings



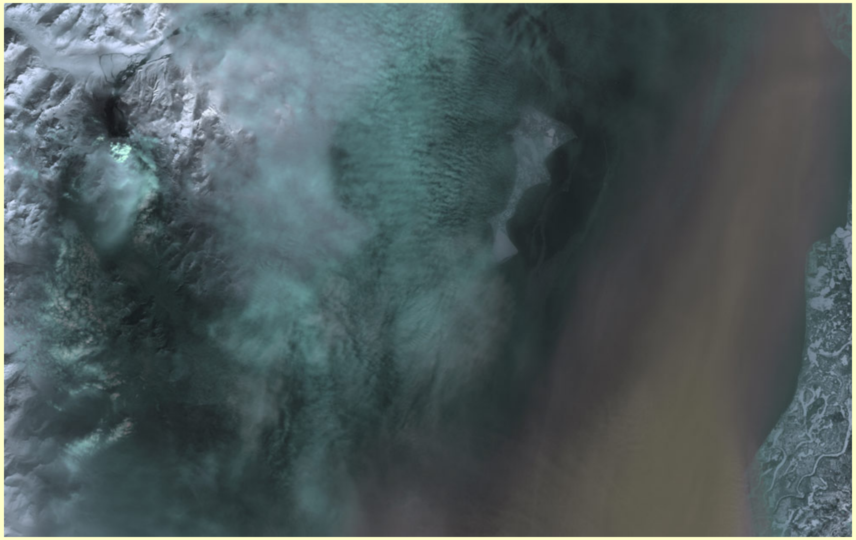
Ash cloud from Mt. Redoubt seen by the geostationary MTSAT satellite, courtesy of the National Weather Service, processed by the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison. Picture Date: March 26, 2009. (Jonathan Dehn / National Weather Service) #



Landsat 5 image of the Mt. Redoubt area on March 26,2009 at 1:07 PM AKDT. The false color image shows the large brown ash cloud extending over the Cook Inlet and the western Kenai peninsula (right side of image). The image also shows a whiter steam and gas plume rising from the summit of Redoubt Volcano (upper left). Dark lahar deposits extend north from the summit over the Drift Glacier an into the Drift River. (Ron Beck, EROS / Alaska Volcano Observatory / U.S. Geological Survey) #

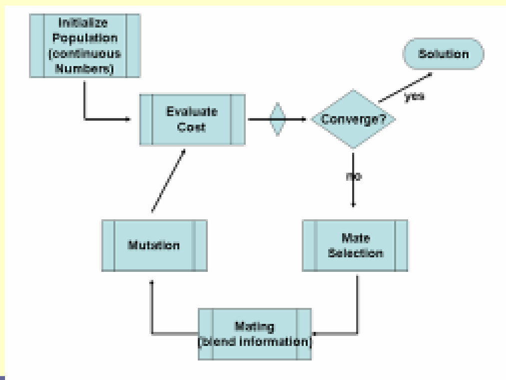
http://www.boston.com/bigpicture/2009/04/alaskas_mount_redoubt.html

Plan of Action



Use satellite data to identify, quantify, and track plume

Apply GA-Var



Estimate Source Term and modeling parameters

http://www.boston.com/bigpicture/2009/04/alaskas_mount_redoubt.html

Impact

- **Supply better source term information**
- **Produce better transport and dispersion conditions**
- **Enable FAA to better route aircraft**

http://www.boston.com/bigpicture/2009/04/alaskas_mount_redoubt.html

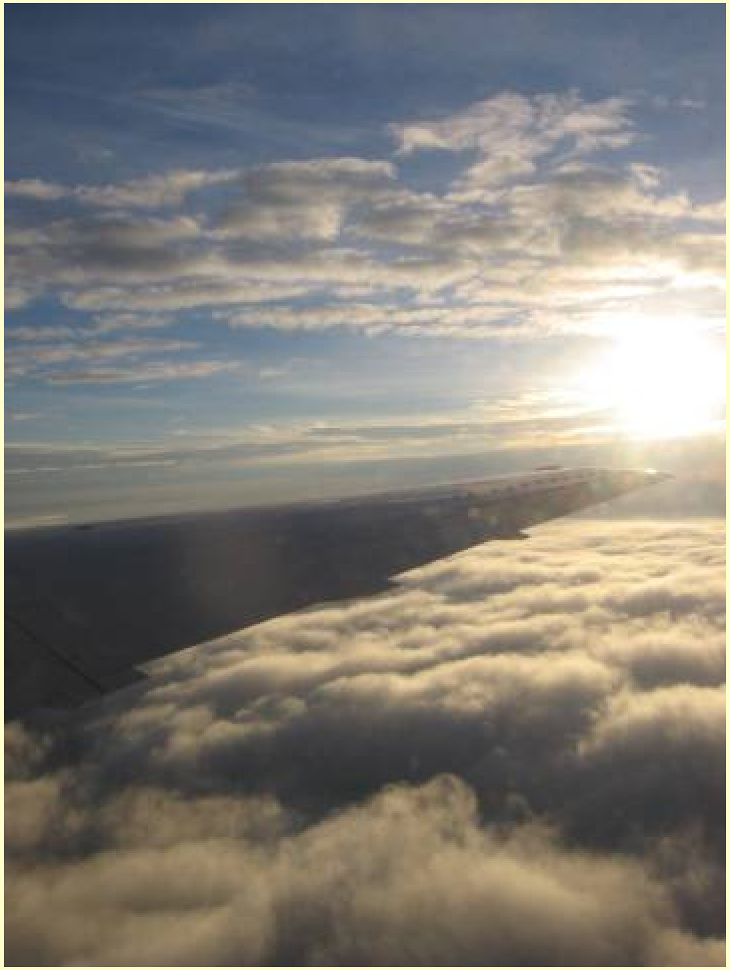
- **PSU/ARL has successfully built Dispersion and Assimilation capabilities**
  - **Assimilation for Dispersion**
  - **Source Term Estimation / Back-calculation**
  - **High Fidelity Modeling Scenarios**
  - **Assimilation for Downscaling**
  - **Plume characterization**
  - **Volcano assimilation and ash cloud modeling**

Goal:

Advance assimilation methods for a wide range of problems using interesting data

Includes:

- **New sources of data**
- **New applications**
- **New combinations of models and data**



Questions?