National Atmospheric Release Advisory Center (NARAC) R&D to Improve Atmospheric Dispersion Modeling for Nuclear Power Plant Accidents

International Expert's Meeting on Strengthening R&D Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant (CN-235)

February 17-21, 2015

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Lawrence Livermore National Laboratory

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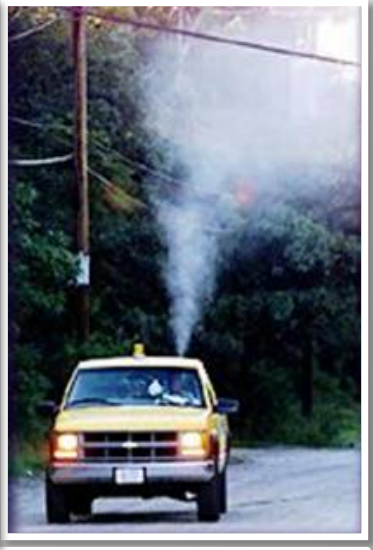
NARAC Provides Critical Information to Protect the Public and the Environment



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

National Atmospheric Release Advisory Center (NARAC)

NARAC → **Capabilities**

Provides real-time predictions of atmospheric transport of radioactivity from a nuclear accident or incident

Plume model predictions

- Airborne or Ground Contamination
- Dose
- Protective Action Guidelines

Access to world-wide weather data and geographical information

- Observed & forecast weather data
- Terrain & land surface
- Maps
- Population

Real-time access to NARAC models

- Unclassified (Internet / Web) and classified communications
- Standalone simple plume models

24x7 scientific & technical support

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

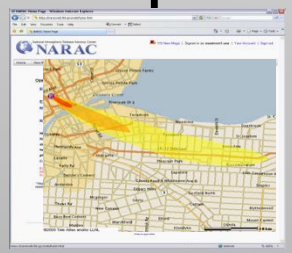
Mapping and product generation software | Population, casualty and fatality estimation

Remote Access Computer System

User interfaces and Analysis Tools for LLNL scientists

Internet/Intranet

Standalone models and mapping



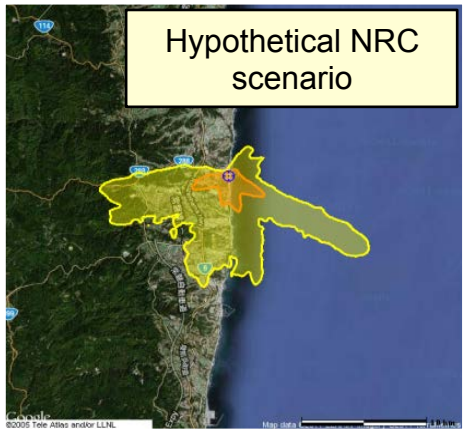
External User Tools

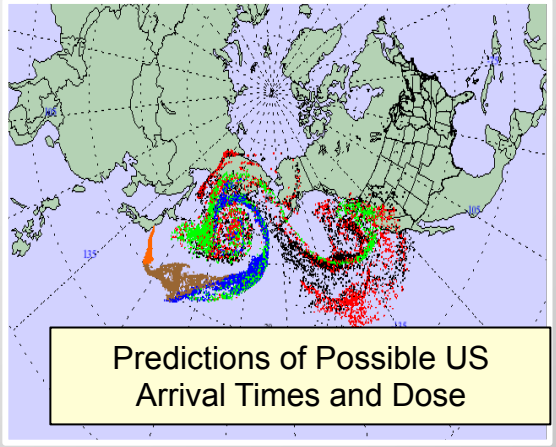
CM/NARAC/IXP Web

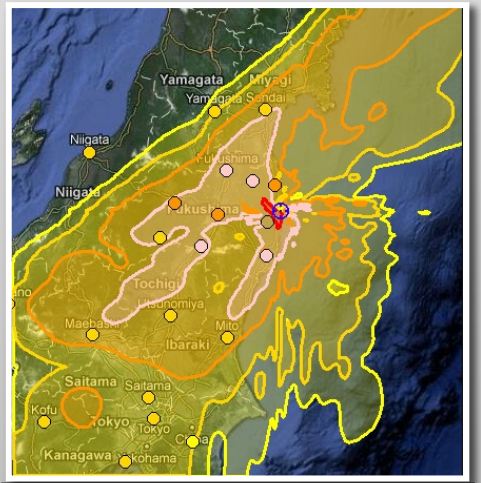
- Over 400 software applications
- 50 databases
- 3 million lines of computer code
- 28 servers
- 8 data storage systems

NARAC Supported A Variety of Requests During the Fukushima Response (March 11-May 28, 2011)

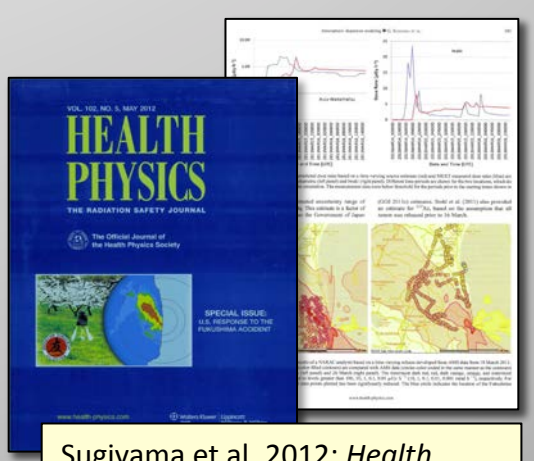
- Daily weather forecasts to support mission planning and situational awareness
- Estimates of possible dose in Japan based on hypothetical U.S. Nuclear Regulatory Commission radionuclide release scenarios to support protective action planning for U.S. citizens in Japan
- Predictions of possible arrival times and dose levels at U.S. locations
- Source term estimation and plume model refinement based on field data







Source estimation and model refinement



Sugiyama et al.,2012: *Health Physics*, 102, p 493–508

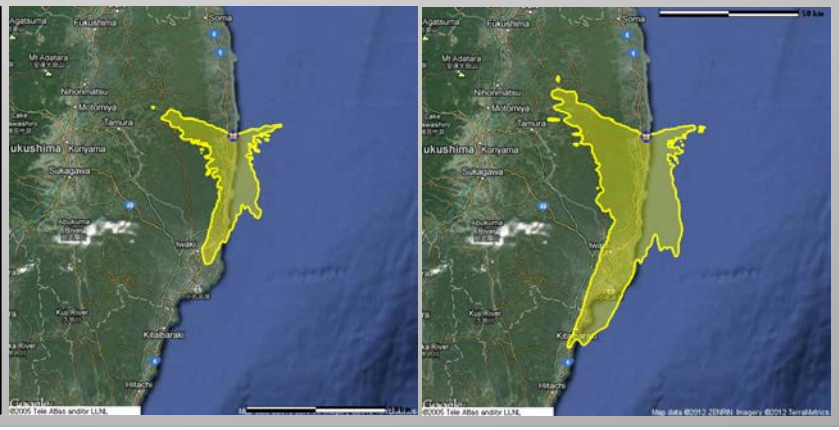
NARAC Has Implemented Enhanced Source Term Exchange Formats and Nuclear Power Plant Scenarios

- Collaborative effort with US Nuclear Regulatory Commission (NRC) for nuclear power plant accidents
  - Expanded electronic files to share/import complex nuclear power plant release information into NARAC model simulations
  - Default set of nuclear reactor release scenarios
  - Exploratory efforts to determine whether/how SNL's MELCOR severe accident analysis code could be effectively coupled to atmospheric dispersion models

Real World	Ci
Chernobyl	2.1E+08
Fukushima	1.2E+07
Three Mile Island	2.5E+06
Tomsk Reprocessing Plant	
Windscale Fire	
RASCAL Workbook	
Assessing a PWR Core Damage Accident	
Loss Of Coolant Accident (pg 14, 200)	
Long Term Station Blackout Source Term (pg 84, 205)	
Release Pathway Reduction Mechanisms (pg 95, 207)	
1 -Sprays and Fans off, Ice bed exhausted, 4 inch hole, pressure 15 lbs/in2	
2 - Sprays and Fans off, Ice bed exhausted, 4 inch hole, pressure 5 lbs/in2	
3 - Sprays and Fans off, Ice bed exhausted, 2 inch hole, pressure 5 lbs/in2	
4 - Sprays and Fans off, Ice bed NOT exhausted, 2 inch hole, pressure 5 lbs/in2	
5 - Sprays Off and Fans On, Ice bed NOT exhausted, 2 inch hole, pressure 5 lbs/in2	
6 - Sprays and Fans On, Ice bed NOT exhausted, 2 inch hole, pressure 5 lbs/in2	
Containment Bypass (pg 101, 210)	
Steam Generator Tube Rupture with Coolant Release (pg 104, 211)	
Containment Holdup (pg 106, 212)	
Specified Core Damage Point (pg 108, 215)	
Spent Fuel Assembly Damaged Underwater (pg 160, 219)	
Spent Fuel Pool Drained (pg 162, 221)	
Spent Fuel Dry Cask Rupture (pg 166, 222)	

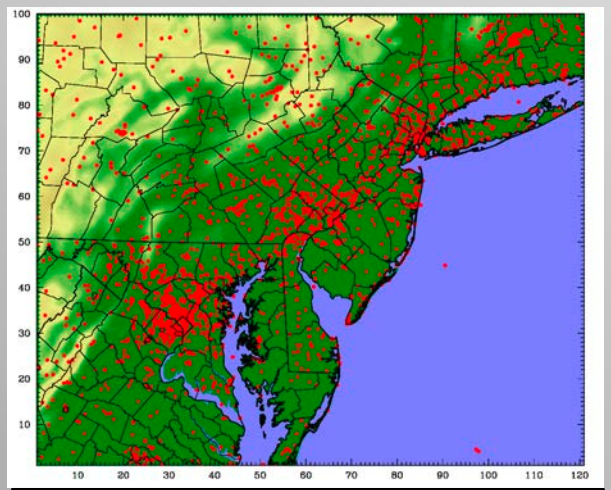
PWR/BWR Examples	
PWR	
Station Blackout, Containment Leakage	1.6E+05
Station Blackout, Steam Generator Tube Rupture	7.2E+08
Station Blackout, Containment Bypass	3.0E+08
Loss of Coolant Accident, Containment Bypass	4.0E+07
Loss of Coolant Accident, Containment Leakage	1.0E+05
Loss of Coolant Accident, Steam Generator Tube Rupture	6.1E+08
Coolant Release, Steam Generator Tub Rupture	2.4E+02
Coolant Release, Containment Bypass	5.0E-01
BWR	
Station Blackout, Containment Bypass, Release from Reactor building	4.9E+08
Station Blackout, Containment Bypass, Release via Standby Gas Treatment System	3.5E+08
Station Blackout, Dry Well, Release from Reactor building	5.2E+05
Station Blackout, Dry Well, Release via Standby Gas Treatment System	3.1E+05
Station Blackout, Suppression Pool, Release from Reactor building	3.1E+05
Station Blackout Suppression Pool, Release via Standby Gas Treatment System	3.1E+05
Coolant Release, Containment Bypass, Release from Reactor building	2.4E+00
Coolant Release, Containment Bypass, Release via Standby Gas Treatment System	2.0E-02
Loss of Coolant Accident, Containment Bypass, Release from Reactor building	1.7E+08
Loss of Coolant Accident, Containment Bypass, Release via Standby Gas Treatment System	6.6E+07
Loss of Coolant Accident, Dry Well, Release from Reactor building	4.4E+05
Loss of Coolant Accident, Dry Well, Release via Standby Gas Treatment System	3.6E+05
Loss of Coolant Accident, Suppression Pool, Release from Reactor building	3.6E+05
Loss of Coolant Accident, Suppression Pool, Release via Standby Gas Treatment System	3.6E+05

Different iodine gas partitioning:
- (Left) 100% respirable particles
- (Right) 25% particles in respirable size range, 45% organically-bound gas, and 30% inorganic gas

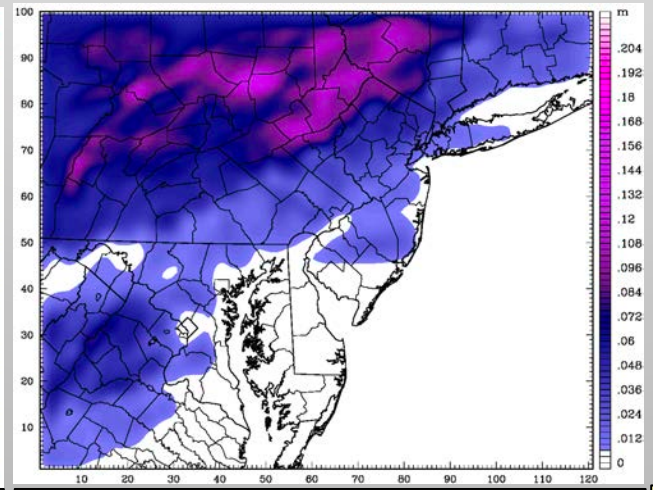


High-Resolution Numerical Weather Prediction (NWP) Modeling and Data Assimilation Enhance Model Fidelity

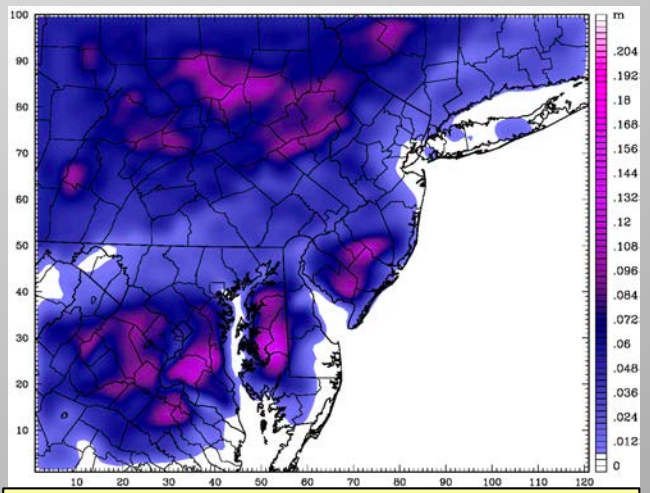
- Weather Research and Forecast (WRF) used to provide high-resolution meteorology
  - Solves atmospheric equations of momentum, heat, and moisture
  - Provides efficient model nesting capability
  - Provides additional meteorological fields (e.g. precipitation)
- 4-dimensional data assimilation (4DDA) found to improve the accuracy of WRF simulations when a sufficient density of observations is available
  - Analysis nudging on outer domains
  - Observational nudging capability on inner domain
  - Sensitivity of results to user specification of observation radius of influence (smaller radii typically improve results in complex terrain)



Surface weather stations used in 4DDA study



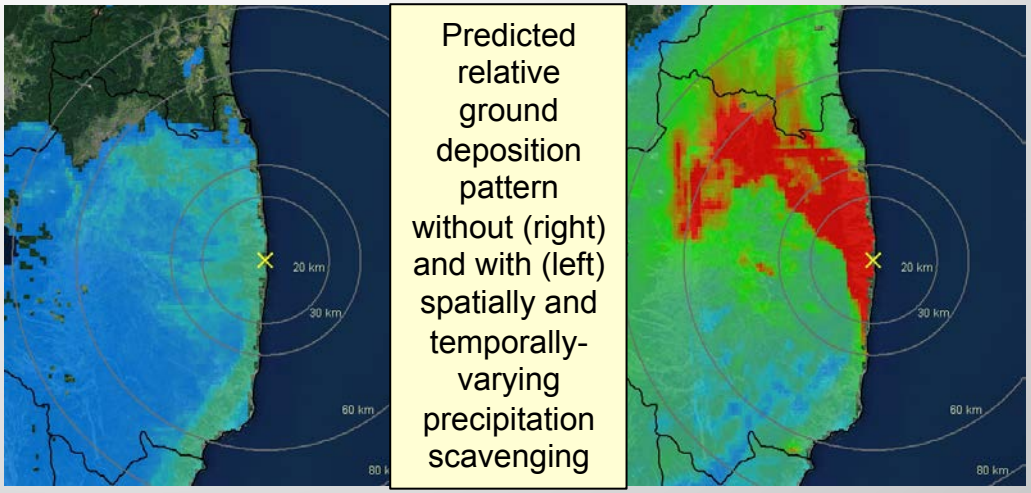
WRF predicted 2013 Dec 09 12:00 UTC snow depth w/o observational nudging



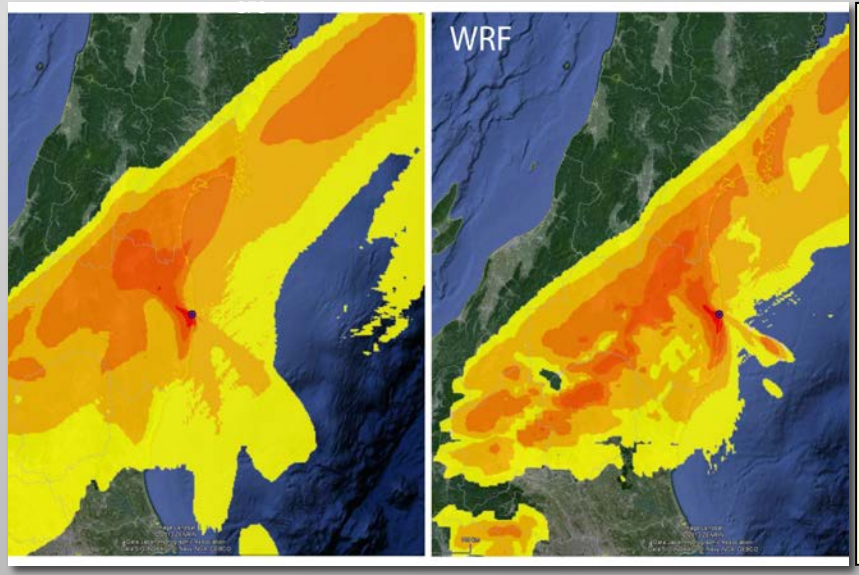
WRF simulation with observational nudging improves predicted snow depth

NARAC is Implementing Improvements to Physics Process Models (Example: Deposition Velocity)

- Particle dry deposition: Petroff & Zhang (2010)
  - Parameterizes effects of vegetation canopies
  - Applicable/validated against widest range of land-use types
- Gas dry deposition: Wesley (1998 & 2002) surface canopy resistance model
- Particle-size and precipitation-rate dependent wet deposition with separate treatment of in-cloud and below-cloud processes
  - In-cloud scavenging: Hertal et al. (1995) and Stohl et al. (2010)
  - Below-cloud scavenging: Slinn (1984) and Loosmore & Cederwall (2005)
  - Height of cloud base and top: Seiber & Arnold (2013)



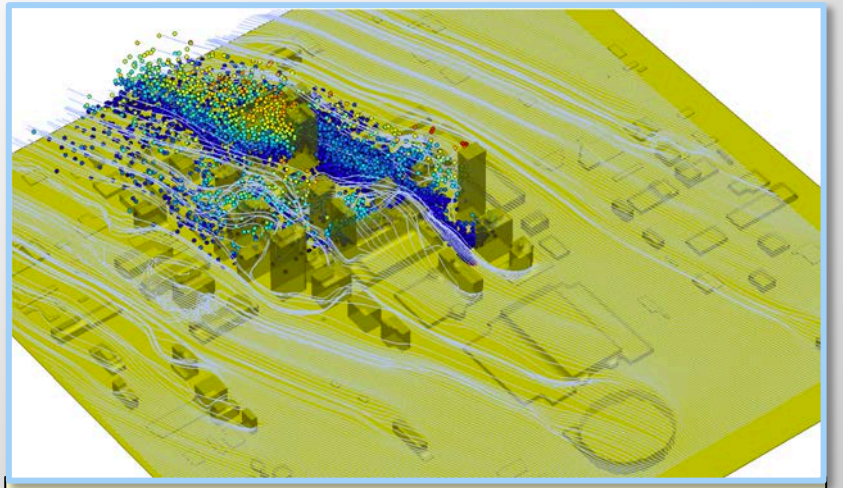
Predicted relative ground deposition pattern without (right) and with (left) spatially and temporally-varying precipitation scavenging



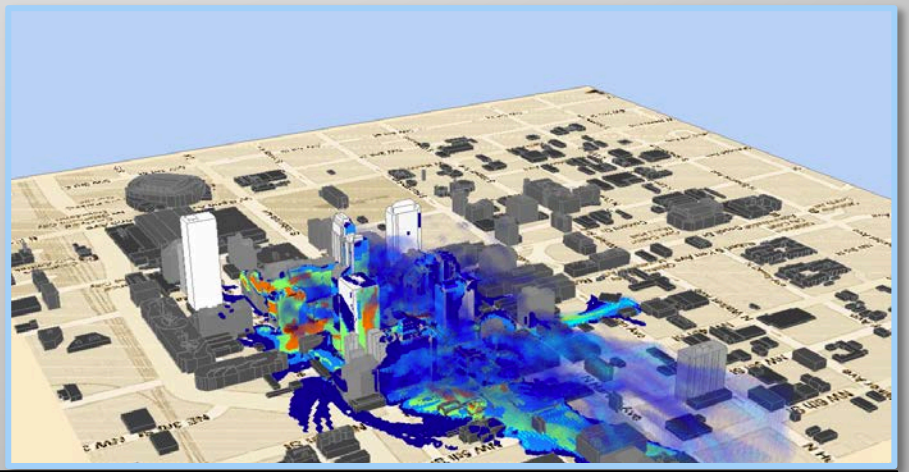
Comparison of Japan wet deposition pattern from lower resolution GFS/LODI (left) and higher resolution WRF/LODI (right) simulation

NARAC is Developing a New CFD Capability For Operational Modeling of Urban Environments

- Building-resolving computational fluid dynamics model *Aeolus* coupled to Lagrangian dispersion code
  - First principles physics solution
  - Particulate, gas, and denser than air gases for static and moving sources
- Rapid automated model grid generation using NARAC US Cities based on NGA/USGS building data
- Fast-running Reynolds Averaged Navier-Stokes model (RANS) steady state solution and higher-fidelity time-dependent Large Eddy Simulation (LES) solution
- Excellent performance for 12 different tracer releases from Joint Urban 2003 field study
- Computational performance suitable for operational applications
- Current effort to add radiological material properties, source terms and processes



RANS simulation



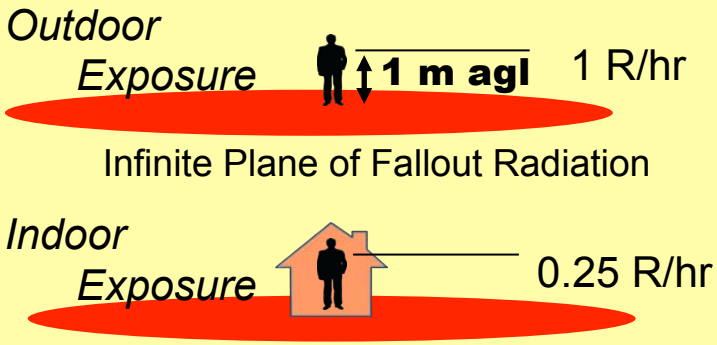
LES simulation including building deposition

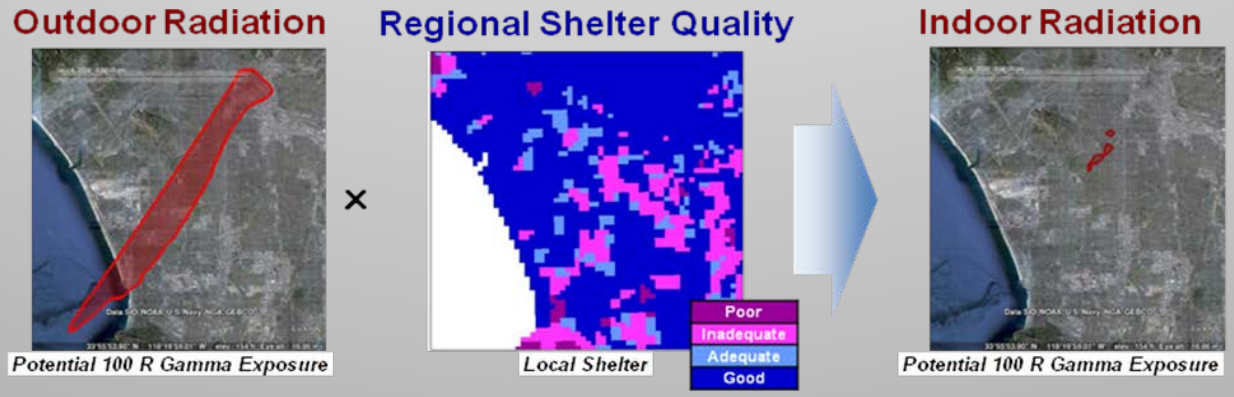
Building Shielding Calculations Improve Estimates of Casualties from Fallout

- Modeling of effects of building sheltering/ shielding to calculate indoor dose exposures and improve casualty estimates
- LLNL *PFscreen* model provides estimates of building protection factors
- LLNL *Regional Sheltering Analysis* tool estimates potential protection against gamma radiation for a variety of shelter strategies based on existing database of building properties (e.g., U.S. FEMA HAZUS data)
- Infiltration models and building leakiness databases

Pfscreen

Building Protection Factor = ratio of outdoor/indoor exposures = 4





NARAC Hardware and Software Upgrades Have Significantly Reduced Response Times

- DOE-funded compute cluster integrated into NARAC operational system
- Software performance enhancements
  - Core physics model run times reduced from 2 hours to 5 min for complex problems
  - Model output pre- and post-processing times reduced from 1+ hour to 10 min for large problems
  - Improved restart capability
  - On-going performance optimization of meteorological data processing software and other subsystems

Configuration

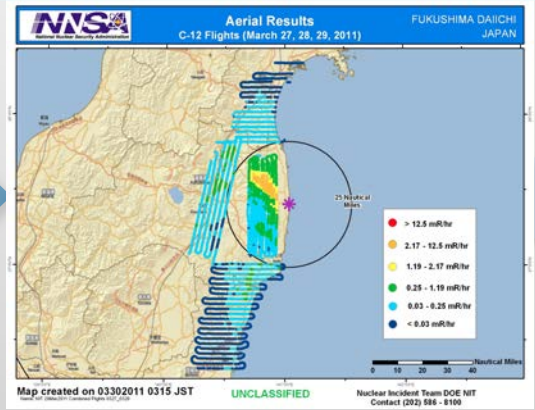
- 336 processor cores (3.46 GHz Intel 5690 chipset)
- 1344 GB total memory (4 GB/ processing core)
- High-speed communications network/switch (40 Gbit QDR)
- Linux-based system

Software upgrades and cluster utilization have reduced computational times for complex long-duration simulations involving multiple radionuclides by a factor of 25

NARAC Source Estimation and Model Refinement is Based on Field Measurement Data

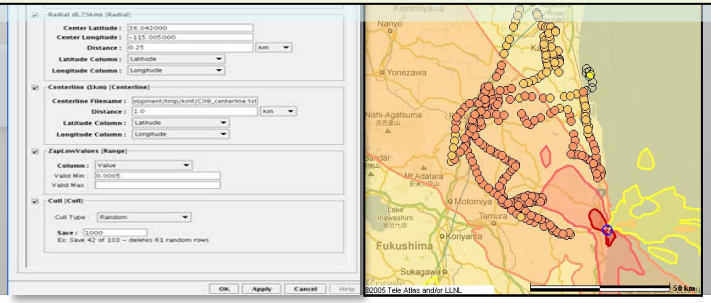
Initial model predictions guide measurement surveys

Measurement surveys and sensor data (DOE field & AMS)

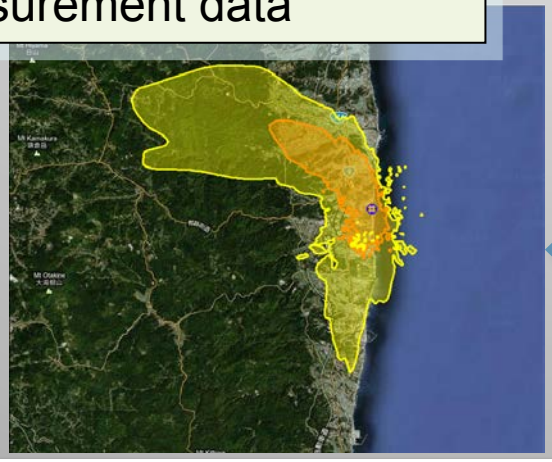


Measurement data transferred electronically to LLNL/ NARAC

Software selects, filters and statistically compares measurements and predictions



Updated predictions using measurement data

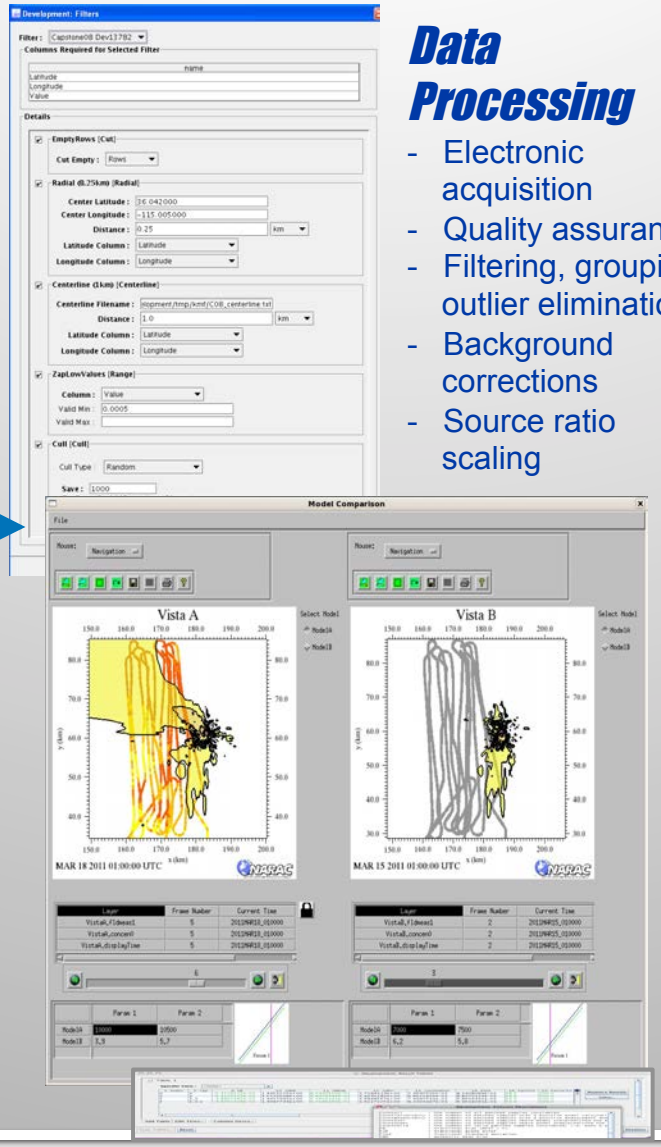


Automated Field Measurement and Model Comparison Tools Reduce Delivery Time for NARAC Data-Model Products

Monitoring / Field Data

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

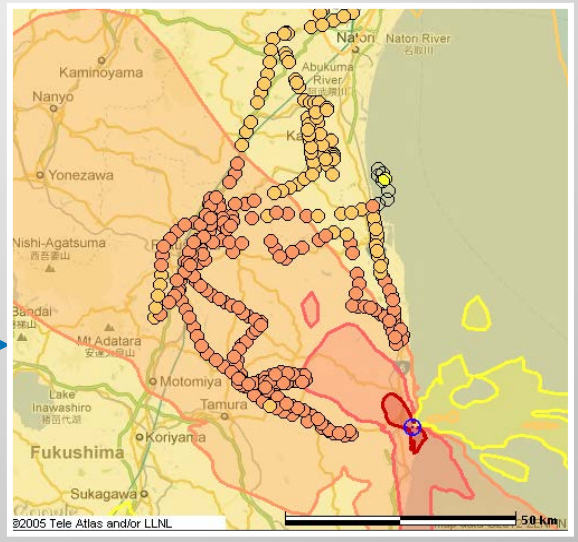
Aerial Measurement - Gamma Spectroscopy
In situ field assays – Gamma Spec, Alpha/Beta Survey, Dose Rate
Air Filters (paper, charcoal) – Gamma Spec, Alpha/Beta Counters, Lab Analysis
Soil and Soil Cores – Gamma Spec, Lab Chemistry



Data Processing

- Electronic acquisition
- Quality assurance
- Filtering, grouping, outlier elimination
- Background corrections
- Source ratio scaling

Data-Model Comparisons Refined Model Predictions



Graphical/Statistical Data/ Model Comparison Tools

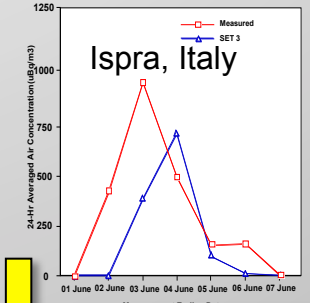
- Data-model comparisons paired in space time
- Statistical metrics (e.g. bias, [geometric] variance, standard deviation, root mean / normalized mean square area, factor of R)
- Measurement map displays
- Graphical model-data

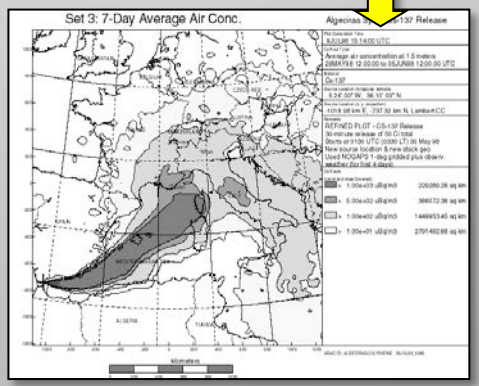
Source Estimation Methods to Refine Plume Models Remains a Key Focus of NARAC Development Efforts

- Backward trajectory methods (accounting for null data)
- Cost functional minimization
- Source-receptor optimization starting with *a priori* estimate ("predictor-corrector")

- Bayesian inferencing and stochastic sampling
  - Statistically-rigorous technique
  - 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
  - Complex sources (e.g., multiple, moving)

NARAC chemical odor source location analysis based on backward trajectories



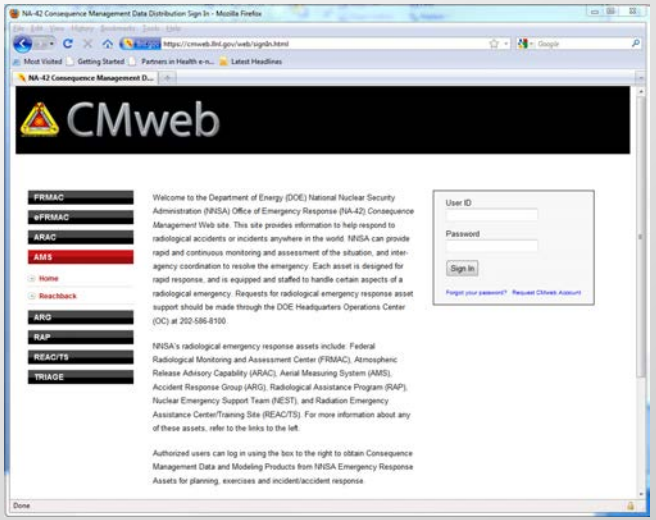


NARAC operational analysis reconstruction of probable source area and emission rate for Algeciras steel mill Cs-137 release

Chemical Odor Analysis: Matthew Simpson
Algeciras: Luca Delle Monache

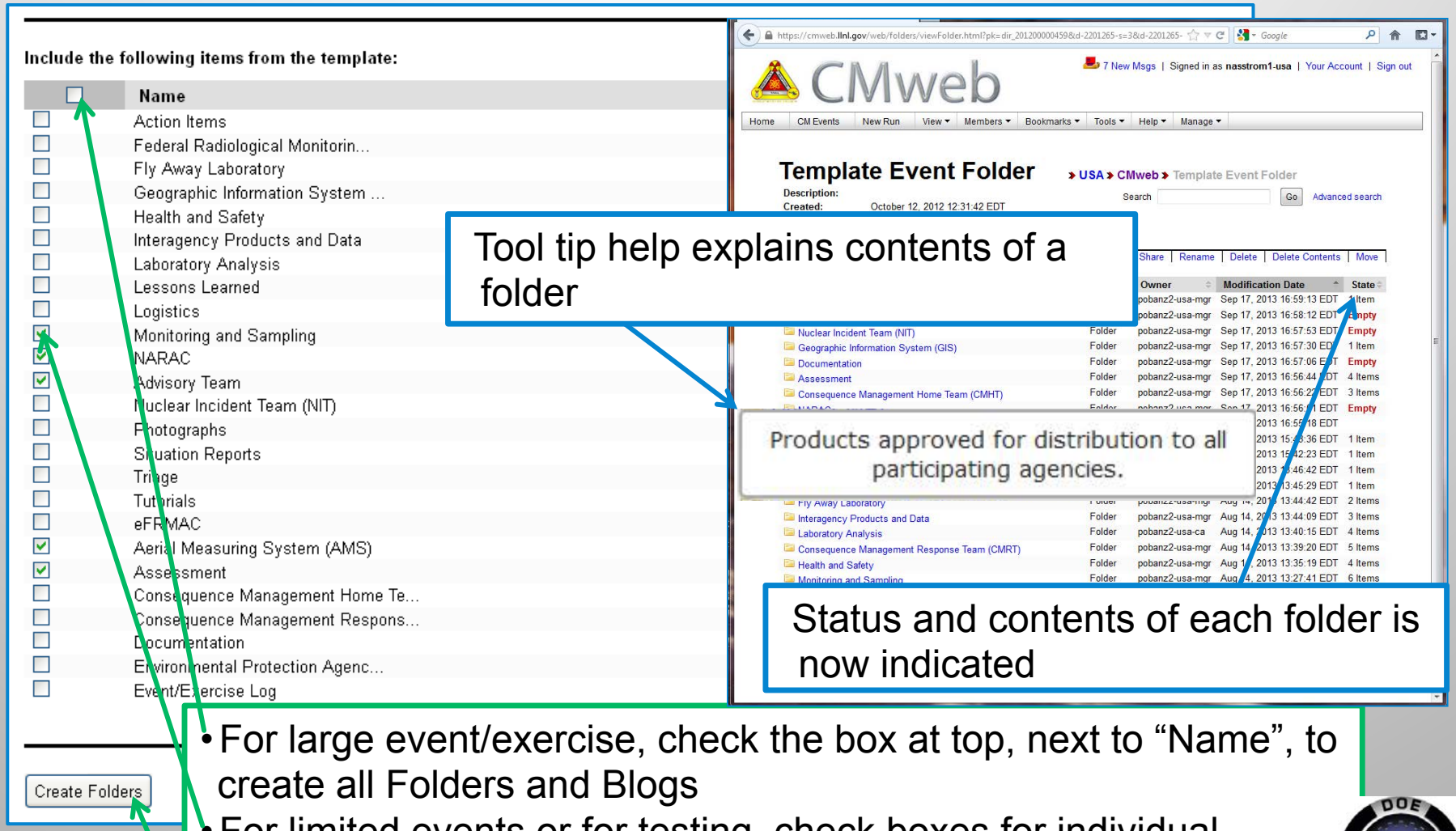
NARAC Web Site Provided 24/7 Access to Information During the Fukushima Response

- NARAC-hosted CMweb system used to store and share information with DOE and the supported interagency community
  - Model predictions (300+ analyses and 115 shared products)
  - Radiological measurement data
  - Mapped data products
  - Reports
  - Status logs



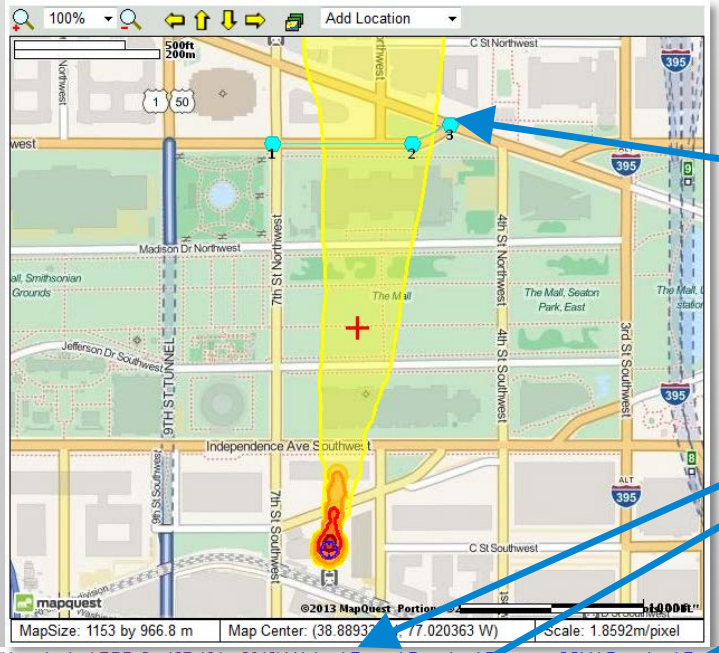
- NARAC-hosted *International eXchange Program* (IXP) Web-based system allows DOE-authorized users to:
  - Run radiological atmospheric dispersion and dose calculations on a *NARAC* computer system
  - Receive dispersion and dose calculations done by experts at NARAC and other Global Dose Assessment Centers (*GDACs*) in Japan (JAEA) and Russia (FEERC)
- IXP used by approximately 40 countries and 3 international organizations

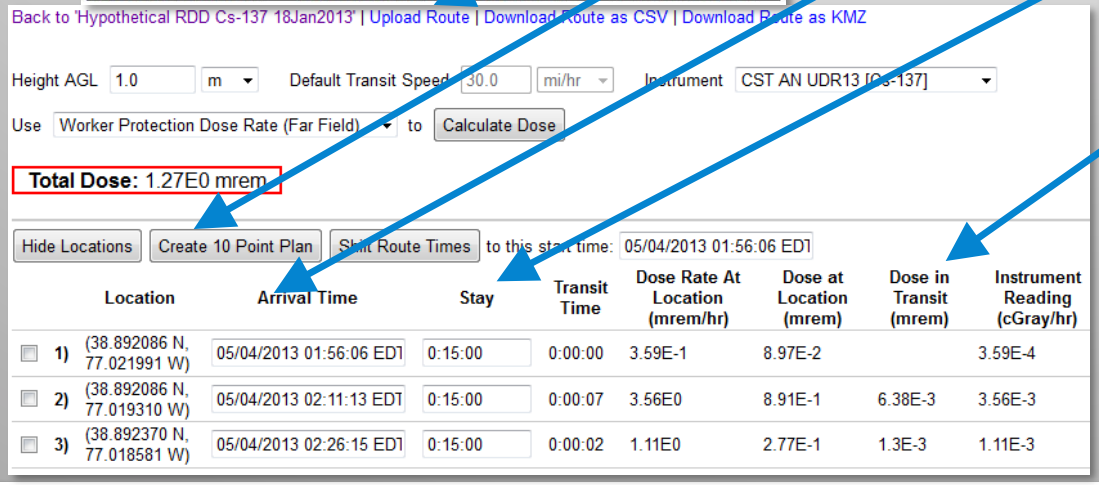
New Event Creation Wizard Facilitates Information Sharing and Organization During Events



- For large event/exercise, check the box at top, next to “Name”, to create all Folders and Blogs
- For limited events or for testing, check boxes for individual Folders/Blogs you would like to include (to avoid time consuming effort to delete unneeded folders)
- Then, click “Create Folders”

NARAC Provides Tools to Support Field Teams: Example Web-based Mission Planning Tool





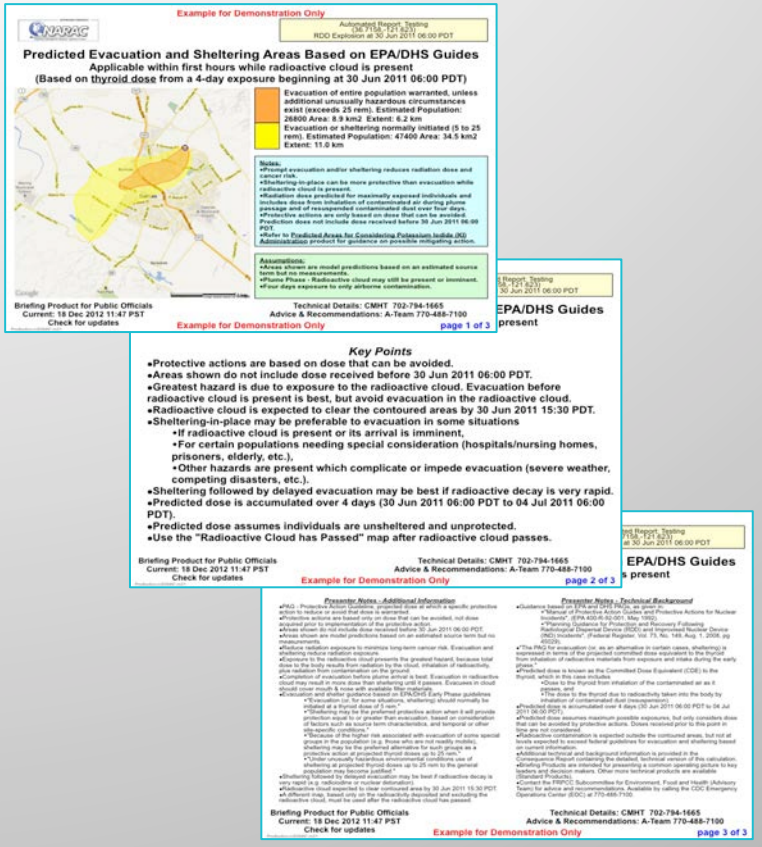
	Location	Arrival Time	Stay	Transit Time	Dose Rate At Location (mrem/hr)	Dose at Location (mrem)	Dose in Transit (mrem)	Instrument Reading (cGray/hr)
1)	(38.892086 N, 77.021991 W)	05/04/2013 01:56:06 EDT	0:15:00	0:00:00	3.59E-1	8.97E-2		3.59E-4
2)	(38.892086 N, 77.019310 W)	05/04/2013 02:11:13 EDT	0:15:00	0:00:07	3.56E0	8.91E-1	6.38E-3	3.56E-3
3)	(38.892370 N, 77.018581 W)	05/04/2013 02:26:15 EDT	0:15:00	0:00:02	1.11E0	2.77E-1	1.3E-3	1.11E-3

Estimate potential dose bases on route and stay times

- Select route by clicking on monitoring route points
- Upload monitoring route or use DOE “10 Point Plan”
- Edit arrival times and stay times
- Shift route times to account for time variation of groundshine dose
- Display calculated dose rate, dose, instrument readings
- Extensions: aerial monitoring and evacuation planning

Improving Communication of Technical Information to Decision Makers and Responders is a Key Ongoing Effort

- U.S. DOE is leading the development of radiological/nuclear "Briefing Products"
  - Goal: improve the communication of technical information to planners, decision makers, and emergency responders
  - Focus on actions and decisions that need to be considered (evacuation/ sheltering, relocation, worker protection, agricultural embargoes)
  - Based on existing pertinent agency-published documents for guidance
  - Developed with extensive interagency input
- Designed for Subject Matter Experts briefing of officials and responders (not intended for the general public)



Briefing Products available for nuclear power plant accidents, radiological dispersal devices, nuclear detonations, and chemical/biological releases

NARAC is Addressing a Number of Challenges Identified During the Fukushima Response

- Model improvements
- Data-model fusion enhancements
- Enhanced products and tools to support decision makers and responders
- Procedural and software management updates to assist in managing large volumes of information during major events
- Training to increase skill level and experience of scientific and technical staff critical in handling complex analyses on an emergency basis and developing non-standard types of analysis and products on the fly

National Atmospheric Release Advisory Center

NARAC

Web: narac.llnl.gov

Email: narac@llnl.gov

Lawrence Livermore National Laboratory

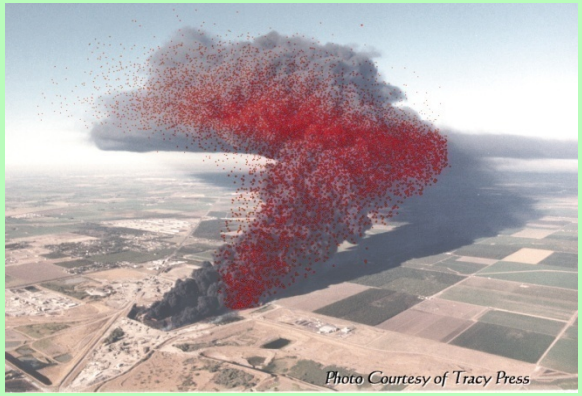
NARAC Provides Operational Services, Tools, and Expertise for Preparedness, Response, & Recovery

Event Information

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

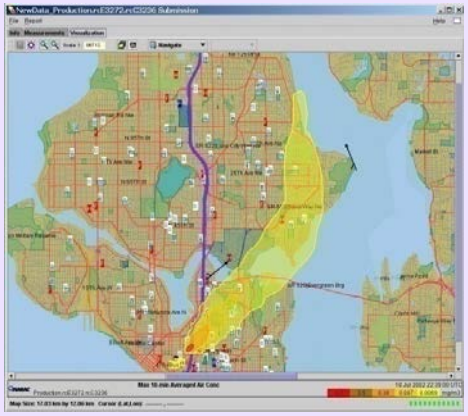
Operational Services and Expertise

- 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



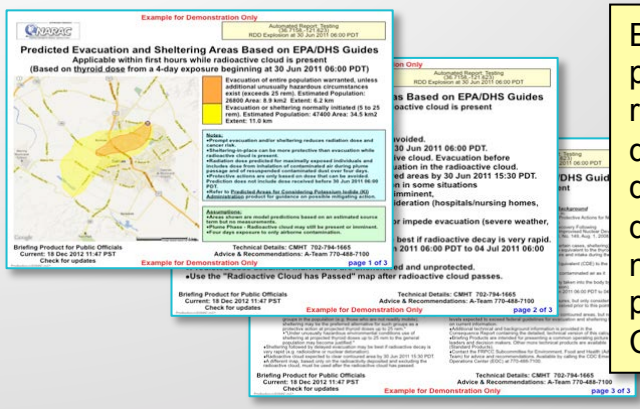
Actionable Information

- 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



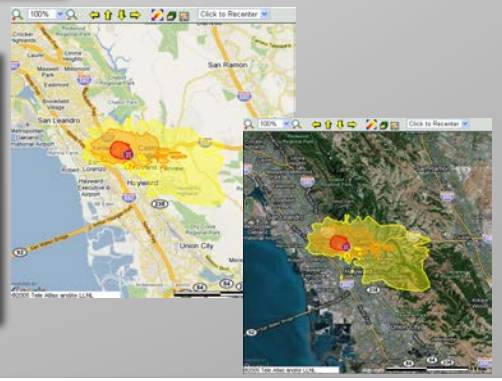
Products for Communication with Users Are Developed with Interagency Input

- Standard suites of CBRN technical products that show plume hazard areas, affected populations, health effects, protective action guide levels, and geographical information
- Consequence reports documenting results, inputs, assumptions, and plot interpretation
- Interagency-developed Briefing Products for decision makers and emergency responders focused on actions that need to be considered to protect the public and the environment
  - Evacuation / shelter-in-place, relocation, worker protection, agricultural embargo
  - Operational products: radiological dispersal devices, nuclear detonations, nuclear power plant accidents
  - Draft versions: toxic industrial chemicals, chemical/biological agents
- Supplementary analyses (meteorology, deposition, field data, animations)
- Product output in multiple formats for integration into user's GIS systems



Briefing products for radiological dispersal devices, nuclear detonations, nuclear power plant accidents, CB releases

Animations and time series plots to display evolving impacts



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

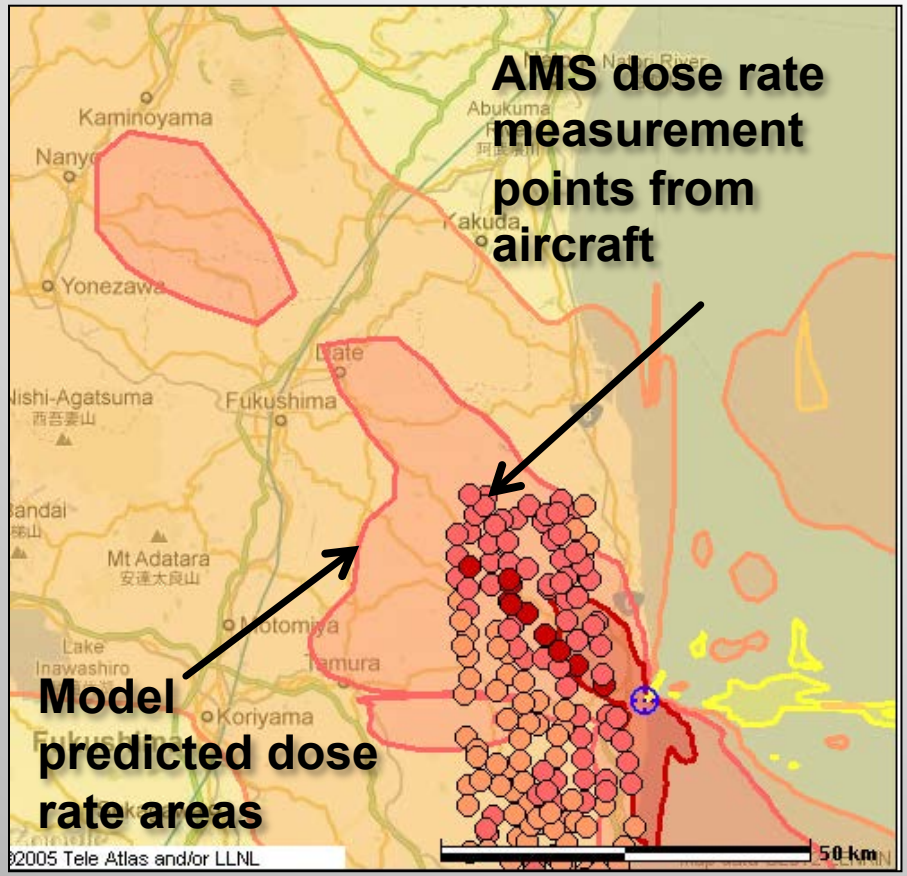
ESRI Shape and Google Earth KMZ GIS files with plume areas

Briefing Products: Kevin Foster, Kristen Yu (LLNL), Harvey Clark (RSL)

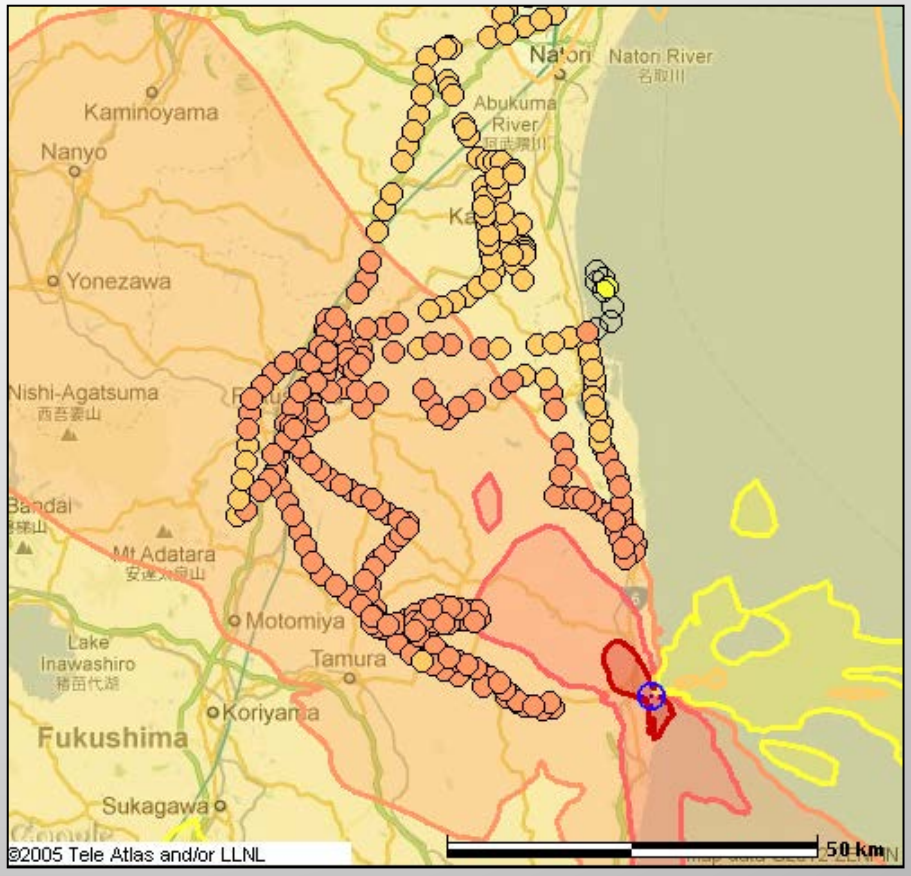
DOE/NNSA Activated Personnel to Respond to the Fukushima Daiichi Accident

- DOE/NNSA mission: Assess the consequences of releases from the Fukushima Daiichi Nuclear Power Plant
- DOE/NNSA deployed personnel and home teams
  - Predictive modeling
  - Air/ground monitoring and sample collection
  - Laboratory sample analysis
  - Dose assessment
  - Data interpretation

NARAC Simulations Were Refined and Compared to U.S. DOE Aerial Measuring System (AMS) Data



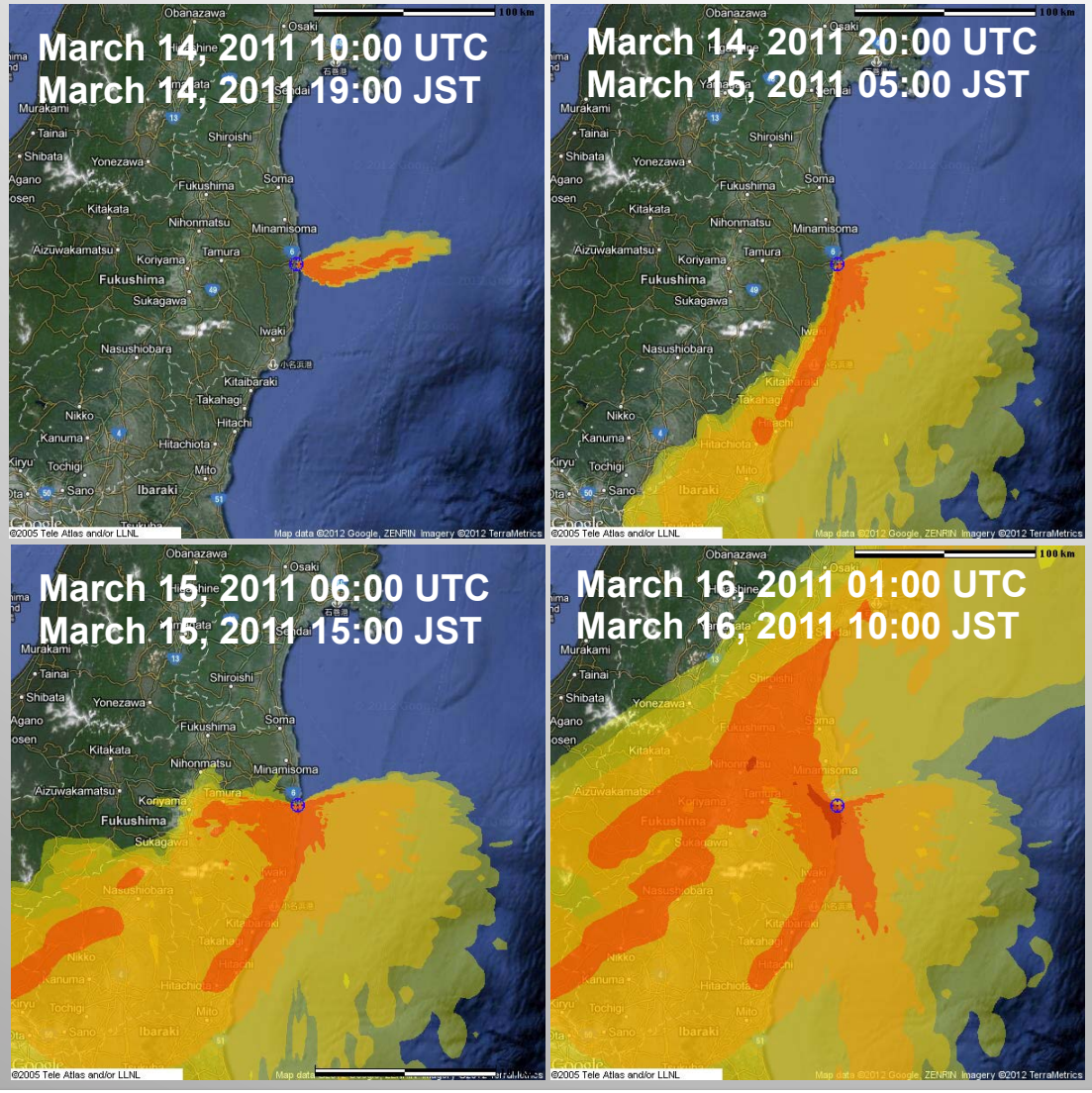
NARAC modeled dose rate levels overlaid with March 18 AMS data. Meteorology based on Japanese weather observations



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

External Dose Rate is Determined From the Effects of Both Ground-Shine and Air Immersion



- Time series shows combined air immersion dose and ground shine dose from the accumulation of ground contamination during March 14 0600 – March 16 0100 UTC

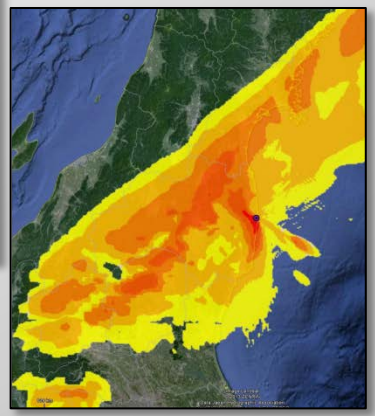
- Dose rate contours:
  - 120.0 μGy h^{-1} (red)
  - 4.0 μGy h^{-1} (dark orange)
  - 0.4 μGy h^{-1} (orange)
  - 0.04 μGy h^{-1} (dark yellow)
  - 0.004 μGy h^{-1} (yellow)

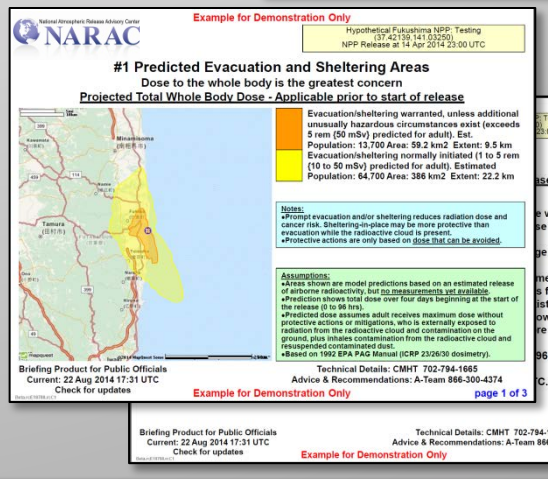
  (12, 0.4, 0.04, 0.004, 0.0004 mrad/hr)

- Baseline" release estimate from March 14 0600 UTC to March 16 0100 UTC (Sugiyama et al., 2012, *Health Physics*)

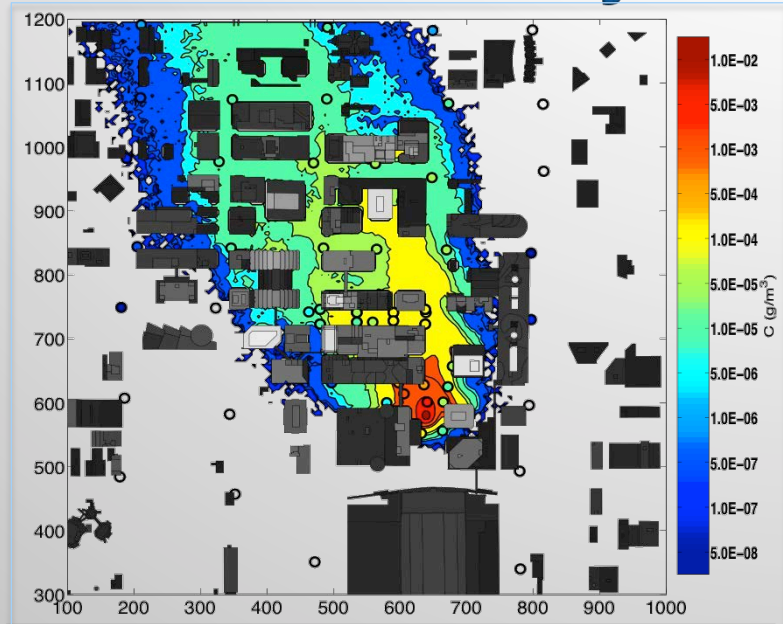
NARAC Enhancements Are Being Made to Improve Response to Future Incidents

- **Significantly reduced time for complex NARAC atmospheric dispersion simulations**, using new dedicated 336-processor compute cluster and optimized software. (Run times reduced by factor of 10-100, e.g., from 2 hours to 5 min)
- **Development of higher-resolution modeling of dry deposition and precipitation / wet deposition**, which was key to prediction of ground contamination levels in Japan
- **Expanded electronic files to import complex nuclear power plant release information** from US Nuclear Regulatory Commission (NRC) in to NARAC model simulations, and created a default set of release scenarios
- **New decision-maker briefing versions of NARAC products** for nuclear power plant accident scenarios for more effective communication of information on actions that are warranted to protect workers and the public (e.g., evacuation, sheltering, relocation) in collaboration with DHS/FEMA and other US government agencies



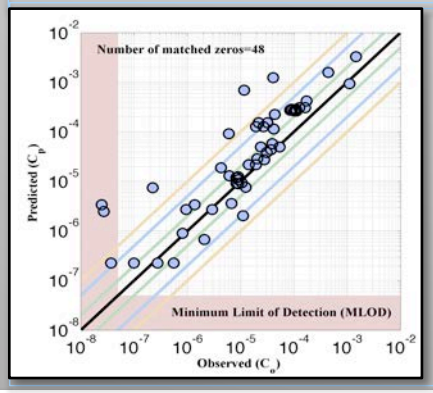


Aeolus Has Been Extensively Validated Against Urban Field Study Data Sets

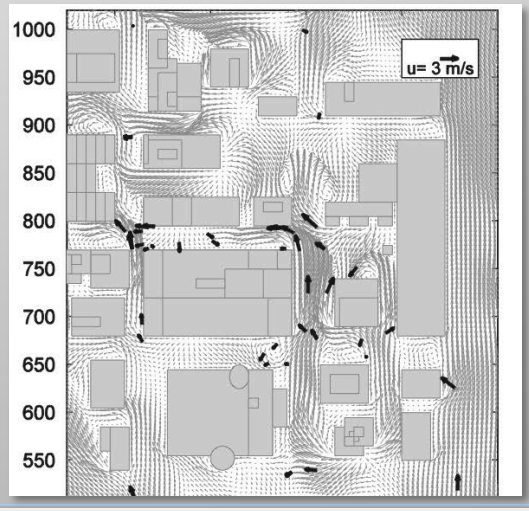


Contours of 30 minute averaged concentration overlaid with 30 min averaged field concentration data (color coded circle): horizontal slice (*x*-*y* plane) at 2 m AGL.

- Model was validated using data from 12 different trials during Joint Urban 2003 field campaign
- Concentrations predicted by the model were found to be in good agreement with the field data (~50% were predicted within a factor of 2, ~70% within a factor of 5 and ~80% within a factor of 10)
- Performance on quad-core laptop
  - RANS model took ~200 sec for each of these cases (4.5 million grid points)
  - Lagrangian dispersion model took ~80 sec (using 0.5 million particles)



Scatter plot of predicted and observed 30 minute averaged concentration (g/m^3) paired in space and time on a horizontal slice (*xy* plane) at 2 m above ground level



Aeolus predicts Important urban flow features including channeling, reversed flow, vortices, divergence etc.

Source Reconstruction Tools Are Used to Optimize of Model Simulations to Data

- Data imported in a variety of formats for importing measurement data (e.g., XML, Excel, CSV, ASCII text/table)
- Graphical displays for displaying and comparing measurement data with plume model predictions (geospatial and time series representations, text-based output, scatter plots, Google Earth overlays)
- Rapid selection, grouping, and editing of measurement data for analyses (e.g., geospatial inclusion/exclusion zones, centerline-located data, measurement sampling, minimum/maximum data ranges, streamlined capabilities for fast turnaround)
- Identification and removal of measurement outliers using Pierce and Gould data rejection method
- Statistical comparison of measurements and predictions using measurement-to-model ratio statistics (e.g., percentage of values with factor R, bias, etc.)
- GUI-based post-processing capabilities to linearly scale predicted source term quantities

International Users Access NARAC Predictions Using the *International eXchange Program* (IXP)

- *International eXchange Program* (IXP) is a Web-based system that allows authorized users around the world to:
  - Run radiological atmospheric dispersion and dose calculations on a *NARAC* computer system for their country only
  - Receive dispersion and dose calculations done by experts at NARAC and other Global Dose Assessment Centers (*GDACs*) in Japan (JAEA) and Russia (FEERC)
- The IXP web site https://ixp.llnl.gov/ provides secure and password-controlled access for users approved by DOE/NNSA and their country's competent authority
- The IXP is used by approximately 40 countries and 3 international organizations including the International Atomic Energy Agency (IAEA), European Commission Joint Research Centre, Nuclear Energy Agency, Org. for Economic Cooperation and Development)

Acknowledgements

- NARAC Operations Scientists, Customer Support, System Administrators, Systems Team – plume modeling, CMweb support, 24/7 systems support, tool updates
- RSL/SNL/LANL/LLNL CMHT – monitoring data; health physics support
- CMHT Laboratory Team – sample analysis
- Radiological Triage – Spectral analysis for isotopic mix
- DOE HQ Nuclear Incident Team – Management, coordination and prioritization of Interagency and White House tasking
- NRC – reactor and spent fuel source term analyses

DOE/NNSA Principal Deputy Administrator Neile Miller (in yellow) with the NARAC team.