

# CHARACTERIZING UNCERTAINTY IN PLUME DISPERSION MODELS

*By*

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9<sup>th</sup> International Conference on Harmonisation within  
Atmospheric Dispersion Modelling for Regulatory Purposes,  
June 1-4, 2004, Garmish-Partenkirchen, Germany

# Motivation

- Additional information for decision makers
  - assess significance of “differences” between alternatives,
  - transparency of assumptions.
- Provides an estimate of “extremes” (i.e., exposure assessments, “safe zones” for hazardous releases).
- Provides a basis for identifying the major contributors to variability and uncertainty (i.e., focus for future research).

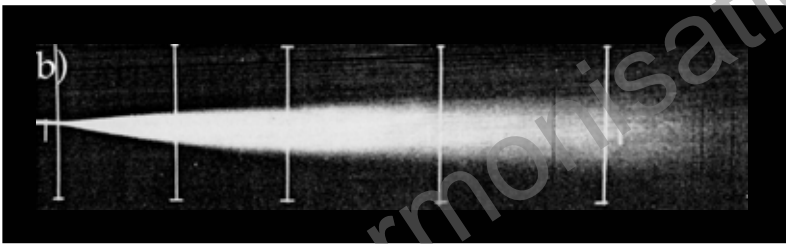
# Modeling Atmospheric Transport and Diffusion is the Characterization of the Effects of Chaos

- Complex Determinism – each molecule obeys deterministic laws of physics, but the complex interaction of billions of particles allows only a statistical characterization of the end result.
- Butterfly Effect – the inevitably incomplete initialization will lead to inevitably growing error in the model's prognoses, even if the physics is perfectly complete.

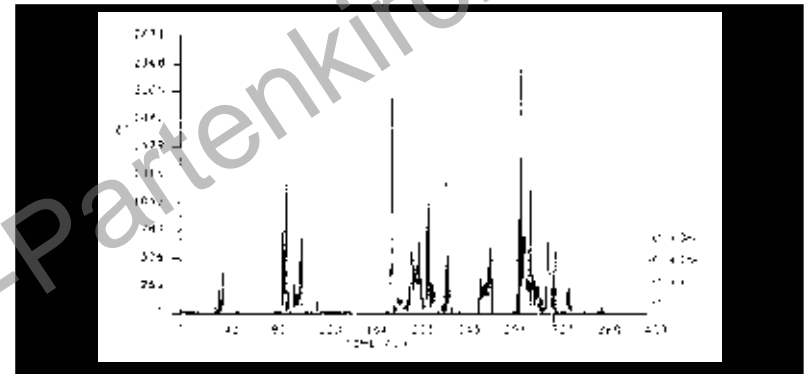
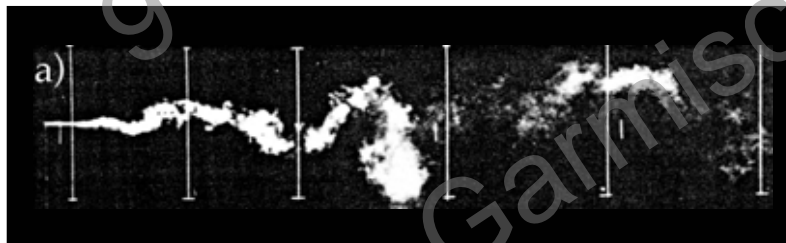
# Concentration Fluctuations

– for toxic gases – instantaneous peaks can be lethal ... these are short term phenomenon ... turbulence controlled ... most models provide the “time-average” result.....remember, models cannot predict exactly what actually will be seen... models can only predict the “average characteristics” of what is to be seen....

time-averaged picture



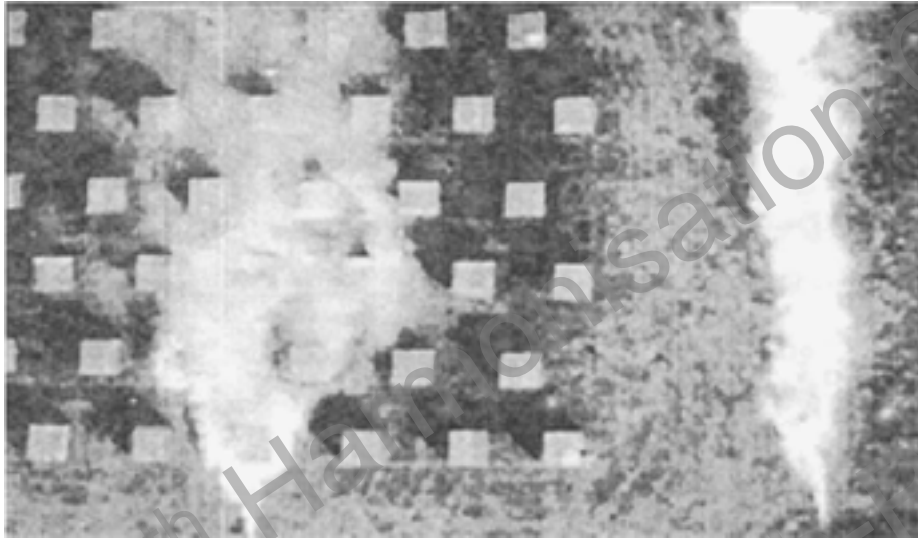
real-time picture



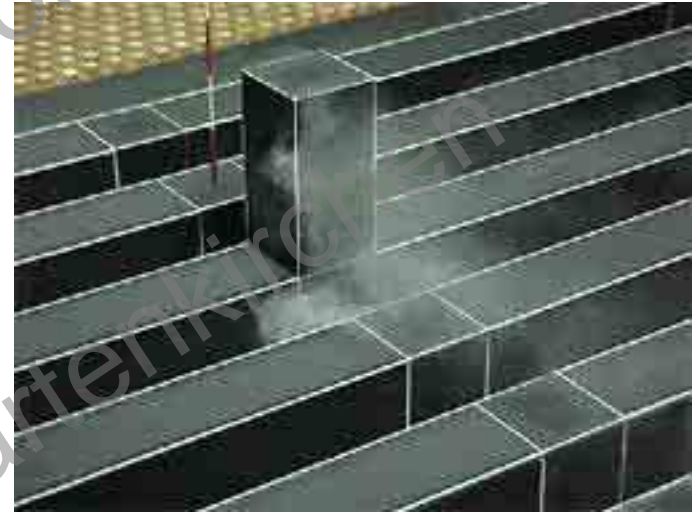
concentration time-series measurements

## Buildings increase mixing in complex ways

Models cannot predict exactly what is actually seen... models can only predict the “average characteristics” of what is to be seen.....



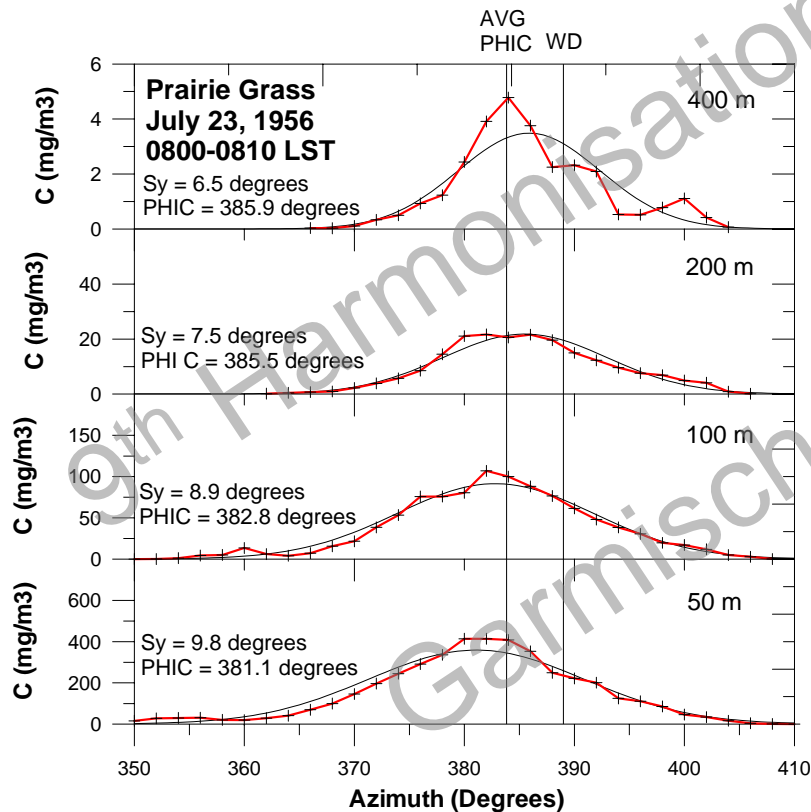
USEPA wind tunnel experiment, plan view. Dispersion over building arrays and unobstructed fetch.



USEPA wind tunnel experiment, release at street level in canyon.

# What Do “Real” Plumes Look Like?

Project Prairie Grass involved a point source release 0.5 meters above the ground. The experiments were conducted in a manicured nearly-flat field near O’Neil Nebraska.

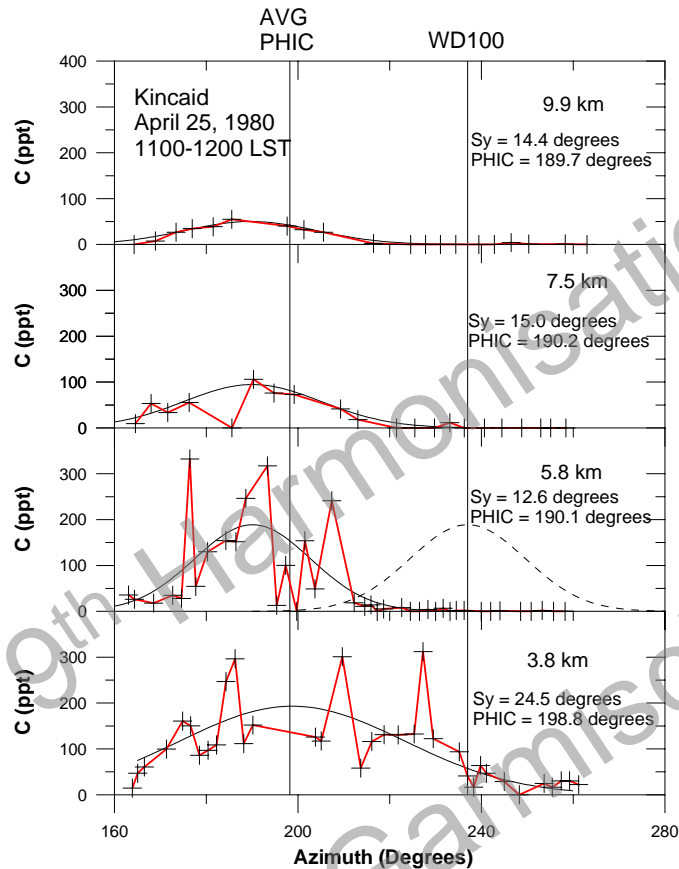


Analysis of 10-minute concentration values seen for July 23, 1956 from 0800 to 0810 LST.

Results shown are for first four arcs. Solid lines with symbols show measured sulfur-dioxide values. A Gaussian fit is shown for each arc. The resulting plume centerline position, PHIC, and lateral dispersion, Sy, is shown for each arc.

The two vertical solid lines illustrates the transport wind direction indicated by the 2-m wind and the average of the PHIC determined individually for each arc.

The Kincaid tracer experiments involved injecting SF6 into the gas exiting up a power-plant smoke stack. The smoke stack was 183 m tall, and the gases were hotter than the air, rose and leveled off at about 300 m above the ground.



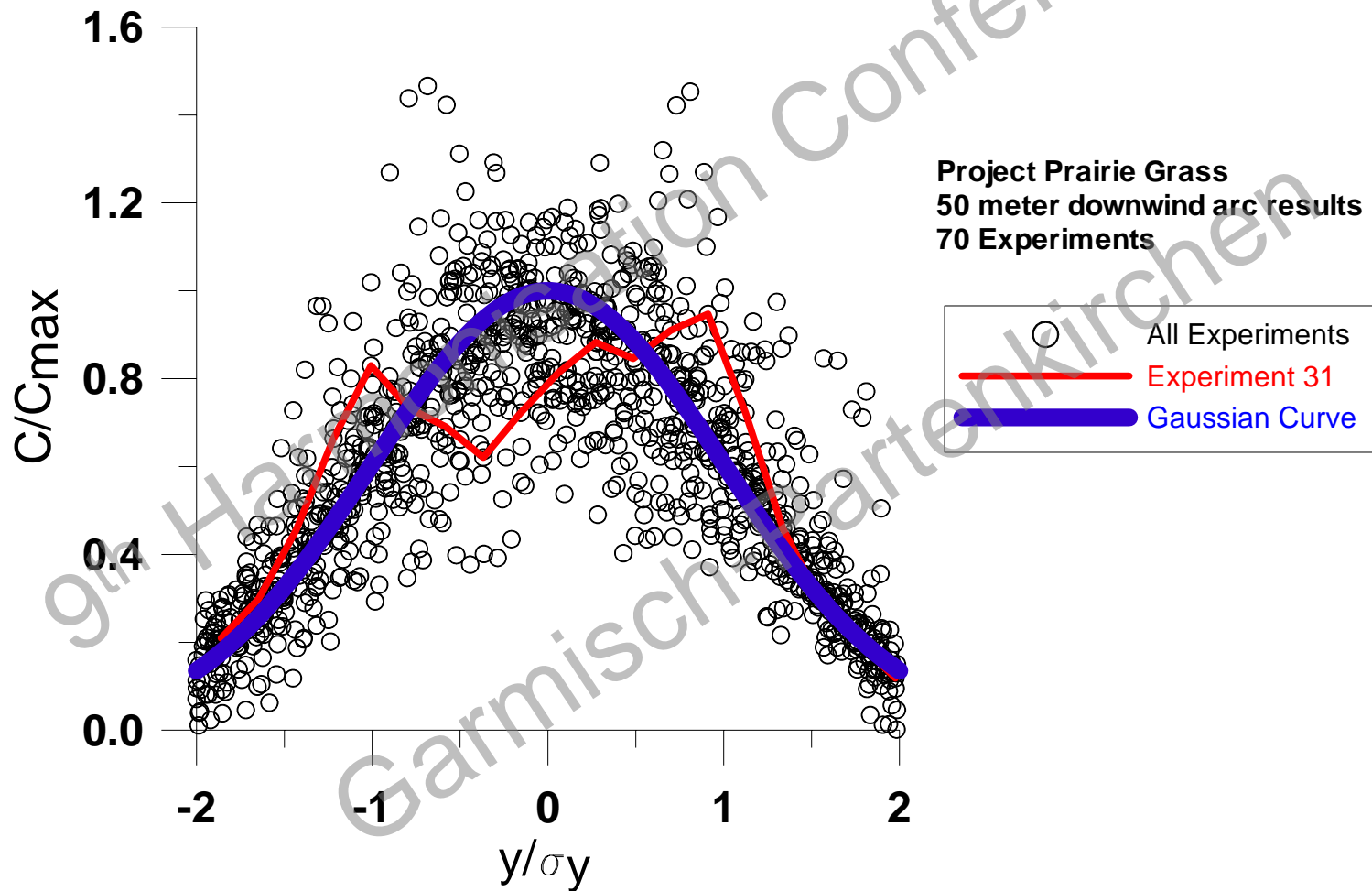
.Analysis of 1-hr concentration values seen for April 25, 1980 from 1200 to 1300 LST. Results are shown for four arcs.

Solid lines with symbols show measured SF6 values. A Gaussian fit is shown for each arc. The resulting plume centerline position, PHIC, and lateral dispersion, Sy, is shown for each arc.

The two vertical solid lines illustrates the transport wind direction indicated by the 100-m wind and the average of the PHIC determined individually for each arc.

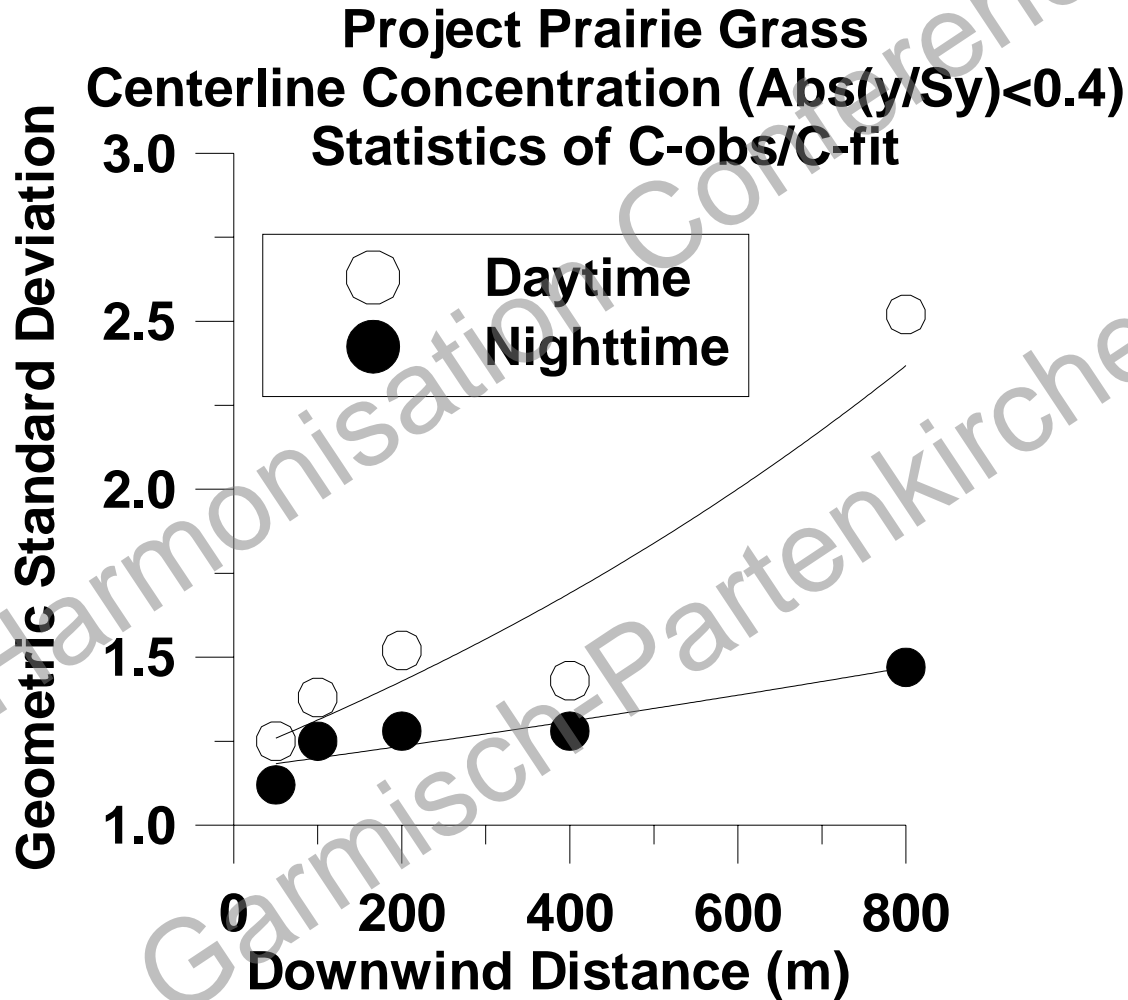
The dotted line (second arc) shows the effect of differences in transport between what is estimated by a wind direction at the release and what actually occurs.

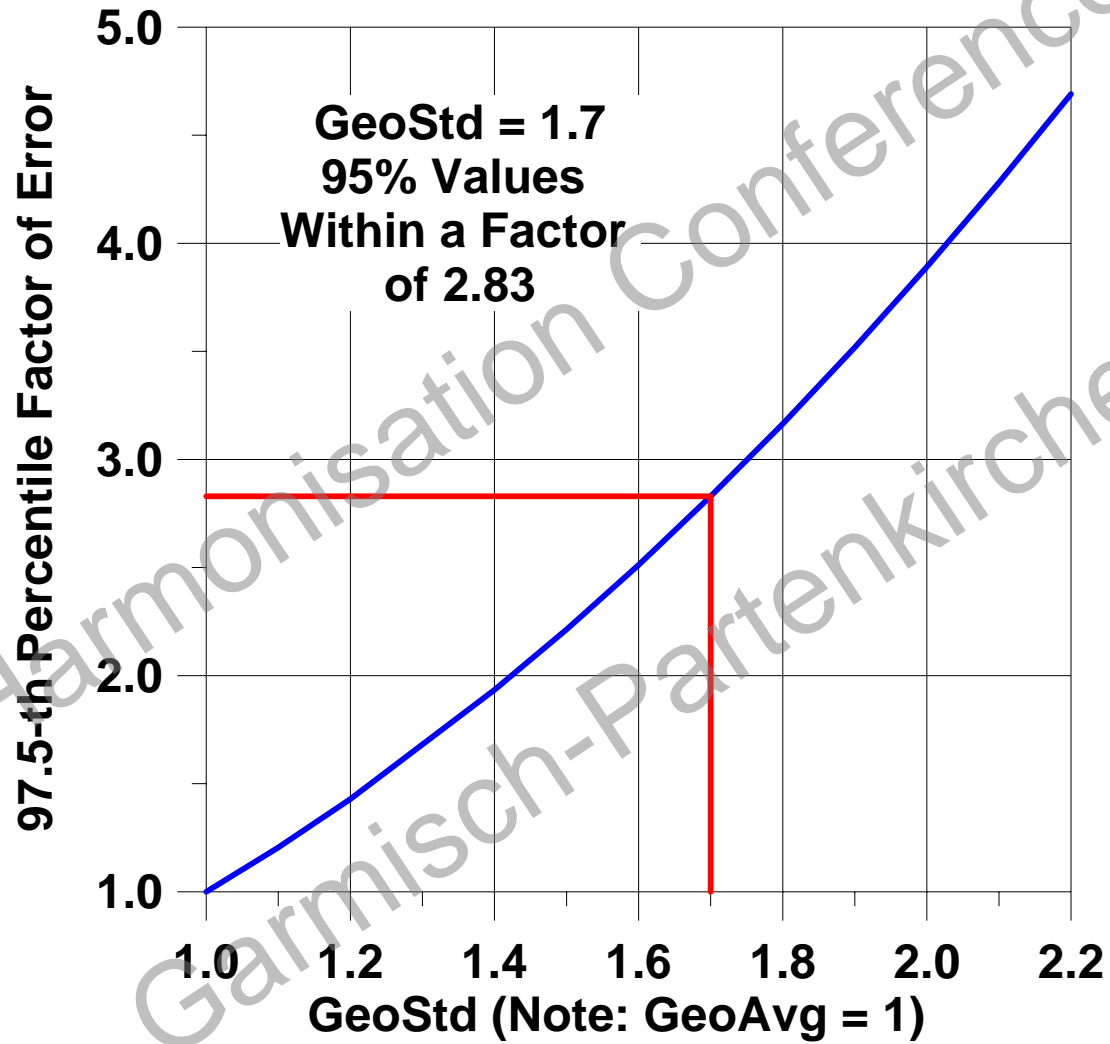
Composite Analysis for Project Prairie Grass Experiments  
All the “scatter” about the blue line (Gaussian fit) is what a Gaussian plume model does not characterize.





# Variability In Prairie Grass Centerline Concentrations





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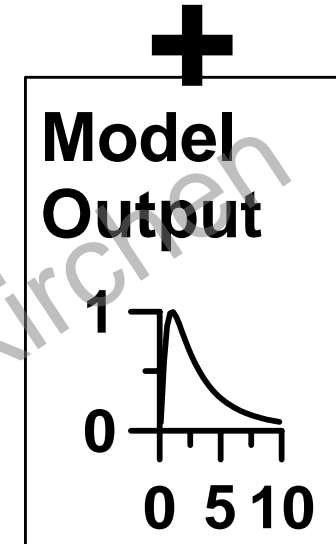
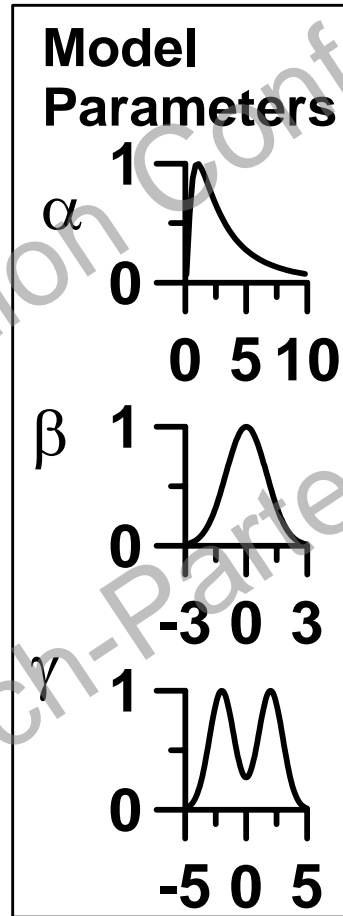
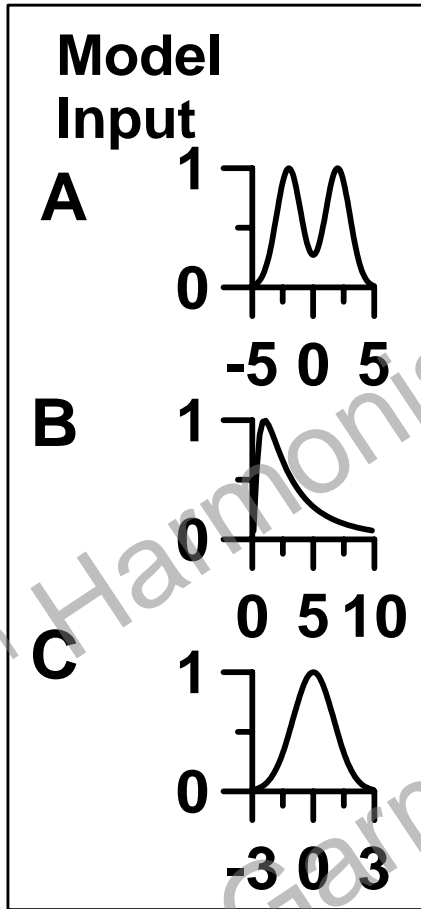
# Can we “add back in” the uncharacterized “scatter”?

- There are more elegant ways, but a brute force (Monte Carlo) approach is to “simulate” the scatter, by running the model 100 to 1000 times, and slightly vary components of the modeling system.
- As depicted on the next illustration, many have simulated the effects of input uncertainties. But this cannot add the “scatter” depicted in the previous figures, as it not part of the modeling system to begin with (the “never” in the upper right corner of the next illustration).
- Some have varied the internal parameters in the model (e.g., lateral and vertical dispersion, plume rise). These internal parameters in the model describe the “average” of what is to be seen, just as the Gaussian profile describes the average lateral profile (the blue line shown on the composite analysis of Project Prairie Grass experiments).

# Variability

Almost  
Never

Not In the  
Model  
Variations



Often



Sometimes

Monte Carlo

Just how much variation is not captured by “average” dispersion or “average” plume rise?

Lateral Dispersion

Summary of comparison of Model 3 ( Irwin, 1983) predictions of vertical and lateral dispersion parameters with field data from 26 sites. GeoSD is the geometric standard deviation.

<u>Elevated Lateral Dispersion Sites</u>				<u>Elevated Vertical Dispersion Sites</u>			
Experiment Site	Number	Bias	GeoSD	Experiment Site	Number	Bias	GeoSD
Hanford(67)-56m	68	1.00	1.52	Agesta	24	1.09	1.39
Hanford(67)-26m	210	0.81	1.51	Karlsruhe	87	1.03	2.04*
NRTS	96	0.92	1.23	Porton	9	0.93	1.46
Karlsruhe	39	0.61	2.37*	Hanford	19	1.46	1.49
Hanford	57	0.90	1.19	NRTS	96	1.49	1.36*
Suffield	104	1.08	1.43				
<u>Near-Surface Lateral Dispersion Sites</u>				<u>Near-Surface Vertical Dispersion Sites</u>			
Experiment Site	Number	Bias	GeoSD	Experiment Sites	Number	Bias	GeoSD
Mt. Iron	161	2.07	1.92*	NRTS-B	42	0.57	1.90
NRTS-B	44	0.91	1.24	NRTS-A	46	1.26	2.32
NRTS-A	84	1.24	1.39	Prairie Grass	203	1.24	1.63*
Hanford 30	117	0.90	1.40*	Round Hill I	52	1.03	1.40*
Green Glow	86	0.82	1.51				
Prairie Grass	315	1.12	1.68*	Values with * denote cases where a Normal distribution best characterizes the random errors, but for which, we also found a log-normal distribution fits nearly as well.			
Dry Gulch	266	1.72	1.62				
Ocean Breeze	172	1.78	1.44*				
Round Hill II	30	1.38	1.29				
Round Hill I	72	1.13	1.41				
Handord(67)-2m	104	1.00	1.49*				

$$\frac{1}{\sigma_y} = \text{Avg} \left[ \frac{b' e'}{\sigma_y} \right]$$

$b'$  accounts for random biases  
(e.g., update every simulated year).  
Lognormal distribution [1.0, 1.35]

$e'$  accounts for random errors,  
(e.g., update every simulated hour).  
Lognormal distribution [1.0, 1.54]

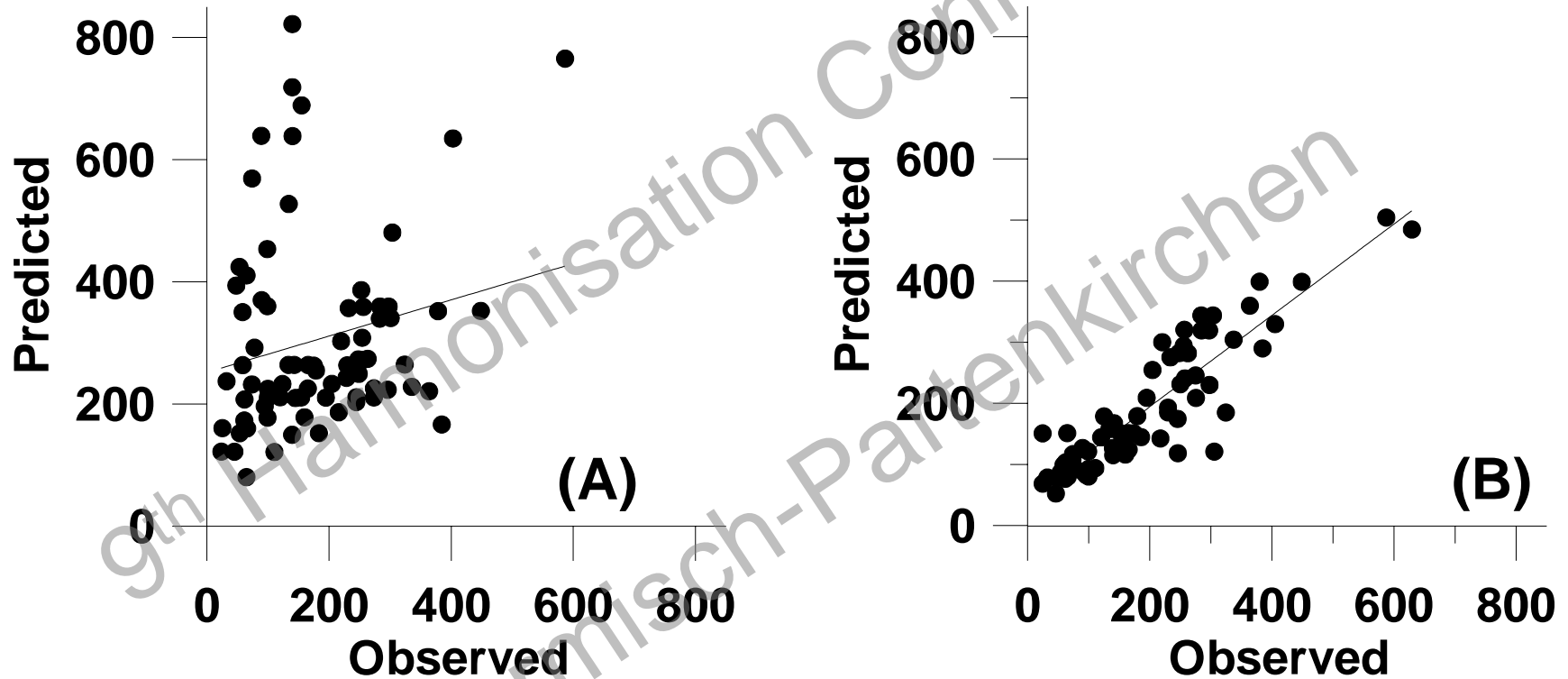
$$\text{GeoStd}(b' e') = 1.70 = \text{Exp} \{ \text{Sqrt}[\ln^2(1.35) + \ln^2(1.54)] \}$$

# Plume Rise

- Briggs (1969) Table 5.1, 17 Power Plants. P/O was Lognormal GeoStd = 1.34
- Liu et al., (1984) Fig 8-3 Kincaid GeoStd = 1.29
- Erbrink (1994)
  - Fig 4: Amer Station, The Netherlands GeoStd = 2.10
  - Fig 5a: Amer, Leipzig, Cracow GeoStd 2.10
  - Fig 5b: Profiles of T, Td, WD and U (**30 meters intervals**), GeoStd = 1.48
  - **Note: GeoStd = 1.4 (Factor of 2); GeoStd = 2 (Factor of 4)**



# Erbrink (1994) Figure 5



(A) Briggs plume rise with stack top winds.

(B) Briggs plume rise using wind and temperature profiles having data every 30 m above stack top.

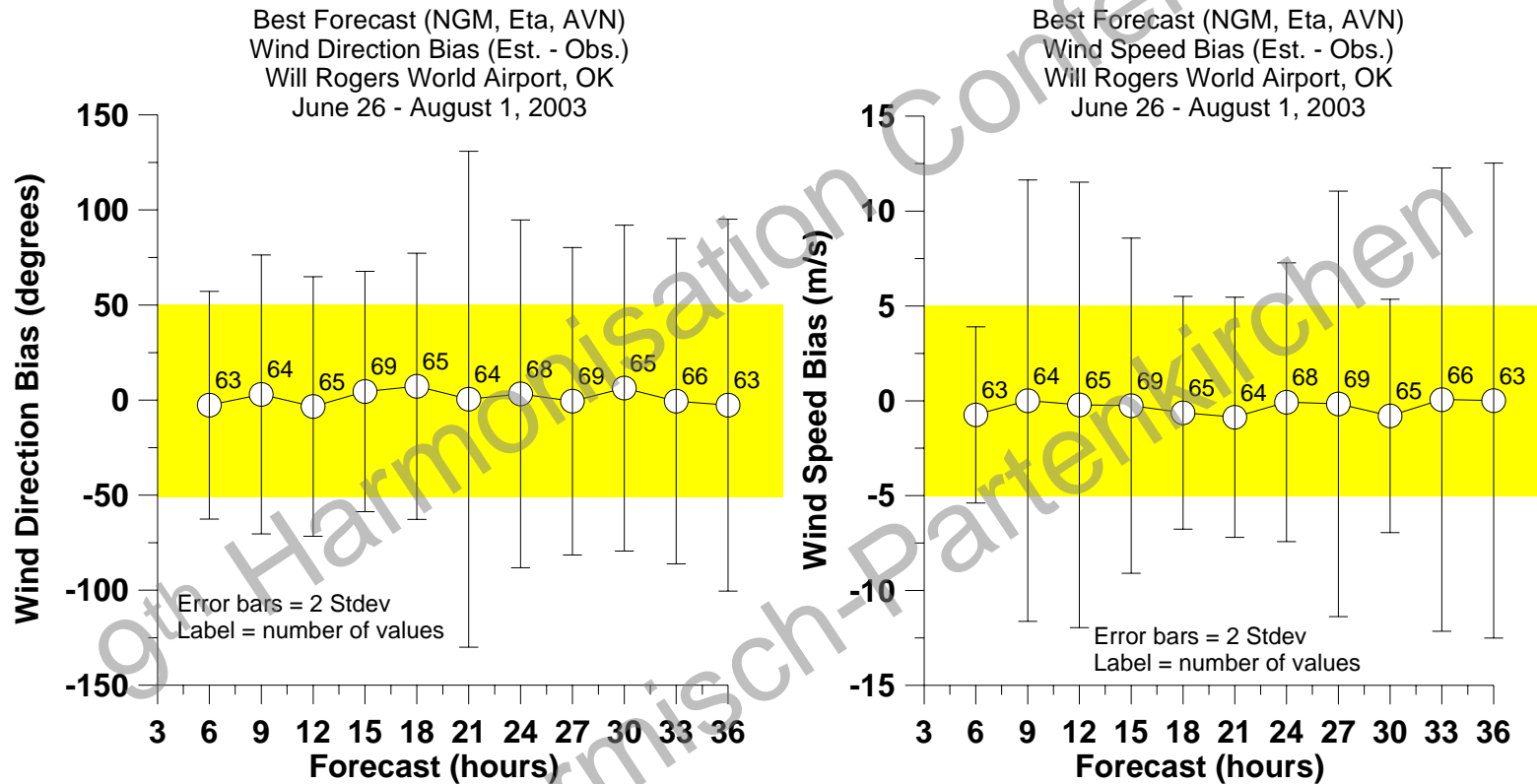
$$\chi = \frac{s \cdot f_{\sigma_y} \cdot f_{\sigma_z} \cdot Q}{\pi \sigma_y \sigma_z u} \exp\left(\frac{-0.5 \cdot f_{\sigma_z}^2 \cdot [h_s + f_{\Delta h} \cdot \Delta h]^2}{\sigma_z^2}\right)$$

- $s$  simulates non-Gaussian crosswind concentration fluctuations, GeoStd = 1.5 to 2
- $f_{\sigma_{z,y}}$  simulates variability in dispersion parameters, GeoStd = (1.35, 1.54) = 1.7
- $f_{\Delta h}$  simulates variability in plume rise, GeoStd = (1.34, 2.0) = 2.12.
- **RESULTS:** It is easy to achieve “scatter” of a factor of 4 to 6!

Just How Variable Are Wind  
Directions and Wind Speeds?

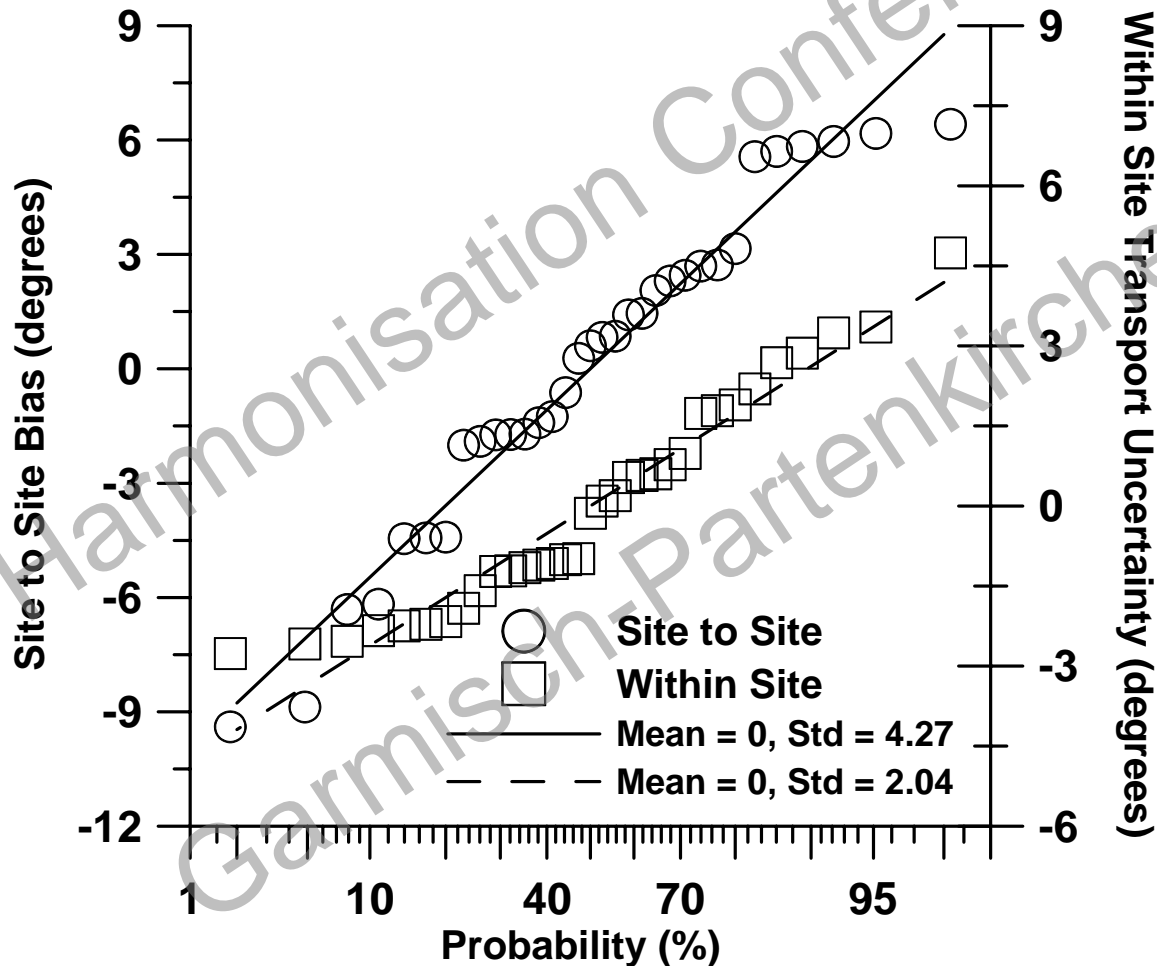
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# An example of comparisons of meso-scale wind predictions with airport observations.



**Differences in wind direction of 50 degrees and in wind speed of 5 m/s are quite typical.**

Analysis of the difference seen in observed plume transport and observed onsite wind direction, during field research studies of plume dispersion. It was seen that there was a combination of two effects: 1) an consistent bias (site-to-site error), and 2) a random error (within site error).



# Wind Variability\*\*

variability = bias + noise

- Offsite (Using NWS airport observations)
  - WD bias: Std = 10 to 20 degrees.
  - WS bias: Std = 1 to 2 m/s.
  - Noise: U and V components Std = 1 to 2 m/s
- Onsite (Research Studies)
  - WD bias: Std = 4 degrees.
  - WD noise: Std = 2 degrees

\*\* Note: Some call this “uncertainty”, but remember a model only describes a portion of the variability that occurs naturally.

# Conclusions

- To improve plume rise estimates requires accurate characterization of the profiles (30 m intervals) of temperature and wind (not likely).
- Results to date are for rural locations. How much more variability will be added due to urban buildings and associated effects?

# Research Initiatives

- Analyze rural and urban field data to relate dispersion variability to bulk statistical properties of the meteorological conditions (e.g., my day/night analysis of centerline concentrations)
- Tailor meteorological models to provide estimates of these bulk statistical properties.
- Develop an index to characterize the wind speed and wind direction variability, and have the meteorological models provide an estimate of this index (which probably is a function of the synoptic situation).
- Modify dispersion models to provide probability estimates of concentration values and related impacts.



# Other Details

- Irwin (1983): Estimating plume dispersion - a comparison of several sigma schemes. J. of Climate and Applied Met., Vol. 22, No. 1, pages 92-114
- Model 3 (simplified version of Draxler's scheme).
  - $\sigma_y = \sigma_a X / F_y(X)$ , where  $X$  is distance downwind.
- Analysis involved 26 experiments (4 groups):
  - 1) elevated vertical dispersion values (5 sites),
  - 2) elevated lateral dispersion values (4 sites),
  - 3) near-surface vertical dispersion values (6 sites), and
  - 4) near-surface lateral dispersion values (11 sites).
- Liu, M-K., G.E. Moore, J.E. Langstaff, A.B. and Hudischewsky (1984): Diagnostic Validation of Plume Models at a Plains Site, EA-3077, EPRI, Palo Alto, CA.
- Erbrink, H.J., (1994): Plume Rise in Different Atmospheres: a practical scheme and some comparisons with LIDAR measurements. Atmos. Environ. (28)28:3625-3636.
- Schere, K.L., and C.J. Coats (1992): A stochastic methodology for regional wind-field modeling. J. of Applied Meteor. (31)12:1407-1425.

# Terminology

- **Variability** - refers to the true heterogeneity that is seen in nature (e.g., animals of the same species have differences in size, weight, and age).
- **Uncertainty** - characterizes our lack of knowledge (e.g., through a series of measurements of the weight of a block of wood, we conclude that 95% of our measurements are within 5% of the average of all measurements taken). We trust that the weight of the block of wood is constant, but we are uncertain as to the exact value due to measurement uncertainty

$$C_o(\alpha) = \overline{C_o(\alpha)} + \Delta c' + c''(\alpha, \beta)$$

where

$\overline{C_o(\alpha)}$  = concentration for  
 $\alpha$ -conditions averaged over  
all possible values of  $\alpha$

$\Delta c'$  = represents the measurement  
errors.

$c''(\alpha, \beta)$  = represents the variability  
due to unresolved physics and  
processes (“ $\beta$ -effects” or ignorance).

$$C_m(\alpha) = \overline{C_o(\alpha)} + \overline{f(\alpha)} + \Delta\alpha'$$

where

$\overline{C_m} = \overline{C_o(\alpha)} + \overline{f(\alpha)}$  = model's average concentration for conditions  $\alpha$ .

$\overline{f(\alpha)}$  = the average deterministic error in the model's estimate for conditions  $\alpha$ .

$\Delta\alpha'$  = the effects of uncertainty and unresolved variability in specifying the model's inputs.

$$C_m(\alpha) = \overline{C_o(\alpha)} + \overline{f(\alpha)} + \Delta\alpha'$$

- A common misconception is that characterization of  $\Delta\alpha'$  (e.g. Monte Carlo simulation of input uncertainties) is a characterization of  $c''(\alpha, \beta)$ .
- Notice that  $c''(\alpha, \beta)$  does not appear in the above equation. No amount of variation in the model's inputs ( $\Delta\alpha'$ ) is going to characterize  $c''(\alpha, \beta)$ .
- Characterizing variability due to unresolved physics,  $c''(\alpha, \beta)$ , can really only be deduced through an analysis that involves observations!