CVT Workshop 2017

Understanding Uncertainties in Atmospheric Transport Modeling for Radionuclide Monitoring

Consortium for Verification Technology
Thrust Area Four

Matthew J. Krupcale, John C. Lee

University of Michigan

November 29, 2017

Outline

- Uncertainties in ATM of RNs
  - Fukushima Daiichi nuclear accident
    - Systematic errors due to meteorological data uncertainty
  - Volcanic ash study
    - Random errors due to Monte-Carlo sampling uncertainty
    - Systematic errors due to physical model uncertainty
  - Gaussian plume model
    - Systematic errors due to physical model uncertainties in characterization of turbulent velocity fluctuations
- Identify source and nature of radionuclides in the atmosphere
  - September 3, 2017 DPRK weapon test

Atmospheric transport model

- Stochastic drift-diffusion equation for turbulent velocity: FLEXPART and HYSPLIT

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\cancel{\nabla \cdot \boldsymbol{\tau}} \tag{1}$$

$$\Rightarrow \frac{\partial (\bar{\mathbf{u}} + \mathbf{u}')}{\partial t} + \nabla \cdot ((\bar{\mathbf{u}} + \mathbf{u}')(\bar{\mathbf{u}} + \mathbf{u}')) = -\frac{1}{\rho}\nabla (\bar{p} + p')$$

$$\Rightarrow \frac{\partial \bar{\mathbf{u}}}{\partial t} = -\bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}} - \frac{1}{\rho}\nabla \bar{p} - \nabla \cdot \langle \mathbf{u}'\mathbf{u}' \rangle$$

$$\frac{\mathrm{d}\bar{\mathbf{u}}}{\mathrm{d}t} = \underbrace{-\alpha \bar{\mathbf{u}} - \frac{1}{\rho}\nabla \bar{p}}_{\text{drift}} + \underbrace{\sigma \frac{\mathrm{d}W_t}{\mathrm{d}t}}_{\text{diffusion}} \tag{2}$$

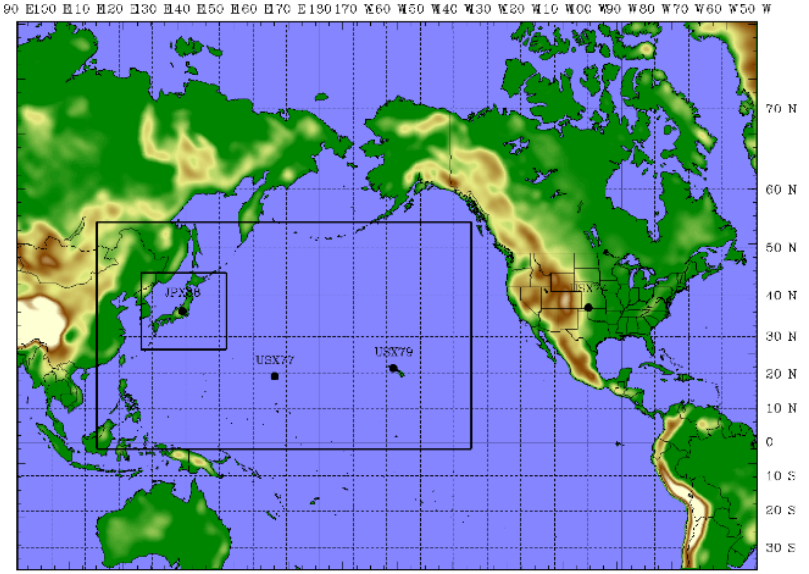
- Advection-diffusion equation: Gaussian plume model

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C - \nabla \cdot (k \nabla C) = q(\mathbf{x}, t) \tag{3}$$

Systematic errors: meteorological data uncertainties – Fukushima

- Fukushima nuclear accident case study in collaboration with LLNL
- Created ensemble of meteorological data sets using WRF model: 3 different global data sets and different planetary boundary layer physics models
- Compared FLEXPART simulated IMS detector concentrations with measurements

Fukushima nuclear power plant

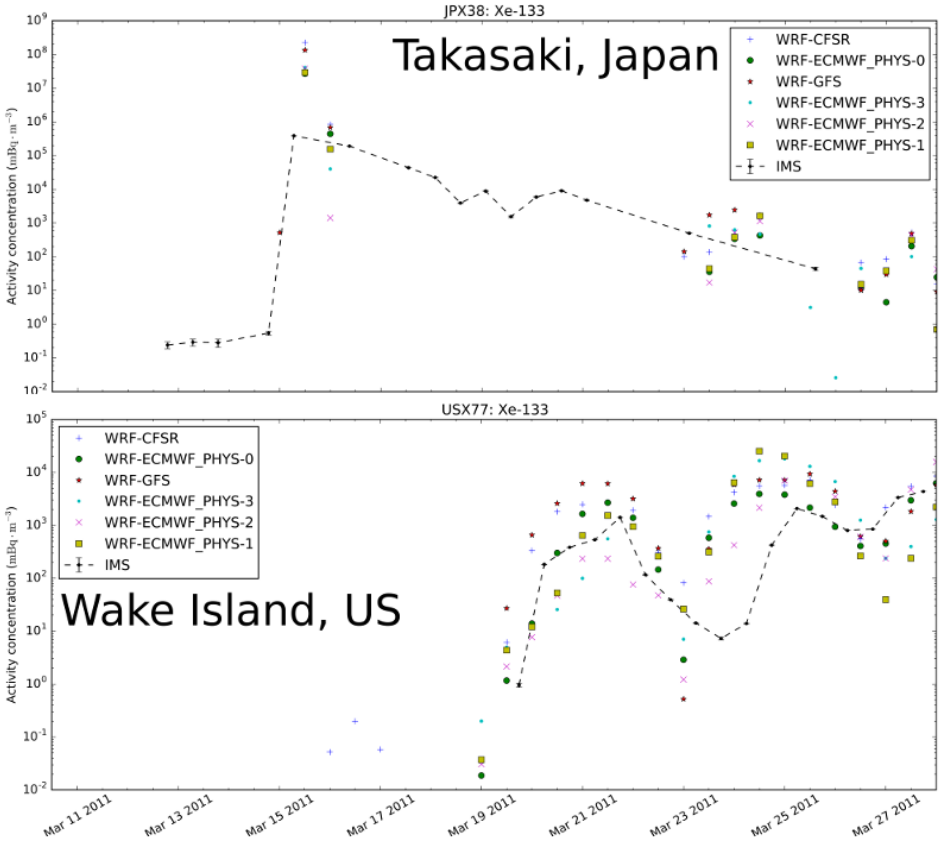


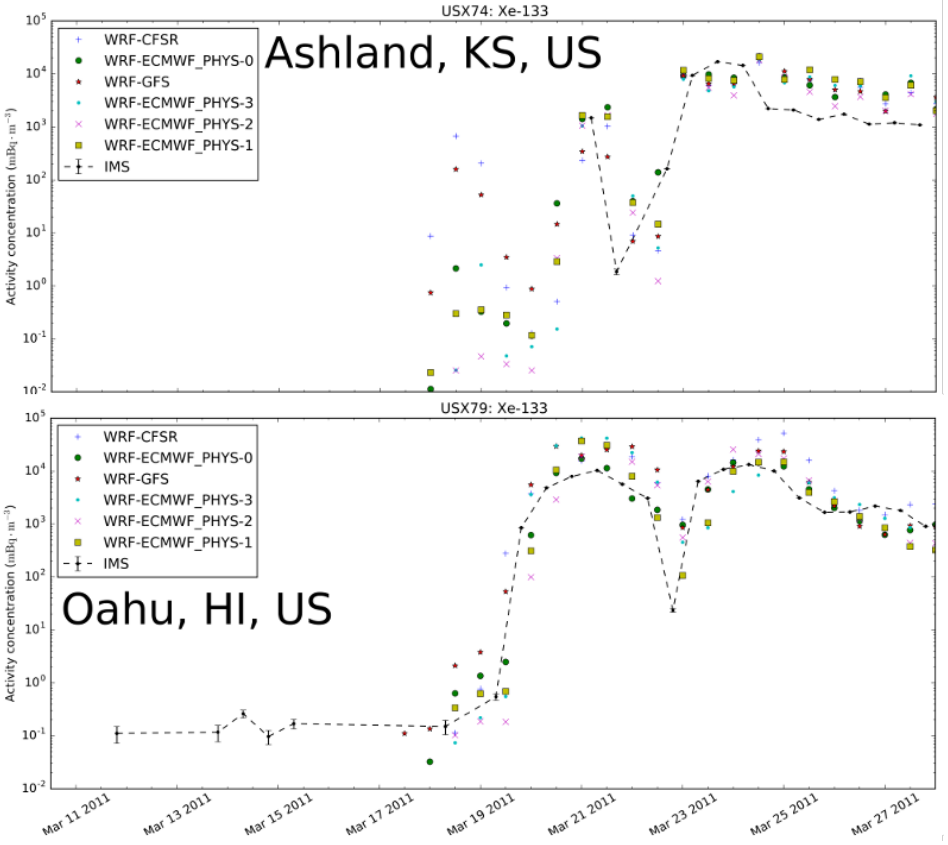
WRF model domain configuration nesting down to 5 km horizontal spacing over Japan.

National Nuclear Security Administration

Systematic errors: meteorological data uncertainties – Fukushima

- Overall good agreement with FLEXPART simulated concentrations and IMS observations
- FLEXPART ensemble predicted concentration ranges 1-4 orders of magnitude

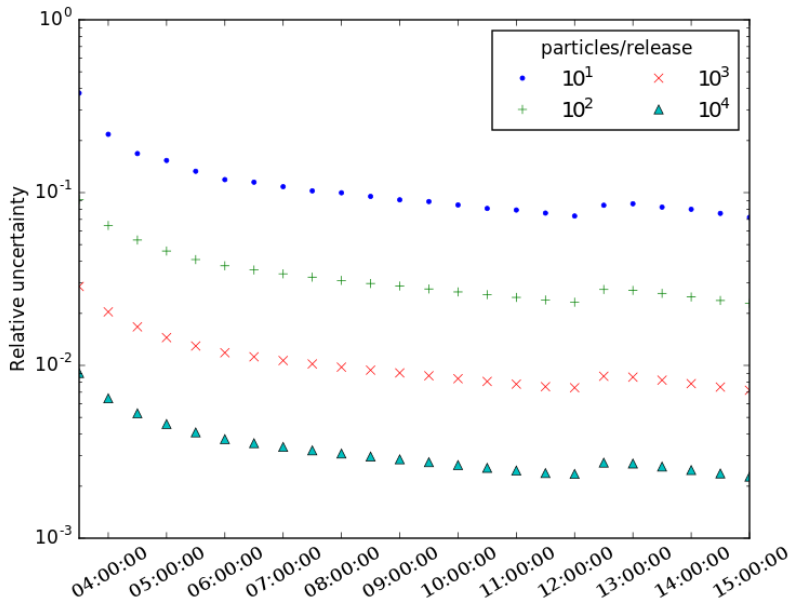


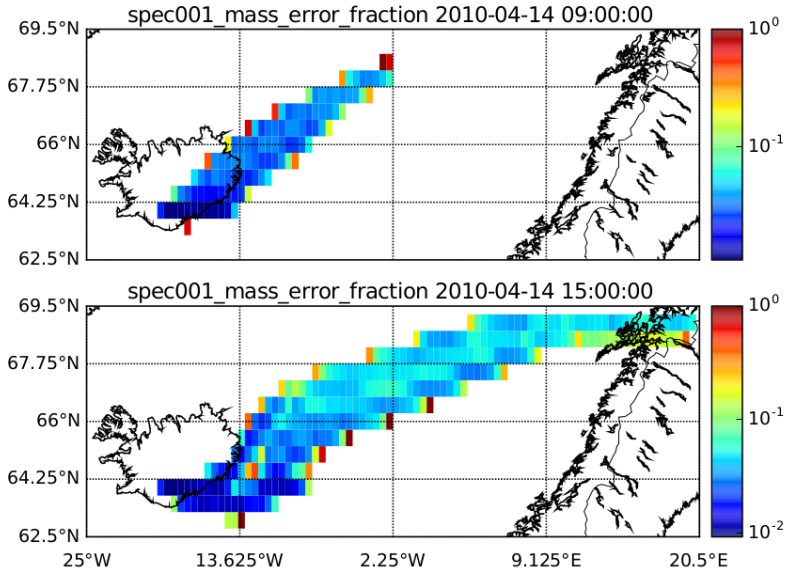


Random errors: particle ensemble statistical uncertainty – volcanic ash

- Concentrations averaged over Green's function through Monte-Carlo sampling

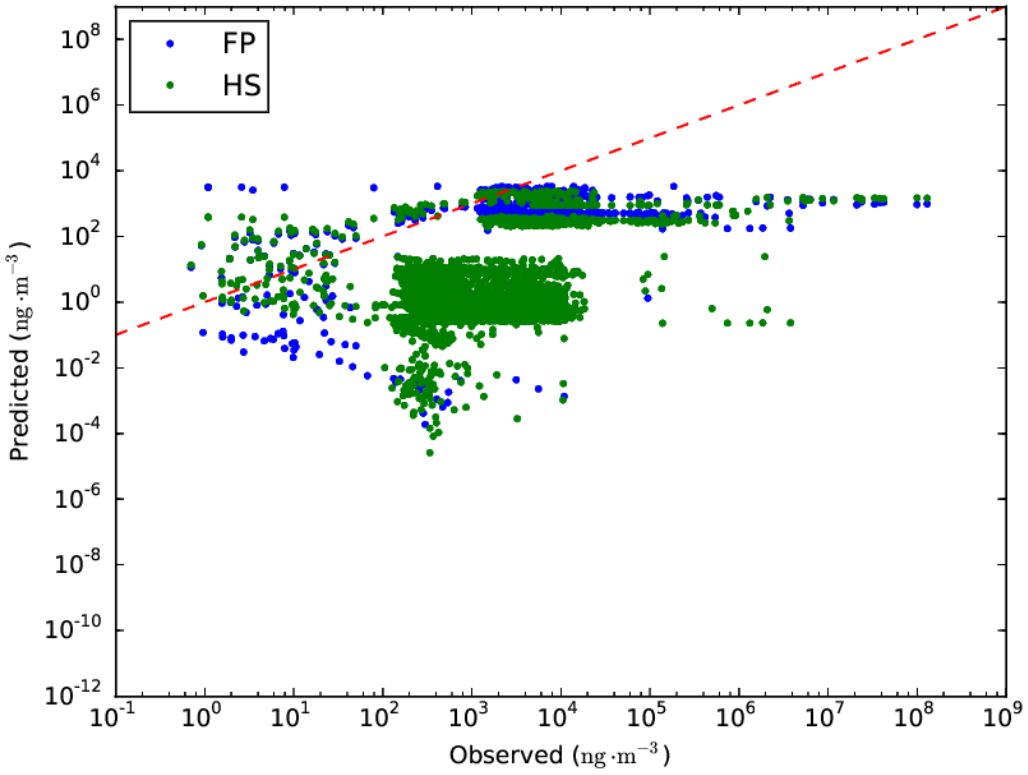
$$\langle C(\mathbf{x},t)\rangle = \int_{t'<t} C(\mathbf{x},t|\mathbf{x}',t')q(\mathbf{x}',t')\mathrm{d}^3\mathbf{x}'\mathrm{d}t'$$





Systematic errors: physical model uncertainties – volcanic ash

- Compared model concentrations to aircraft measured concentrations
- Relatively good agreement between ATM codes, but underestimating concentration



Systematic errors: physical model uncertainties – Gaussian plume

- Gaussian plume study with parameterized atmospheric stability
- Puff source at t=0, z=z_0 with uniform, time-invariant wind velocity
- Compared FLEXPART simulated concentration profile with Pasquill empirical dispersion correlations

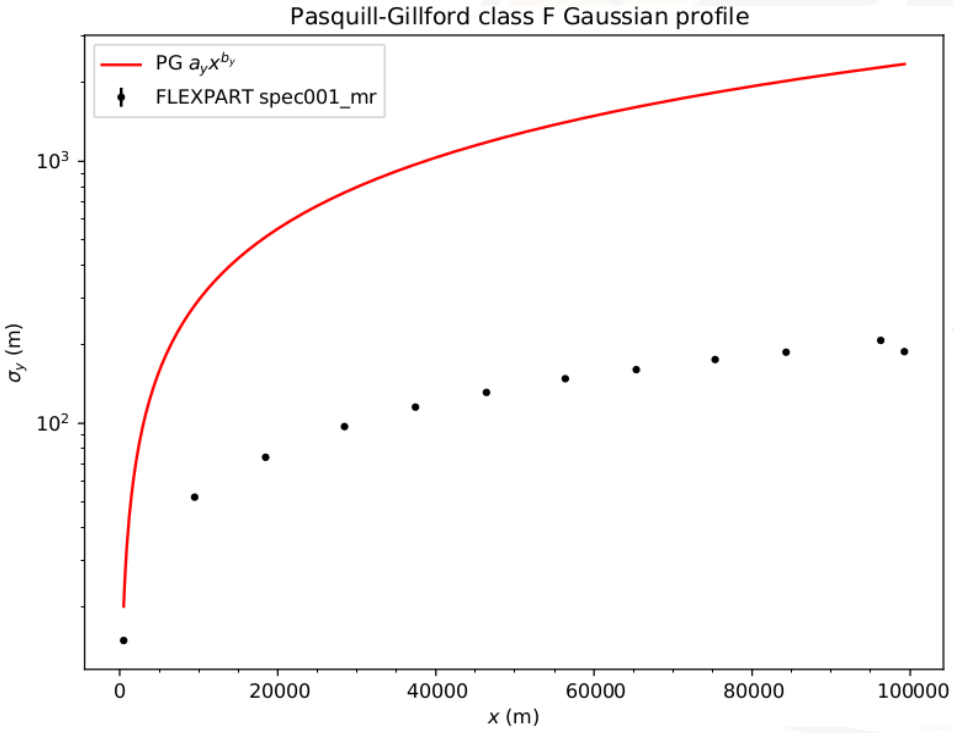
$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C - \nabla \cdot (k \nabla C) = Q(\mathbf{x}, t)$$

$$\Rightarrow C(\mathbf{x}, t) = \frac{Q_0}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp\left(-\frac{(x - ut)^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right) \times \left[\exp\left(-\frac{(z - z_0)^2}{2\sigma_z^2} \right) + \exp\left(-\frac{(z + z_0)^2}{2\sigma_z^2} \right) \right]$$

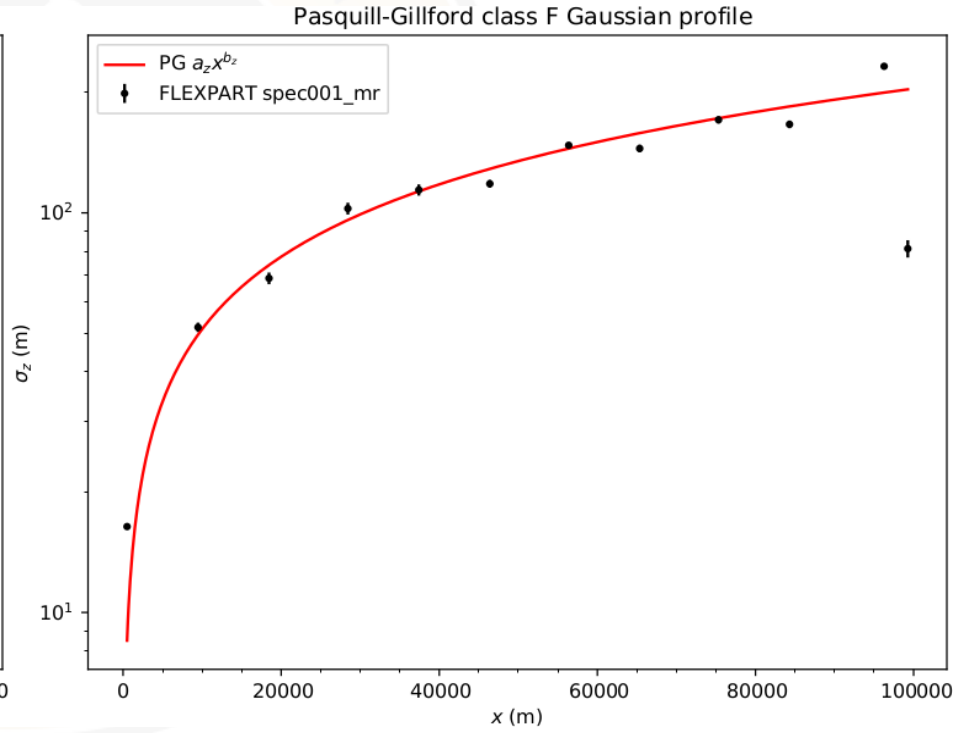
$$\sigma_i = \sigma_i(x)$$

Systematic errors: physical model uncertainties – Gaussian plume

- Agreement better for vertical σ_z than horizontal σ_y needs further understanding



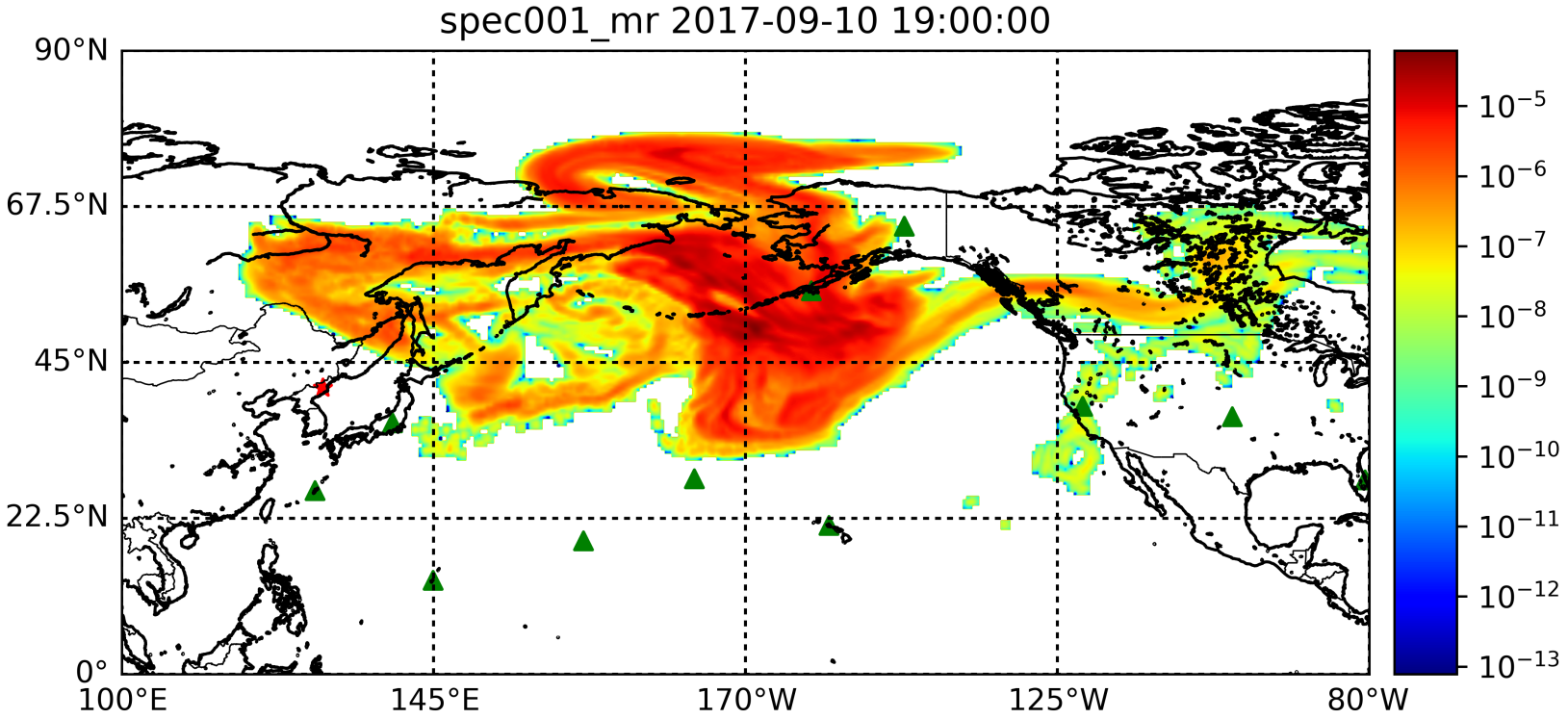
Horizontal dispersion coefficient σ_y



Vertical dispersion coefficient σ_z

September 3, 2017 DPRK weapon test Xe-133 emissions

- Initial simulations of September 3, 2017 DPRK nuclear weapons test
- May not support KINS report of Xe-133 observations on Sept. 10
- Limited US IMS radionuclide detection information



Conclusions and future work

- Fukushima ATM
  - Overall good agreement between predicted and observed IMS concentrations
  - FLEXPART ensemble predicted concentration ranging 1-4 orders of magnitude, indicating large meteorological data uncertainties
- Volcanic ash study
  - At least 10^4 particles/release or 10^7 total particles required for reasonable relative uncertainties due to random errors
  - Deposition model is a large source of uncertainties
- Gaussian plume study
  - There are significant variations observed in the dispersion factors within a meteorological stability class
  - FLEXPART model may not be able to represent the Gaussian plume model with Langevin equation
- Future work
  - Continue to characterize and quantify systematic uncertainties due to meteorological data and physical model parameterizations
  - Incorporate statistical and systematic uncertainties into source estimation methods using Bayesian maximum a posteriori or Kalman filtering algorithms
  - Study the connection between the advection-diffusion and stochastic drift-diffusion models