National Atmospheric Release Advisory Center's Urban Plume Dispersion Modeling Capability for Radiological Sources

June 19th , 2018

Akshay Gowardhan, **Brenda Pobanz**, Stephanie Neuscamman, John Donetti, Hoyt Walker, Rich Belles, Bill Eme, Steven Homann, Matthew Simpson and John Nasstrom

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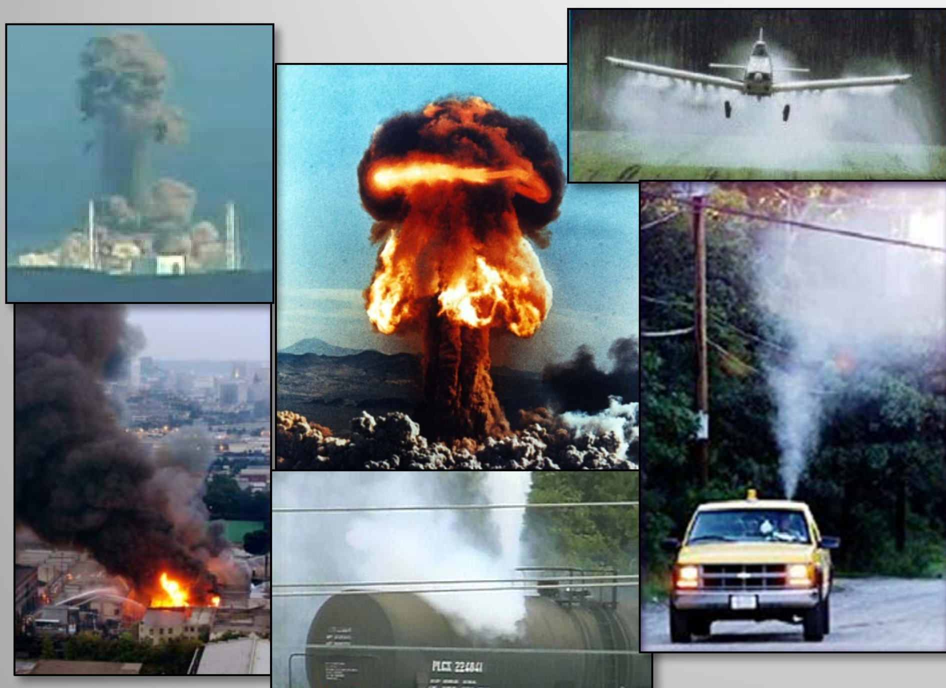
LLNL-PRES-751301

NARAC can predict the impact of a wide range of airborne releases of hazardous material that can rapidly impact large areas and populations



- Nuclear facility accidents
- Radiation dispersal devices
- Nuclear detonations
- Toxic industrial chemical spills and fires
- Biological and chemical agents

Hazardous airborne releases may cause:
- Immediate danger to life and health
- Long-term health risks
- Economic impacts in contaminated areas

NARAC atmospheric modeling services and tools for hazardous atmospheric releases

Worldwide data: meteorological & geographical

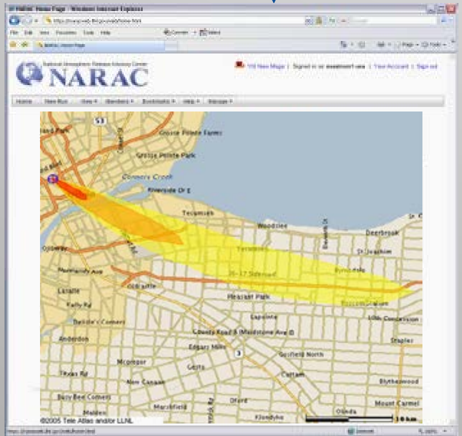
NARAC: National Atmospheric Release Advisory Center

- **Computer center for 3-D atmospheric transport model simulations**
- **Scientists provide 24x7 data analysis and model predictions**

Incident information

Field measurements

Web tools: Receive, create, and distribute NARAC model predictions and other information



U.S. and international emergency response organizations

Sponsored by the Department of Energy (DOE) National Nuclear Security Administration (NNSA)

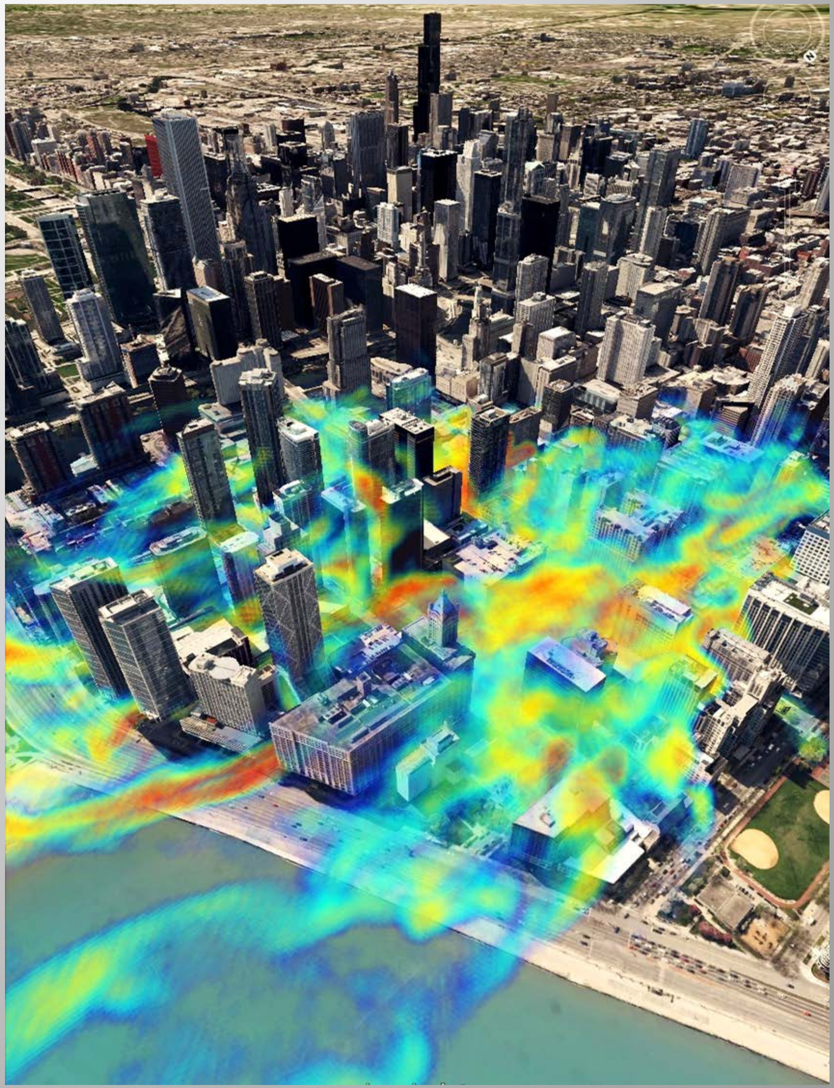
LLNL NARAC Facilities

- Facilities
  - Emergency operations center
  - Dedicated computer center:
    - — Unclassified and classified computer systems
    - — Backup, redundant systems
    - — Computer cluster for high-resolution, complex calculations
  - Uninterruptible backup power supply
  - Unclassified and classified network communication
  - Access to LLNL supercomputing

- Security
  - Physical site security (gates, guards, etc.)
  - Security clearances
  - Classified data handling and storage
  - Cybersecurity
  - Secure communications

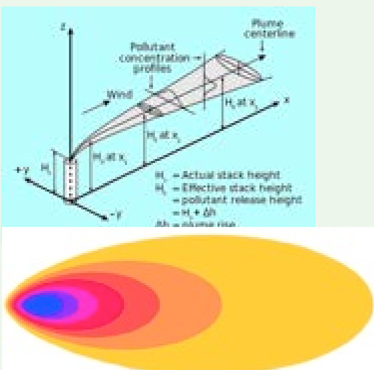
Urban Dispersion Modeling Tools Can Assist With Threat Assessment, Emergency Response And Recovery

- More than half of the world population is living in urban areas and the danger from an accidental or deliberate release of CBRN agents in an urban area can be significant.
- A high-resolution computer model can predict how airborne hazardous material spreads around buildings in urban areas. **Non-urban models predict much smaller spread.**
- The modeling tool must be fast enough to run operationally for both emergency planning and response
- The modeling tool should be coupled to all relevant databases for emergency responder/ analysts to make informed decisions

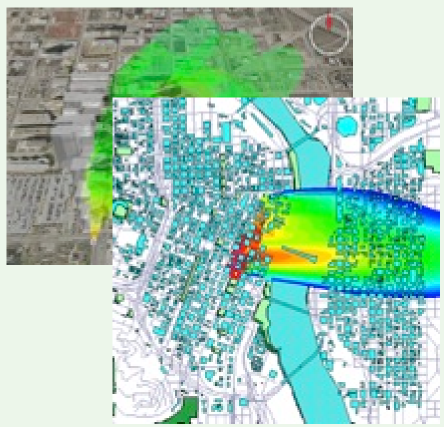


Different Types Of Urban Dispersion Models

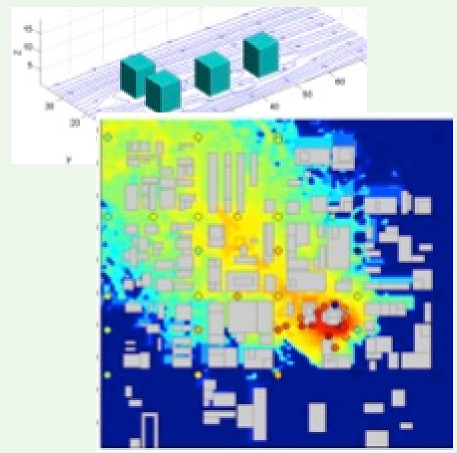
Seconds on laptops	Minutes on laptops	Minutes on laptops	*Previously* Hours to Days on supercomputers
Gaussian Plume model	Gaussian Puff model	Empirical/ Diagnostic model + Lagrangian dispersion modeling	Computational Fluid Dynamics



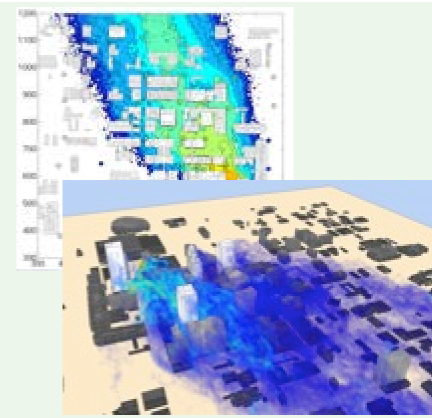
- No spatial variability of winds
- Simplified urban effect included by parameterizing the spread



- Winds are not building resolving



- Building resolving, parameterized winds



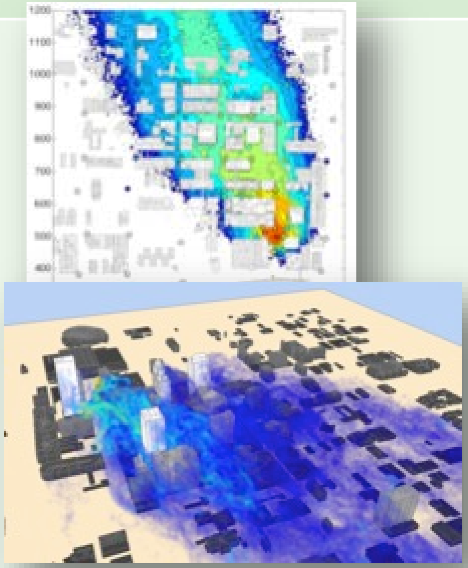
- More detailed and higher resolution simulation
- Based on first principles laws of physics

Increasing complexity, accuracy, and computational effort

Aeolus Urban Dispersion Model Runs Fast And Includes Physics

Hours – Days on Supercomputers

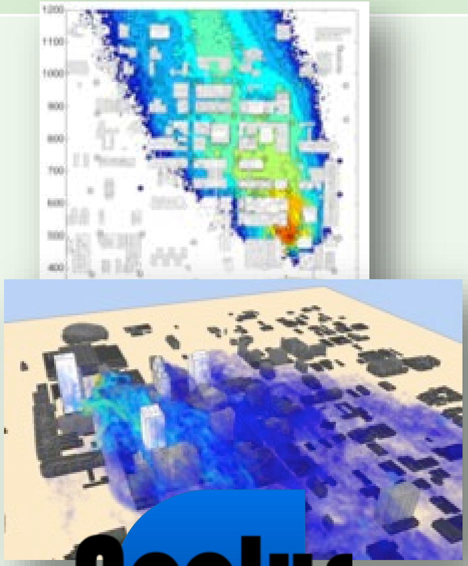
Computational Fluid Dynamics



- Based on work done at University of Utah and Los Alamos National Laboratory, Lawrence Livermore National Laboratory has advanced fast running Computational Fluid Dynamics models
- Fast and efficient algorithm
- Full physics equations for higher-fidelity results
- Fast grid generation from existing building data set

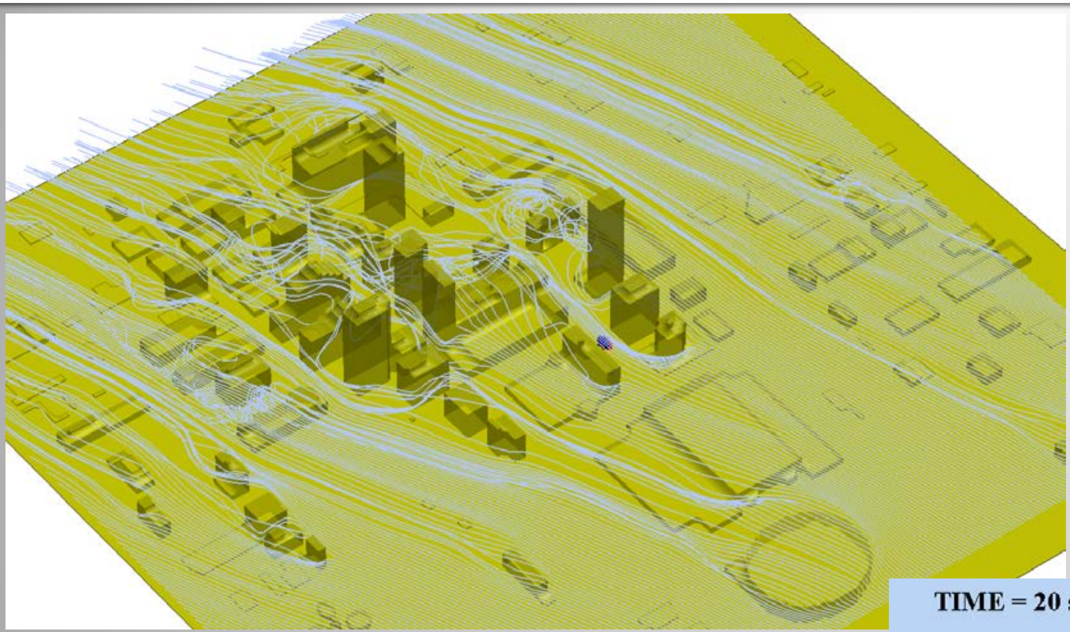
Minutes – Hours on Laptop

Computational Fluid Dynamics



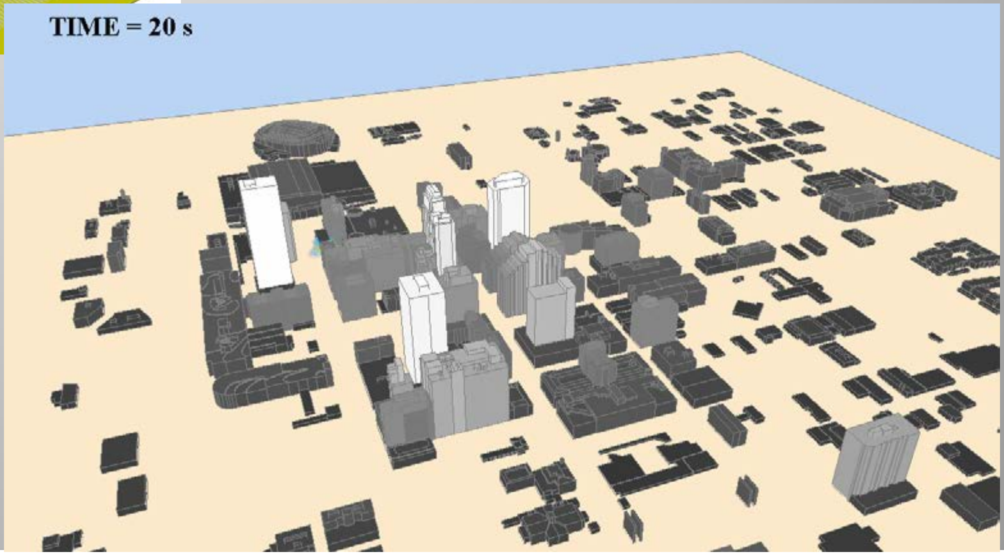
Aeolus

Aeolus Can Be Run In Two Physics Modes



(Top) The high-resolution model can be run efficiently (~5 min) using a Reynolds Averaged Navier-Stokes model (RANS) : *used for operational purposes, exercise where large number of simulations are needed*

RANS simulation *time =*
5 min on laptop

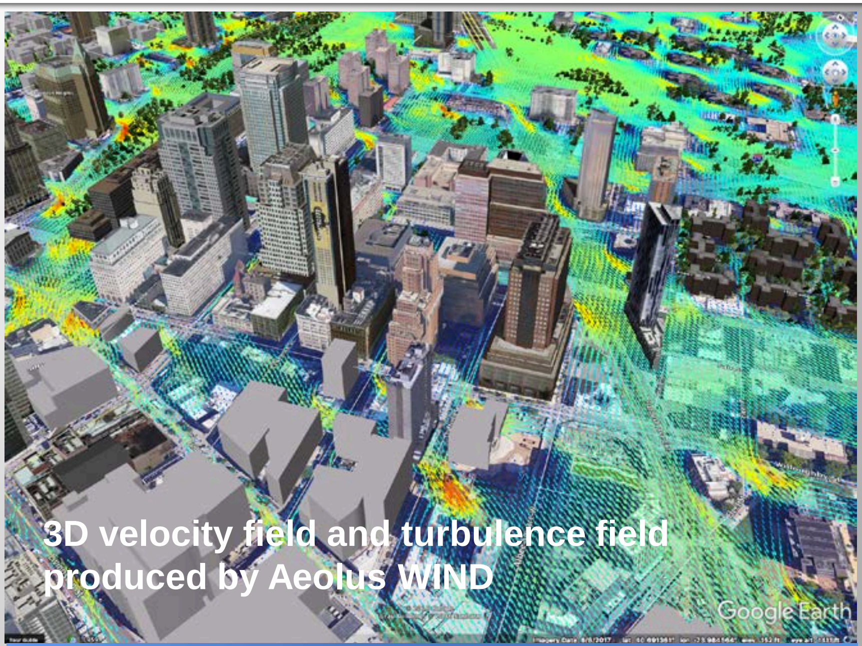


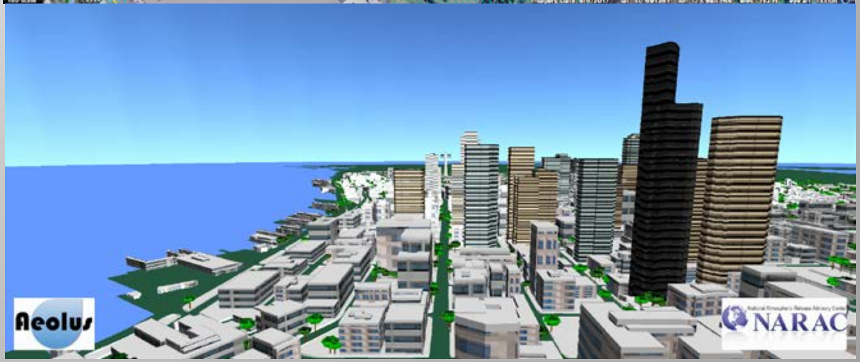
(Bottom) Alternatively, it can be run at even higher resolution using a *high fidelity Large Eddy Simulation* (LES) mode (~ hours) : *used for R&D and planning projects, validation of fast running model*

LES simulation *time =*
several hours on a laptop

Aeolus RANS is being operationalized

- Aeolus model (RANS) consist of two parts:
- Aeolus WIND produces a 3D steady state wind field, 3D turbulence information via RANS closure
- Aeolus LDM is a Lagrangian dispersion model which predicts dispersion of contaminates in urban area





Aeolus LDM: Lagrangian dispersion model

Model Has Been Validated Against Urban Field Study Data Sets: Continuous Release

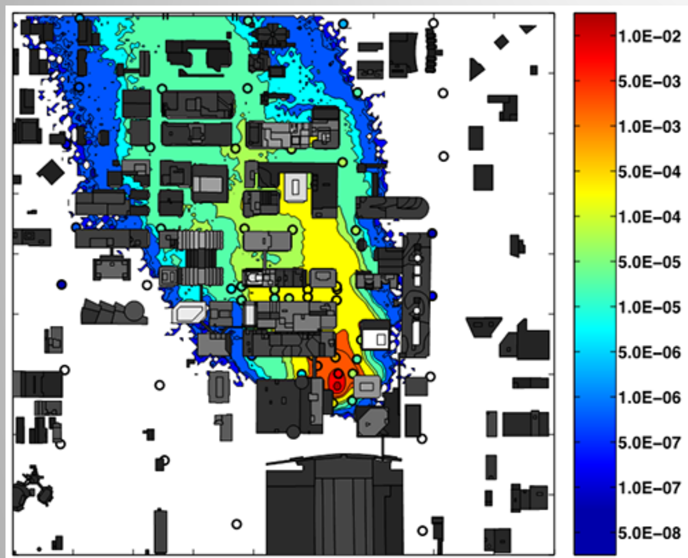


Figure 1. Contours of 30 minute averaged concentration overlaid with 30 min averaged field concentration data (color coded circle): horizontal slice (*x*-*y* plane) at 2 m AGL.

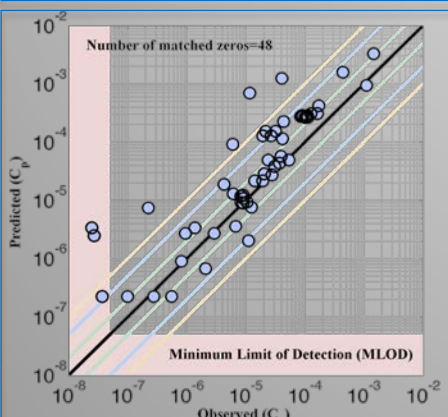
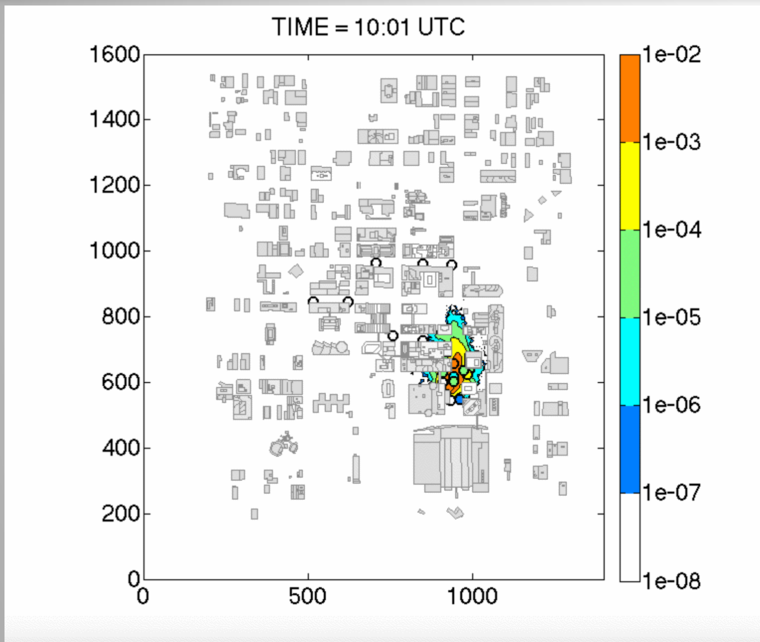


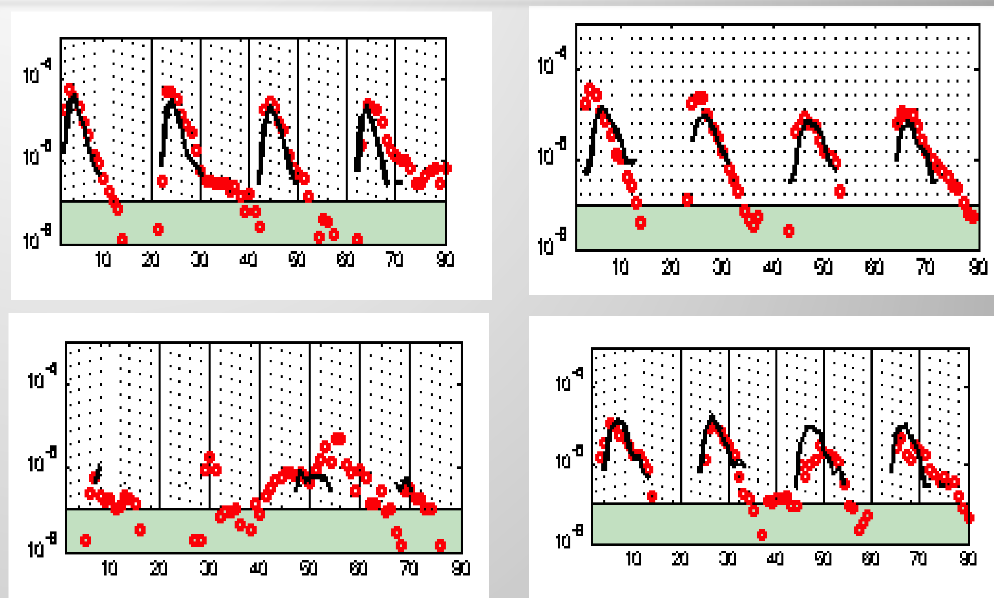
Figure 2: Paired in time and space scatter plot for predicted and observed 30 minute averaged concentration (g/m^3): horizontal slice (*xy* plane) at 2 m AGL

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

Model Has Been Validated Against Urban Field Study Data Sets: Instantaneous Release



1 minute averaged concentration: contours are model predictions and filled circles are observed data

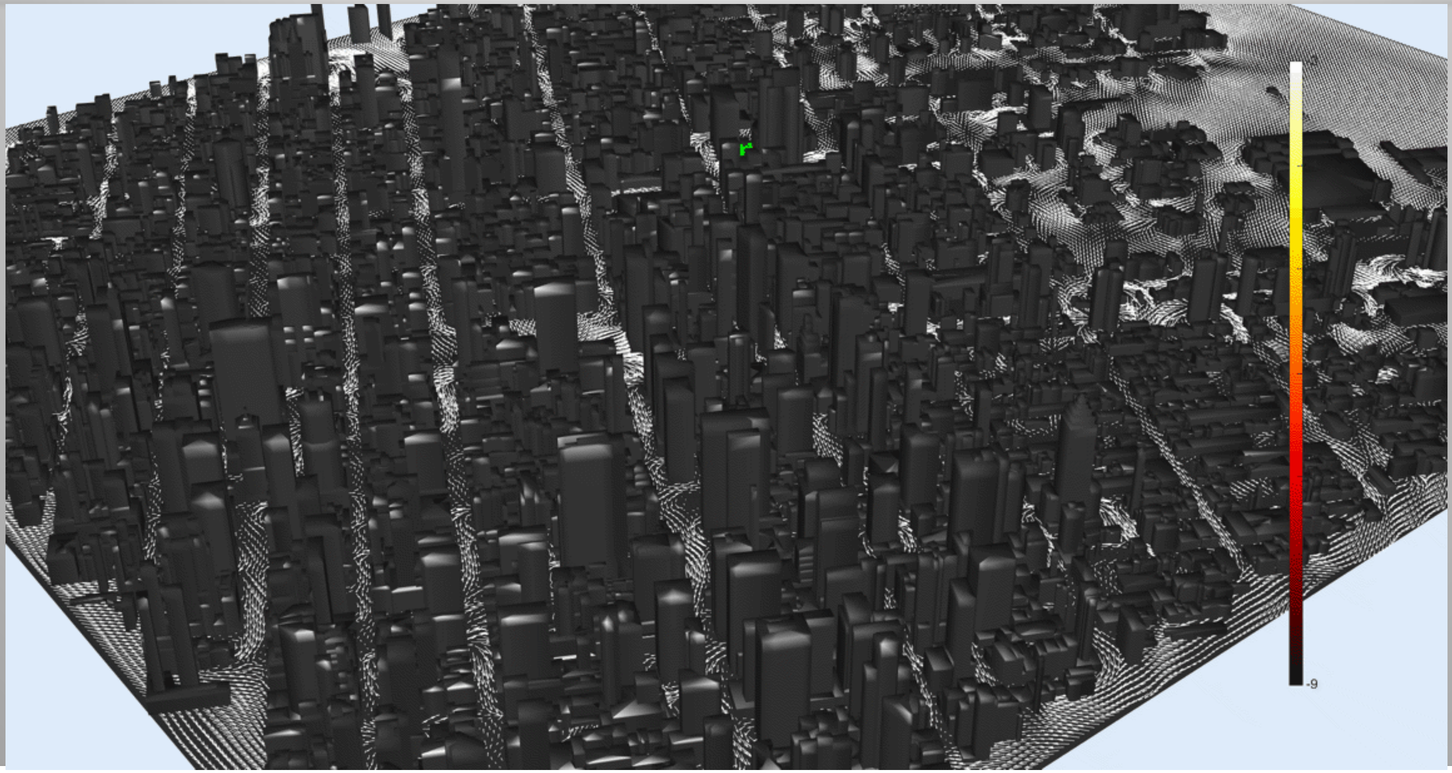


1 minute averaged concentration at few sites inside the Central Business District: — Model prediction (Black line) vs o observed data (Red circle)

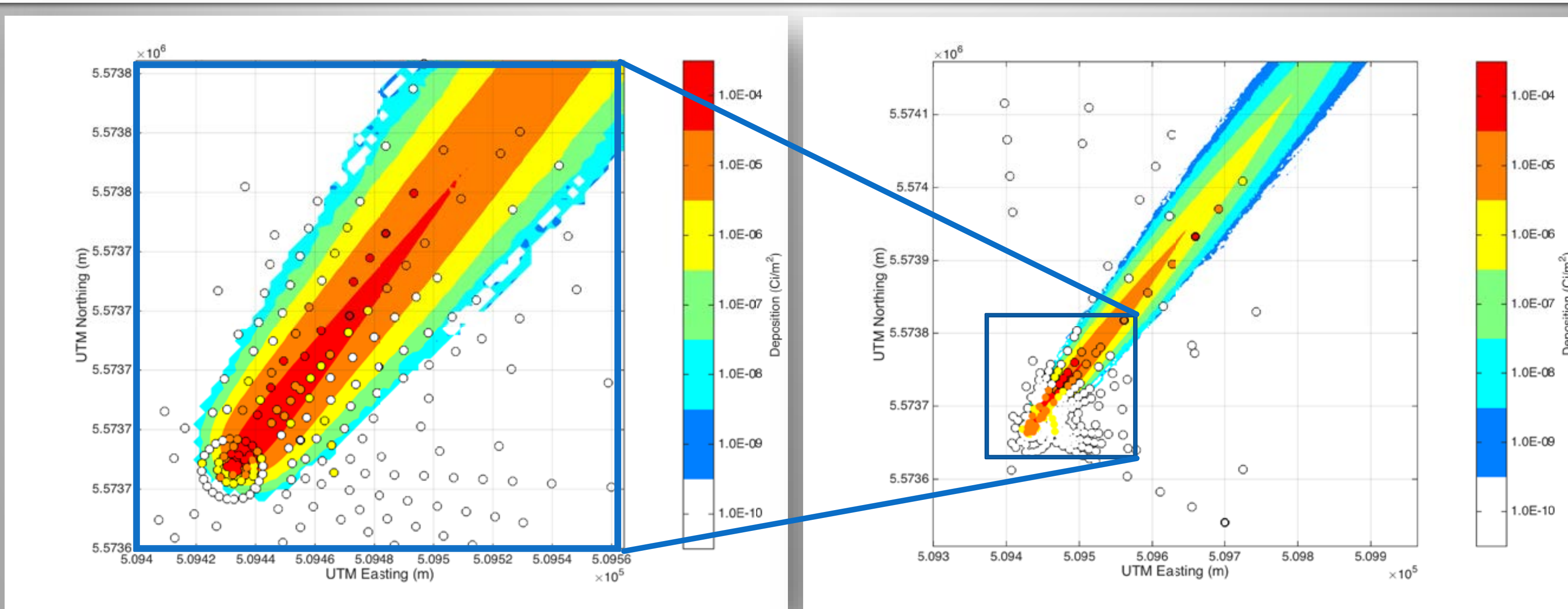
- The timing of arrival and departure of the plume is well predicted by the model
- Predicted 1 minute average SF_6 concentrations compare well with observed data at most sensor locations

Radiological Dispersal Device Capability (Sponsored by DHS S&T)

- Enhanced algorithms to predict deposition and decay of radioactive materials on the ground and building surfaces
- Develop Source term module for RDD
- Develop Products and Operationalize the model



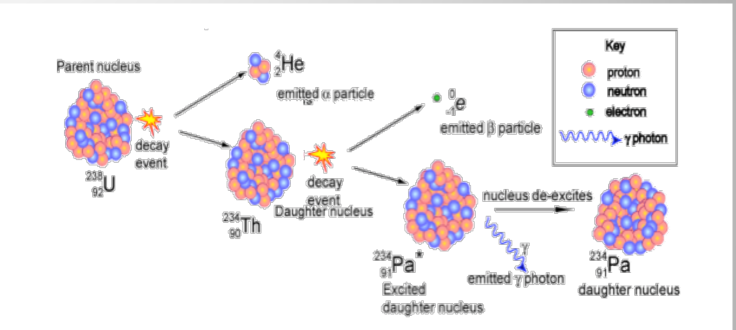
Validation of the Deposition model

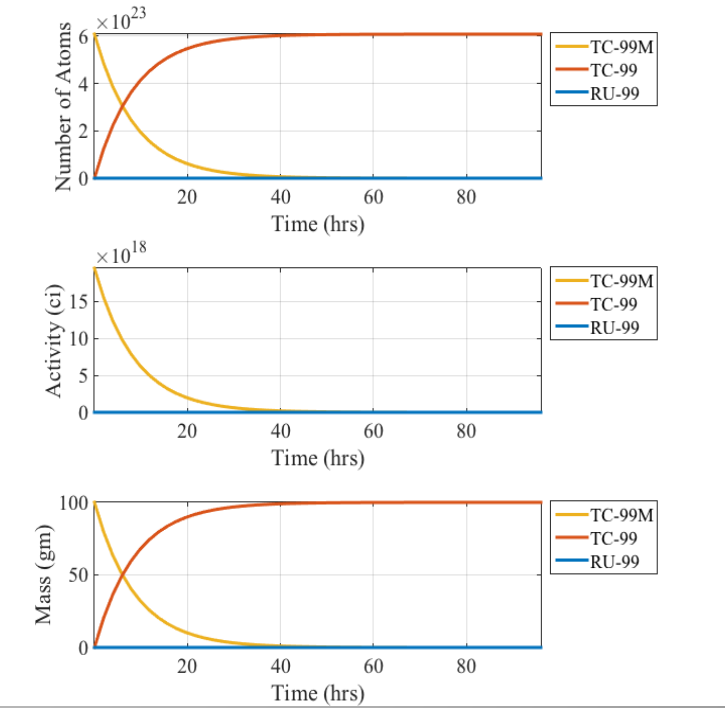


Aeolus deposition results compared to the Canadian Full-Scale RDD field trials shot 1 (June 6, 2012). Right: extent of plume compared to measurement grid; Left: zoomed image showing near release comparison. The colored circles represent the measured data; white circles are near or below the device measurement detectability threshold (0.3μCi/m^2). The contours show predicted deposition concentration (Ci/m2) on a log scale. Each step change in color along the gradient represents an order of magnitude change in concentration.

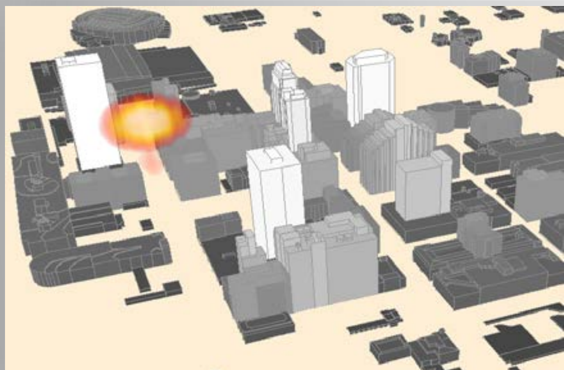
Important Radiological Processes Are Incorporated In The Model

- Radioactive materials undergo decay through a series of transformations rather than in a single step. Until the last step, these radionuclides emit energy or particles with each transformation and become another radionuclide
- Radionuclide decay chain simulation (Bateman's equations) is incorporated and validated to accurately predict level of radioactive contamination in the air and on the surfaces
- Database of more than 2000 radionuclides integrated within the model

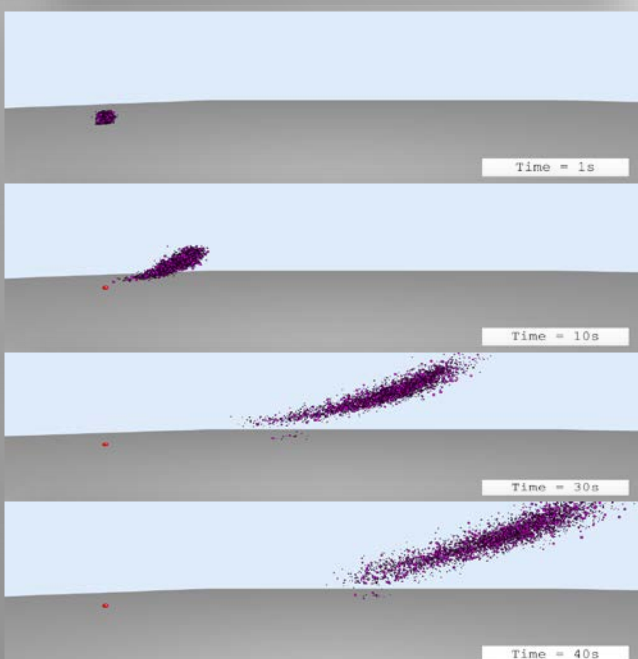




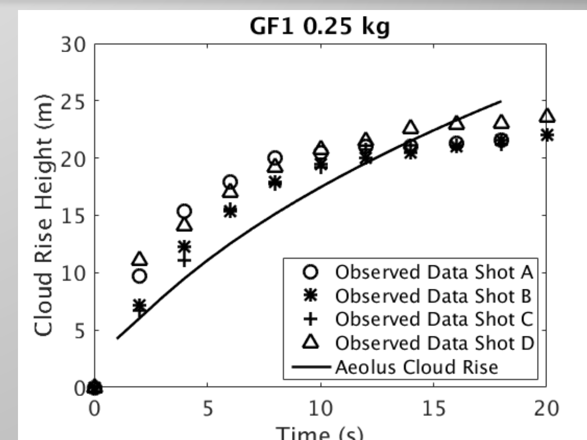
Radiological Dispersion Device Source Term Development



Aeolus uses the PUFF explosive cloud rise code developed by Sandia National Laboratories (Boughton and DeLaurentis 1987) to predict the time-dependent vertical rise rate and size of a spherical cloud representing the buoyant gas cloud resulting from an explosive detonation.



The PUFF-calculated cloud vertical velocity is used in a subsequent Aeolus simulation to lift particles entrained within the cloud. Larger particles, with correspondingly larger settling velocities, detrain more rapidly than smaller particles

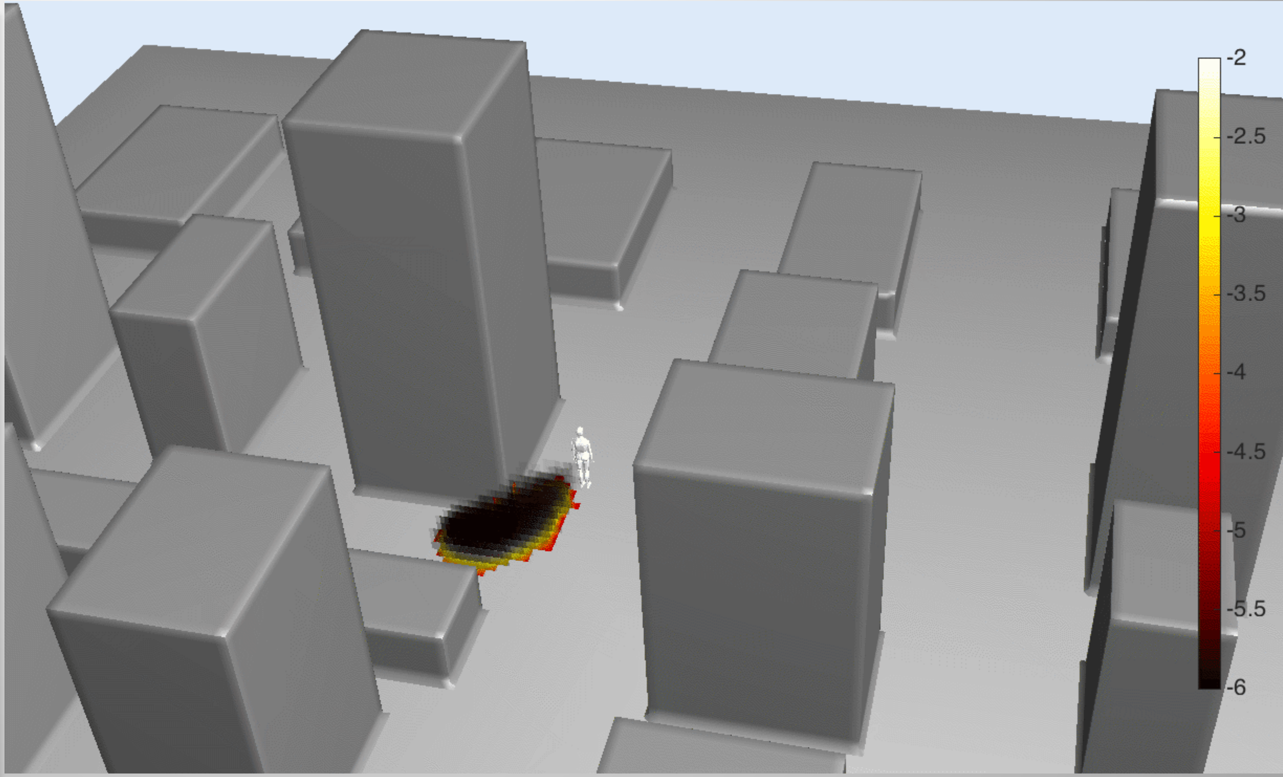


Aeolus predictions of cloud rise from a 0.25 kg HE detonation (line) compared to measured values (symbols).

Total Effective Dosage Estimation

Dose Pathways included:

- *CED_{in}* = Committed Effective Dose from inhalation of activity during plume passage (internal exposure)
- *ED_{sub}* = Effective Dose from submersion within airborne activity during plume passage (external exposure)
- *ED_{sur}* = Effective Dose from activity deposited on surfaces (external exposure)



$$\boldsymbol{TED\ (x, y, z) = CED_{in} + ED_{sub} + ED_{sur}}$$

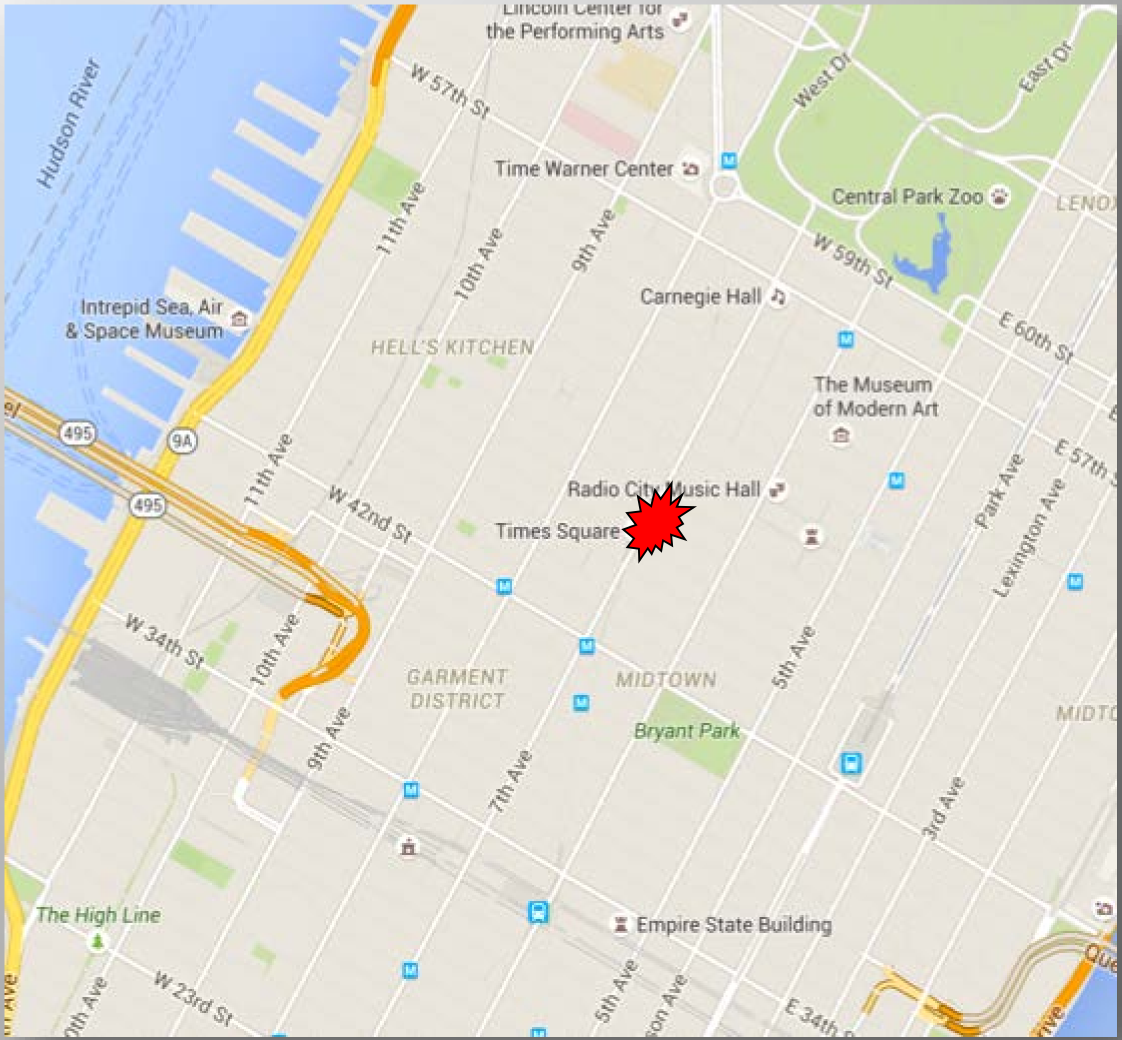
For "*n*" radionuclides, the total TED is,

$$TED_T(x, y, z) = \sum_{i=1}^{n} TED_i\ (x, y, z)$$

Aeolus Demonstration

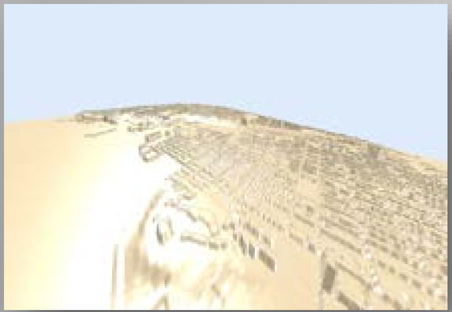
Aeolus Model Requires Minimal Input To Run

- User Input: Latitude and Longitude of the release location, Domain size, resolution, start and end time and Source characteristics
- Setup time is minimal: less than 2 minutes (default parameters)
- Using user inputs, the system extracts terrain data and available building data and generates a grid for Aeolus



Model Grid Generation Is Rapid And Fully Automated Using Building Data

Using user inputs, the system extracts terrain data and available building data and generates a grid for Aeolus



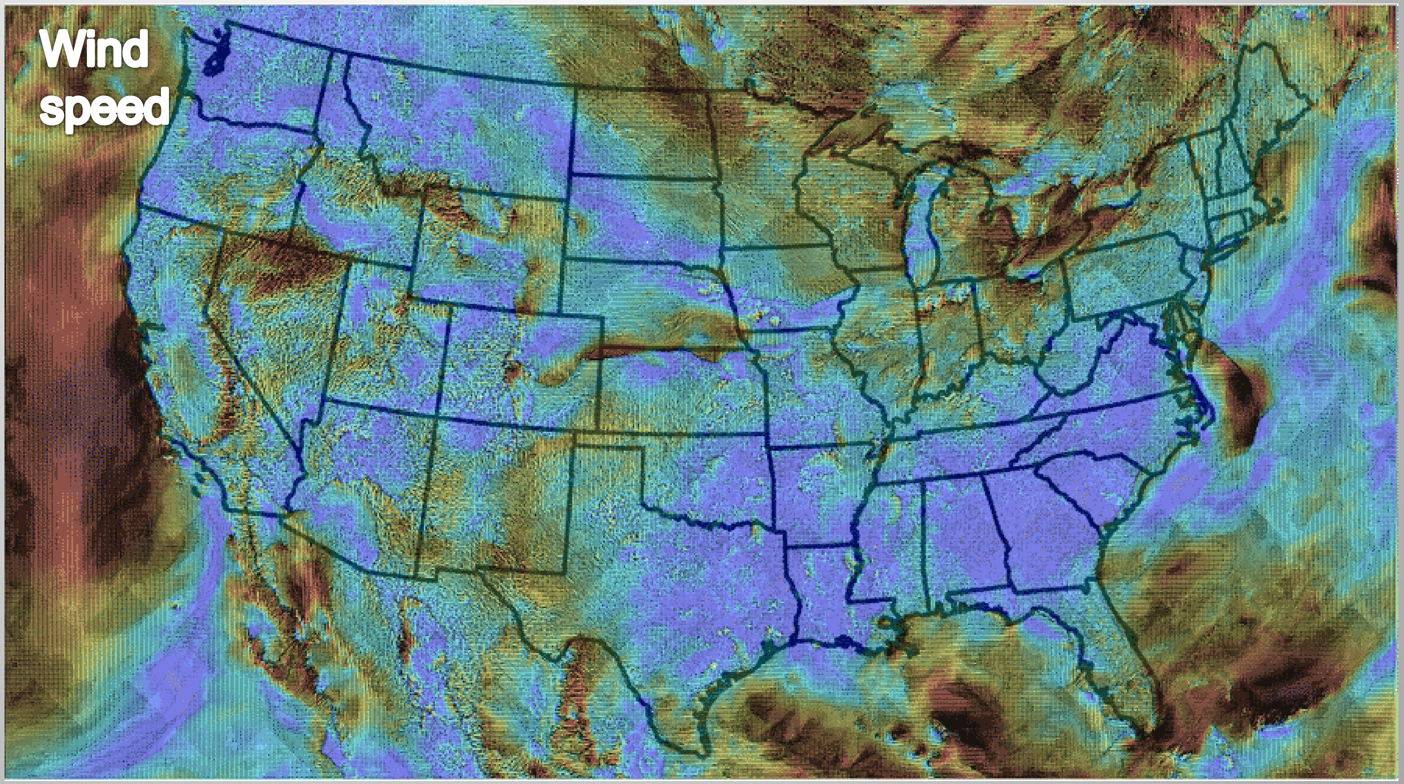
Terrain data (USA):
Primary dataset: NED10 (**10 m resolution**; 2013 update, covers 48 states, Hawaii and portions of Alaska)

Building data (☐):
NGA/SAIC 3D building shapefiles (building footprints supplemented with height attributes). Covers most of the HSIP Gold 133 cities plus selected military and border areas

High Resolution Analyzed/ Forecasted Winds Or User Prescribed Winds Can Be Used To Initialize The Model

Meteorological Field Options:

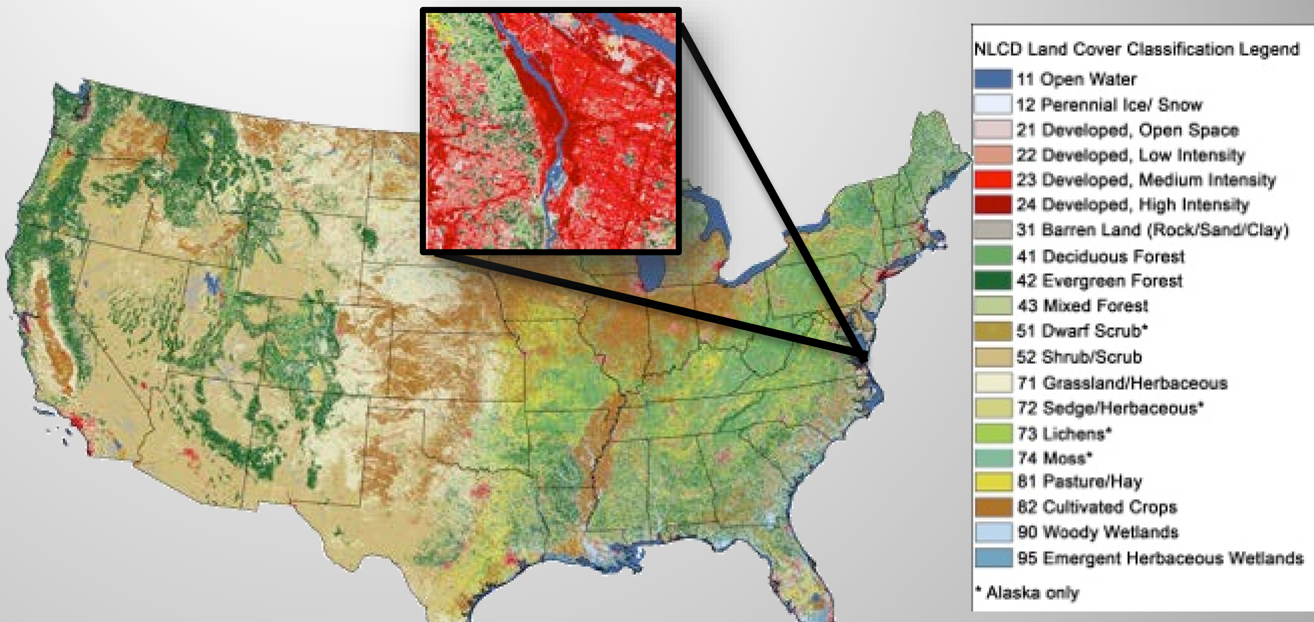
- HRRR (Default)
- NAM3
- RAP/RUC
- NAM12
- GFS
- User prescribed



The HRRR is a NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model. Radar data is assimilated in the HRRR every 15 min over a 1-h period

Integrated High Resolution Land Characteristics Database (NLCD 2011)

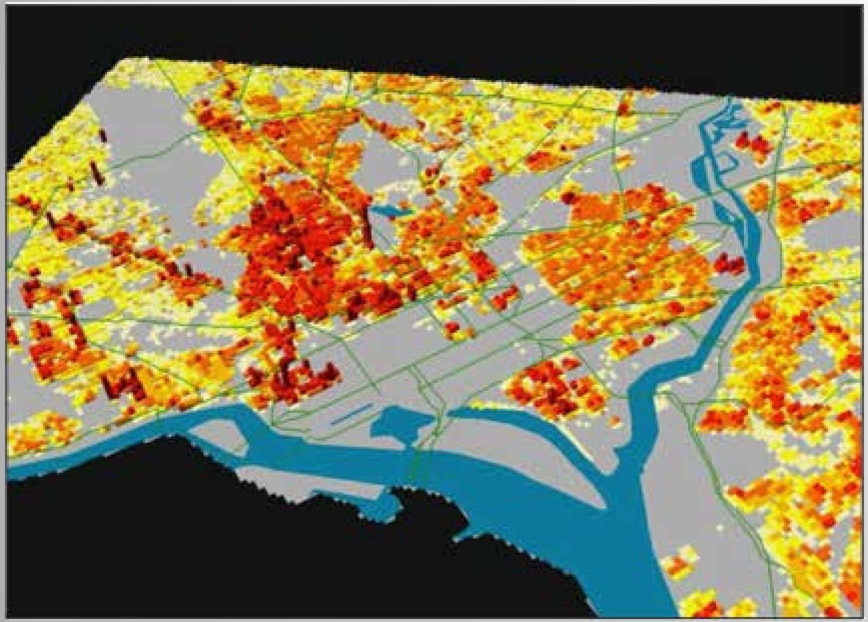
- National Land Cover Database 2011 is a 16-class land cover classification scheme applied across CONUS at a spatial **resolution of 30 meters**.
- It is based primarily on a decision-tree classification of circa 2011 Landsat satellite data.



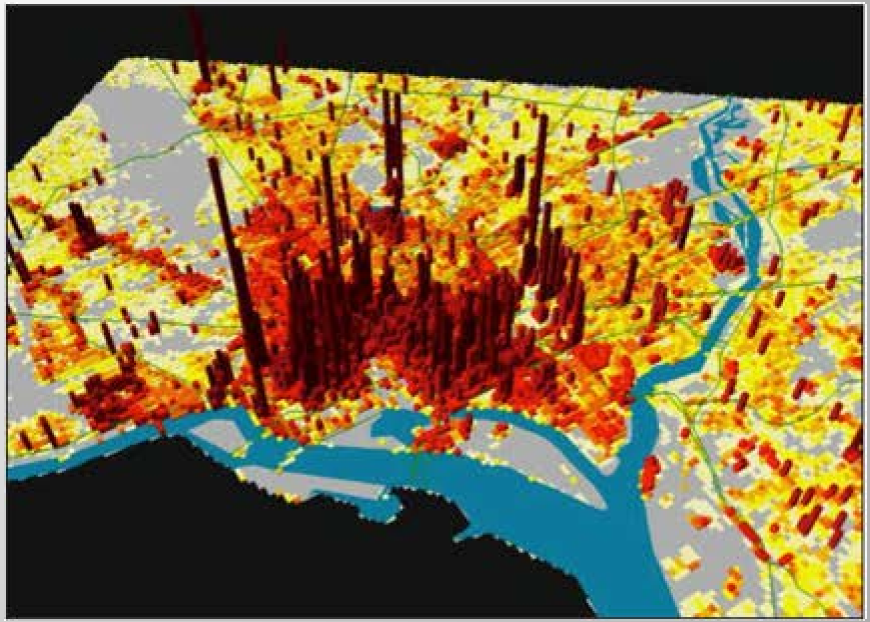
Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

- Landuse information is incorporated in the model by spatially varying surface roughness (z_o)
- The model uses logarithmic law of the wall to determine wind stress ($u_* = u/ln(z/z_o)$) at the surface

Integrated High Resolution Day/Night Population Database (Landscan, ORNL)



Washington DC Nighttime



Washington DC Daytime

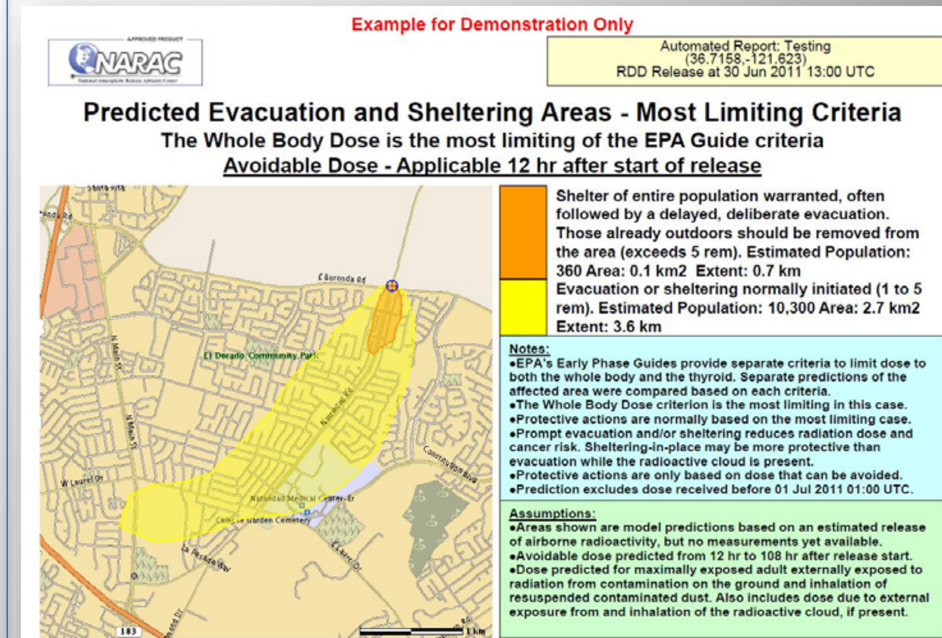
- LandScan USA 2015: 90m spatial resolution; 2010 Census based; nighttime and daytime distributions; 120 major urban area

- Database is utilized to develop standard/ technical products by overlaying plume products on the population database to estimate number of people affected

For more details: http://web.ornl.gov/sci/landscan/

Model Prediction Products Will Be Developed And Provided Through National Centers

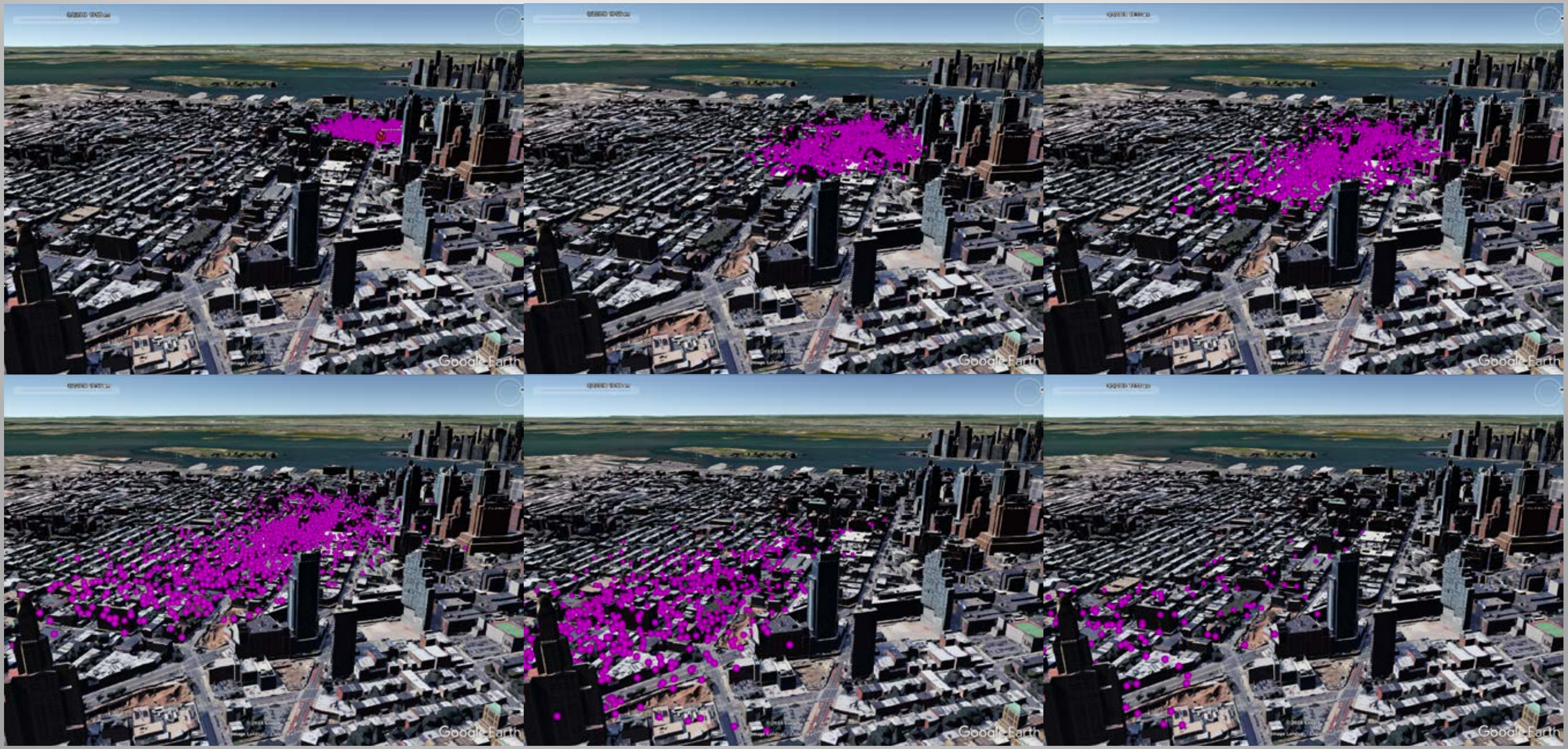
- The Aeolus model is operationalized for use by NARAC analyst to generate urban modeling products that will be provided to state and local agencies through IMAAC process
- NARAC analysts will be trained to use a LLNL-based Aeolus urban modeling system
- Standard briefing/ technical products will be produced in support of IMAAC for providing guidance on protective action such as public sheltering/evacuation and worker protection



For additional information see https://narac.llnl.gov

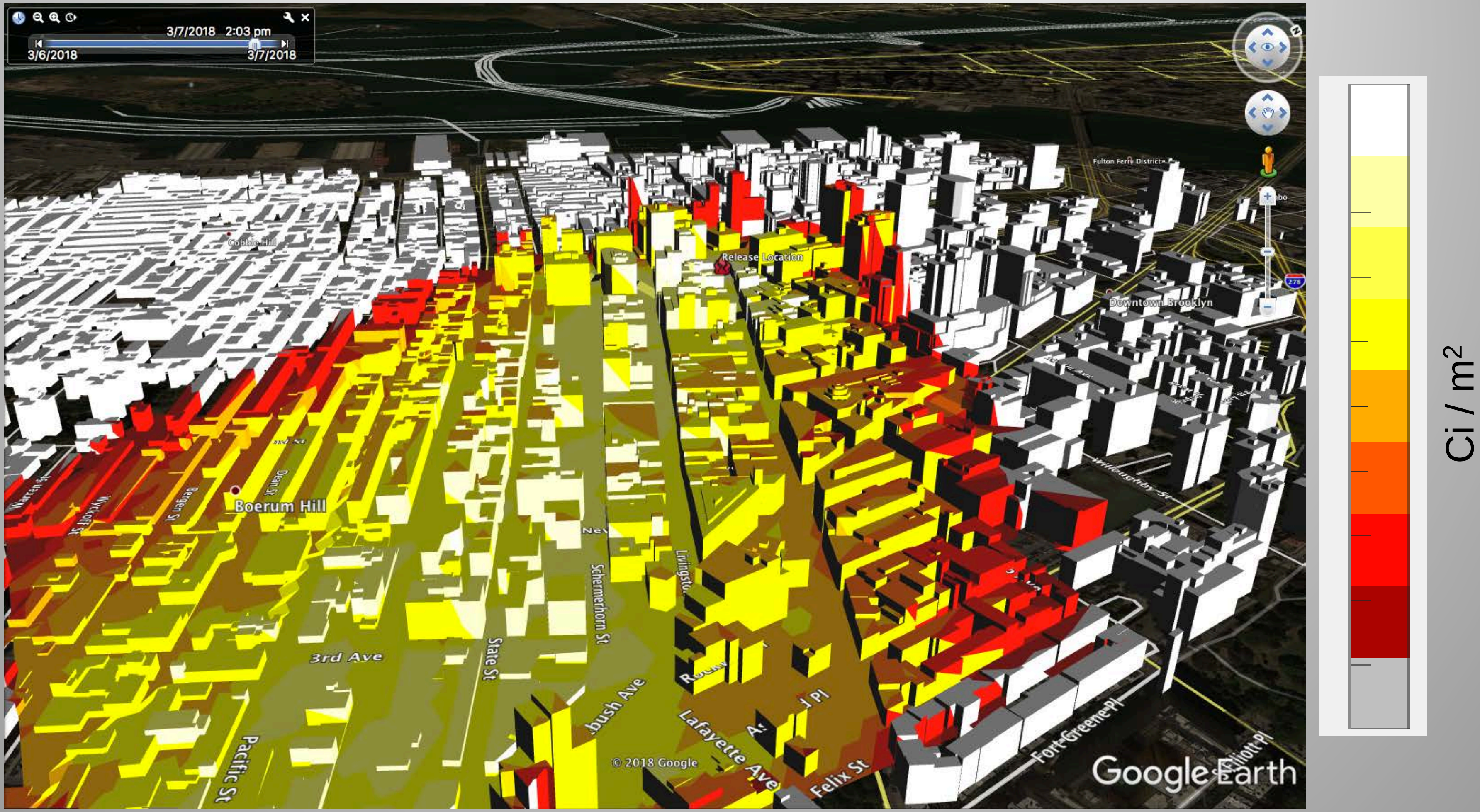
Aeolus Products

Aeolus simulation showing time evolution of particles as it disperses through an urban area



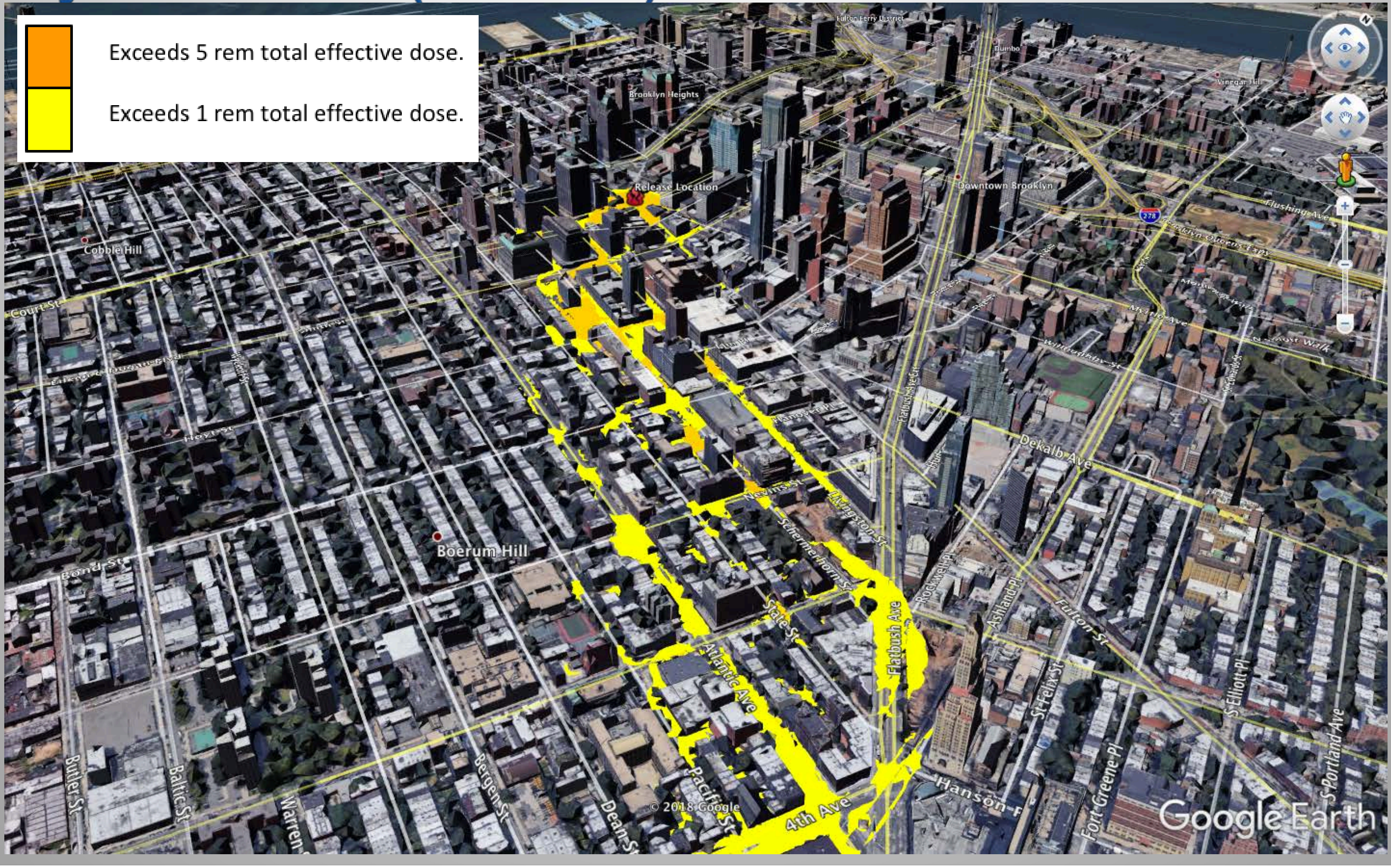
Aeolus products (Google Earth , KML)

3D surface deposition (at 12 hrs)



Aeolus products (Google Earth , KML)

Early Phase TED (0-96 Hrs)



Aeolus products (Google Earth , KML)

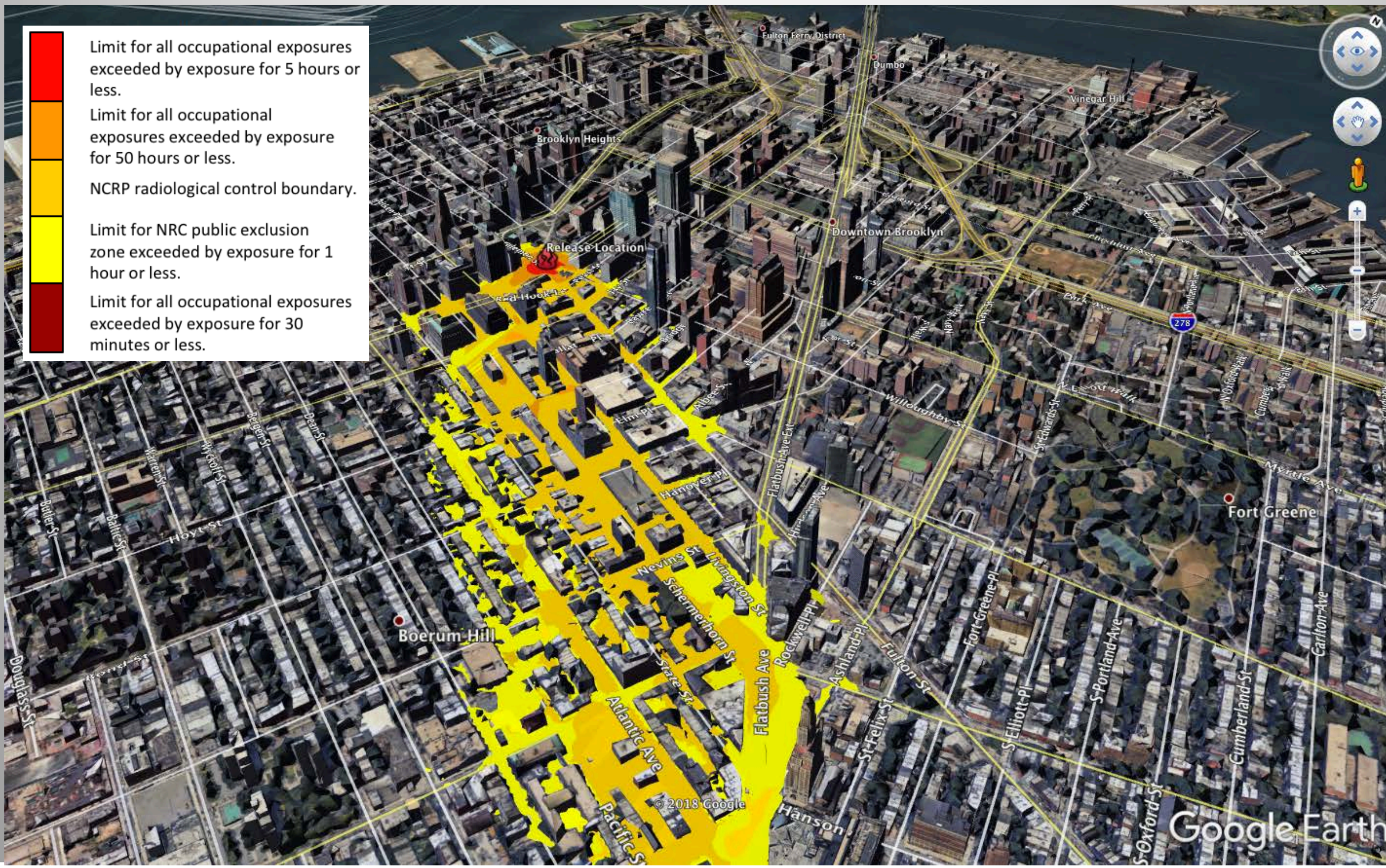
Early Phase Evac Shelter TED (12-108 Hrs)

Aeolus products (Google Earth , KML)

Near Field Worker Protection Dose Rate (12 hrs)

Aeolus products (Google Earth , KML)

Far Field Worker Protection Dose Rate (12 hrs)



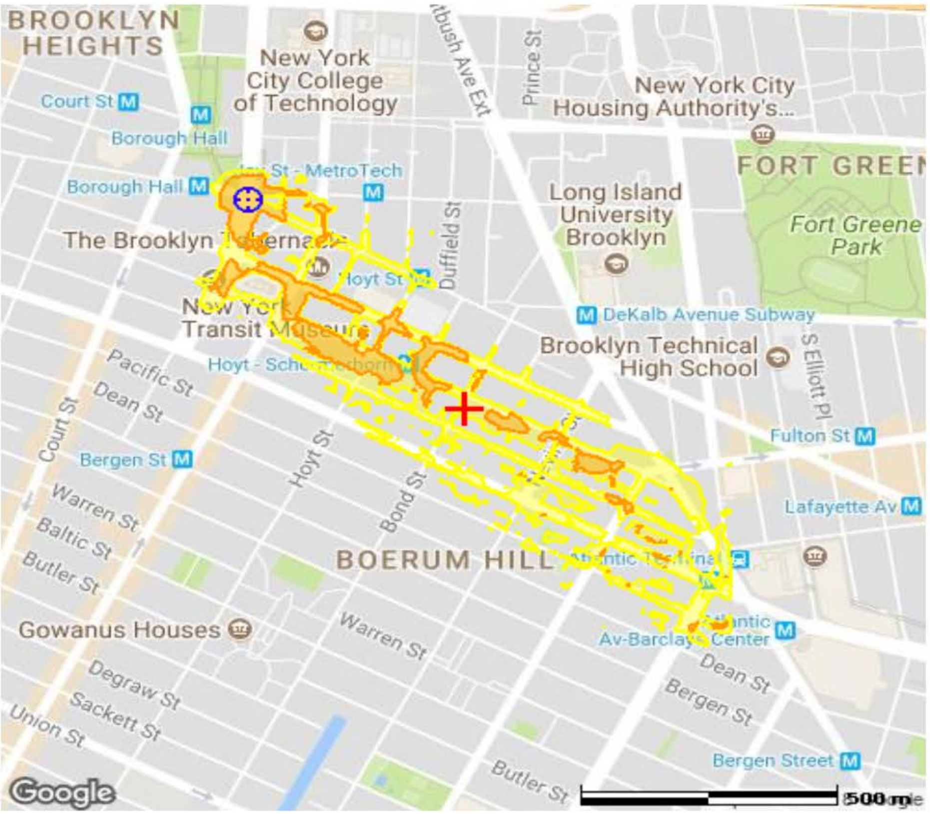
APPROVED PRODUCT
NARAC
National Atmospheric Release Advisory Center

DRAFT for Review

Aeolus Product: Example
Brooklyn
RADIOLOGICAL Release at 22 May 2015 20:00 UTC

Early Phase TED (0-96 hrs) (Eff Whole Body ICRP60)

(Total Effective Dose Including Plume Passage)



Orange	Exceeds 5 rem total effective dose.
Yellow	Exceeds 1 rem total effective dose.

Legend Table Information

Levels: 5.0 rem, 1.0 rem
Extents: 1.33km, 1.35km
Areas: 46471.78m2, 249185.23m2
Population: 6780.0, 20200.0

Notes

Effects or contamination from 22 May 2015 20:00 UTC to 22 May 2015 20:30 UTC
Release Location: 40.692140 N, 73.989000 W
Material: CS-137
Generated On: 28 Feb 2018 21:11 UTC
Model: AEOLUS
Comments: Release starting at 22 May 2015 20:00 UTC for 1 sec, GRIDDED at 22 May 2015 20:00 UTC

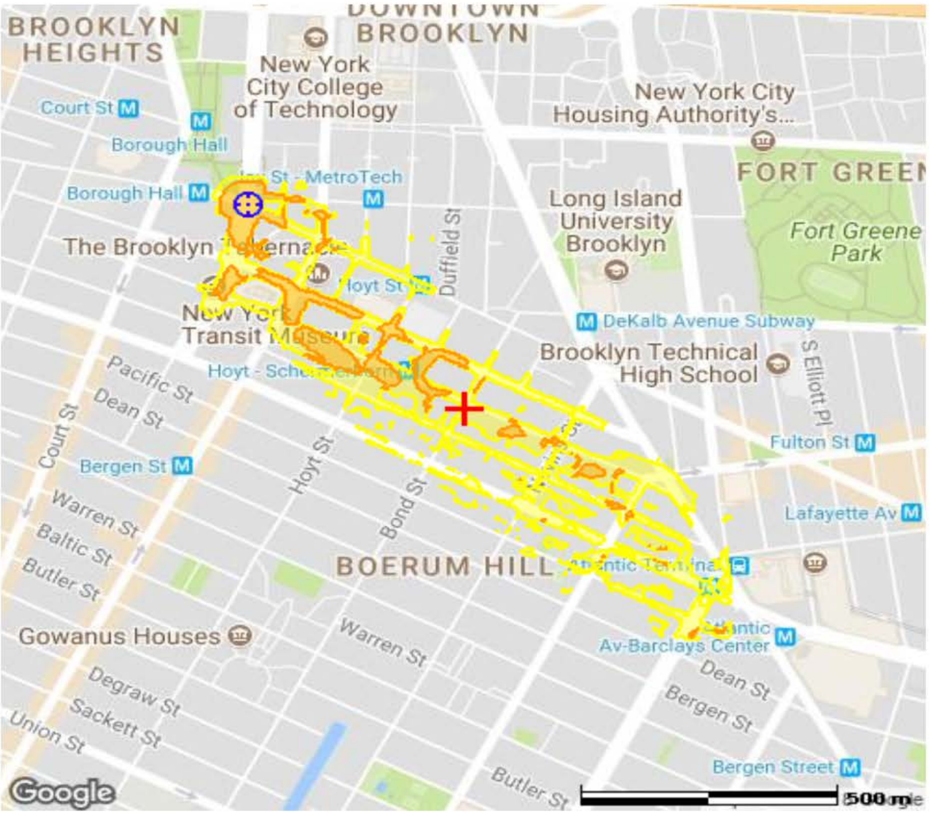
Briefing Product for Public Officials
Produced: 28 Feb 2018 21:12 UTC
Check for Updates

DRAFT for Review

Aeolus Product: Example
Brooklyn
RADIOLOGICAL Release at 22 May 2015 20:00 UTC

Early Phase Evac Shelter TED (12-108 hrs) (Eff Whole Body ICRP60)

(Evacuation/Sheltering based on Avoidable Total Effective Dose)



Exceeds 5 rem total effective dose (upper limit early phase PAG for evacuation/sheltering).

Exceeds 1 rem total effective dose (lower limit early phase PAG for evacuation/sheltering.

Legend Table Information

Levels: 5.0 rem, 1.0 rem
Extents: 1.33km, 1.35km
Areas: 38732.72m2, 239272.09m2
Population: 5790.0, 19200.0

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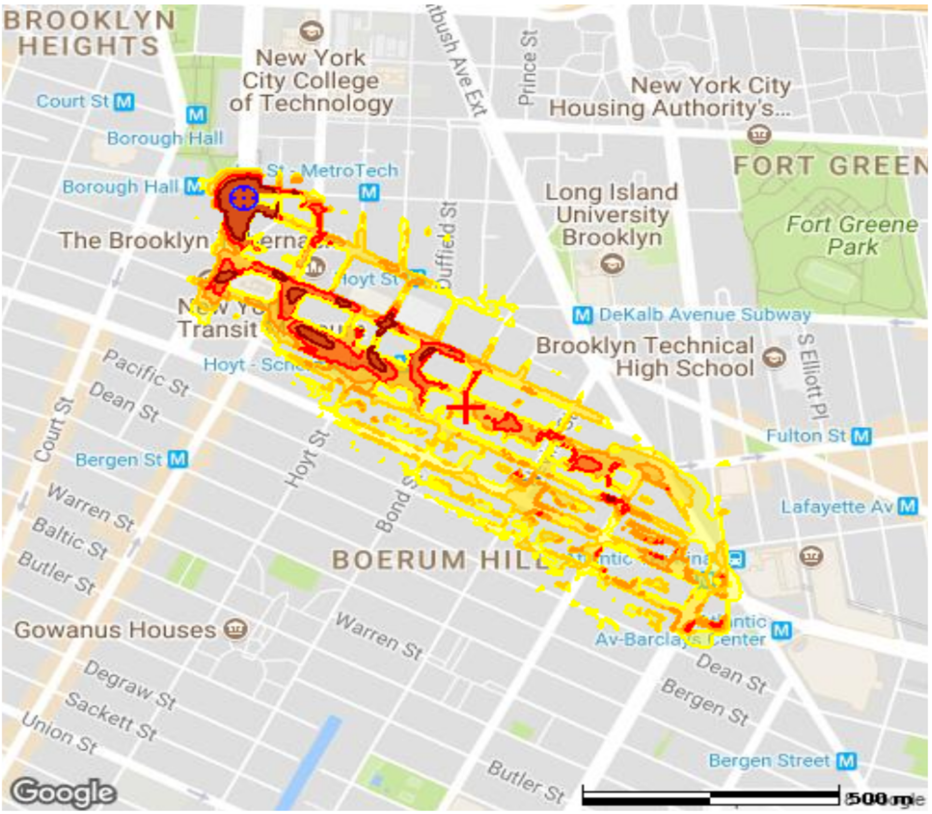
NARAC — National Atmospheric Release Advisory Center (APPROVED PRODUCT)

Aeolus Product: Example
Brooklyn
RADIOLOGICAL Release at 22 May 2015 20:00 UTC

Worker Protection Dose Rate at 12 hrs (Near Field)

(Groundshine and Air Immersion Dose Rate at $TIME_ZONE)



Four times PAG for lifesaving and protection of large populations exceeded by exposure for 1 hour or less.

Twice PAG for lifesaving and protection of large populations exceeded by exposure for 1 hour or less.

PAG for lifesaving and protection of large populations exceeded by exposure for 1 hour or less.

PAG for protection of major property needed for public welfare exceeded by exposure for 1 hour or less.

Limit for all occupational exposures exceeded by exposure for 1 hour or less.

Legend Table Information

Levels: 100.0 rem/hr, 50.0 rem/hr, 25.0 rem/hr, 10.0 rem/hr, 5.0 rem/hr
Extents: 0.985km, 1.33km, 1.34km, 1.35km, 1.35km
Areas: 13990.8m2, 41104.0m2, 101952.09m2, 258050.0m2, 458361.0m2
Population: 2330.0, 6040.0, 12000.0, 19500.0, 24300.0

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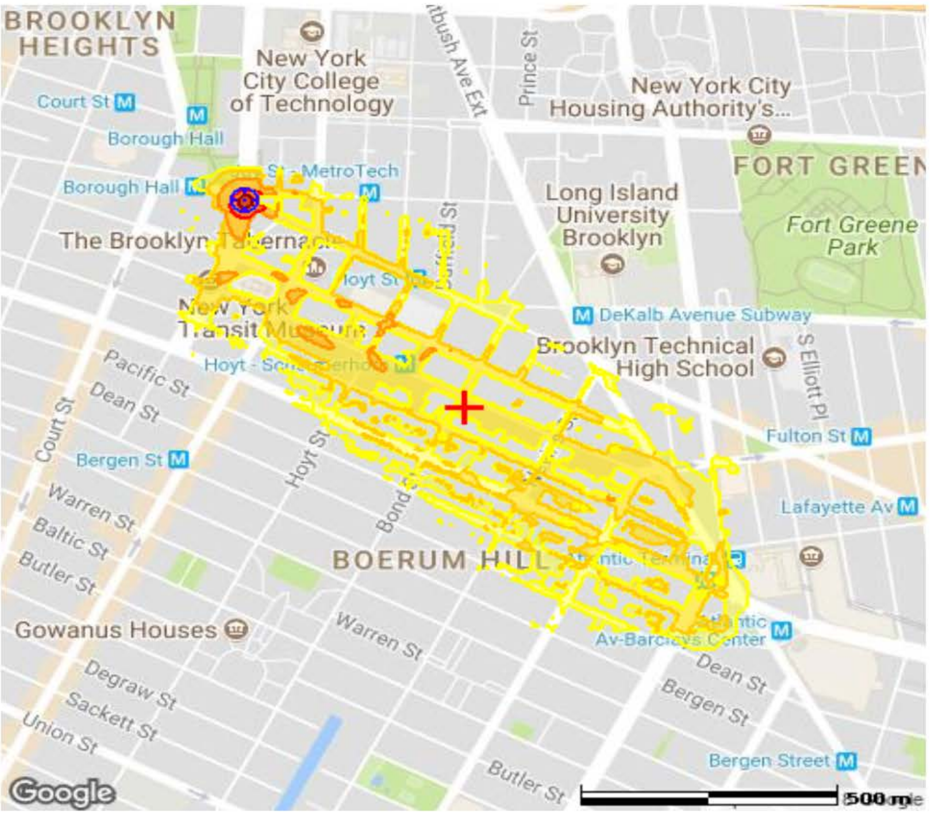
Brooklyn
RADIOLOGICAL Release at 22 May 2015 20:00 UTC

Worker Protection Dose Rate at 12 hrs (Far Field)

(Groundshine and Air Immersion Dose Rate at $TIME_ZONE)



- Red: Limit for all occupational exposures exceeded by exposure for 5 hours or less.
- Orange: Limit for all occupational exposures exceeded by exposure for 50 hours or less.
- Light orange: NCRP radiological control boundary.
- Yellow: Limit for NRC public exclusion zone exceeded by exposure for 1 hour or less.
- Dark red: Limit for all occupational exposures exceeded by exposure for 30 minutes or less.

Legend Table Information

Levels: 1000.0 mrem/hr, 100.0 mrem/hr, 10.0 mrem/hr, 2.0 mrem/hr, 10000.0 mrem/hr
Extents: 0.0436km, 0.985km, 1.35km, 1.36km, 0.0183km
Areas: 3032.24m2, 13990.8m2, 241251.91m2, 520883.15m2, 575.22m2
Population: 610.0, 2330.0, 19500.0, 28900.0, 120.0

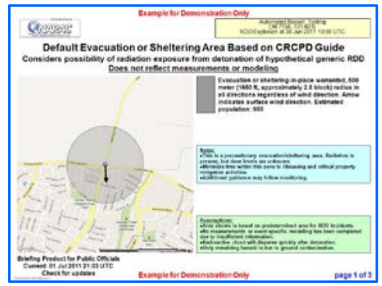
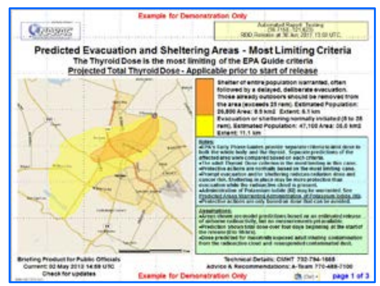
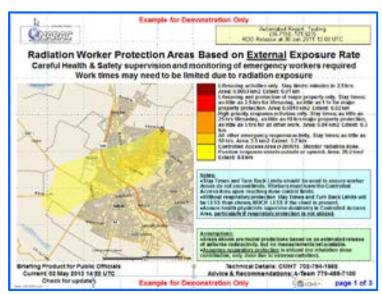
Notes

Effects or contamination from 22 May 2015 20:00 UTC to 22 May 2015 20:30 UTC
Release Location: 40.692140 N, 73.989000 W
Material: CS-137
Generated On: 28 Feb 2018 21:12 UTC
Model: AEOLUS
Comments: Release starting at 22 May 2015 20:00 UTC for 1 sec, GRIDDED at 22 May 2015 20:00 UTC

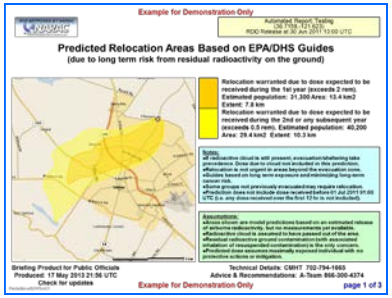
Briefing Product for Public Officials
Produced: 28 Feb 2018 21:13 UTC
Check for Updates

DRAFT for Review

RDD Briefing Products: Summary

Time Phase	Product		Purpose
Early (minutes)	Default Evacuation or Sheltering Area		• Guide precautionary sheltering and evacuation decision • Guide access control and monitoring
Early (hours to days)	Predicted EPA/DHS Sheltering/ Evacuation Areas (TED or Thyroid CDE)		• Update guide for sheltering and evacuation decisions • Assess avoidable additional long-term cancer risk • Uses most-limiting 4-day dose (Whole-body Total Effective Dose [TED] of 5 Rem and1-5 Rem <u>or</u> Adult Thyroid Committed Dose Equivalent [CDE] of > 25 Rem and 5-25 Rem)
	Predicted Worker Protection Areas		• Use for worker protection and stay time guidance • Determine access control area

RDD Briefing Products: Summary

Time Phase	Product	Sample	Purpose
Intermediate (days to months) and Late Phases (months to years)	Predicted EPA/DHS Relocation Areas		• Guide population relocation decisions • Assess avoidable additional long-term cancer risk, not acute radiation injury or death (2 Rem in first year and 0.5 Rem in second or later year)

Note: ICRP60 dose conversion factors are used for radiological dispersal device products

Questions?

BACKUP

What is Aeolus-WIND?

- Solves incompressible RANS equations for steady-state solution very quickly

$$\frac{\partial \overline{u_i}}{\partial t} = -\frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j} - \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)\right] - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}$$

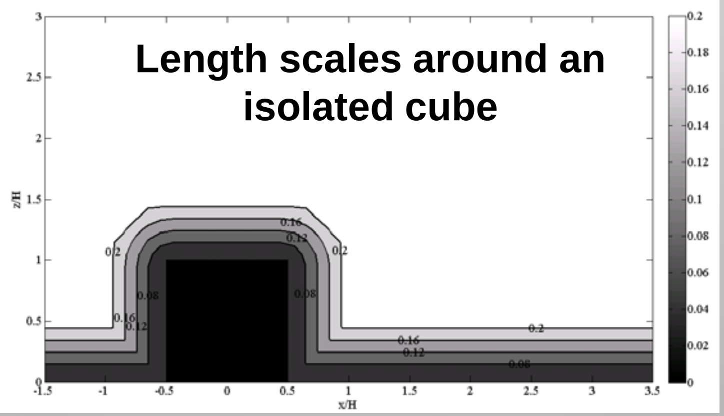
- Usual projection methods are slow because on pressure poisson equation
- Based on artificial compressibility method (Chorin 1967)
  - Pressure is marched in time along with the velocity
  - Solution is not mass conserved at each time step
  - incompressibility is recovered once the solution reaches steady state
  - Unique multi-time stepping approach for pressure

Turbulence Model

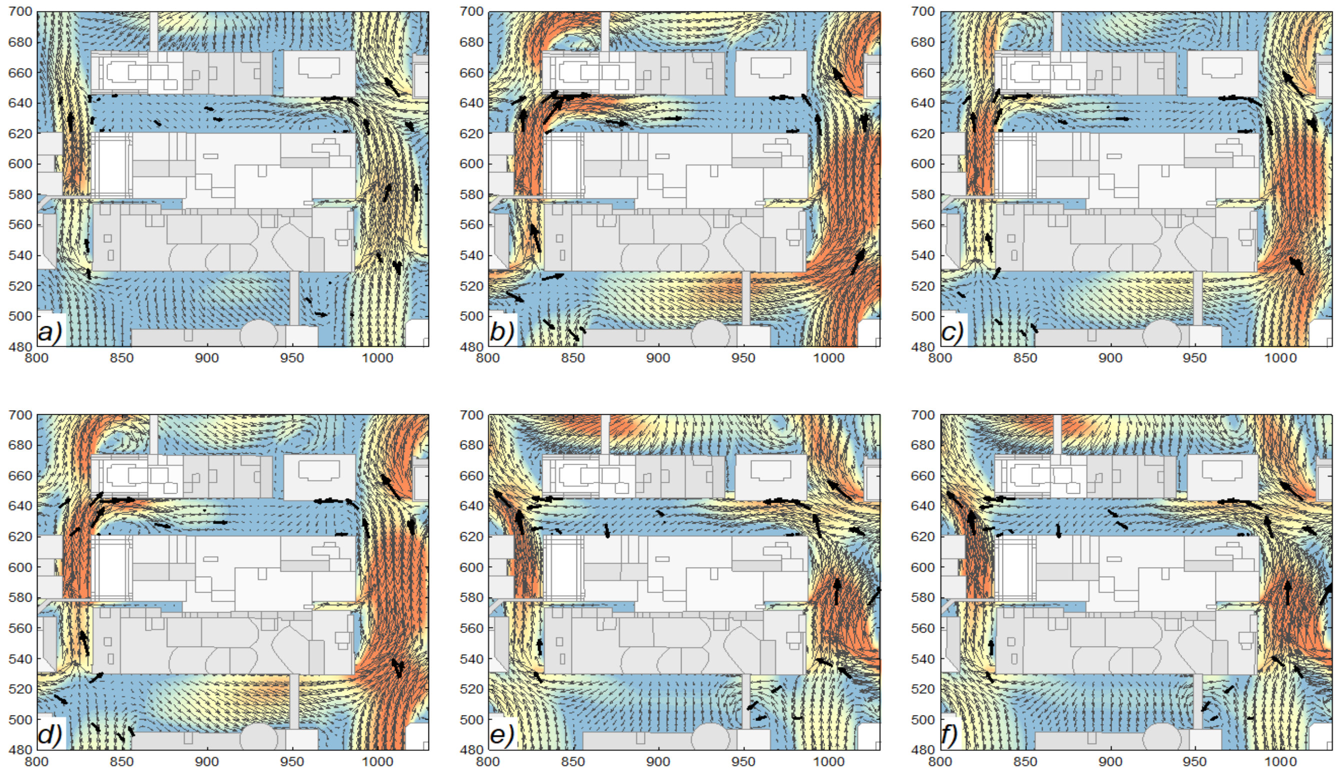
- **Very simplified algebraic turbulence model based on Prandtl's mixing-length theory used**
- ***Law of wall* used at the wall**

$$\overline{u'_i u'_j} = -\nu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right)$$

$$\nu_t = (l_{mix})^2 \sqrt{\overline{S_{ij}}\,\overline{S_{ij}}} \qquad l_{mix} = k y_{\min} \qquad \overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right)$$



Validation



Velocity vectors from the simulation results (gray arrow) overlaid with 30 min averaged field data (black arrow) for ***selected trials*** during Joint urban 2003 field experiment: horizontal slice (*xy* plane) at 8m AGL.

What is Aeolus-LDM?

- To model dispersion within the atmosphere, ***Aeolus*** solves the three-dimensional, incompressible, advection- diffusion equation with sources and sinks:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial z} = \frac{\partial}{\partial x}\left(\nu_t \frac{\partial \bar{c}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_t \frac{\partial \bar{c}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_t \frac{\partial \bar{c}}{\partial z}\right) + Q$$

- *Aeolus* solves the stochastic differential equations that describe the same process as the above equation within a Lagrangian framework (Durbin, 1983). The equations for the particle displacement due to advection, diffusion, and settling in the three coordinate directions are:

$$dx = \bar{u}dt + \frac{\partial \nu_t}{\partial x}dt + (2\nu_t)^{1/2}\, dW_x$$
$$dy = \bar{v}dt + \frac{\partial \nu_t}{\partial y}dt + (2\nu_t)^{1/2}\, dW_y$$
$$dz = \bar{w}dt + \frac{\partial \nu_t}{\partial z}dt + (2\nu_t)^{1/2}\, dW_z$$

- where $dW_{x,y,z}$ are three independent random variates with zero mean and variance dt

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Lawrence Livermore National Laboratory