PSU Applied Research Laboratory
Assimilation Projects

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Associate Professor of Meteorology

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April 15, 2009
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
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

Transport and Dispersion Model

Source Information

Meteorological Information

Sensor Data
Dynamical Prediction System: \[ \frac{\partial x}{\partial t} = Mx + \eta \]

Assimilation Process: \[ \frac{\partial x}{\partial t} = Mx + \eta + G(x^0, x^f) \]

Objectives:

1. Determine realization characteristics
2. Assimilate data into forecast

Can separate into wind and concentration equations

\[ \frac{\partial \tilde{v}}{\partial t} = M_v(\tilde{v})\tilde{v} + \eta_v + G_v(\tilde{v}^0, \tilde{v}^f, C^o, C^f) \]

\[ \frac{\partial C}{\partial t} = M_c(\tilde{v})C + \eta_c + G_c(\tilde{v}^0, \tilde{v}^f, C^o, C^f) \]
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
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.
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
1 b. TusseyPuff Assimilation

- Shallow Water Model
- Wind Field
  + Concentration Field
- Puff Dispersion

TusseyPUFF

Anke Beyer-Lout
• Assess performance via RMSE:

\[ RP = \sqrt{\frac{1}{T} \sum_{\tau=1}^{T} \left[ (\bar{x}_\tau^f - \bar{x}_\tau^t)^2 + (\bar{y}_\tau^f - \bar{y}_\tau^t)^2 \right]} \]

• Puff trajectories:

\[ RW = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left[ (u_n^t - u_n^f)^2 + (v_n^t - v_n^f)^2 \right]} \]

Anke Beyer-Lout
Assimilate field sensor data to improve transport and dispersion estimate in real time.

Much better prediction with assimilation.
Sensor data fusion improves dispersion prediction.

Anke Beyer-Lout
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 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**
Given these puff locations, where is the source? What meteorological conditions exist?

Use time varying measurements

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<th>Grid Spacing</th>
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<td>2 x 2</td>
<td>8000 m</td>
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<tr>
<td>4 x 4</td>
<td>4000 m</td>
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<tr>
<td>6 x 6</td>
<td>2667 m</td>
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<td>2000 m</td>
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<td>16 x 16</td>
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<td><strong>32 x 32</strong></td>
<td><strong>500 m</strong></td>
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<td>64 x 64</td>
<td>250 m</td>
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Kerrie Long
<table>
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<tr>
<th>Grid Size</th>
<th>Found θ (°)</th>
<th>Strength (Kg s²)</th>
<th>(x,y) (m,m)</th>
<th>Release Time (s)</th>
<th>Speed (m s⁻¹)</th>
<th>Cost Function</th>
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<tr>
<td>Actual Solution</td>
<td>180.00</td>
<td>1.00</td>
<td>(0,0)</td>
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</tr>
</tbody>
</table>
Sensor Constraints

Detection Levels

Saturation Levels

Luna Rodriguez
Gaussian Puff with Thresholds

Luna Rodriguez
Skill Score Results

Detection Level at 1e-16

Detection Level at 1e-12

Detection Level at 1e-8

Detection Level at 1e-4

Luna Rodriguez
Currently modeling actual DTRA field data – reconstruct source information

Luna Rodriguez
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

Predicted dispersion about cube agrees well with measurements

Joel Peltier

Robert Wilson
• 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
High Fidelity Model of Chlorine Release

- Natatorium Footprint
- Idealized Chlorine Tank
- Exhaust Fan
- Open Door

Frank Zajakowski
Chlorine release from container

Frank Zajakowski
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

Frank Zajakowski
Chlorine Dispersion – CFD

Frank Zajakowski
Chlorine Spread through campus
Cross-Sectional Concentration (ppm)
Time ~ 6 min from release

Predicted levels of chlorine exposure in the stadium small
Hypothetical Chlorine Release

Frank Zajakowski

Kerrie Long
Regional Chlorine Dispersion - HPAC
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
WRF-ARW Setup

- Five grid nests
  - 36 km
  - 12 km
  - 4 km
  - 1.33 km
  - 444 m
- One-way interface from coarse to fine
- 43 Vertical layers
- 5 layers in lowest 10 m with 2 m spacing
- FDDA
- http://www.meteo.psu.edu/~wrfrt/
• 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
Case – Rock Springs

1.33 km grid

Dataset: d04 480 realtime tfe
Init: 0000 UTC Wed 6 Jan 08
Post: 1200 UTC Wed 6 Jan 08
Valid: 1200 UTC Wed 6 Jan 08
Temperature at k-index = 30

Dataset: GR4 480 realtime dpwsc
Init: 0000 UTC Wed 6 Jan 08
Post: 1200 UTC Wed 6 Jan 08
Valid: 1200 UTC Wed 6 Jan 08 (1800 EST Wed 6 Jan 08)
Temperature

Velocity m/s
Effect of Including Mesoscale Model Data

Constant Inflow

Mesoscale Inflow

Frank Zajaczkowski & Kerrie Long
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?

Data Sources

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) #

Plan of Action

Use satellite data to identify, quantify, and track plume

Apply GA-Var

Estimate Source Term and modeling parameters

Impact

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

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