A Fast-Running, High Quality, Transport and Dispersion System for Urban Areas

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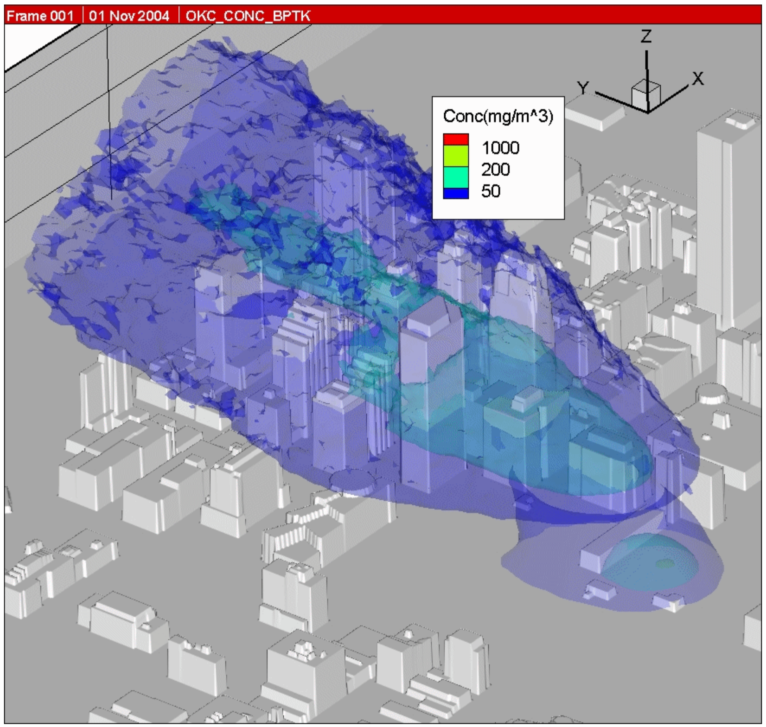
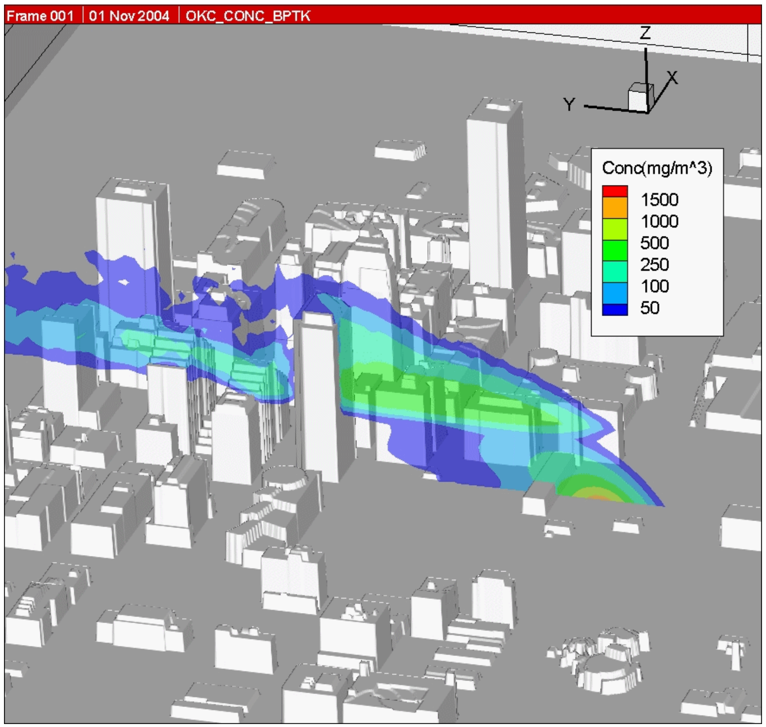
MESO/RUSTIC Outline

1. MESO/RUSTIC Urban Dispersion and Wind Flow Background
2. Comparison to Oklahoma City Data
3. RUSTIC Upgrades for FY06 JSTO Tech Base Effort





Simulated concentration levels for volatile drops release in Oklahoma City

Unclassified

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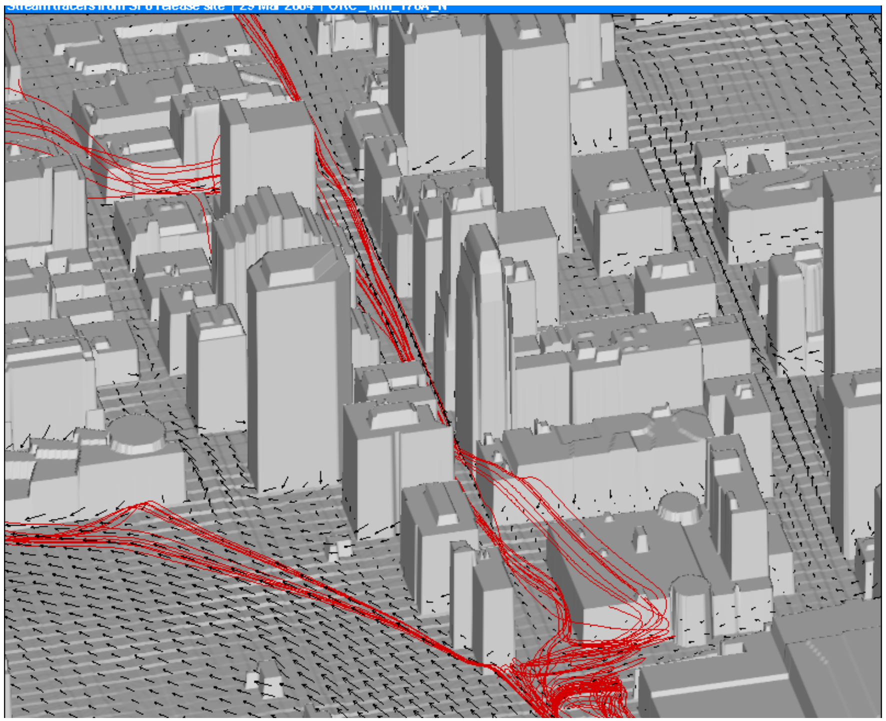
MESO/RUSTIC is a New Generation Model That Provides Accurate 3D Urban Hazard Definitions

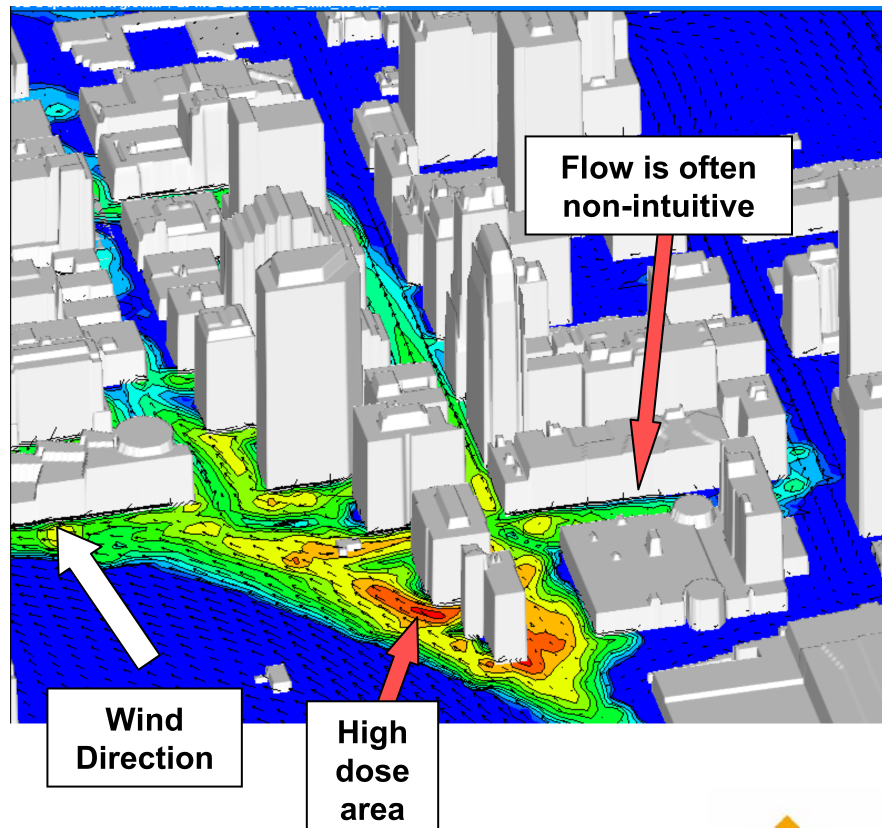
Two Steps for Urban CBR Hazard Definition with MESO/RUSTIC

1. **Compute turbulent "wind flow" with RUSTIC for urban scenarios.**

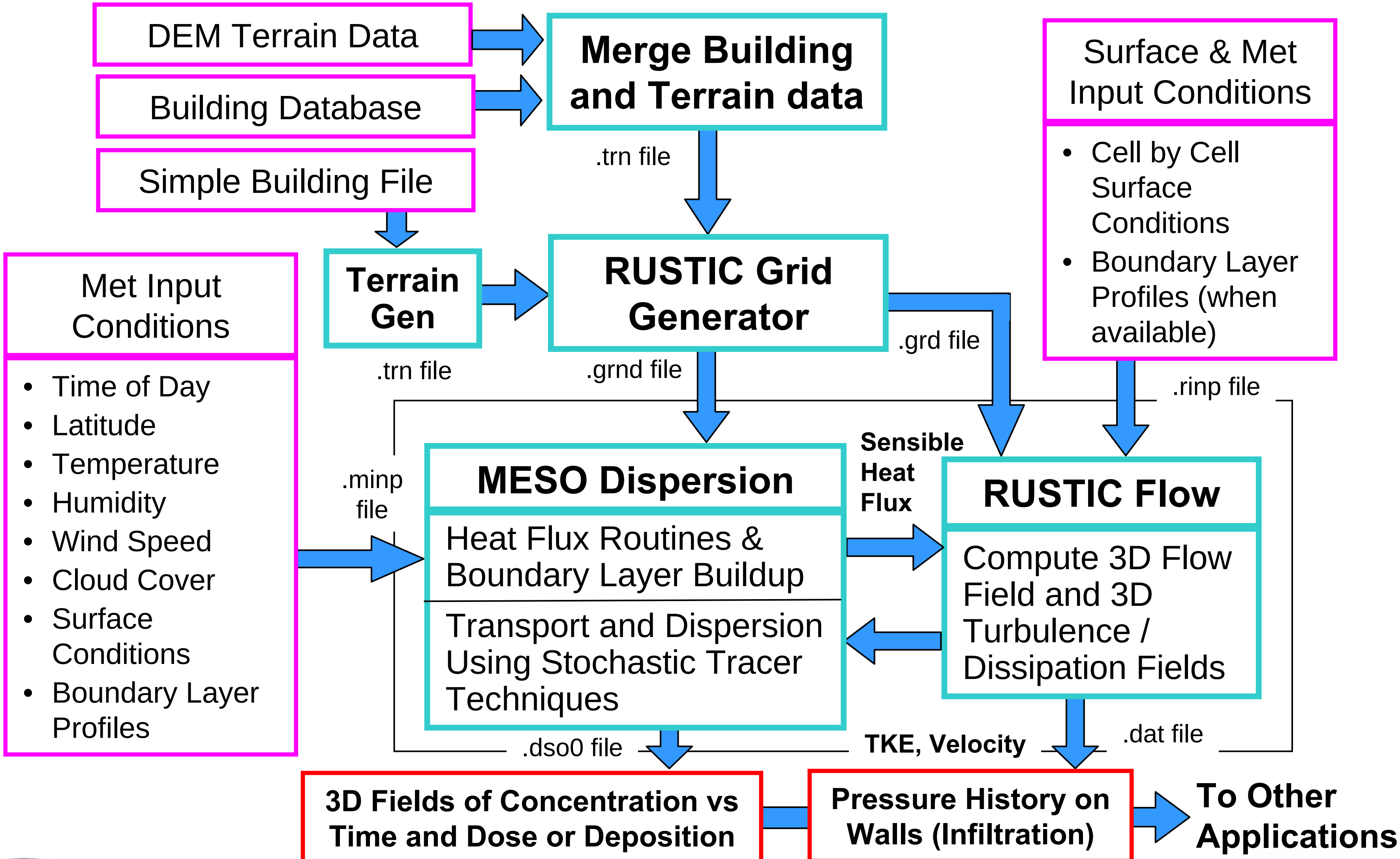
   Downtown Oklahoma City July 2003



2. **Use MESO to compute contaminant dispersion with flow and turbulence predicted by RUSTIC.**

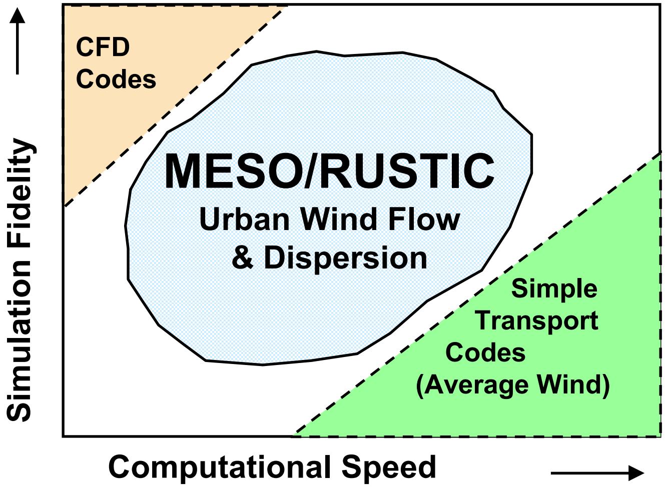


MESO / RUSTIC Urban Transport & Dispersion Data Flow



RUSTIC - A Fast-Running Urban Airflow Model

- RUSTIC is a model that solves the equations of motion and includes a k-ω turbulence model as well as heat flux and stability effects.
- It's simplified implementation allows it to run in a reasonable time on an ordinary PC with only a single processor.



- For the most accurate solutions, run times for ~1 km square urban areas with 5 meter minimum grid cell size may require 8 - 24 hours (single PC).
- For quick "good-enough" solutions using the multi-grid technique run times can be reduced to the 0.5 - 1 hour range.
- Proposed CY07 ITT IR&D project will enhance MESO/RUSTIC speed.

RUSTIC: A Fast-Running Urban Airflow Model

Momentum Equation

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{1}{\rho} \nabla P - \vec{g} + \frac{1}{\rho} \left(\nabla \cdot \rho K_m \nabla \right) \vec{u}$$

$$K_m = \frac{k}{\omega}$$

k = Turbulence Kinetic Energy

ω = Dissipation Coefficient

k- ω Turbulence Equations

$$\frac{\partial k}{\partial t} = -u_j \frac{\partial k}{\partial x_j} + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[\left(\nu + \sigma^* \frac{k}{\omega} \right) \frac{\partial k}{\partial x_j} \right]$$

$$\frac{\partial \omega}{\partial t} = -u_j \frac{\partial \omega}{\partial x_j} + \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\nu + \sigma \frac{k}{\omega} \right) \frac{\partial \omega}{\partial x_j} \right]$$

$$\tau_{ij} = \frac{k}{\omega} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij}$$

RUSTIC: A Fast-Running Urban Airflow Model

Pressure Equation

Mass Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{U} = 0$$

+

Thermodynamic Equation
(no heat sources or sinks)

$$\frac{\partial \theta}{\partial t} + \vec{U} \cdot \nabla \theta = \frac{1}{\rho}\left(\nabla \bullet \rho K_H \nabla\right)\theta$$

Results in Pressure Tendency Equation

$$\frac{\partial P'}{\partial t} = -\vec{U} \cdot \nabla P + w\bar{\rho} g - \bar{\rho} c^2 \left(\nabla \cdot \vec{U} - \frac{1}{\bar{\rho}\theta}\left(\nabla \bullet \bar{\rho} K_H \nabla\right)\theta \right)$$

Speed of Sound

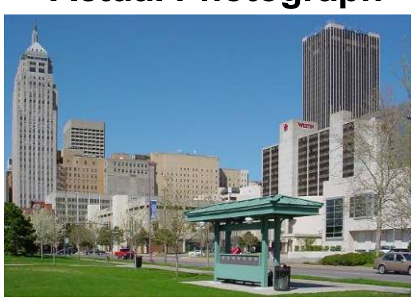
Note: $\rho = \rho' + \bar{\rho}(z)$

And for this model $\rho' \equiv 0$

RUSTIC Grid Generation Procedure

Bird's eye view of urban area building

Actual Photograph

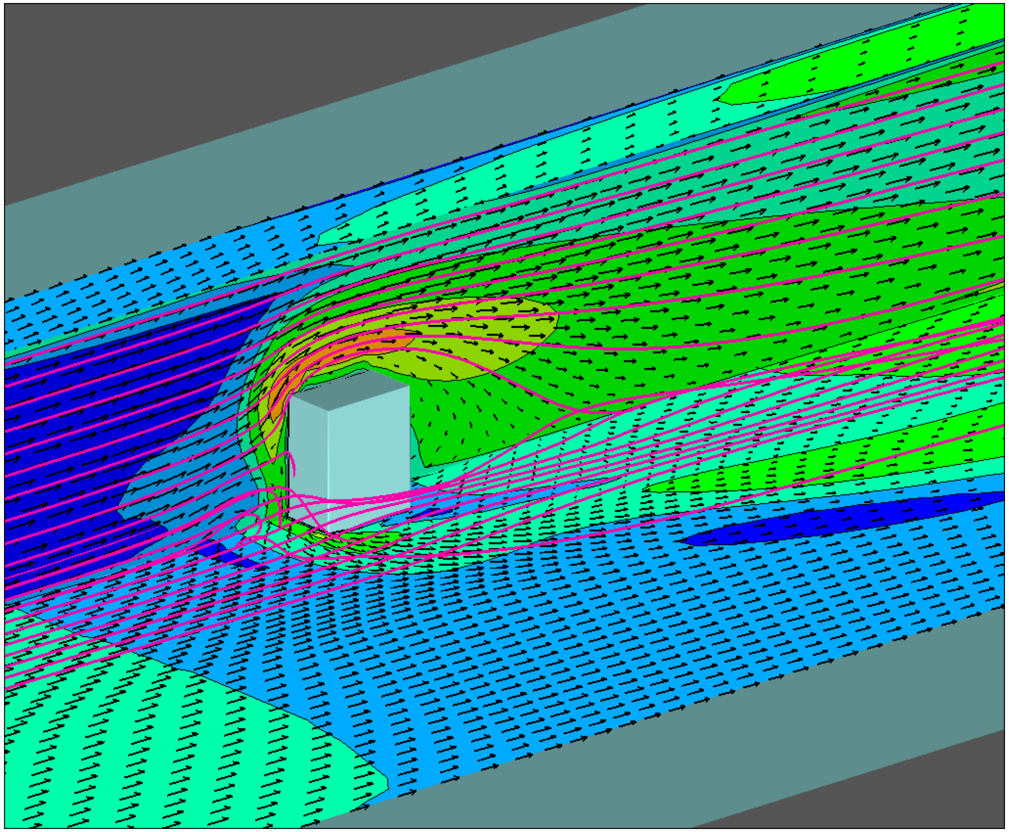


Automated RUSTIC

- Starting with terrain data as a DEM file the buildings are added
- Initial building data is in form of ESRI shape files containing a footprint outline with a roof height
- The footprints are sorted by roof top height to be processed one at a time from lowest to highest
- DEM file, 2-D array of elevations at 1 m resolution aligned with wind direction, is created for the city
- Finally the city DEM file is merged with model grid volume
- RUSTIC accepts eight (8) different terrain formats.

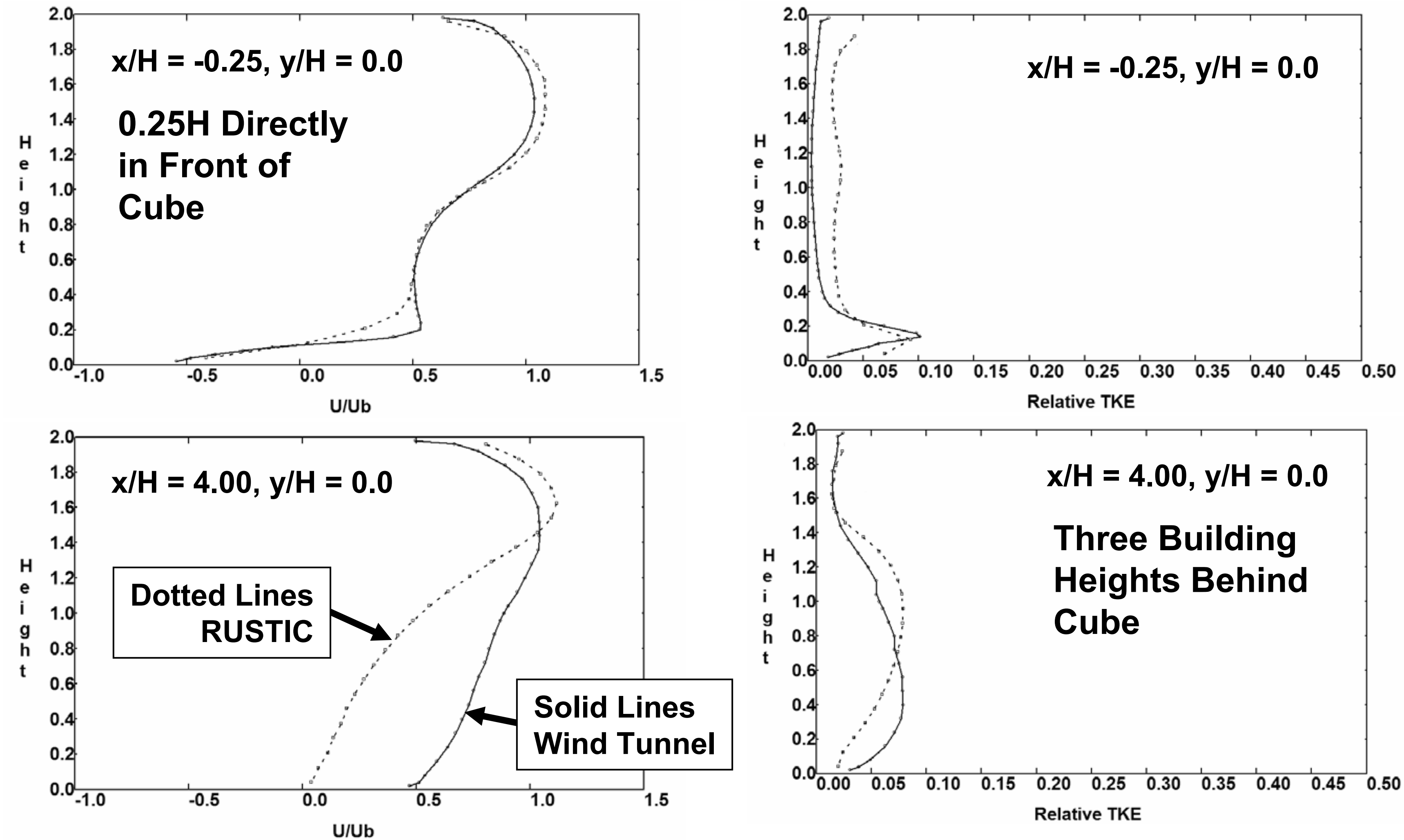
RUSTIC Validation Studies

- Comparison with wind tunnel measurements of flow around a cube in a channel (Martinuzzi and Tropea, 1993)
- Measurements were made of u,v,w velocity components and TKE
- RUSTIC simulation run to convergence using three different resolutions
- A simulation was also run for this scenario using a CFD model, ADVEDS_NS



Streamlines and wind vectors from RUSTIC simulation of flow around a cube in a channel. Contours are of TKE.

RUSTIC Comparisons with Martinuzzi and Tropea (1993) "Cube in a Channel" Wind Tunnel Data



H is building height, x/H=0.0 is upwind face of building and x/H=1.0 is downwind face of building, U is wind velocity, Ub is mean wind velocity and TKE is Turbulent Kinetic Energy.

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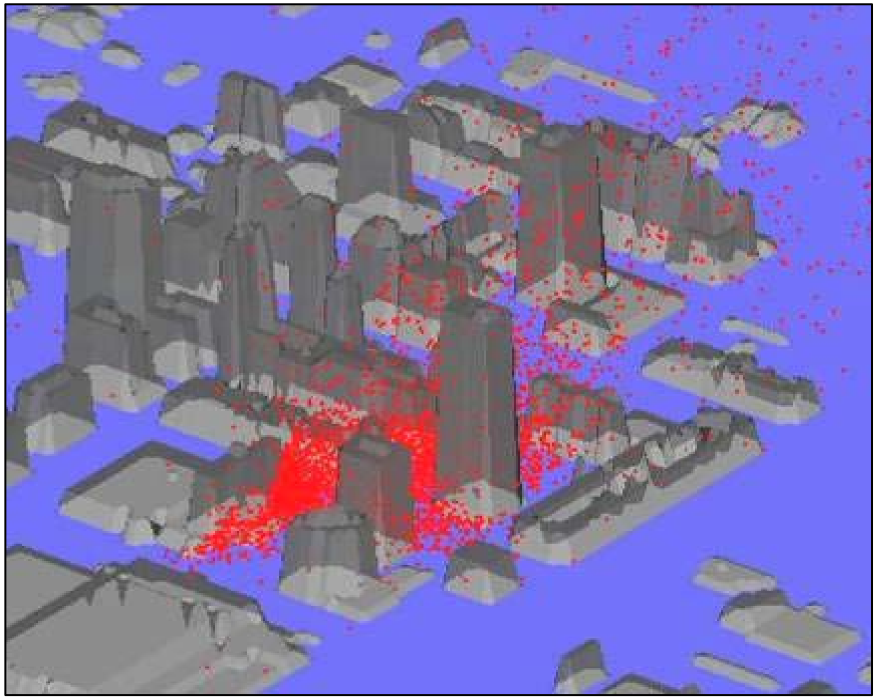
MESO Random-Walk Excursion Techniques for Accurate Dispersion

Random-Walk Tracer Techniques • First-Principles Physics • Not Based on Gaussian Puffs • No Grid or Numerical Instabilities • Excellent Spatial Resolution • Accurate Advection in Complex Terrain • Rapid Execution
3D Time-Dependent Wind Fields Over Rough Terrain
Spatially-Varying Surface Characteristics
State-of-the-Art Meteorology
Full Chem/Bio Capabilities
Dose/Deposition Variance
Urban Dispersion Capability



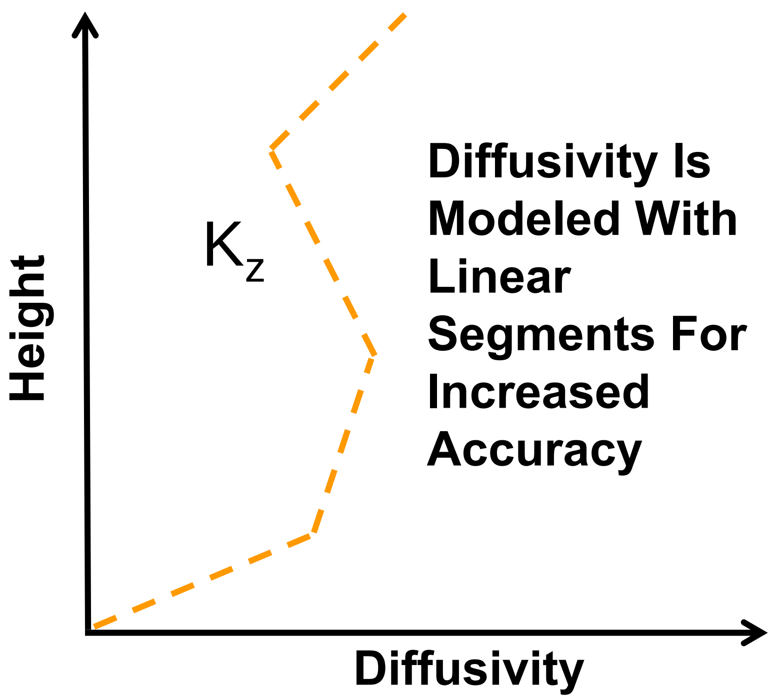
MESO/RUSTIC handles urban and rural cases

MESO Uses Random-Walk Tracer Techniques For Urban Dispersion

Random-Walk Technique: Diehl, et al. 1982, J. Applied Met., 21, 69-83.

- Rigorously meets well-mixed condition (i.e. no artificial drift)
- Numerically fast (single random bit per displacement)
- No grid required; good spatial resolution (1 to 4 m typical)
- Diffusivity is reduced for droplet inertia

Diffusivity: 3D Time-Dependent Turbulence Fields From RUSTIC



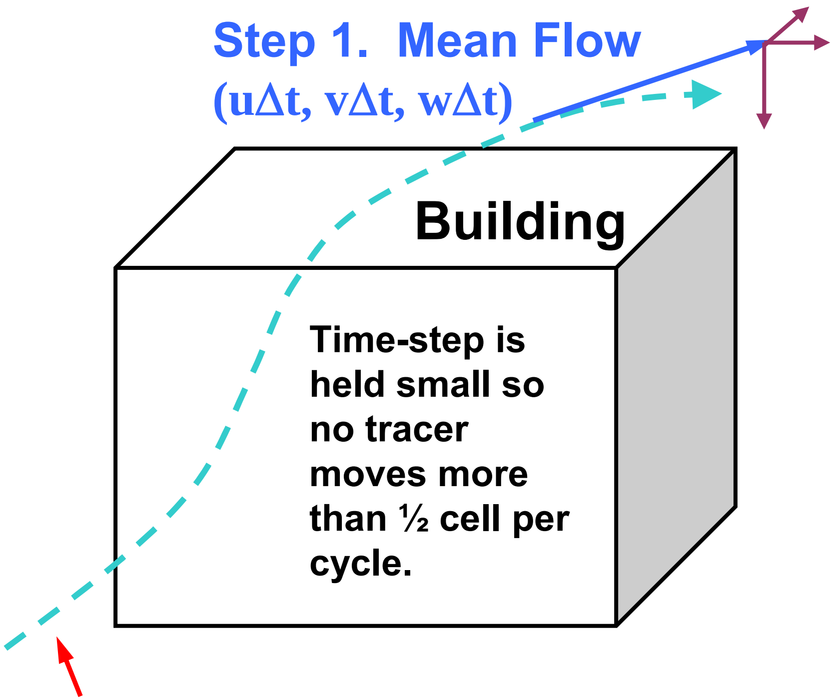
Scale-Dependent Dispersion

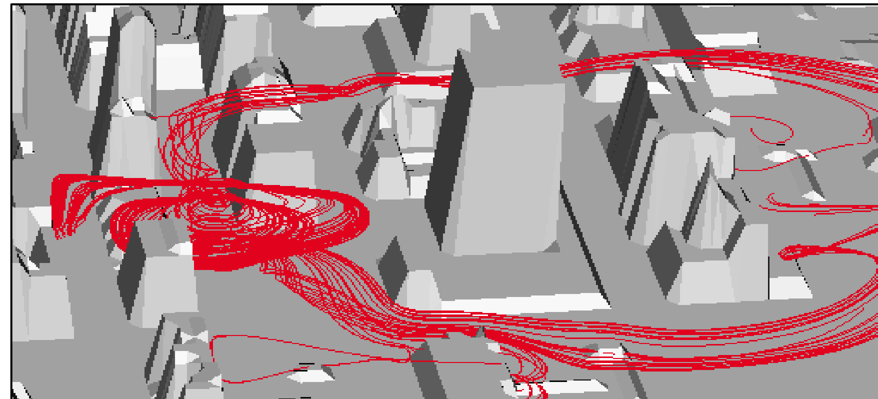
For Instantaneous Releases, i.e. Clouds, Scale-Dependent Techniques Are Required:

- Only turbulence scales smaller than cloud are included in the dispersion.
- Horizontal: Cloud divided into layers
- Vertical: Whole cloud

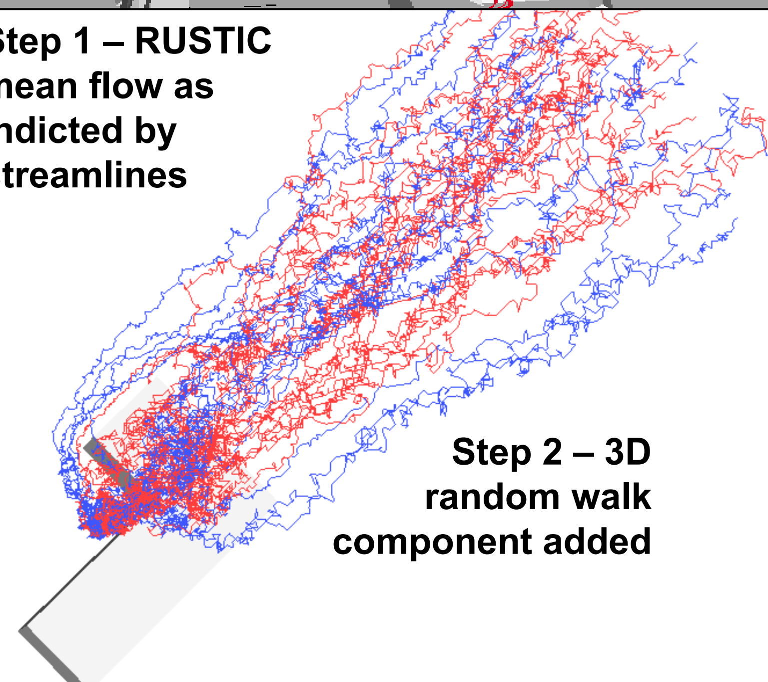
MESO Numerical Techniques: Turbulent Flow

MESO moves tracers with the mean flow and uses a random-walk process to represent the turbulent motion.





Step 1 – RUSTIC mean flow as indicted by streamlines



Step 2 – 3D random walk component added

MESO Capabilities Used for Accurate Transport and Dispersion

Heat Flux Models

State-of-the-Art Using Numerical Iteration Based On:

- Long and Short Radiation
- Cloud Cover (3 altitudes)
- Albedo vs Angle
- Wind Speed
- Surface Roughness
- Humidity
- **Surface Evaporation Resistance**
- Vegetation Thickness
- Validated with FIFE field data

Planetary Boundary Layer Model

Numerically Integrated Ahead in Time Based On:

- Sensible Heat Flux
- Wind Speed
- Potential Temperature Profile
- Surface Roughness z_o
- **Convective Boundary Layer Decay Model**
- **Dynamic 2nd-Order Closure CBL Model**

Turbulent Deposition

State-of-the-Art Algorithm Based on:

- Particle Size
- Wind Speed (u_*)
- Stability (L)
- Surface Roughness (z_o)
- Vegetation Characteristics (Filtration Effects)

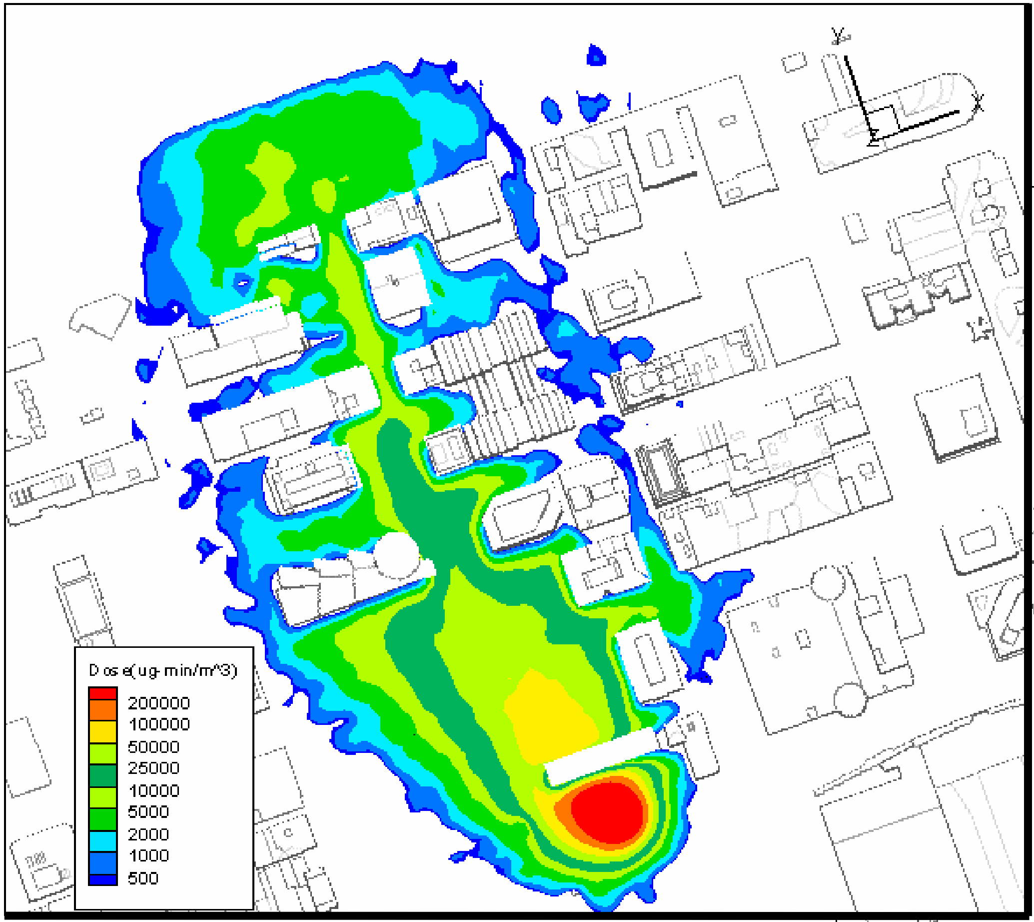
Chemical and Biological Agents

- Droplet Size Bins
- Auto Lognormal Size Distribution
- Evaporation With Vapor Feedback (Numerical First-Principle)
- Accurate Settling Velocity
- **Diffusivity Decreases with Droplet Size (Inertial Effect)**

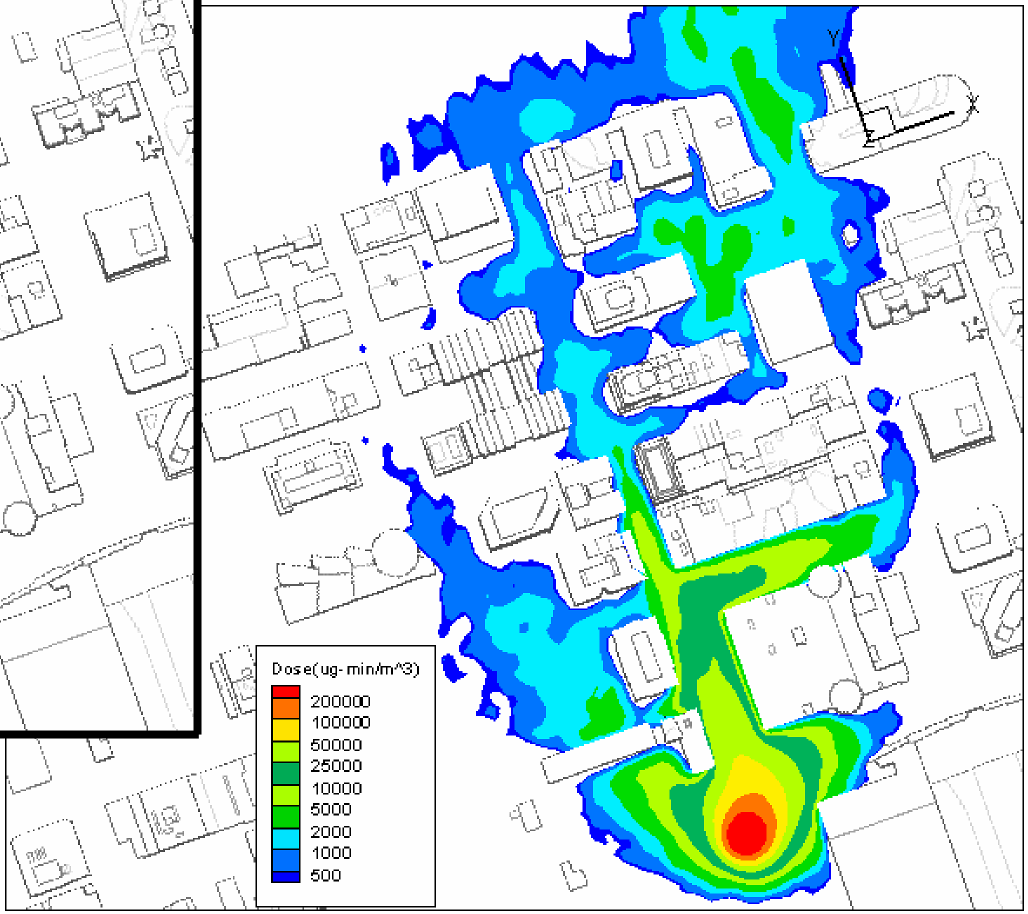
MESO Output

- Ground Deposition
- Dosage
- Concentration
- **Conditional Probability**

Why Higher-Fidelity Modeling is Especially Needed in the Urban Environment

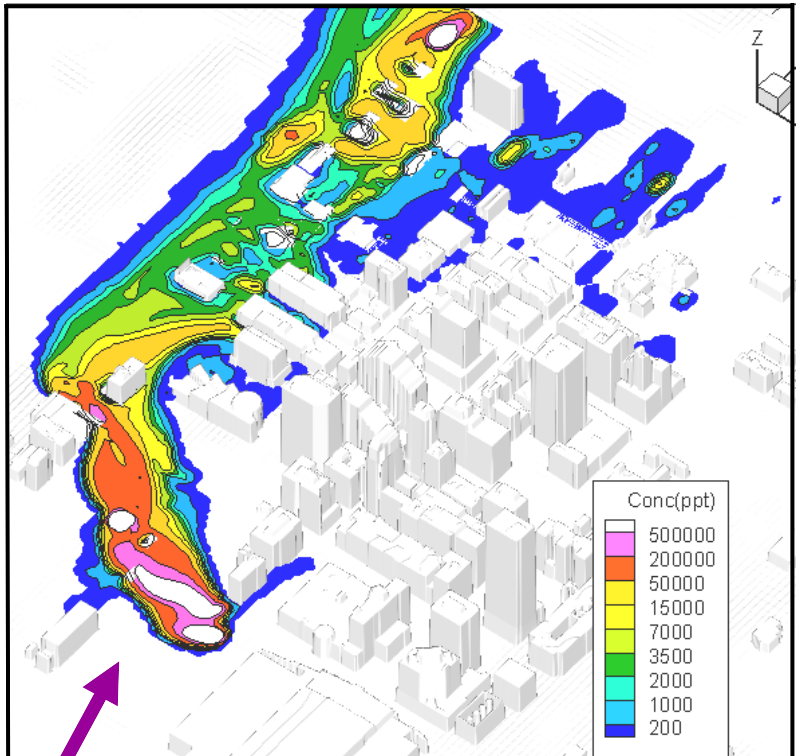


Small shift in the source location results in large shift in the hazard area.



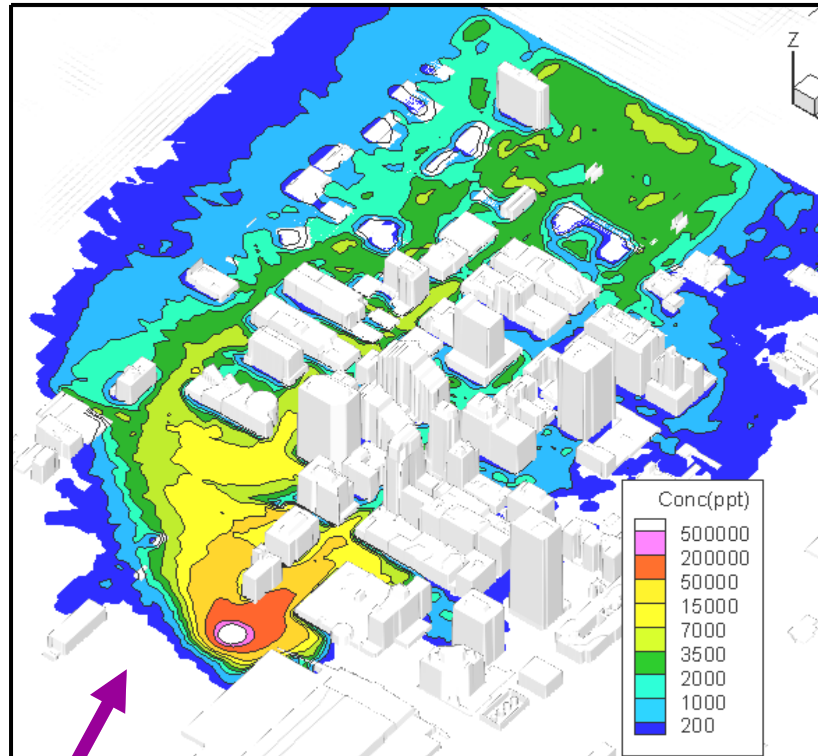
MESO / RUSTIC Simulations

Why Higher-Fidelity Modeling is Especially Needed in the Urban Environment



WD 170°

STABLE
Heat flux upwind: -30 W m^{-2}
Heat flux grid: -5 W m^{-2}



WD 170°

UNSTABLE
Heat flux upwind: 250 W m^{-2}
Heat flux grid: 50 W m^{-2}

Concentration levels vary greatly for different atmospheric stabilities

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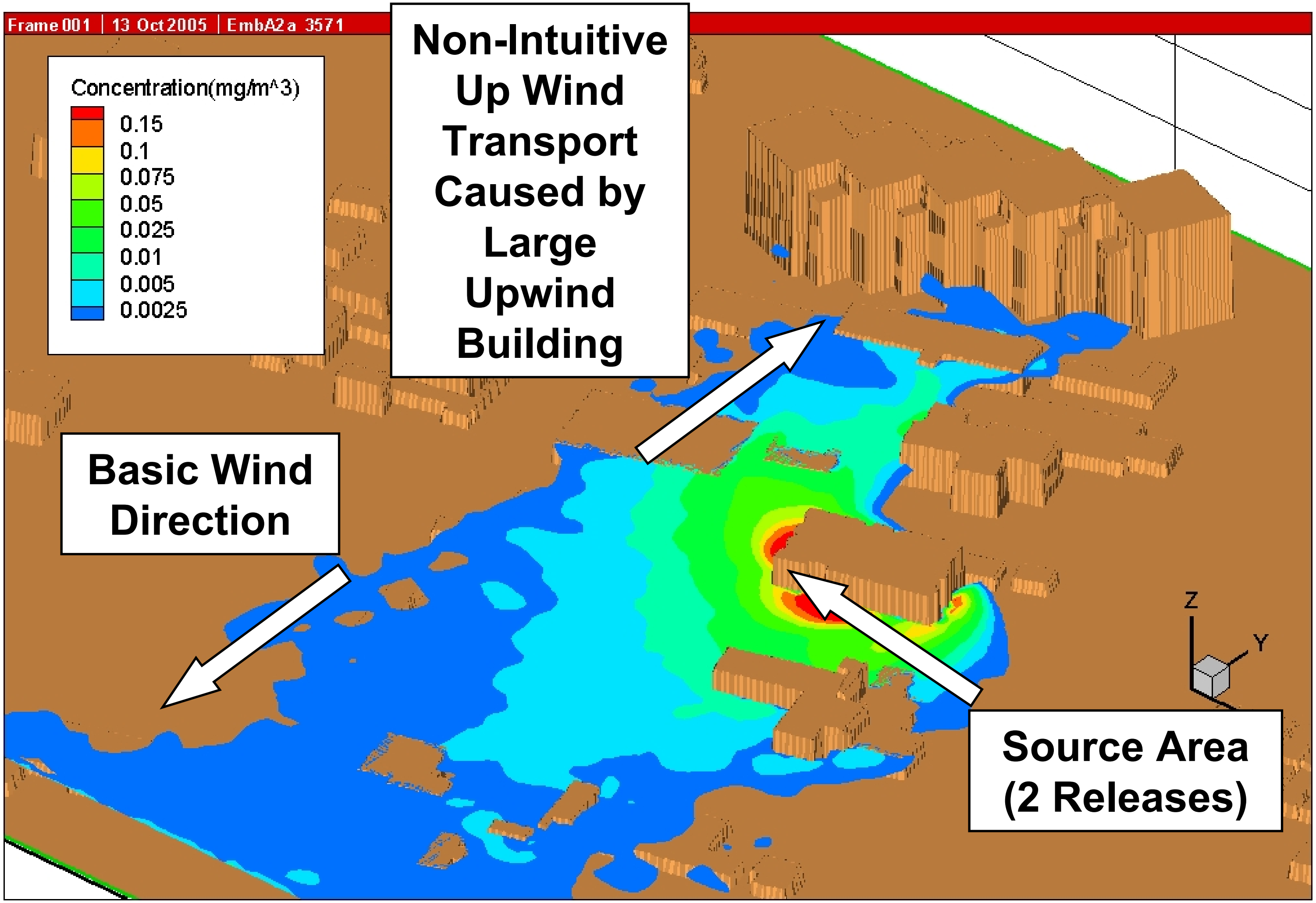
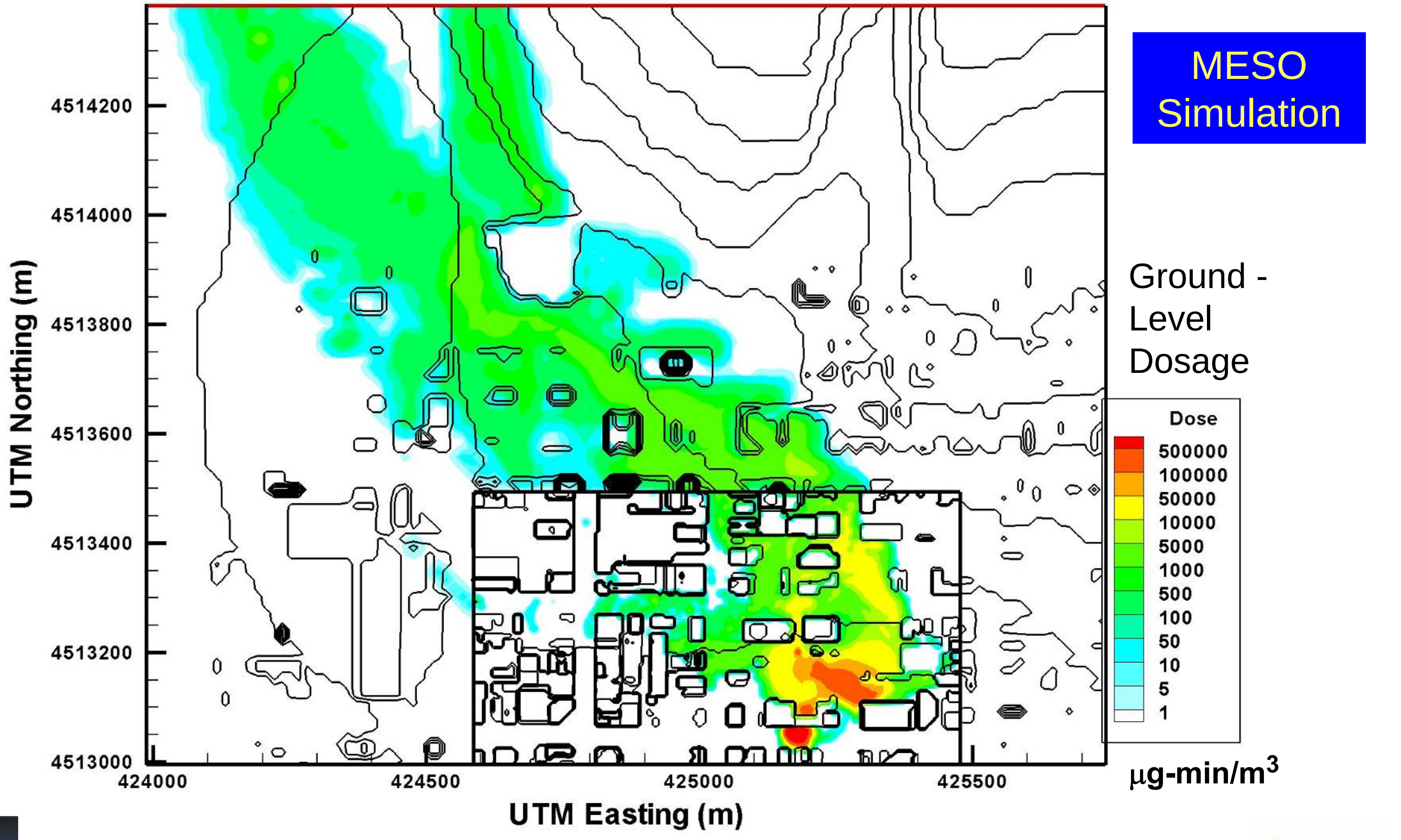
Why Higher-Fidelity MESO/RUSTIC is Especially Needed in the Urban Environment



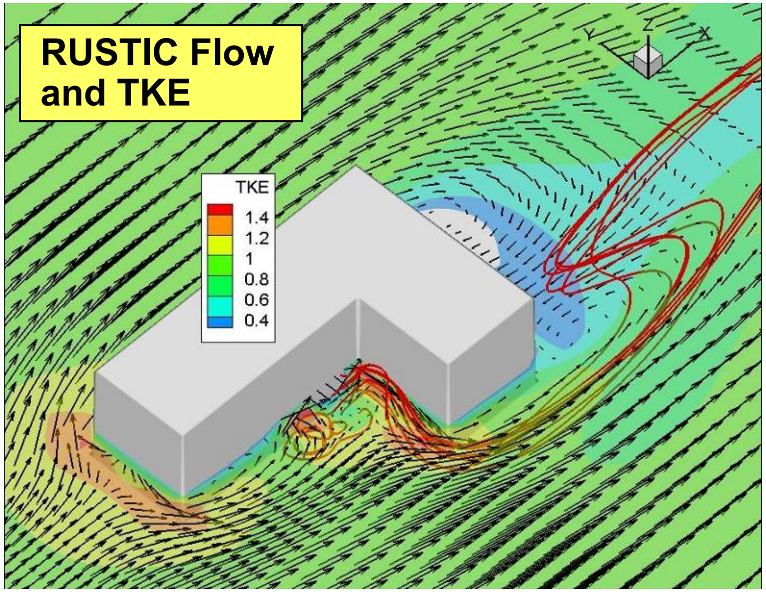
Preliminary Fine-to-Coarse Grid Simulations Give Detail Where Needed Most and Yet Remains Sensitive to Land Features

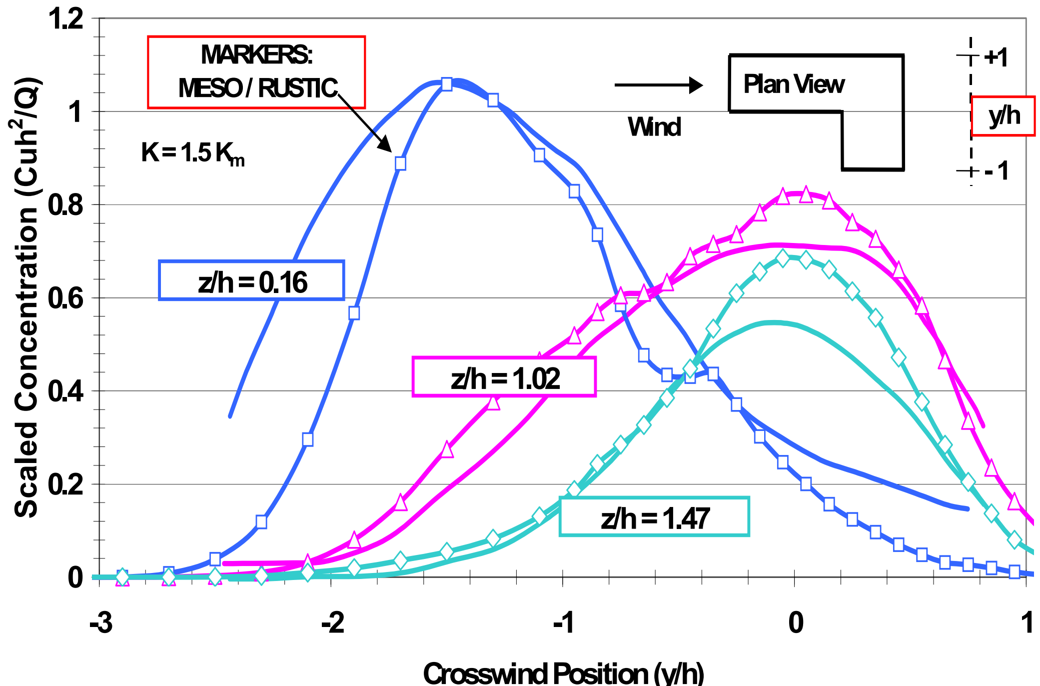
10 kg Instantaneous Release of 3 μm Particles in Salt Lake City

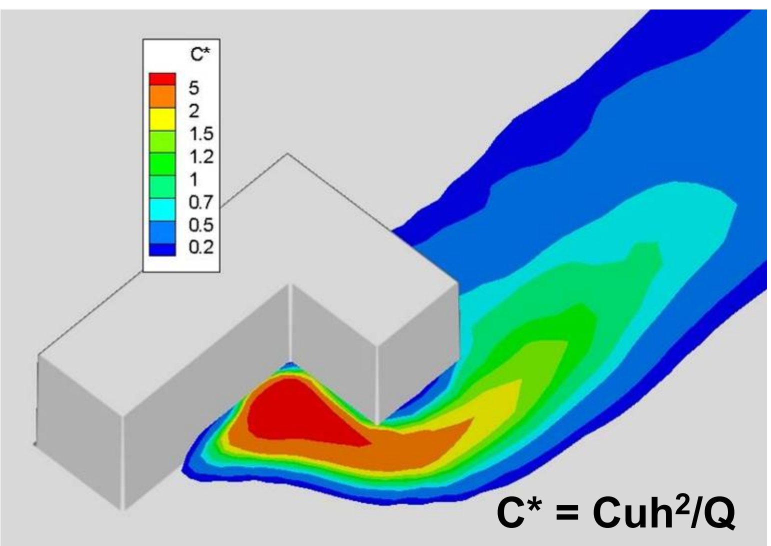


EMU Wind Tunnel Test Geometry for Case A1

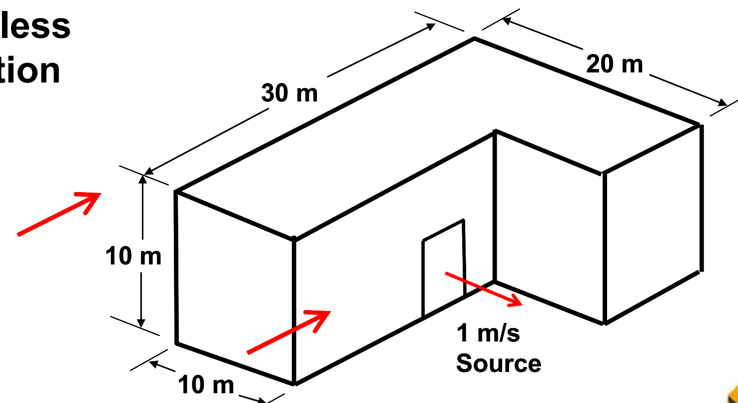
Cowan, I. R., I. P. Castro and A. G. Robins (1997 and 1999)







RUSTIC Dimensionless Concentration



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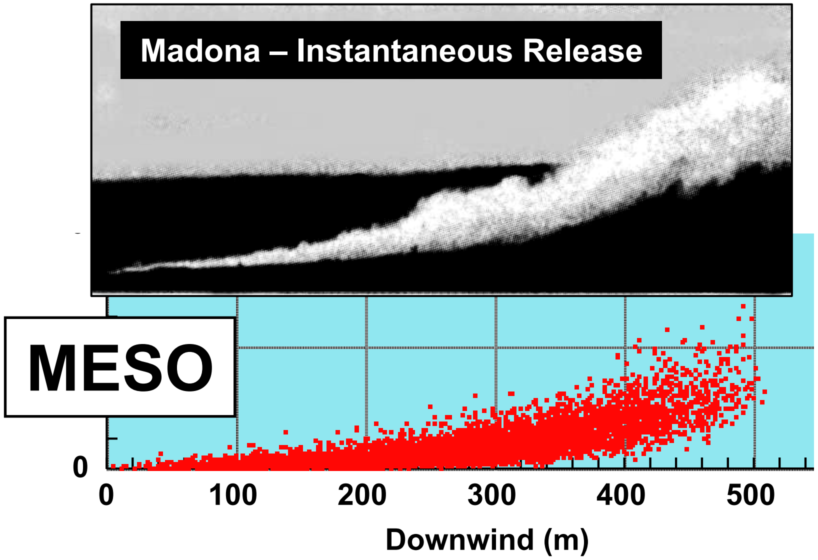
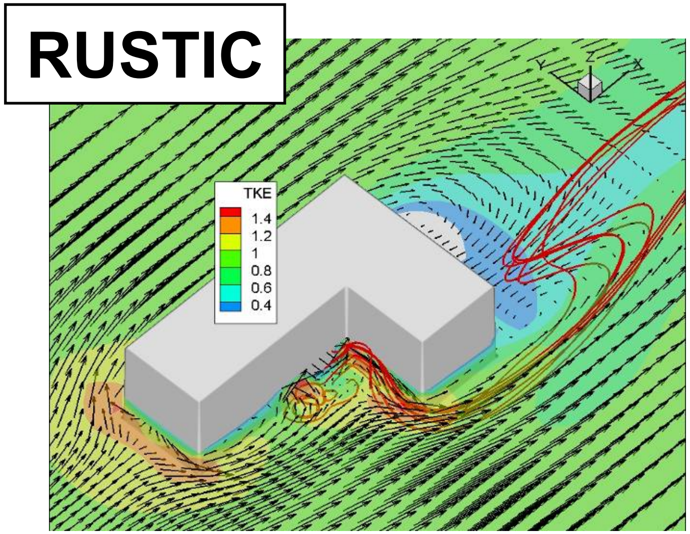
MESO and RUSTIC Validation Examples

- MADONA lidar data
- Optical cloud data
- Standard Short-Range Surface Releases
- High Stack Emissions
- Crystal Mist Test Data (High Altitude/PBL)
- Dugway Test Data (Surface Deposition)
- Pea Sooper (1.0 and 1.5 mm Beads)
- Numerous sub-model validation efforts

- Wind Tunnel Urban Testing
  - L-Shaped Building
  - Cube in a Channel
  - Parking Garage
- Joint Urban 2003 Oklahoma City Tests
  - Day and night releases
  - Instantaneous releases
  - Continuous releases





Joint Urban 2003 Field Program

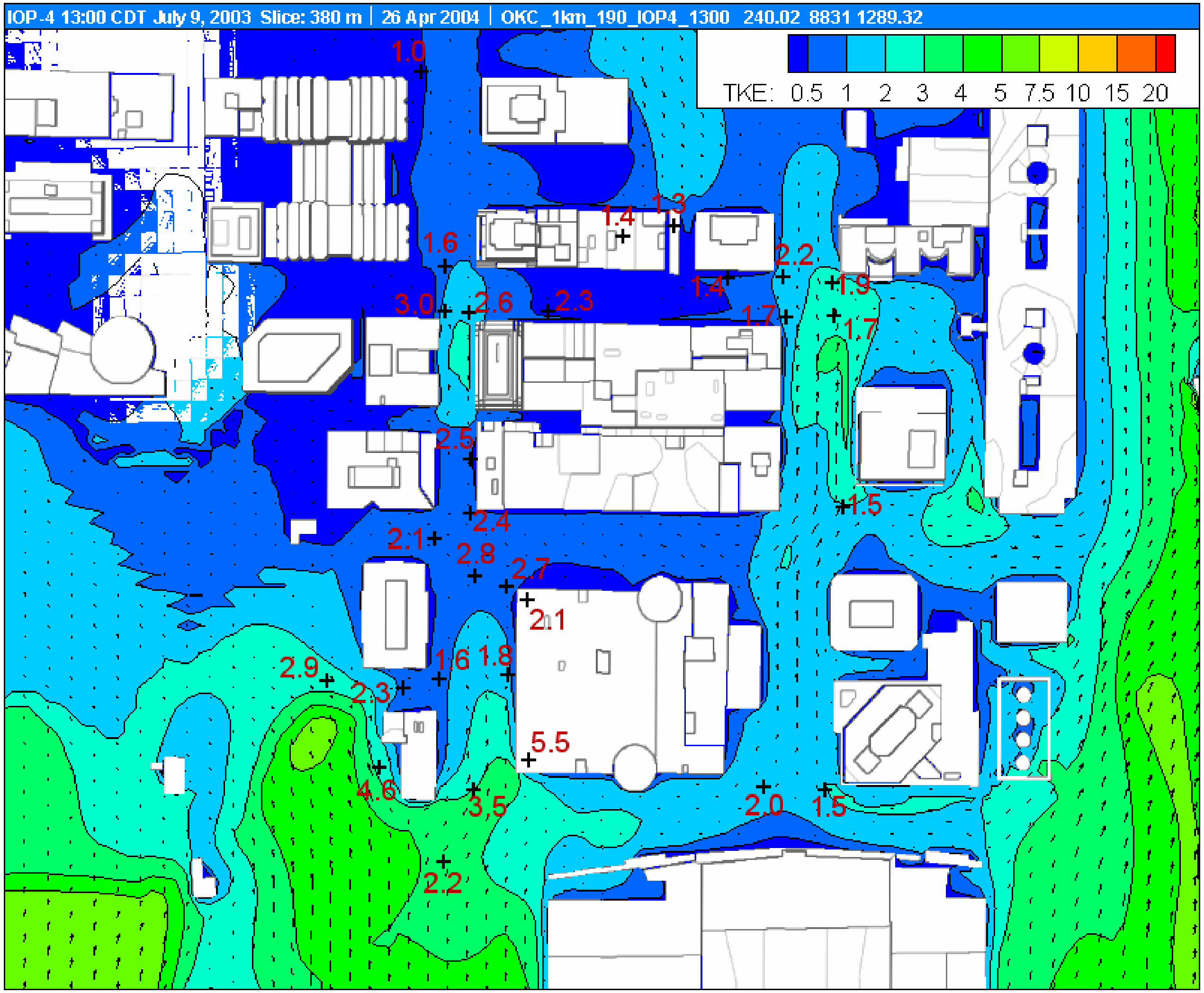
- **Joint Urban 2003 Atmospheric Dispersion Study – June 28th through July 31st, 2003**
  - Ten test events with releases of SF6 and other tracers
  - Detailed wind, turbulence, tracer concentrations and other meteorological measurements during test periods
- **DARPA provided ITT support for fielding**
  - Five (5) SF6 analyzers
  - Eleven (11) 3D sonic anemometer systems
- **Instrument manufacturing and delivery**
  - SF6 sensors manufactured by ScienTech
  - ITT built data acquisition and calibration systems
  - Campbell Scientific 3D sonic anemometer systems

July 2003 urban dispersion field test was in downtown Oklahoma City

DARPA ITT

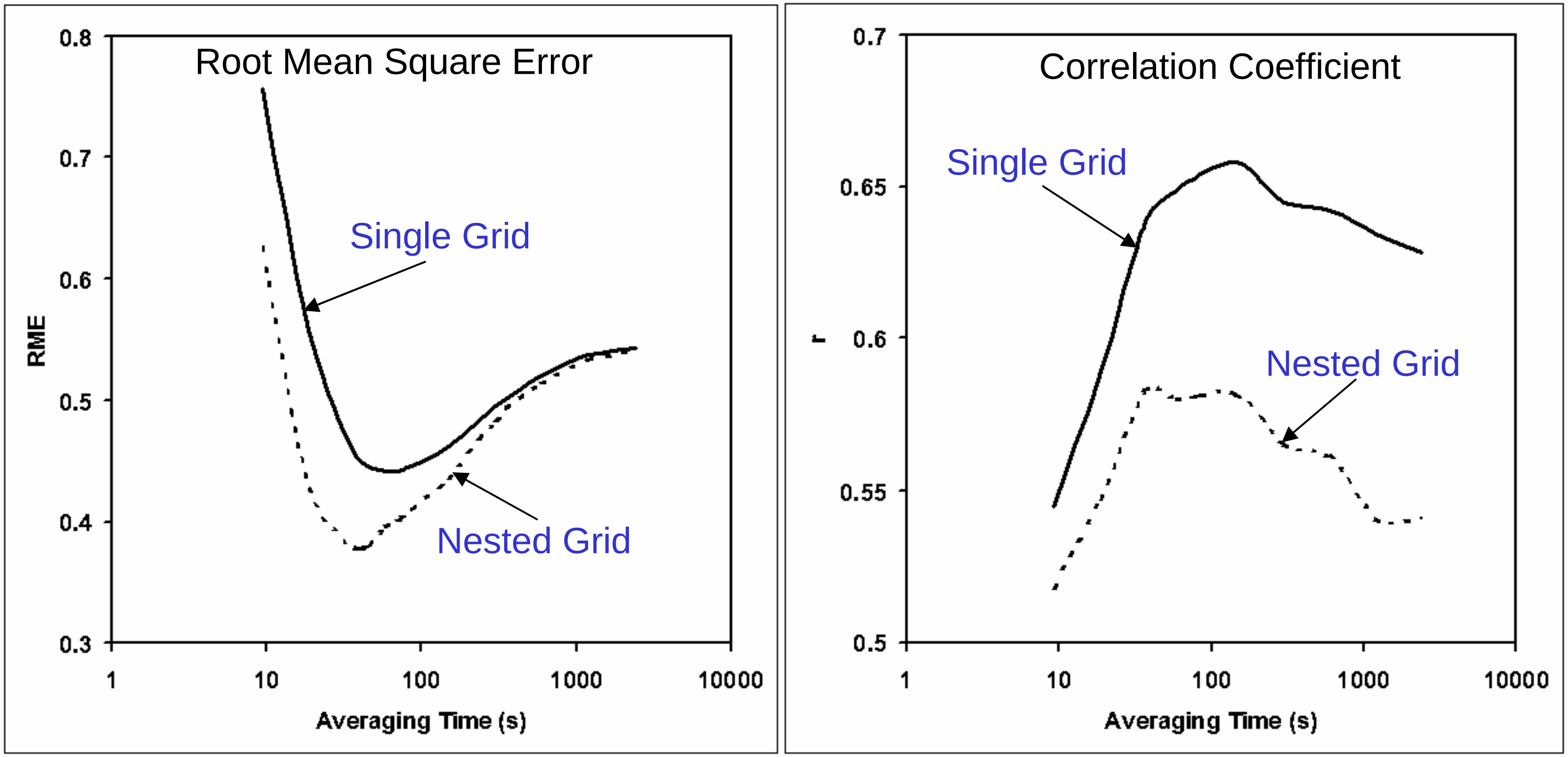
Unclassified

A Study of Turbulent Kinetic Energy produced by Buildings in an Urban Central Business District



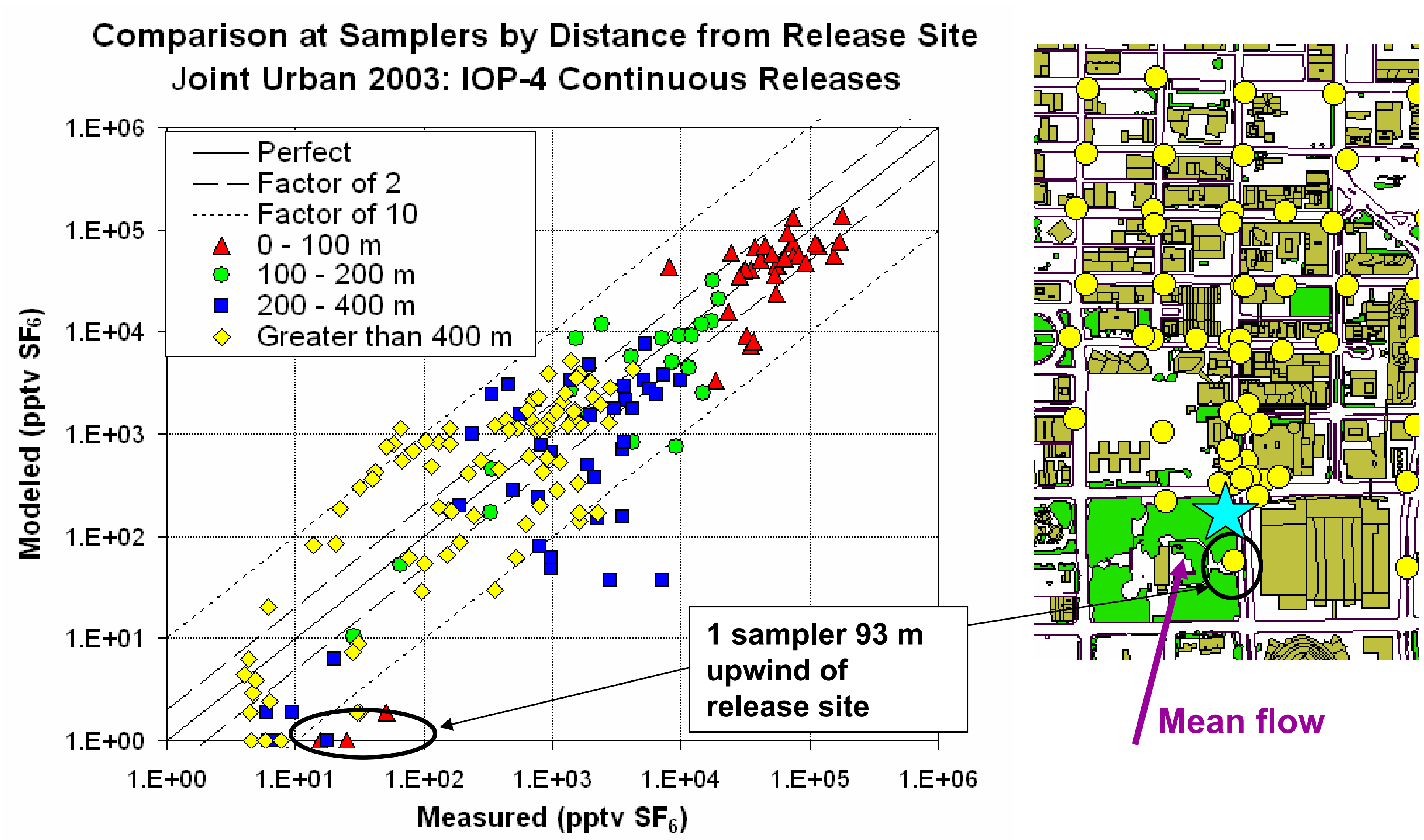
- **TKE contours for simulation for 13:00 - 14:00 CDT on July 9, 2003.**
- **Points are mean TKE measured by sonic anemometers.**

A Study of Turbulent Kinetic Energy produced by Buildings in an Urban Central Business District

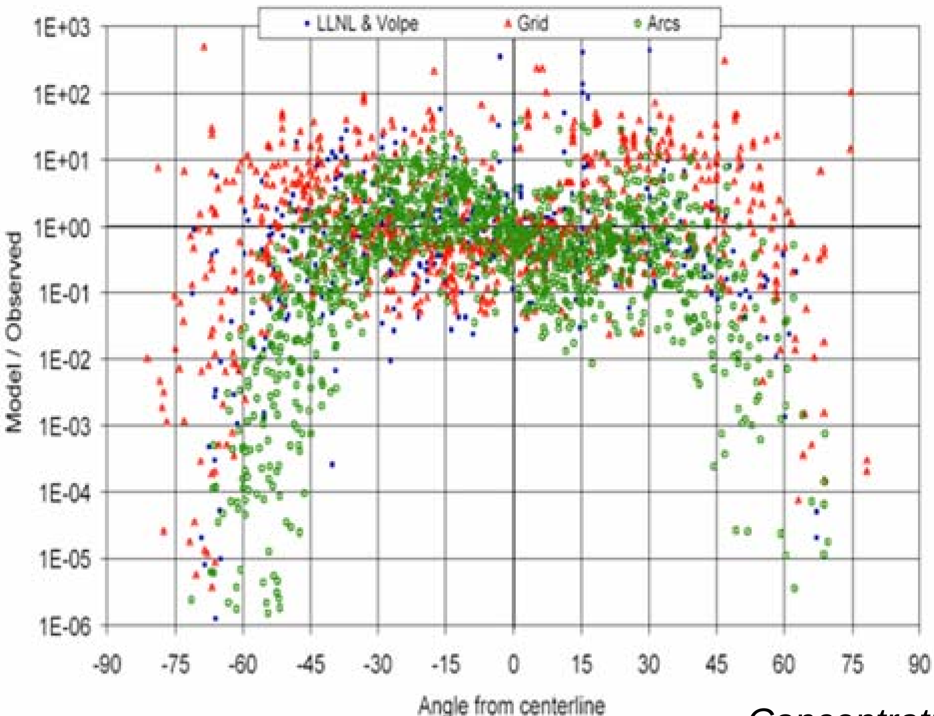


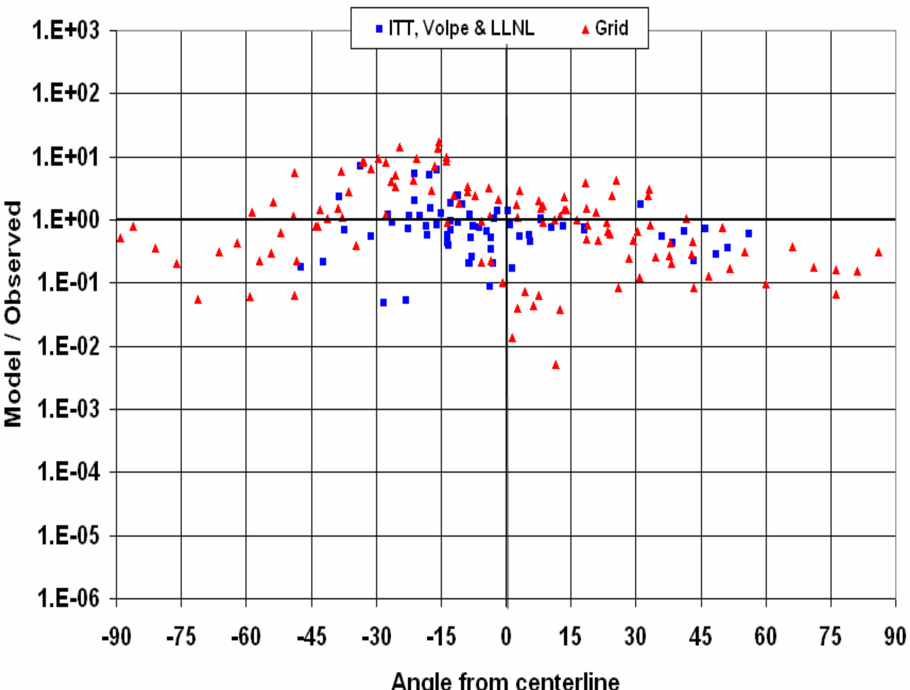
- **Little change in correlation between model and sonic anemometers for averaging times from 40 seconds to 2400 seconds.**
- **Slight peak for 150 second averaging period.**
- **RMS error was a minimum from 60 to 150 second averaging time.**

Validation of MESO/RUSTIC with Joint Urban 2003



Plume Centerline Comparison to Joint Urban 2003
Gaussian plume model vs. MESO/RUSTIC





Concentration Ratios Plotted
Perfect Correlation is on 1E+00 Line

Gaussian Plume model simulation of all continuous releases of Joint Urban 2003 (Gouveia, 2004, preprints from the AMS Fifth Symposium on the Urban Environment)

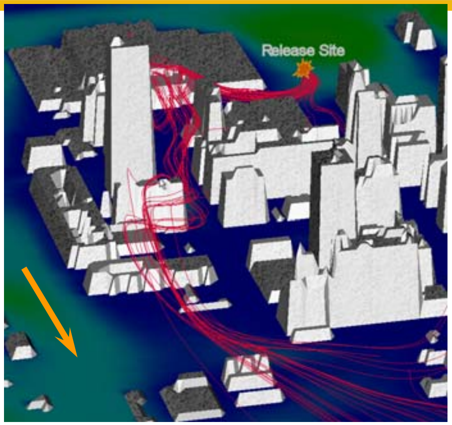
MESO/RUSTIC simulation of the three continuous releases of IOP-4

Improving RUSTIC for Coastal, Ocean and Rolling/Rough Terrain Areas (II.B.2.b) PI: Dr. Donald Burrows, ITT Corporation

<u>Objective</u>: To make major modifications to the existing RUSTIC flow code to permit fast high-fidelity predictions of dispersion in rolling/mountainous areas, coastal areas, and the open ocean.

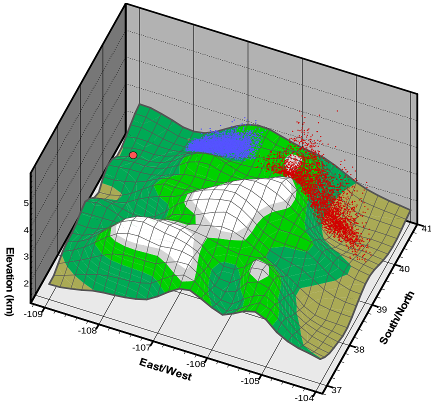
<u>Description of Effort</u>: Although very fast at modeling urban flow, RUSTIC can be modified to accurately model the objective stated areas requiring up to a 4-5 km thick boundary layer.

ITT will leverage the advanced NSWC second-order-closure (SOC) boundary layer model by adding it to RUSTIC. ITT will develop a heat flux model for water surfaces. Both are significant efforts. A large part of the project will be validation and documentation.



Streamlines Predicted by RUSTIC in OK City. Turbulence Produces Complex and Non-intuitive Flow (above).

The MESO simulation of the western ¾ of Colorado based on COAMPS (below) will be done by RUSTIC with SOC.



<u>Benefits to Warfighter</u>: Highly accurate estimates of hazard regions in rolling/mountainous areas, coastal areas, and the open ocean.

<u>Challenges</u>: Major modifications are needed to incorporating the SOC model into RUSTIC in a manner that keeps RUSTIC a fast tool.

<u>Maturity of Technology</u>: TRL 4-5. Both RUSTIC and the SOC boundary layer model are reasonably mature.

<u>Capability Area</u>: 2. Modeling & Simulation
b) Chemical/Biological Weapon Environment Prediction

<u>Major Goals / Milestones by FY:</u>

FY06 – Restructuring RUSTIC, installation of SOC model

FY07 – Develop surface heat flux model for water, code testing and verification, speed enhancements

FY08 – Documentation and validation

Could be integrated into ITT submittal E1. Different scopes can be made to accommodate tech-base needs.

<u>PI contact info</u>: Dr. Donald Burrows (719) 599-1840
don.burrows@itt.com

Coastal and Rolling RUSTIC Upgrades
JSTO Sponsored Tech Base Effort Begun in FY06

A. **Increase area of coverage to tens of kilometers with a few hundred meters resolution**

B. **Modify RUSTIC to apply to areas with significant terrain in proximity to large bodies of water. ("Coastal and Rolling" RUSTIC)**

C. **Allow nesting of grids to provide detailed coverage of local areas with resolutions of a few meters**

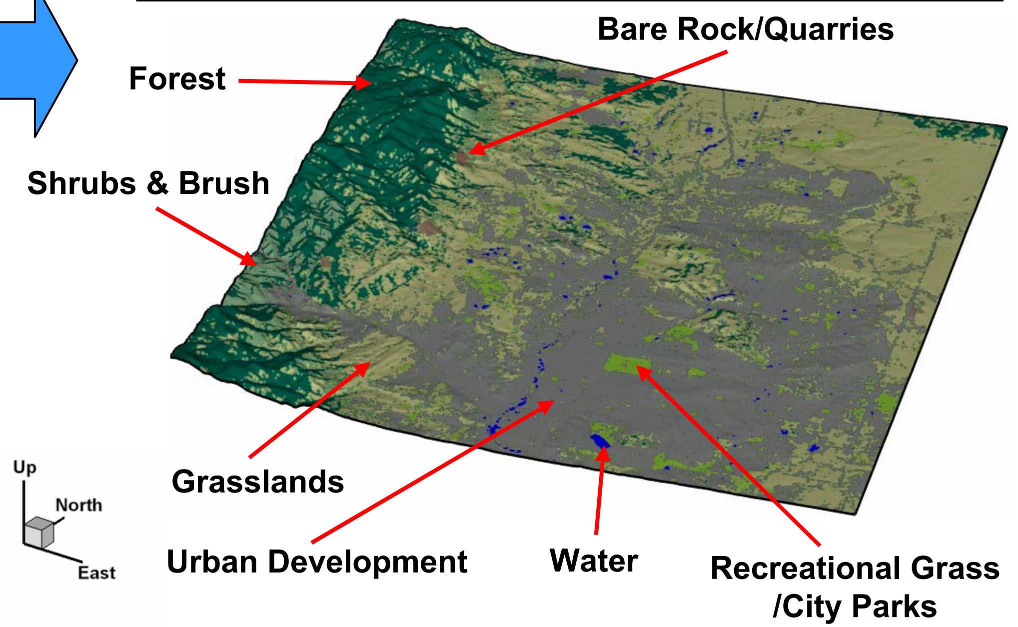
D. **Goal is for RUSTIC to be initialized from a mesoscale forecast model and provide accurate wind predictions for areas of hundreds of sq km down to areas of less than 1 sq km.**

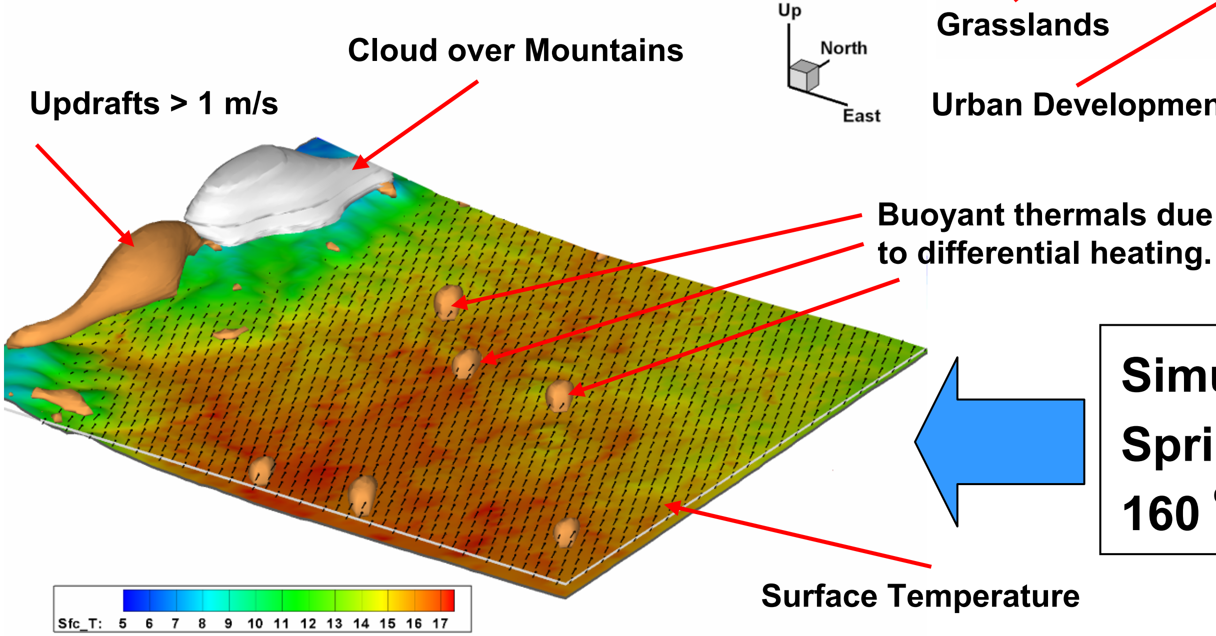
New York City Metro Area

RUSTIC Capabilities Recently Added for JSTO Tech Base Effort

1. **Now uses 30 m resolution Land Cover data to describe surface characteristics.**
2. **A complete thermodynamic equation has been added.**
3. **Moisture physics has been added.**

National Land Cover Data – Colorado Springs





Simulation for Colorado Springs area with winds from 160 ° on a 20 km x 20 km grid

Unclassified

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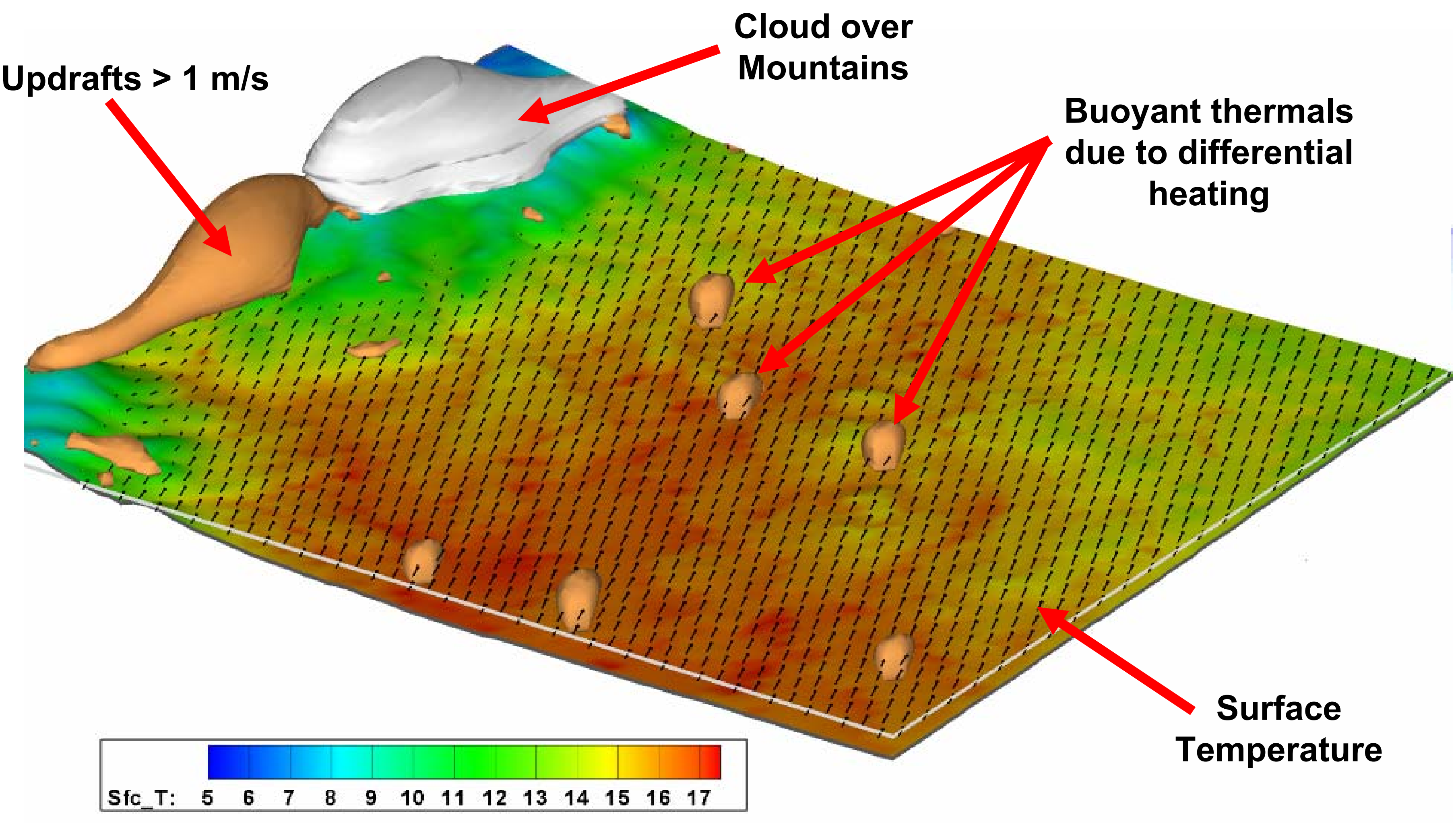
Recent RUSTIC Simulation for Colorado Springs Area for JSTO Tech Base Effort

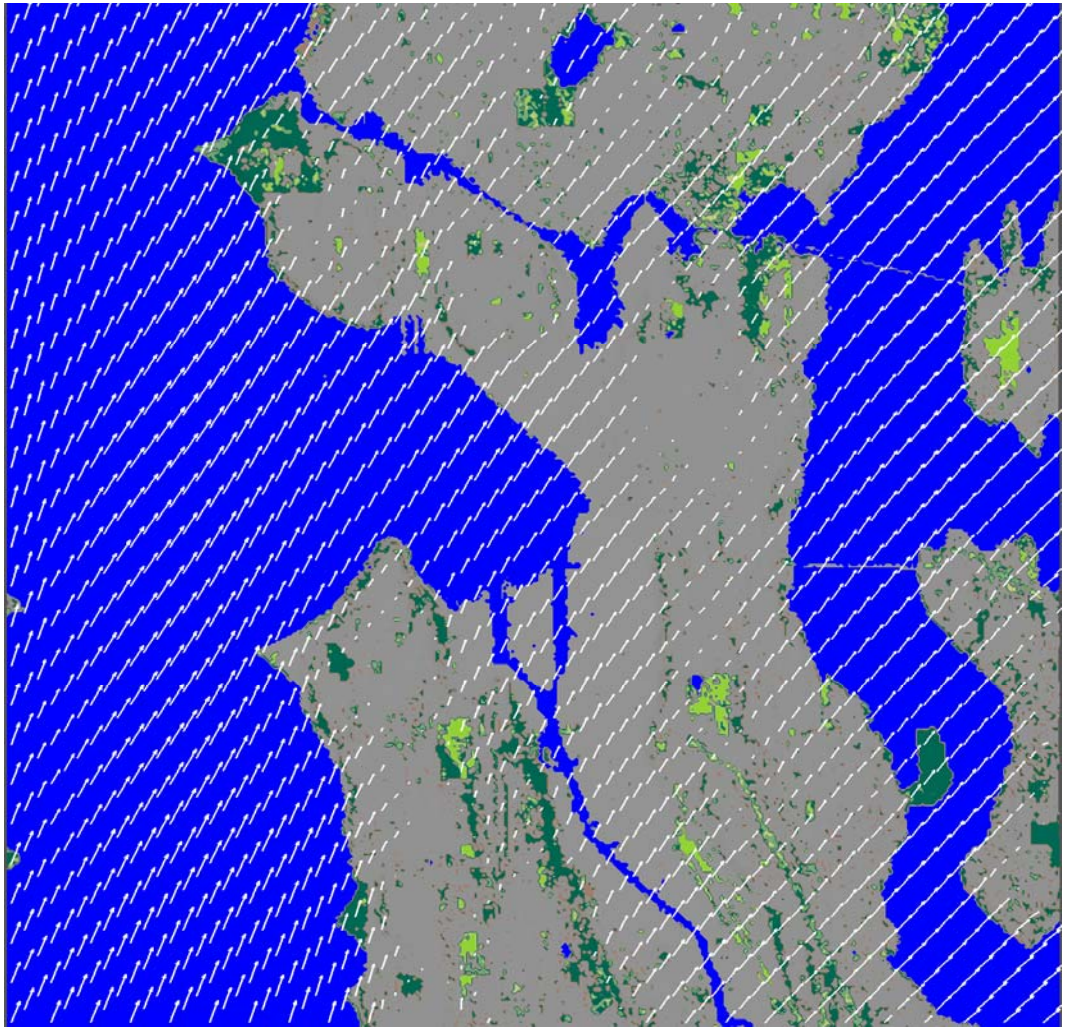


Winds from 160^{o} on a 20 km x 20 km grid

RUSTIC Capabilities Recently Added for JSTO Tech Base Effort

4. **Added:** The ability to make short range forecasts from mesoscale model inputs.
5. **Adding Soon:** The ability to update the boundary conditions as they change with time.

Example initialized from MM5 output
10 minute wind forecast for 100 m above sea level
2010 UTC
26 May 2006



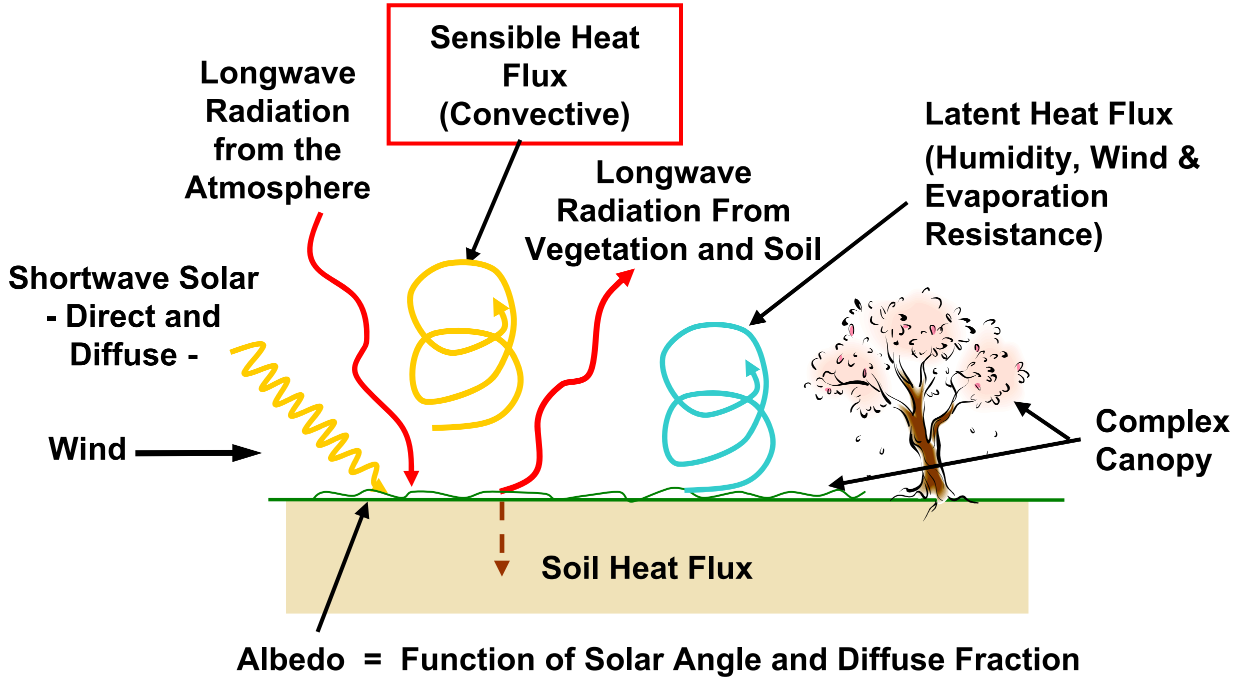
RUSTIC Upgrades in Progress for JSTO Tech Base Effort

6. Currently we are in the process of replacing the k-ω turbulence model with a Mellor-Yamada (1975) level 3 turbulence closure model.

7. The level-3 scheme employs prognostic equations for turbulence kinetic energy, k, and the mean magnitude of the temperature fluctuations, $\theta'^2/2$. Diagnostic equations are then solved for the moments: u'u', u'v', u'w', v'v', u'w', w'w', u'θ', v'θ', w'θ'.

8. The main coding of this algorithm into RUSTIC has been accomplished and debugging and verification of the code is in progress.

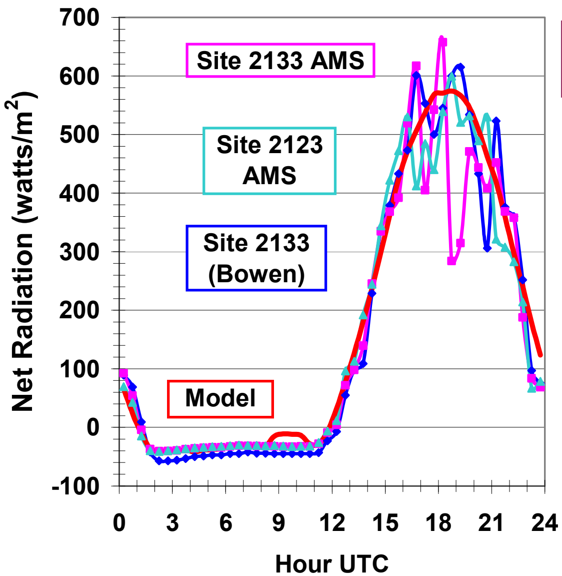
Future RUSTIC Upgrades Planned for JSTO Tech Base Effort



Heat Budget : *Solar (1 - albedo) + LWin - LWout = Net Radiation = Latent + Sensible + Soil*

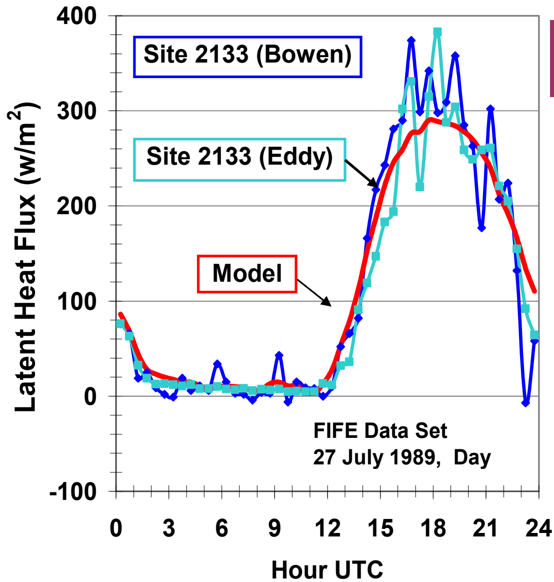
9. **MESO has a sophisticated Heat Flux Model that is currently used with RUSTIC. The capability will be added to accurately model the heat flux over ocean surfaces**

MESO's Rigorous Heat Flux Model Compares Well with Data – Model for Water Will be Added to RUSTIC

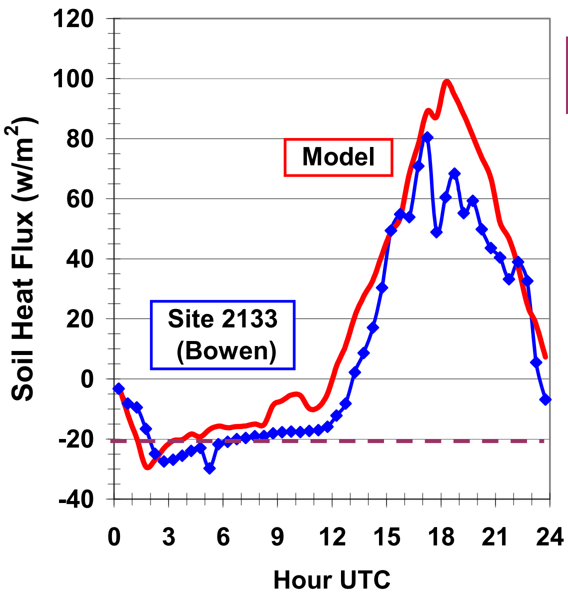


Net Radiation

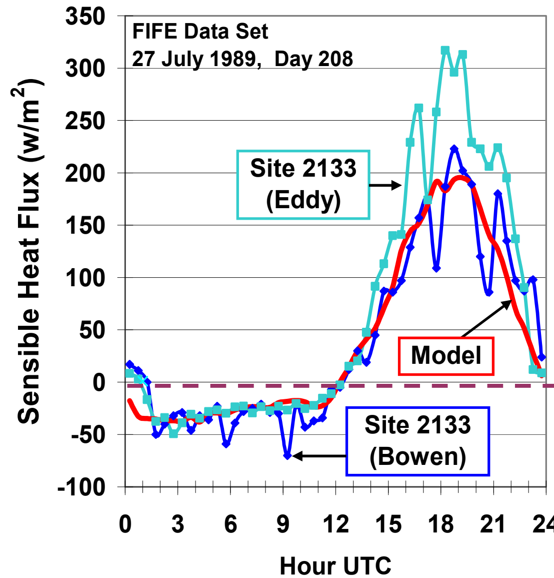
27 July 1989
Day 208



Latent



Soil

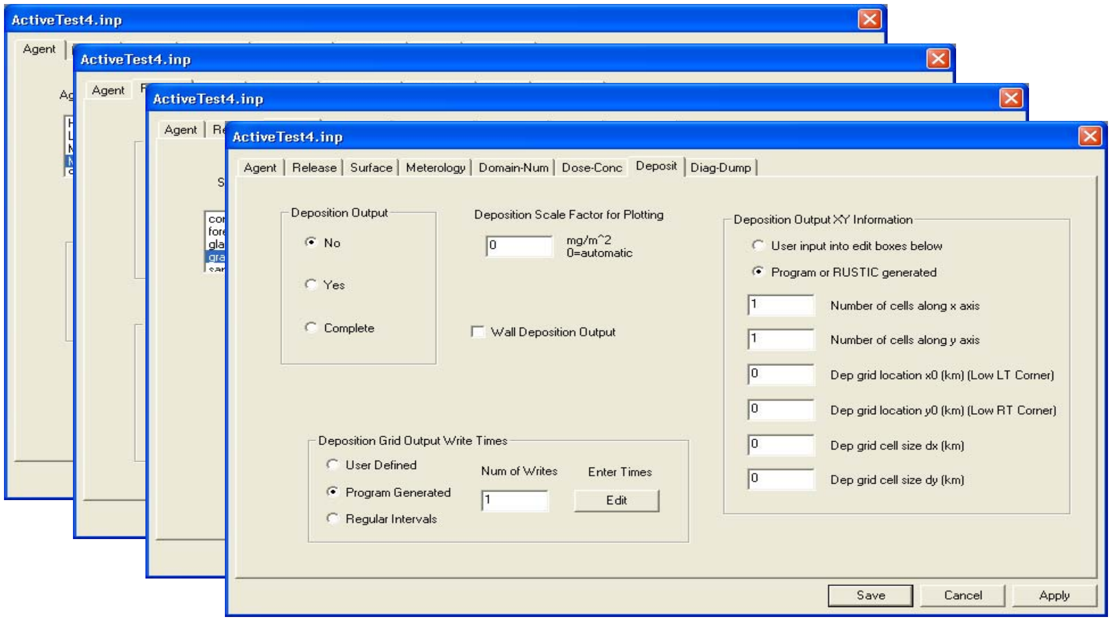


Sensible

Unclassified

RUSTIC Upgrades Coming Next

- An API for MESO/RUSTIC was developed for MESO/RUSTIC as a part of the DARPA BPTK program.
- MESO/RUSTIC has been integrated with the Building Protection Tool Kit (BPTK) and is now being integrated with Dugway's NCBR code.
- A MESO/RUSTIC GUI that utilizes the API is nearing Beta release.



10. **<u>The new JSTO "Coastal and Rolling" version of RUSTIC will be incorporated in to the MESO/RUSTIC GUI</u>**

Recent Papers Accepted For Publication in Journal of Applied Meteorology and Climatology Joint Urban 2003 Special Issue

1. **Modeling Turbulent Flow in an Urban Central Business District.** D. A. Burrows, E. A. Hendricks, S. R. Diehl, R. Keith.

2. **Urban Dispersion Modeling: Comparison to Single-Building Measurements.** S. R. Diehl, D. A. Burrows, E. A. Hendricks, R. Keith.

3. **Evaluation of a Fast-Running Urban Dispersion Modeling System with Joint Urban 2003 Field Data.** E. A. Hendricks, S. R. Diehl, D. A. Burrows, R. Keith.

End of Presentation

Any Questions?