Cornell University

A “mixture” approach for downwash modeling

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Acknowledgments

- Jiajun Gu and Kevin Kircher at Cornell EERL for technical assistance
- Margaret LaFarr at NYSDEC, Ellen Burkhard at NYSERDA and Lisa Rector at NESCAUM for valuable discussions
- Drs. Steve Perry and David Heist at EPA for data sharing and consultations.
- Dr. Wei Tang for valuable discussions and data sharing on CFD modeling techniques
- New York State Energy Research and Development Authority (NYSERDA) for funding support

NEW YORK STATE OF OPPORTUNITY. | NYSERDA Supported

Charge questions

Q1: AERMOD version 19191 includes ALPHA options that represent formulation changes in the PRIME downwash algorithm. Two sets of options are available, one set which incorporates changes recommended by the EPA's Office of Research and Development (ORD) and the other recommended by the PRIME2 subcommittee of the Air & Waste Management Association (AWMA). An additional change was made to the BPIPPRM building processor in the way the effective building dimensions are determined for rectangular buildings when oriented at an angle to the wind flow. The updates to BPIPPRM were released in a draft version of BPIPPRM (19191_DRFT) to facilitate the testing and evaluation of the ALPHA options in AERMOD.

> Please comment on the EPA's collaborative activities and this approach to incorporate options into AERMOD to make them available to the user and scientific communities for testing and evaluation. Do you have any specific comments or thoughts regarding the updates to AERMOD version 19191 based on the work by ORD and by AWMA?

Q2: With regard to improving and refining AERMOD's treatment of building downwash, in your expert opinion, what should be the EPA's highest development priority (e.g., effective building parameters/BPIPPRM for simple and/or complex building configurations, elongated buildings, corner vortex issues, streamlined structures, porous structures, elevated platforms)?

Q3: With regard to improving AERMOD's treatment of downwash, should the EPA focus its energy on continuing to improve and maintain the PRIME algorithm or replace PRIME altogether? In other words, do you consider that PRIME is now based on science that is out-of-date? Based on your response, please share any insights you have on the direction the EPA should consider in the near-term and longer-term for improving AERMOD's treatment of building downwash.



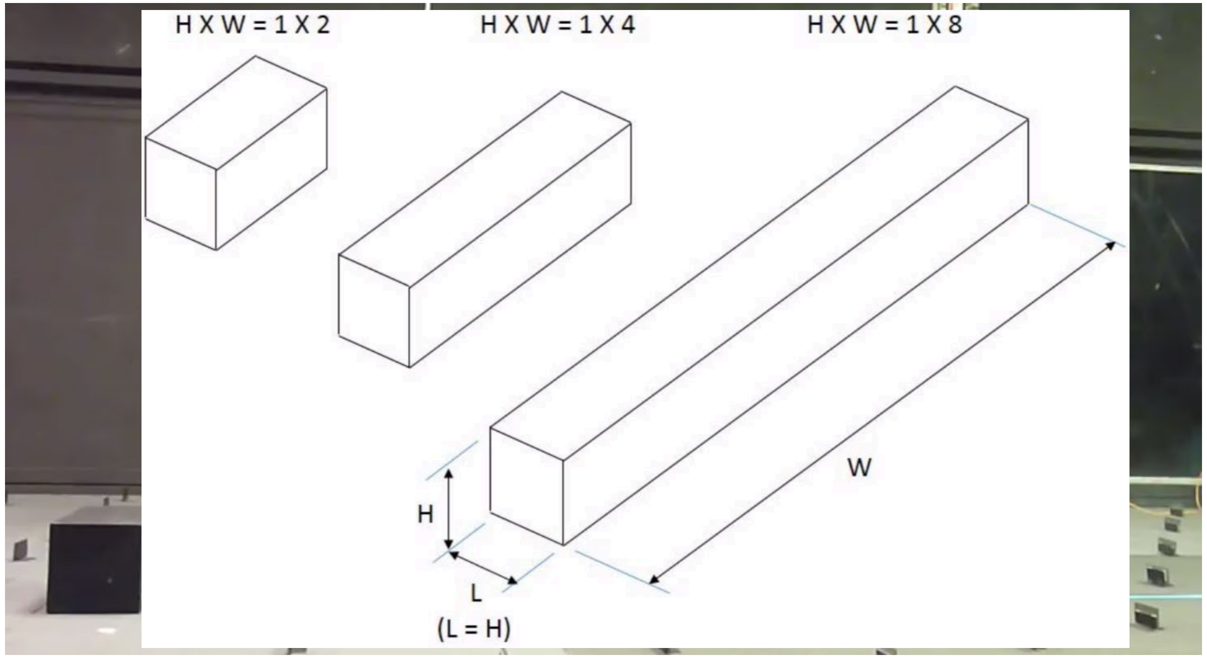



Photo credit: NYSERDA

Downwash modeling approaches in this presentation

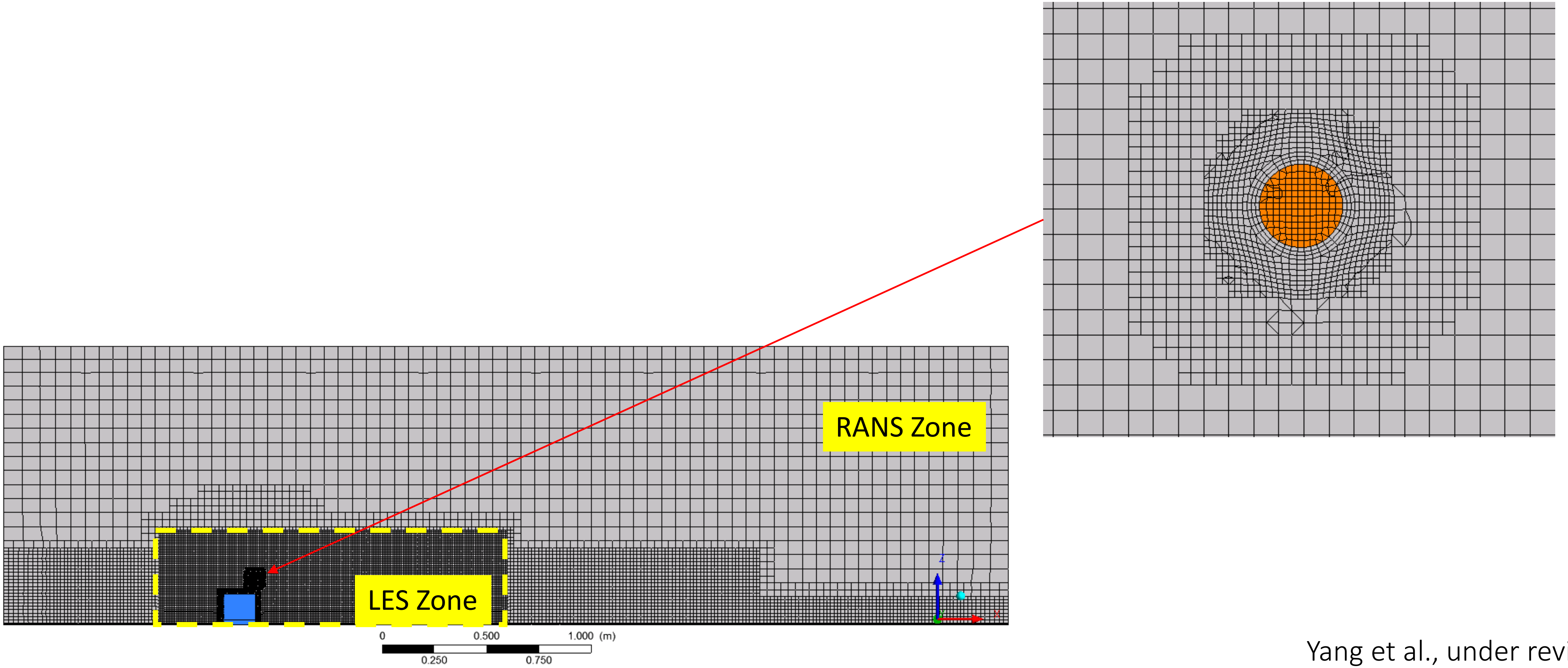
- BPIP-PRIME, the building downwash mechanism in AERMOD
- Computational fluid dynamics (CFD):
  - ➢ Computationally expensive
  - ➢ Well-configured models could lead to good results
  - ➢ Difficult to standardize
- New parameterization approach: the Mixture model
  - ➢ Assisted by CFD simulations
  - ➢ Capturing both “downwash” and “sidewash”
  - ➢ Addressing two inherent challenges in BPIP-PRIME
    - ✓ Discontinuity in the transition zone
    - ✓ Oblique wind conditions
    - ✓ Potentially more

Data: EPA wind tunnel experiment for building downwash



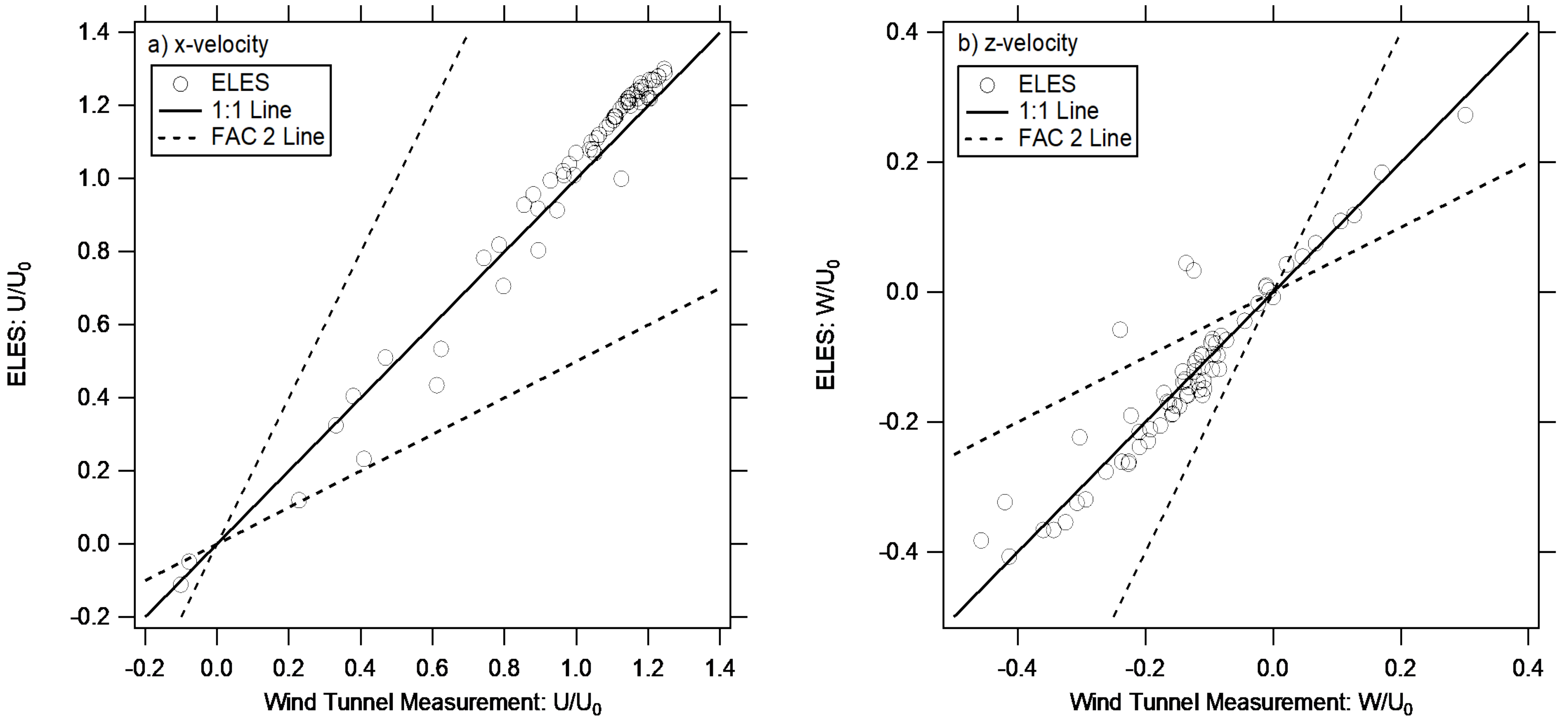
Neutrally buoyant, Low momentum, low stack height

CFD Approach: Embedded Large Eddy Simulation (**ELES**)



Yang et al., under review

CFD approach: ELES results



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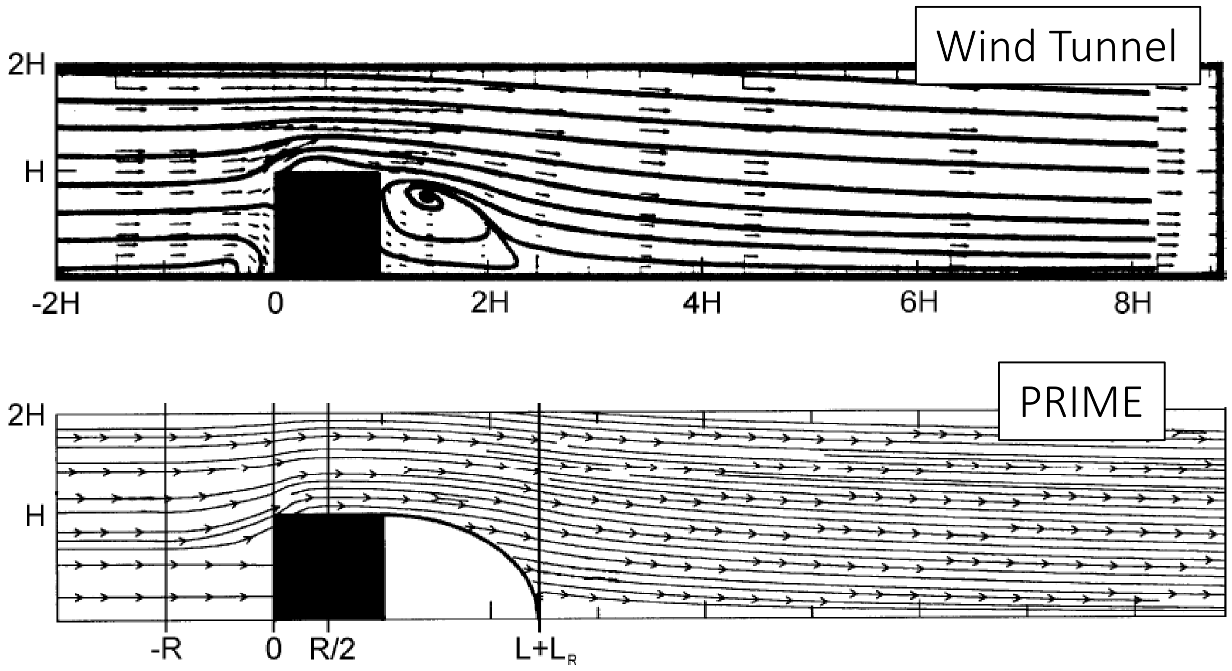
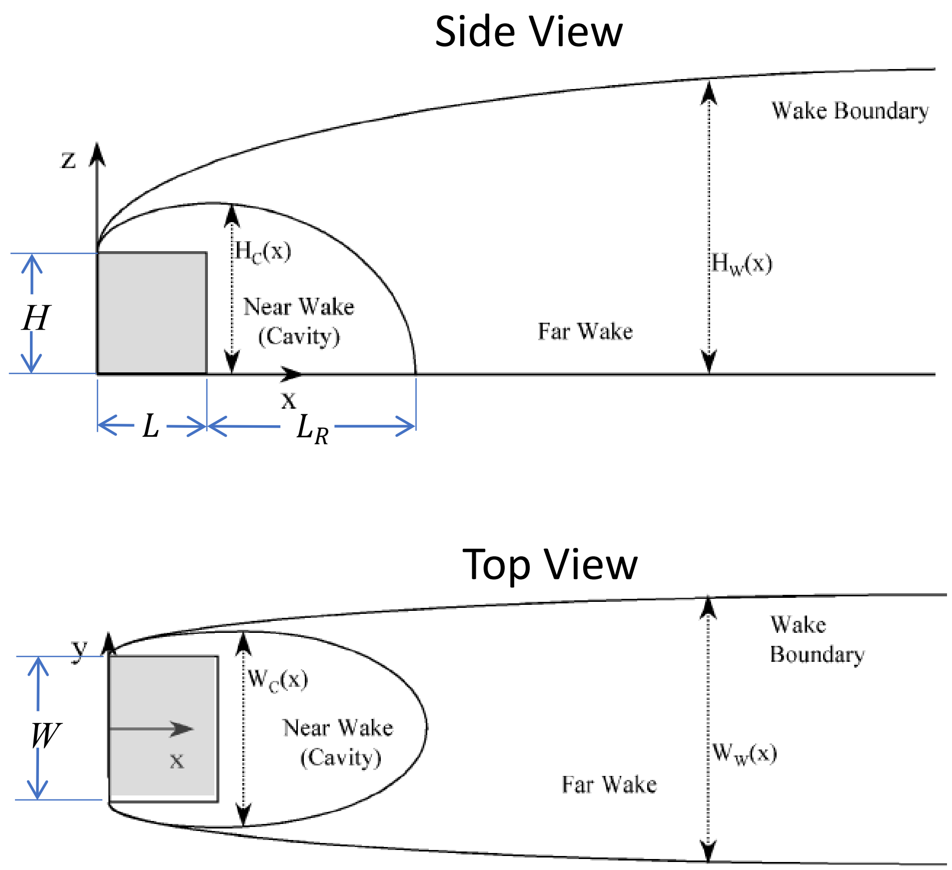
BPIP-PRIME formulation review: Flow field



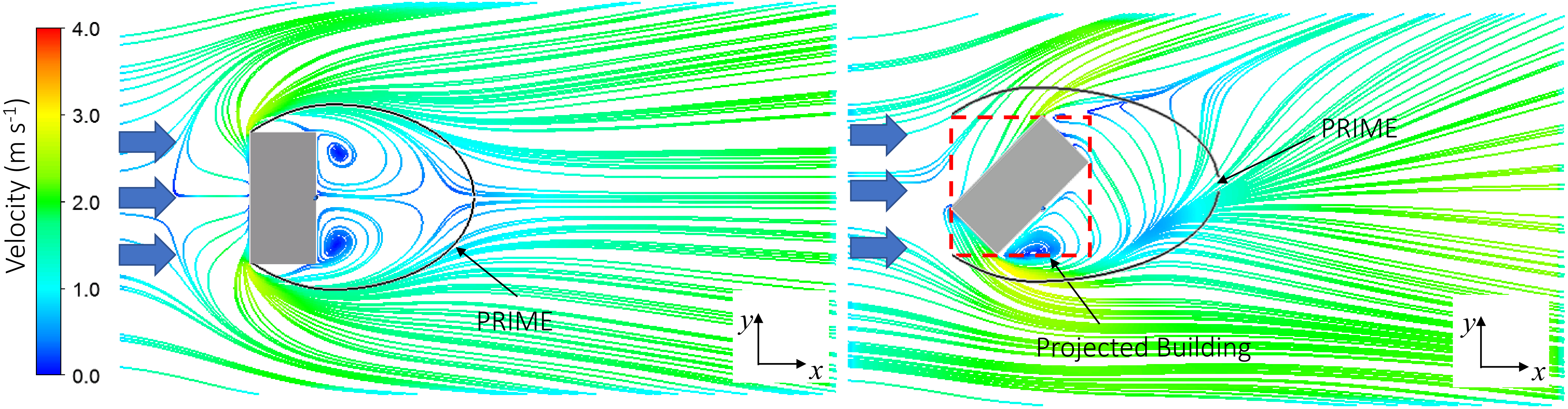


Schulman, L.L. et. al. (2011)

BPIP-PRIME formulation review: Flow field

Perpendicular wind, works well

Oblique wind, not so well



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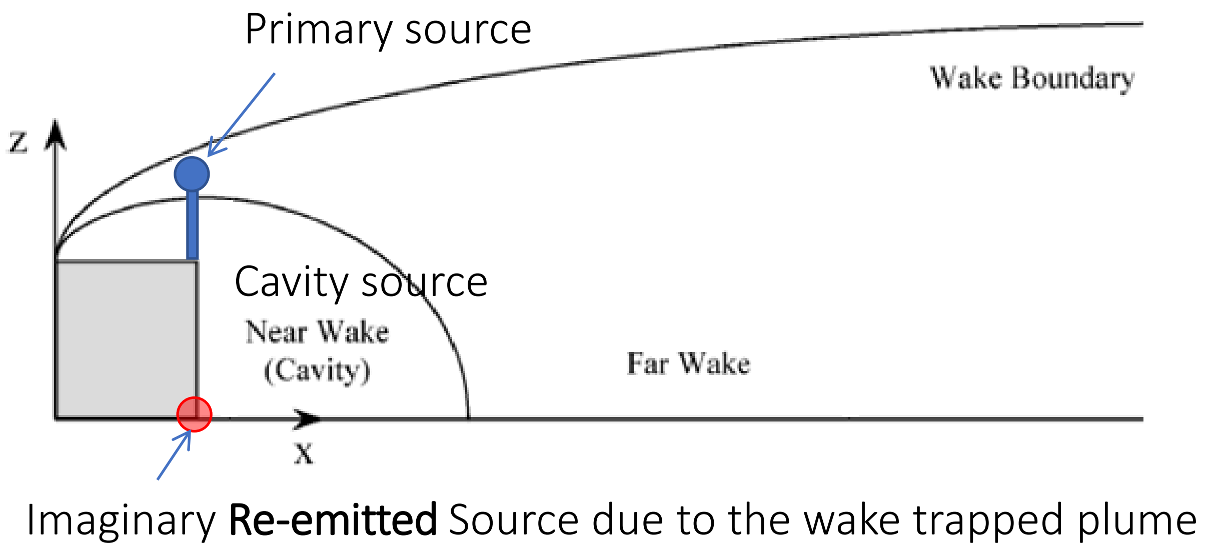
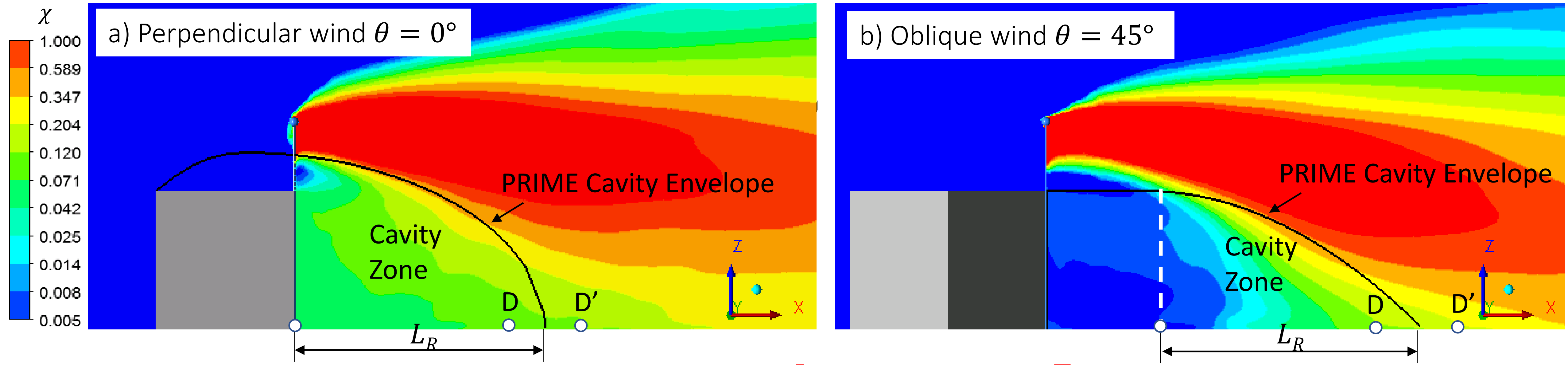
PRIME formulation review: Concentration

Ground Level Concentration (GLC)

$$C_{PRIME} = \underbrace{\frac{[(1-f)Q]}{\pi\sigma_y\sigma_z U_S}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\exp\left(-\frac{1}{2}\frac{(z-H_P)^2}{\sigma_z^2}\right)}_{\text{Primary}} +$$



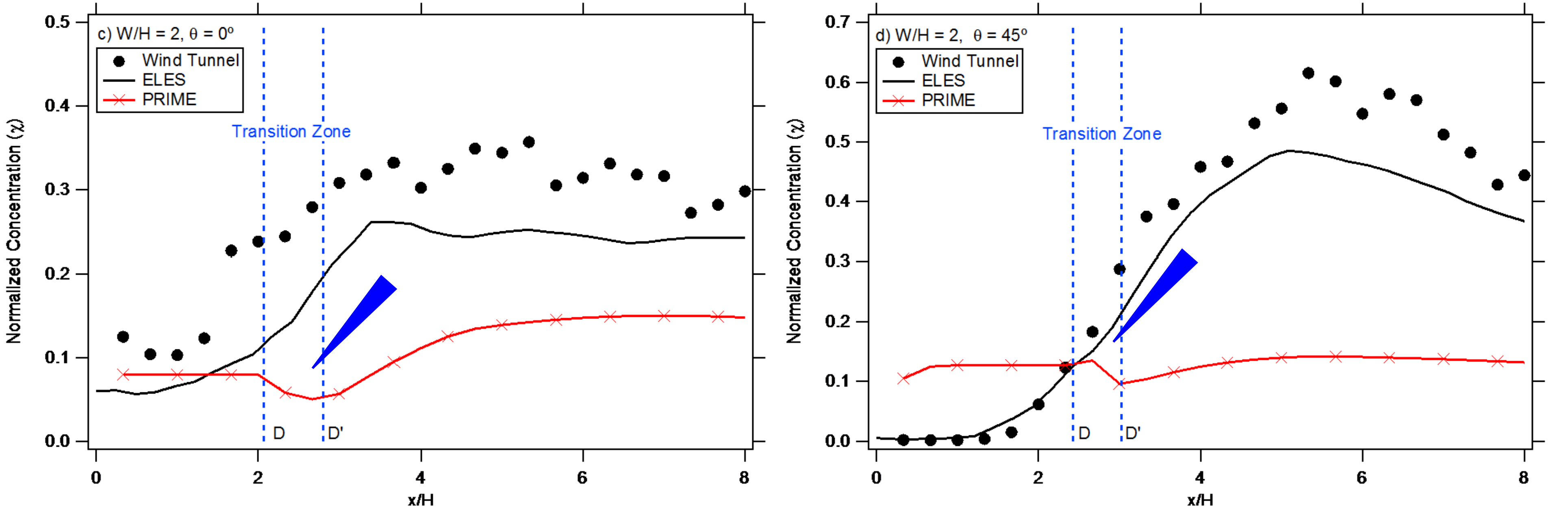
Schulman, L.L. et. al. (2011)



GLC

$$C_{PRIME} = \underbrace{\frac{[1-f_Q]}{\pi \sigma_y \sigma_z U_s} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right) \exp\left(-\frac{1}{2}\frac{(z-h_p)^2}{\sigma_z^2}\right)}_{Primary} + \underbrace{\frac{3[\lambda f_Q]}{H_c W_B U_H} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_{yc}^2}\right)}_{Cavity} + \underbrace{\frac{[1-\lambda f_Q]}{\pi \sigma_{yc} \sigma_{zc} U_s} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_{yc}^2}\right) \exp\left(-\frac{1}{2}\frac{z^2}{\sigma_{zc}^2}\right)}_{Re-emitted}$$

Discontinuity, unphysical trend in the transition zone



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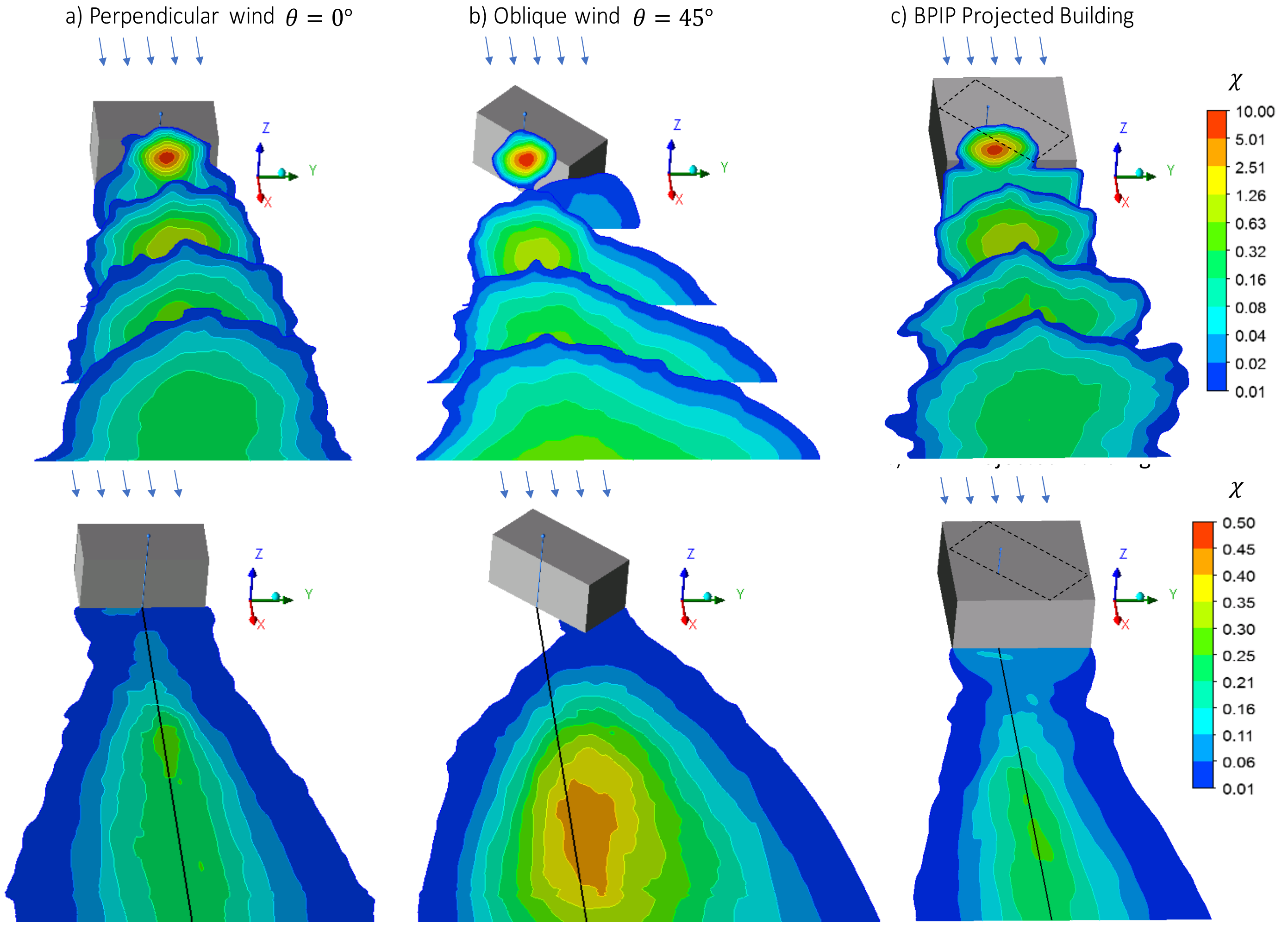
Oblique wind matters

Perpendicular | Oblique | BPIP-projected



Normalized concentration distribution at various cross-sections

Normalized ground-level concentration (GLC) distribution

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Q2: With regard to improving and refining AERMOD's treatment of building downwash, in your expert opinion, what should be the EPA's highest development priority (e.g., effective building parameters/BPIPPRM for simple and/or complex building configurations, elongated buildings, corner vortex issues, streamlined structures, porous structures, elevated platforms)?

Responses:

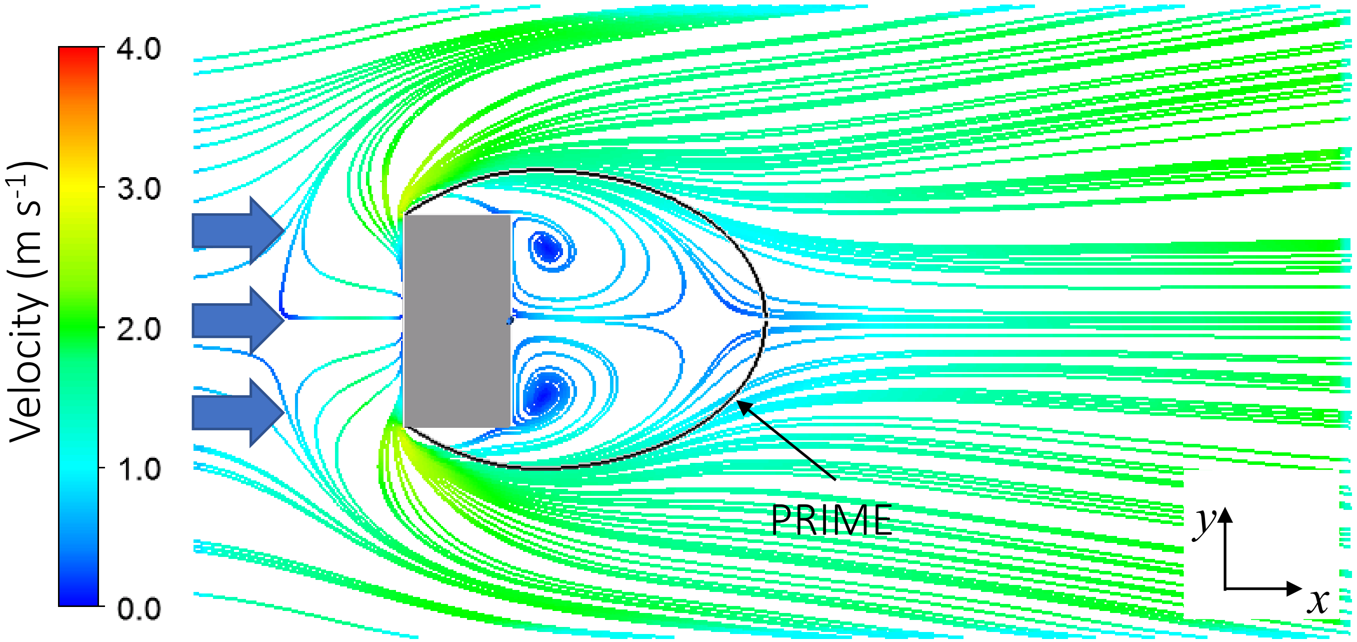
- Sources (among many other important ones)
  - Distributed generation
  - Low momentum, neutral buoyancy and short stack emission sources
- Physical mechanisms
  - Discontinuity
  - Oblique wind

Q3: With regard to improving AERMOD's treatment of downwash, should the EPA focus its energy on continuing to improve and maintain the PRIME algorithm or replace PRIME altogether? In other words, do you consider that PRIME is now based on science that is out-of-date? Based on your response, please share any insights you have on the direction the EPA should consider in the near-term and longer-term for improving AERMOD's treatment of building downwash.

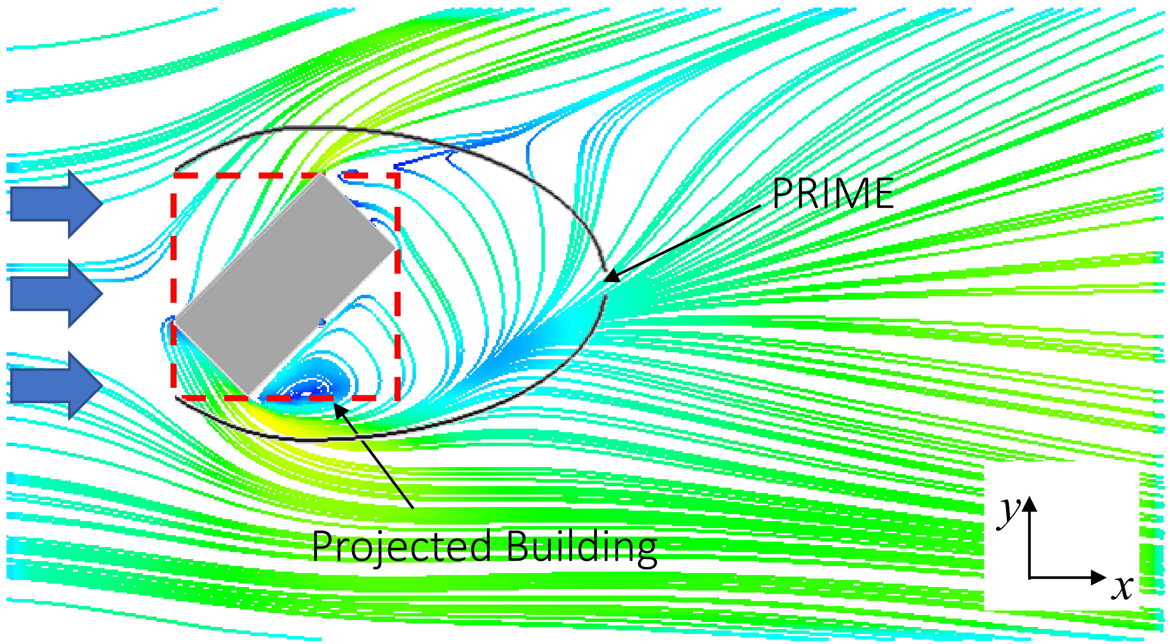
Response: Cautiously, It is strategic for EPA to support the development of an alternative modeling approaches. The rest of the presentation discusses a potential alternative approach.

BPIP-PRIME formulation review: Flow field

Perpendicular wind, works well



Oblique wind, not so well



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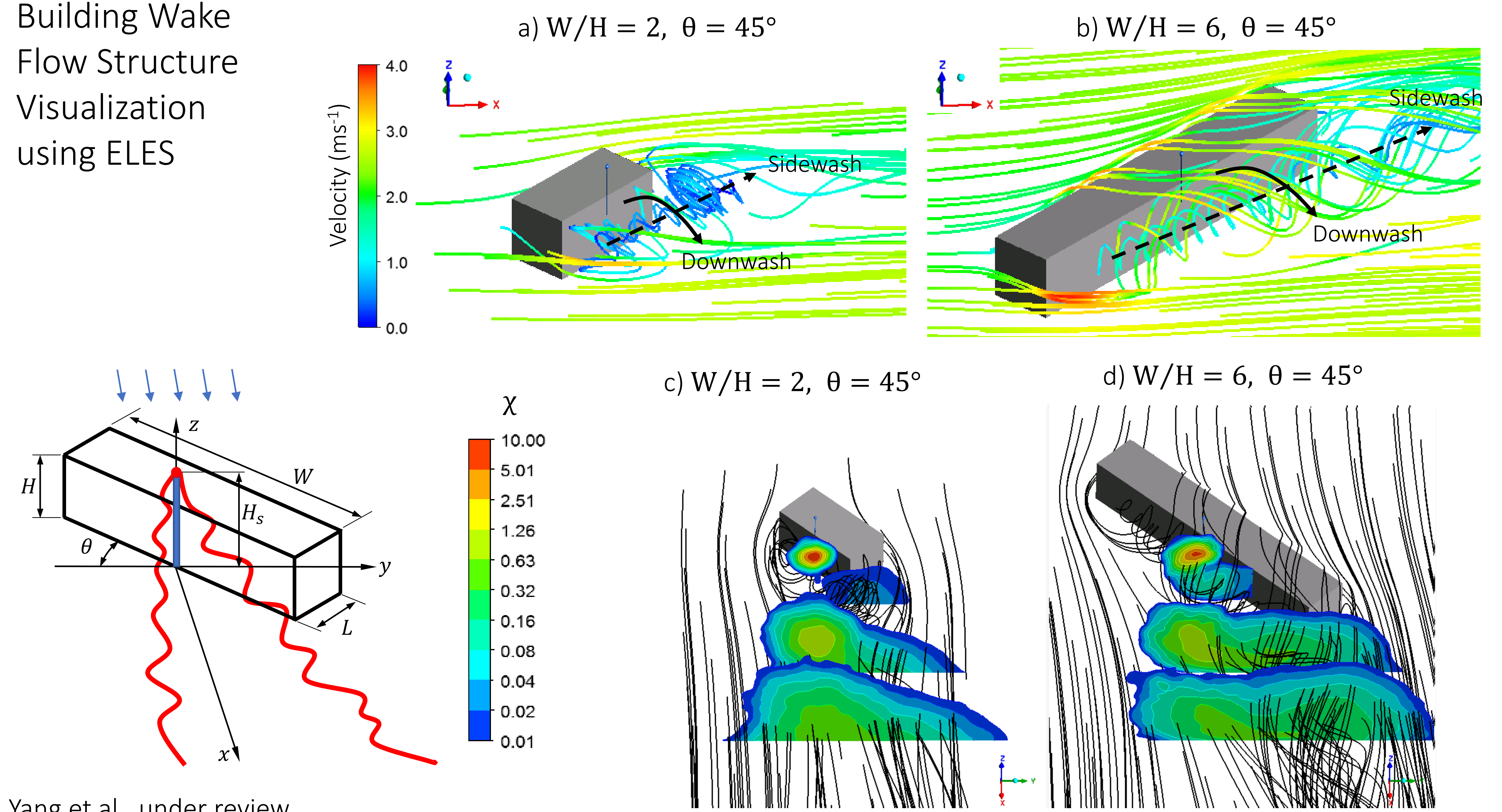
Building Wake Flow Structure Visualization using ELES



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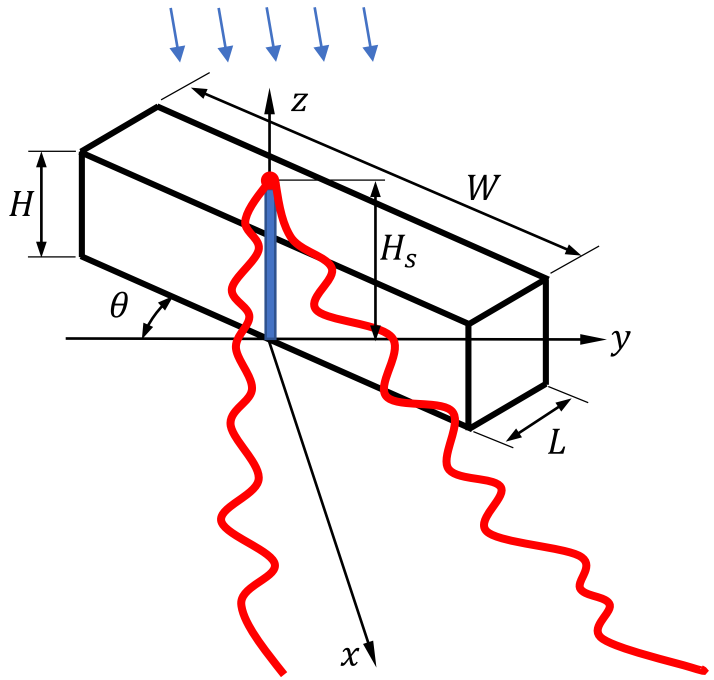
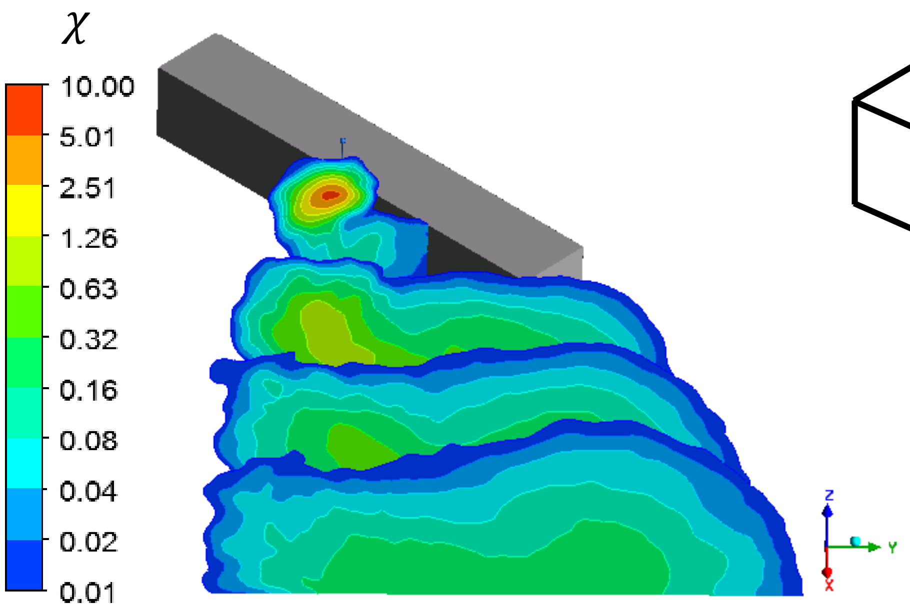
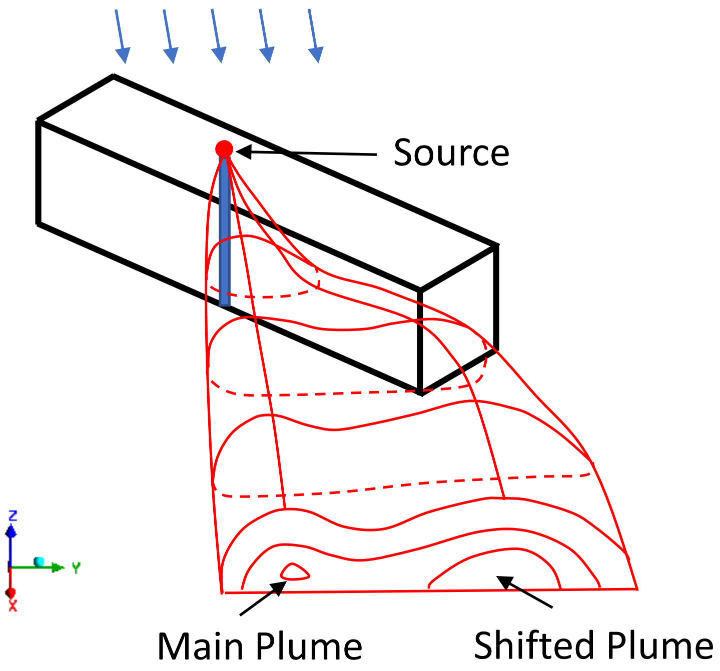
The Mixture Model







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The Mixture Model

$$C(y,z) = \sum_{i=1}^{n} \lambda_i \cdot \quad {}_i(y,z;Q,u,\mu_i,\Sigma_i)$$

$$\mu_i = \begin{pmatrix}\mu_{yi} \\ \mu_{zi}\end{pmatrix}, \Sigma_i = \begin{pmatrix}\sigma_{yi}^2 & \rho_i\sigma_{yi}\sigma_{zi} \\ \rho_i\sigma_{yi}\sigma_{zi} & \sigma_{zi}^2\end{pmatrix}$$

λ_i: The weight of each aussian   distribution, $\sum_{i=1}^{n} \lambda_i = 1$

${}_i(\cdot)$: Bivariate aussian   distribution on a YZ plane

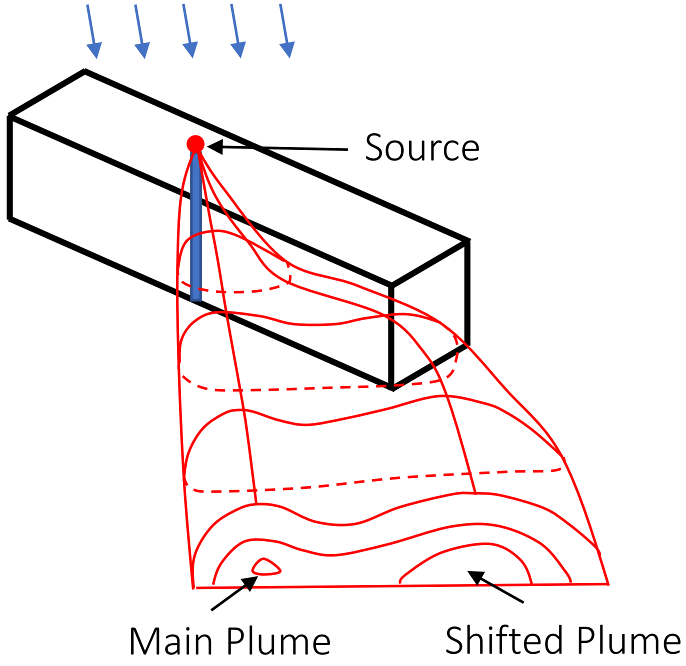
Q: Emission rate, which is given

u: Mean velocity magnitude on a YZ plane

μ_i: Peak location of each aussian   distribution

Σ_i: Covariance matrix

ρ_i: the correlation between y and z

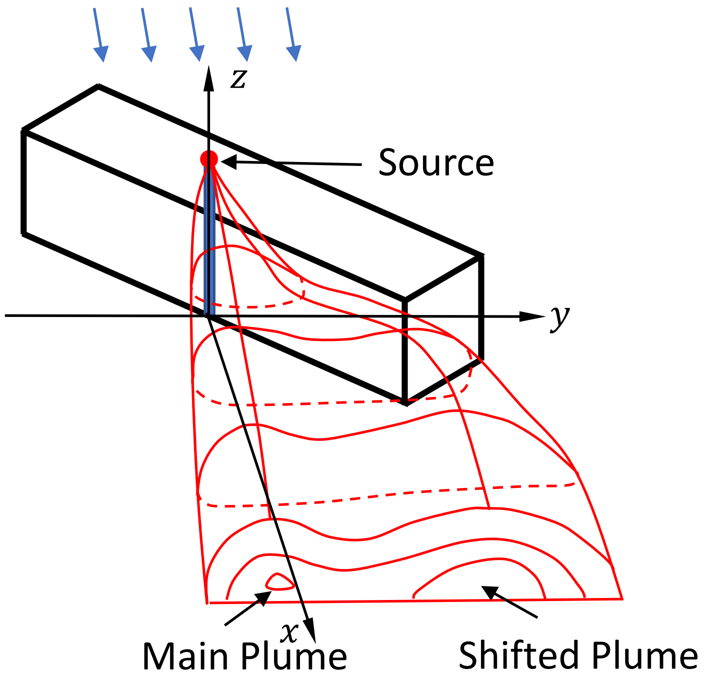


Yang et al., under review

The Mixture Model

Concentration on a YZ plane

$$C(y,z) = \sum_{i=1}^{n} \lambda_i \cdot G_i(y,z;Q,u,\boldsymbol{\mu}_i,\boldsymbol{\Sigma}_i)$$



$$n = 2 \qquad C(y,z;\beta_m) = \underbrace{\lambda \cdot G_1(y,z;Q,u,\boldsymbol{\mu_1},\boldsymbol{\Sigma}_1)}_{Main\ Plume} + \underbrace{+(1-\lambda)\cdot G_2(y,z;Q,u,\boldsymbol{\mu_2},\boldsymbol{\Sigma}_2)}_{Shifted\ Plume}$$

$$where\ \beta_m = (\lambda, u, \rho, \mu_{y1}, \mu_{z1}, \mu_{y2}, \mu_{z2}, \sigma_{y1}, \sigma_{z1}, \sigma_{y2}, \sigma_{z2})$$

$$C(y,z) = \frac{\lambda Q}{2\pi u \sigma_{y1}\sigma_{z1}\sqrt{1-\rho_1^2}}\left(exp\left(-\frac{1}{2(1-\rho_1^2)}\left[\frac{(y-\mu_{y1})^2}{\sigma_{y1}^2} + \frac{(z-\mu_{z1})^2}{\sigma_{z1}^2} - \frac{2\rho_1(y-\mu_{y1})(z-\mu_{z1})}{\sigma_{y1}\sigma_{z1}}\right]\right) + exp\left(-\frac{1}{2(1-\rho_1^2)}\left[\frac{(y-\mu_{y1})^2}{\sigma_{y1}^2} + \frac{(z+\mu_{z1})^2}{\sigma_{z1}^2} - \frac{2\rho_1(y-\mu_{y1})(z+\mu_{z1})}{\sigma_{y1}\sigma_{z1}}\right]\right)\right) + \underbrace{\frac{(1-\lambda)Q}{2\pi u \sigma_{y2}\sigma_{z2}}\left(exp\left(-\frac{1}{2}\left[\frac{(y-\mu_{y2})^2}{\sigma_{y2}^2} + \frac{(z-\mu_{z2})^2}{\sigma_{z2}^2}\right]\right) + exp\left(-\frac{1}{2}\left[\frac{(y-\mu_{y2})^2}{\sigma_{y2}^2} + \frac{(z+\mu_{z2})^2}{\sigma_{z2}^2}\right]\right)\right)}_{Shifted\ Plume}$$

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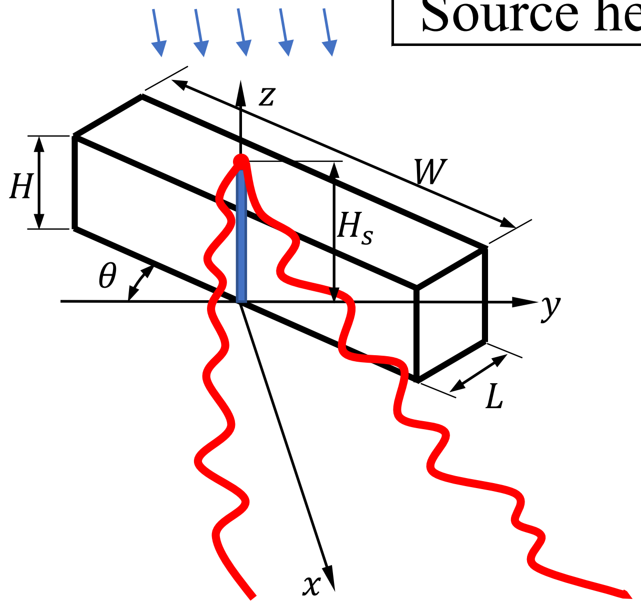
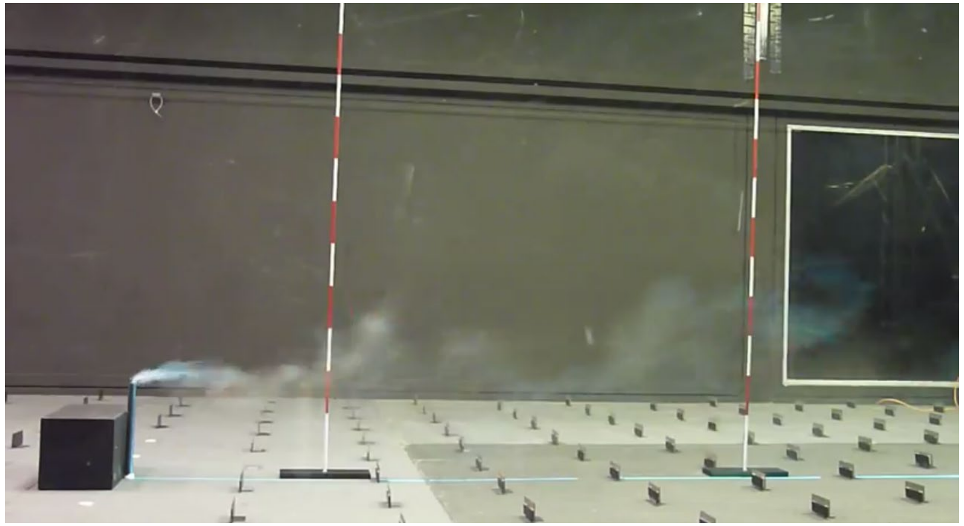
Training and Test Data

Features	Training (ELES)	Test (Wind Tunnel [14])
Building aspect ratio (W/H)	3, 4, 5, 6, 7, 9	2, 8
Wind direction (θ)	0°, 30°, 45°, 60°	0°, 15°, 30°, 45°, 60°
Source height (H_s)	1.5H	1.2H, 1.5H

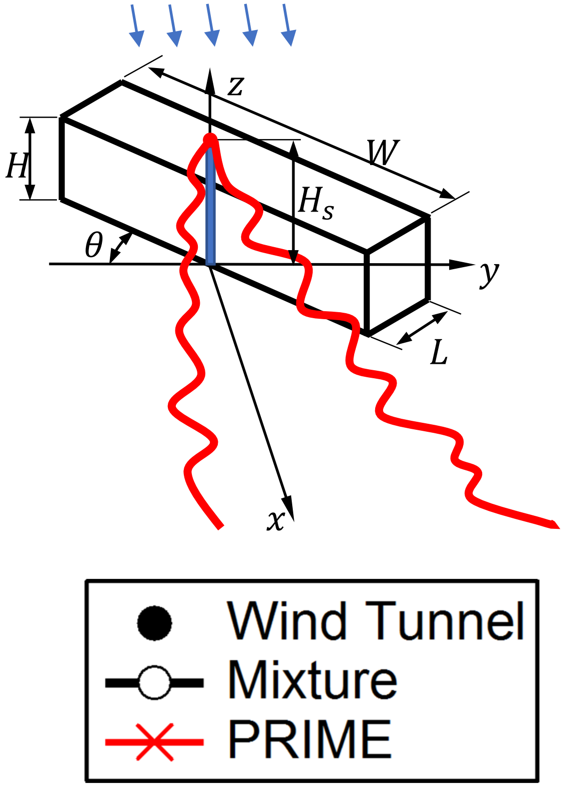


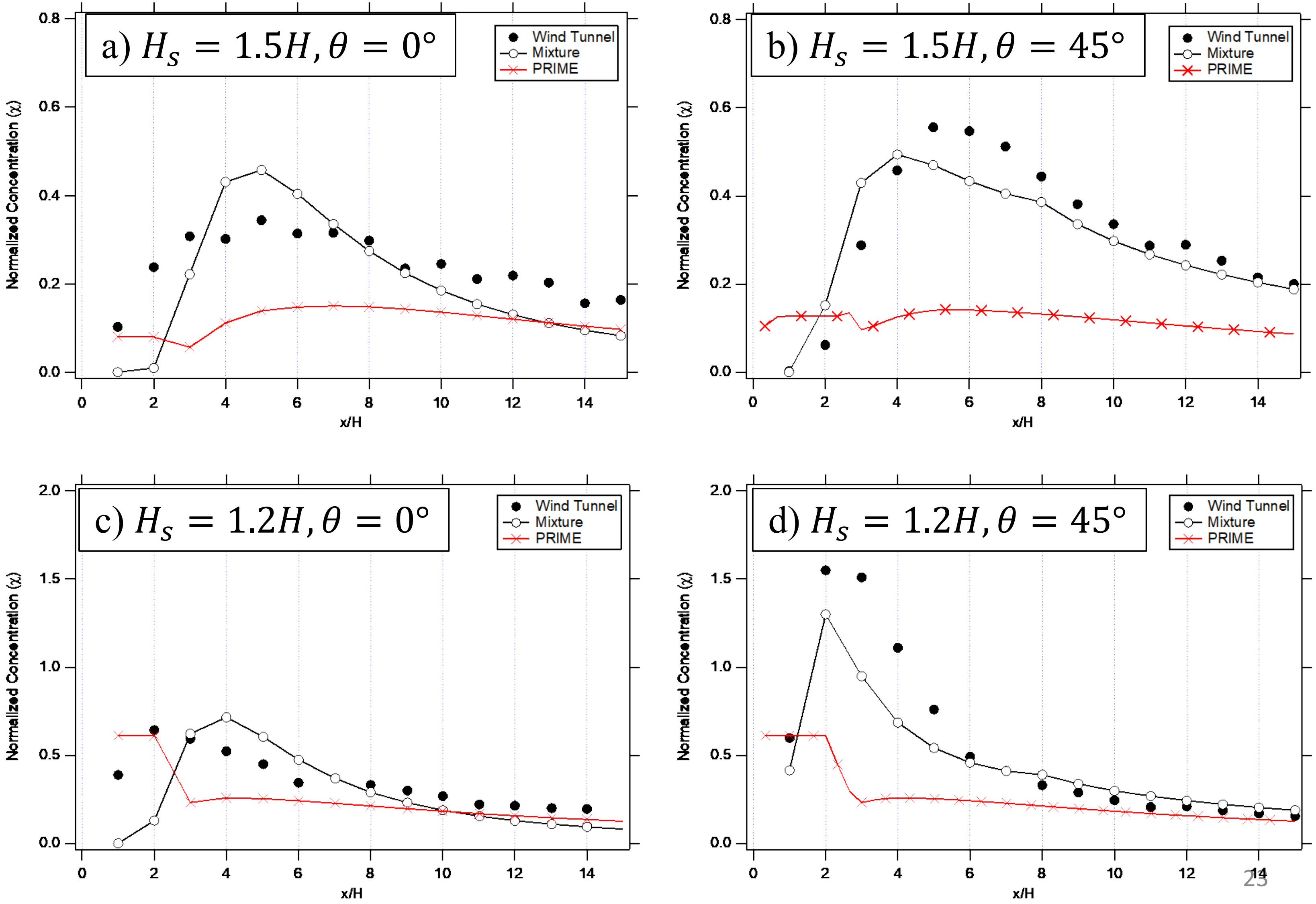


Perry, S.G. et. al. (2016)

Results: Longitudinal distributions (W/H=2)

The results from the Mixture model are continuous.





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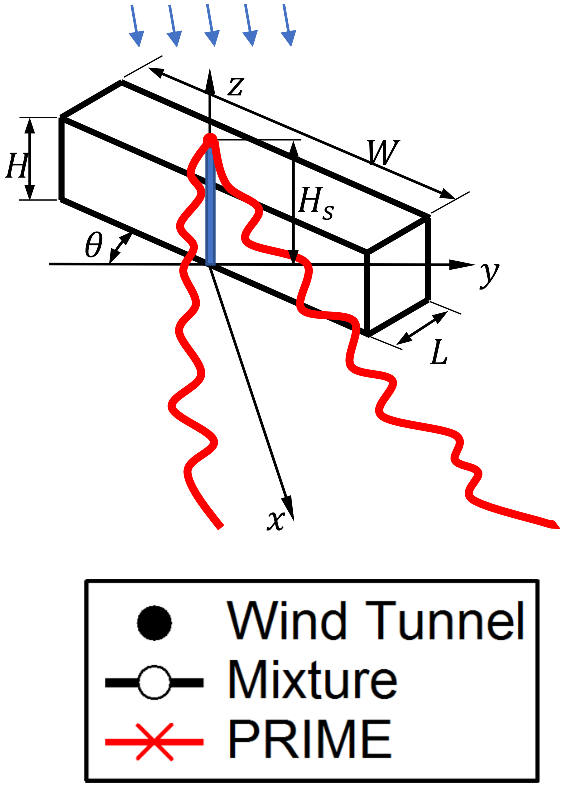
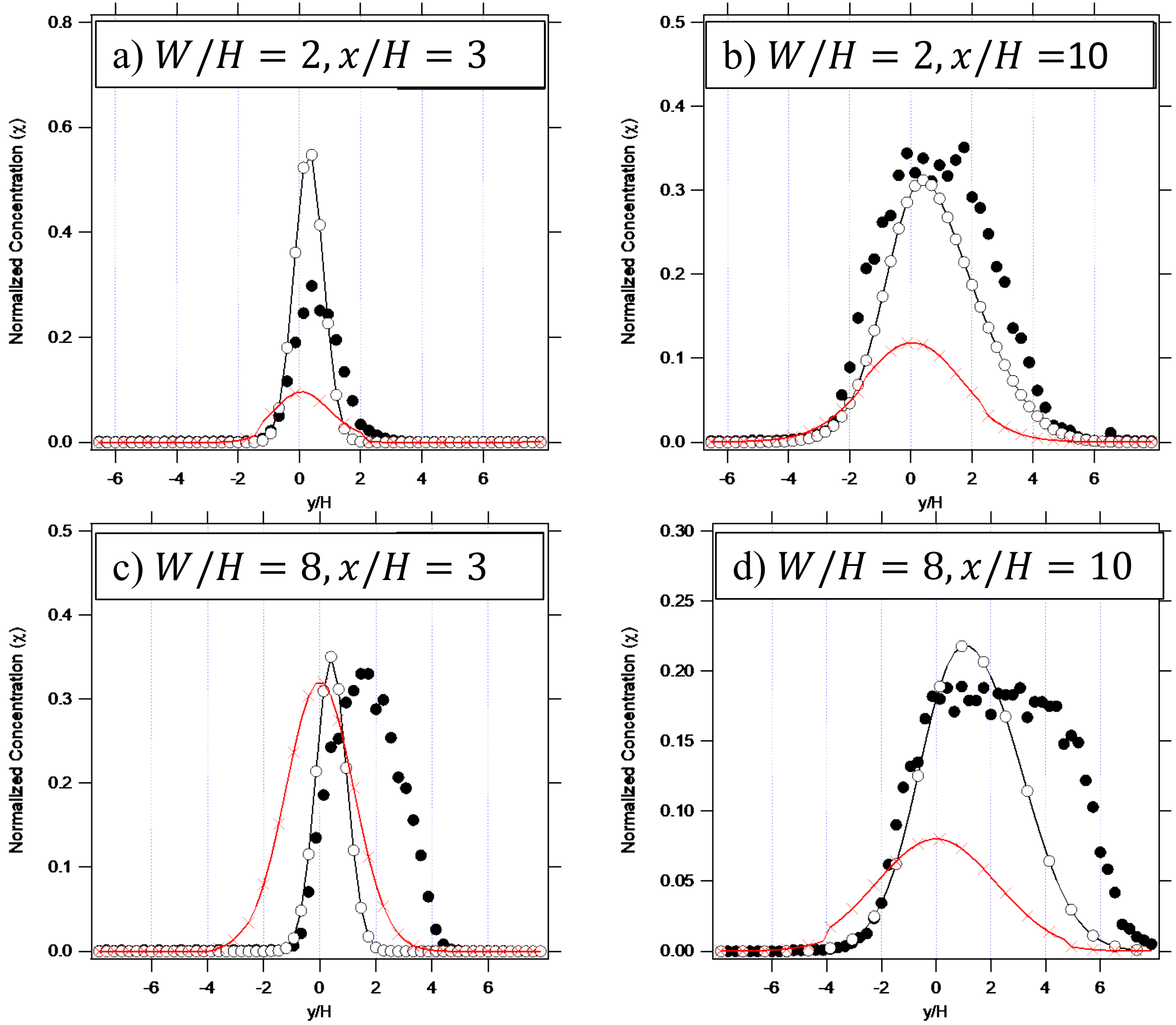
Results: Lateral distributions ($\theta = 45°, H_s = 1.5H$)

The Mixture model captured the lateral shift in plume distribution.





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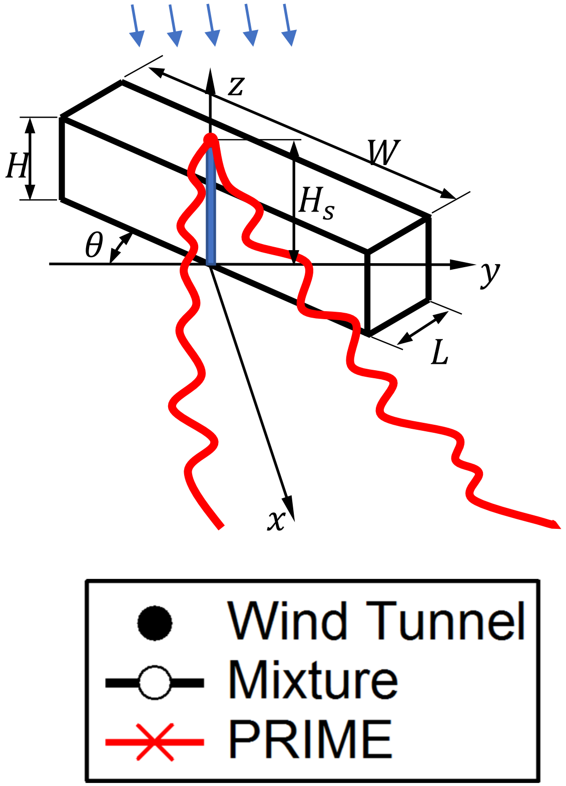
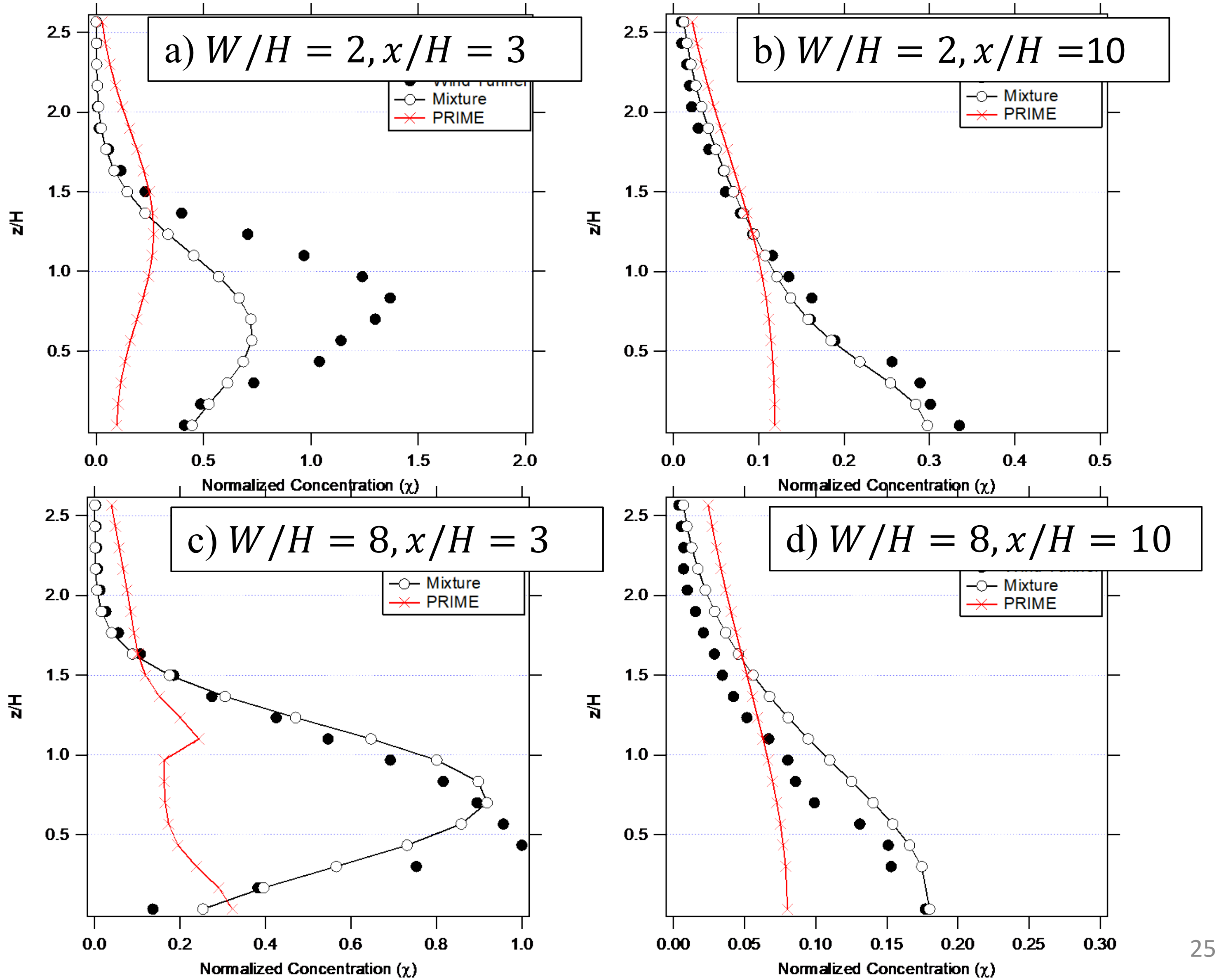
Results: Vertical distributions ($\theta = 45°, H_s = 1.5H$)

The Mixture model captured the positions of peak concentrations.





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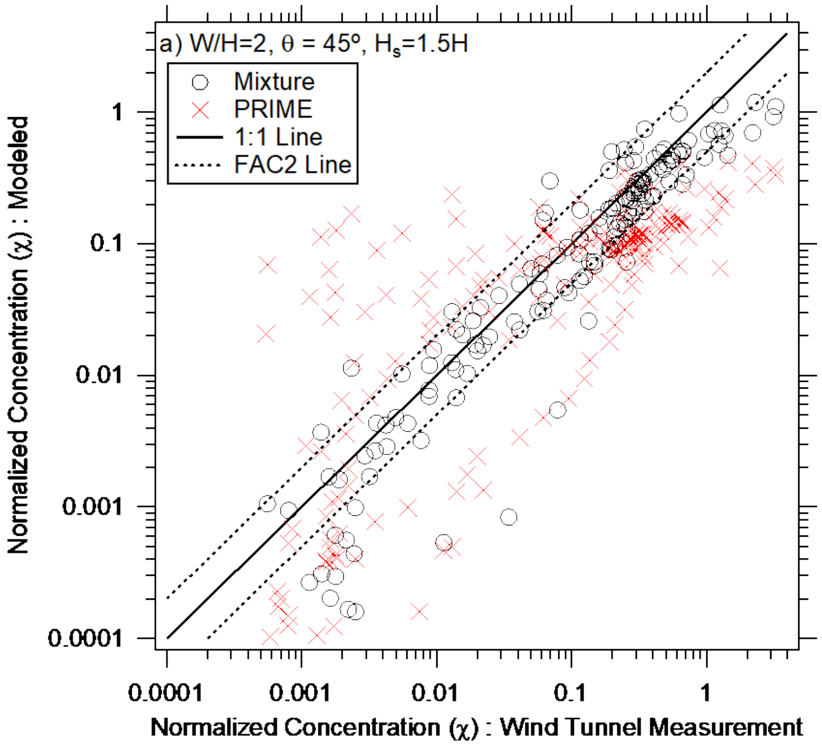
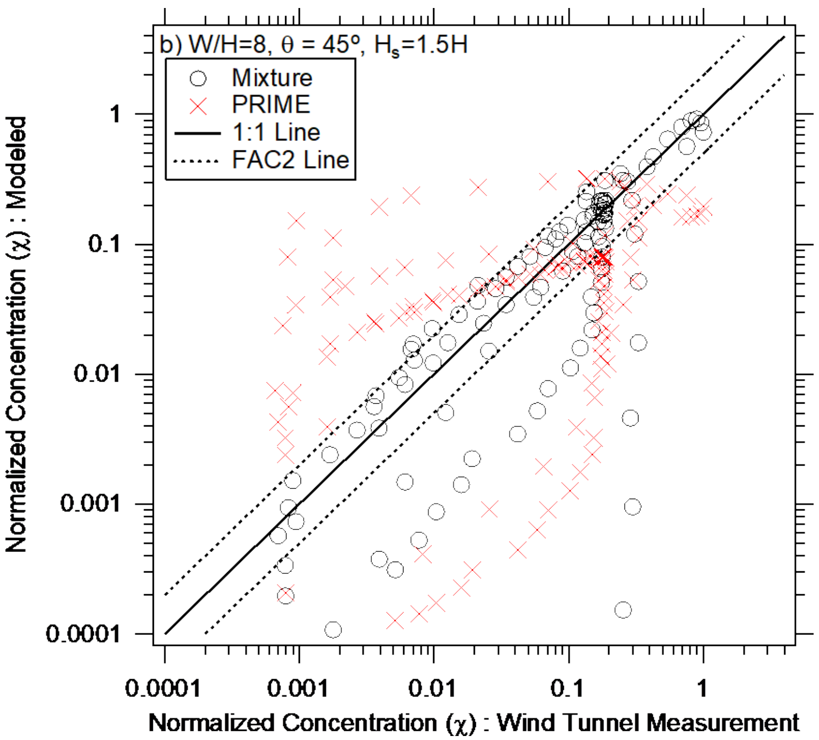
Results: All data points

W/H=2, θ=45°, Hs = 1.5H	PRIME	Mixture
FB	0.996	0.370
NMSE	3.92	0.667
FAC2	0.205	0.532

W/H=8, θ=45°, Hs = 1.5H	PRIME	Mixture
FB	0.602	0.194
NMSE	1.85	0.151
FAC2	0.170	0.453





Yang et al., under review

Summary

- The Mixture Model showed good performance through three-dimensional comparisons (longitudinal, lateral and vertical).
- It captured the plume centerline trajectory when the building downwash impact is strong.
- Limitations
  - Due to the training data limitation (Hs=1.5H), the current Mixture model did not perform well for a taller stack (Hs=2.0H).
  - Other source locations (like the building corner and the upwind center) were not included in the training set.
  - Only the neutral atmospheric boundary layer (ABL) was considered
- We are testing the Mixture Model against field datasets (Millstone, etc.).