Use of Turbulence Measurements in Dispersion Model Applications

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Dispersion Models for Applications

- Applications
  - Air quality: surface concentrations, AQ stds
  - National security: hazard zones, evacuation plans
- Model attributes
  - Numerically simple for fast turnaround
  - Capture essential physics of PBL & dispersion
  - Ensemble-average approaches (mostly)
- Development and testing
  - Lab & numerical (LES) simulations, field observations
- Use of turbulence measurements
  - Turbulence statistics input for dispersion (not much & why)
  - Develop turbulence parameterizations
  - Forcing in high resolution models (e.g., LES)

Model Types

- Simple analytical, statistical
  - Probability density function (PDF) models, Gaussian plume
    AERMOD, SCIPUFF
- Lagrangian particle models
  - Stochastic displacement (NARAC)
  - Stochastic velocity (QUIC)
- Large-eddy simulations
  - Lagrangian particle
  - Diffusion equation
- CFD RANS approaches
- Eulerian grid models

Outline

- Background
  - Plume behavior, statistical theory, PBL parameterization
- Convective boundary layer
  - PDF model
  - NARAC/LLNL (eddy diffusion)
  - Lagrangian particle model with LES
- Urban boundary layer
  - LES with real-time winds/turbulence (FEM3MP)
- Stable boundary layer
  - Lagrangian particle model with LES

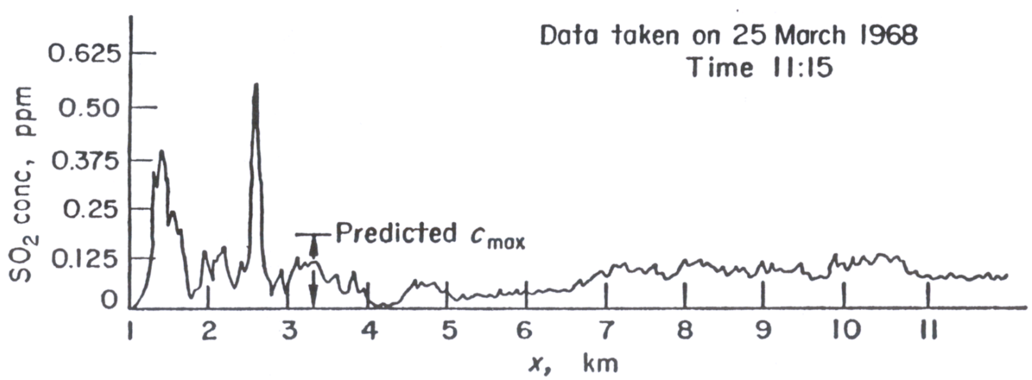
Dispersion in the Planetary Boundary Layer (PBL)

Convective boundary layer (CBL)

Figure 14. Keystone plume, May 25, 1968, 1047 EST.

Stable boundary layer (SBL)

Surface concentrations from above case

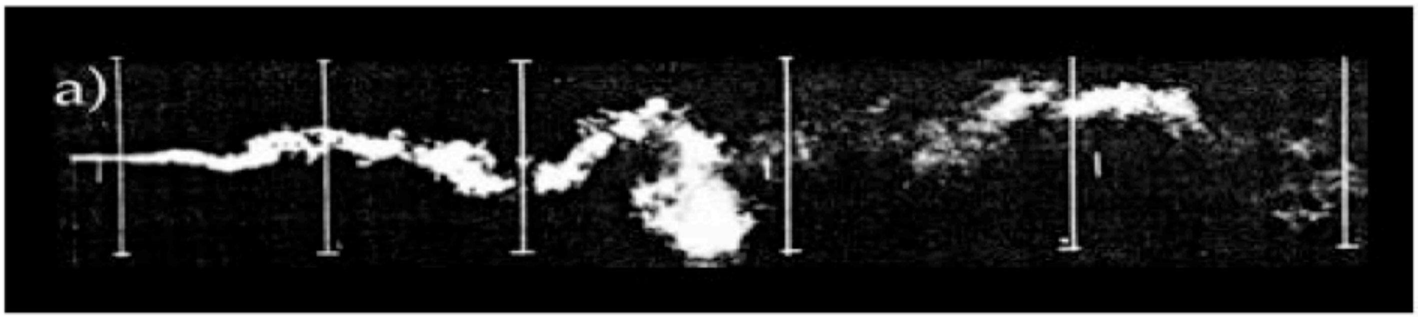


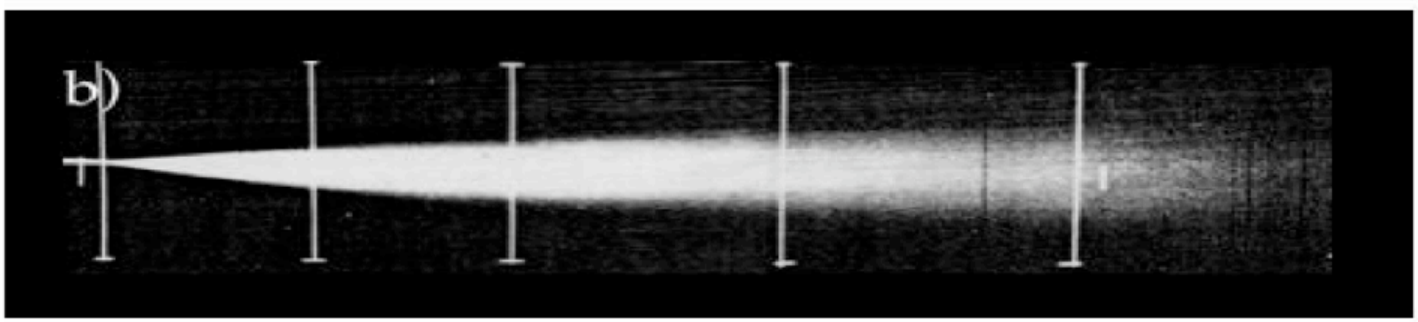
Effect of Averaging on Dispersion

(From EPA Fluid Modeling Facility)

Smoke visualization downstream of a point source in a wind tunnel with turbulent flow

Instantaneous plume (short-time exposure)

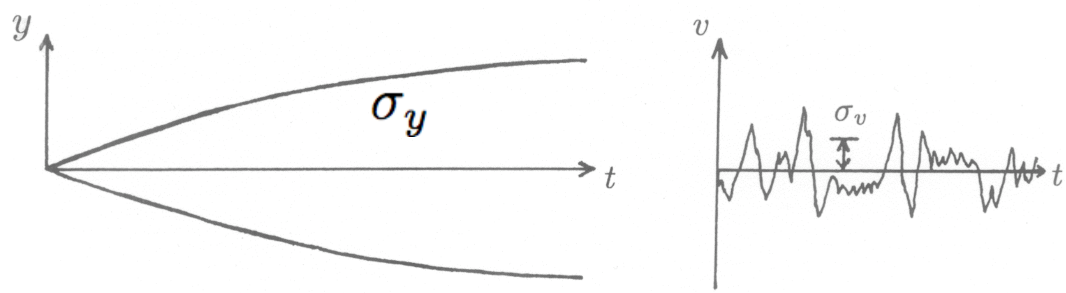




Ensemble-average plume (long-time exposure)

Statistical Dispersion Theory (Taylor, 1921)

Ensemble-average spread with time *t*
Homogeneous, stationary turbulence



σ_v = Lateral rms velocity
σ_y = Lateral spread
T_L = Lagrangian time scale or "memory time"

$t \ll T_L \quad \sigma_y = \sigma_v t$

$t \gg T_L \quad \sigma_y = (2\sigma_v^2 T_L t)^{1/2}$

$\text{All } t \quad \sigma_y = \sigma_v t f_y(t/T_L)$

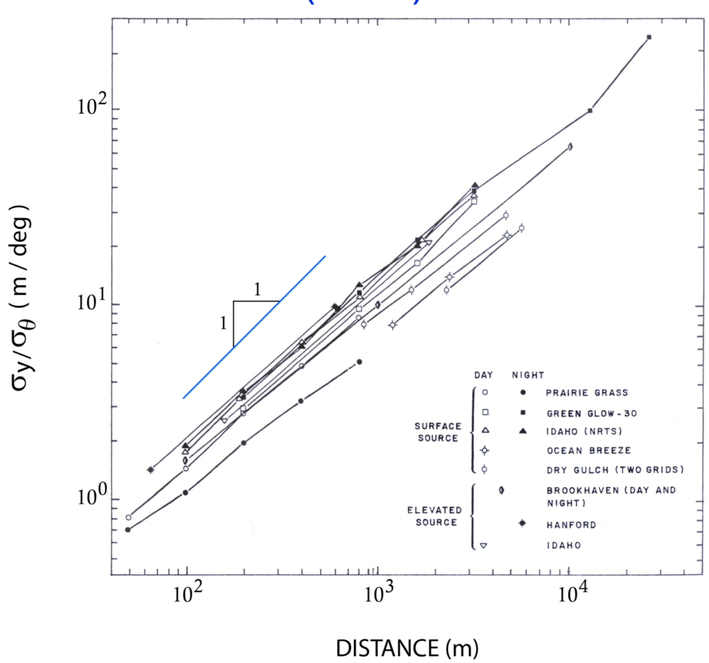
$$f_y = (1 + 0.5t/T_L)^{-1/2}$$

Effective diffusivity

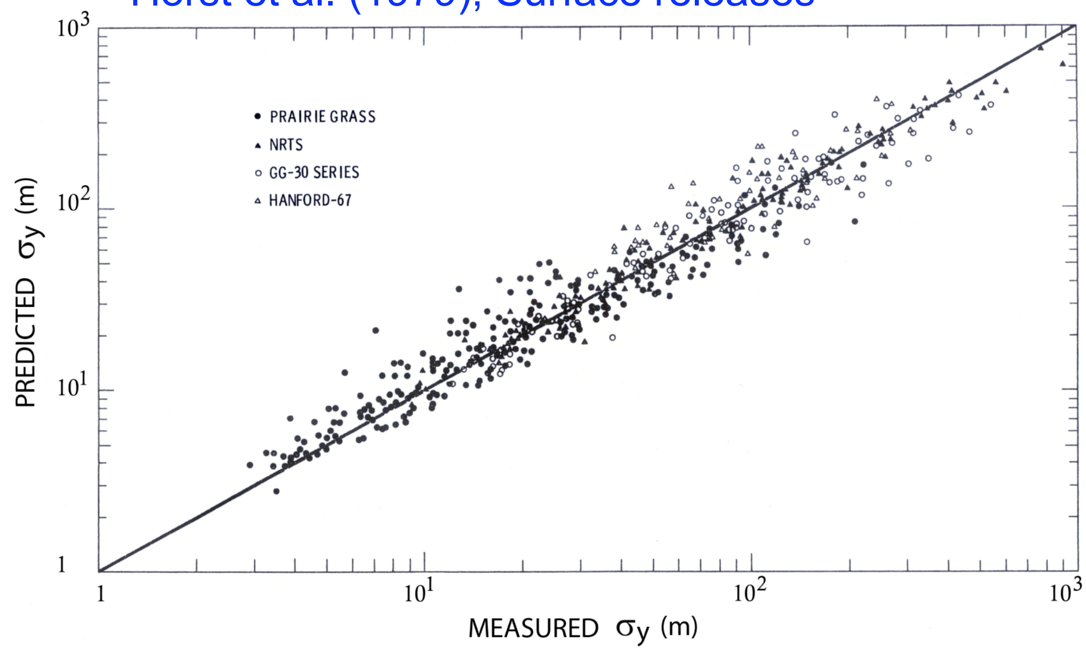
$$K_y = \sigma_v^2 T_L$$

Demonstration of Statistical Theory Using Turbulence Measurements & Dispersion Obs

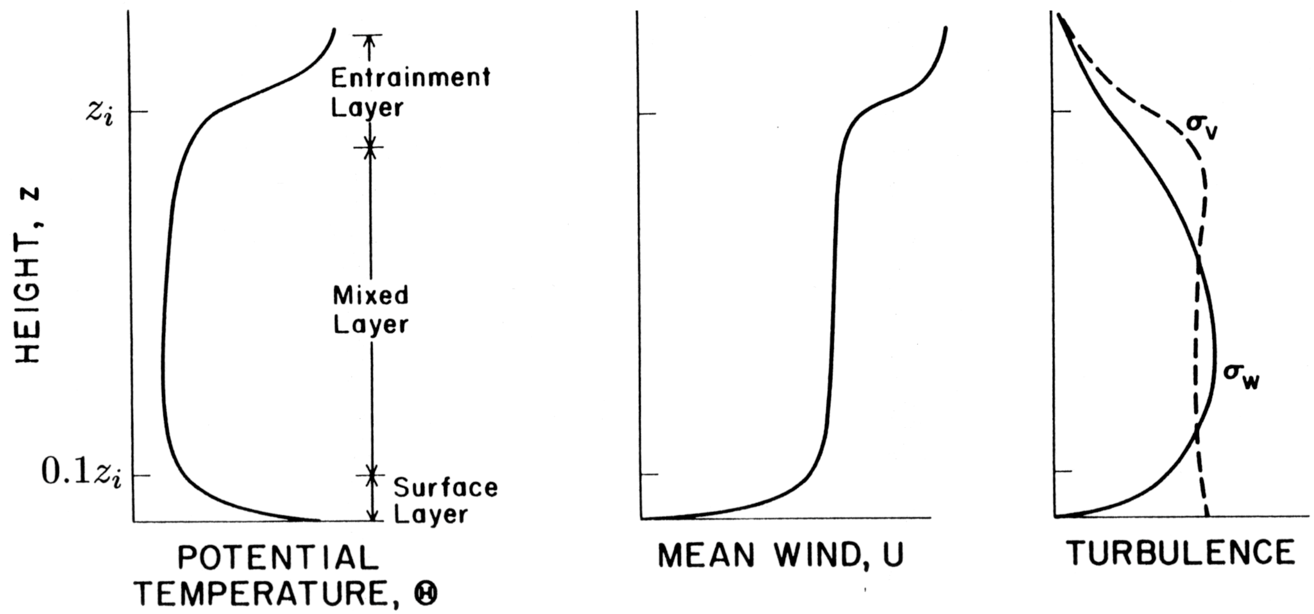
Slade (1968)



Horst et al. (1979); Surface releases



Convective Boundary Layer



Turbulence scales

Friction velocity u_*

Convective velocity scale $w_* \propto (\overline{w\theta}_0 z_i)^{1/3}$

Lengths $z_i,\ L \propto -u_*^3/\overline{w\theta}_0$

Stability parameter:

$$-z_i/L,\ u_*/w_*,\ w_*/U$$

Key variables

Near-surface wind speed U_{10}

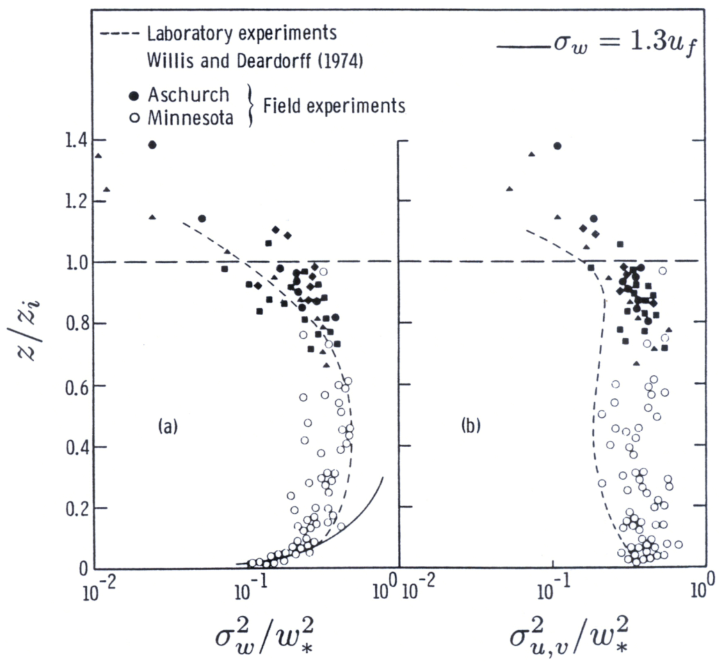
Surface heat flux, net or solar rad

CBL depth (meas or modeled)

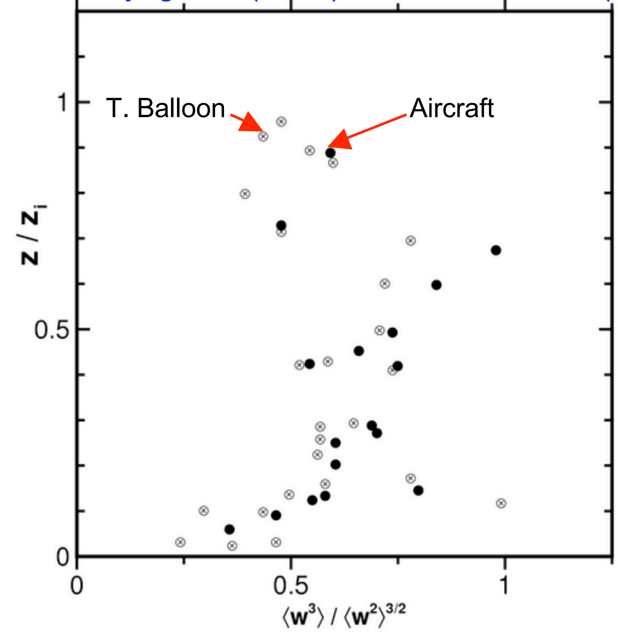
Surface roughness length z_0

Field Measurements for Parameterizing Turbulence

Tethered balloon; Caughey & Palmer (1979)



From Wyngaard (1988); Lenschow et al., (1993)



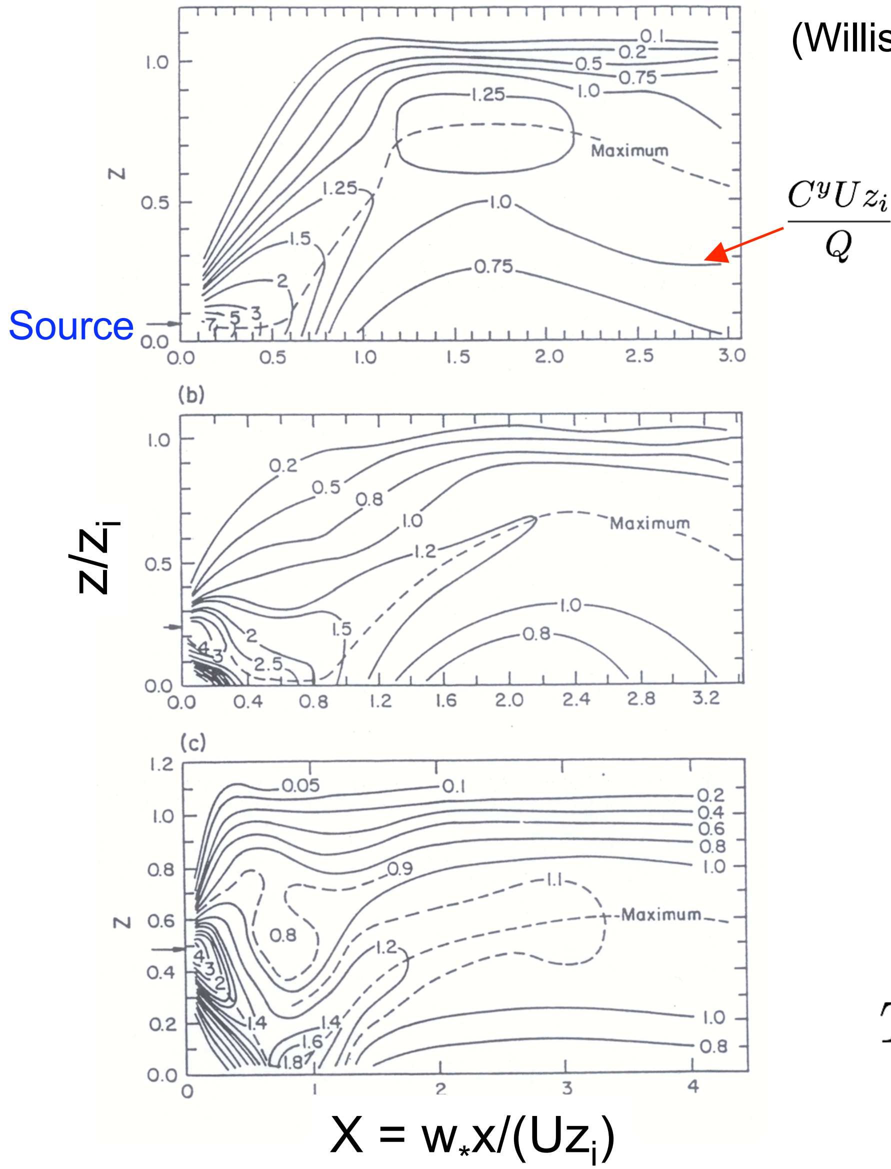
$$\sigma_v^2 = u_*^2 f_{SV} + w_*^2 f_{BV}$$
$$\sigma_w^2 = u_*^2 f_{SW} + w_*^2 f_{BW}$$
$$\overline{w^3} = w_*^3 f_3$$

$f_{SV}, f_{BV}, f_{SW}, f_{BW}, f_3$ are $f(z/z_i)$

Convection Tank Data

Crosswind-Integrated Concentration (CWIC)

(Willis & Deardorff 1976, 1978, 1981)

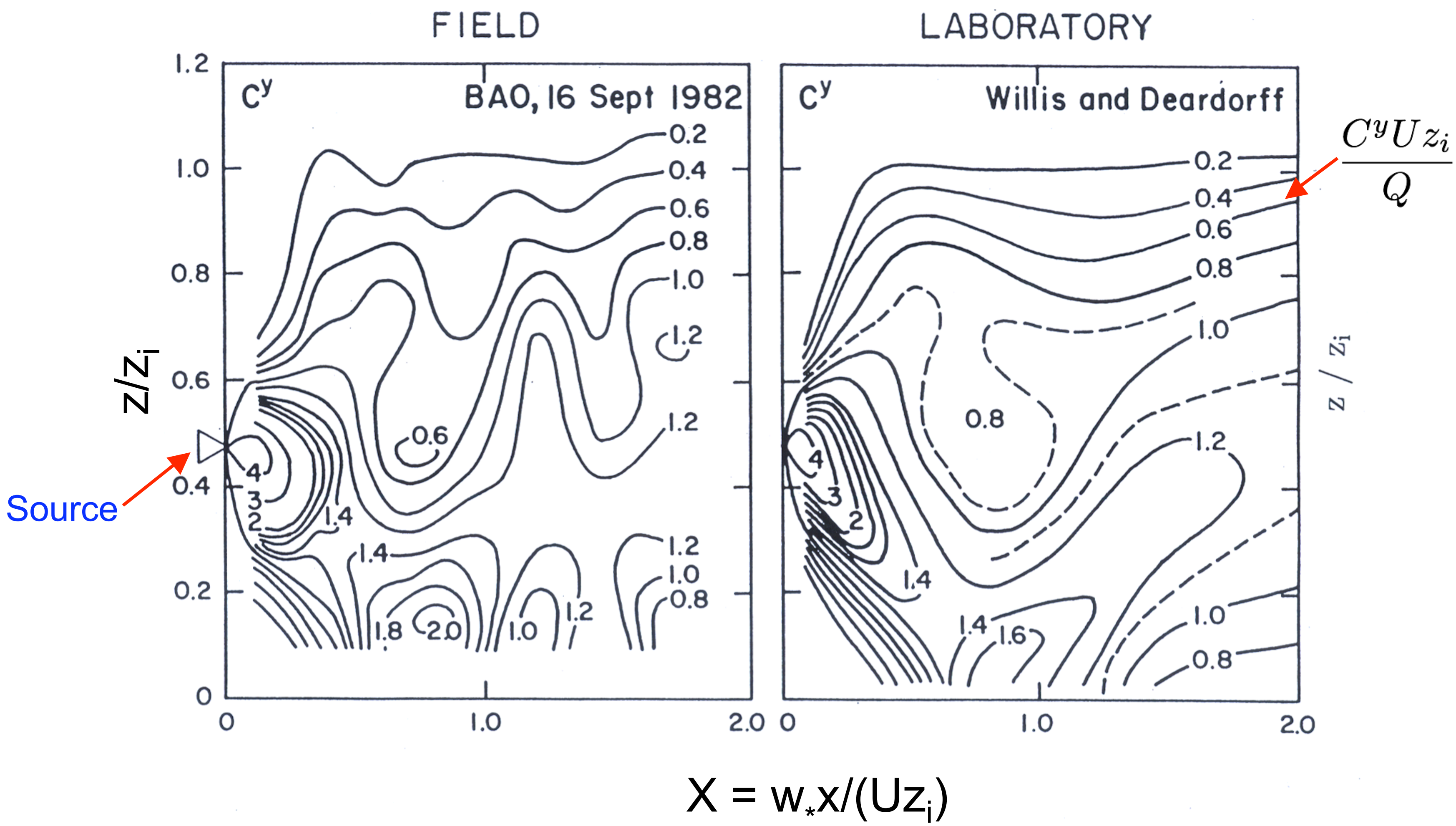


$$T_L \propto z_i / w_*$$

Field vs. Convection Tank Data

Crosswind-Integrated Concentration (CWIC)

(Moninger et al, 1983)



PDF Model

(Misra, 1982; Venkatram, 1983; Weil, 1986)

Key assumptions:

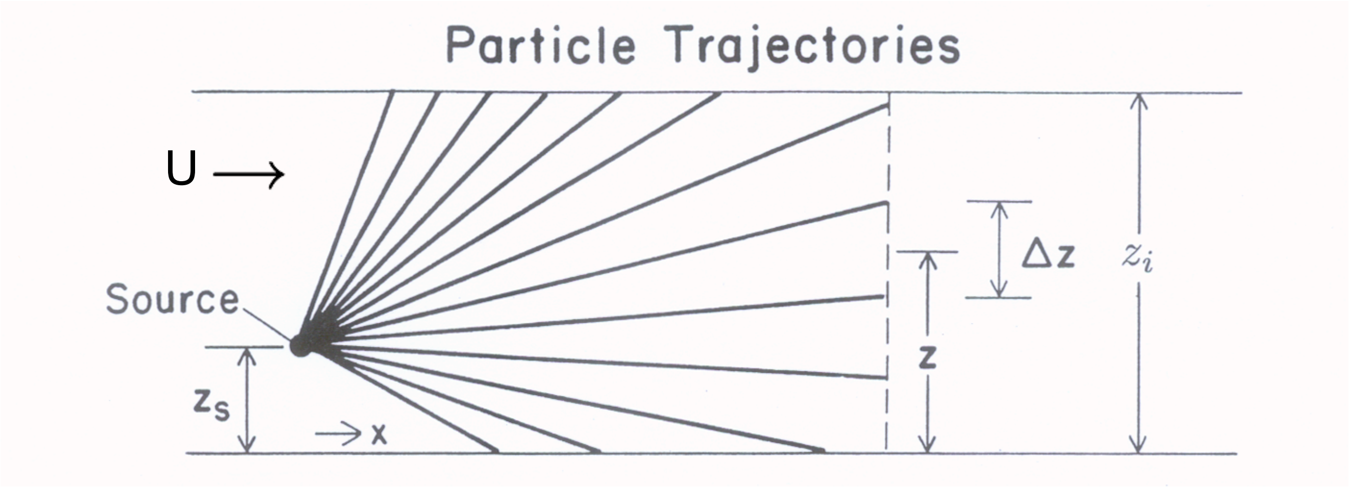
Uniform wind and turbulence with z

Very large time scale T_L

Skewed w PDF

$$C^y = \frac{Q p_z}{U} \qquad p_z = p_w[w(z_p)]|dw/dz_p|$$

$$p_w = \lambda_1 G_1(w) + \lambda_2 G_2(w)$$



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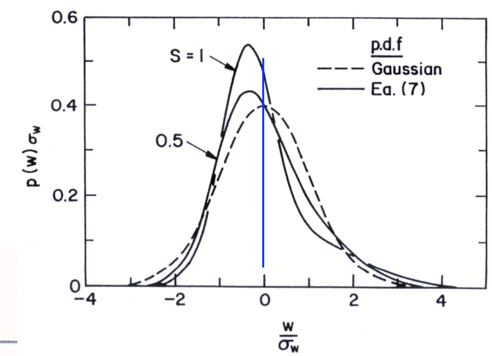
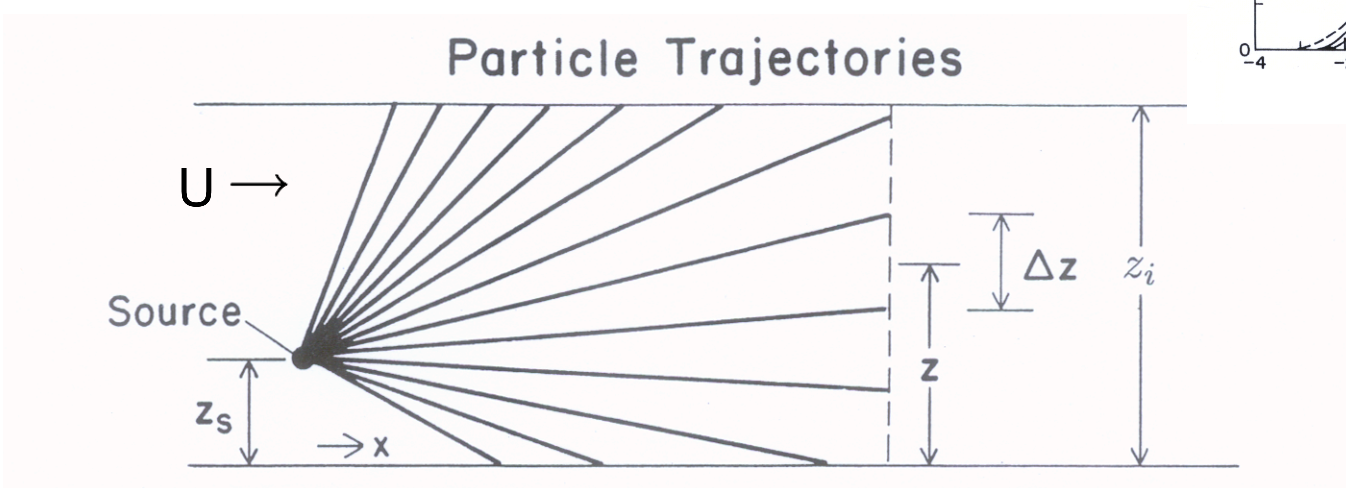
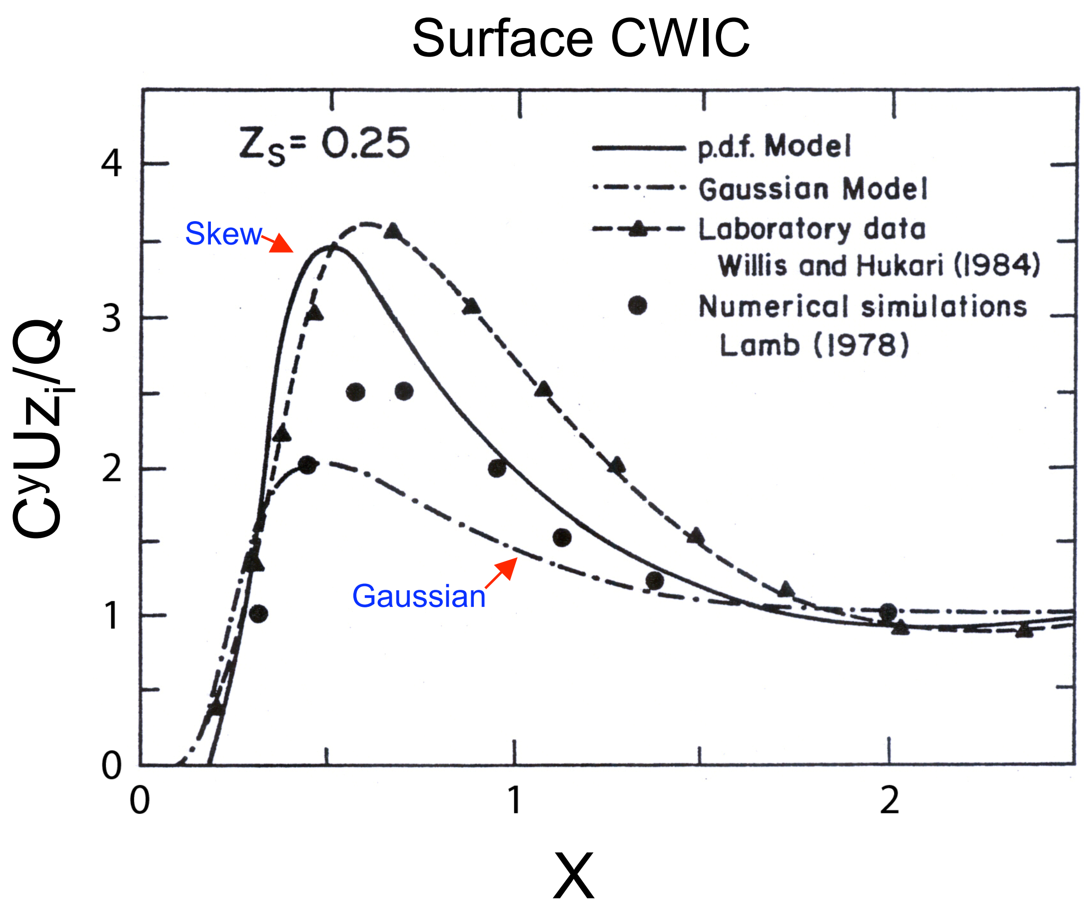


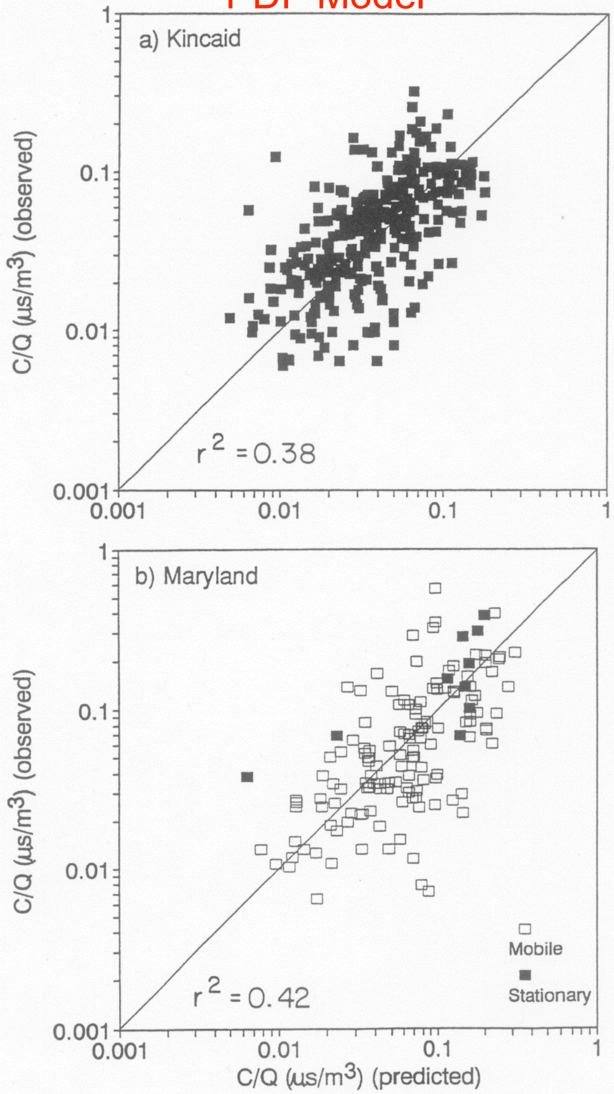


PDF Model vs Tank Data

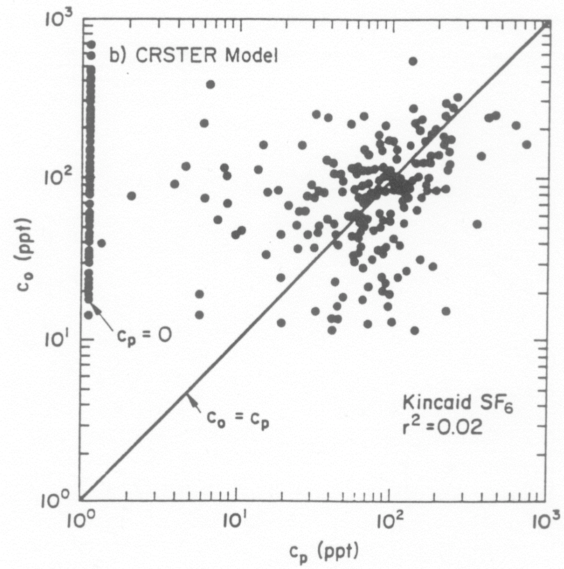


PDF Model vs Field Data: Buoyant Releases

Ground-level concentrations
PDF Model



EPA Gaussian Model



Centerline concentrations; 1 hr avgs.
h_s: 107 m -- 305 m
x : 0.5 km -- 50 km

(Weil et al., 1997)

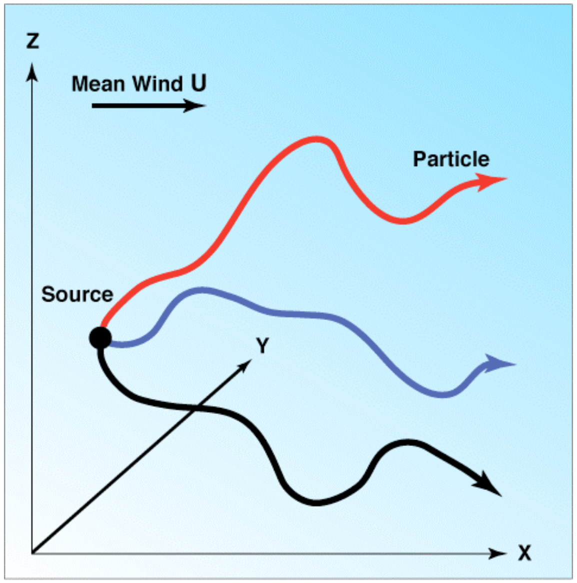
AERMOD -- New EPA Regulatory Model

- Adopted December 2006
- Key EPA model for industrial source applications
- Parameterizes turbulence using PBL scaling; accepts wind & turbulence measurements
- Includes PDF model for CBL
- Gaussian model for SBL
- Addresses building downwash, elevated terrain, urban dispersion, etc
- Committee (AERMIC) 14 years

National Atmospheric Release Advisory Center (NARAC) Model; Lawrence Livermore Natl. Lab. (LLNL)

(Nasstrom et al., 2000)

- Uses: emergency response; national security
- Meteorological assimilation model (ADAPT)
  - Surface, tower, radiosonde data
  - Diagnostic wind field
- Lagrangian stochastic displacement model (LODI); ideally for $t >> T_L$



$$dz_p = \frac{\partial K_z}{\partial z} dt + (2K_z)^{1/2} d\xi$$

$$K_z = \frac{k u_*}{\phi(z/L)} \exp\left(\frac{-c_k z}{z_i}\right)$$

LODI Evaluation with Copenhagen Data

Copenhagen Field Experiment (Gryning & Lyck, 1984)
SF_6 release; z_s = 115 m; 23 1-h periods; 9 days; CBL
Tower winds & temp.; radiosondes; turbulence info; $1.4 \leq -z_i/L \leq 14$
Sampling arcs: x = 2, 4, 6 km; 1-h avg. SF_6 concs.

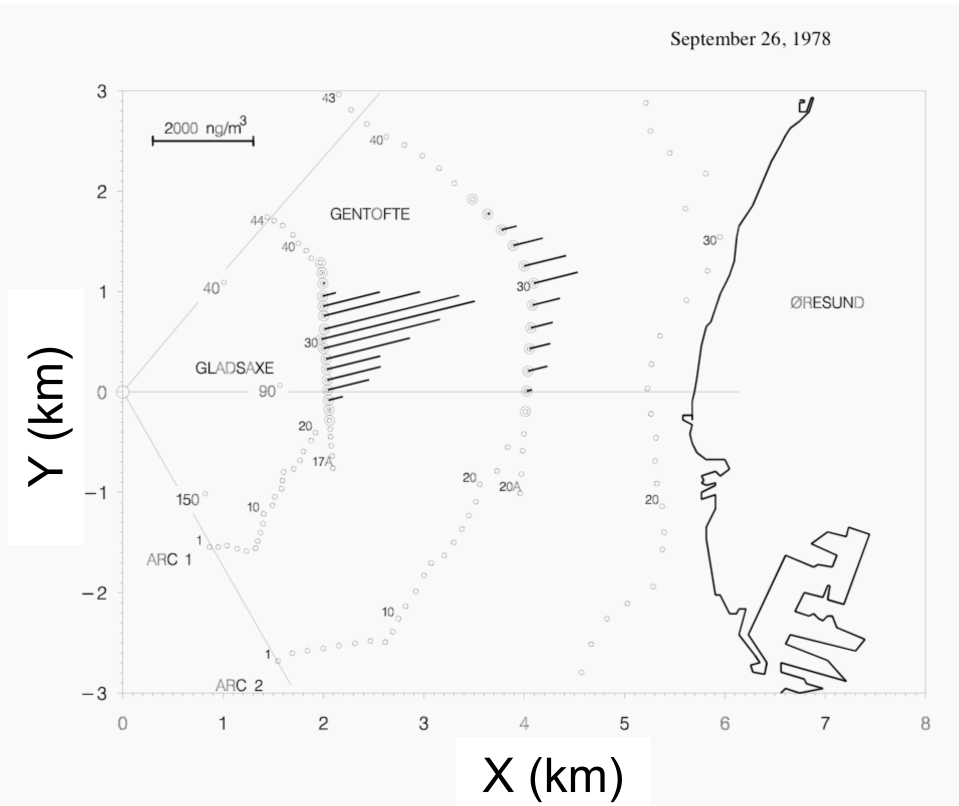
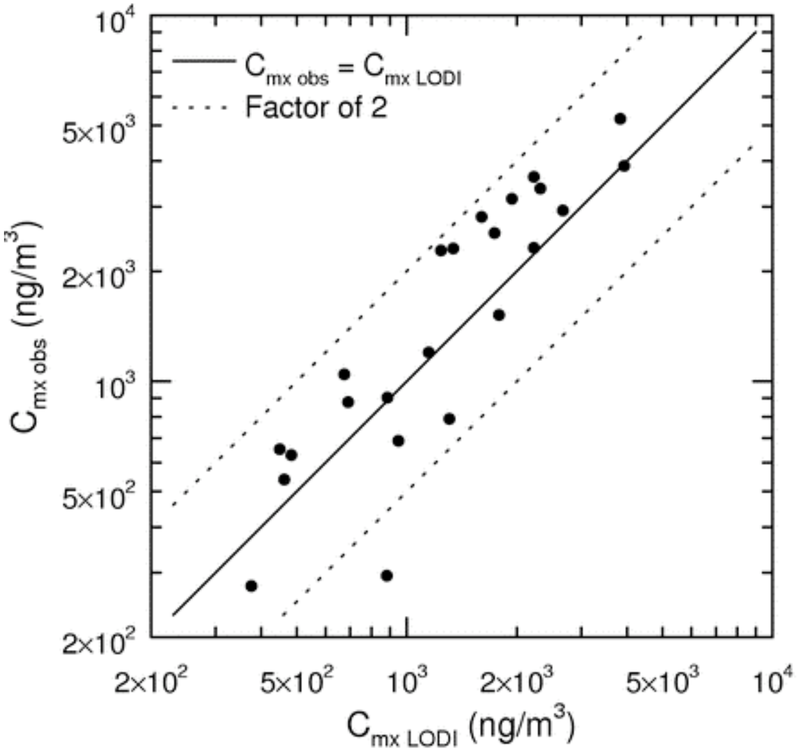


Figure 4. Experiment on September 26, 1978. The bars indicate the mean measured tracer concentrations for the period 11:40-12:40 (run 1-3, Table 11-12), for the individual measuring positions.

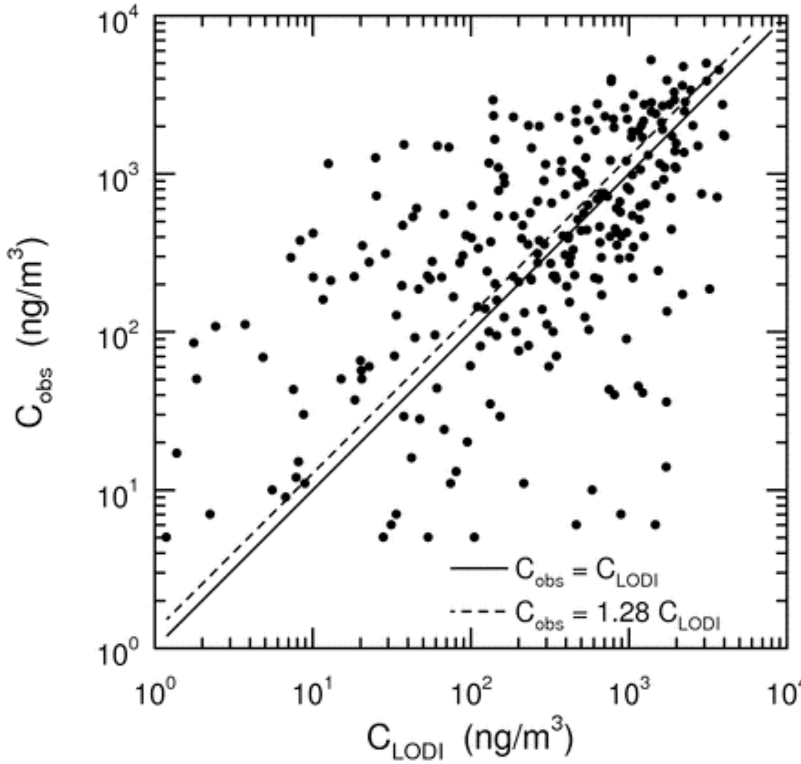
Observed Surface Concentrations vs LODI Predictions

(Weil & Dillon, 2005)

Arc-maxima only



All



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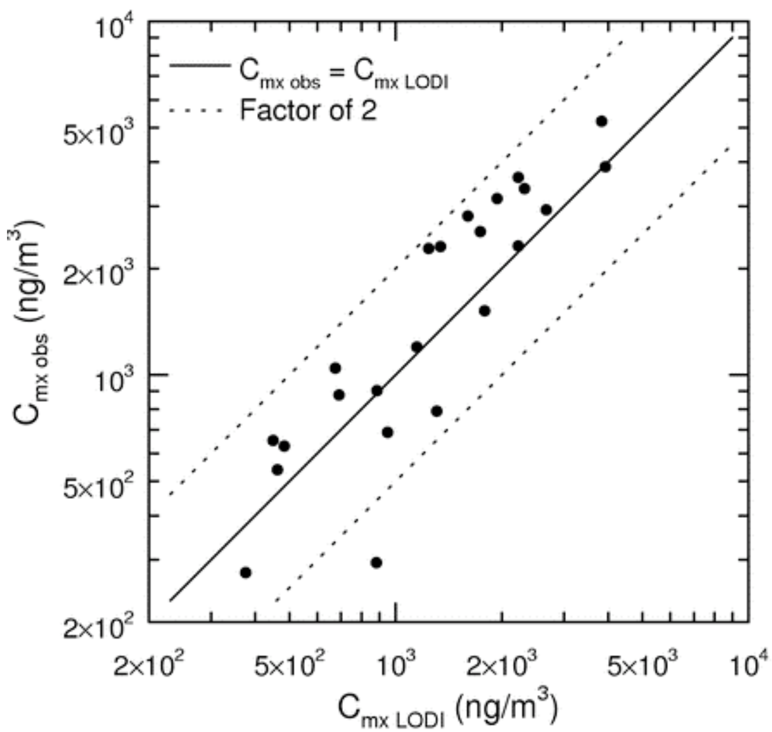
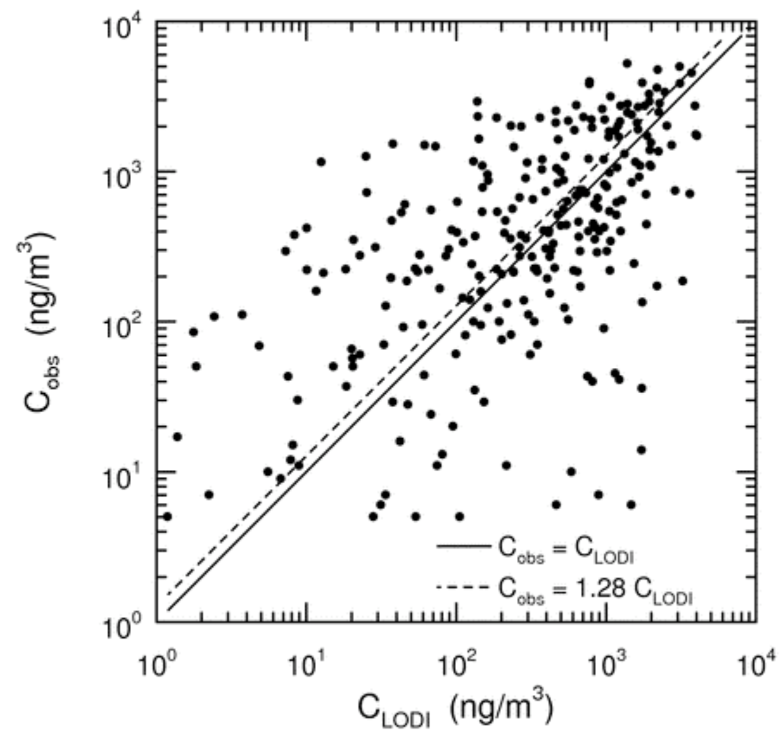


All



Model	GM (C_p/C_o)	GSD	
NARAC	0.88	1.5	Non-buoyant
PDF	0.95	2.0	Buoyant

GM = geometric mean

GSD = geometric std deviation

Generation of Concentration Fluctuations

Meandering Plume Model
Gifford (1959)

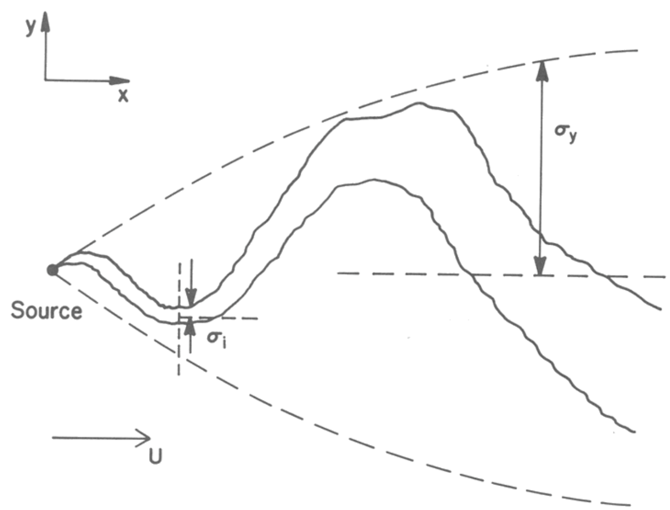


Figure 7.3. Schematic representation of Gifford's meandering-plume model.

Concentration Fluctuation Intensity
Csanady (1973)

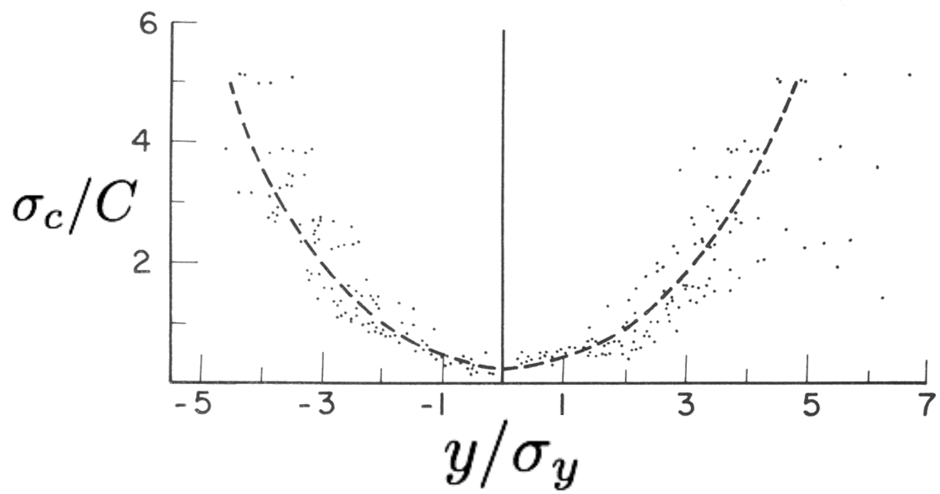
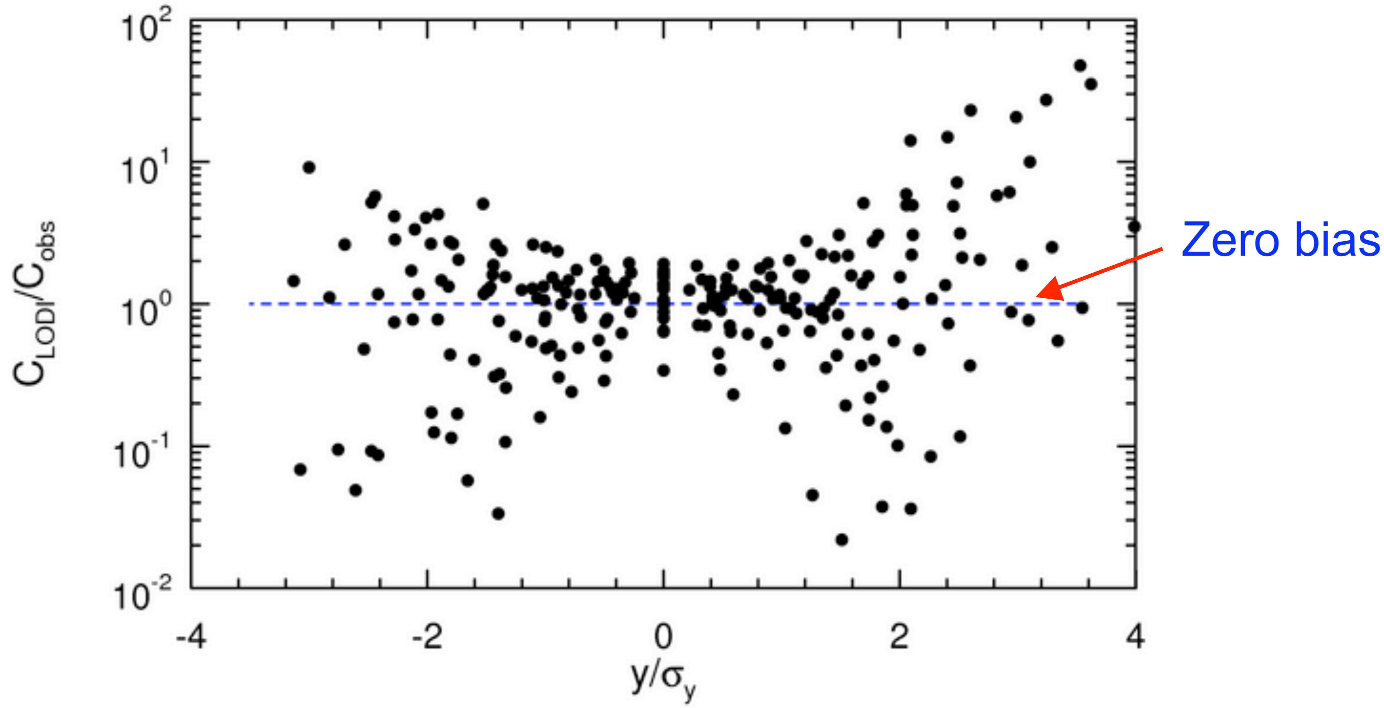


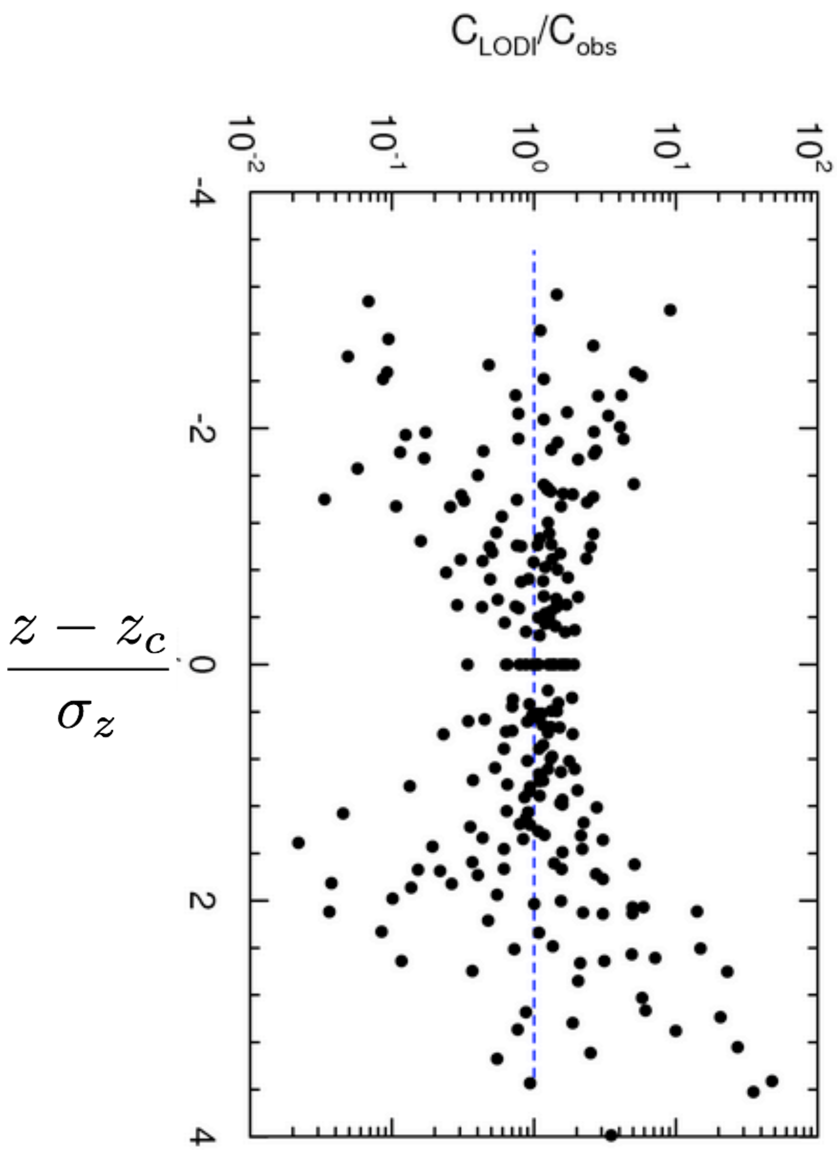
Fig. 7.11. Rms to mean concentration ratio at fixed *nondimensional* distances from center of gravity (distance scale: standard deviation of concentration distribution). Dots represent data at four different sections (Murthy and Csanady, 1971).

Variability of Predicted/Observed Concentration



"Bowtie" or "Butterfly" Pattern

Variability of Predicted/Observed Concentration in Vertical



Model	GM (C_p/C_o)	GSD	
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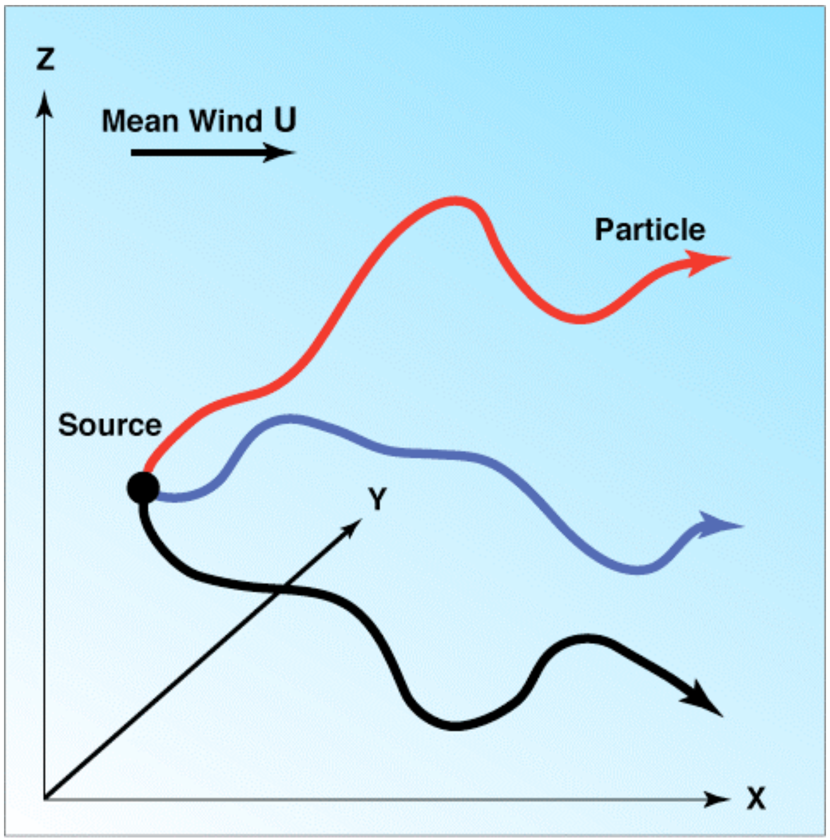
Lagrangian Particle Model Driven by LES Fields
(Weil, et al., 2004, J. Atmos. Sci.)



$\boldsymbol{v}(\boldsymbol{x}_0,t) = \boldsymbol{u}_{\text{RES}}(\boldsymbol{x}_{\text{p}},t) + \boldsymbol{u}_{\text{SGS}}(\boldsymbol{x}_{\text{p}},t)$

$\boldsymbol{u}_{\text{RES}}$ = resolved LES velocity

$\boldsymbol{u}_{\text{SGS}}$ = stochastic subgrid-scale (SGS) velocity

Adopt Thomson's (1987) stochastic model for $\boldsymbol{u}_{\text{SGS}}$

Concentrations (CWIC)

$$C^y = Q \int p_1(x - x_s, z - z_s, t_d)\, dt_d$$

$$t_d = t - t_{em}$$

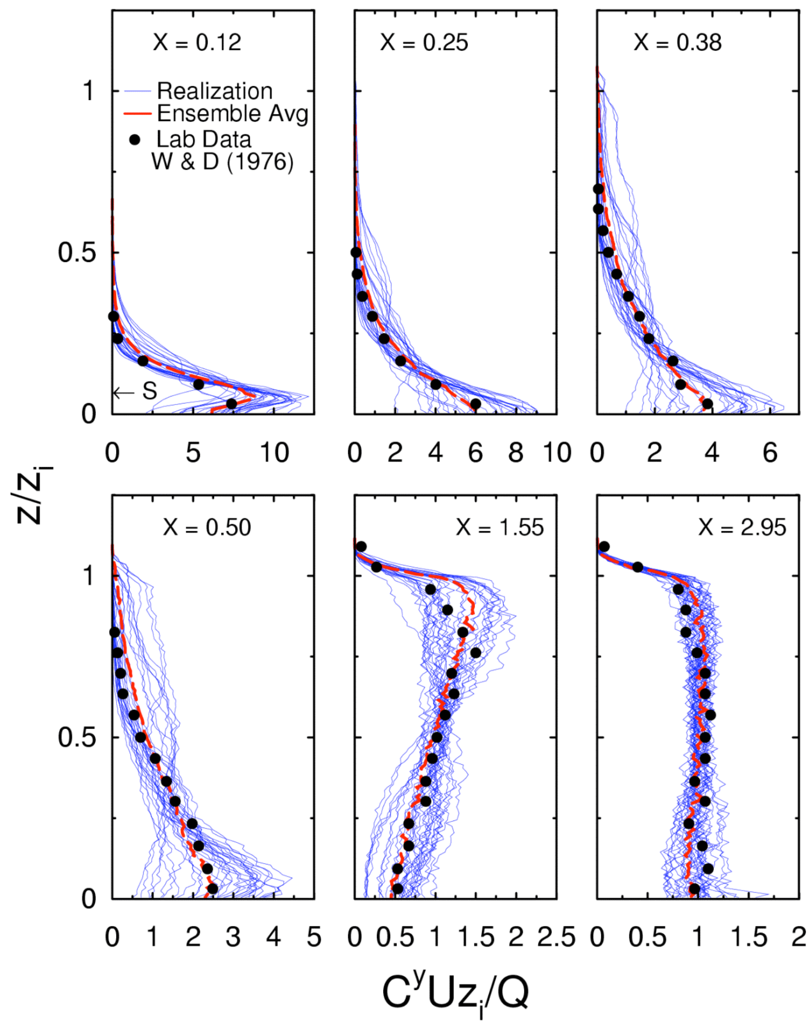
Mean and Realizations of Vertical CWIC Profiles

(Weil, Sullivan, Moeng, Patton, 2006)

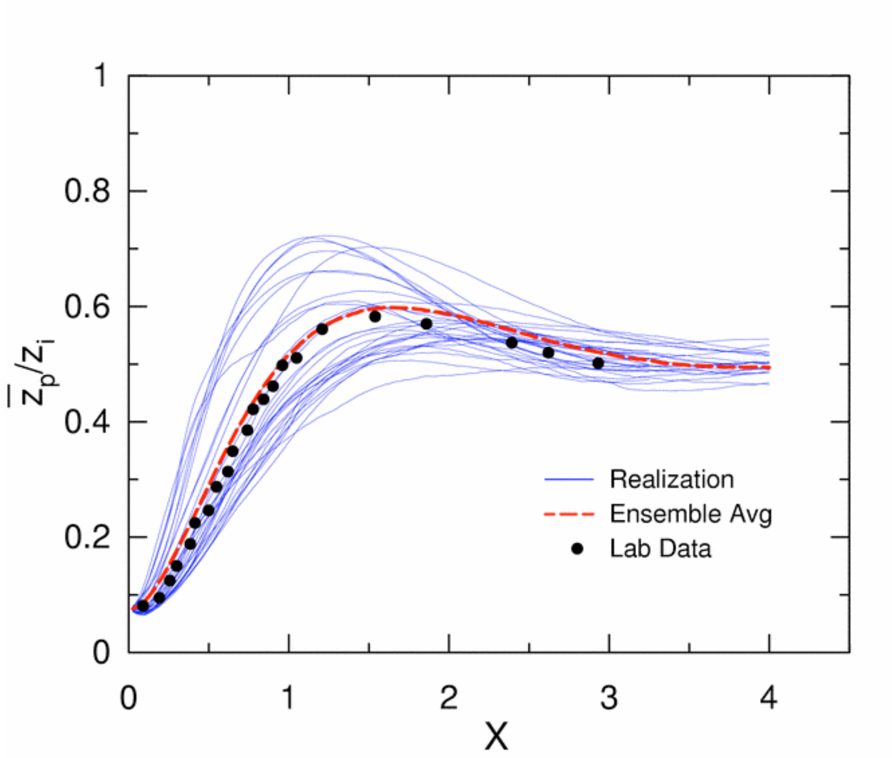
LES conditions:

96^3 grid points; 5 km X 5 km X 2 km domain; 1/2 h release

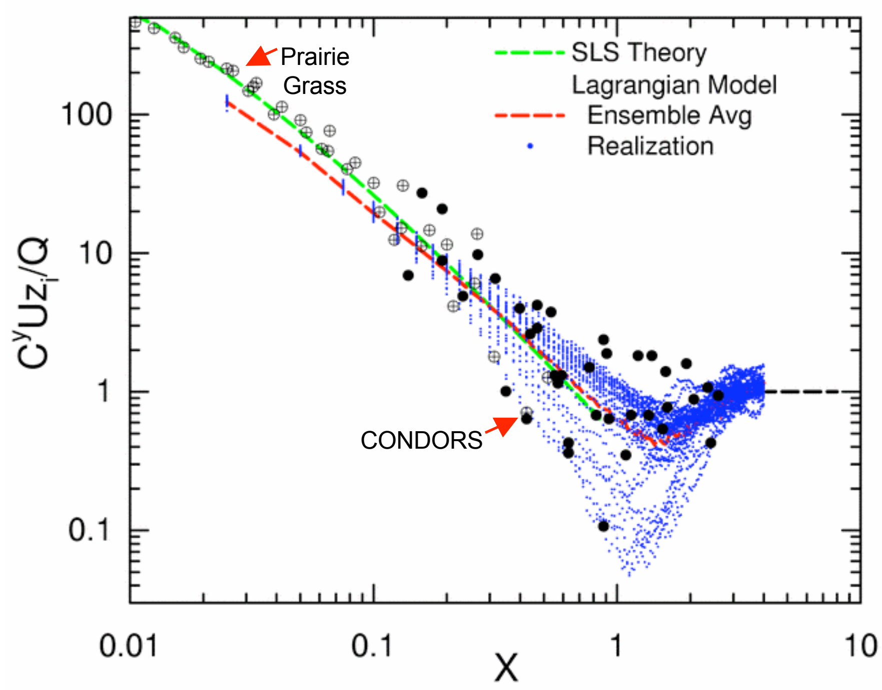
z_i = 1000 m, w_* = 2 m/s, z_i/w_* = 500 s, U = 3 m/s, $-z_i/L$ = 106



Ensemble Mean and Realizations:
Average Plume Height & CWIC Profiles



Surface source



LES of an Urban 2000 Experiment: Salt Lake City

(Chan & Leach, 2004)

- LES with FEM3MP (LLNL model)
- Massively parallel CFD model
- Finite element method
- Smagorinsky SGS
- Forcing by COAMPS mesoscale model and field measurements

LES of an Urban 2000 Experiment

IOP7 Release 1 of Urban 2000

Wind velocity: very low and varying (mean speed: 0.4-0.65 m/s)

Friction velocity: ~0.05 m/s

Source rate: 1 g/s (line source of SF_6 released near ground for 1 hr)

Neutral stability

Model Simulations

Domain size(m): 943 x 945 x 210 (graded mesh)

Grid points: 229 x 227 x 35 (~1.82M)

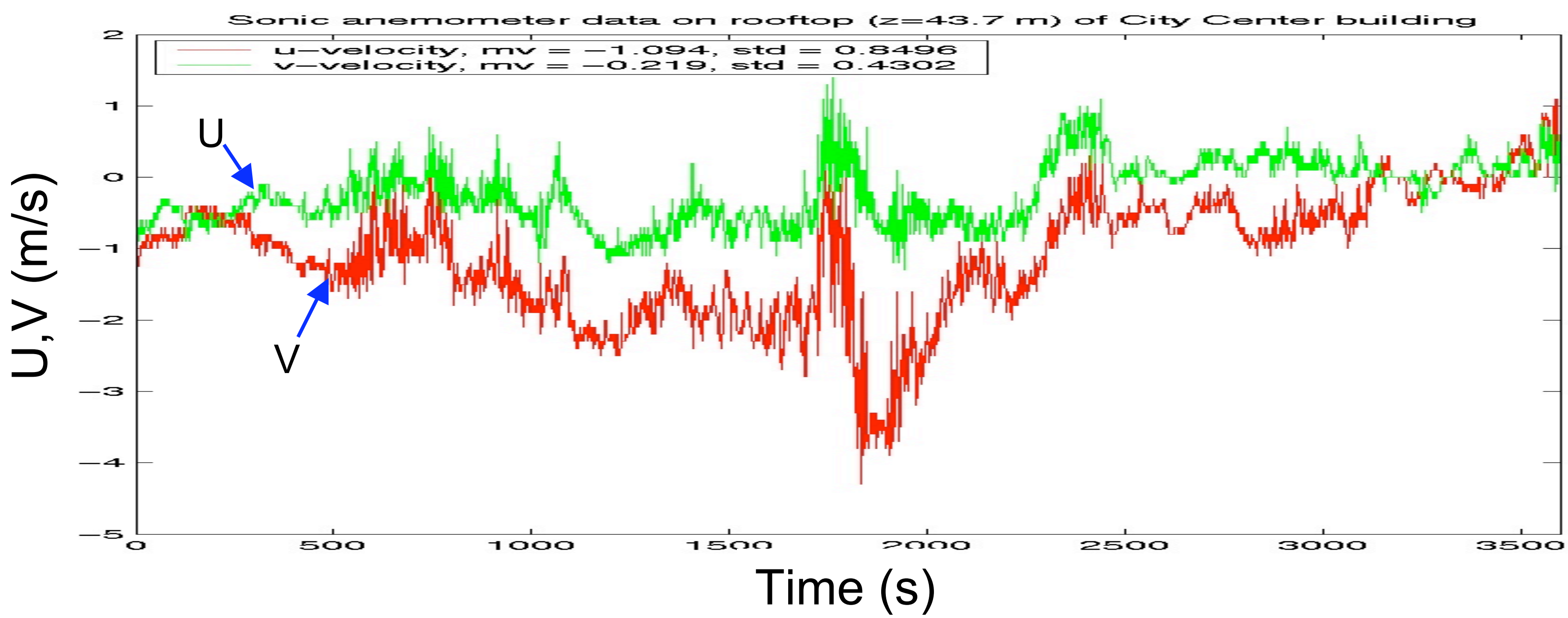
Boundary conditions:

- No slip on ground surface & no penetration on top boundary
- Time-dependent boundary conditions on inlet and side planes

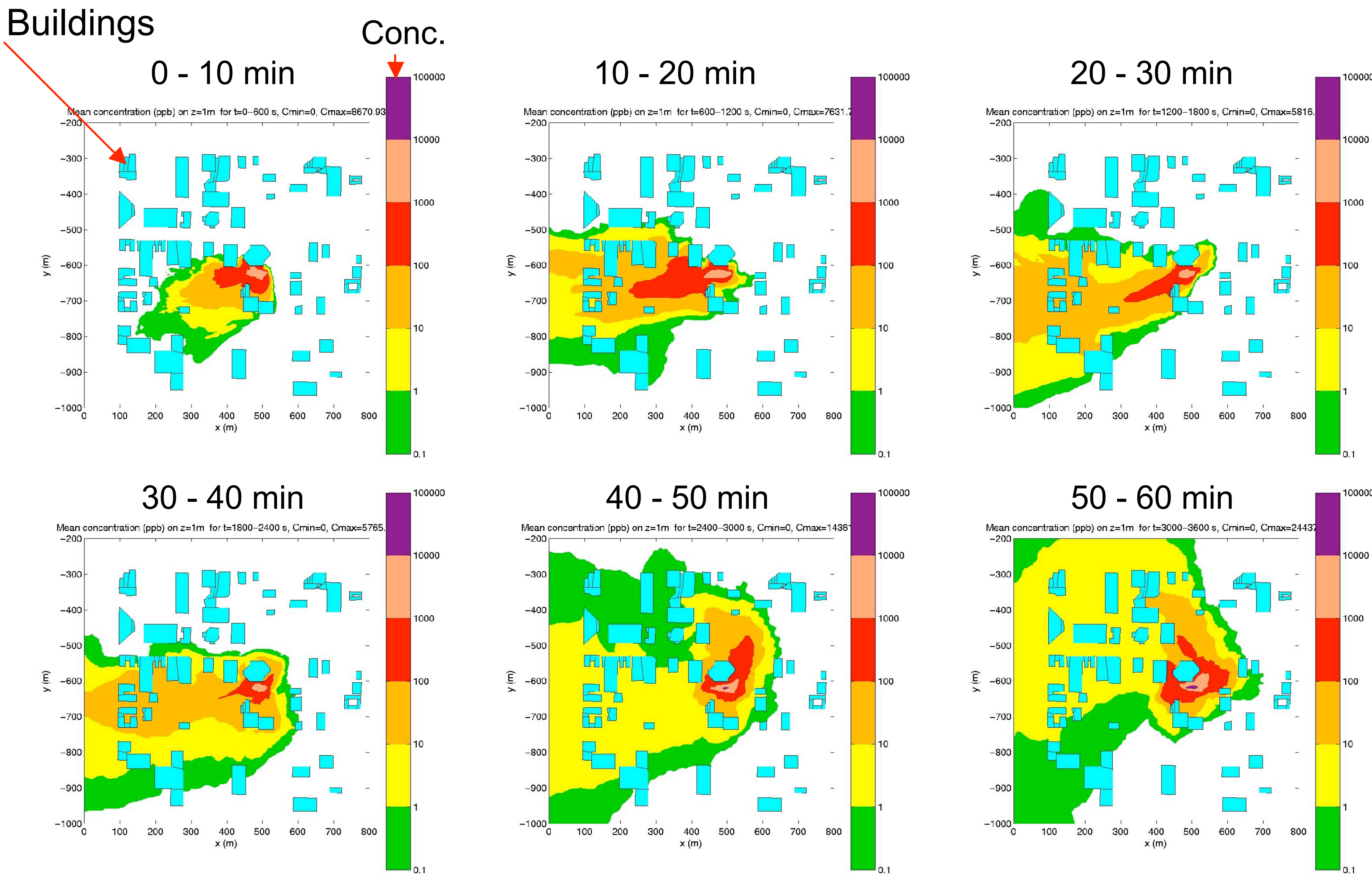
Sonic Data in Salt Lake City; Roof of City Center Building; z = 44 m

Measured data used to construct time-dependent boundary conditions with logarithmic variation in the vertical

Conditions applied on South, North, and East boundary of domain



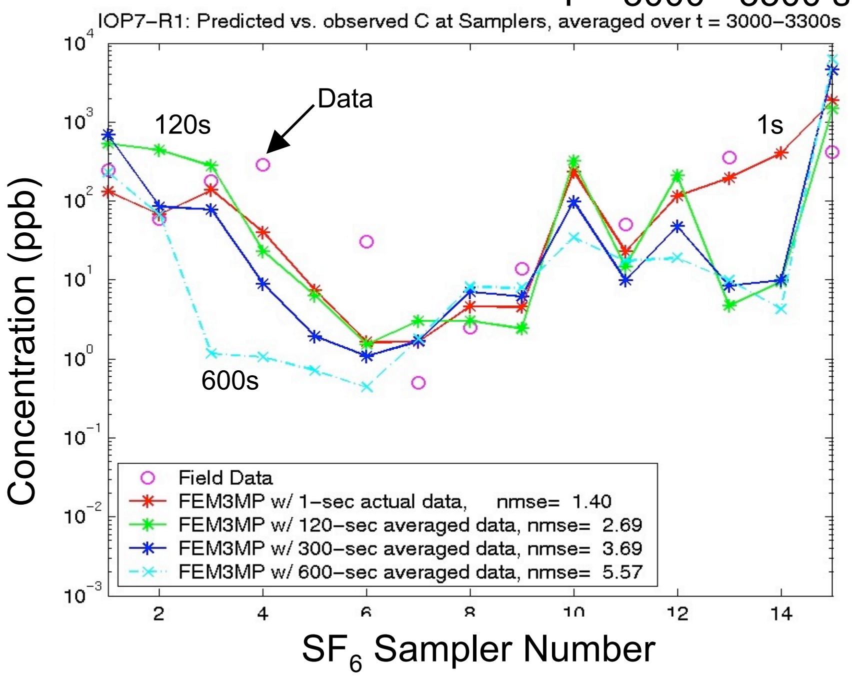
Average Concentration Patterns for Sequential 10-min Periods: Time-dependent BCs



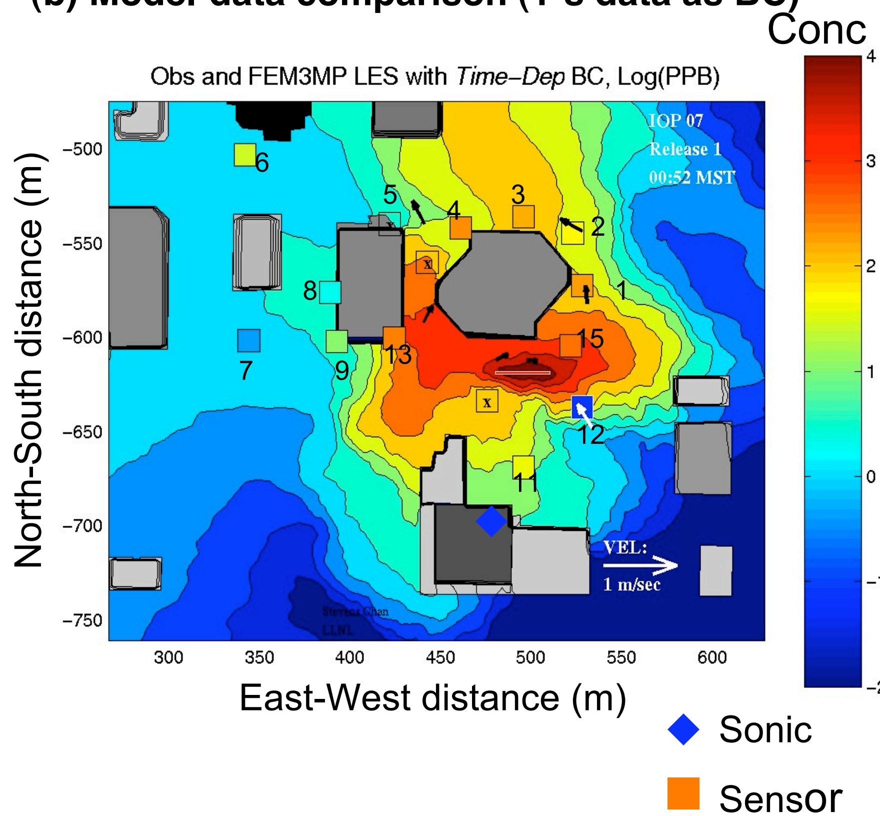
Predicted vs. Observed Concentrations Using Various Time-dependent Wind Forcings

(a) Model-data comparison for all cases

T = 3000 - 3500 s

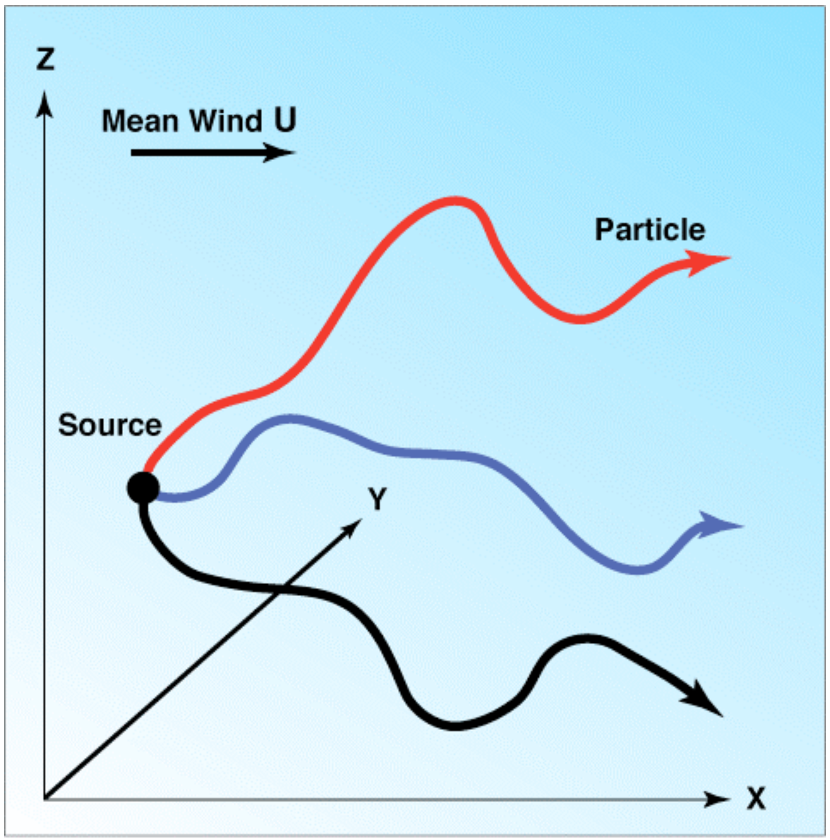


(b) Model-data comparison (1-s data as BC)



Imposing proper time-dependent forcing by large scale flows has led to accurate prediction of tracer concentrations for complex and usually more hazardous dispersion scenarios under light and highly variable winds

Lagrangian Particle Model
(Weil, et al., 2004, J. Atmos. Sci.)



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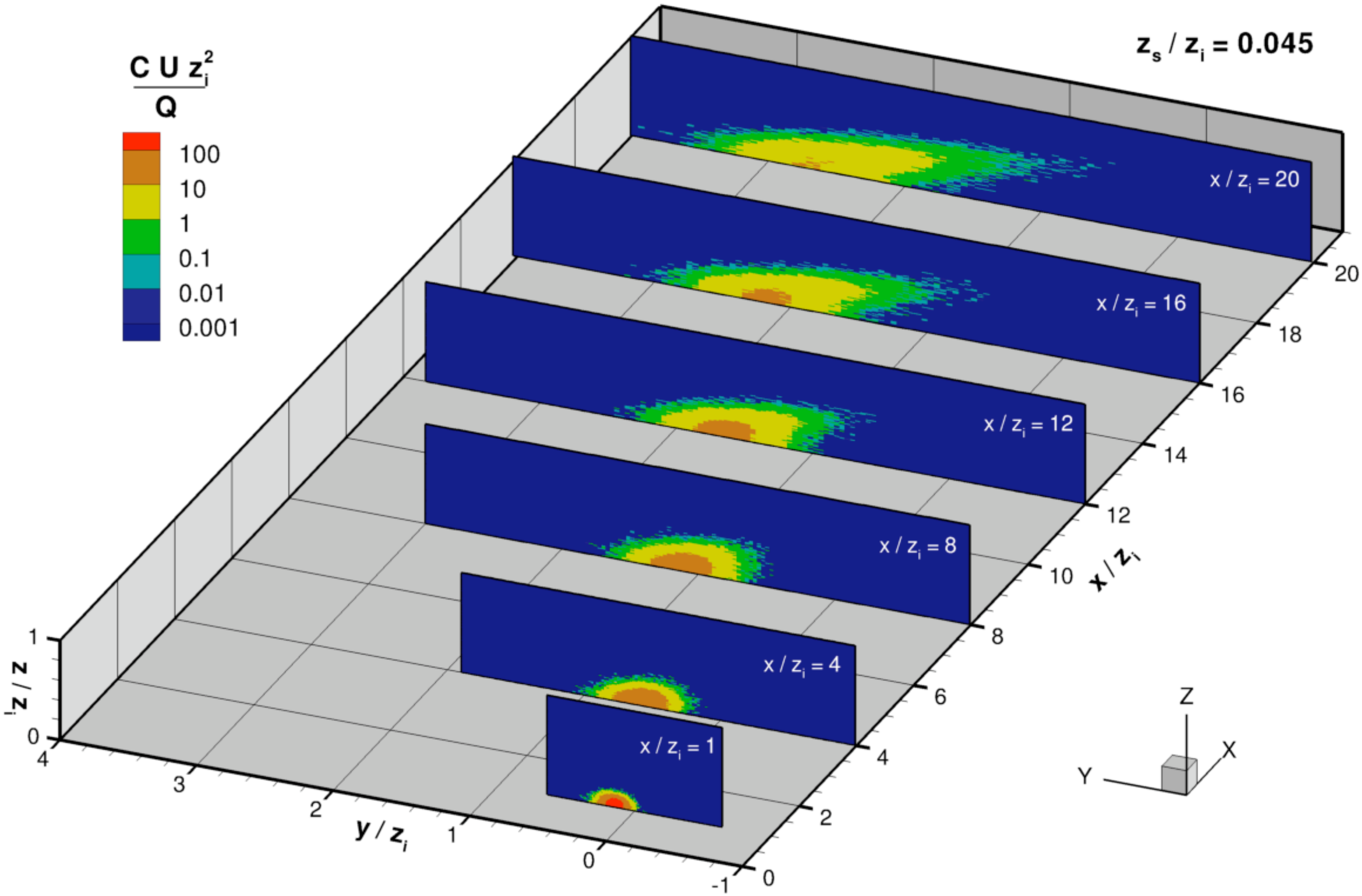
$$t_d = t - t_{em}$$

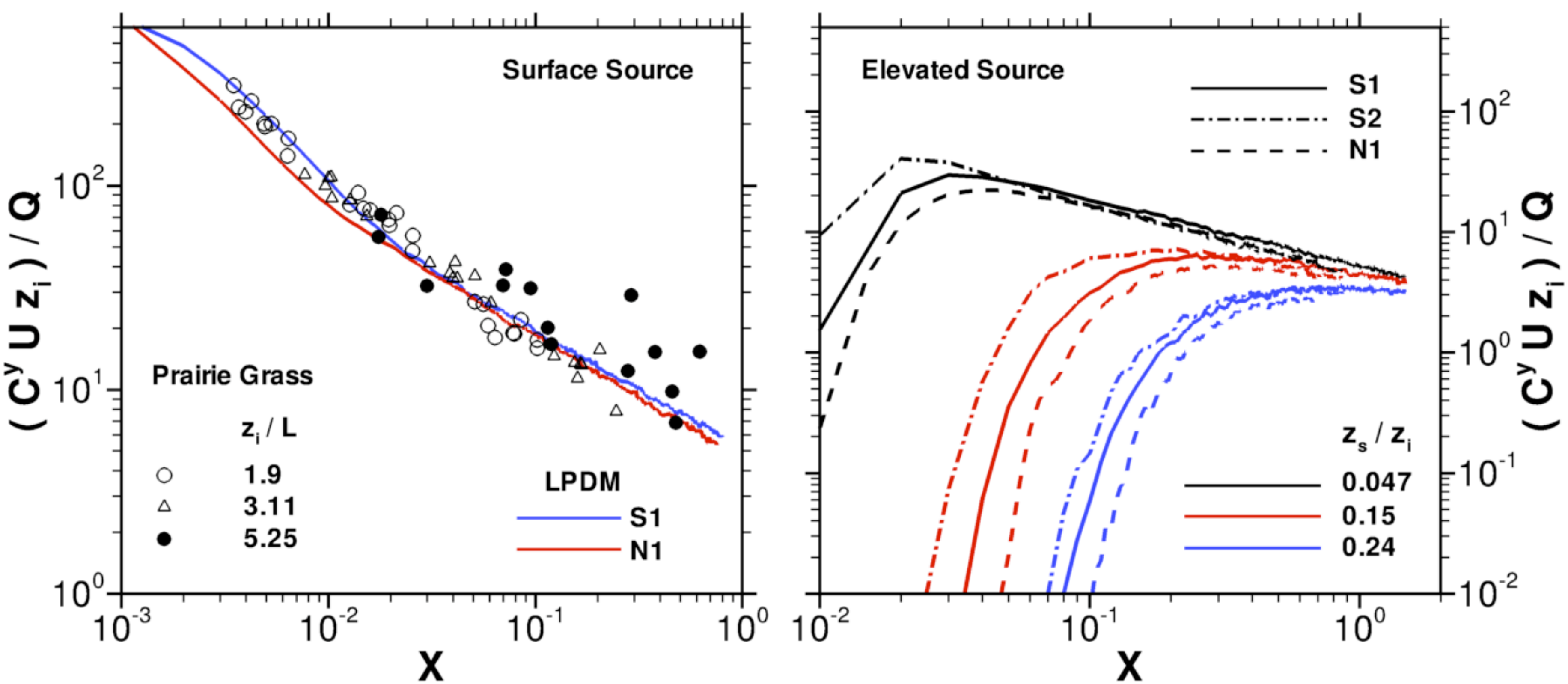
Large-Eddy Simulations (LES)

(Moeng & Sullivan, 1994; Sullivan et al., 1994; GABLS, Beare et al., 2005)

- Filtered Navier-Stokes equations with parameterized SGS fluxes to produce 3D volume of wind fields
- Stable boundary layer (SBL)
- Horizontally homogeneous
- Conditions:
  400 m X 400 m X 400 m domain
  200 X 200 X 192 grid points, $\Delta \cong 2$ m
  $z_i = 200$ m, $u_* = 0.28$ m/s, $z_i/u_* = 714$ s, $U = 7$ m/s,
  $L = 125$ m, $z_i/L = 1.6$
- 640 stored LES data files at 5 s intervals



$\frac{C U z_i^2}{Q}$
100
10
1
0.1
0.01
0.001
$z_s / z_i = 0.045$
$x / z_i = 20$
$x / z_i = 16$
$x / z_i = 12$
$x / z_i = 8$
$x / z_i = 4$
$x / z_i = 1$
z / z_i
y / z_i
x / z_i
Z
X
Y



Surface Source
Prairie Grass
z_i / L
1.9
3.11
5.25
LPDM
S1
N1
Elevated Source
S1
S2
N1
z_s / z_i
0.047
0.15
0.24
(C^y U z_i) / Q
X

Extra Slides

NARAC Model Urban Modifications

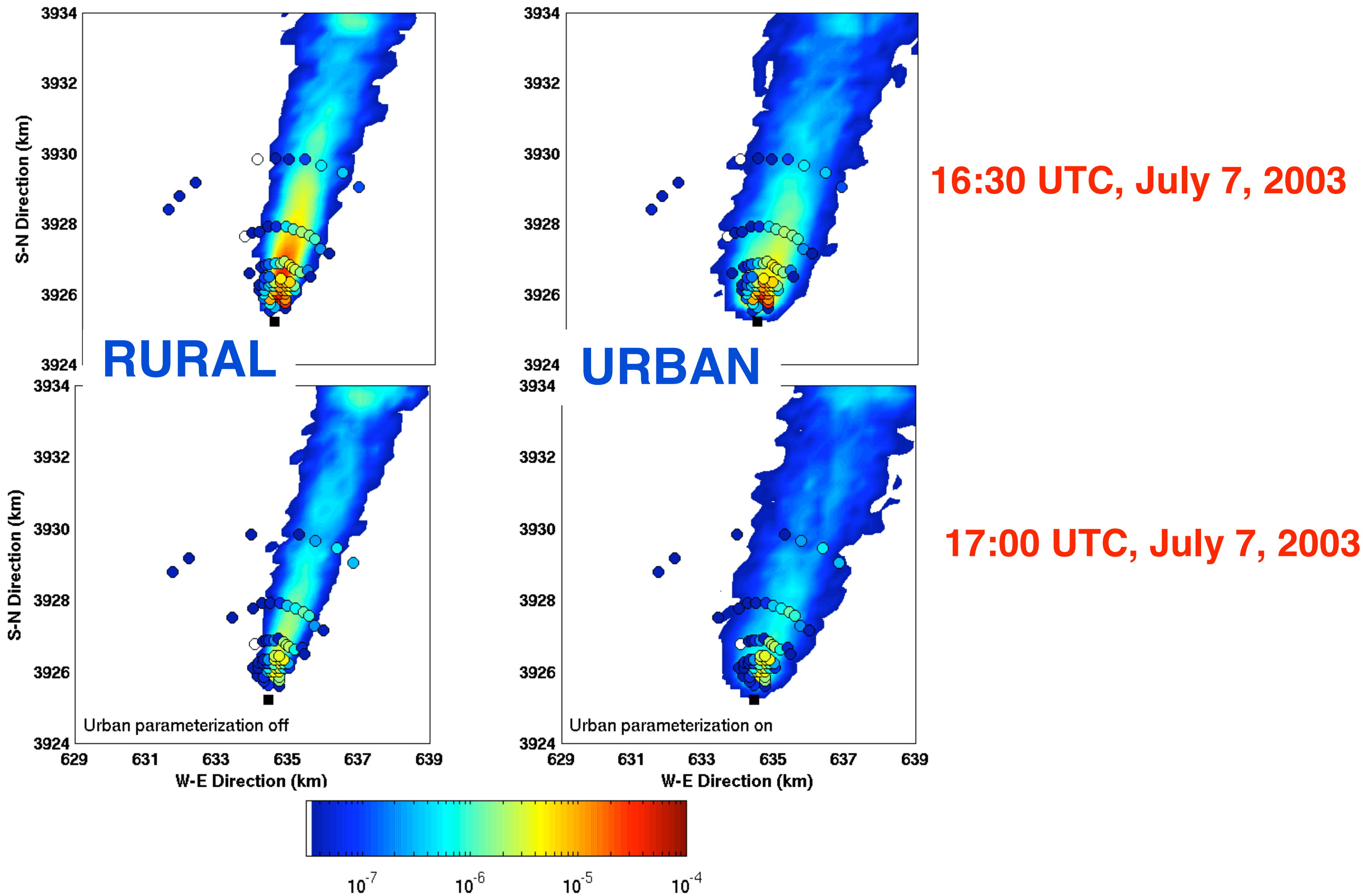
(Delle Monache and Weil, 2008)

- Capture average effects of urban surface on wind & turbulence
- Triple-layer UBL structure

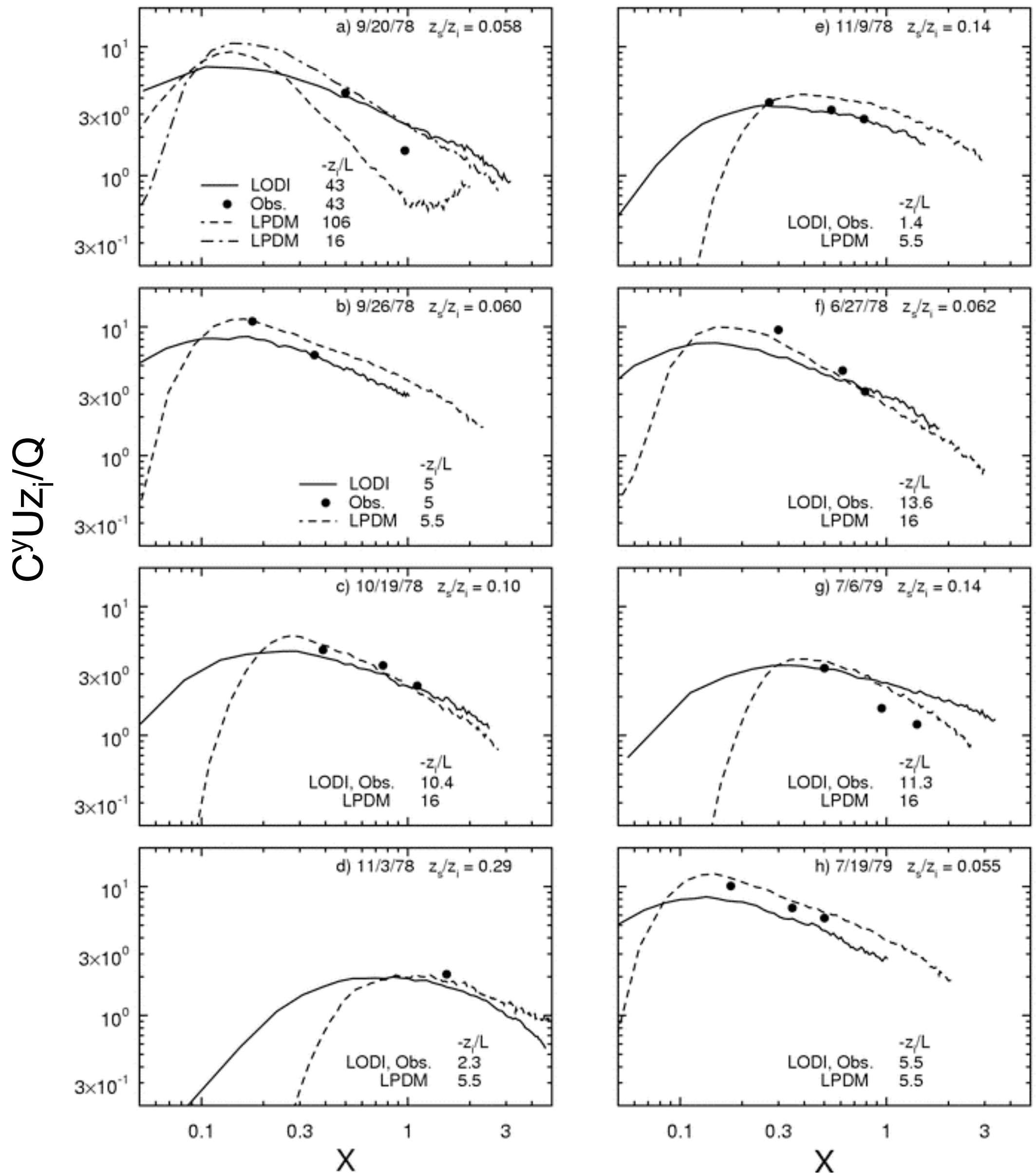
  canopy, roughness sublayer, inertial sublayer
- Mean wind, turbulence, K_z parameterization

  fractional frontal area, average building height h_b
- Tests with Joint Urban 2003 data (OKC)

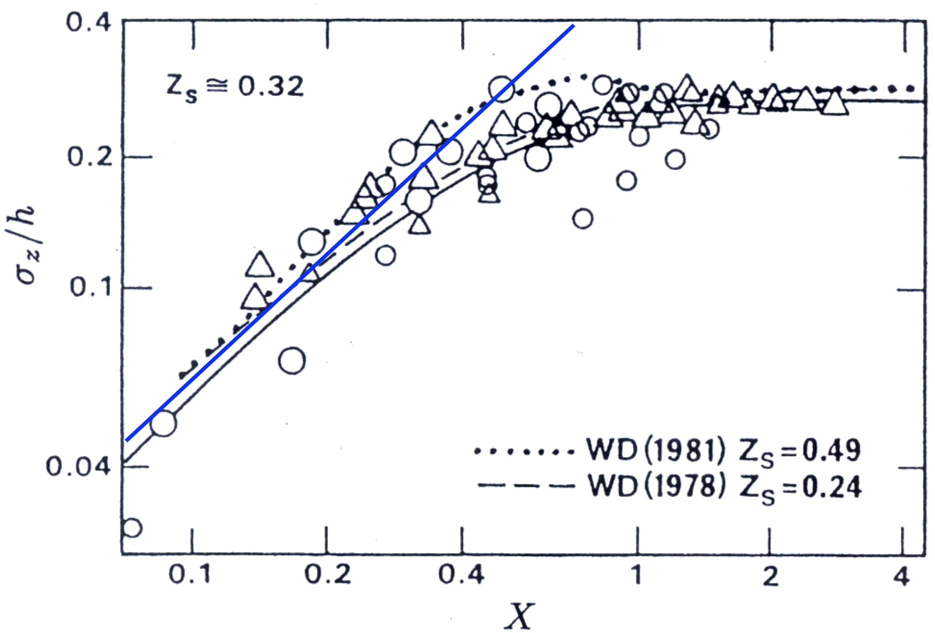
NARAC Comparisons with JU03 Data



Surface CWIC: LODI, LPDM-LES, & Observations



Vertical Dispersion



Dispersion in the CBL

Figure 14. Keystone plume, May 25, 1968, 1047 EST.

Figure 13. Keystone plume, October 31, 1968, 0920 EST.

Dispersion in a Stable Environment

Surface Concentrations: Observations vs LODI Predictions
(Weil & Dillon, 2005)

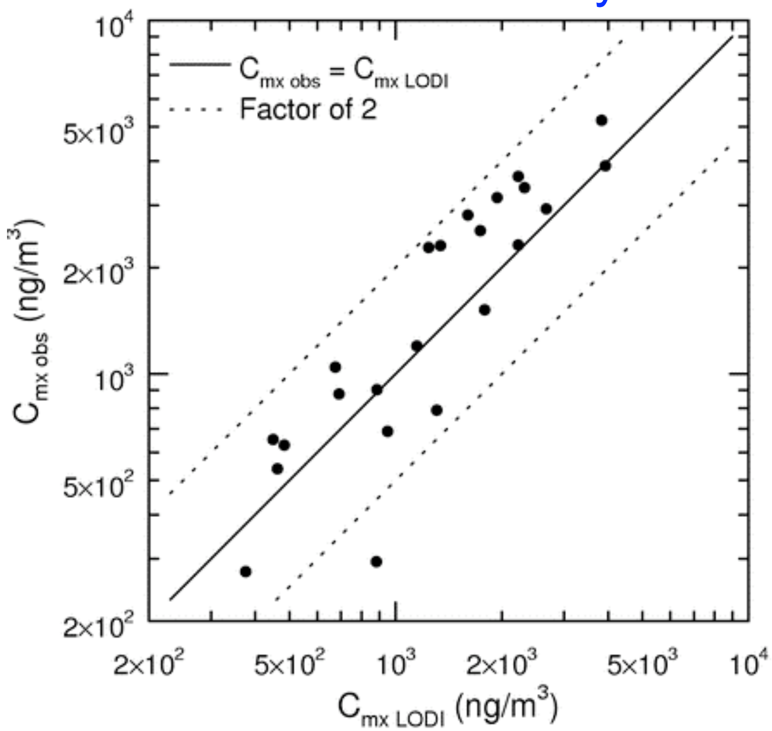
Copenhagen Field Experiment (Gryning & Lyck, 1984)

SF_6 release; z_s = 115 m; 23 1-h periods; 9 days;

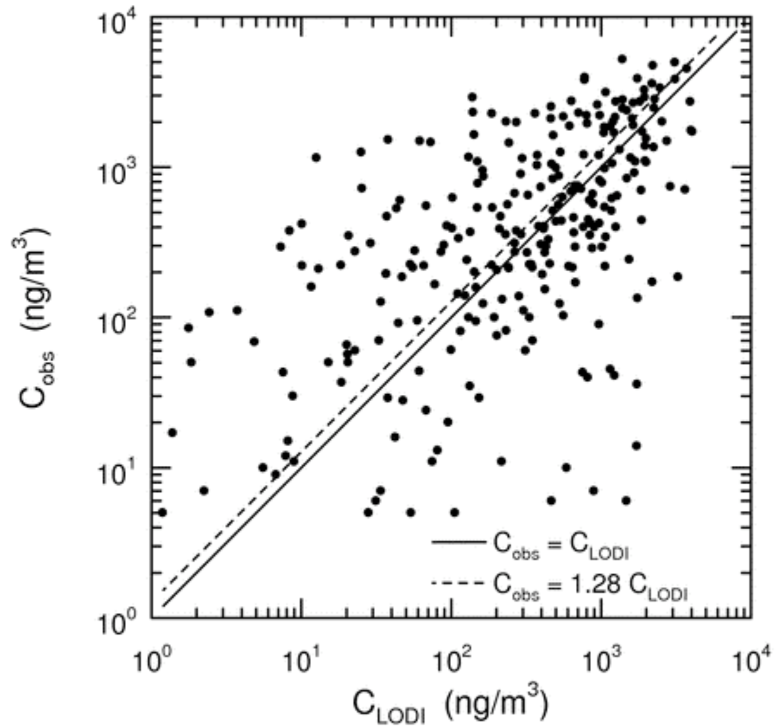
Tower winds & temp.; radiosondes; turbulence info; $1.4 \leq -z_i/L \leq 14$

Sampling arcs: x = 2, 4, 6 km; 1-h avg. SF_6 concs.

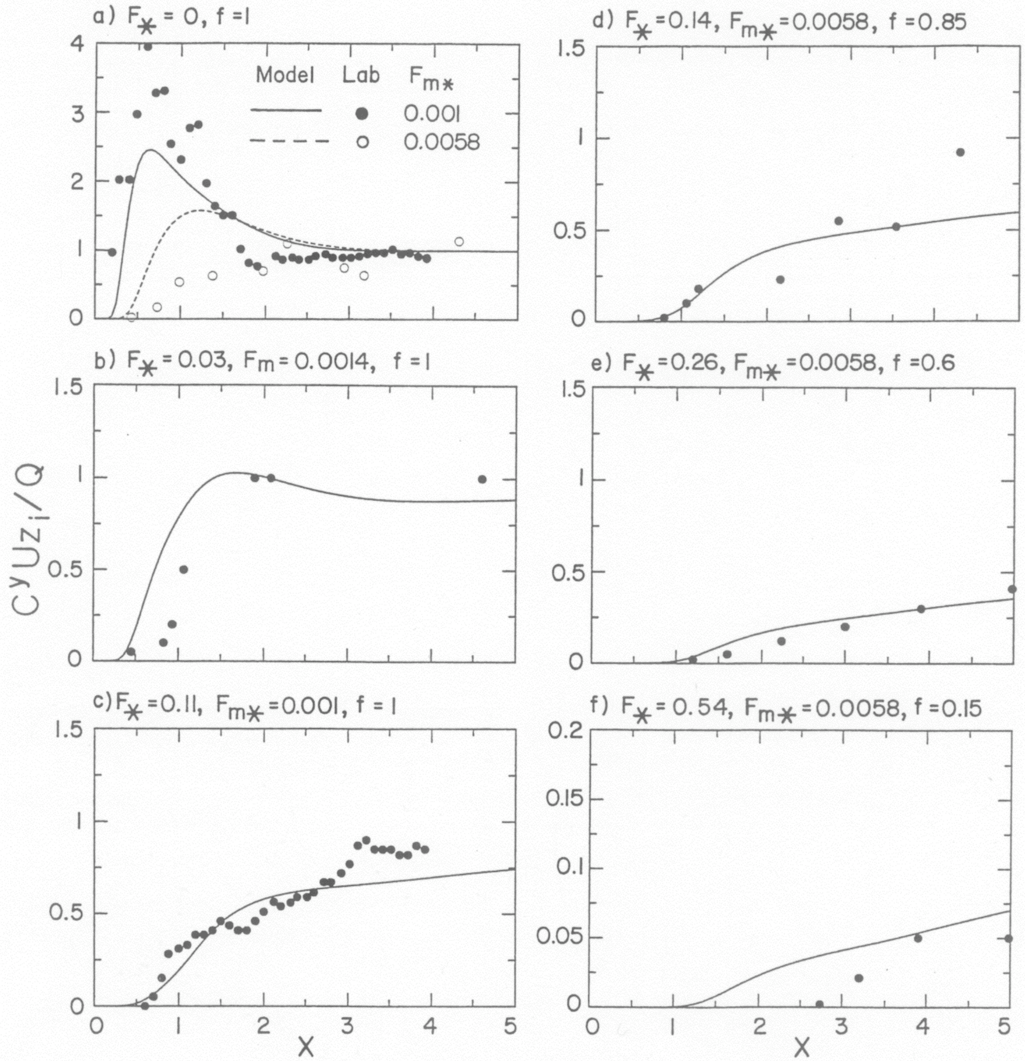
Arc-maxima only



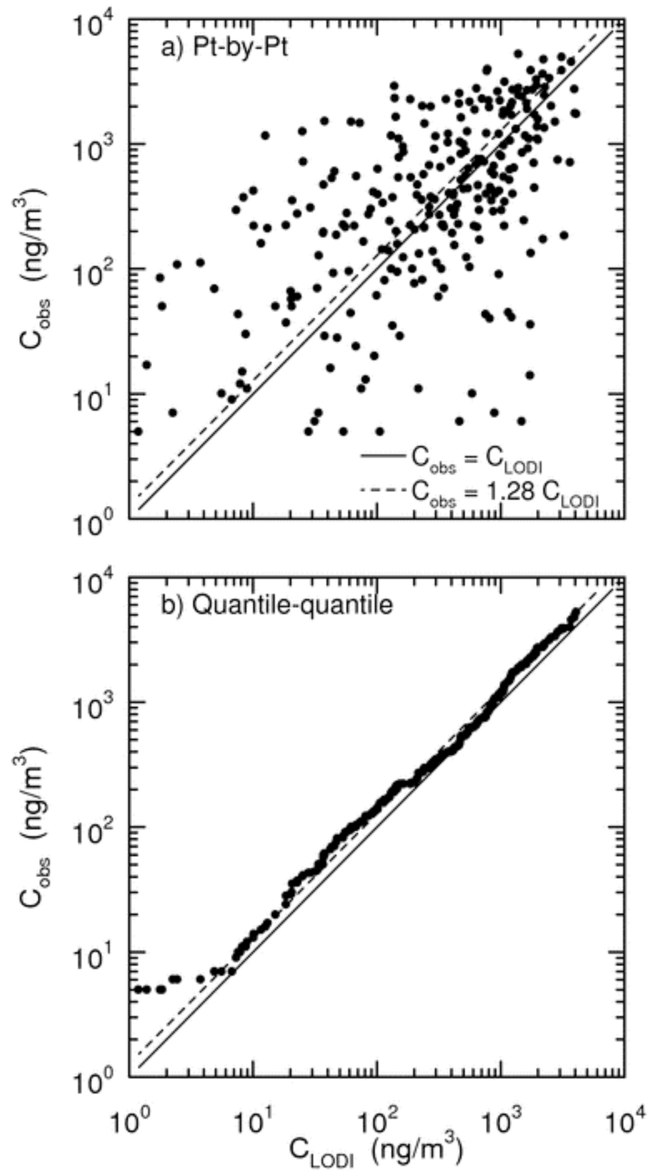
All



PDF Model vs Convection Tank Data

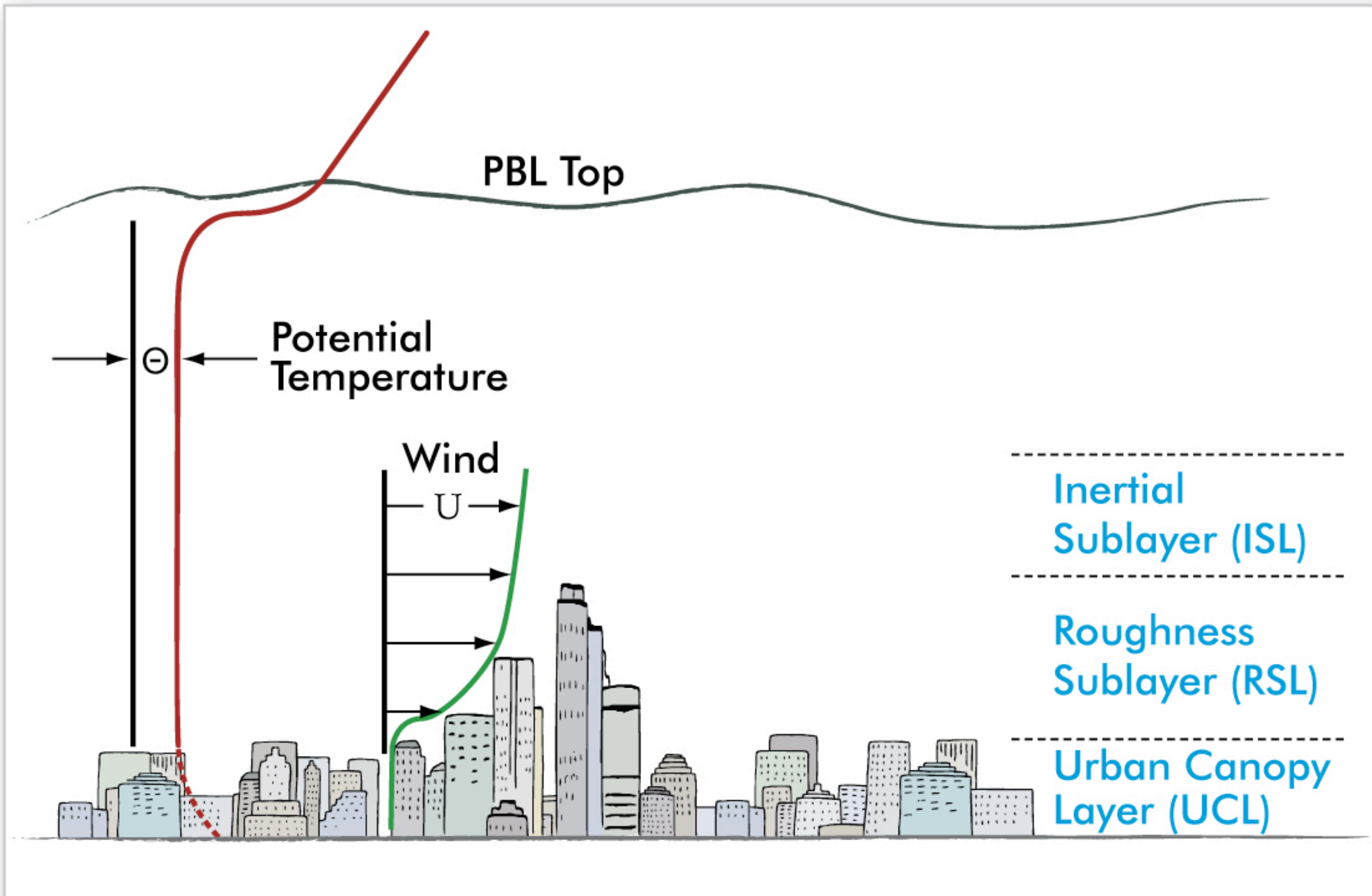


Observed Surface Concentrations vs LODI

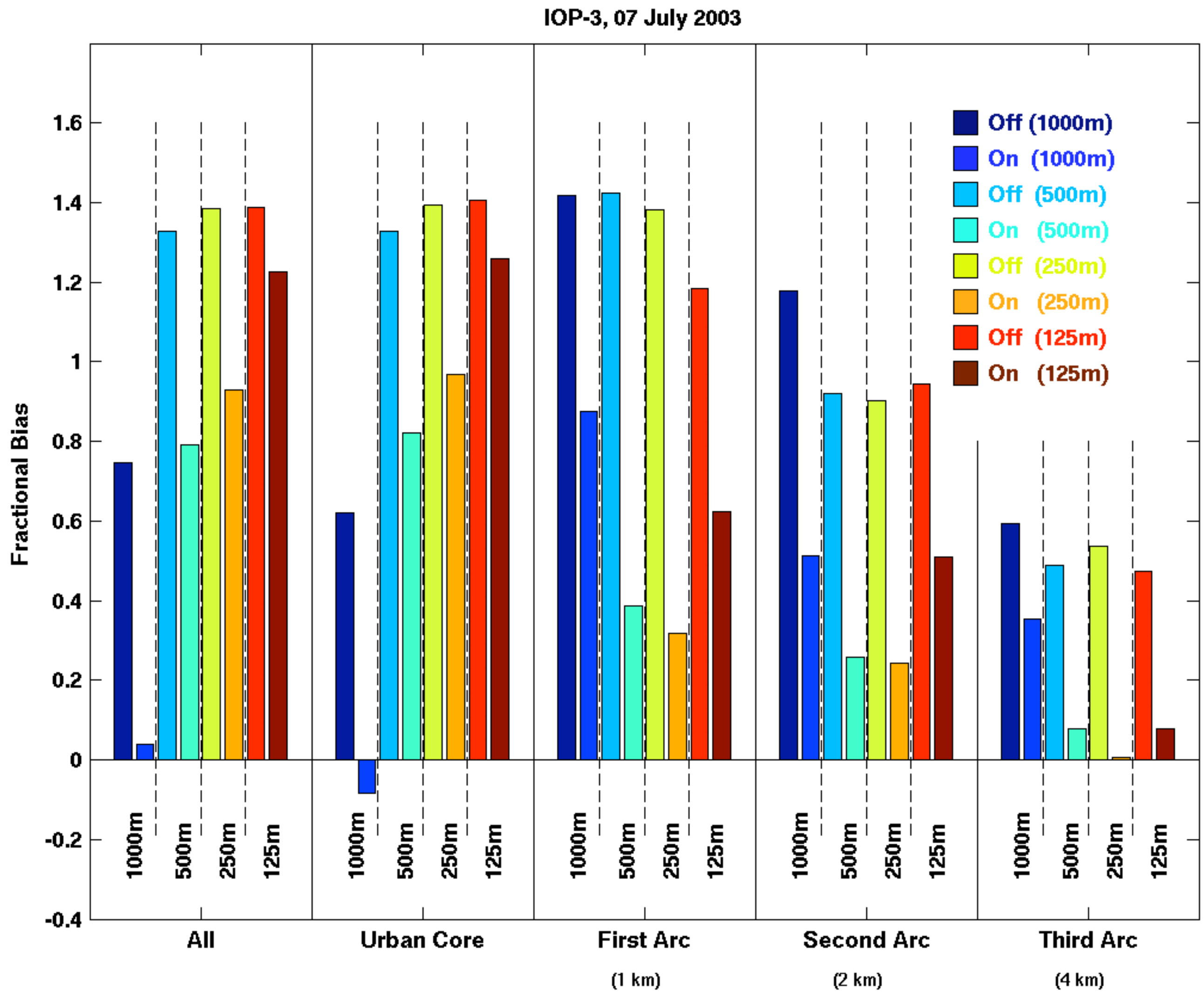


Urban Boundary Layer

Daytime - Convective boundary layer

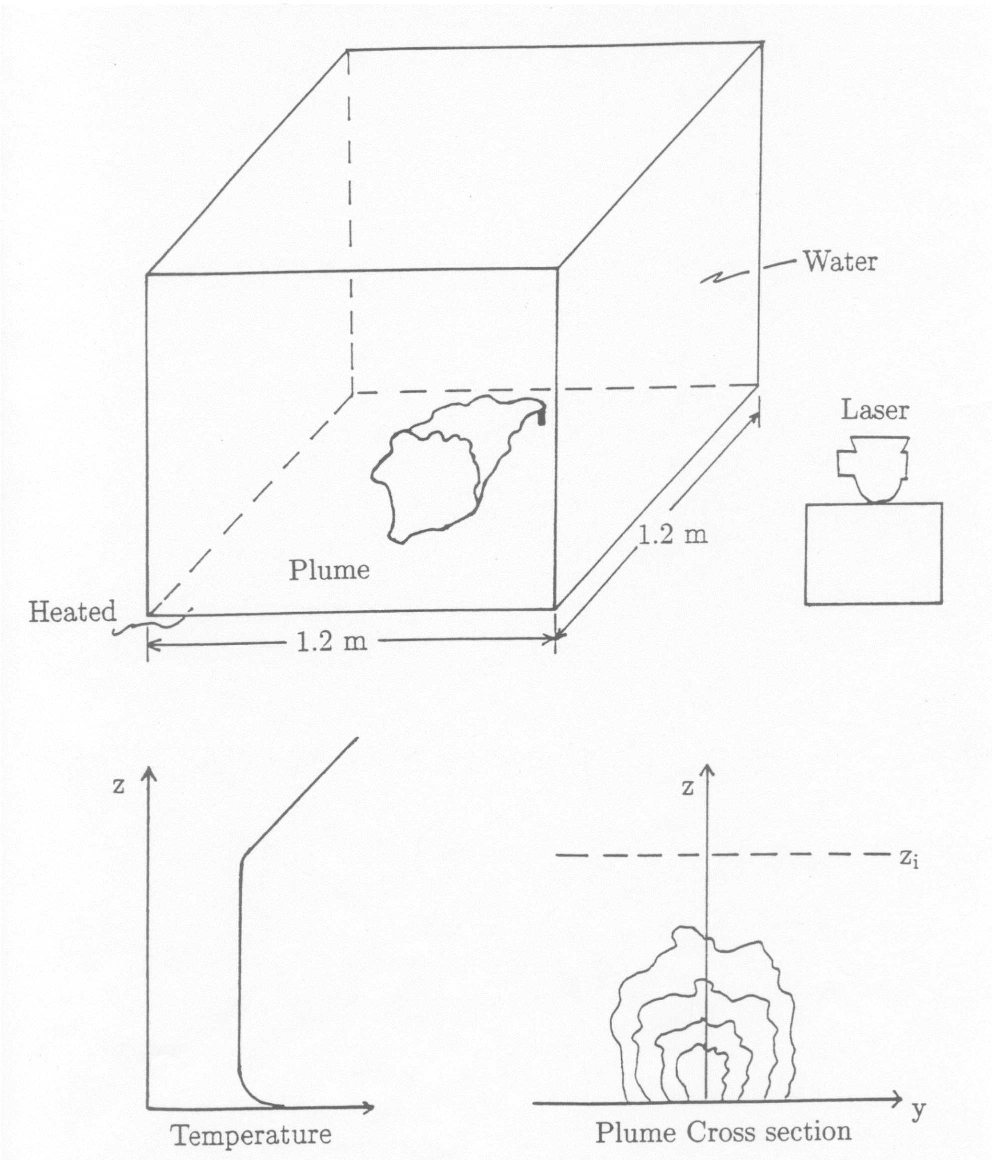


Fractional Bias: $2(C_p - C_o)/(C_p + C_o)$



Convection Tank Experiments

Willis & Deardorff (1976, 1978, 1981)



Basis for experiments:
"Mixed layer" & uniform wind