Experience, Lessons Learned and Improvements Resulting from the Use of the National Atmospheric Release Advisory Center (NARAC) During the Fukushima Daiichi Accident

International Expert's Meeting on Radiation Protection after the Fukushima Daiichi Accident (CN-224)

February 17-21, 2014

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LLNL-PRES-650086
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

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

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

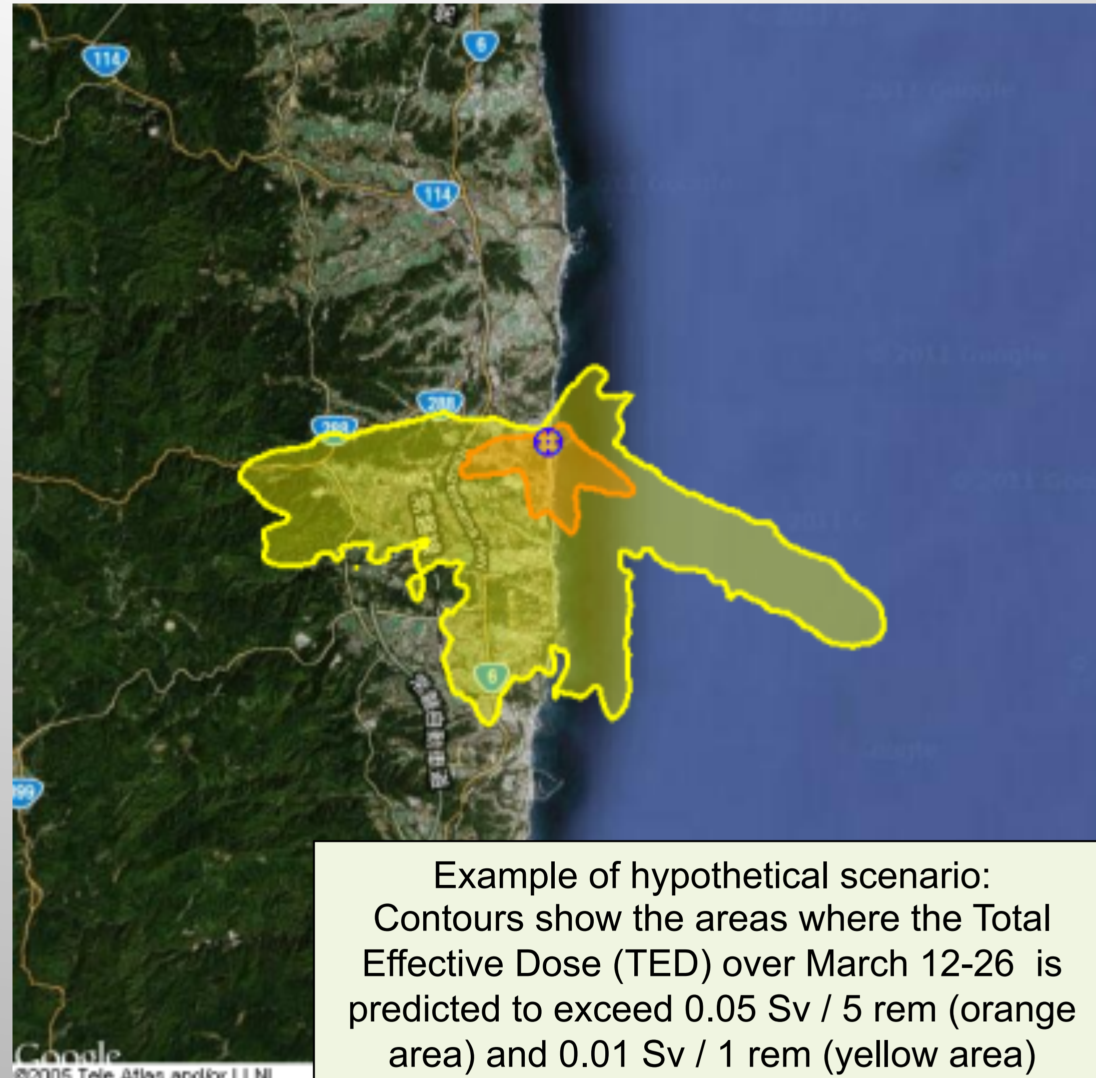
24x7 scientific & technical support

NARAC Provided Regular Forecasts to Support Mission Planning and Model Analysis

Daily weather forecasting visualized as hypothetical hourly plume to illustrate predicted shifts in wind direction

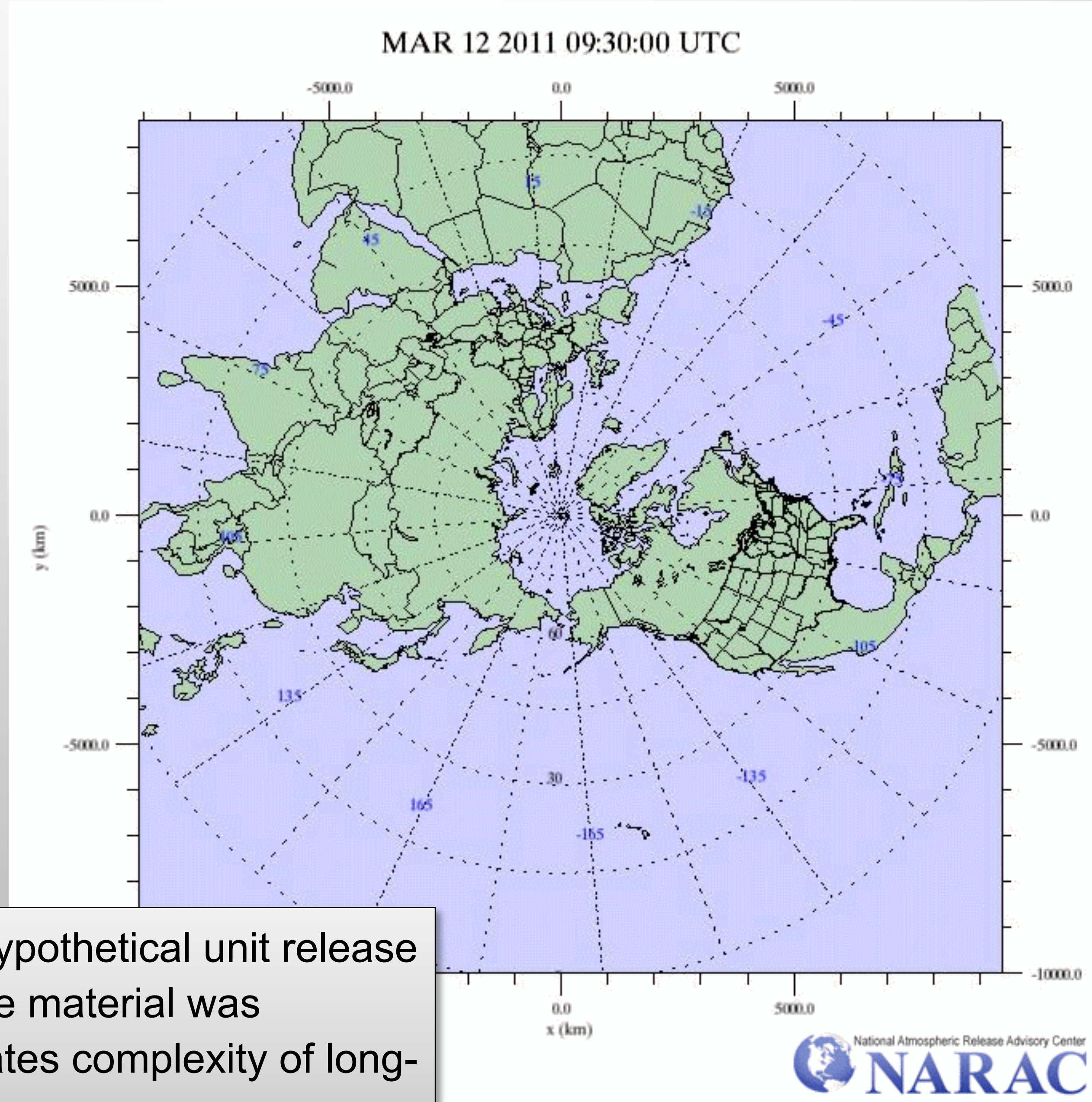
DOE/NARAC Worked Closely with the U.S. NRC to Estimate Impacts for a Wide Range of Hypothetical Scenarios

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



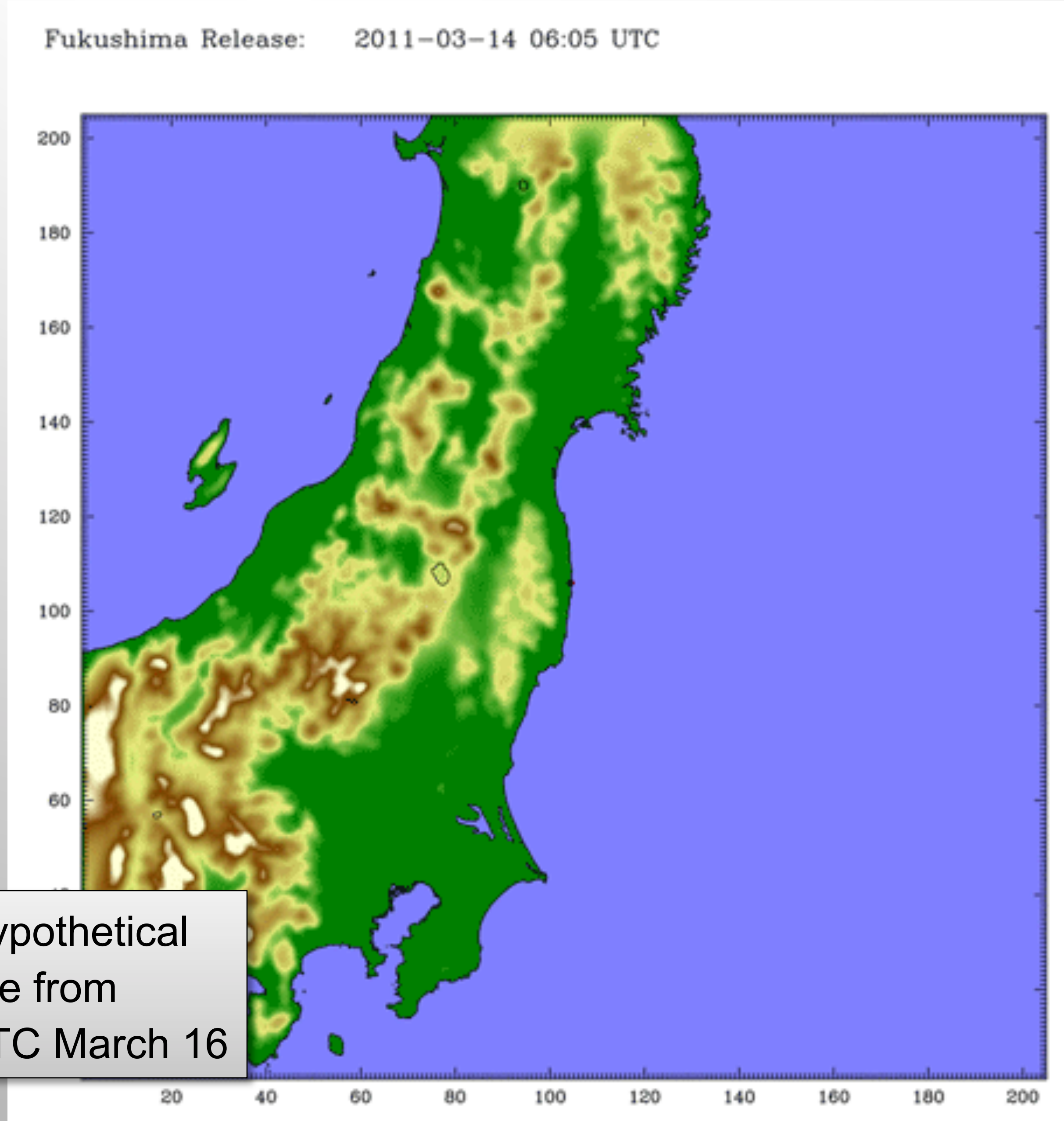
Example of hypothetical scenario: Contours show the areas where the Total Effective Dose (TED) over March 12-26 is predicted to exceed 0.05 Sv / 5 rem (orange area) and 0.01 Sv / 1 rem (yellow area)

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



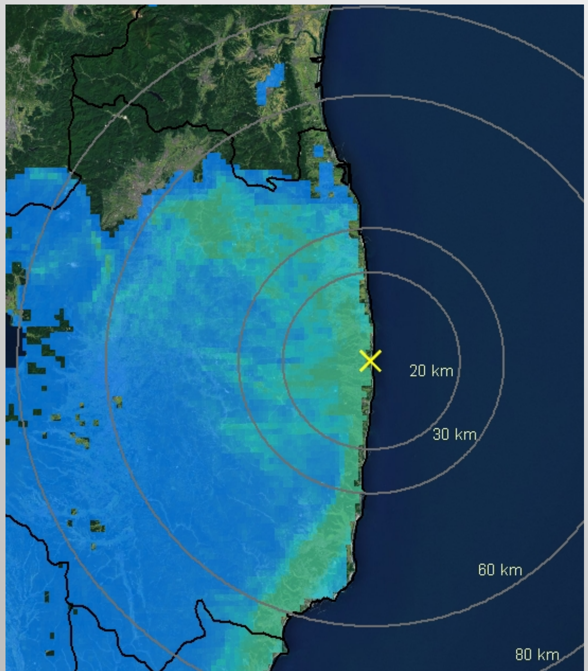
Particle animation of hypothetical unit release shows when and where material was transported and illustrates complexity of long-range dispersion

Rapidly Changing Meteorological Conditions in Japan Presented a Significant Modeling Challenge

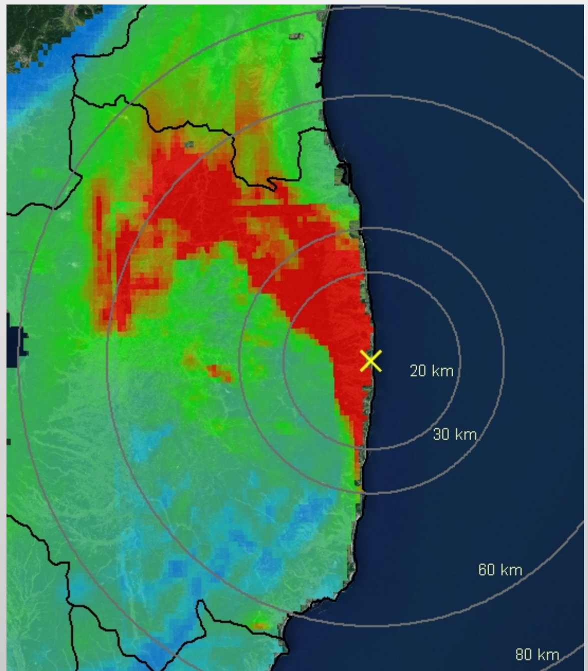


Particle animation for hypothetical constant release rate from
00 UTC March 14 – 00 UTC March 16

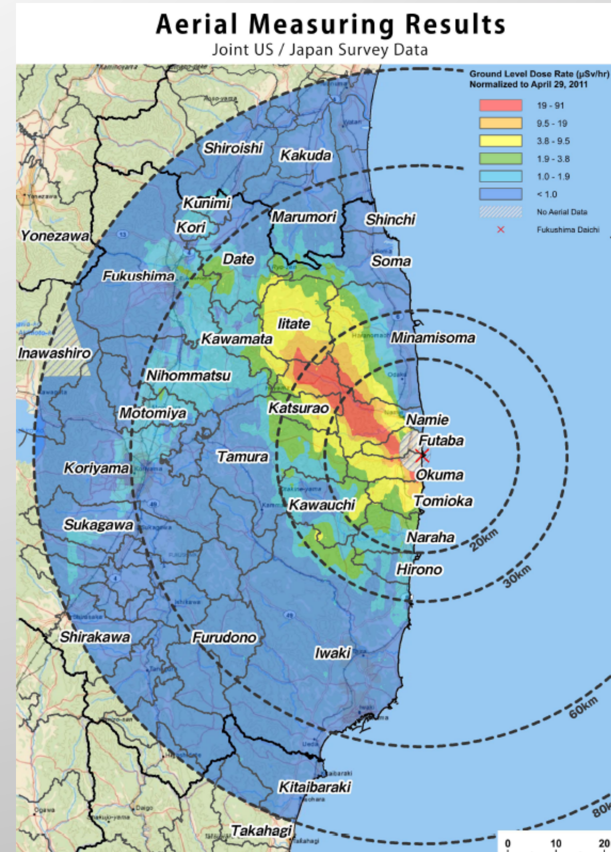
Precipitation Scavenging is Key to Realistic Predictions of Ground Deposition



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



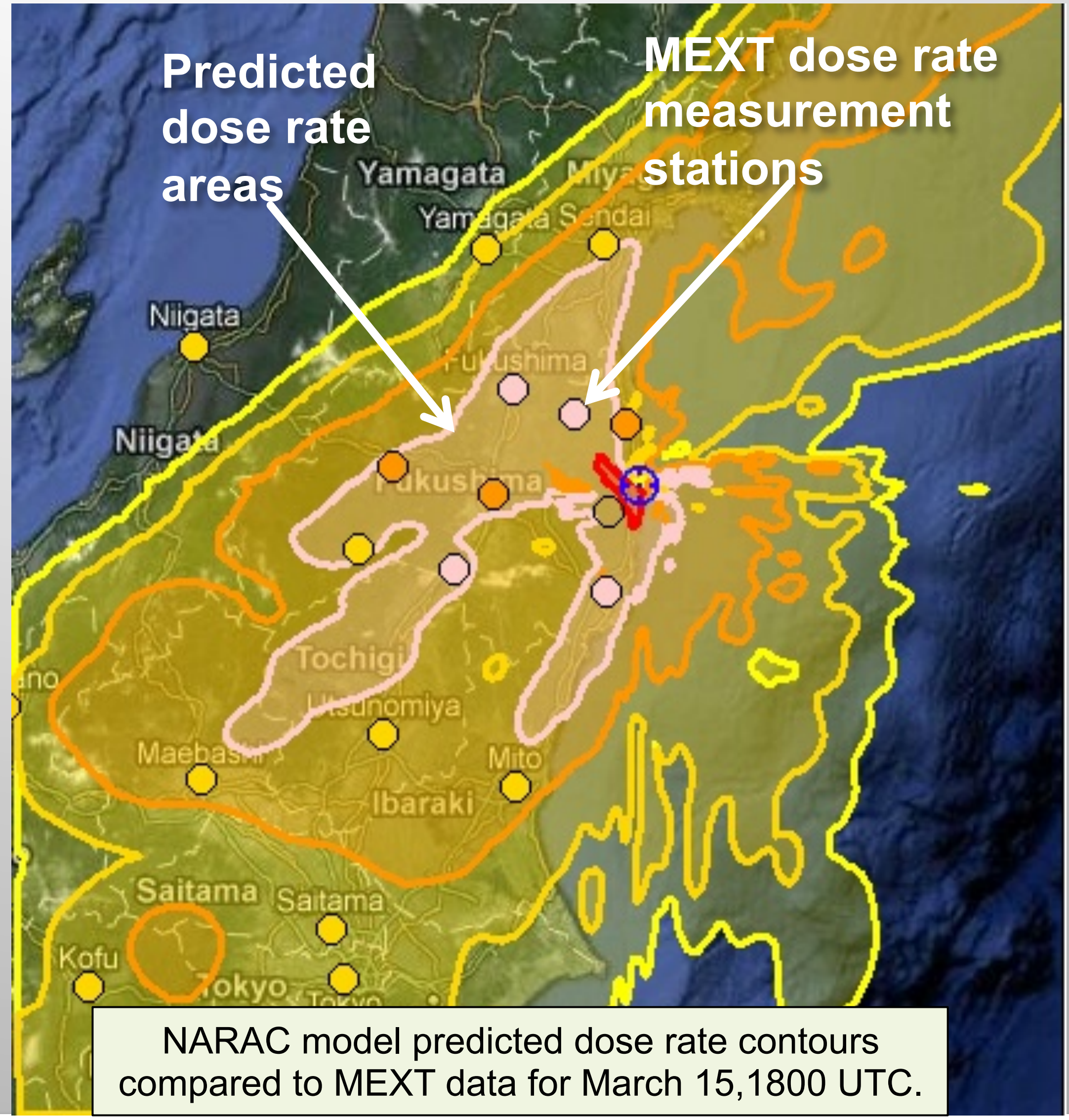
Predicted relative ground deposition pattern with precipitation scavenging (spatially and temporally-varying)



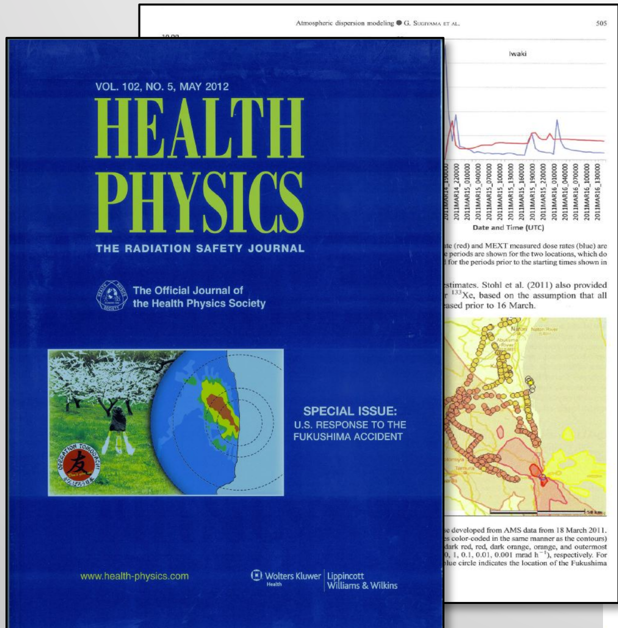
Measured AMS groundshine dose rate pattern

NARAC Radioactive Release Estimates and Models are Refined Based on Measurement Data

- Radiological dose rate data from MEXT monitoring stations and DOE's Aerial Measuring System were used to develop source term estimates
- NARAC model predictions were optimized using graphical and statistical comparisons to data
- Key contributors to dose and relative activity ratios were determined from initial data (^{131}I, ^{132}I, ^{132}Te, ^{137}Cs, ^{134}Cs, ^{133}Xe)
- Release estimates consistent with other published estimates within a factor of six

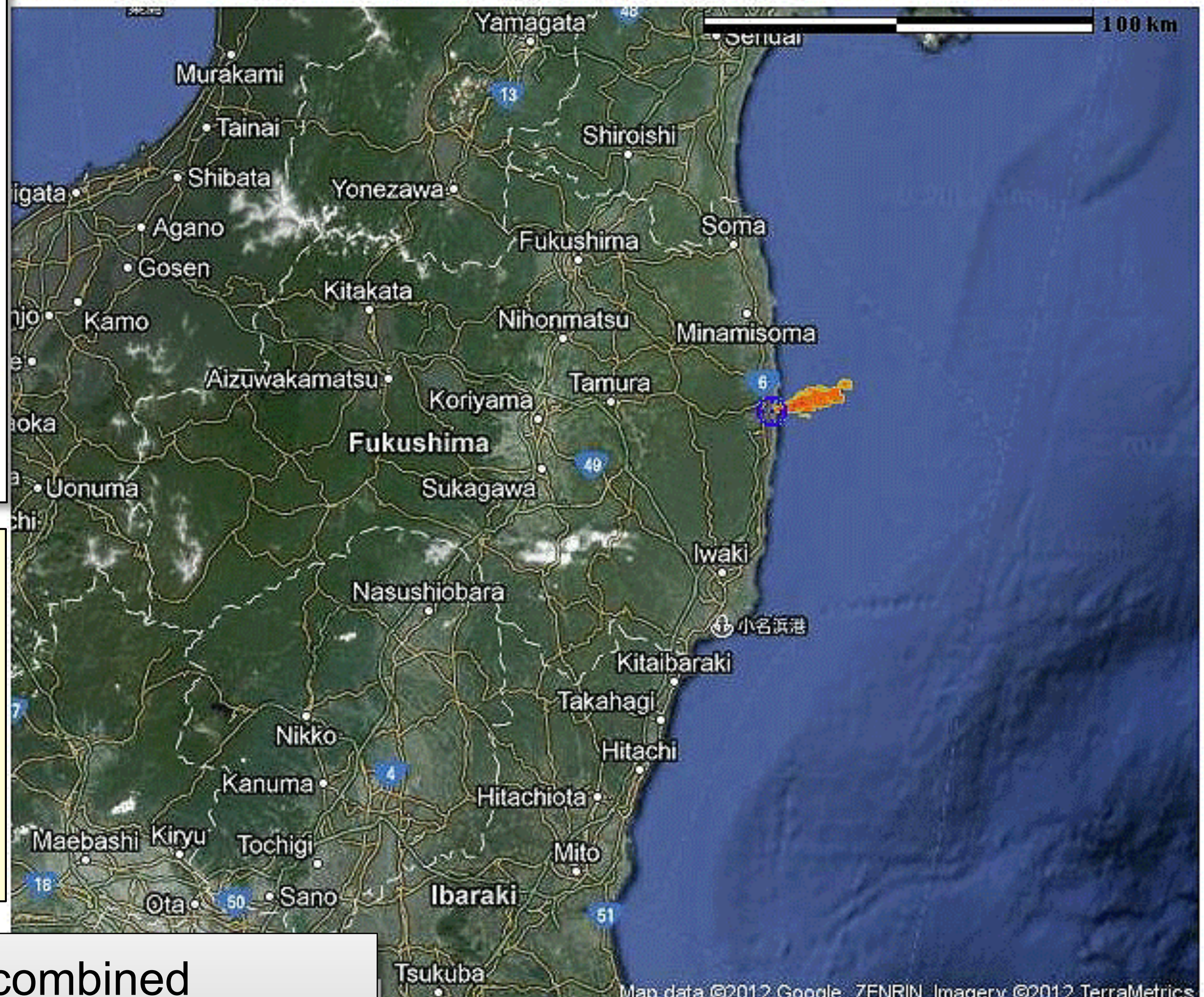


NARAC model predicted dose rate contours compared to MEXT data for March 15,1800 UTC.



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

Groundshine and Immersion Dose Rate



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

NARAC Encountered a Number of Challenges During the Fukushima Response

- Computational and personnel resources were strained
- High level of skill and experience of scientific and technical staff were critical for fulfilling requests for complex analyses on an emergency basis
- Treatment of multi-reactor and long-duration time-varying release scenarios coupled with complex rapidly changing wind and precipitation patterns posed technical challenges
- New, non-standard types of analysis and products needed to be developed on the fly
- Huge demands on time and resources limited the ability to communicate and share information

Procedural and training improvements have been proposed or are underway to address some of the operational challenges identified during the response.

NARAC is Making Hardware and Software Upgrades To Improve Computational Performance

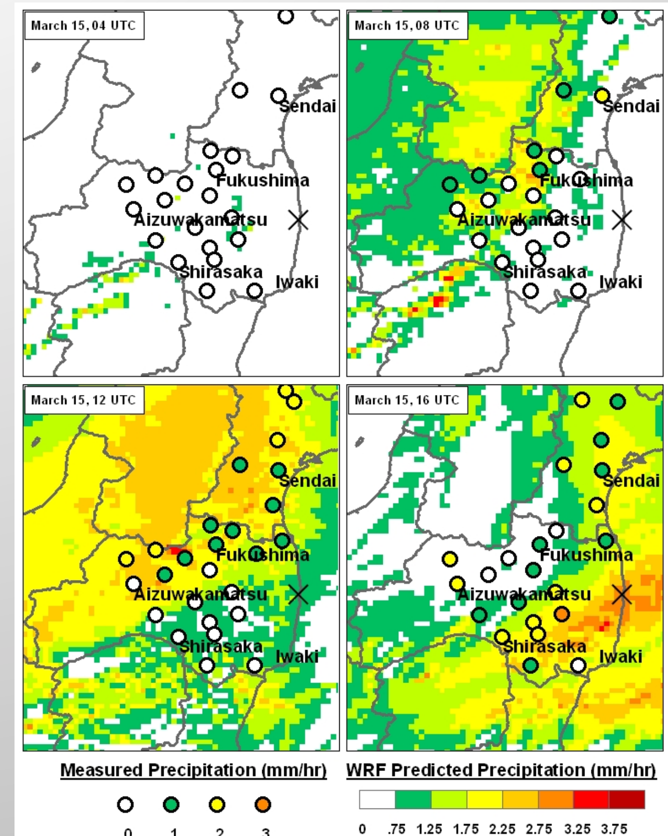
- Integration of new compute cluster into NARAC operational system
- Software performance enhancements
  - Core physics model run times reduced from 2 hours to 5 min for complex problems (on average)
  - Model output post-processing times reduced from 1+ hour to 10 min for large problems
  - Restart capability has been improved
  - Performance optimization of meteorological data processing software and other subsystems is on-going

Configuration
- 336 processor cores (3.46 GHz Intel 5690 chipset)
- 1152 GB total memory (4 GB/ processor)
- High-speed communications network/switch (40 Gbit QDR)
- Linux-based system

Upgrades have reduced computational times for complex simulations involving large numbers of radionuclides and/or extended release periods by one-to-two orders of magnitude.

NARAC is Addressing the Need for Improved Physics Models Identified During the Response

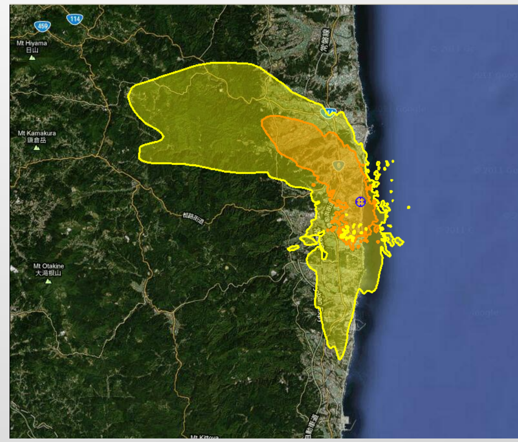
- Improved nuclear power plant accident scenarios (in collaboration with the U.S. Nuclear Regulatory Commission)
- Routine use of higher-resolution modeling to simulate complex meteorological conditions and dispersion
- Improved numerical weather prediction modeling via standard use of data assimilation (e.g, WRF 4DVAR)
- Enhanced deposition models
  - Petroff and Zhang (2010) dry deposition model for particles
  - Improved wet deposition modeling for both in-cloud and below-cloud processes
- On-going database updates of geographical, material, dose response, and other data



NARAC prediction of precipitation using the Weather Research and Forecasting (WRF) model

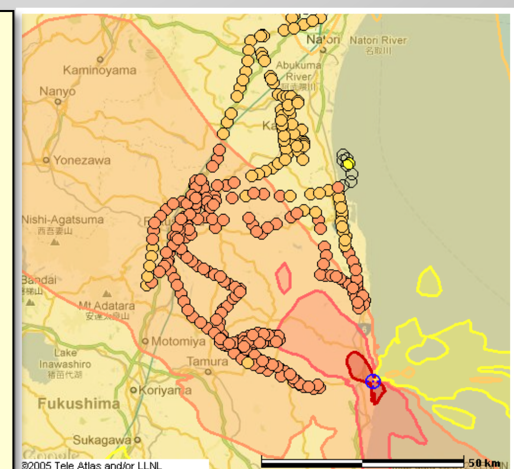
Improved Data-Model Fusion Methods Remains a Key Focus of NARAC Development Efforts

- Key development priorities
  - Electronic acquisition of field-data
  - Software to rapidly process measurement data
  - Graphical/statistical data-model comparison and analysis tools
  - Improved source estimation capabilities



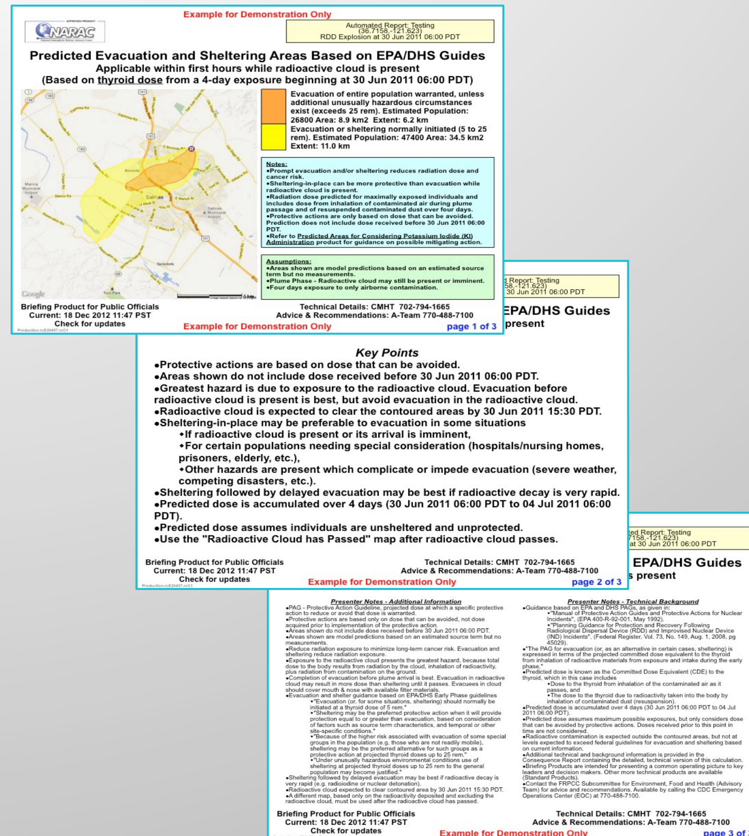
NARAC Fukushima predictions based on source estimation from measurement data

NARAC Fukushima prediction based on source estimation Aerial Measuring Survey data compared to independent data set



Improved Communication of Technical Information is an Important Ongoing Activity

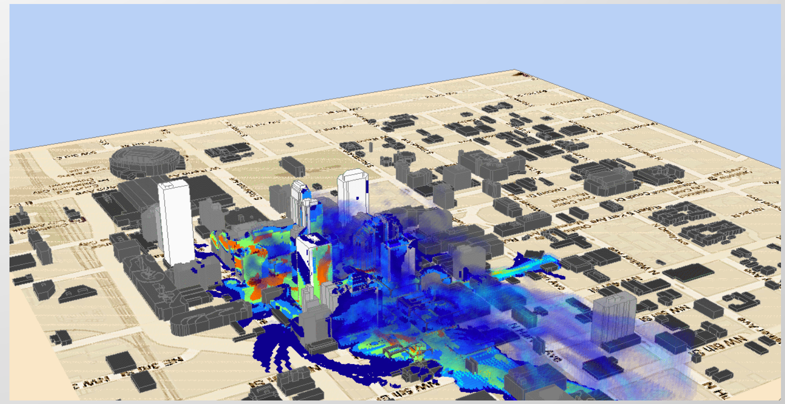
- U.S. DOE is leading the development of radiological/nuclear "Briefing Products"
  - Goal: improve the communication of technical information to planners, decision makers, and emergency responders
  - Focus on actions and decisions that need to be considered (evacuation/ sheltering, relocation, worker protection, sampling plans)
  - Develop with interagency consensus



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

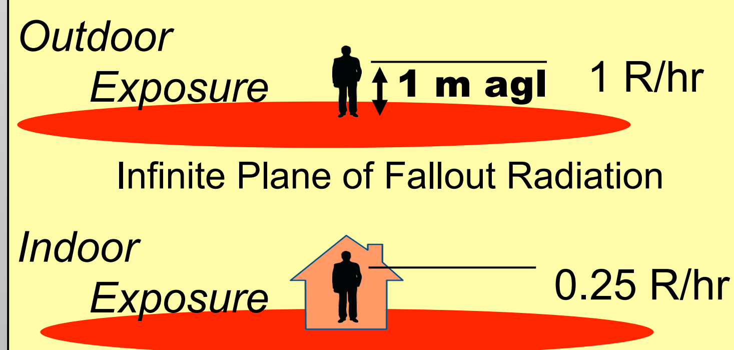
NARAC is Developing Capabilities to Improve Its Future Response For Urban Environments

- *Aeolus* building-resolving model
  - Efficient computational fluid dynamics code with RANS and LES modes
  - Lagrangian dispersion algorithm
  - Rapid grid generation from building data
  - Coupling to regional scale model



- Building-sheltering corrections to improve indoor dose exposure and casualty estimates
  - *PFscreen* model provides estimates of building protection factors
  - *Regional Sheltering Analysis* tool estimates potential protection from gamma radiation for a variety of shelter strategies based on existing database of building properties

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



- Infiltration models and building leakiness databases

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.

National Atmospheric Release Advisory Center

NARAC

Web: narac.llnl.gov

Email: narac@llnl.gov

Lawrence Livermore National Laboratory

Reference Material

(Details on results shown in main presentation)

Lawrence Livermore National Laboratory

LLNL-PRES-650086

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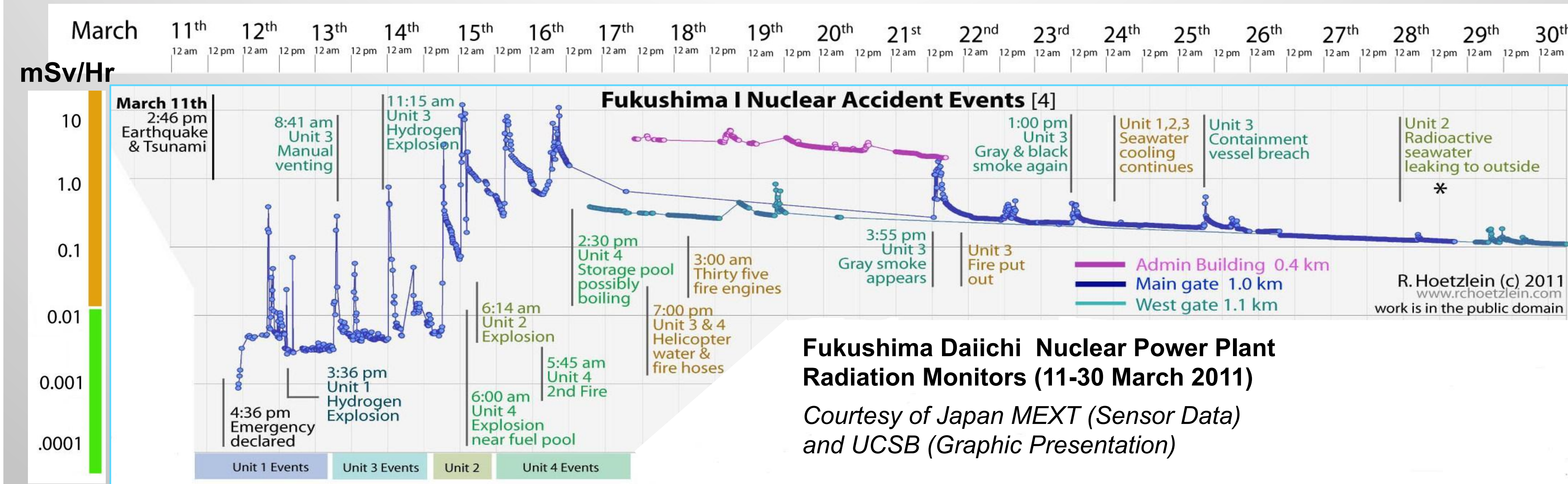
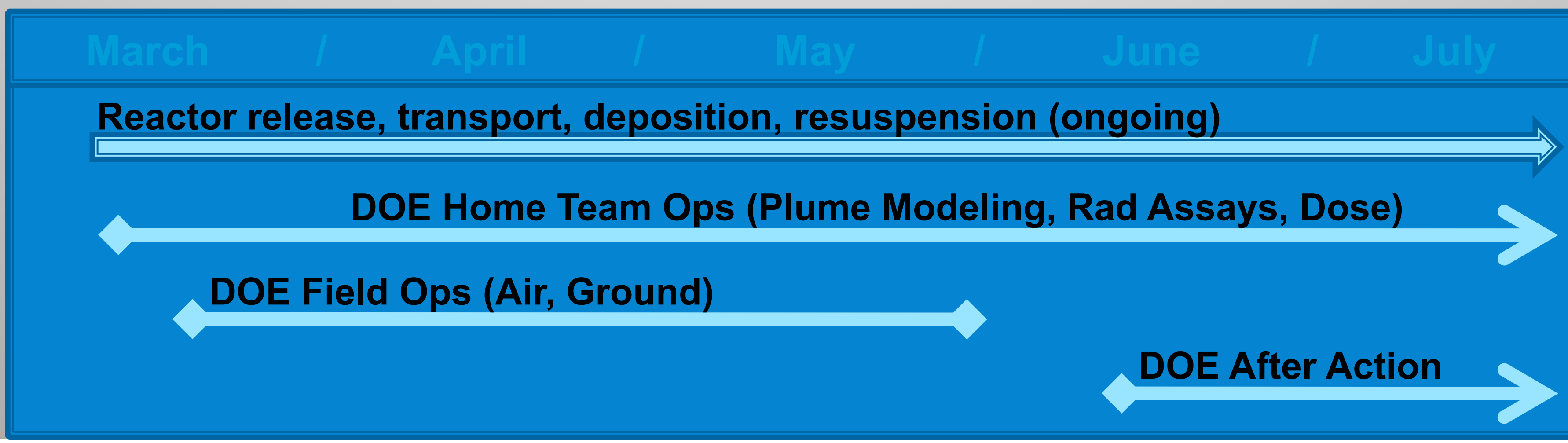
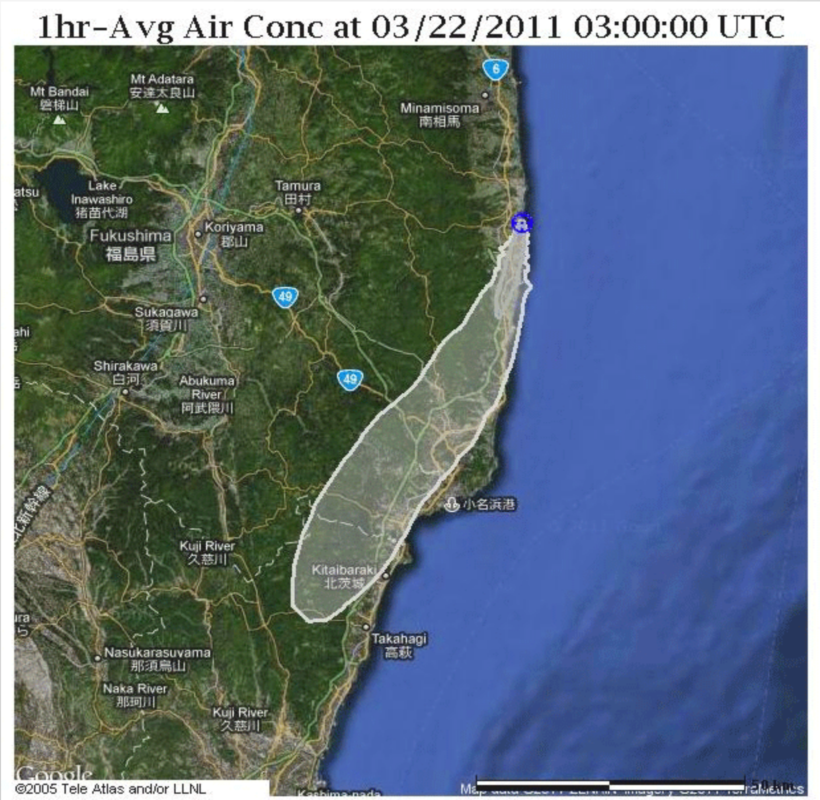
Time Progression of Fukushima Daiichi Accident and DOE/NNSA Response





NARAC Provided Regular Forecasts to Support Mission Planning and Model Analysis

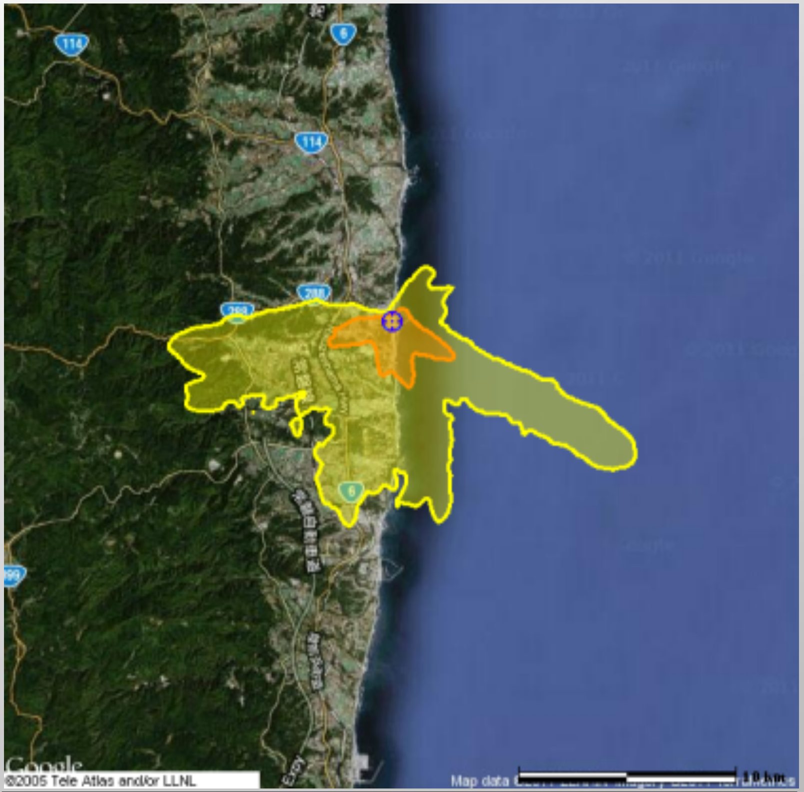
- Up to thrice-daily forecasts of hourly relative air concentrations to inform field operations, monitoring, and emergency planning
- Tabular summaries of wind speed and direction, atmospheric stability, and precipitation for selected locations
- 5-km resolution forecasts generated using Weather Research 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

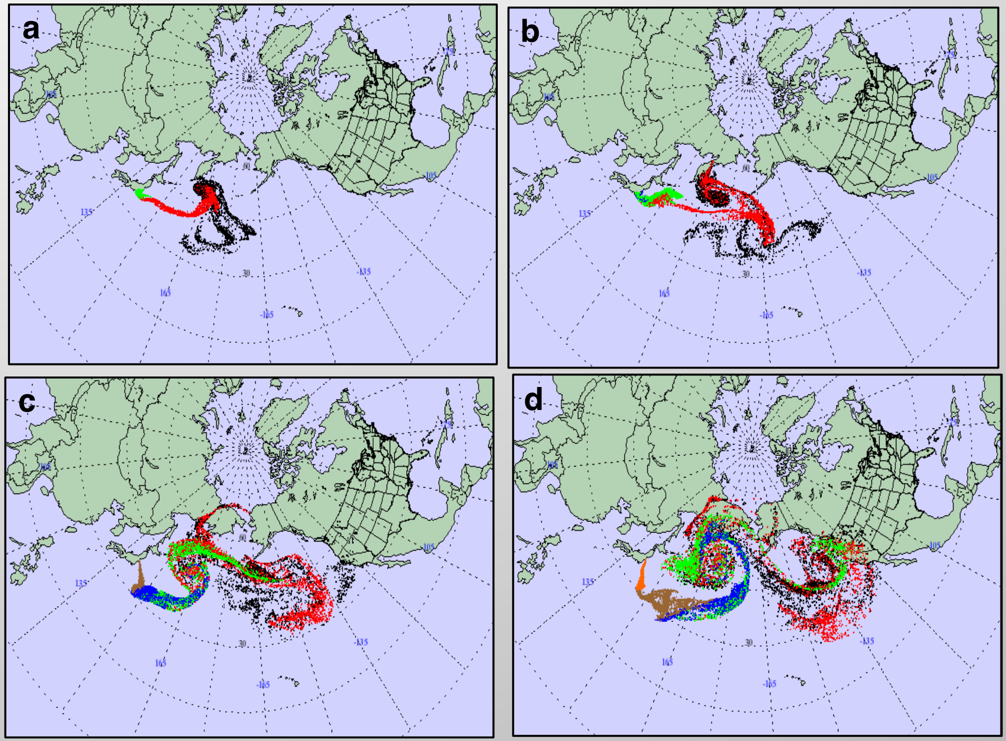
- Predictions of arrival times and protective action areas for sheltering / evacuation, relocation, iodine administration, and worker protection to inform emergency planning
- Analyses based on a range of hypothetical scenario source terms provided by the U.S. Nuclear Regulatory Commission (NRC)
  - 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

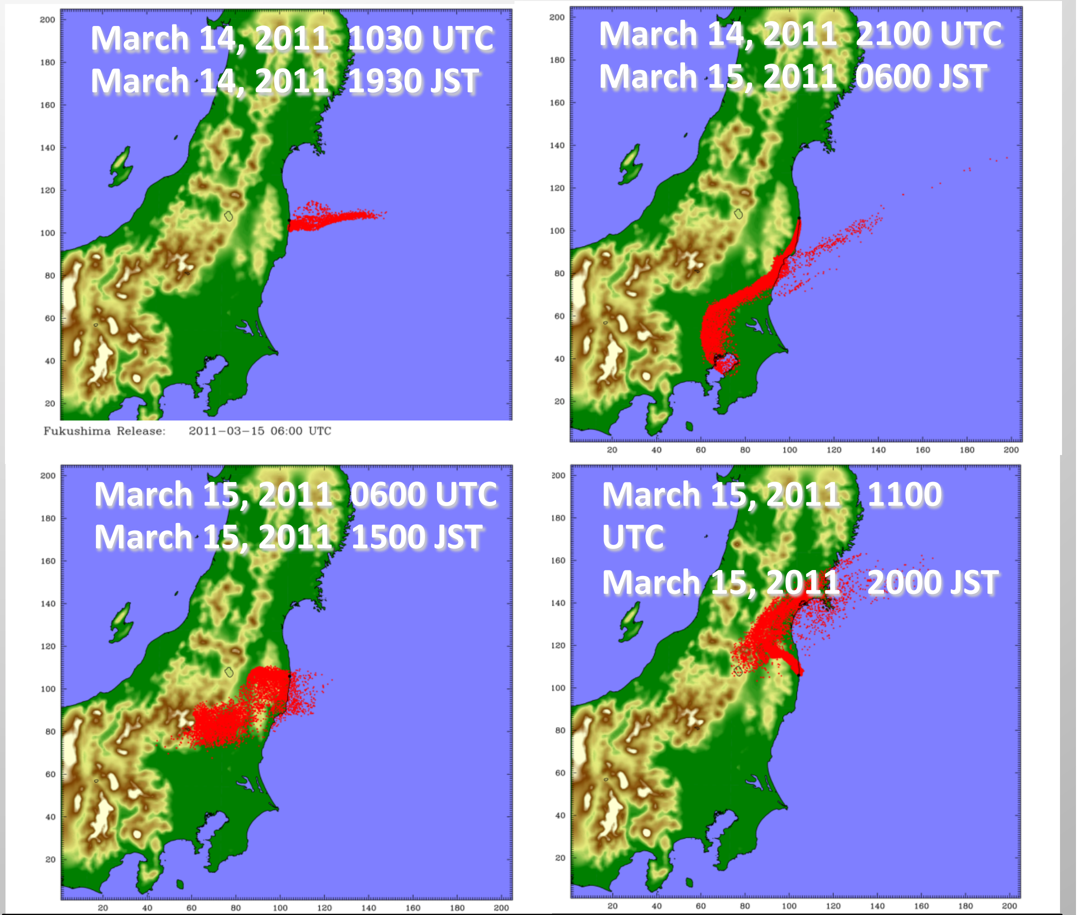
- NARAC estimated arrival times and radiation dose for selected locations in the US using:
  - NOAA GFS 0.5 degree meteorological forecasts and analyses
  - NRC source term analyses
  - DOE Consequence Management Home Team (CMHT) dose conversion analyses
- 12 or 24-hour unit release rates, scaled by 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

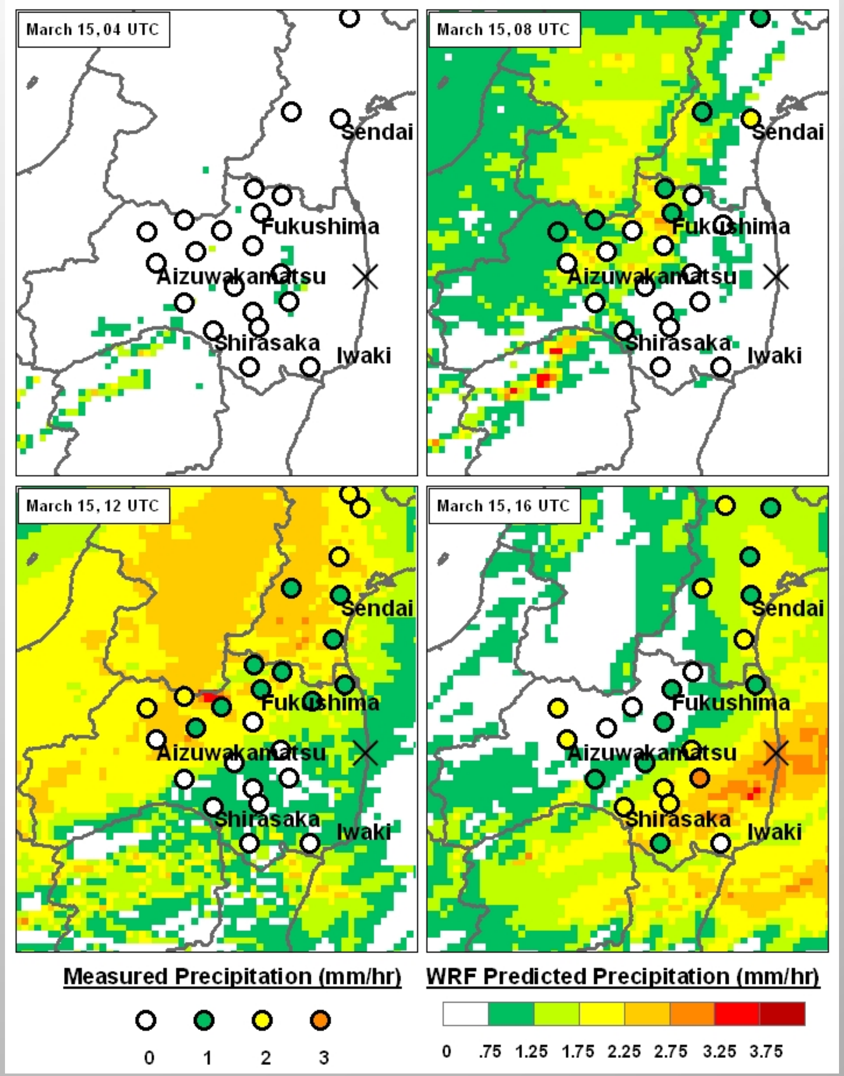
- Winds primarily off-shore until March 14 – March 16 when wind direction rotated clockwise apart from a brief period on March 12
- Winds remained primarily off-shore until March 21
- Initial NARAC forecasts captured overall pattern of winds and occurrence of precipitation
- Subsequent higher resolution (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



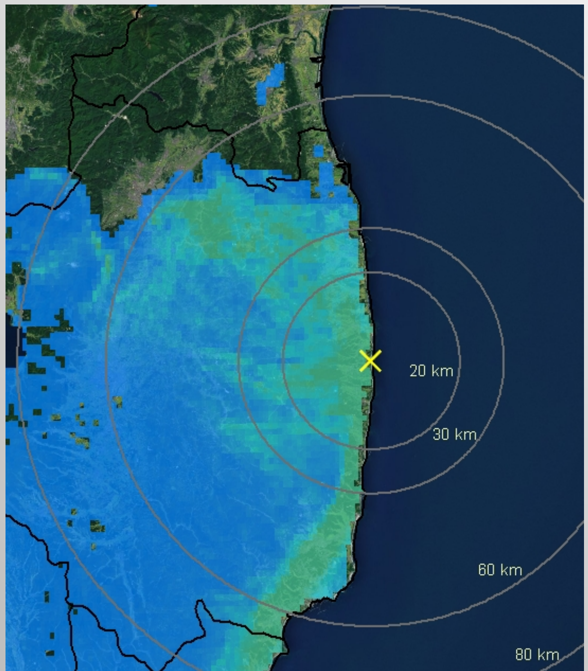
Particle animation for constant release rate from March 14 00 UTC - March 16 00 UTC

Significant Precipitation Occurred Episodically Throughout the Release Period

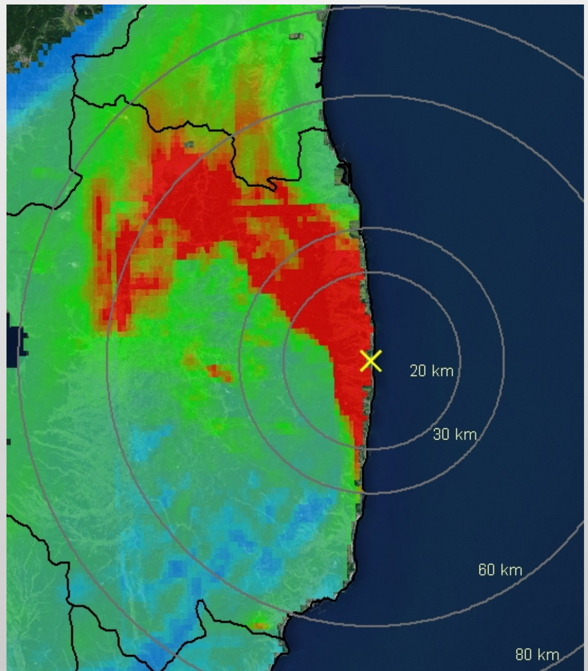
- Significant precipitation occurred near the Fukushima Daiichi Plant on March 15 and episodically throughout the release period
- In-cloud and below-cloud scavenging by precipitation significantly impact plume transport and deposition patterns
- NARAC simulations investigated
  - Uniform grid-wide time-varying 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



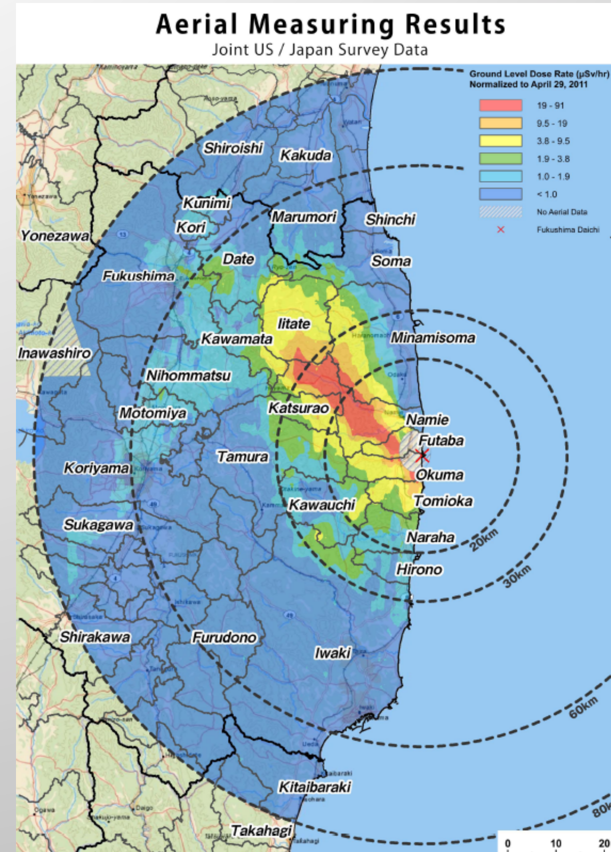
Precipitation Scavenging is Key to Realistic Predictions of Ground Deposition



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



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

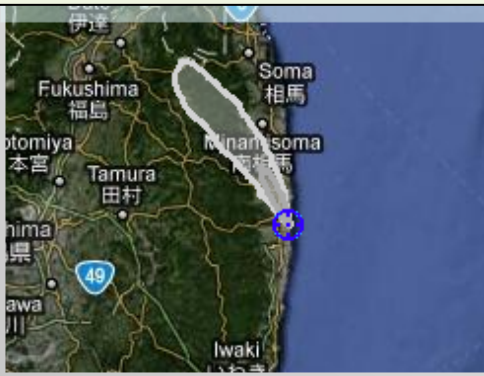


Measured AMS groundshine dose rate pattern

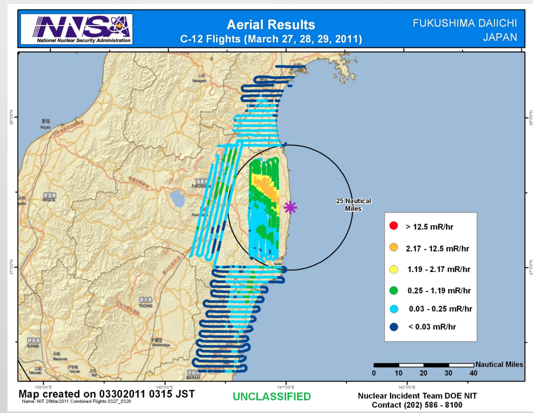
NARAC simulations using Flexpart and WRF-generated winds and constant release

NARAC Source Estimates and Models are Refined Based on Measurement Data

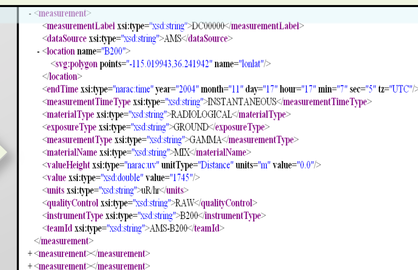
Initial model predictions guide measurement surveys



Measurement surveys and sensor data (DOE field & AMS)



Measurement data transferred electronically to LLNL/ NARAC



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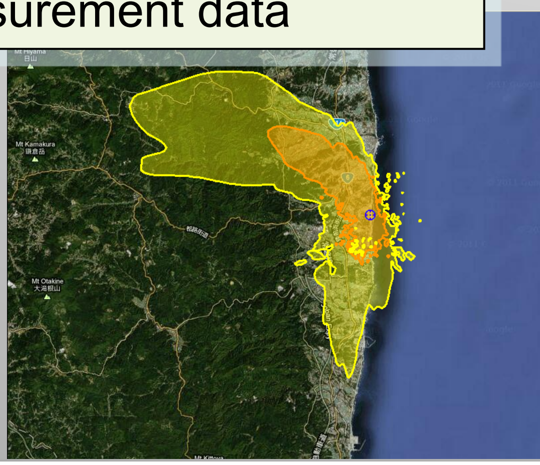
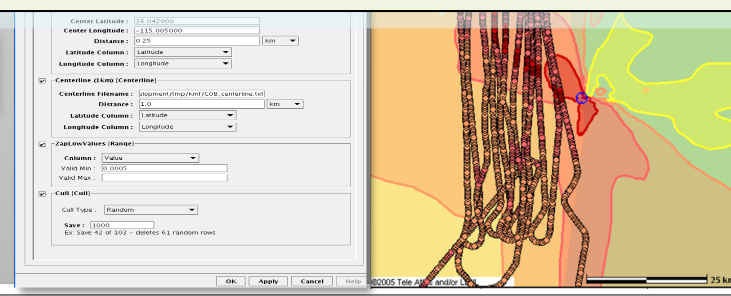
Updated predictions using measurement data



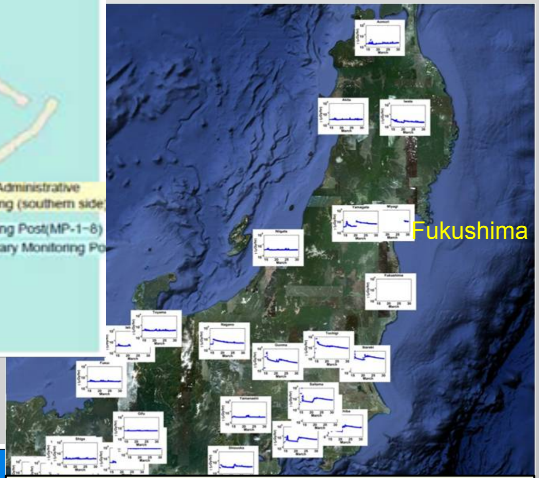
Software selects, filters and statistically compares measurements and predictions



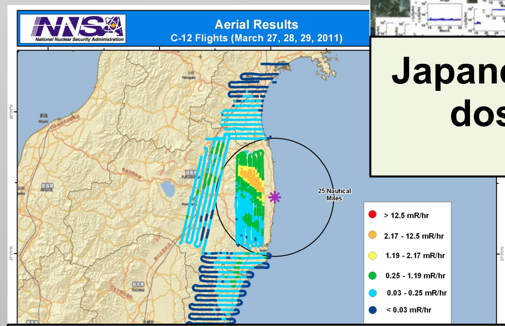
Radiological Dose Rate Data From Japan Were Used in Reconstruction of the Release

- Limited on-site TEPCO plant radiological measurements used for qualitative guidance on possible release periods (data gaps occurred following earthquake/tsunami and during March 15 site evacuation)
- Total external dose rate time series from MEXT regional monitoring stations
  - Most data only available after March 15 0900 UTC
  - Includes air immersion and ground-shine
- Joint U.S. DOE - Japan Aerial Measuring Survey (AMS) data collected beginning March 17-18
- U.S. DOE / Department of Defense ground monitoring data

Plant monitoring locations



Japanese MEXT prefectural dose rate monitoring station data



Aerial Measuring System (AMS) data March 27-29

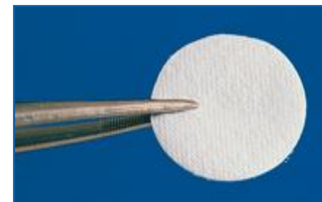
Source Reconstruction Tools Are Used to Optimize of Model Simulations to Data

- 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

LLNL Coordinated Sample Analyses for US DOE and Performed Thousands of Assays

- Gross α/β for screening / shipping
- γ spectrometry
  - Identify & quantify major airborne, surface and re-suspended dose contributors: ^{131}I, ^{134}Cs, ^{137}Cs…
  - Depth profiling Cs migration
- (Limited) actinide analysis for fuel - U, Np, Pu, Am, Cm
- Commercial analytical subcontract - Total Sr & ^{89}Sr/^{90}Sr

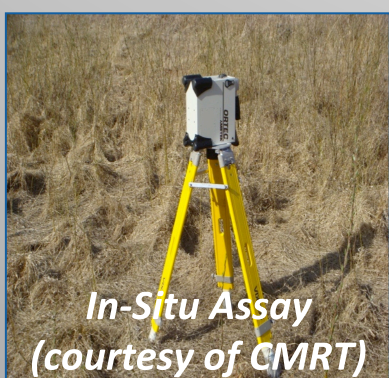
Air Filters and Swipes – airborne, re-suspension



Courtesy CMRT

Soils and Soil Cores – deposition, shine and migration assessment

Courtesy CMRT

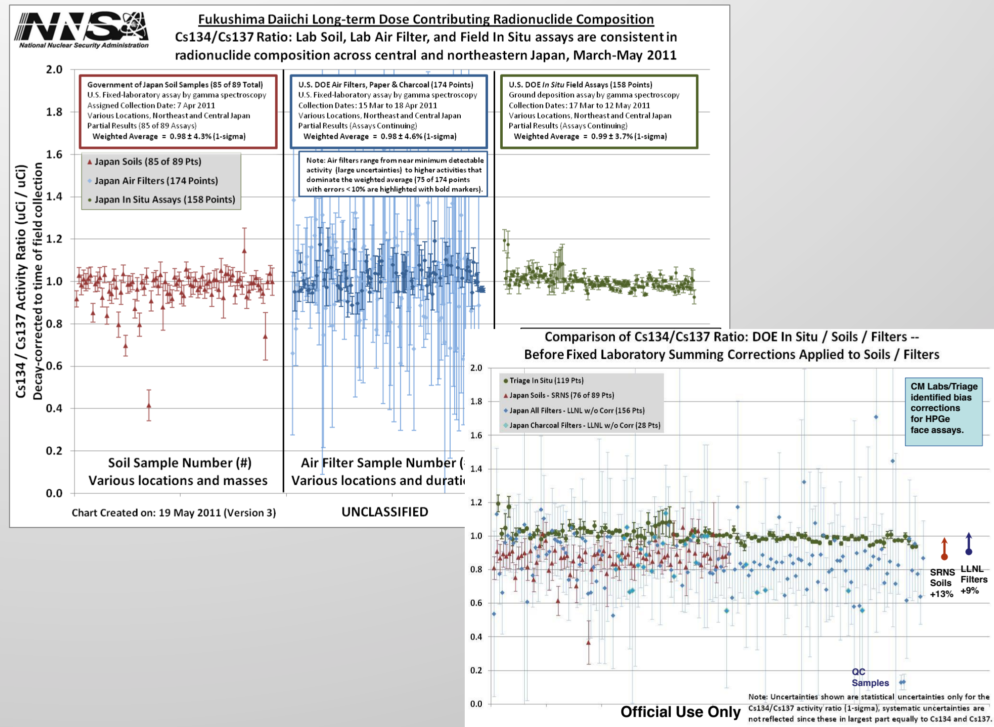


In-Situ Assay (courtesy of CMRT)

(Courtesy of S. Kreek, LLNL)

NARAC Source Estimation Used Assumed Radionuclide Mixes and Relative Activities

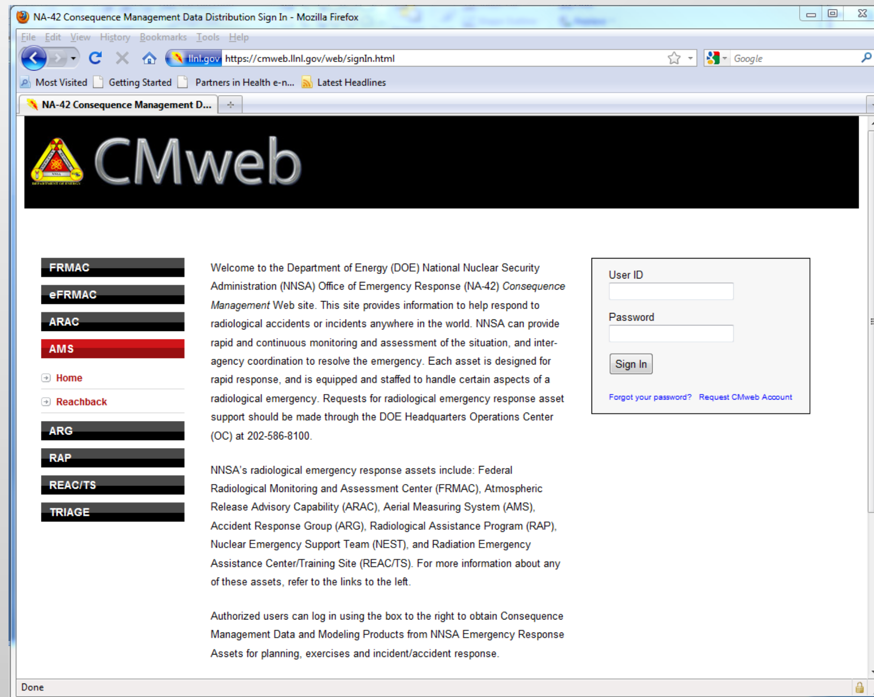
- Key radionuclide contributors to dose: iodine, cesium, tellurium, and xenon
- Relative activity ratios determined *a priori* based on
  - DOE laboratory analyses
  - NRC radionuclide mixes for reactor scenarios
- Typical activity ratios used for ^{133}Xe:^{131}I: ^{132}I: ^{132}Te:^{137}Cs:^{134}Cs
  - 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)

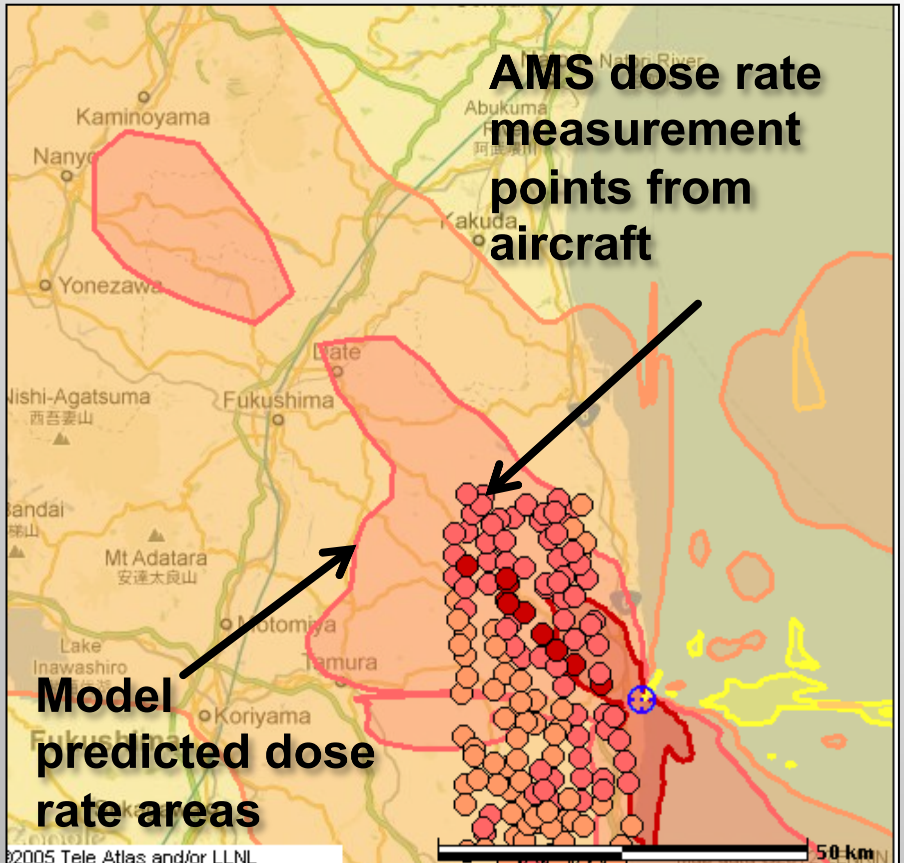
NARAC Web Site Provided 24/7 Access to Information During the Fukushima Response

- 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

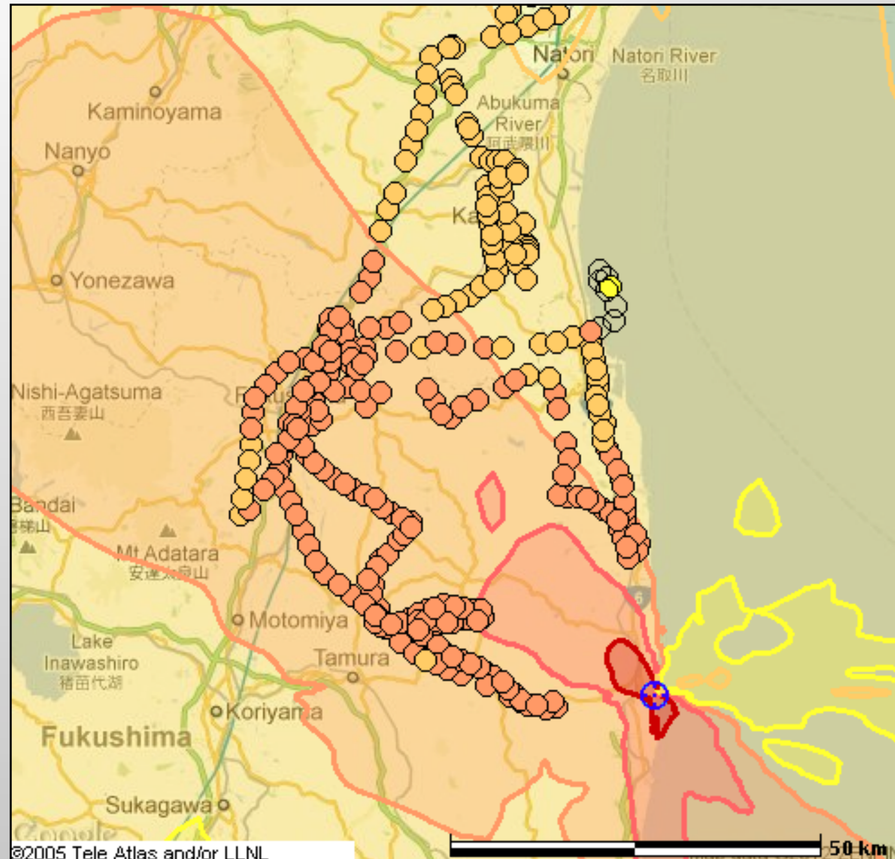


NARAC staff supplemented by other LLNL scientists invested more than 5,000 person-hours of time and produced more than 300 analyses and predictions during the response

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



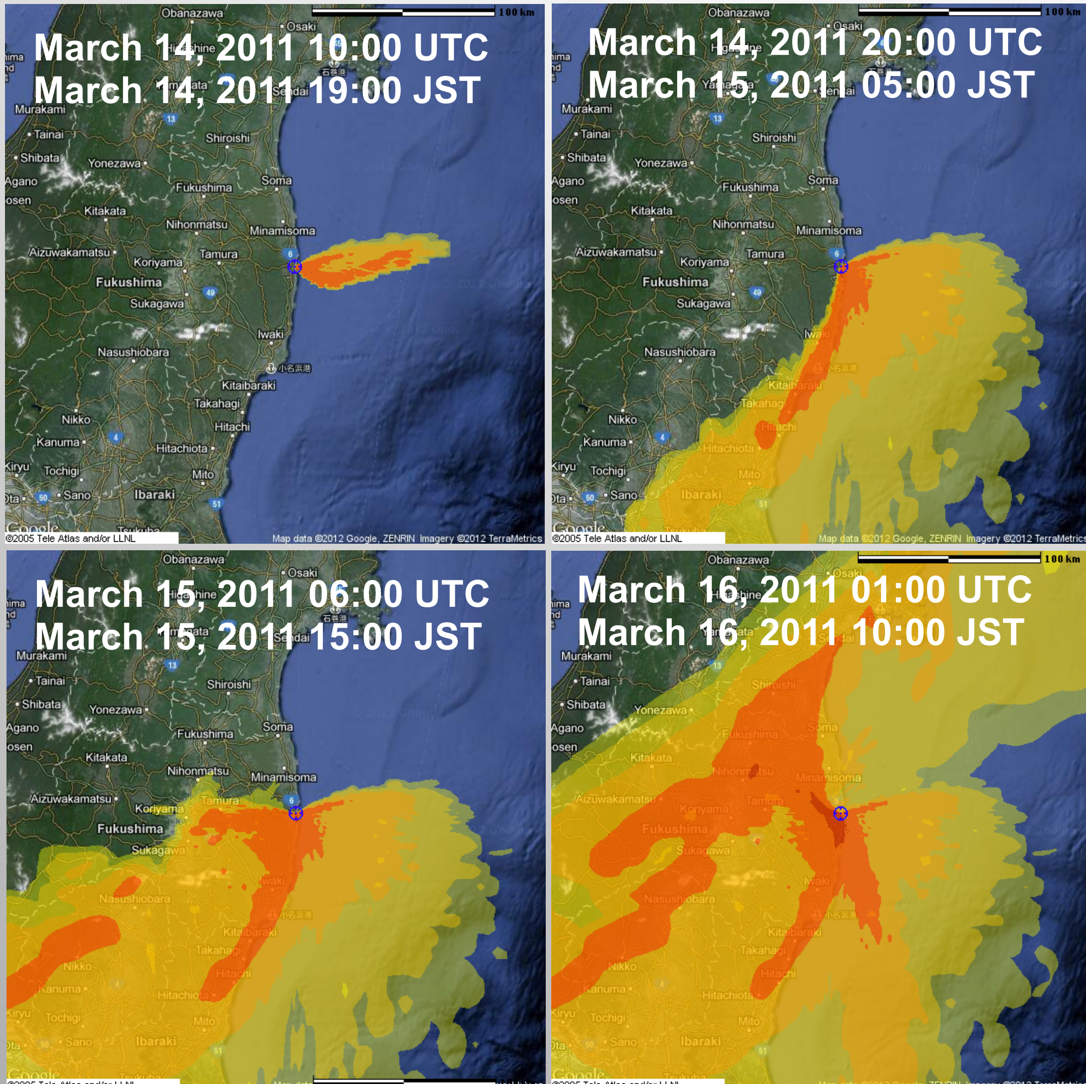
NARAC modeled dose rate levels overlaid with March 18 AMS data. Meteorology based on Japanese weather observations



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

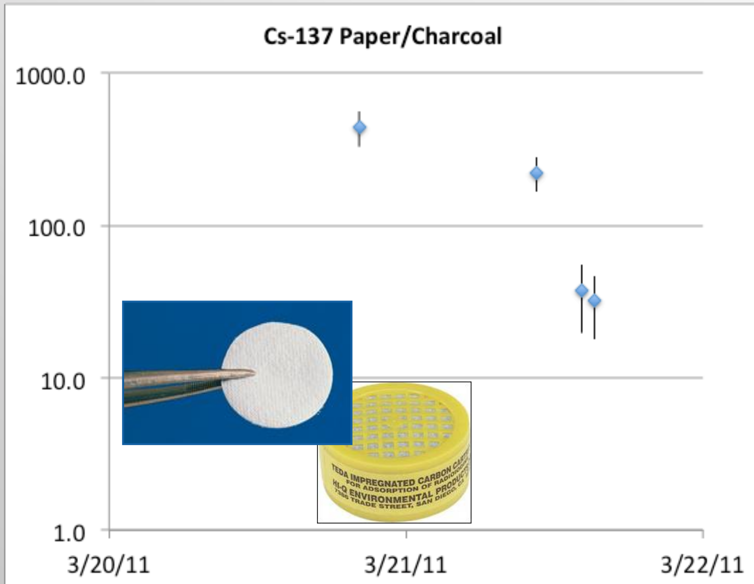
- Dose rate contours:
  120.0 μGy h^{-1} (red)
  4.0 μGy h^{-1} (dark orange)
  0.4 μGy h^{-1} (orange)
  0.04 μGy h^{-1} (dark yellow)
  0.004 μGy h^{-1} (yellow)
  (12, 0.4, 0.04, 0.004, 0.0004 mrad/hr)

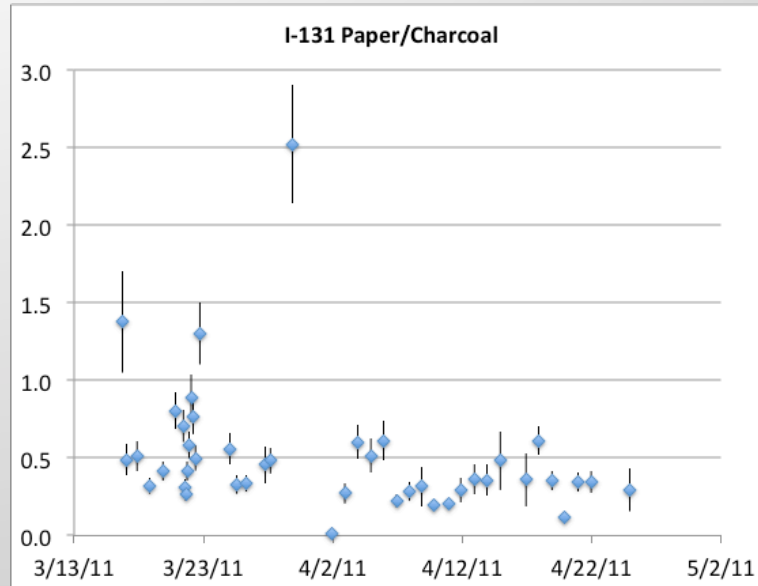
- Baseline” release estimate from March 14 0600 UTC to March 16 0100 UTC (Sugiyama et al., 2012, *Health Physics*)

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 μm 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)

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





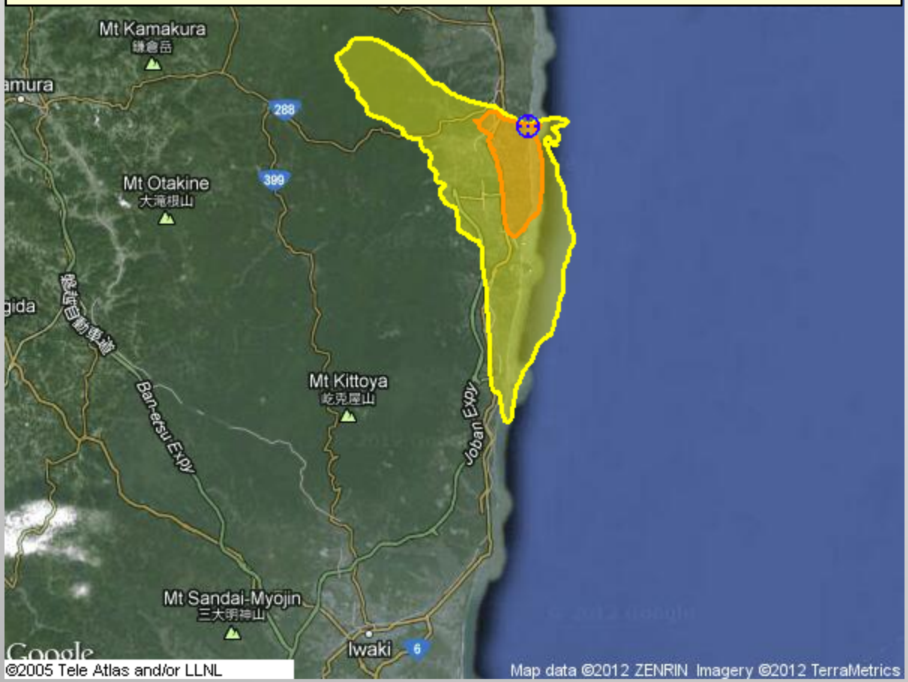
- Cesium observed almost exclusively on particulate filters (a few instances where ^{137}Cs assayed above MDA on charcoal)
- Iodine split between the two filters, with particulate Iodine assumed to be primarily trapped by the paper filter, and gaseous Iodine on charcoal (the absence of ^{137}Cs on the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

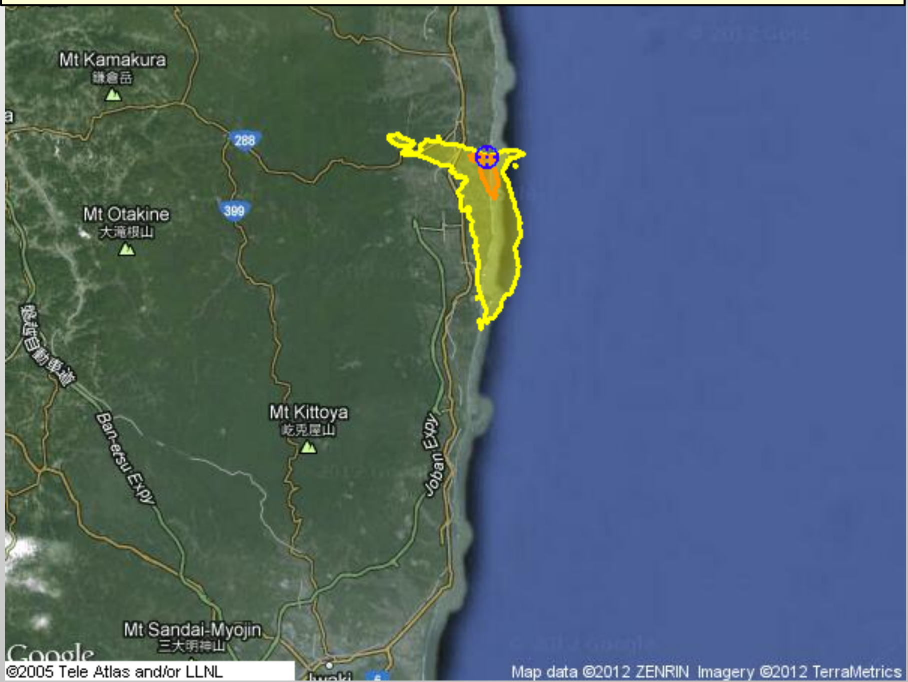
(Courtesy of S. Kreek, LLNL)

Total Effective Dose Includes External Ground-Shine, Air Immersion, and Internal Committed Effective Dose

Total Effective Dose (TED) is the adult whole body dose from inhalation and air immersion (due to the initial plume and resuspension) as well as ground-shine

50-year Committed Effective Dose is the adult whole body internal dose from inhalation using a weighted sum of doses to various organs

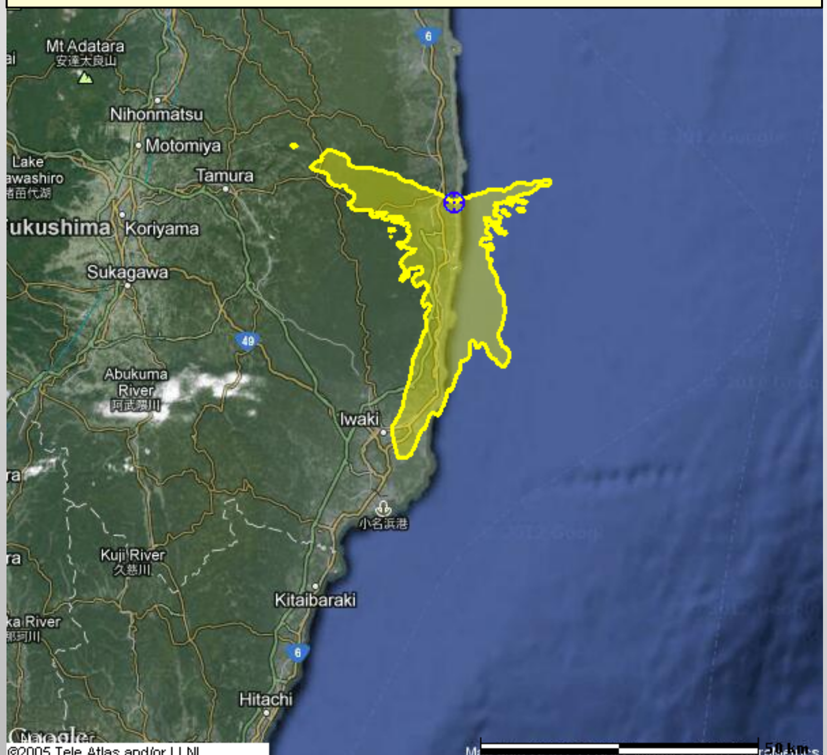




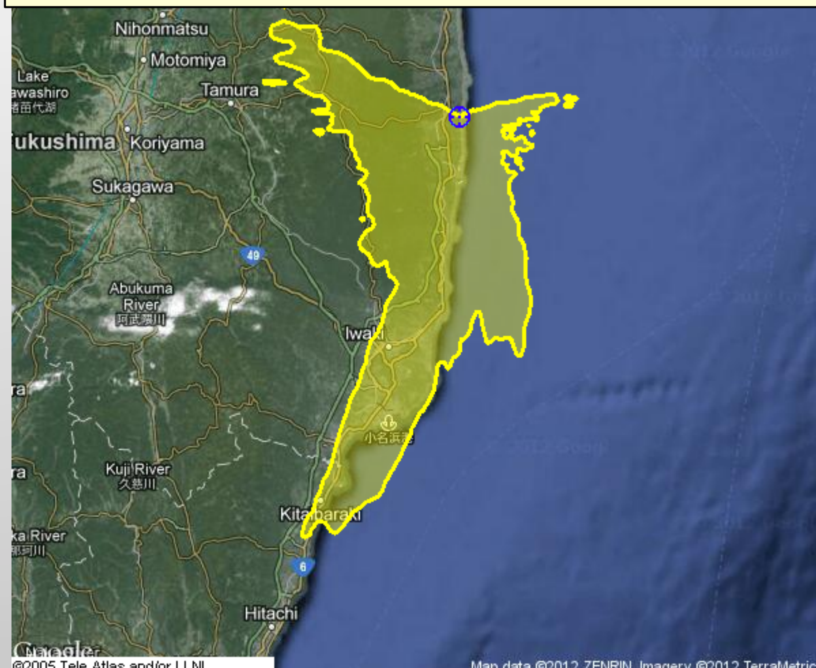
- Contours show predicted areas greater than 50 mSv / 5 rem (orange) and 10 mSv / 1 rem (yellow) for 4 days of exposure based on the “baseline simulation for 2011 March 14-16
- TED levels are early phase upper and lower limits U.S Protective Action Guide levels for evacuation / sheltering

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

Future Work is Needed to Address Remaining Questions and Refine Release Estimates

- Utilize the complete set of Japanese (e.g., 550000+ data records in DOE database) and global radiological data sets (e.g., Japan data, sample and spectral analyses, Comprehensive Test Ban Treaty Organization, EPA RadNET, and U.S. nuclear power plant data) to conduct a comprehensive source term analysis
- Use nuclear reactor expert analyses and measurement data to improve and/or constrain source term estimates and refine radionuclide mix
- Improve modeling to more accurately simulate complex meteorological conditions and dispersion on both regional and global scales (e.g., precipitation scavenging, ensemble forecasts)
- Investigate the use of ensemble forecasts to develop probabilistic arrival times and impact estimates for both regional (e.g. Japan) and long-range (e.g., trans-Pacific) cases
- Determine to what degree
  - Multiple release events can be distinguished via time-varying radionuclide signatures and/or reactor analyses
  - Data constrains release rates during off-shore flow periods