Improving Sensor Siting for Plume Detectability with Multiscale Atmospheric Transport Modeling

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Abstract

Multiscale simulations of atmospheric transport models (ATM) resolve both mesoscale meteorology, such as frontal passages, and microscale meteorology near-source, which is often strongly influenced by complex terrain and heterogeneity of the land surface. Local variations in atmospheric flow and transport can drive the ability of sensors to detect passing plumes of noble gas and particulates. Insight into these variations can help optimize sensor siting to maximize network detectability. Resolving the diverse meteorological phenomena of interest within a multiscale simulation requires a highly capable model, significant computational resources, and detailed knowledge of the local and synoptic conditions. Here, we discuss model skill and lessons learned from multiscale transport and dispersion simulations of controlled smoke releases during a recent observational field campaign in Nevada using the Weather Research and Forecasting model as well as legacy films and data. Additionally, we introduce runtime improvement using Adaptive Mesh Refinement and the Energy Research and Forecasting (ERF) model, which is a young model undergoing rapid development for multiscale ATM simulations. ERF is a highly efficient and scalable atmospheric model designed to take advantage of the latest supercomputing resources with hybrid (CPU and GPU) architectures, which will allow for fast-running multiscale simulations approaching operational timescales.

Sensor Placement

- Multiple factors can play a role in determining sensor placement.
- Optimal locations for detectability may not be accessible, especially in regions of complex terrain.
- Detection probabilities are typically derived from expected weather conditions, not actual conditions (i.e., weather vs climate).
- Multi-dimensional, multi-objective optimization can be combined with Bayesian inference to improve sensor placement and plume detectability.
- Signal detection theory (i.e., Receiver Operating Characteristic, ROC, curves) are used to discriminate signal from background values.

Challenge of sensor siting and complex environments

Sensor Optimization Loop

Choose sampling locations and times

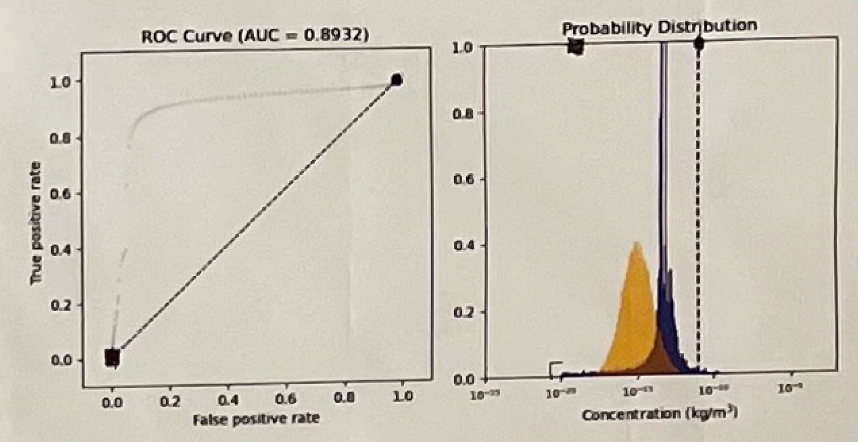
Bayesian Estimation Loop

For a given sensor network

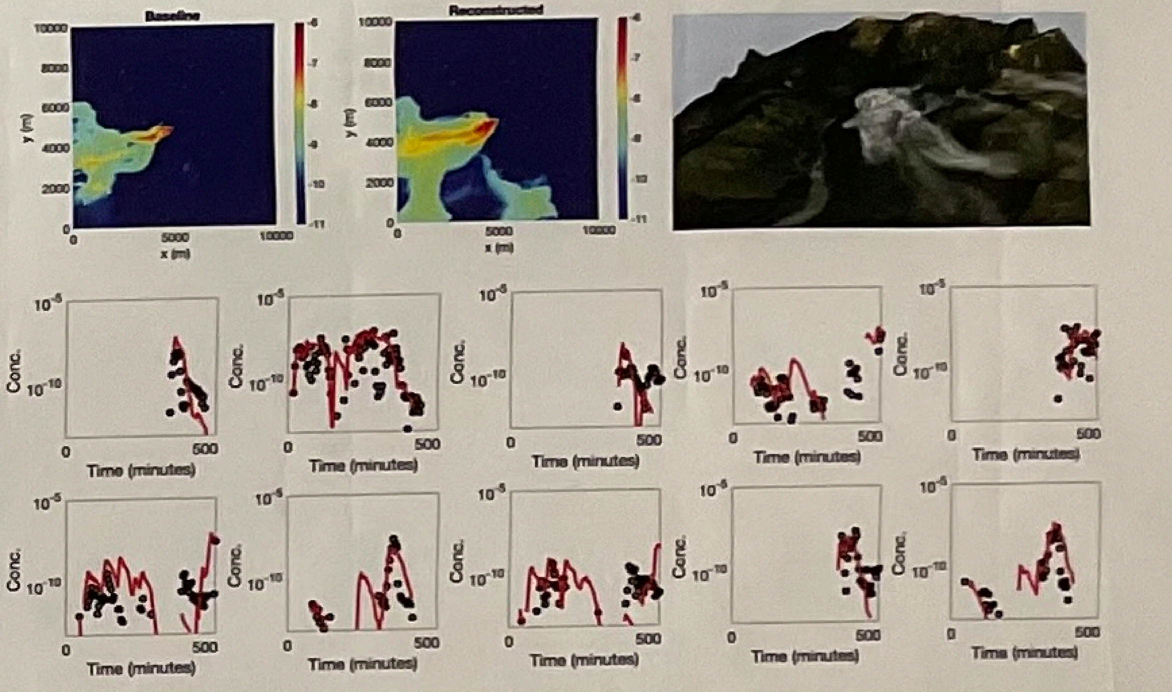
$$p(D|N) = \frac{p(N|D)\,p(D)}{p(N)}$$

Detection PDFs from a network for a given sensor configuration.

Minimize detection uncertainty subject to constraints (e.g., site accessibility)



- The blue probability distribution is the raw sensor data from the sensor network for a given scenario and environmental conditions.
- The yellow probability distribution is the background concentration.
- The detection limit is varied to generate an ROC curve which gives the measure of sensor sensitivity and false positive rate for the group of sensors in the given conditions.
- Curves that are above the 1:1 line indicate sensors that can discriminate signal from background.



An ensemble of ATM simulations can quickly approximate long-duration releases from an underground source. The figure compares atmospheric dilution factors between high fidelity "ground truth" simulation (baseline and red line) with the approximation (reconstructed and black dots).

Meteorology focused experiment METEX21 and model validation

Nevada experiment

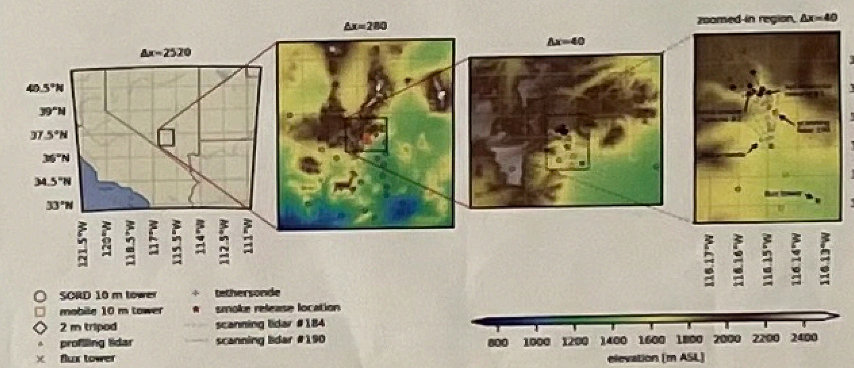
- 5-km domain of interest including Aqueduct Mesa, Aqueduct Valley, and Tongue Wash
- Dense meteorological observations:
  - 20 meteorological towers
  - 11 mobile 10-meter meteorological towers
  - 6 2-meter meteorological tripods
  - LiDAR systems
    - ✓2 scanning
    - ✓3 profiling
  - 1 tethered balloon system
    - ✓Met & particle sensors
  - Weather balloon launched radiosondes
  - 1 3-meter energy flux tower
  - 40 smoke releases across 7 release sites
- Archived data available upon request

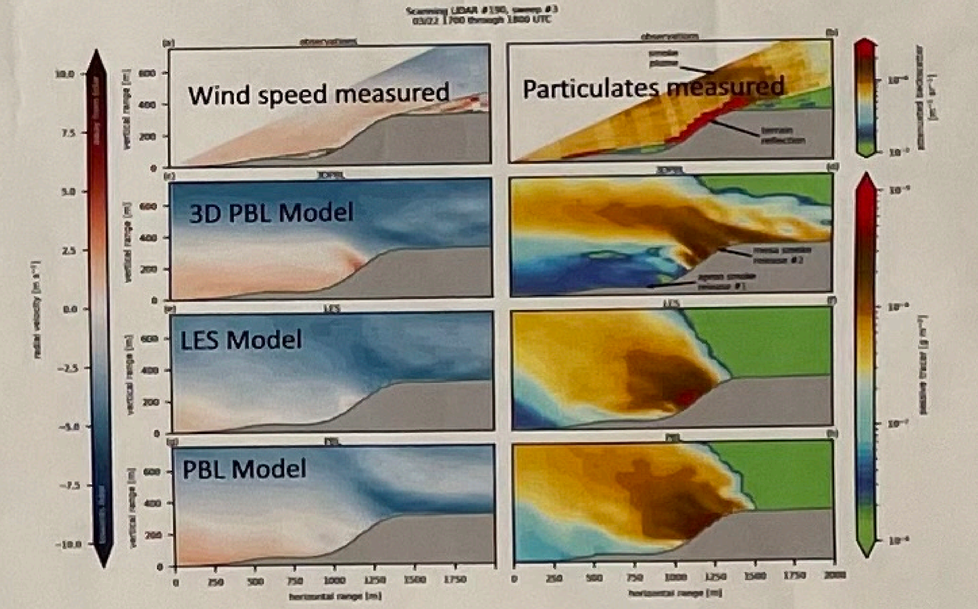
Please see our recent publication! Wharton et. al 2023, "Capturing plume behavior in complex terrain: an overview of the Nevada National Security Site Meteorological Experiment (METEX21)"

Weather Research Forecast (WRF) Model Configuration

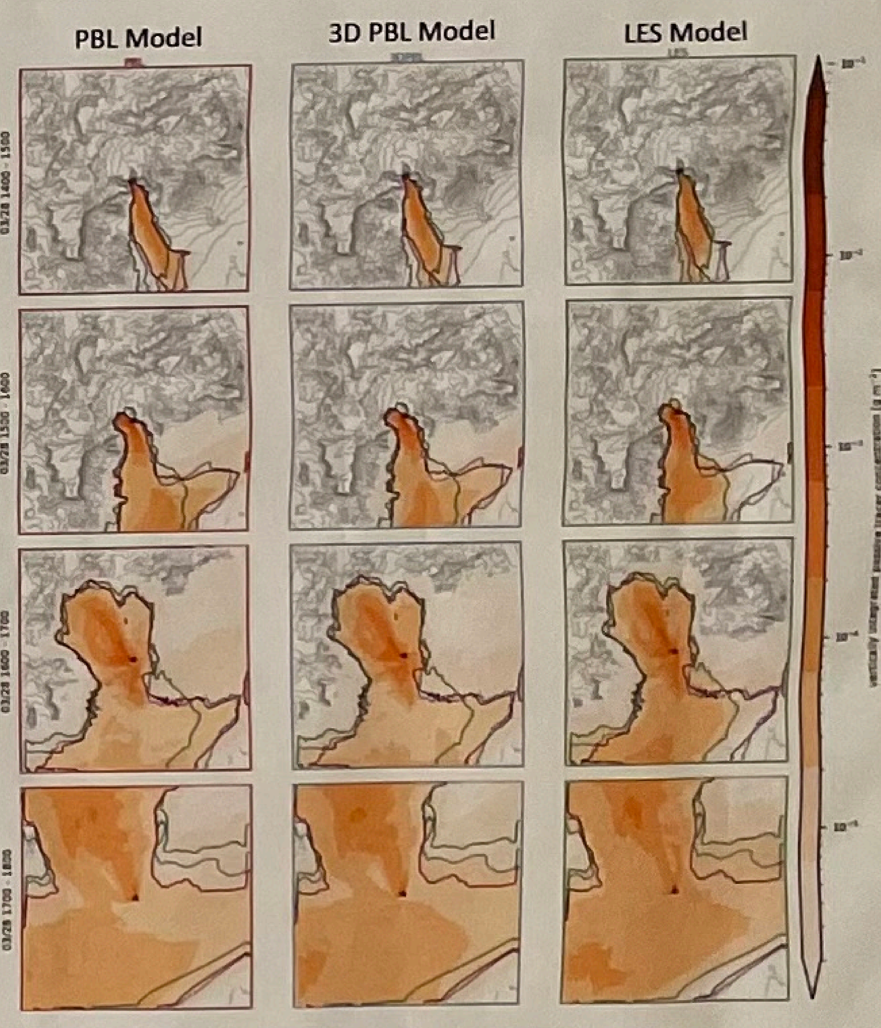
- Large Eddy Scale (LES) version of WRF
- Transitions from mesoscale → microscale
  - cell perturbation method
    - ✓develops turbulence after grid refinement
  - planetary boundary layer scheme used at mesoscale
  - 3D Planetary Boundary Layer (PBL) scheme used at intermediate resolutions
  - large eddy simulation used at microscale
- Resolution of mountainous terrain
  - high resolution digital elevation model (10 meter SRTM)
- Resolution of thermally driven slope flows
  - shading of incoming solar radiation by topography

Please see our recent publication! Wiersema et. al 2023, "Assessing turbulence and mixing parameterizations in the gray-zone of multiscale simulations over mountainous terrain during the METEX21 field experiment"





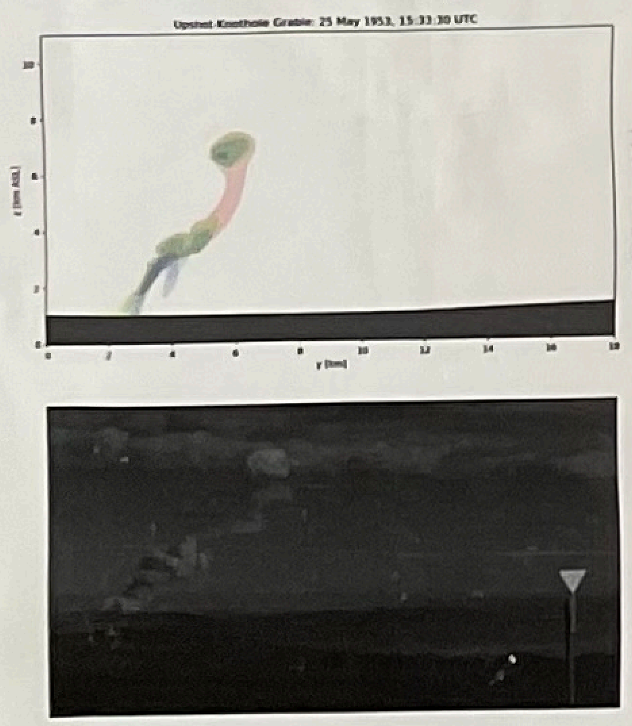
Example of data-model comparison, vertical profile



Birds eye comparison of predicted plumes using three methods to parameterize turbulence and mixing

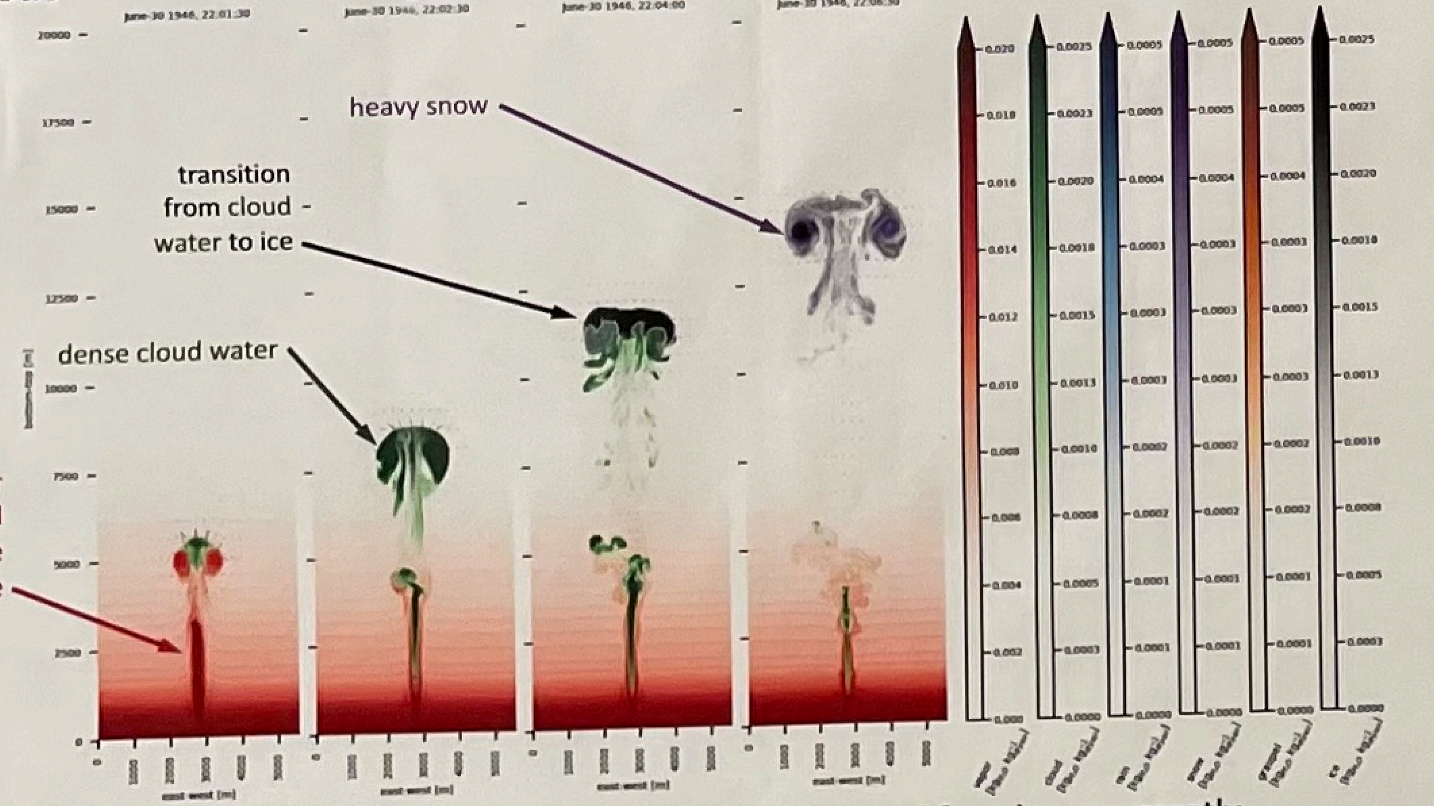
High-fidelity simulations of cloud rise using legacy codes

Model Validation Using Film And Debris Fallout



Please see our recent publication! Lundquist et. al (2023) "Examining the effects of soil entrainment during nuclear cloud rise on fallout predictions using a multiscale atmospheric modeling framework"

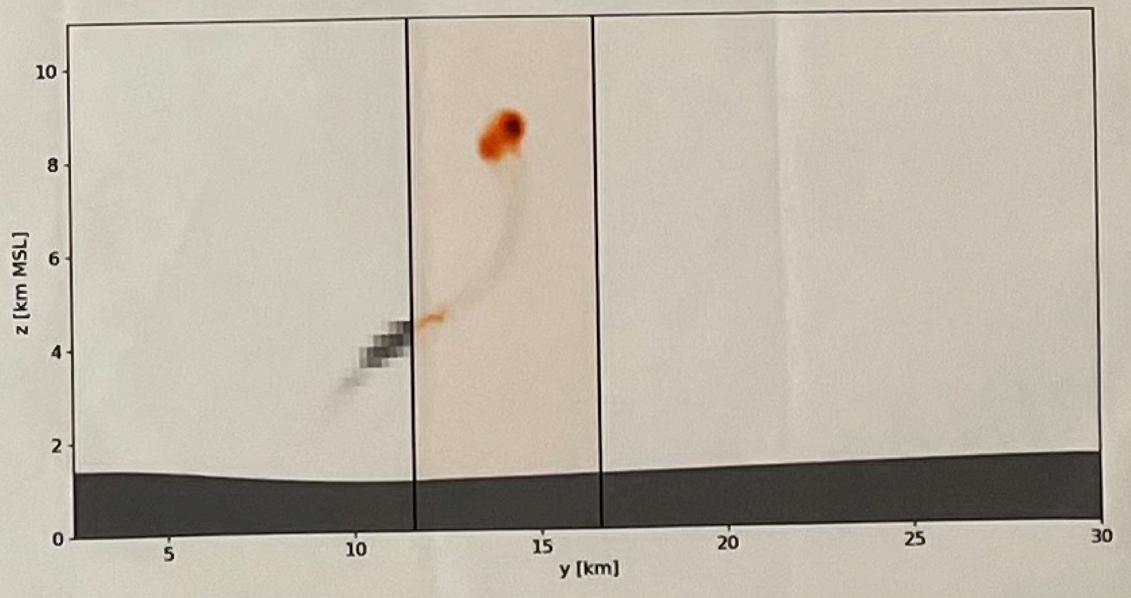
Simulating Precipitation In A Humid Environment



- Latent heating due to water condensation and freezing can greatly increase predicted cloud heights.
- Predictions are sensitive to moisture content of the atmosphere.

Development of exa-scale methods and capabilities for faster simulation

Adaptive Mesh Refinement Simulation Increases Run-time



- WRF moving nests track cloud rise, reducing simulation time from 50 to 5 hours. With Adaptive Mesh Refinement this simulation could be completed on an operational timescale.

Please see our recent publication! Almgren et. al 2023, "ERF: Energy Research and Forecasting"

ERF will enhance scientific capabilities

- Cloud-tracking moving grids for current WRF LES model
- Development of exa-scale weather model, Energy Research and Forecasting (ERF) model
- Coupling ERF model with ALE3D (microscale) and E3SM (global scale) codes to enable multiscale simulation
- Methods for tracking debris evolution and coupling between Lagrangian and Eulerian quantities on adaptive grids
- Cut cell/immersed boundary methods for representing complex domains and approaches for representing processes across multiple resolutions
- Numerical methods tailored to tracking hazardous releases on adaptive grids

Anticipated impacts of ERF

- A performance portable simulation tool optimized for large-scale heterogenous systems
- Sustainable software enabling future development and continued performance across computing systems
- Efficient algorithms for multiscale simulation including methods for code coupling, bridging scales, Lagrangian methods with AMR, and time evolution

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