# National Atmospheric Release Advisory Center (NARAC) Source Estimation Capabilities: R&D to Operations

*CTBTO ATM Workshop*
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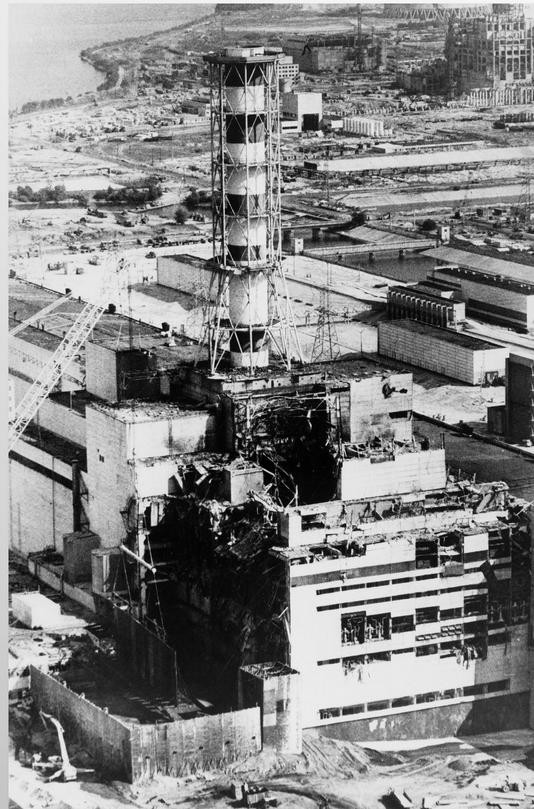
Lawrence Livermore National Laboratory

National Atmospheric Release Advisory Center
NARAC

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC. The Department of Homeland Security sponsored part of the production of this material.

LLNL-PRES-660636

# NARAC Provides Critical Information to Protect the Public and the Environment

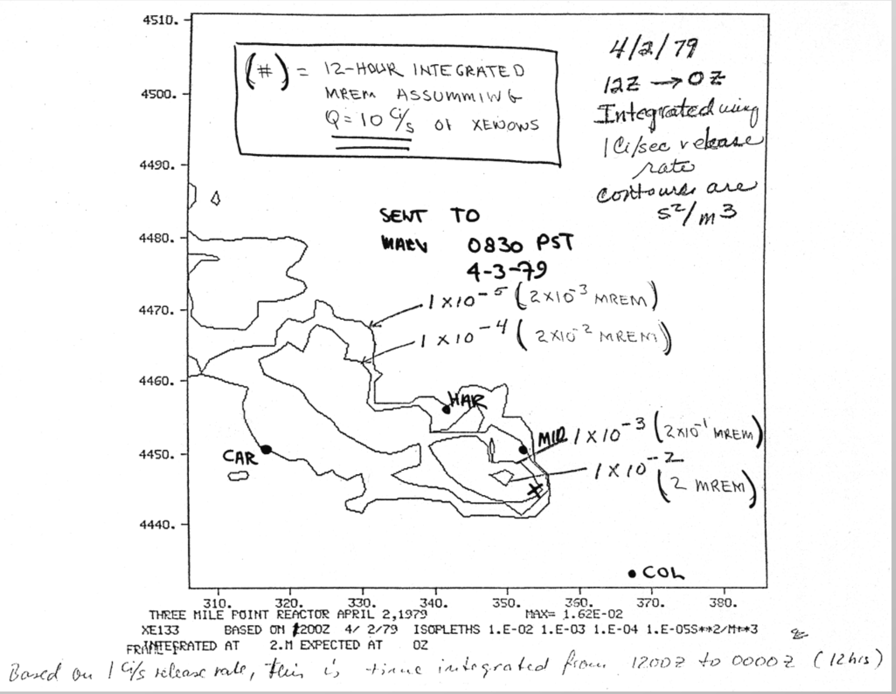


Hazardous airborne releases are a rapid and effective means to impact large populations. NARAC responds to toxic industrial chemical spills, nuclear-power plant accidents, fires, chemical/biological agents, radiological dispersal devices (RDDs), nuclear detonations, and some natural airborne hazards.

# Operational Center Founded During Three Mile Island (Dept. of Energy / Nuclear Regulatory Commission)

Original DOE Operations Center at LLNL

Three Mile Island Nuclear Power Plant and DOE Aerial Measuring System (AMS)




NARAC prediction of downwind dose from a potential release from the Three Mile Island nuclear power plant

# Component-based NARAC Computer Systems at LLNL Support In-house and External Users

**LLNL Computer Systems**

Central System: Automated model set-up and execution software

- Weather Data & Forecasts
- Geographic/Terrain Data
- CBRN Material Property Data
- Dose/Risk Factor Data
- Measurement Data
- Source models
- 3-D Meteorological, Dispersion and Fallout Models
- Prompt Effects Models
- Data-driven modeling tools
- Mapping and product generation software
- Population, casualty and fatality estimation

Remote Access Computer System

User interfaces and Analysis Tools for LLNL scientists

**Internet/Intranet**

External User Tools

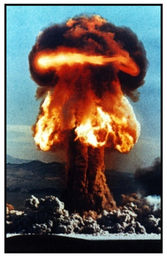

*CM/NARAC/IXP Web*

Standalone models and mapping

*HotSpot*
*EPIcode*

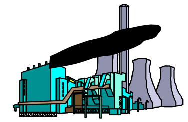
# NARAC Modeling System Predicts Consequences of Radiological/Nuclear Incidents

Nuclear Detonation source models:
- LLNL *KDFOC*
- LLNL *LWAC*
- ORNL *ORIGEN*
- ORNL *DELFIC*



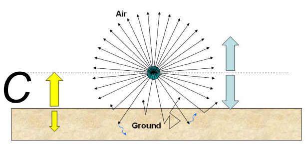
RDD Source models:
- SNL *Source Term Calculator*
- SNL *PUFF*

Nuclear power and fuel sources:
- NRC *RASCAL*

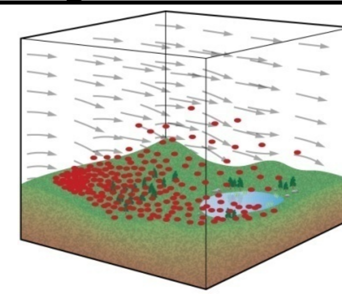


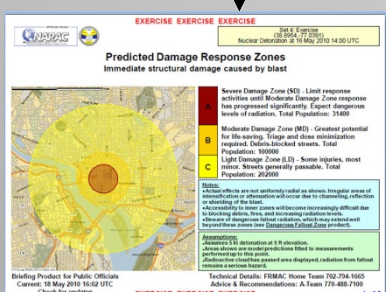
Fire source model:
- LLNL

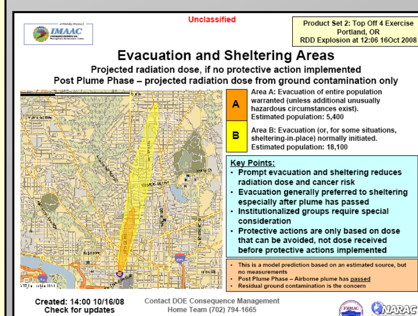
NucDet (IND) and RDD Prompt effects models:
- SNL *Nuke*
- SNL *Blast*
- LLNL *LWAC*




3-D Atmospheric Dispersion and Fallout models:
LLNL *ADAPT/LODI*



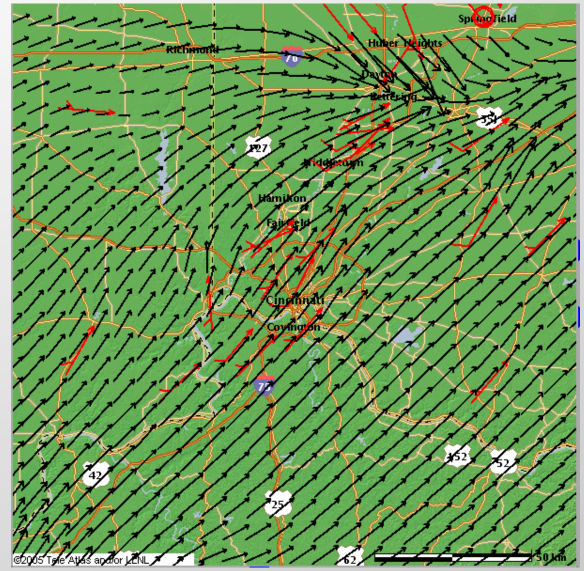


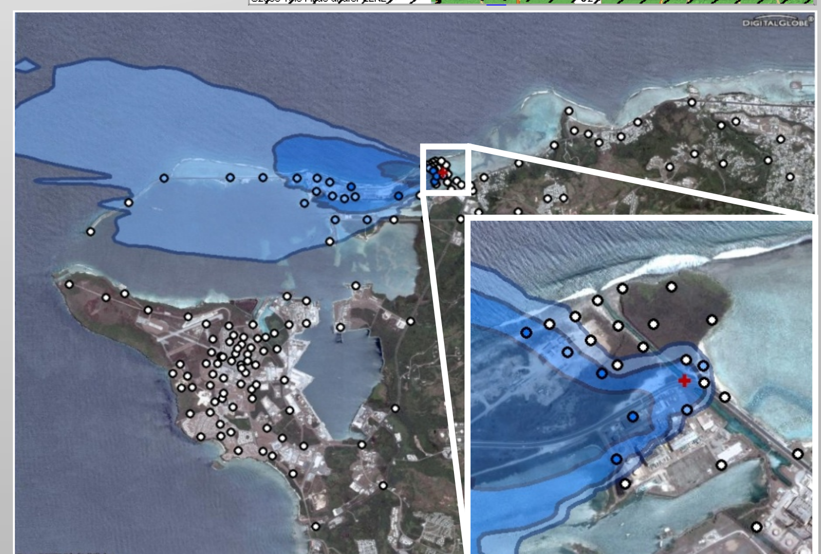

Products:
- Airborne and ground contamination for public exposure predictions (evacuation / sheltering, relocation)
- Affected population and casualty estimates
- Worker protection (stay times)
- Building damage from blast overpressure
- Radiation, blast and thermal casualty estimates
- Neutron-activation ground shine dose

# Auxiliary Analyses Are Provided For Situational Awareness

- Wind observations and fields
- Numerical weather prediction forecasts
- Field measurement data
- Deposition
- Time series, particle, or plume animations



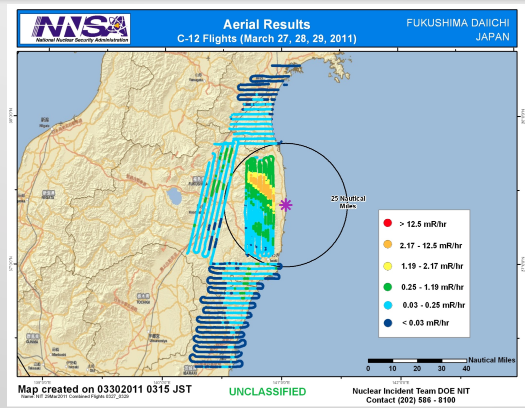




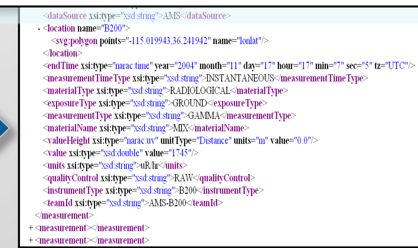
# Refinement of Dispersion Model Simulations Is Made Based on Radiological Measurements

Initial Model Predictions Guide Measurement Surveys

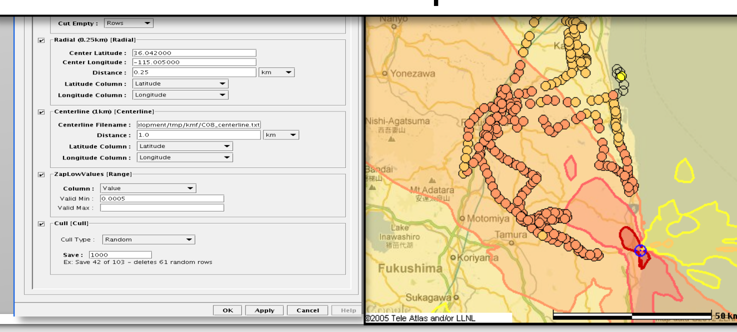

Measurement surveys and sensor data, e.g., DOE AMS, DOE, DoD, and Japan field data



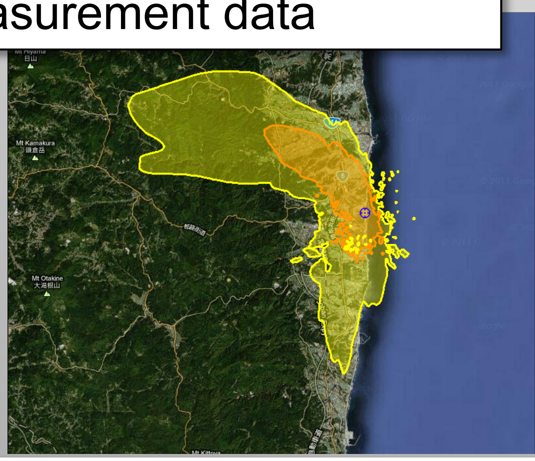

Measurement Data transferred electronically to LLNL/NARAC



Software used to help select, filter and statistically compare measurements and predictions



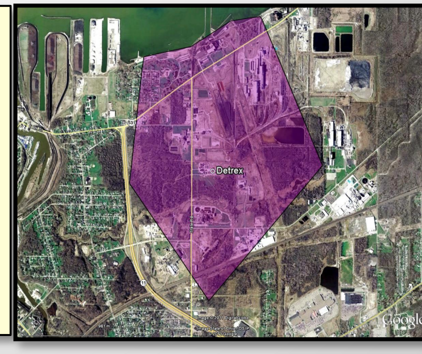

Updated predictions using measurement data

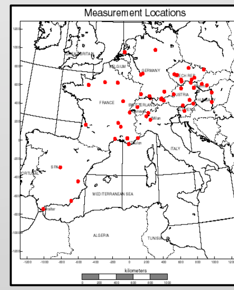


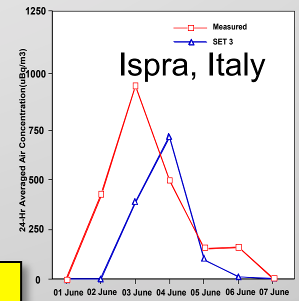
# Multiple Methods Exist for Source Estimation Based on Field Data

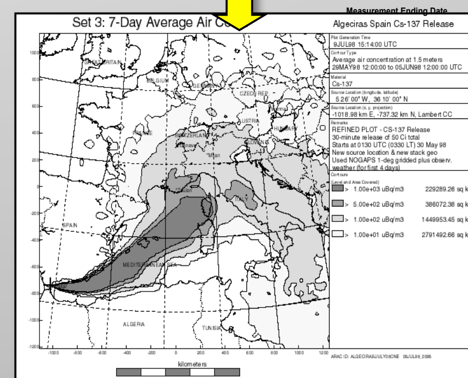
- Backward trajectory methods (accounting for null data)
- Source-receptor inversion based on optimization of fit starting from *a priori* estimate of source rate
- Adjoint modeling (not used)
- Operational expert analysis based on ensemble simulation accounting for source and meteorology variability and use of statistical/graphical analysis tools
- Bayesian inferencing and stochastic sampling
  - Backwards analyses to determine probabilistic distribution of unknown source characteristics
  - Optimal forward predictions for consequence assessment
  - Dynamic reduction in uncertainty as additional data become available
  - Multiple / moving sources
  - Sensor network optimization

NARAC chemical odor source location analysis based on backward trajectories




NARAC operational analysis reconstruction of probable source area and emission rate for Algeciras steel mill Cs-137 release

Emergency Response / Consequence Management (ER/CM) data-model capabilities for source reconstruction can be adapted or extended for CTBTO applications.

# Operational Source Reconstruction: Fukushima Dai-ichi Nuclear Power Plant Accident

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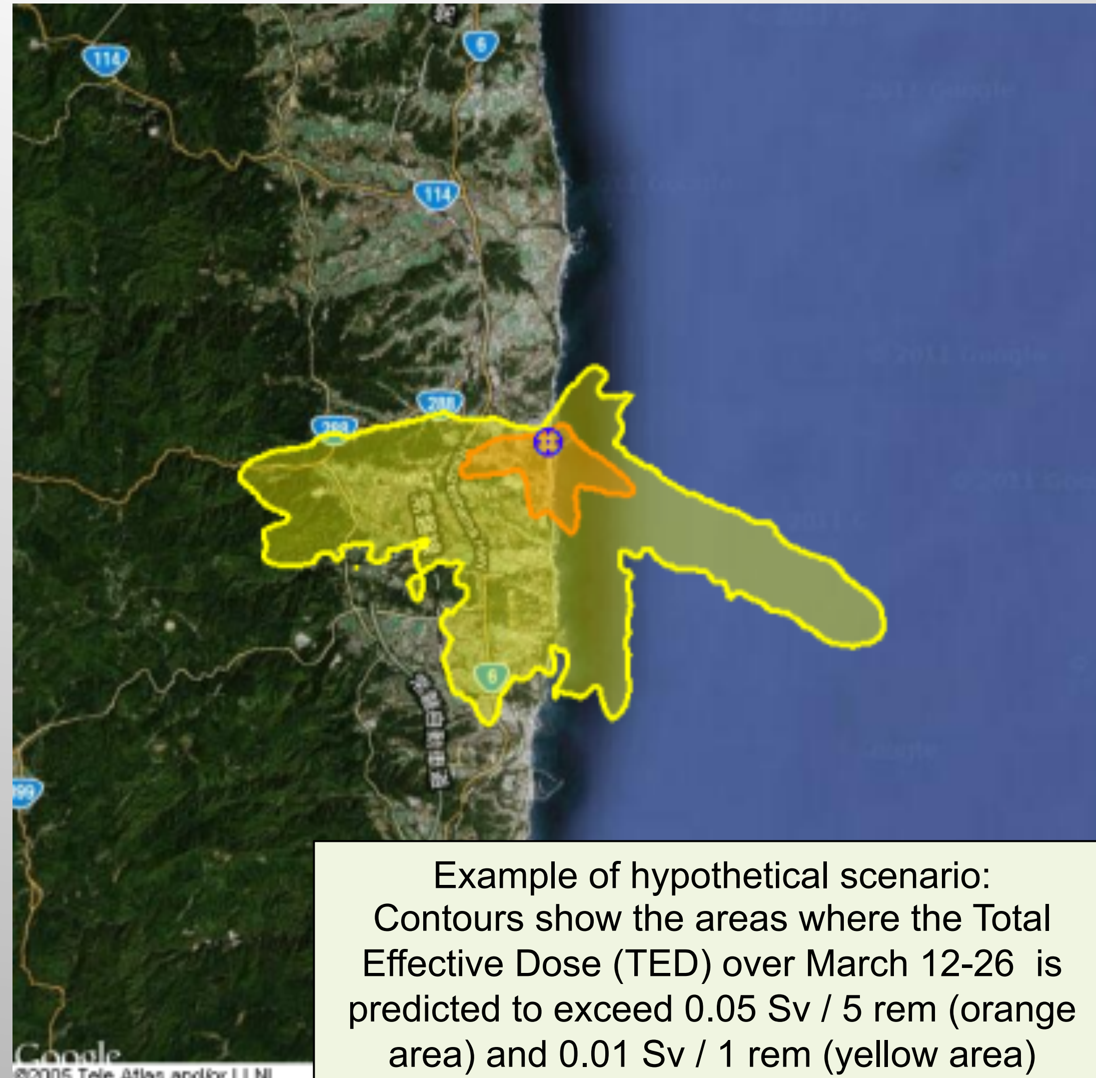
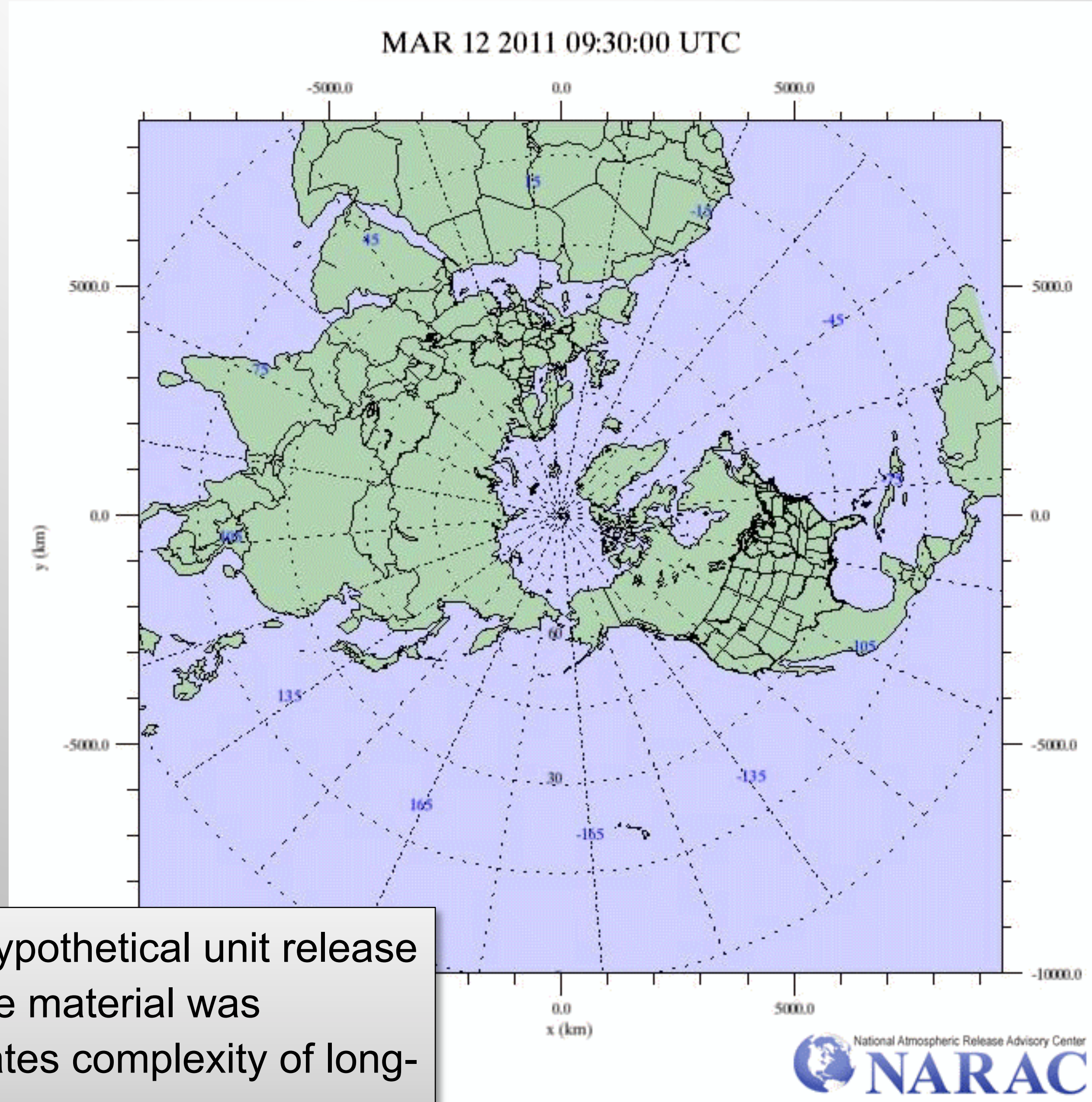
# DOE/NARAC Worked Closely with the U.S. NRC to Estimate Impacts for a Wide Range of Hypothetical Scenarios

- Predictions of arrival times and protective action areas for
  - Sheltering / evacuation
  - Relocation
  - Iodine administration
  - Worker protection to inform emergency planning
- Used to inform U.S. recommendations regarding actions needed to protect US citizens in Japan



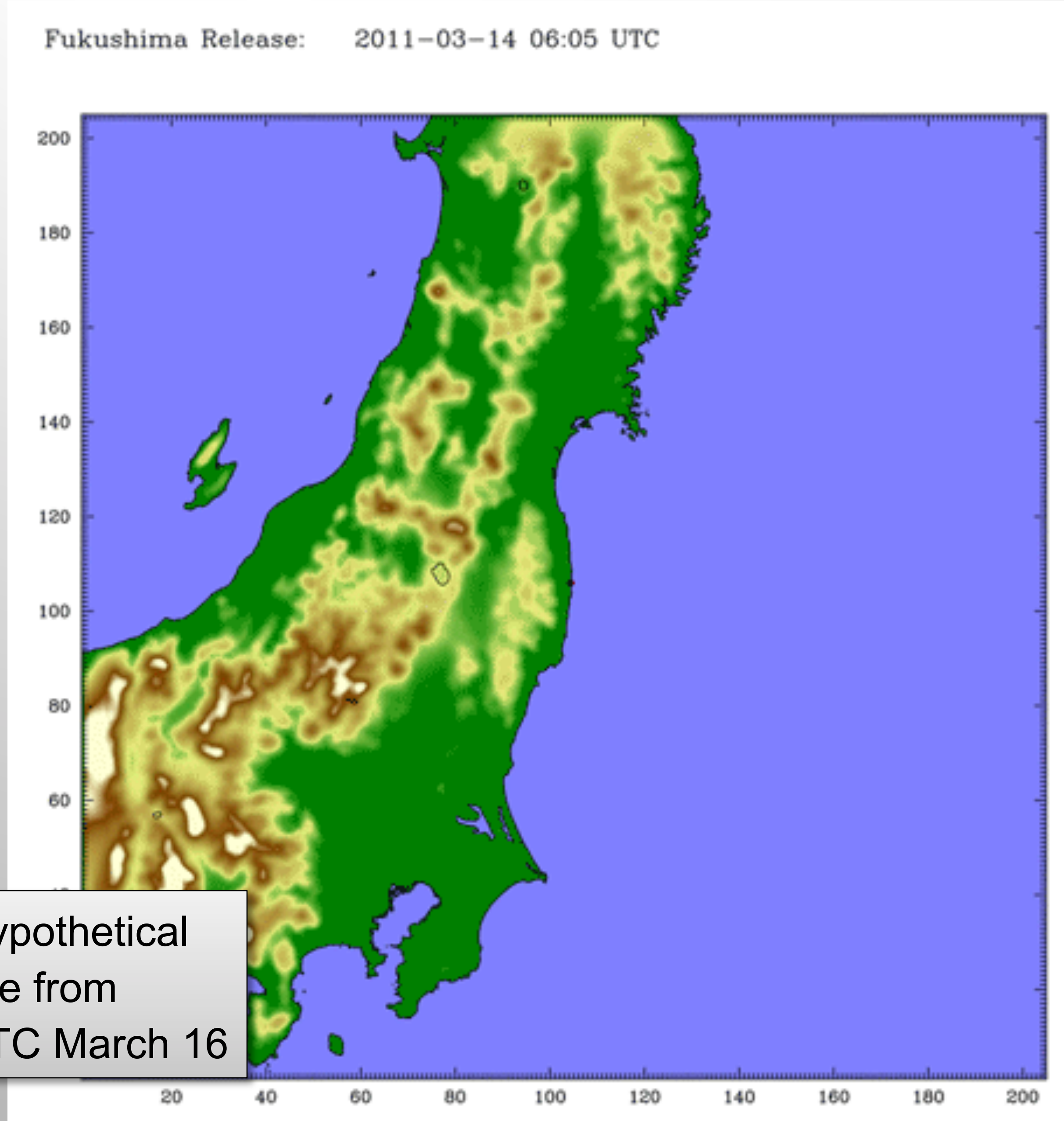

Example of hypothetical scenario: Contours show the areas where the Total Effective Dose (TED) over March 12-26 is predicted to exceed 0.05 Sv / 5 rem (orange area) and 0.01 Sv / 1 rem (yellow area)

# DOE/NARAC Provided Predictions of Possible Arrival Times and Dose in U.S. Territories



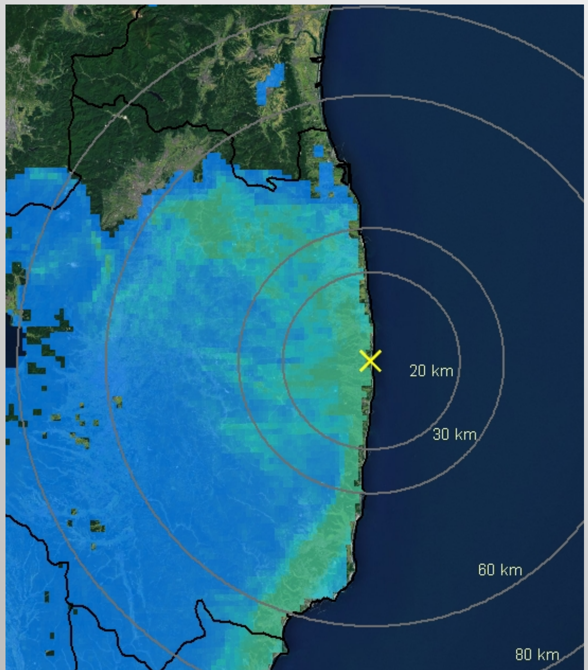

Particle animation of hypothetical unit release shows when and where material was transported and illustrates complexity of long-range dispersion

# Rapidly Changing Meteorological Conditions in Japan Presented a Significant Modeling Challenge

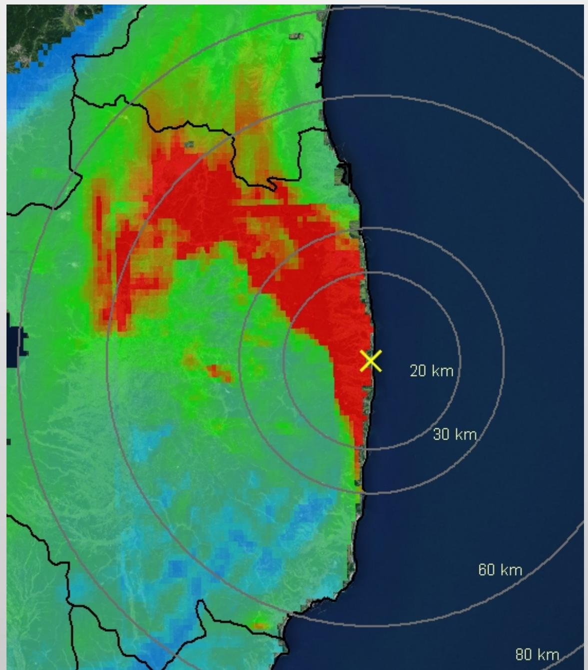



Particle animation for hypothetical constant release rate from
00 UTC March 14 – 00 UTC March 16

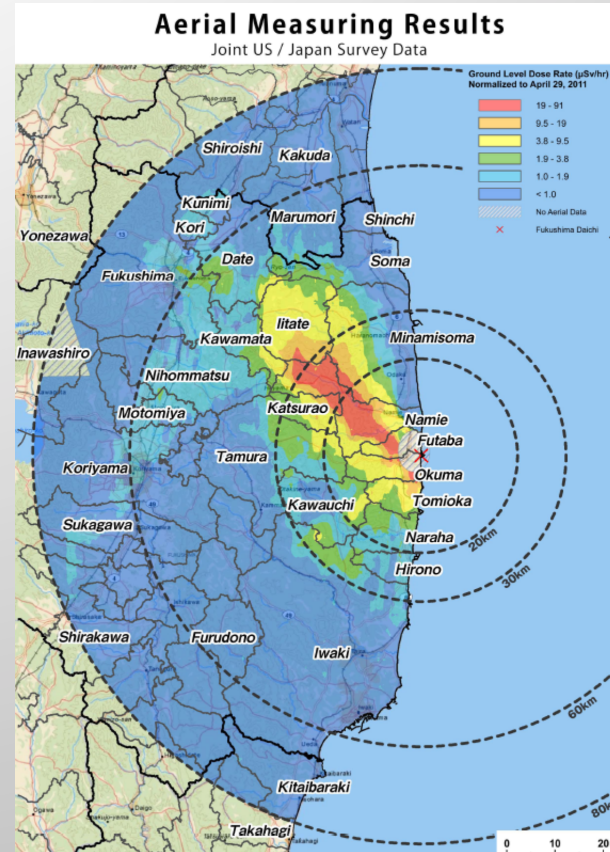
# Precipitation Scavenging is Key to Realistic Predictions of Ground Deposition




Predicted relative ground deposition pattern with dry deposition, but no precipitation scavenging




Predicted relative ground deposition pattern with precipitation scavenging (spatially and temporally-varying)

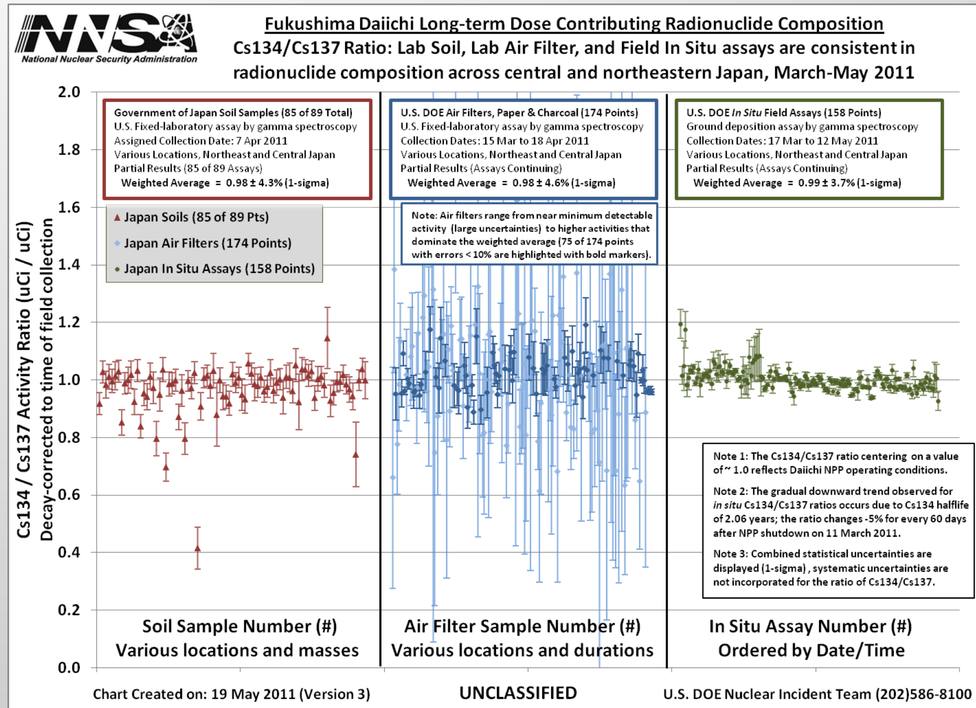



Measured AMS groundshine dose rate pattern

NARAC simulations using Flexpart and WRF-generated winds and constant release

# NARAC Source Estimation Was Based on Dose Rate Data and an Assumed Radionuclide Mix

- Key radionuclide contributors to dose: iodine, cesium, tellurium, and xenon
- Relative activity ratios determined *a priori* based on
  - DOE laboratory analyses
  - NRC radionuclide mixes for reactor scenarios
- Typical activity ratios used for $^{133}Xe$:$^{131}I$: $^{132}I$: $^{132}Te$:$^{137}Cs$:$^{134}Cs$
  - 100:20:20:20:1:1
  - 100:10:10:10:1:1
- Refinements made as additional radionuclide data became available

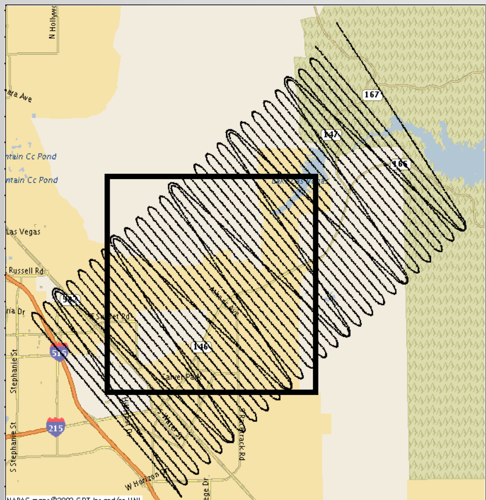



Cs-134/Cs-137 activity ratio from U.S. DOE laboratory analysis of soil, laboratory air filter, and *in situ* field assays corrected to time of field collection (courtesy of N. Wimer and S. Kreek, LLNL)

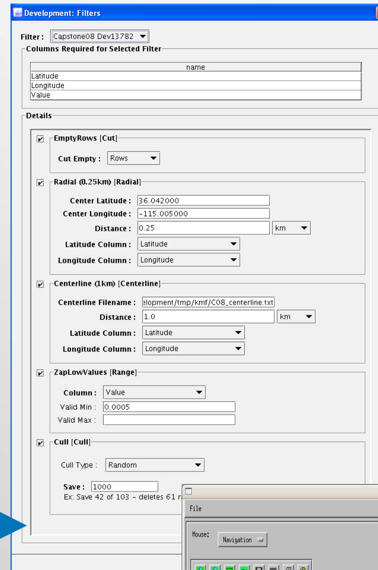
# Automated Field Measurement Processing Reduces Delivery Time for Data-Model Products

## Monitoring / Field Data

- Multi-agency data / databases
- Electronic data acquisition (standardized and custom formats0

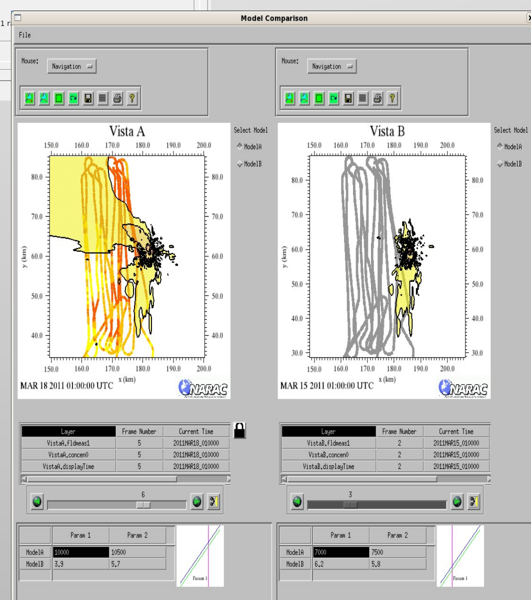


Aerial Measurement - Gamma Spectroscopy
In situ field assays – Gamma Spec, Alpha/Beta Survey, Dose Rate
Air Filters (paper, charcoal) – Gamma Spec, Alpha/Beta Counters, Lab Analysis
Soil and Soil Cores – Gamma Spec, Lab Chemistry

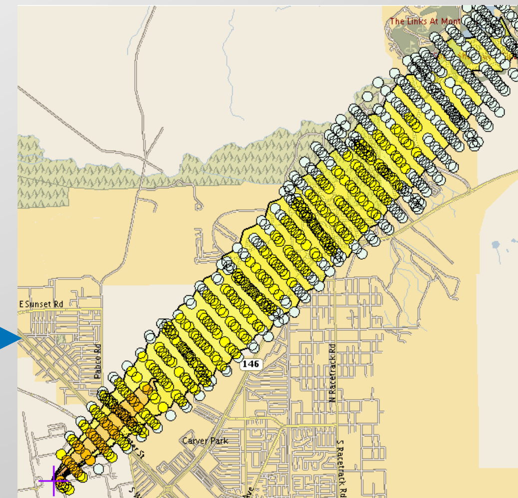


## *DataFilter, DataStats/ DataScaling*

- Filtering, grouping, outlier elimination
- Background corrections
- Source ratio scaling



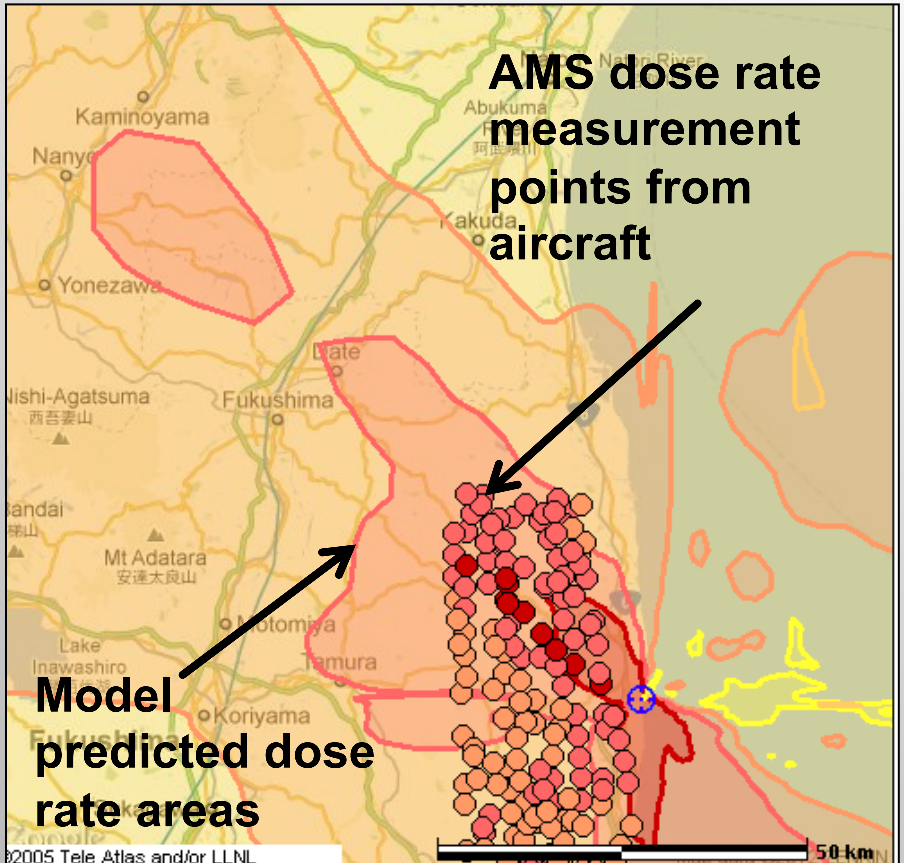
## *Data-Model Comparisons Refined Model Predictions*



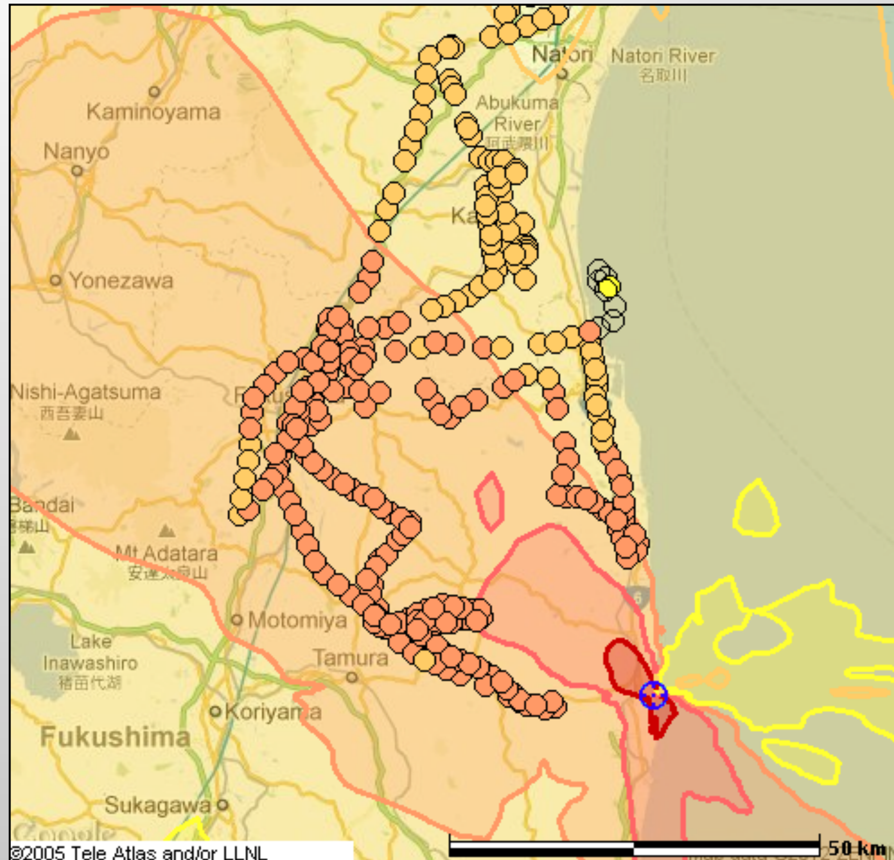
## *Graphical/Statistical* Data/ Model Comparison Tools

- FB, MG, NMSE, VG, Factor of R
- Measurement map displays
- Graphical model-data
- Data-model comparisons (paired in space time)

# NARAC Conducted Source Reconstruction From Limited Radiological Data (Aerial Measuring Survey Data Example)




NARAC modeled dose rate levels overlaid with **March 18 AMS data** using meteorology based on Japanese weather observations

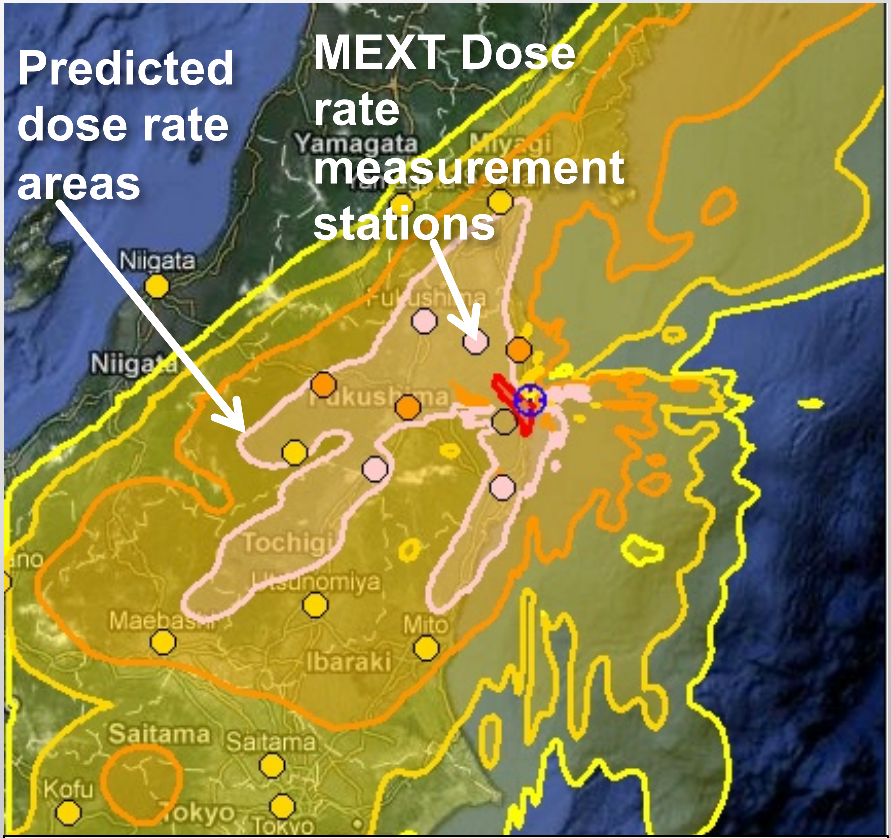



NARAC modeled dose rate levels overlaid with **March 26 AMS data** (data not used in source estimation process)

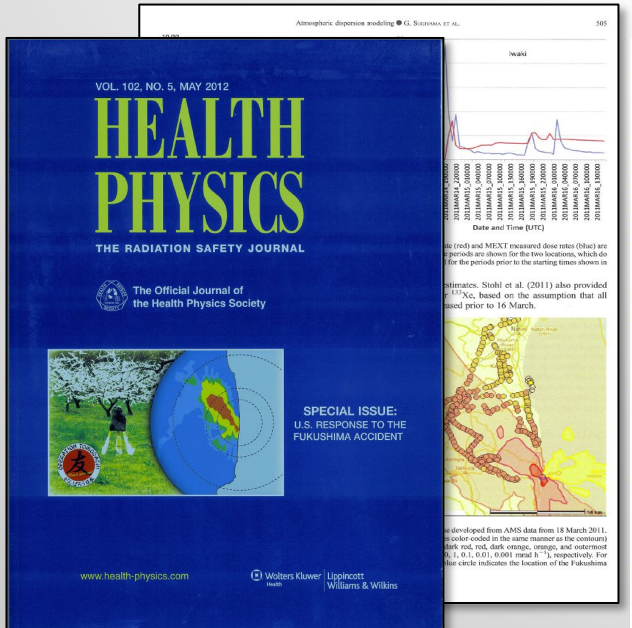
Dose rate levels greater than 100, 10, 1, 0.1, 0.01 μGy $h^{-1}$ (10, 1, 0.1, 0.01, 0.001 mrad $h^{-1}$) are shown as dark red, red, dark orange, orange, and yellow contours respectively

# NARAC ADAPT/LODI Source Reconstruction Based on MEXT Dose Rate Data for March 14-16

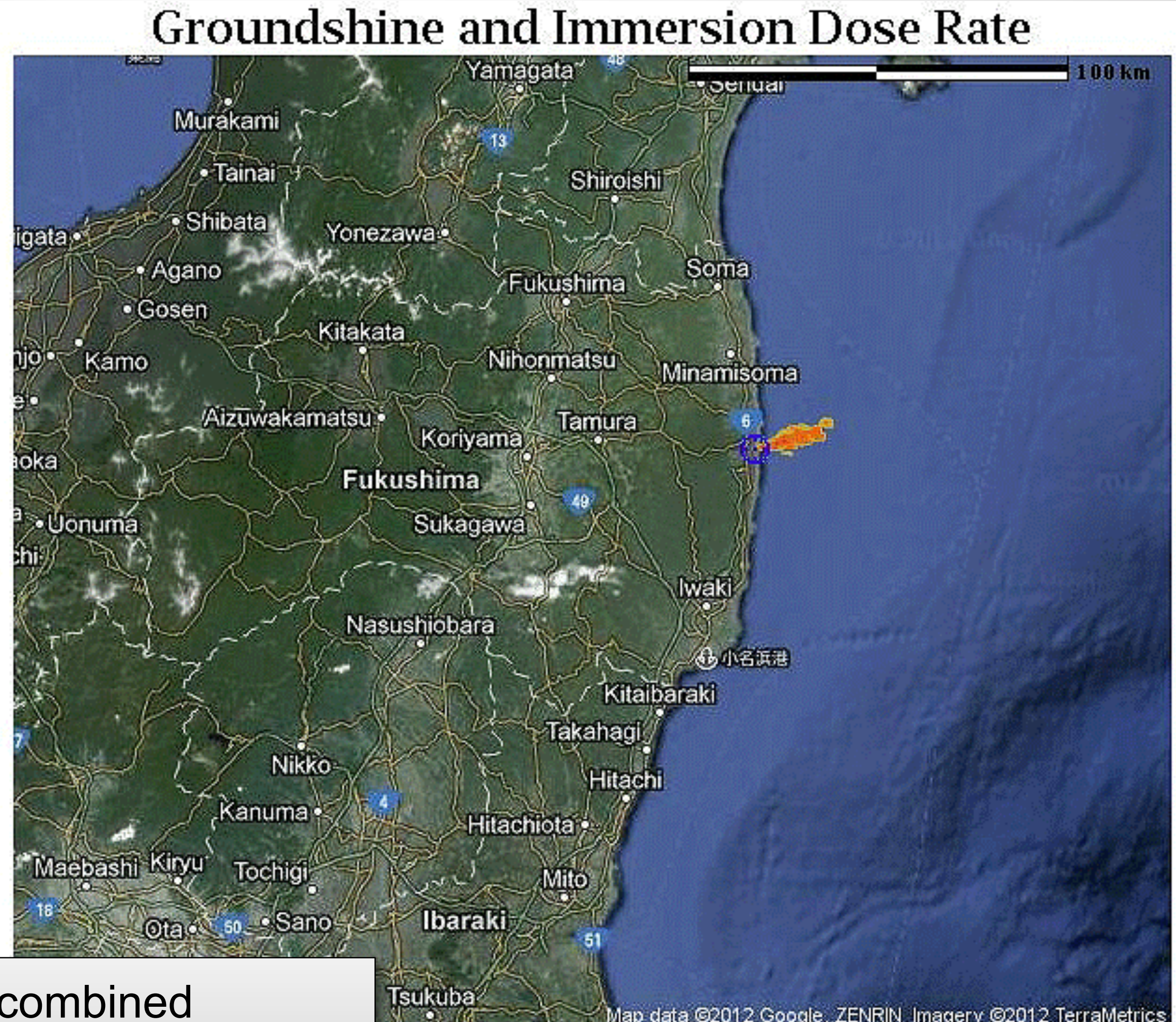
- NARAC "baseline" simulation
  - 3-km WRF FDDA model meteorology
  - Cs-134, Cs-137, I-131, I-132, Te-132, Xe-133 in relative activity ratios of 1:1:20:20:20:100
  - Uniform release rate
- Good agreement with AMS data collected on March 18 (not shown), that was *not* used in this source estimation analysis
- "Baseline" release estimate for March 14-16 release period
  - Cs-137 $3.7 \times 10^{15}$ Bq ($1 \times 10^{5}$ Ci)
  - I-131 $7.4 \times 10^{16}$ Bq ($2 \times 10^{6}$ Ci)




NARAC model predicted dose rate contours compared to MEXT data for March 15,1800 UTC. Contours and data circles color coded to show levels: 120μGy h$^{-1}$ (red), 4μGy h$^{-1}$ (pink), 0.4μGy h$^{-1}$ (orange), 0.04μGy h$^{-1}$ (light orange) and 0.004μGy h$^{-1}$ (yellow).




G. Sugiyama, J. Nasstrom, B. Pobanz, K. Foster, M. Simpson, P. Vogt, F. Aluzzi, S. Homann, (2012): Atmospheric Dispersion Modeling: Challenges of the Fukushima Daiichi Response, *Health Physics*, 102, p 493–508




NARAC animation of combined predicted ground shine and air immersion dose rate

# *Event / Source Reconstruction*

Lawrence Livermore National Laboratory

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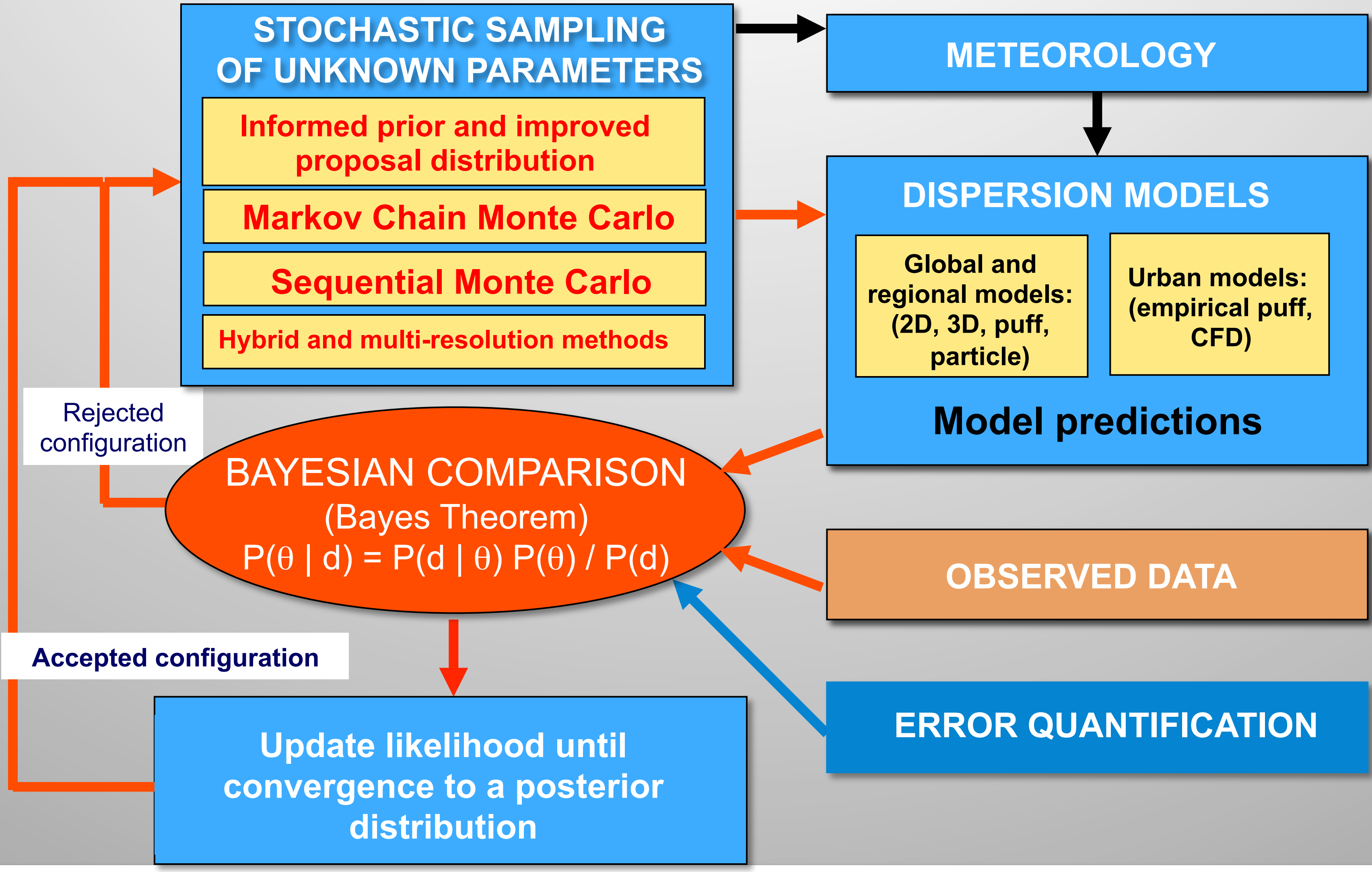
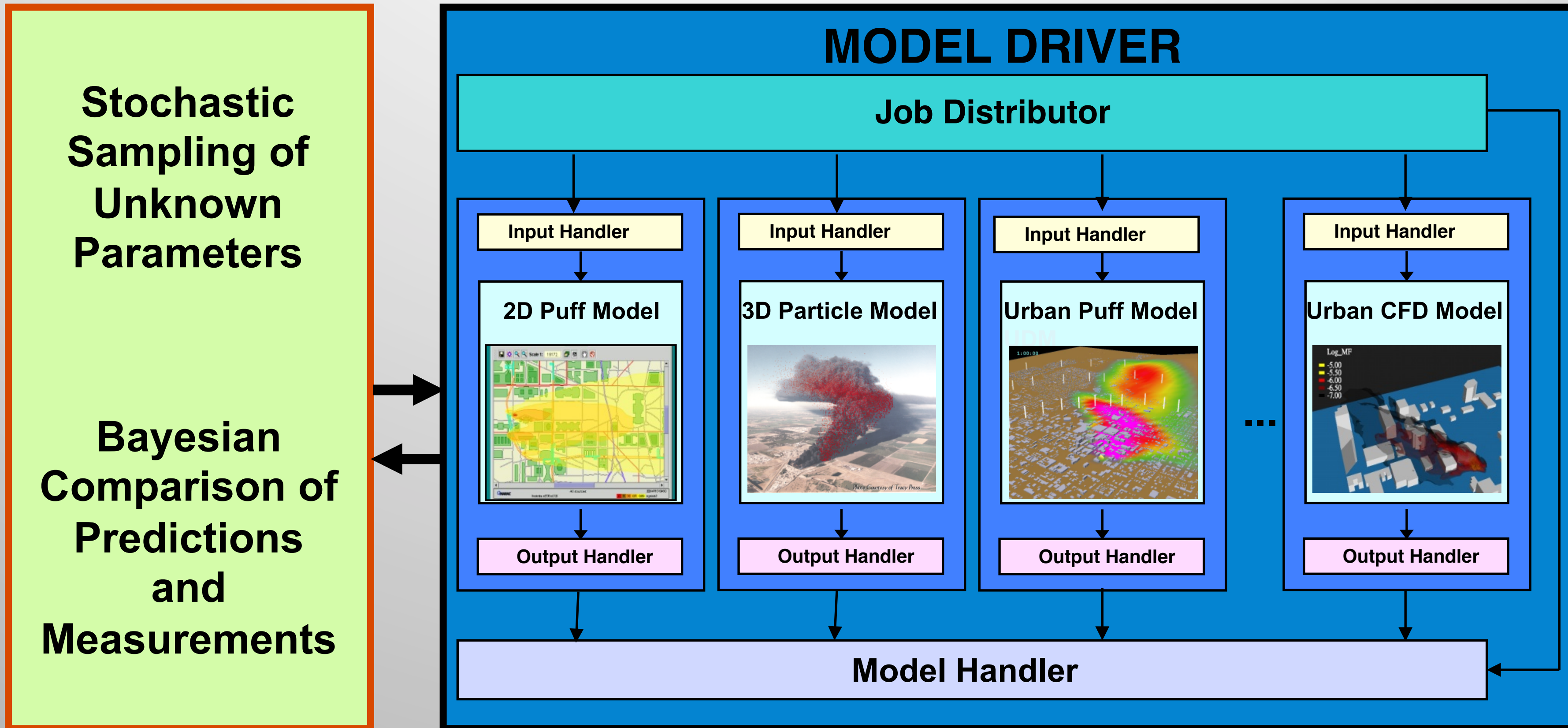
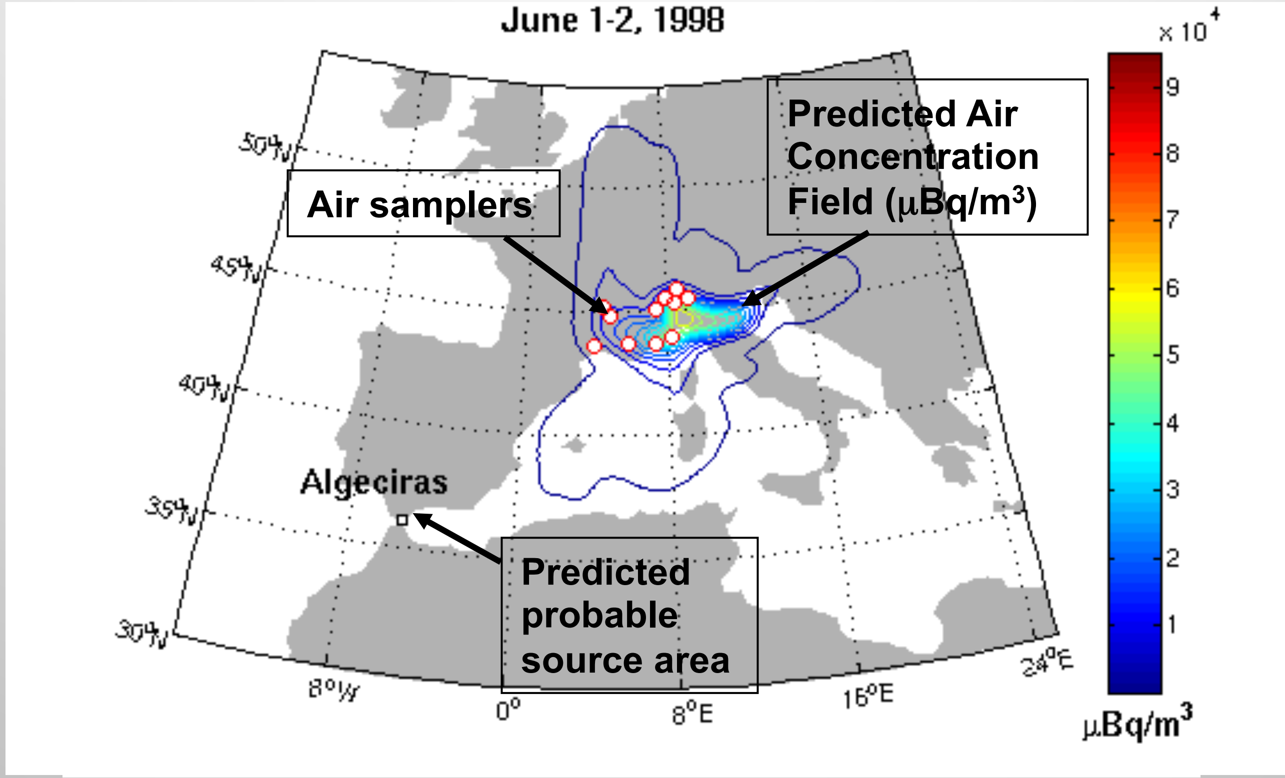
# Event Reconstruction Uses Data-Driven Simulation to Answer Critical Questions About Release Events



# Computational Framework Supports Multiple Atmospheric Models and Stochastic Algorithms



# NARAC Reconstructed the Source of Cesium-137 Detection in Europe (1998)

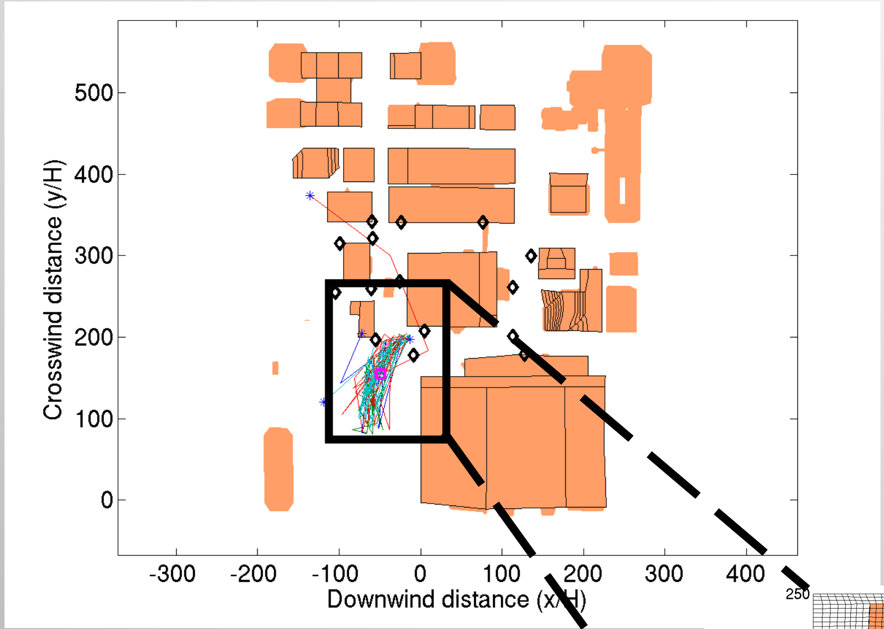


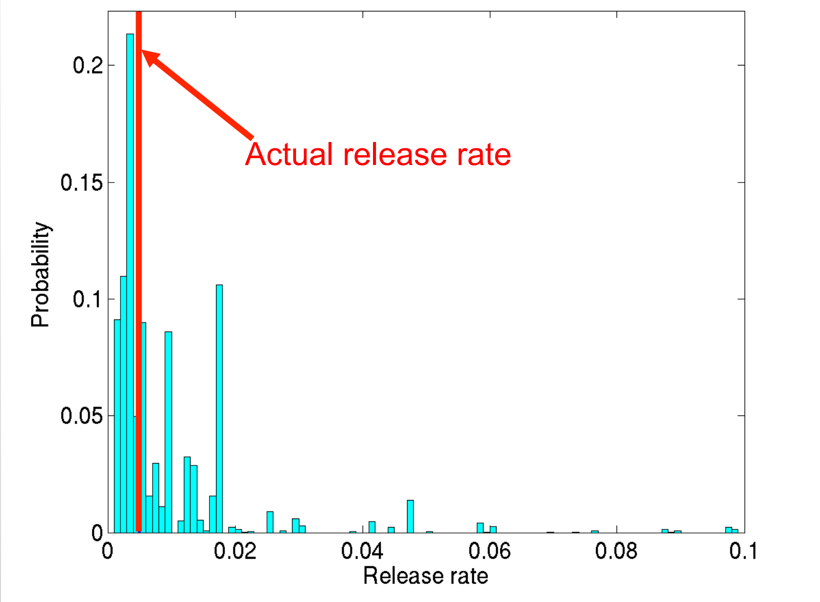

Air concentration (color contours) of plume on the 1st day of detection (June1-2, 1998), was reconstructed using known winds and sensor measurements (at locations shown by red circles) by the event reconstruction tool

- NARAC also tested new automated Bayesian inferencing and stochastic sampling techniques with a small subset of data to determine the likely source area, emission amount and air concentration fields (see figure above)

# Event Reconstruction is Performed Via Bayesian Inferencing and Stochastic Sampling

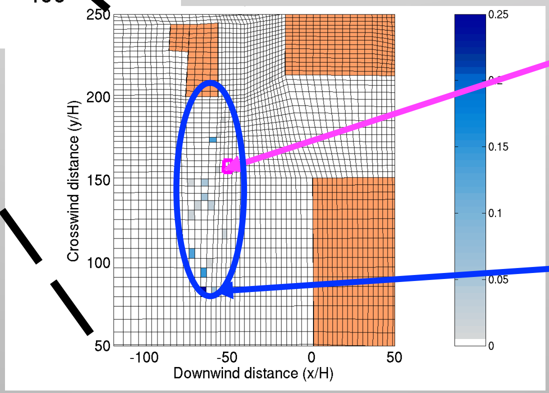
Markov chain sampling




Inflow wind

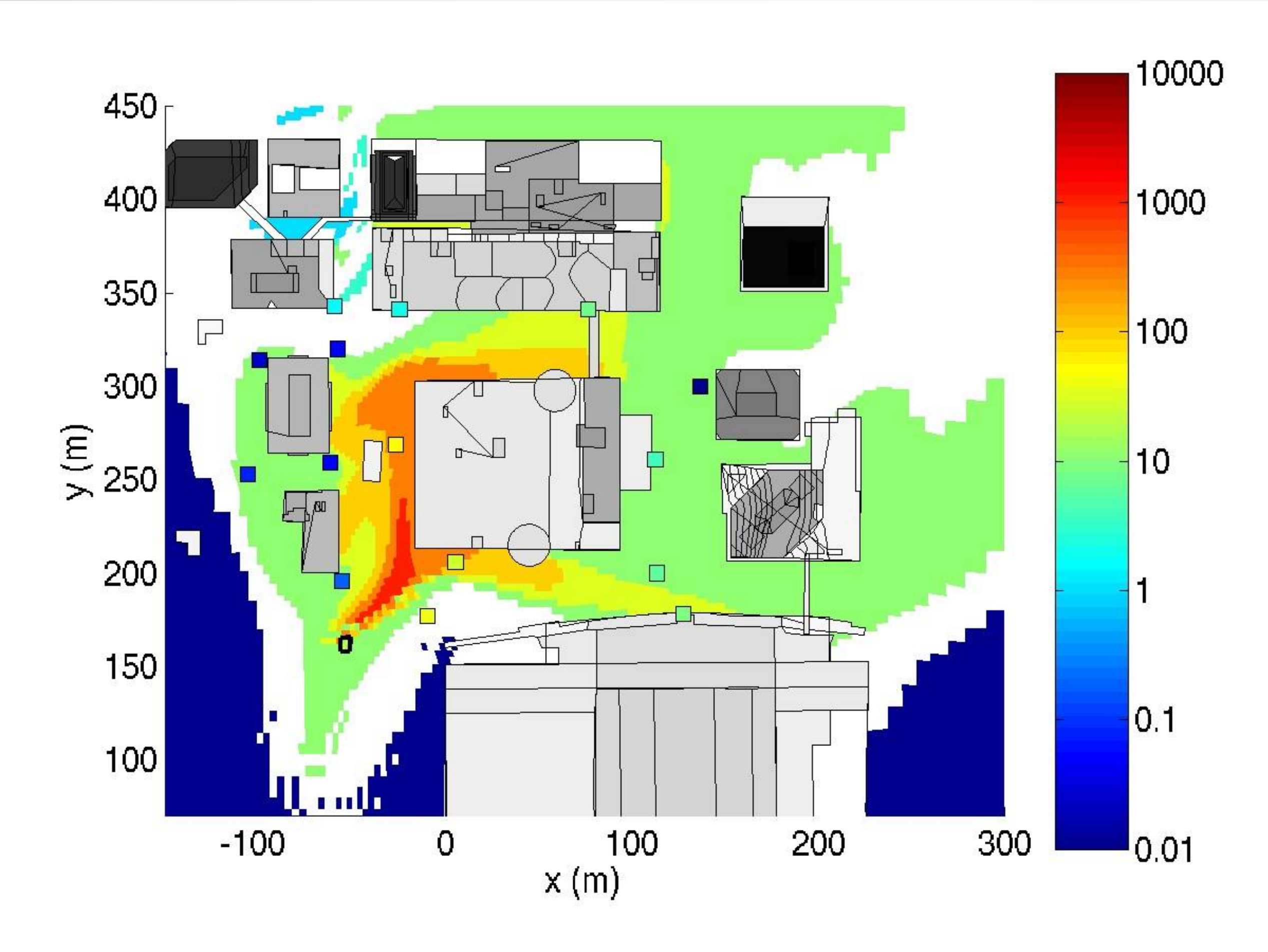
Sensors (◊)




Actual source location

Source location determined to <½ block area

# Event Reconstruction Composite Plume Provides Confidence Levels (Quantitative Uncertainty Estimates)




- JU2003 Oklahoma City release
- Contours of 90% confidence limits for given air concentration level compared to data (colored squares)
- Dark blue region envelopes composite plume (< 0.01 ppb)
- White indicates areas where 90% confidence limit cannot be determined (depends on chosen threshold of 0.01 ppb)

Event reconstruction based on Bayesian inference and stochastic sampling estimates source location to within a half block and release rate (left figures) for the JU2003 Oklahoma City release.

# Data-Model Fusion is Used For Source Estimation and Refined Model Analyses

| Current Status / Ongoing Work | Future Needs |
|---|---|
| ✓ **Field data acquisition**<br>• Global meteorological observations<br>• DOE/FRMAC radionuclide measurements<br>• Data processing software (selection, filtering, quality assurance, outlier identification/elimination) | **Field data acquisition**<br>• Robust electronic data feeds, standard formats and metadata from multiple providers<br>• Disparate data types (e.g., radar data, airborne sampling, satellite, spectral) |
| ✓ **Meteorological data assimilation**<br>• Numerical weather prediction (WRF) model 4D data assimilation<br>• Improved precipitation and wet/dry deposition models | **Physical processes**<br>• Improved understanding / modeling of vertical mixing and precipitation effects<br>• Analysis of background contamination levels |
| ✓ **Source term estimation**<br>• Ensemble simulations (source and meteorological)<br>• Data-model graphical and statistical comparison and analysis tools for expert analysis | **Advanced source and uncertainty estimation**<br>• Automated statistically rigorous source estimation methods<br>• Quantitative uncertainty estimation accounting for both source and meteorology variability |
| ✓ **Communications**<br>• Products targeted at decision-makers<br>• Product interpretation | **Other**<br>• Sensor network optimization |

National Atmospheric Release Advisory Center

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# Backup / Alternative Slides

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# NARAC Provides Operational Services, Tools, and Expertise for Preparedness, Response, & Recovery

## Event Information

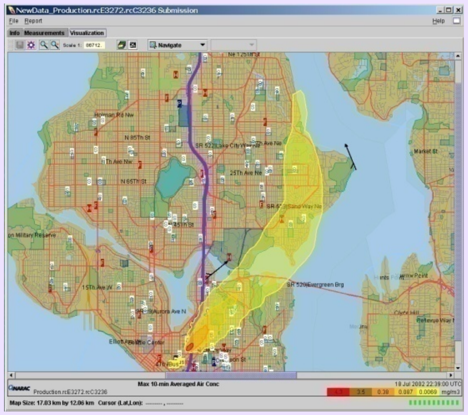
- Weather data
- Nuclear, radiological, chemical, and biological source information
- Terrain, land use, and population databases
- Measurement data and observations

## Operational Services and Expertise

- Suite of stand-alone to advanced WMD modeling tools (multi-scale models)
- 24/7/365 expert scientific staff (< 5 min. reach-back)
- Detailed analysis, expert interpretation, quality assurance, and training
- Event reconstruction

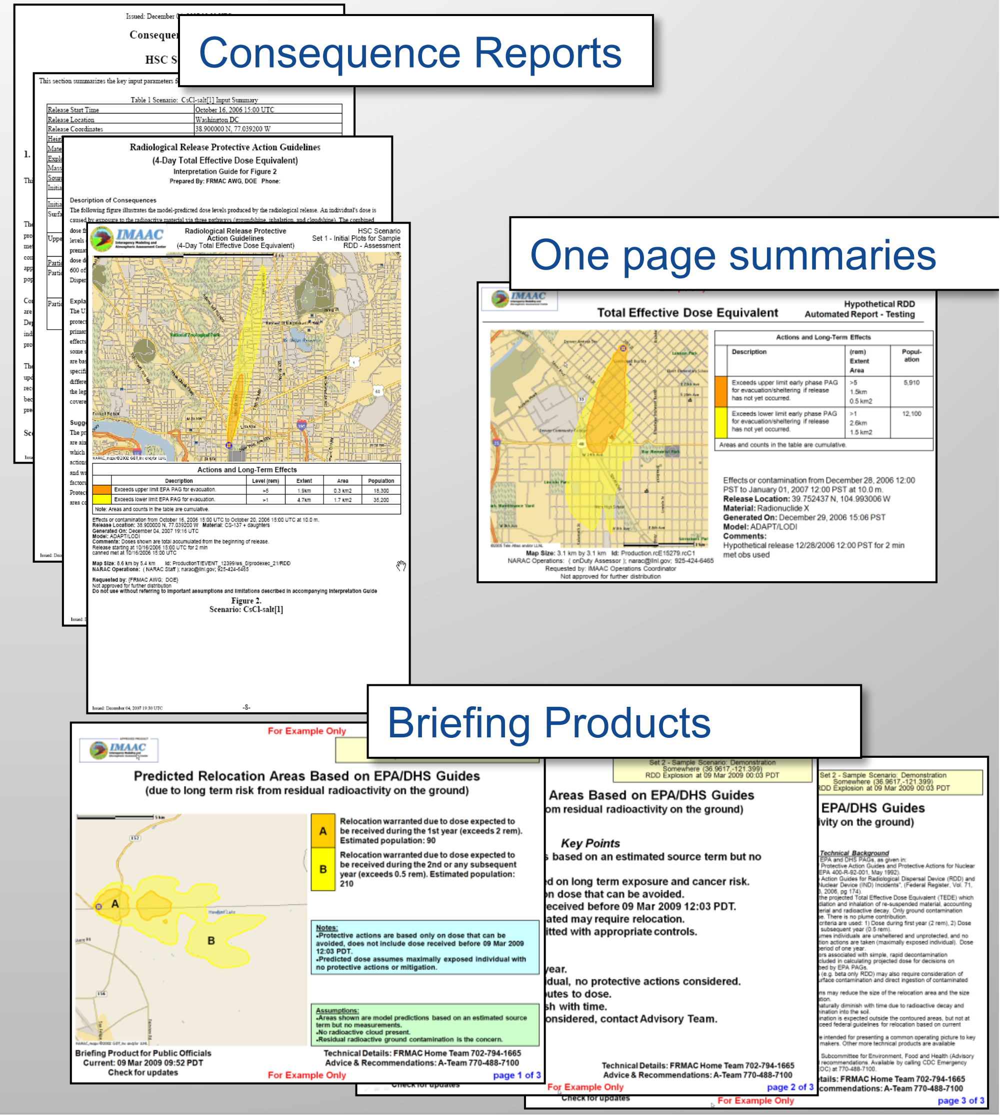

## Actionable Information

- Hazard areas and affected populations
- Health effect, public protective action, and worker protection levels based on federal guidelines
- Casualty, fatality, and damage estimates
- Planning and consequence assessments

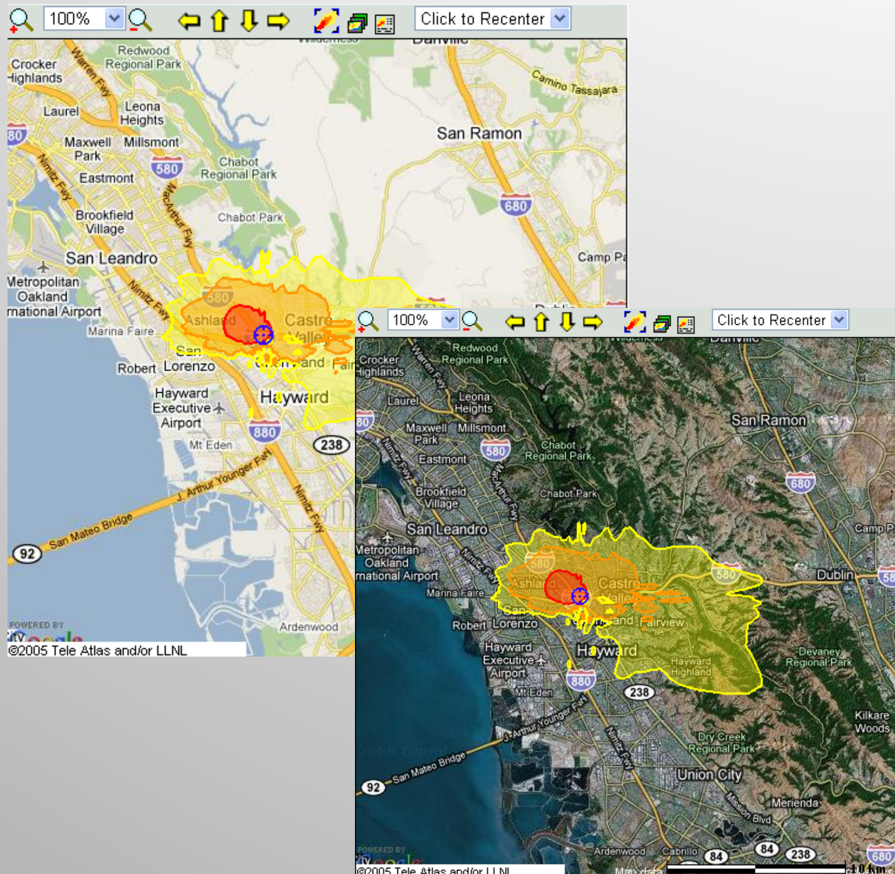


# Products Inform Decisions on Evacuation, Sheltering, Relocation, Worker Protection, and Sampling Plans

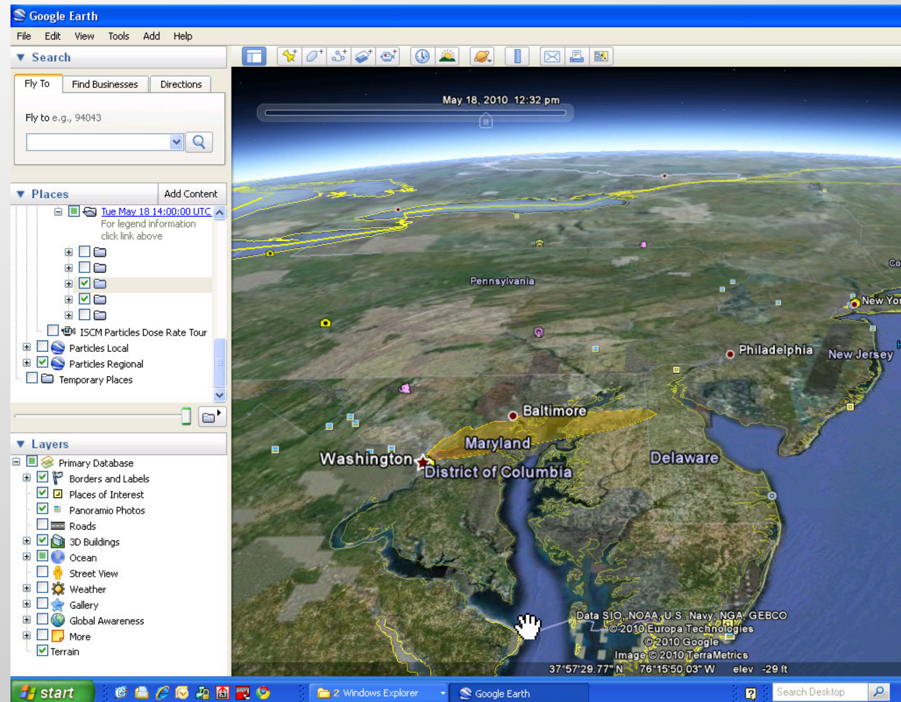
- Standard plot sets
  - Plume hazard areas
  - Affected population numbers
  - Expected health effects
  - Protective action guide levels
  - Geographical information
- One-page map summary plots
- Multi-page consequence reports
  - Expanded descriptions
  - Input data and assumptions
  - Interpretation guides
- Briefing Products
  - Focus on actions and decisions that need to be considered
  - RDD, IND, nuclear power plants, chemicals, and biological agents
  - Developed with interagency consensus



# Products and Map Layers are Provided in Multiple Formats (PDF, ESRI, Google)




Worldwide Google Street and satellite displays



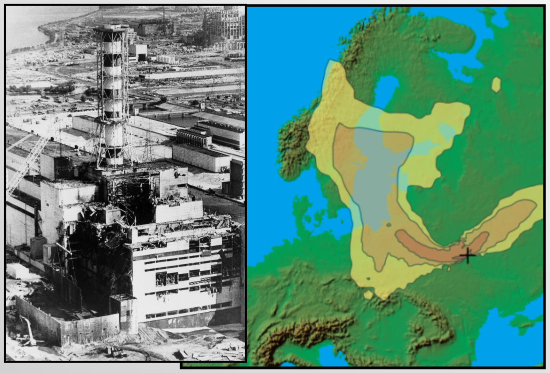

Export plumes to *Google Earth* (FEMA)

Available on NARAC/CM Web

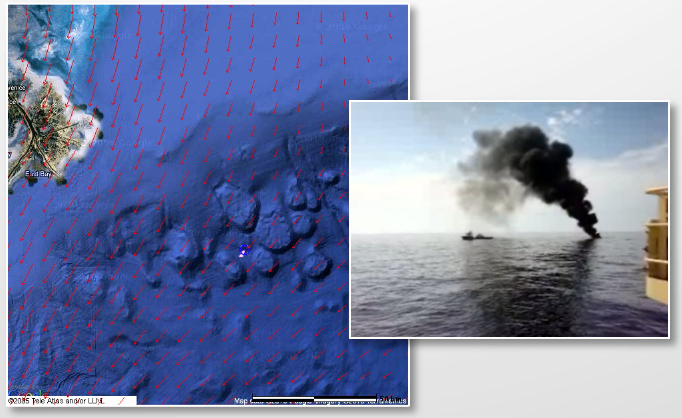
PDF, PowerPoint, HTML/XML, JPG/PNG graphics,

ESRI Shape and Google Earth KMZ GIS files with plume areas

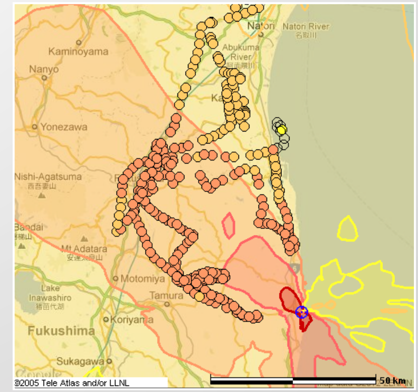
# NARAC Responds to Real-World Events (Examples)



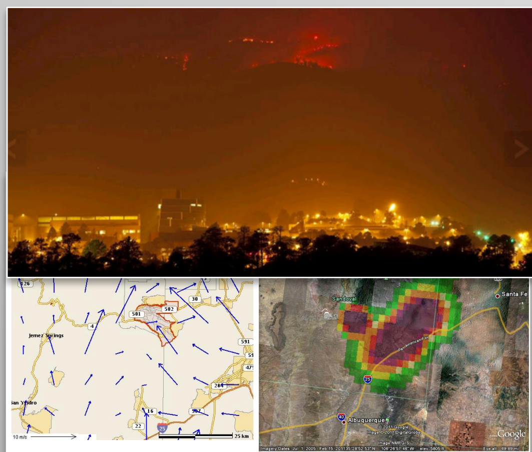
April 26, 1986
Chernobyl nuclear power plant accident



May-June, 2010 in-situ burns
Deepwater Horizon, Gulf of Mexico

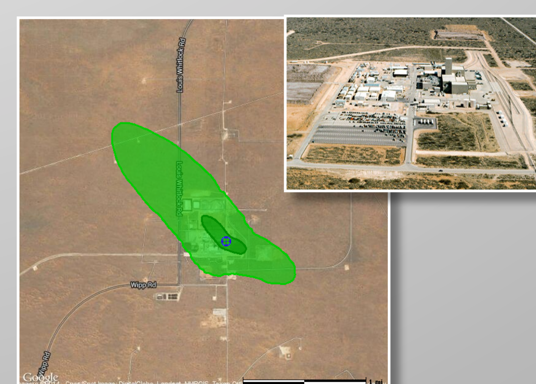



March 11 – May 28, 2011
Fukushima Dai-ichi Nuclear Power Plant accident



June 26 - July 1, 2011
Las Conchas Wildfire, NM

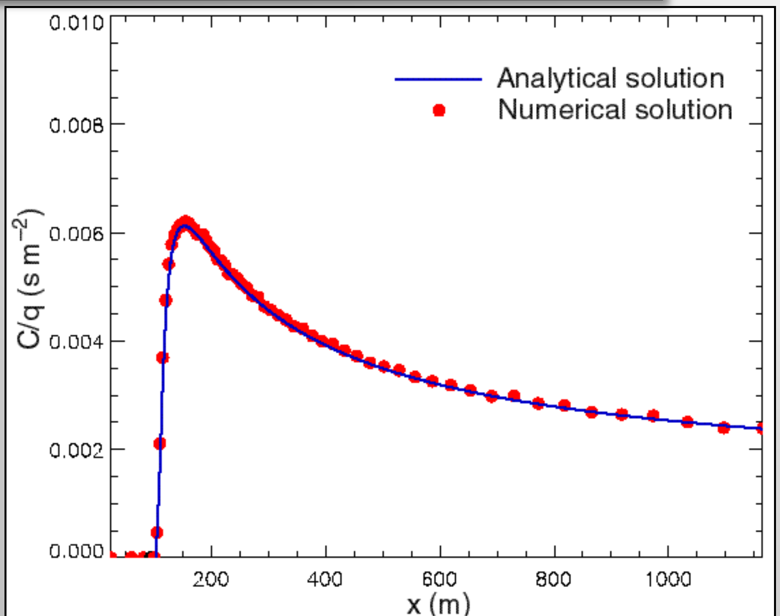
November 26, 2011
Mars Science Laboratory Launch, Cape Kennedy, FL



February 14-20, 2014
Waste Isolation Pilot Plant underground release venting

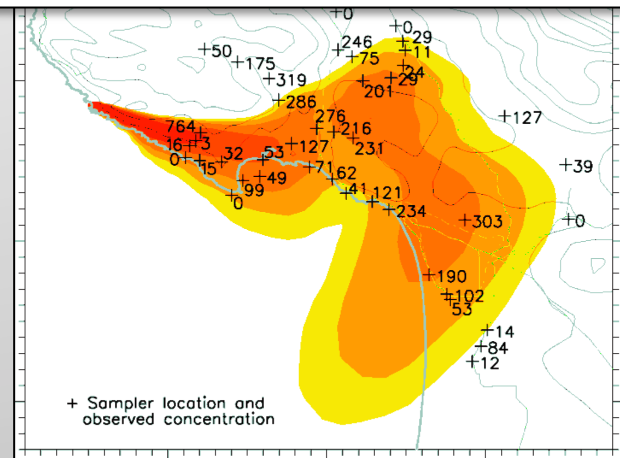
# NARAC Models and Capabilities are Extensively Tested and Evaluated

- Analytic solutions test models versus known, exact results




- Field experiments test models in real-world cases

Examples: Roller Coaster, Project Prairie Grass, Savannah River Musicale Atmospheric Tracer Studies, Diablo Canyon Tracer Study, ETEX, Urban 2000, Joint Urban 2003, UDP




- Operational testing evaluates the usability, efficiency, consistency and robustness of models for operational conditions

Examples: Chernobyl, Kuwait oil fires, tire fires, industrial accidents, Algeciras Spain Cesium release, Tokaimura criticality accident, Cerro Grande (Los Alamos) fire, Fukushima NPP acident

# Graphical/Statistics Metrics Guide Refinement of Source and Other Model Paramters

- Source term characteristics
  - *Release height*
  - *Cloud height / geometry*
  - *Activity / particle size distributions and physical/chemical form*
- *Meteorological inputs* can help improve spatial distribution patterns:
  - Additional or higher-resolution meteorological data/models to improve plume direction
  - Refined atmospheric stability estimates to improve spread of plume
  - Data on precipitation rates / type and land-use for improved dry / wet deposition modeling of ground deposition pattern

The statistical measures include fractional bias (FB), geometric mean bias (MG), normalized mean square error (NMSE), geometric mean variance (VG), correlation coefficient (R), fraction of predictions within a factor of 2 (FAC2), fraction of predictions within a factor of 5 (FAC5), and fraction of predictions within a factor of 10 (FAC10). These measures are defined below:

$$FB = \frac{\left(\overline{C_o} - \overline{C_p}\right)}{0.5\left(\overline{C_o} + \overline{C_p}\right)} \qquad (2\text{-}7)$$

$$MG = \exp\left(\overline{\ln C_o} - \overline{\ln C_p}\right) = \exp\left(\overline{\ln\left(\frac{C_o}{C_p}\right)}\right) \qquad (2\text{-}8)$$

$$NMSE = \frac{\overline{\left(C_o - C_p\right)^2}}{\overline{C_o}\,\overline{C_p}} \qquad (2\text{-}9)$$

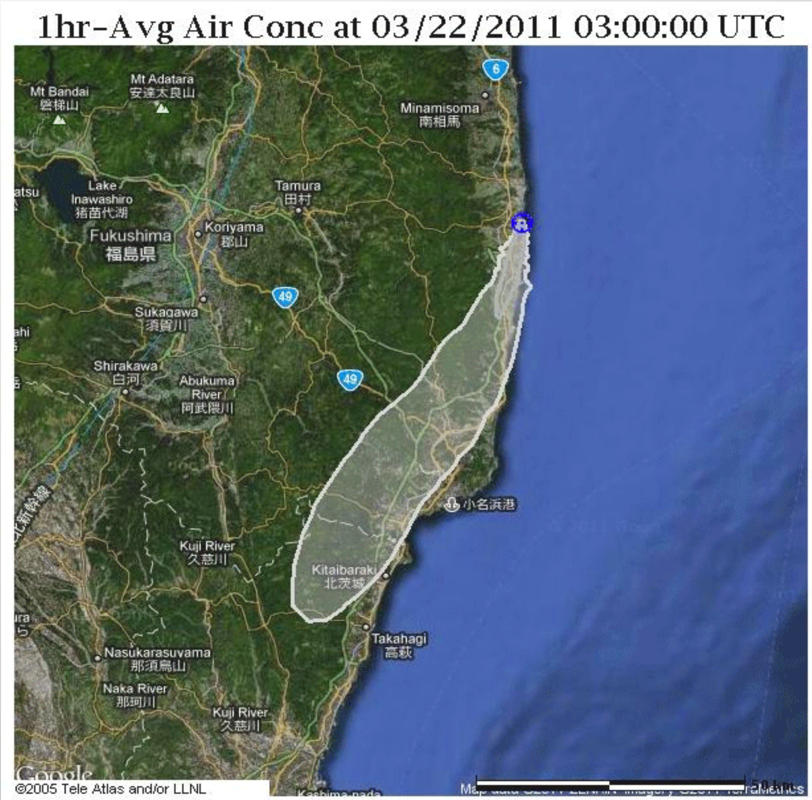
$$VG = \exp\overline{\left(\ln C_o - \ln C_p\right)^2} = \exp\left[\overline{\left(\ln\left(\frac{C_o}{C_p}\right)\right)^2}\right] \qquad (2\text{-}10)$$

$$R = \frac{\overline{\left(C_o - \overline{C_o}\right)\left(C_p - \overline{C_p}\right)}}{\sigma_{C_p}\sigma_{C_o}} \qquad (2\text{-}11)$$

$$\text{FAC(x)} = \text{fraction of data for which } \frac{1}{x} \le \frac{C_p}{C_o} \le x \qquad (2\text{-}12)$$

# NARAC Provided Regular Forecasts to Support Mission Planning and Model Analysis

- Up to thrice-daily forecasts of hourly relative air concentrations to inform field operations, monitoring, and emergency planning
- Tabular summaries of wind speed and direction, atmospheric stability, and precipitation for selected locations
- 5-km resolution forecasts generated using Weather Research and Forecast (WRF) model, driven by National Oceanic and Atmospheric Administration (NOAA) global GFS model output
  - Regular checks for consistency with NOAA HYSPLIT forecasts
  - Comparisons against available Japanese meteorological data




Daily weather forecasting for mission planning (hypothetical hourly plume to illustrate predicted shifts in wind direction)

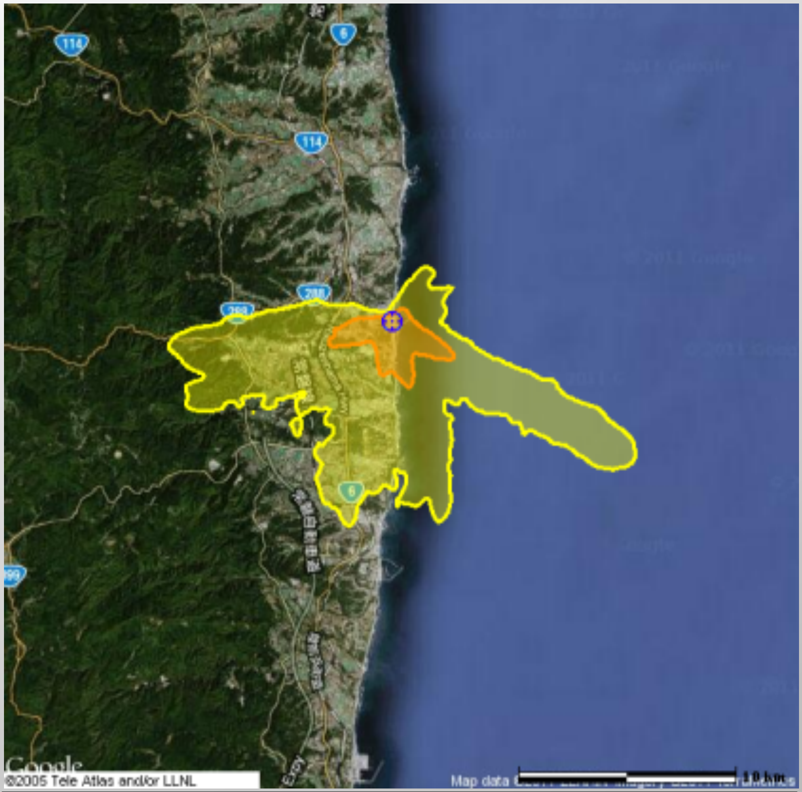
# DOE/NARAC Worked Closely with the U.S. NRC to Estimate Impacts for a Wide Range of Hypothetical Scenarios

- Predictions of arrival times and protective action areas for sheltering / evacuation, relocation, iodine administration, and worker protection to inform emergency planning

- Analyses based on a range of hypothetical scenario source terms provided by the U.S. Nuclear Regulatory Commission (NRC)
  - RASCAL and MELCOR reactor modeling
  - Separate and combined impacts for reactor cores and spent fuel

- Use of a variety of meteorological conditions, including real-world weather and artificial hypothetical weather conditions

- Used to inform U.S. recommendations regarding actions needed to protect US citizens in Japan



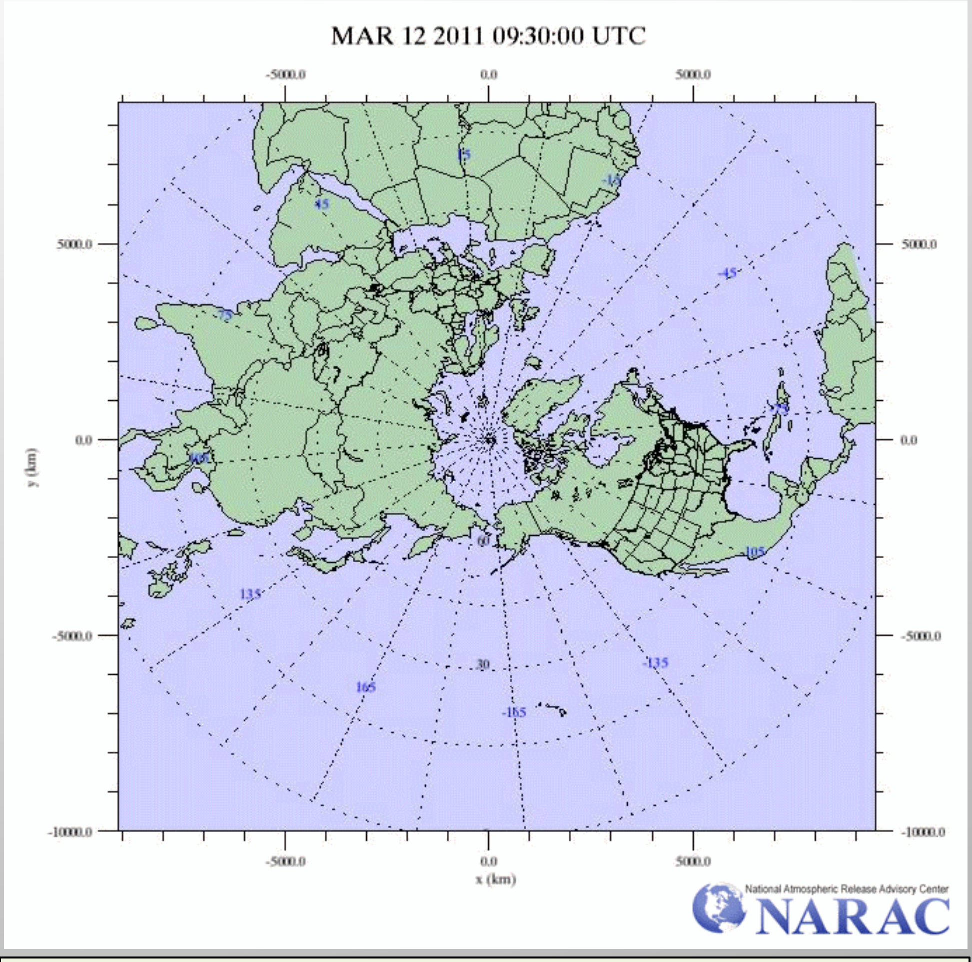

Example of hypothetical scenario: Contours show the areas where the Total Effective Dose (TED) over March 12-26 is predicted to exceed 0.05 Sv / 5 rem (orange area) and 0.01 Sv / 1 rem (yellow area)

# DOE/NARAC Provided Predictions of Possible Arrival Times and Dose in US Territories

- NARAC estimated arrival times and radiation dose for selected locations in the US using:
  - NOAA GFS 0.5 degree meteorological forecasts and analyses
  - NRC source term analyses
  - DOE Consequence Management Home Team (CMHT) dose conversion analyses

- 12 or 24-hour unit release rates, scaled by NRC source quantities and DOE CMHT dose conversion values

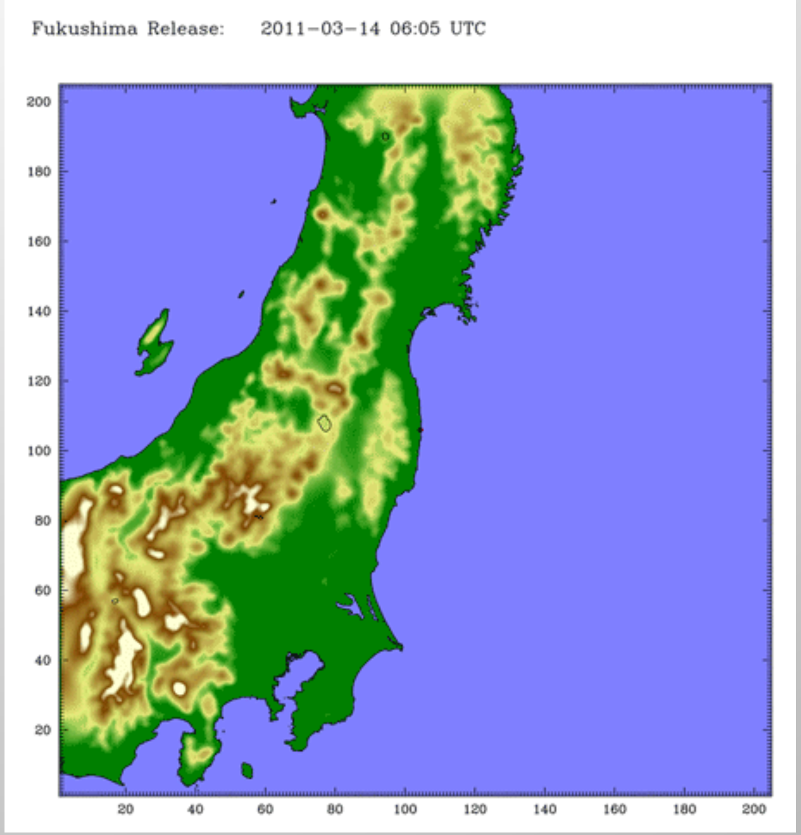
- Predictions consistent with detected plume arrival times and low levels of radiation




Particle animation of hypothetical unit release illustrates complexity of trans-Pacific dispersion

# Rapidly Changing Meteorological Conditions Presented a Significant Modeling Challenge

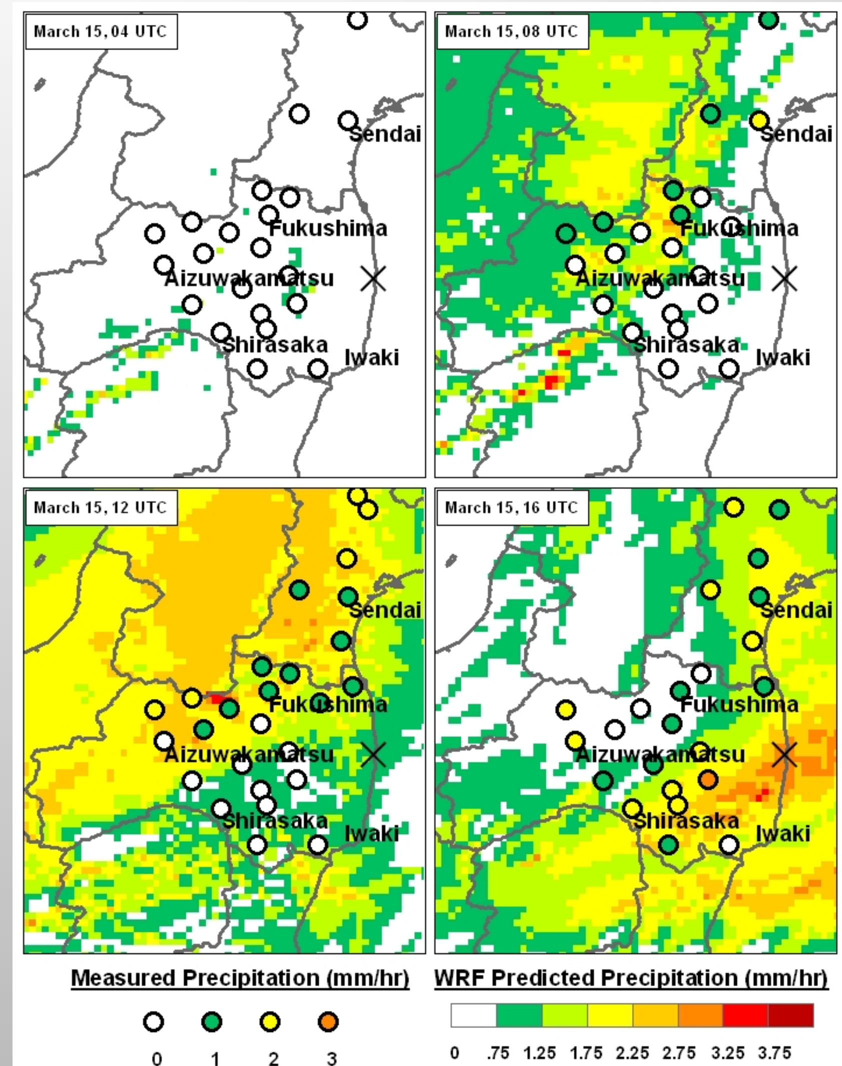
- Winds primarily off-shore until March 14 – March 16 when wind direction rotated clockwise apart from a brief period on March 12
- Winds remained primarily off-shore until March 21
- Initial NARAC forecasts captured overall pattern of winds and occurrence of precipitation
- Subsequent higher resolution (3-km) Weather Research and Forecasting Four-Dimensional Data Assimilation (WRF FDDA) simulations provided increased accuracy in modeling the timing of the wind shifts and precipitation patterns




Particle animation for hypothetical constant release rate from March 14 00 UTC - March 16 00 UTC

# Significant Precipitation Occurred Episodically Throughout the Release Period

- Significant precipitation occurred near the Fukushima Daiichi Plant on March 15 and episodically throughout the release period
- In-cloud and below-cloud scavenging by precipitation significantly impact plume transport and deposition patterns
- NARAC simulations investigated
  - Uniform grid-wide time-varying precipitation based on Japanese meteorological observations
  - WRF FDDA spatially and temporally varying precipitation (see figure)
- Measured and WRF-modeled precipitation rates show good agreement for stations near Fukushima and Tokyo

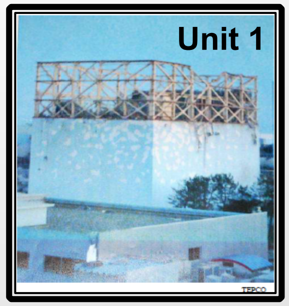


# Input Assumptions Were Based on Information Available at the Time of the Analysis

- Measurement data and information available during the response
  - Background and detector characteristics such as threshold and maximum measured levels were not included
  - AMS data required extensive calibration, altitude corrections, and time extrapolation to produce composite plots
  - Rain gauge data only (radar data not available)
- Limited information on reactor conditions
  - Times of venting (largely unknown) and explosions
  - Limited information available regarding reactor conditions
  - Confusing information (e.g., Unit 4 spent fuel pool)
- Resuspension / weathering not modeled

# NARAC Conducted Source Reconstruction From Limited Radiological Data

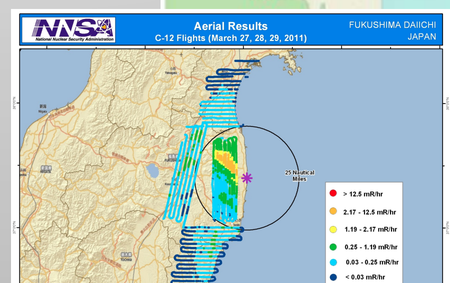
- Limited information available regarding reactor and spent fuel pool conditions and monitoring of release rates
- Limited data from early stages of release
  - TEPCO data gaps occurred following earthquake/tsunami and during March 15
  - MEXT regional monitoring stations data primarily available after March 15 0900 UTC
  - Joint U.S. DOE - Japan Aerial Measuring Survey (AMS) beginning March 17-18
- Reconstructed source focused on critical period from March 14-16
  - Time-varying releases from multiple reactor units treated as one combined source
  - Statistical / graphical optimization of overall fit of model results and data paired in space and time



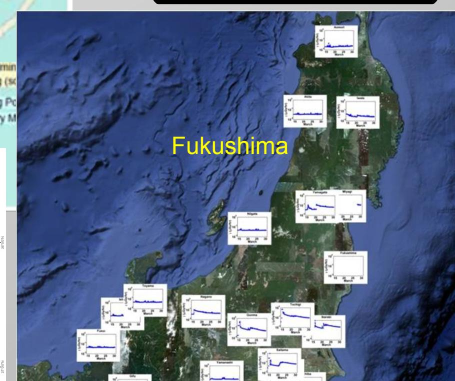



TEPCO Plant monitoring locations






Aerial Measuring System (AMS) data March 27-29

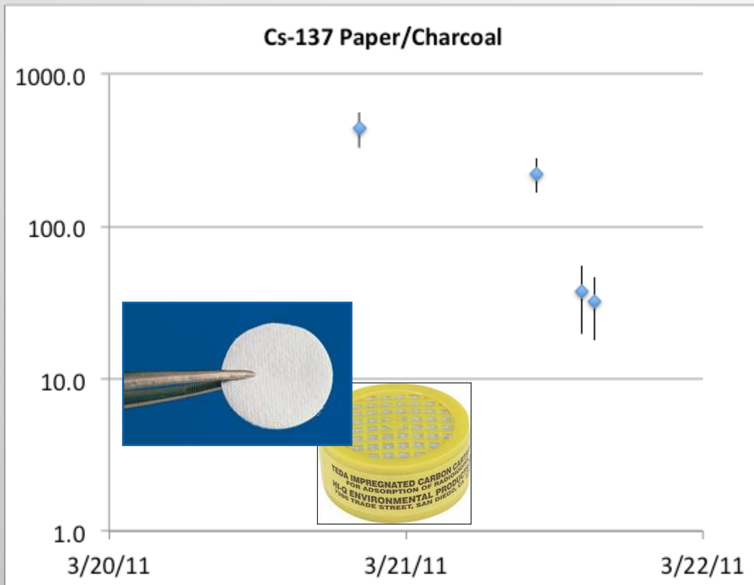


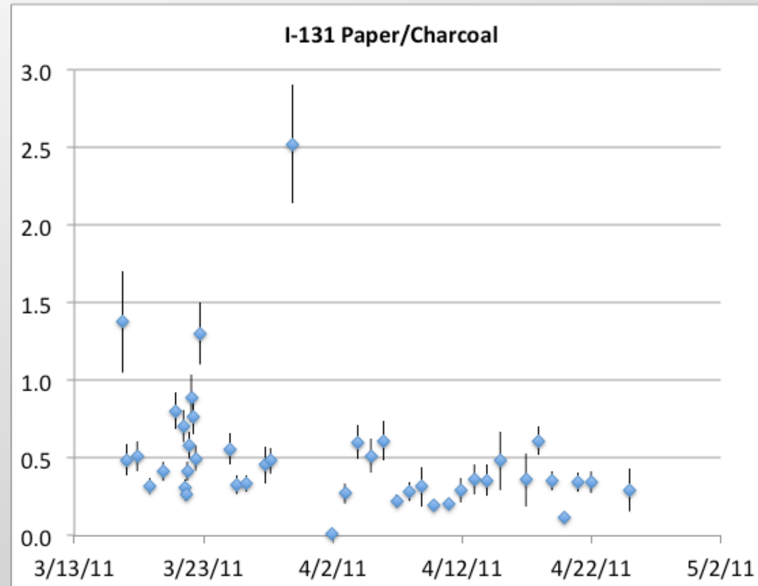

Japanese MEXT prefectural dose rate monitoring station data

# Limited Investigation of Sensitivity to Other Input Assumptions Were Made During the Response

- Limited investigation of sensitivity to input assumptions
  - Radionuclide mix and activity ratios
  - Release height: Gaussian distribution between surface and 400m AGL (0 – 400 m)
  - Particle size: 0.1 – 10 $\mu$m with AMAD = ~1 $\mu$m
  - Deposition velocity 0.3 cm/s (1.0 cm/s iodine)
  - Precipitation scavenging (baseline case used both in-cloud and below-cloud scavenging for rain rates > 1 mm/hr)

# Partitioning of Iodine on Filters are Indicative of Multiple Physical/Chemical Forms




- Cesium observed almost exclusively on particulate filters (a few instances where $^{137}Cs$ assayed above MDA on charcoal)
- Iodine split between the two filters, with particulate Iodine assumed to be primarily trapped by the paper filter, and gaseous Iodine on charcoal (the absence of $^{137}Cs$ on the cartridges could indicate that particulate matter did not significantly penetrate past paper filter)

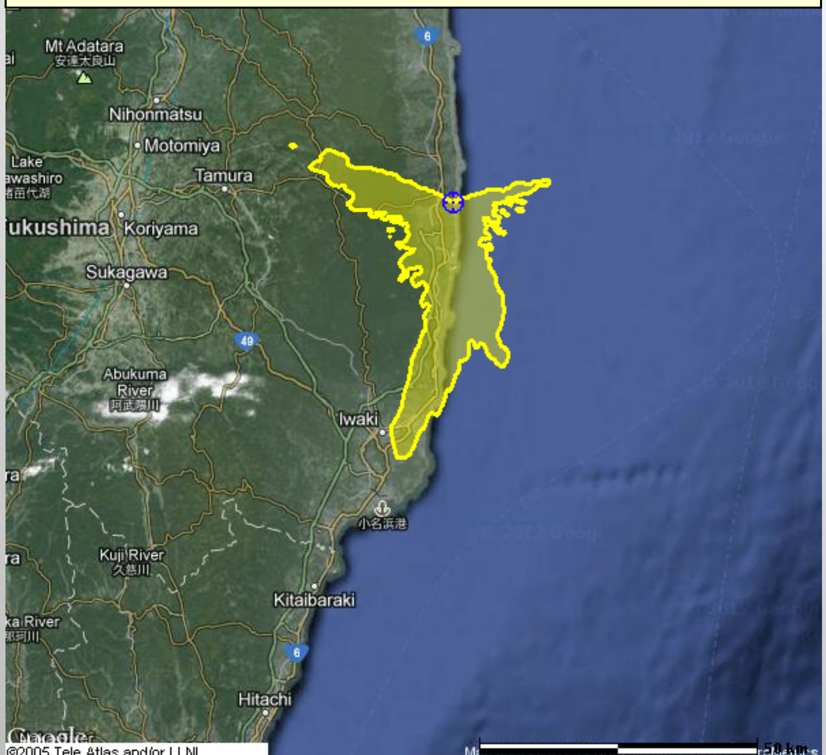
(Courtesy of S. Kreek, LLNL)

# Iodine Occurs in Multiple Physical / Chemical Forms that Impact Inhalation Dose Estimates

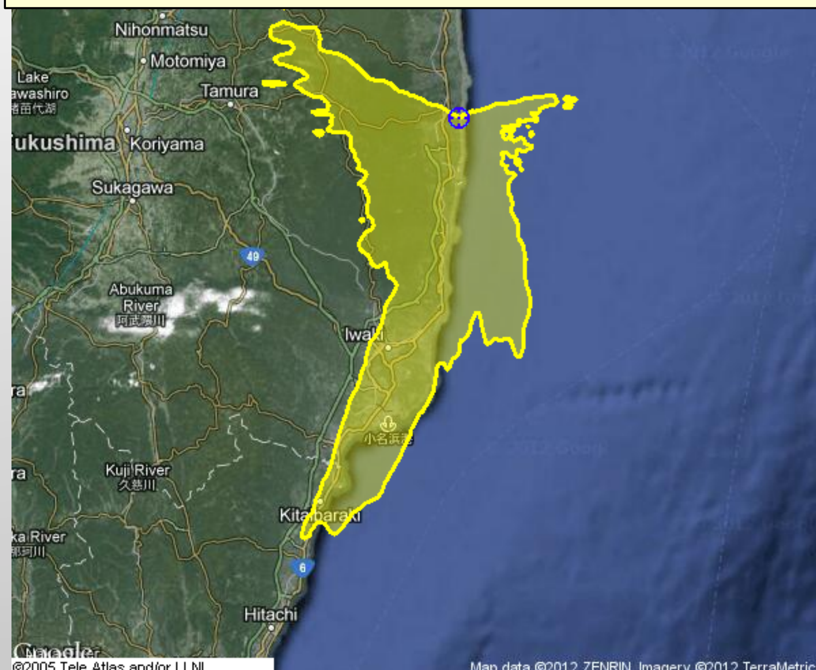
- Preliminary investigation of the effect of different gas-particle partitioning of iodine:
  - 100% particles
  - 100% organically-bound gas ($CH_3I$)
  - 100% inorganic gas ($I_2$)
  - 25% particles, 30% inorganic gas, 45% organically-bound gas (default partitioning from NRC RASCAL model)
- Same modeling assumptions as “baseline” case, apart from different deposition and dose conversion factors
  - Effective wet deposition velocity much smaller than dry deposition for inorganic iodine gas
  - Organically-bound gas has no dry deposition velocity
  - Gases assumed not to be scavenged by precipitation
- Activity particle-size distribution is log-normal with median 1 $\mu$m AMAD
- Thyroid dose is calculated from inhalation
  - Different dose conversion factors for children vs adults and for different physical activity levels (breathing rates)
  - Dose conversion factors for inorganic gases are 20-30% higher than for organically-bound gases, and twice as high as for particles (DCFPAK 1.8 and ICRP Publications 56, 60, 66, 67, 69, 71, 72)

# Iodine Gas-Particle Partitioning Assumptions Lead to Different Predicted Downwind Extent of Thyroid Dose

100% particles in respirable size range




25% particles in respirable size range,
45% organically-bound gas, and
30% inorganic gas




- 70-year committed 1-year old child thyroid dose for iodine inhalation over 2011 March 14-16
- 50 mSv / 5 rem contour is  early phase U.S. Protection Action Guide level for KI administration
- Both inorganic and organically-bound gases show higher dose and downwind extent than particulates
- Inorganic and organically-bound Iodine gas thyroid dose estimates are predicted to be similar