Tracer Validation of Lagrangian Analytic Solution inside a Forest Canopy

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2007 AmeriFlux Science Meeting
October 17-19, 2007
Boulder, Colorado

Contents:

Rationale

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Materials and Methods

- Site Description
- Field Experiments

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- Turbulence Statistics
- Lagrangian Time Scales
- Comparison of Model with Observed tracer profiles

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Summary and Conclusions

How does the atmosphere feel the existence of the vegetation?

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  - Lagrangian analytic solution is compact and suitable for footprint climatology and incorporation into regional or global scale numerical models.

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- Lagrangian analysis is currently one of the best tools for studying turbulent dispersion of scalars within plant canopies, where 'near-field' dispersion is significant.
  - Lagrangian analytic solution is compact and suitable for footprint climatology and incorporation into regional or global scale numerical models.
- Most studies focus on the one-dimensional situation of an infinite, horizontally homogeneous canopy (Raupach, 1987; Warland and Thurtell, 2000).

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  1. Lee (2004) developed a model for scalar advection inside canopies for footprint analysis.
  2. Qiu and Warland (2007) developed a model for in-canopy concentration profiles near the edge of the canopy.

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  - The data required for such a test is demanding and expensive to collect.
  - It is difficult to identify natural tracers which have a source only in the canopy.
- $\rightarrow$ Putting significant limitations on its usage and further improvement.

Any remedy like a pacifier?

Motivation: Model Validation

- The use of artificial tracers is one means to allow for a controlled experiment in field conditions (Foken and Leclerc, 2004).

  Elevated and ground line sources

- Though some studies have examined one-dimensional Lagrangian models in the field (e.g., Denmead et al., 2000; Qiu and Warland, 2006), to date there has been no field test of a two-dimensional Lagrangian model.

Motivation: Stability Correction

Stability correction plays an important role in modeling turbulent dispersion inside a plant canopy?

- Accounting for local local stability effects on the velocity field may not substantially contribute to improvement in the source-sink estimation (Siqueria and Katul, 2002; Hsieh et al. 2003)
- Stability inside the canopy exerts a substantial influence on the diffusion (Leclerc et al., 1988 ; Leuning, 2000)

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   - This study details the derivation of a semi-analytic Lagrangian model for a line source in a canopy
   - Sensitivity test of model results to various parameterizations for Lagrangian time scales

Site Description

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A series of tracer experiments in 2002, 2004 and 2006.

Location: Florida AmeriFlux site ($29^o45'$N, $82^o10'$W)

- A managed slash pine (*Pinus elliottii L.*) forest in flat terrain.
- LAI: 1.9 in 2002 to 3.1 in 2006
- canopy height: 11.5 m in 2002 / 13.5 m in 2006
- Large amount of forest understory

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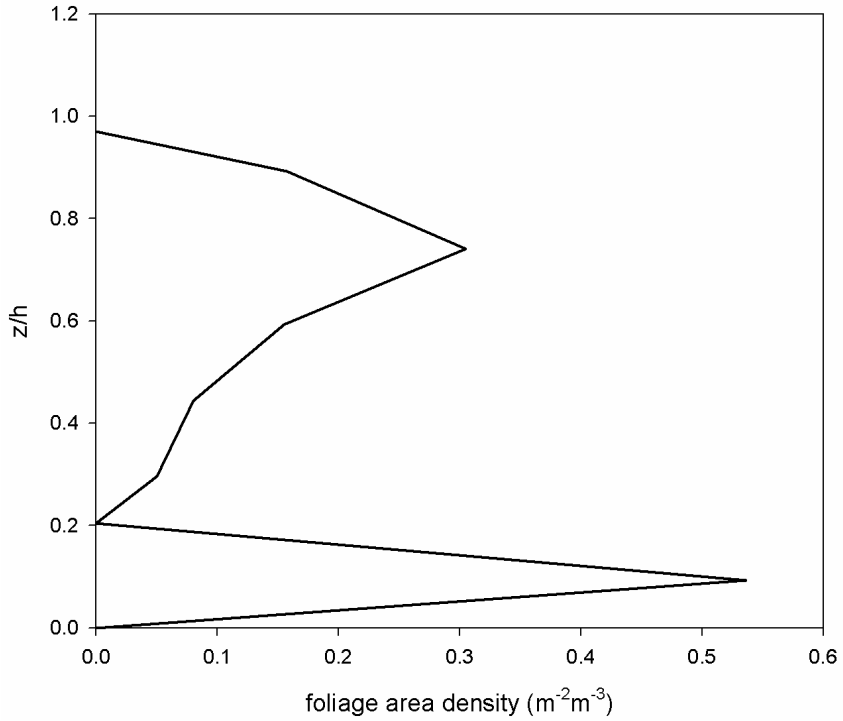


Turbulence Measurements

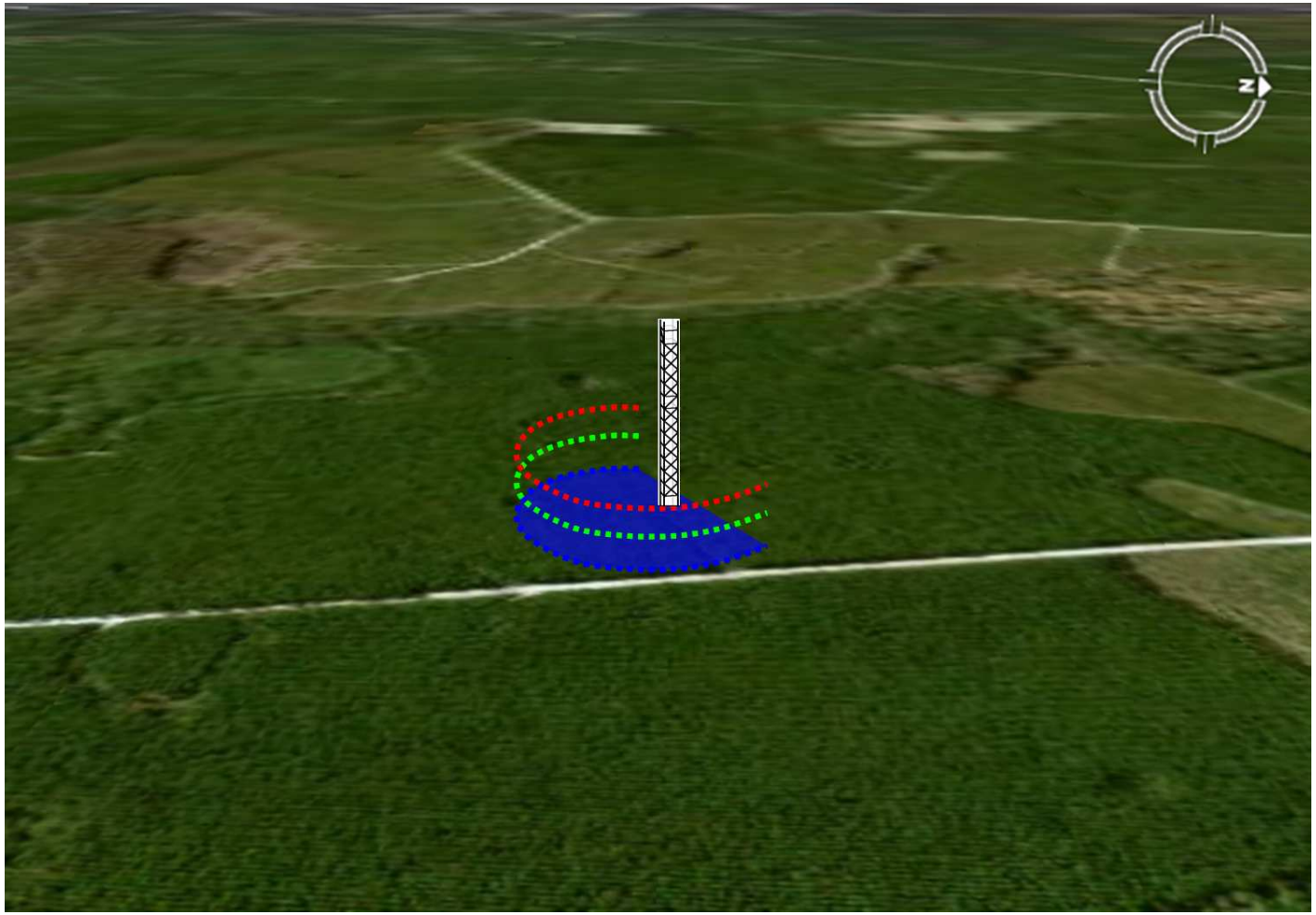
- Turbulence statistics profile were calculated from 3-d sonic anemometers (CSAT3/RMY) and thermocouples.
- 10 Hz sampling rate / 30 minutes averaging time

Tracer Experiments

- Perfluorocarbon tracers (PFT) are colorless, odorless compounds that consist of a carbon and fluorine atoms joined by covalent single bonds.
- PFTs are chemically inert, non-flammable, and have no biological effects.

Acronym	Chemical name	Formula	molecular weight
PMCP	Perfluoromethylcyclopentane	C_6F_{12}	300
PDCB	Perfluorodimethylcyclobutane	C_6F_{12}	300
PMCH	PerfluoroMethylcyclohexane	C_7F_{14}	350
ocPDCH	Perfluoro1,2dimethylcyclohexane	C_8F_{16}	400
PECH	Perfluoroethylcyclohexane	C_8F_{16}	400
iPPCH	Perfluoroisopropylcyclohexane	C_9F_{18}	450
PTCH	Perfluorotrimethylcyclohexane	C_9F_{18}	450

Tracer Experiments



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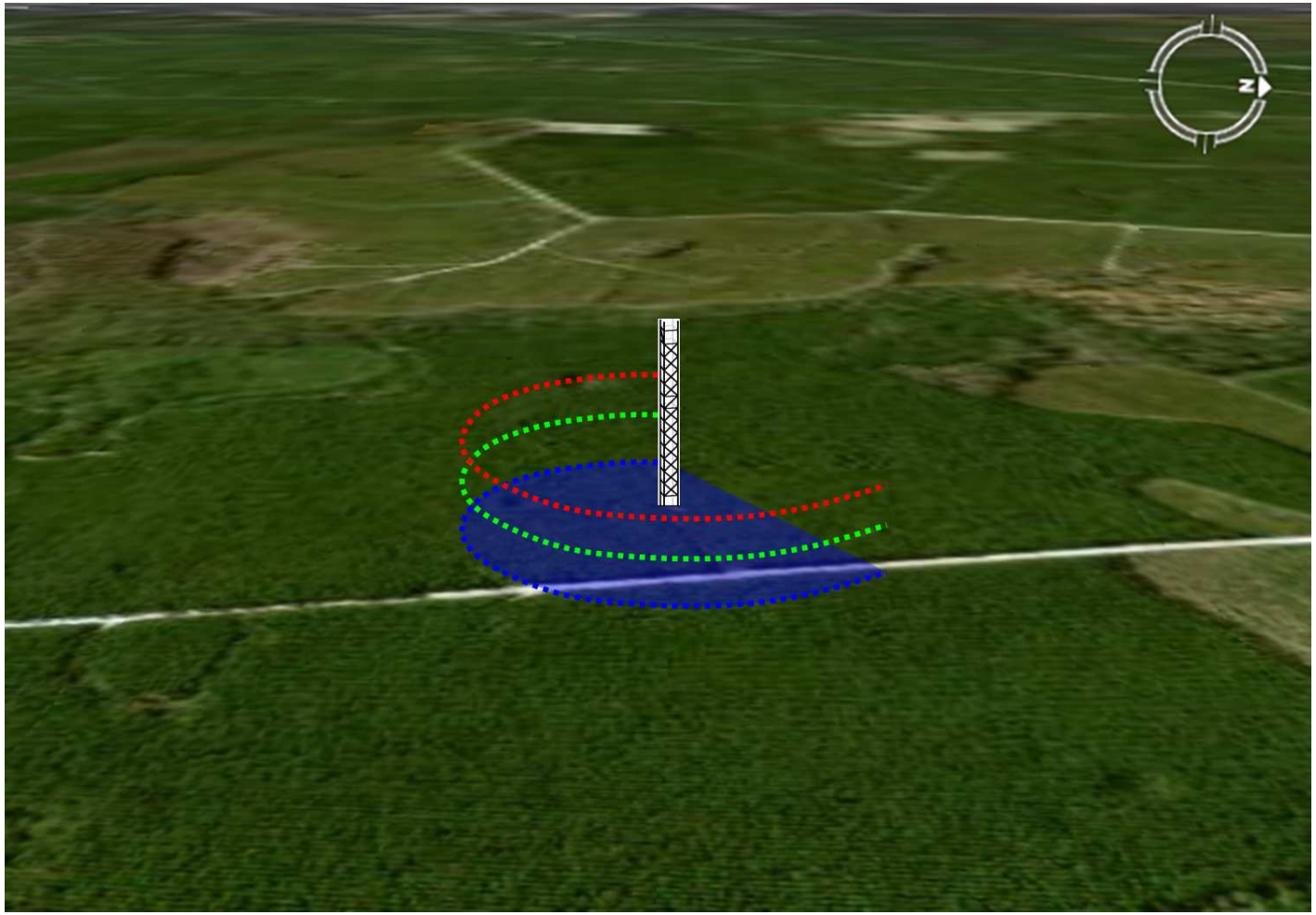

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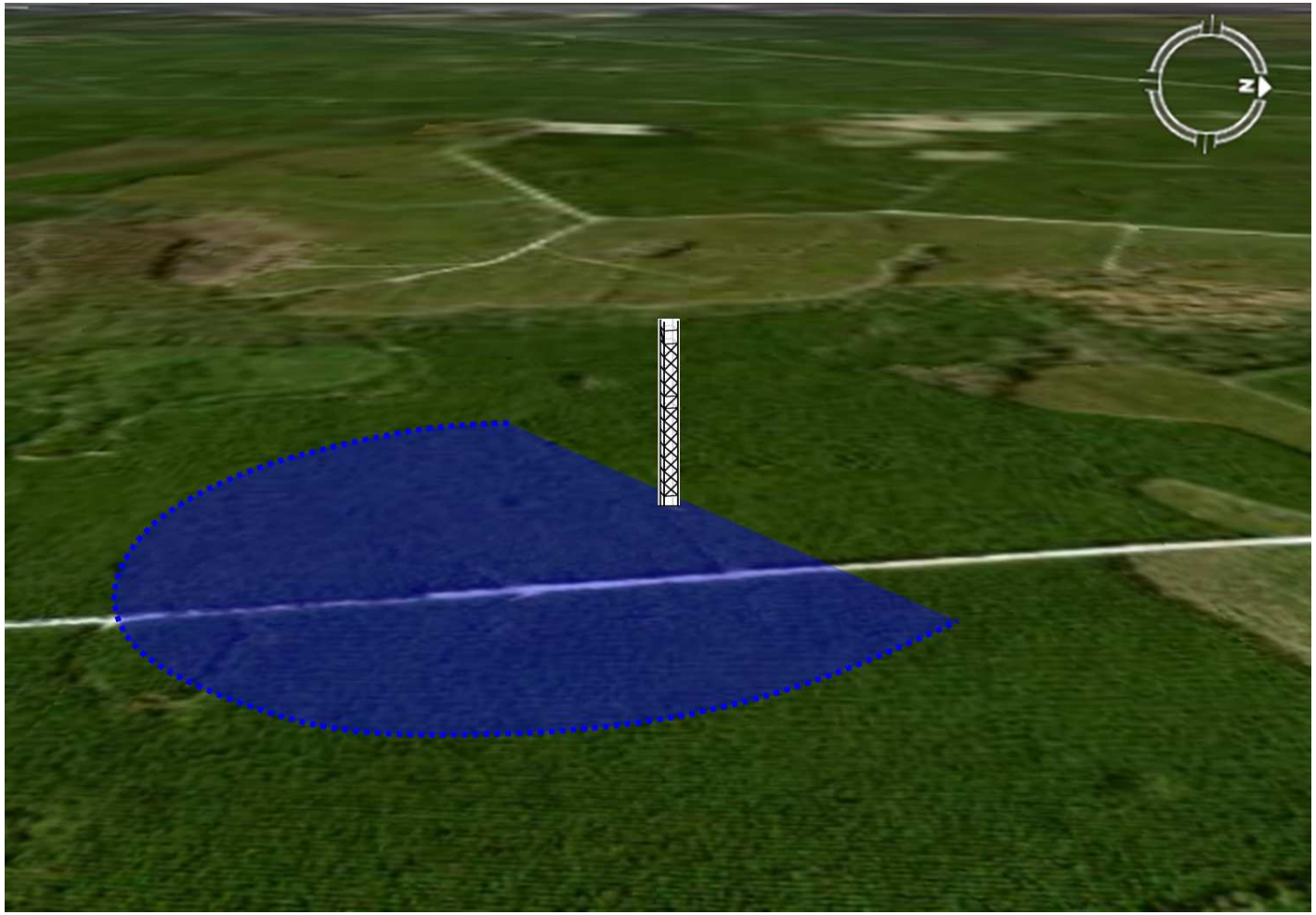

Tracer Experiments

Table: Analyzed Tracer Experiments in Florida AmeriFlux site

year	tracer	arc radius (m)	release height
2002	PMCP, PMCH, ocPDCH, PECH, iPPCH, PTCH	10.8/21.5/43.0	0.1h/0.56h/0.87h
2004	PMCH	50/125/300	0.1h
2006	PMCP, PMCH, PDCB	100/200/400	0.01h

MODEL DESCRIPTION:

Semi-Analytic Lagrangian Model for a Line Source

$$\lim_{\frac{x-x_s}{u\tau_L}\to 0} \sigma_z^2 = \sigma_w^2((x-x_s)/u)^2 \qquad \lim_{\frac{x-x_s}{u\tau_L}\to \infty} \sigma_z^2 = 2\sigma_w^2\tau_L(x-x_s)/u.$$

- The Lagrangian line source model is based closely on the two-dimensional finite plane source model of Qiu and Warland (2007).

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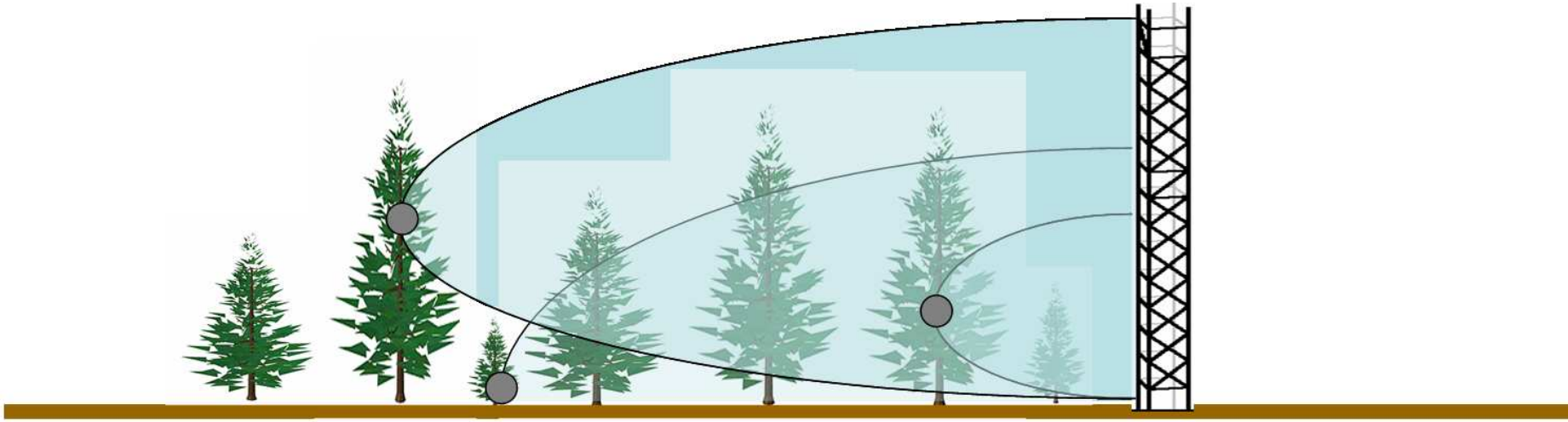
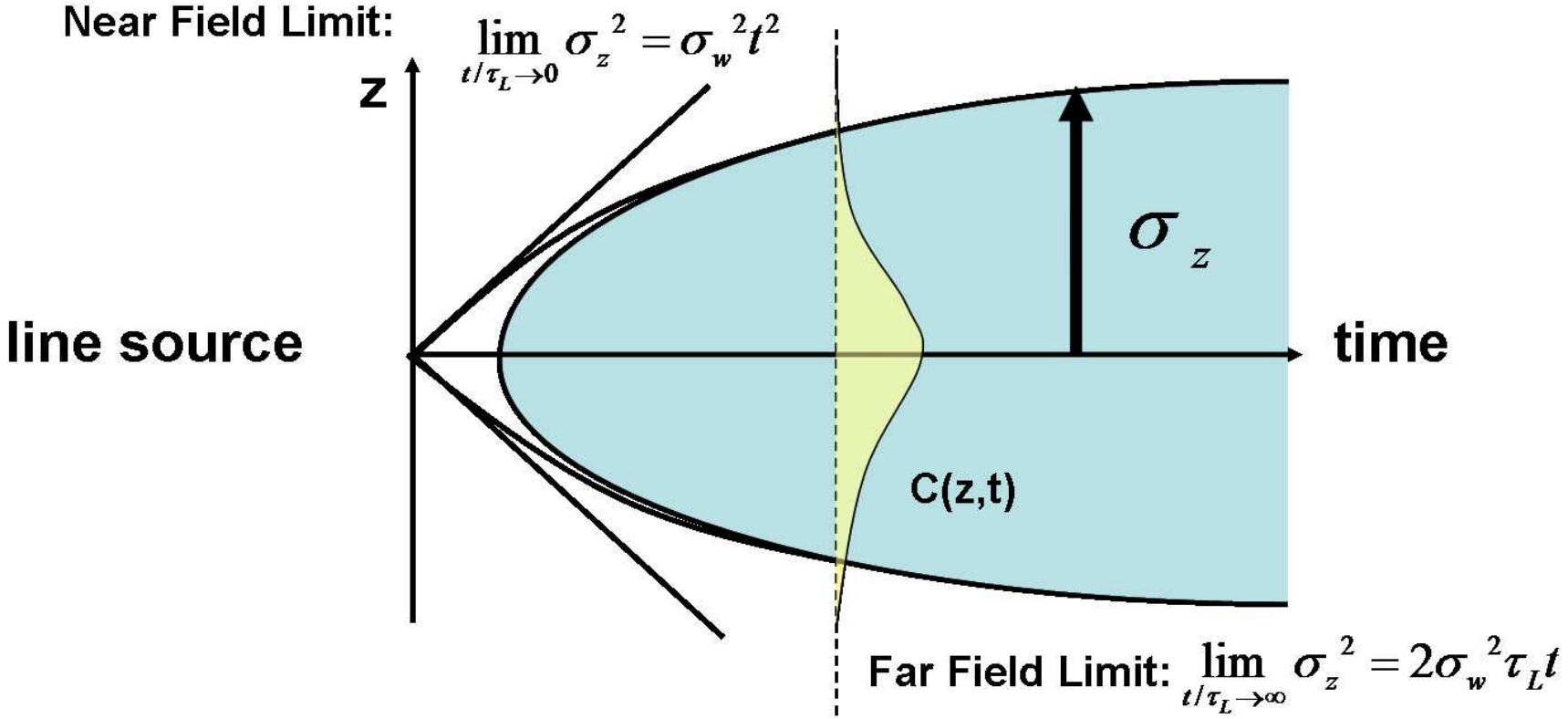
- The basic shape of the scalar concentration profile is determined by the one-dimensional solution by Warland and Thurtell (2000) with an added advection term describing the growth of the internal boundary layer.
  - A homogeneous solution
  - A dispersion in a uniform flow can be used to describe dispersion in real world condition.
  - The advection effect on concentration is manifested only in the far field (Hsieh et al., 2003; Qiu and Warland, 2007).
  - Longitudinal diffusion is negligible compared to mean mass transport.




Near Field Limit: $\lim_{t/\tau_L \to 0} \sigma_z^2 = \sigma_w^2 t^2$
z
σ_z
line source
time
C(z,t)
Far Field Limit: $\lim_{t/\tau_L \to \infty} \sigma_z^2 = 2\sigma_w^2 \tau_L t$

Near field and Far field

- The near-field is defined as the distance from the source that fluid particles move in a time T_L, the characteristic Lagrangian time scale of the turbulence, whereas the far-field is the distance from the source a fluid particle travels in times T_L.
- The transition between the near-field and far-field regions occurs at a distance downwind of Δx uT_L away from the emitting source.

Derivation of a line source solution

The standard deviation of particle displacement after travel time $t = (x - x_s)/u$ can be expressed in terms of the travel distance $x - x_s$.

$$\lim_{\frac{x-x_s}{u\tau_L} \to 0} \sigma_z^2 = \sigma_w^2((x - x_s)/u)^2$$

$$\lim_{\frac{x-x_s}{u\tau_L} \to \infty} \sigma_z^2 = 2\sigma_w^2 \tau_L (x - x_s)/u.$$

Derivation of a line source solution

The shape of the profile is described by the derivative of concentration with height (Csanady, 1973; Warland and Thurtell, 2000).

$$\frac{\partial c(x,z)}{\partial z} = -\frac{q(z-z_s)}{\sqrt{2\pi}u\sigma_z^3}\exp\left[-\frac{(z-z_s)^2}{2\sigma_z^2}\right]$$

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Derivation of a line source solution

$$\left.\frac{\partial c(x,z)}{\partial z}\right|_{NF} = -\frac{qu^2(z-z_s)}{\sqrt{2\pi}u\sigma_w^3|x-x_s|}\exp\left[-\frac{u^2(z-z_s)^2}{2\sigma_w^2(x-x_s)^2}\right]$$

$$\left.\frac{\partial c(x,z)}{\partial z}\right|_{FF} = -\frac{q\sqrt{u}(z-z_s)}{\sqrt{4\pi}(\sigma_w L_L(x-x_s))^{2/3}}\exp\left[-\frac{u(z-z_s)^2}{4\sigma_w L_L(x-x_s)}\right]$$

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$$\left.\frac{\partial c(x,z)}{\partial z}\right|_{FF} = -\underbrace{\frac{q}{2\sigma_w L_L}}_{I}\underbrace{\frac{\sqrt{u}(z-z_s)}{\sqrt{4\pi\sigma_w L_L}(x-x_s)^{3/2}}\exp\left[-\frac{u(z-z_s)^2}{4\sigma_w L_L(x-x_s)}\right]}_{II}$$

Derivation of a line source solution

$$\begin{aligned}\frac{\partial c(x,z)}{\partial z} &= Mq = M_1 M_a q \\ &= -M_1 \left(\frac{\sqrt{u}(z-z_s)}{\sqrt{4\pi\sigma_w L_L}(x-x_s)^{3/2}} \exp\left[-\frac{u(z-z_s)^2}{4\sigma_w L_L (x-x_s)} \right] \right) q\end{aligned}$$

M_1 is the one-dimensional dispersion matrix from Warland and Thurtell (2000).

Derivation of a line source solution

$$\left.\frac{\partial c(x, z_i)}{\partial z}\right|_j = \sum_{j=1}^{n} M_{ij}(x) q_j \Delta z_j$$

$$M_{ij}(x) = M_{1ij}\left[\frac{\sqrt{u_i}(z_i - z_j)}{\sqrt{4\pi\sigma_{wi}L_i}(x - x_s)^{3/2}}\exp\left[-\frac{u_i(z_i - z_j)^2}{4\sigma_{wi}L_i(x - x_s)}\right]\right]$$

Derivation of a line source solution

$$M_{1ij} = \begin{cases} \dfrac{-\left[1-\exp\left(\dfrac{-(z_i-z_j)^2}{2\Delta z_j^2}\right)\right]}{2\sigma_w L_L\left[1-\exp\left(-\sqrt{\dfrac{\pi}{2}}\dfrac{(z_i-z_j)}{L_L}\right)\right]} - \dfrac{\left[1-\exp\left(\dfrac{-(z_i+z_j)^2}{2\Delta z_j^2}\right)\right]}{2\sigma_w L_L\left[1-\exp\left(-\sqrt{\dfrac{\pi}{2}}\dfrac{(z_i+z_j)}{L_L}\right)\right]} & \text{for } z_i > z_j \\ \dfrac{-\left[1-\exp\left(\dfrac{-(z_i+z_j)^2}{2\Delta z_j^2}\right)\right]}{2\sigma_w L_L\left[1-\exp\left(-\sqrt{\dfrac{\pi}{2}}\dfrac{(z_i+z_j)}{L_L}\right)\right]} & \text{for } z_i = z_j \\ \dfrac{\left[1-\exp\left(\dfrac{-(z_i-z_j)^2}{2\Delta z_j^2}\right)\right]}{2\sigma_w L_L\left[1-\exp\left(-\sqrt{\dfrac{\pi}{2}}\dfrac{(z_j-z_i)}{L_L}\right)\right]} - \dfrac{\left[1-\exp\left(\dfrac{-(z_i+z_j)^2}{2\Delta z_j^2}\right)\right]}{2\sigma_w L_L\left[1-\exp\left(-\sqrt{\dfrac{\pi}{2}}\dfrac{(z_i+z_j)}{L_L}\right)\right]} & \text{for } z_i < z_j. \end{cases}$$

Derivation of a line source solution

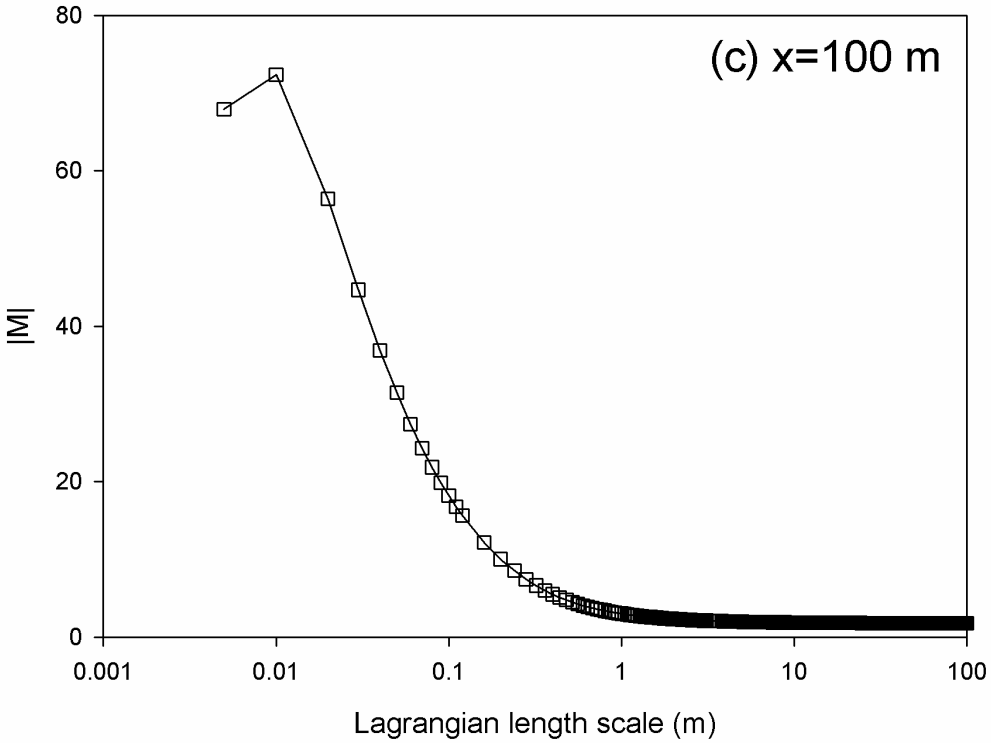
$$
\begin{aligned}
U\frac{\partial C}{\partial x} &= K\frac{\partial^2 C}{\partial z^2} \\
\frac{\partial c(x,z)}{\partial z} &= f(U(z), \sigma_w(z), L(z)) \\
|M_{1ij}| &\leq |M_1|
\end{aligned}
$$

Model Sensitivity to Lagrangian Time Scales

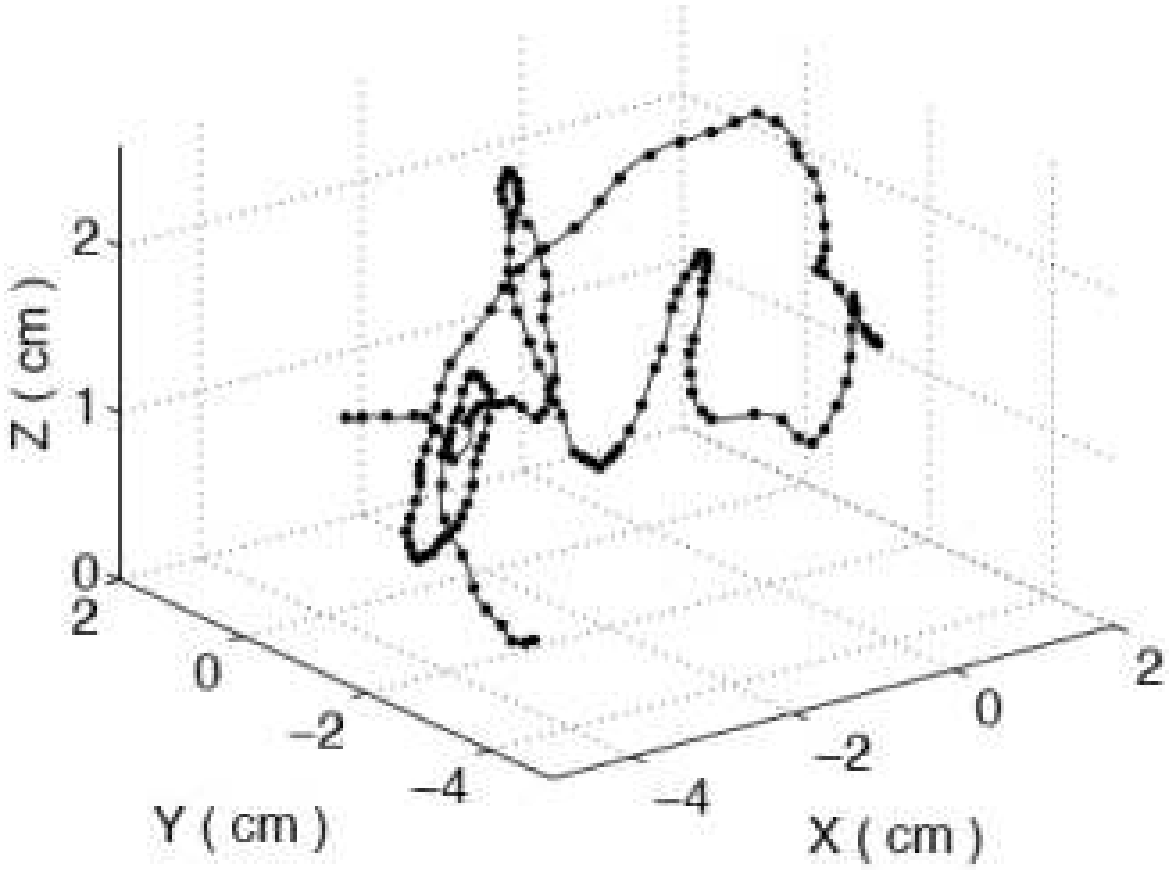
$\frac{\partial |M|}{\partial L}$ is a decreasing function to Lagrangian length scale.

$$\left.\frac{\partial c(x,z)}{\partial z}\right|_{NF} = f(q, z, x, u, \sigma_w)$$

$$\left.\frac{\partial c(x,z)}{\partial z}\right|_{FF} = f(q, z, x, u, \sigma_w, L_L)$$



Parameterization of Lagrangian Time Scale



Parameterization of Lagrangian time scale

Raupach (1989) profile

- $T_L \propto (z - d)$ above roughness sublayer
- Parameterization from the various data sets for neutral condition:

$$\frac{T_L u_*}{h} = max\left[0.3, \frac{k(z-d)}{a_1 h}\right]$$

- Constant Lagrangian time scales with height inside a canopy ($= 0.3$)

Parameterization of Lagrangian time scale

Leuning et al. (2000) profile

- $T_L \propto (z-d)$ above roughness sublayer
- Constant Lagrangian time scales inside a canopy ($\frac{T_L u_*}{h} = 0.4$) with matched $T_L = 0$ at $z/h = 0$

$$\frac{T_L u_*}{h} = \begin{cases} \frac{(4az/h+b_1)-\sqrt{(4az/h+b_1)^2-16\theta a b_1 z/h}}{2\theta} & \text{z<1/4h} \\ \frac{(a_2(z/h-0.8)+b_2)+\sqrt{(a_2(z/h-0.8)+b_2)^2-4\theta a_2 b_2 (z/h-0.8)}}{2\theta} & \text{z>1/4h} \end{cases}$$

Parameterization of Lagrangian time scale

Leuning (2000) profile

- $T_L \propto (z - d)$ above roughness sublayer
- Correction of atmospheric stability by assuming that dispersion inside the canopy can be described by MOST (h/L):

$$\frac{T_L(h/L)}{T_L(0)} = \frac{1}{\phi_h(h/L} \left(\frac{1.25}{\phi_w(h/L)} \right)^2$$

- Time scale increases (decreases) in unstable (stable) conditions.

Parameterization of Lagrangian time scale

Massman and Weil (1999) profile

- $T_L \propto (z-d)$ above roughness sublayer

$$\frac{T_L u_*}{h} = \begin{cases} A_1(1-d/h)\gamma_3/(\sigma_w(z)/u_*) & \text{z<h} \\ A_1(z-d)/h & \text{z>h} \end{cases}$$

$$A_1 = 0.6\left(\sigma_w(z)/u_*\gamma_3\right)^{1/2}(1-d/h)^{-1/2}$$

- Qiu and Warland (2006) applied MW profile to test the diurnal variation of the modeled surface fluxes.

Parameterization of Lagrangian time scale

Estimation from Eulerian Time Scales with Taylor's frozen-turbulence hypothesis.

$$
\begin{aligned}
L_L &= \sigma_w T_L = \beta L_E = \sigma_w \left(\beta \frac{\overline{u}}{\sigma_w} T_E \right) \\
T_L &= \beta \frac{\overline{u}}{\sigma_w} T_E
\end{aligned}
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- $\beta = 1$: Kraichnan(1964); Raupach(1989b); Katul et al. (1997); Warland and Thurtell (2000); Hong et al. (2002)

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Parameterization of Lagrangian time scale

Estimation from Eulerian Time Scales with Taylor's frozen-turbulence hypothesis.

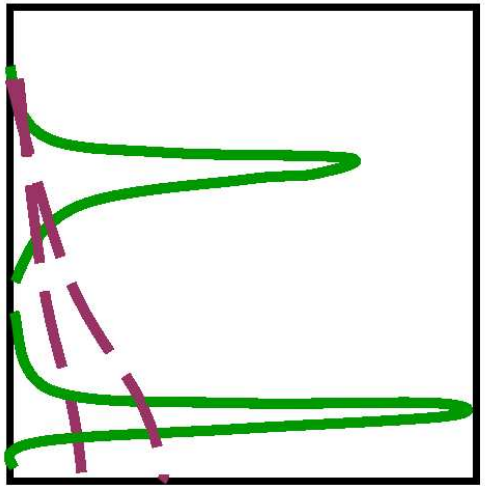
$$T_L = \beta \frac{\overline{u}}{\sigma_w} T_E$$

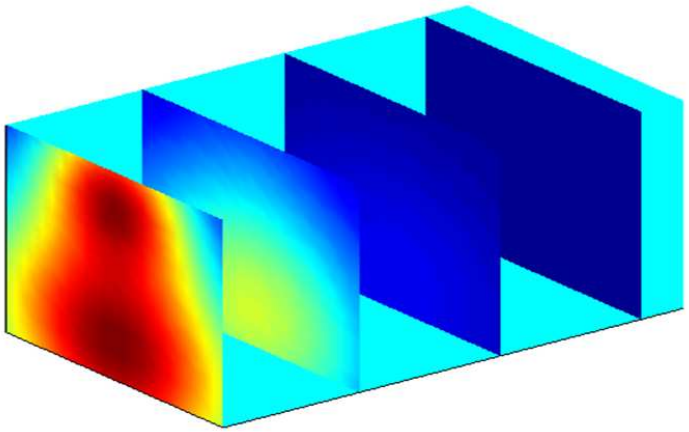
- Wind meandering and Wind speeds

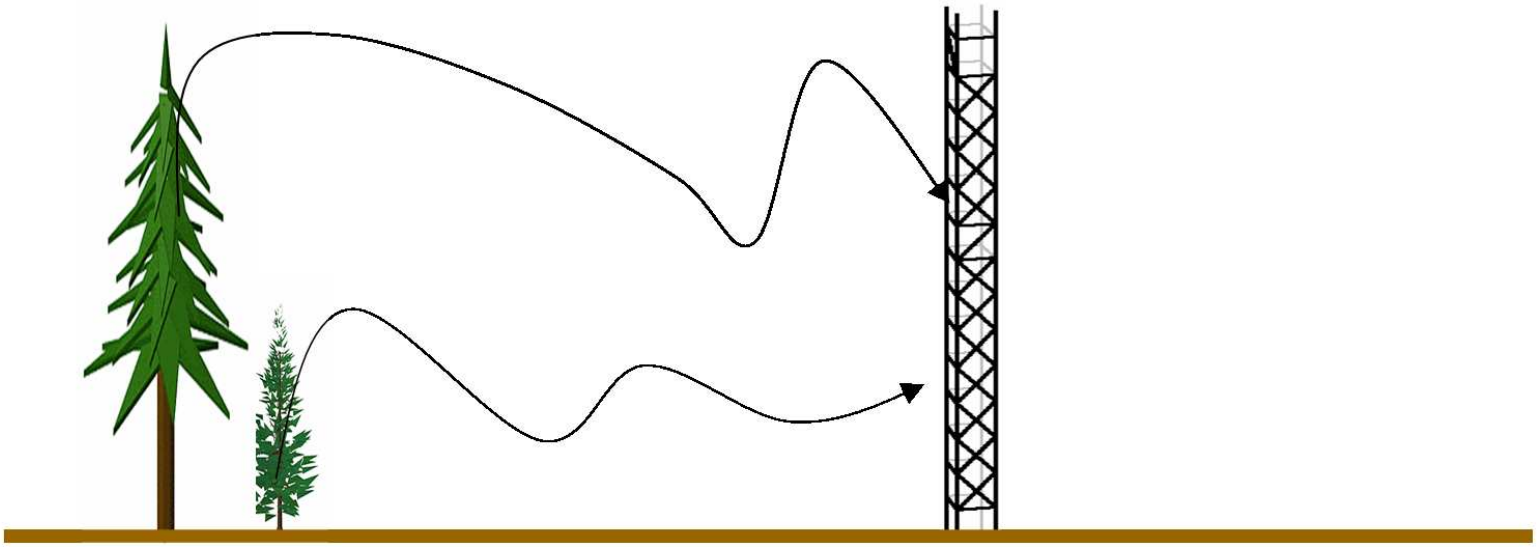
$$\begin{aligned} U &\equiv \frac{1}{N}\sqrt{\sum_i (u_i^2 + v_i^2)} \\ &\geq \overline{u} \equiv \sqrt{\left(\frac{1}{N}\sum_i u_i\right)^2 + \left(\frac{1}{N}\sum_i v_i\right)^2} \end{aligned}$$

- $U \equiv$ wind vector / $\overline{u} \equiv$ cup wind speed

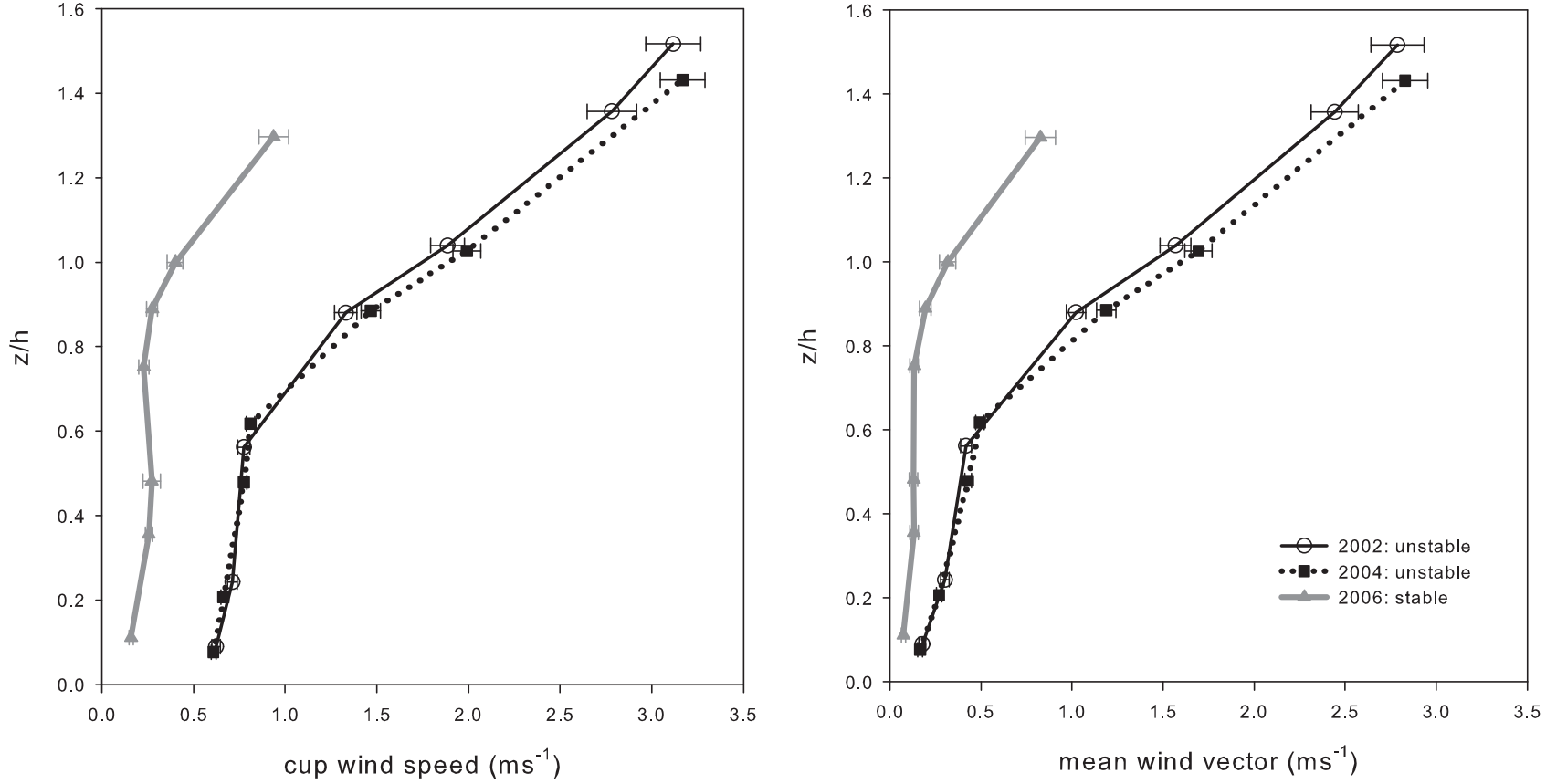
Results and Discussion







Turbulence statistics



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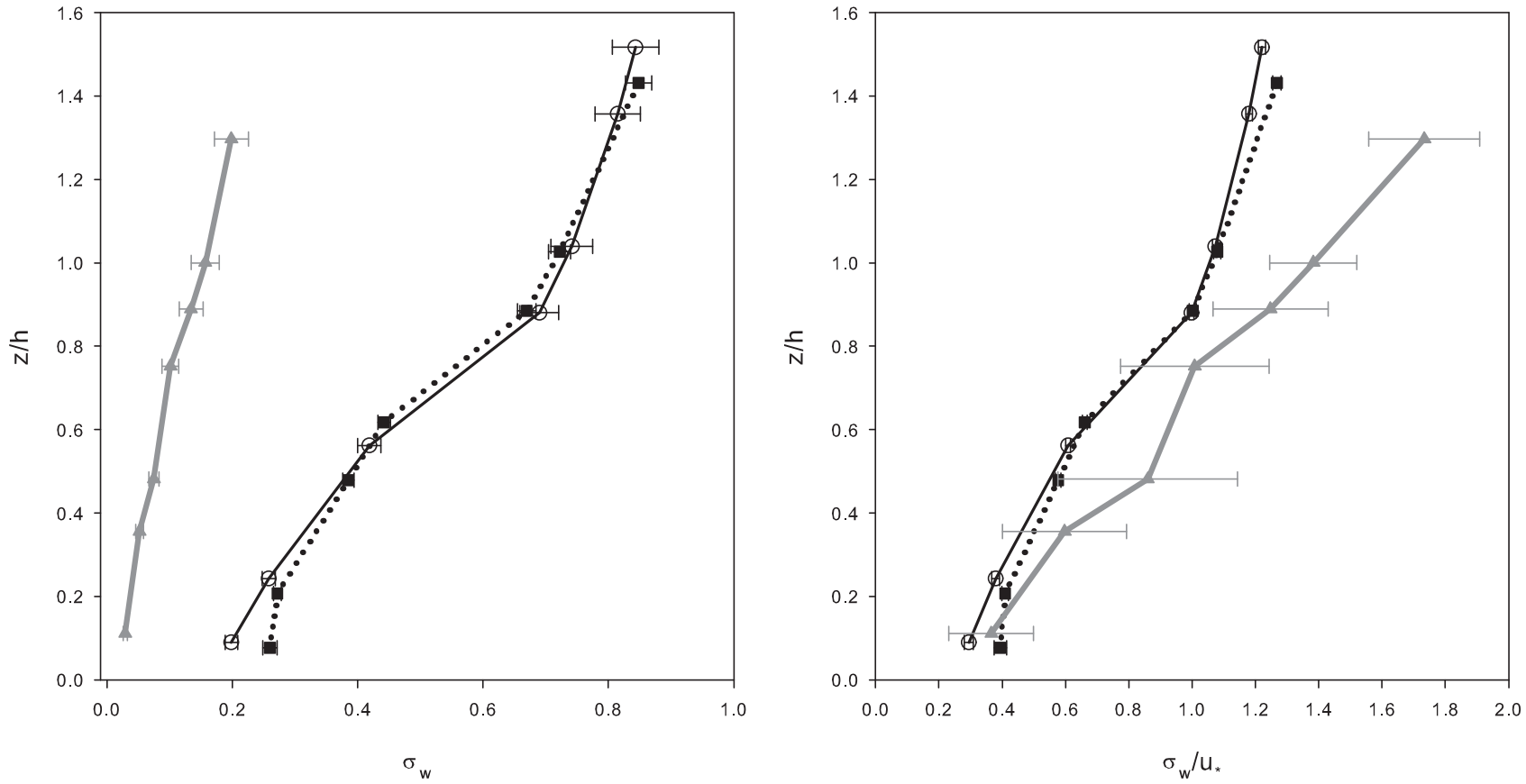
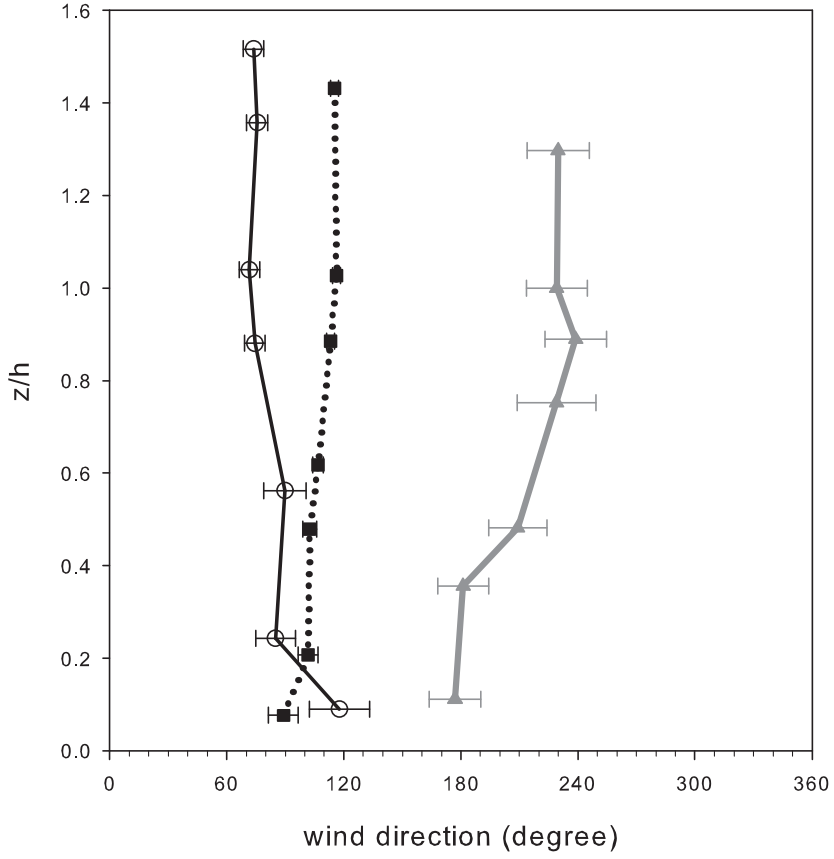
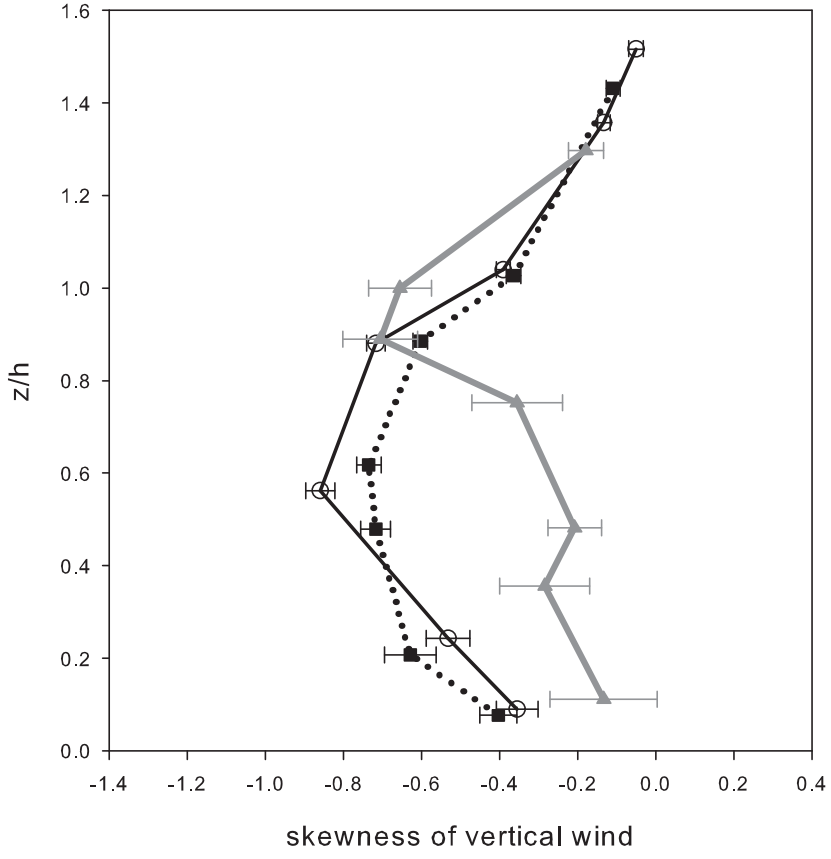


Turbulence statistics





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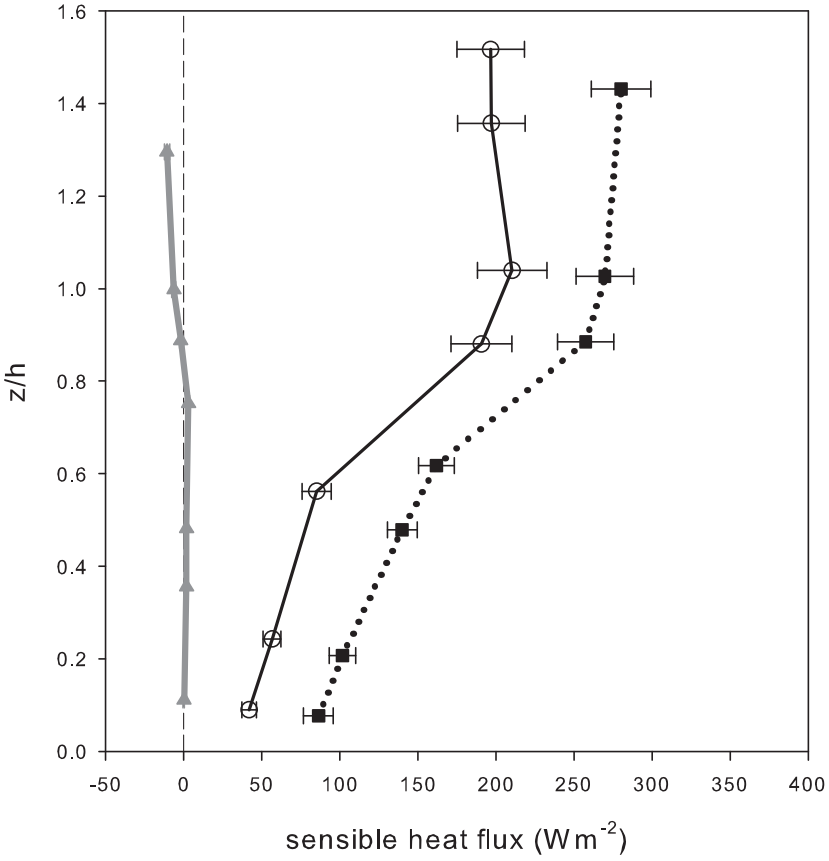
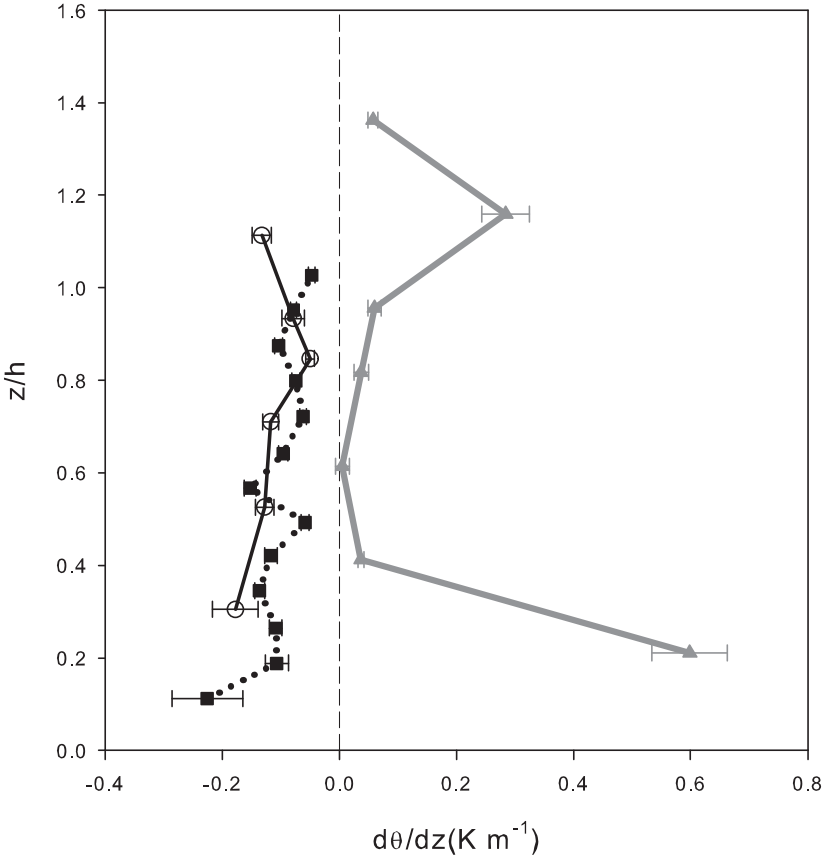
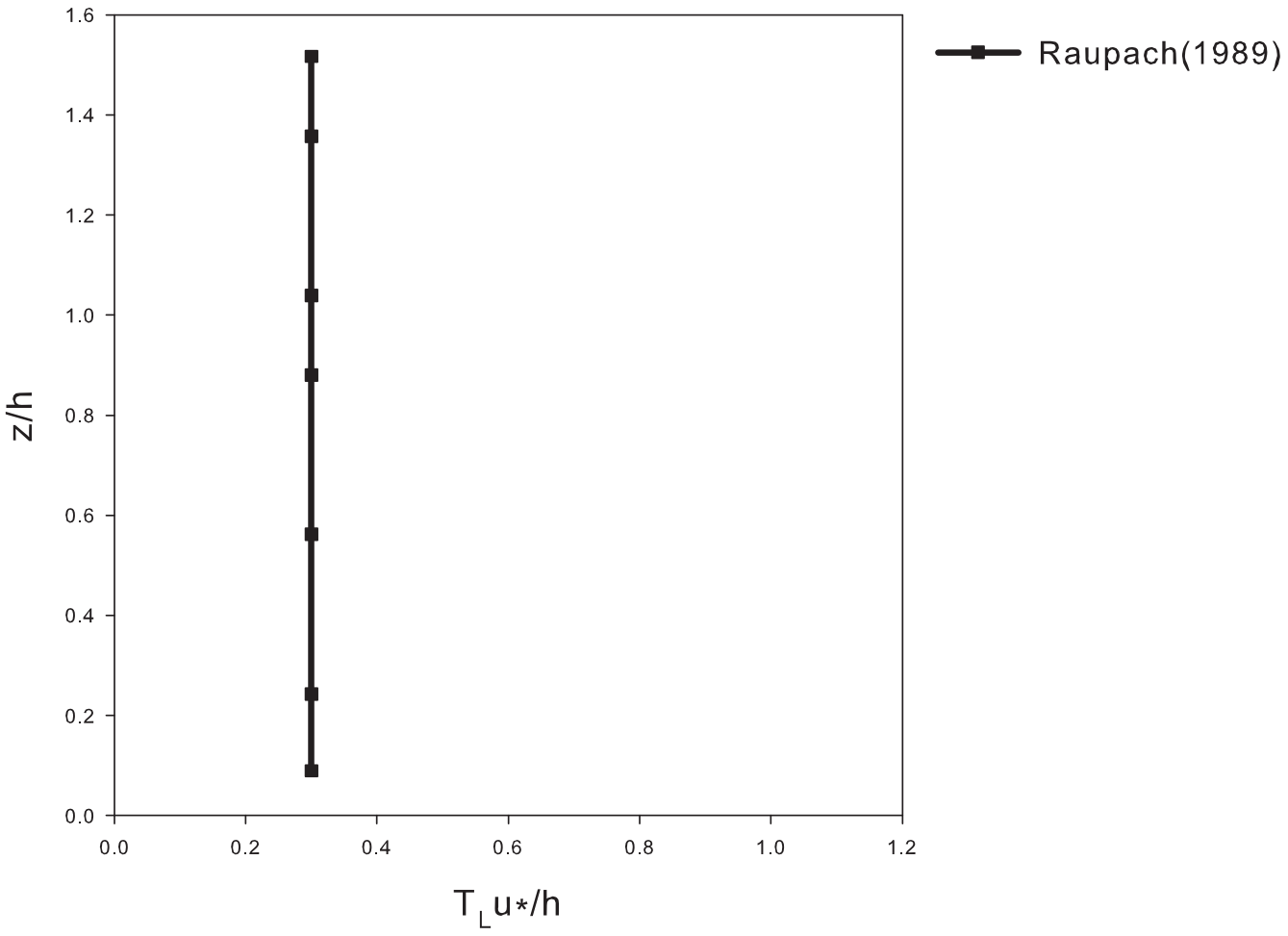




Lagrangian time scale

Lagrangian Time Scale: Unstable condition



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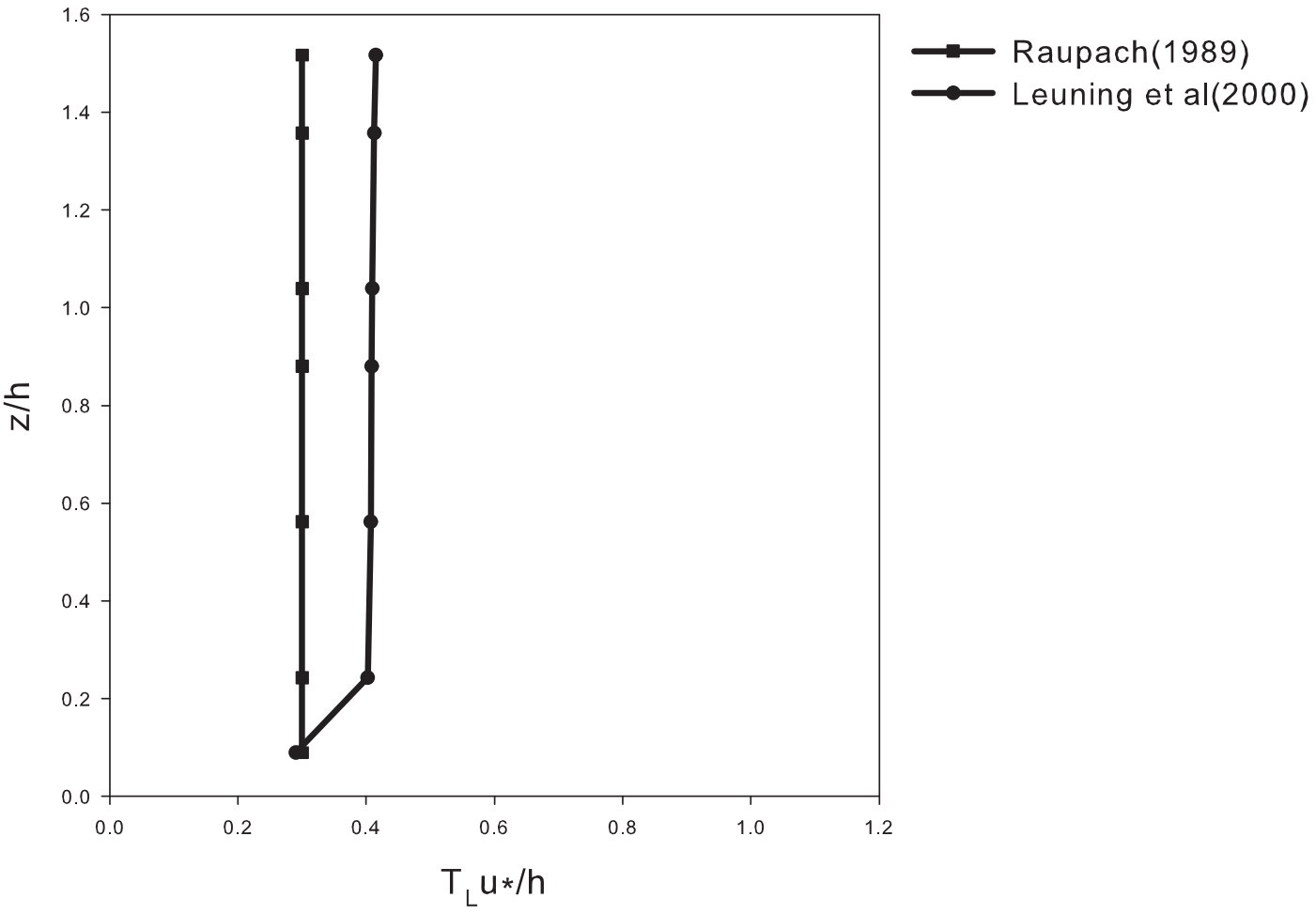

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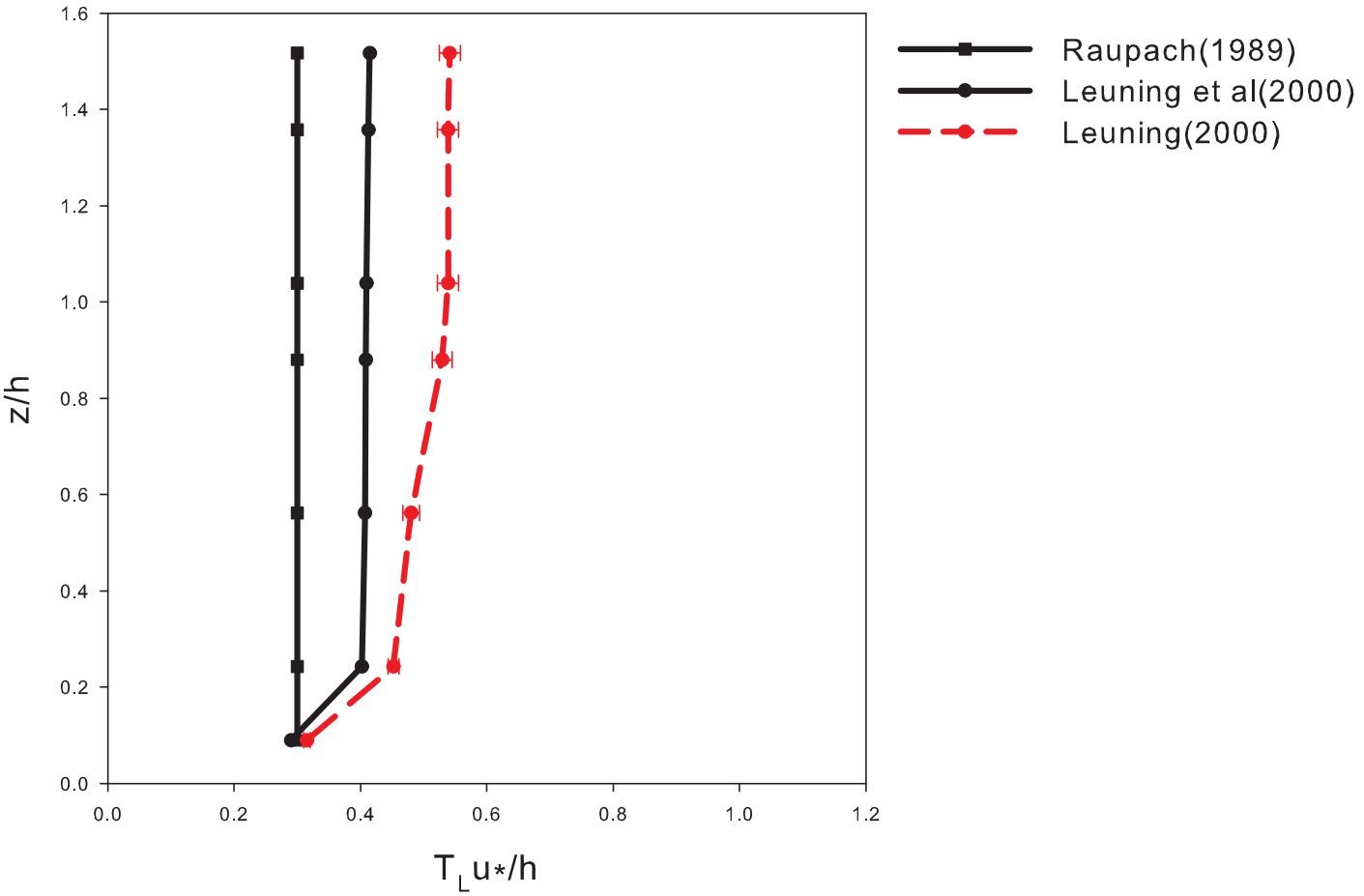

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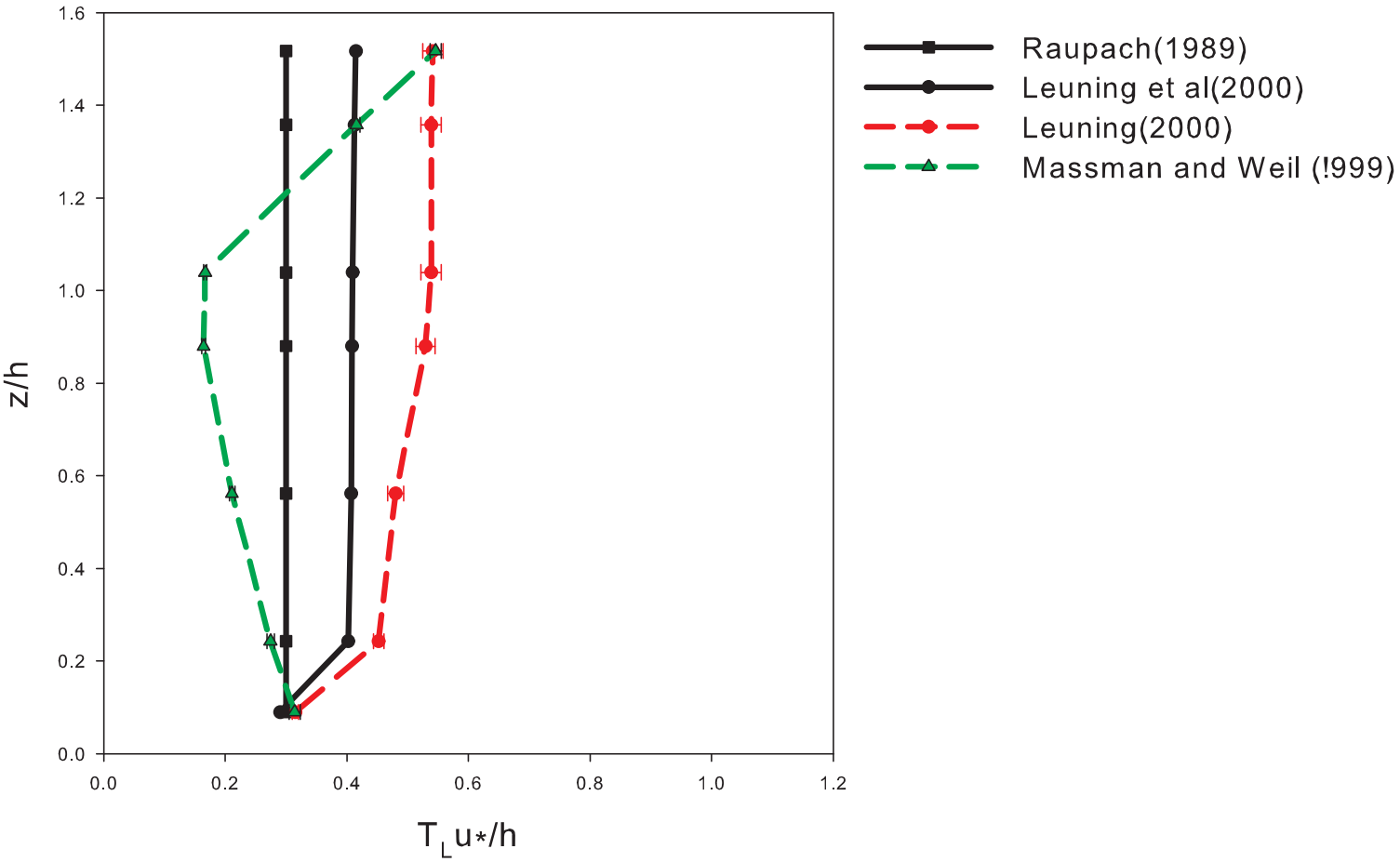

What does make such difference?

Constant Lagrangian time scale or length scale??

- $T_L U_* / h$=0.3 (Raupach, 1989)
- $T_L U_* / h$=0.4 from $\sigma_w(h)/u* = 0.9$ (Leuning, 2000)
- $T_L \propto \sigma_w^{-1}$ (Massman and Weil, 1999)
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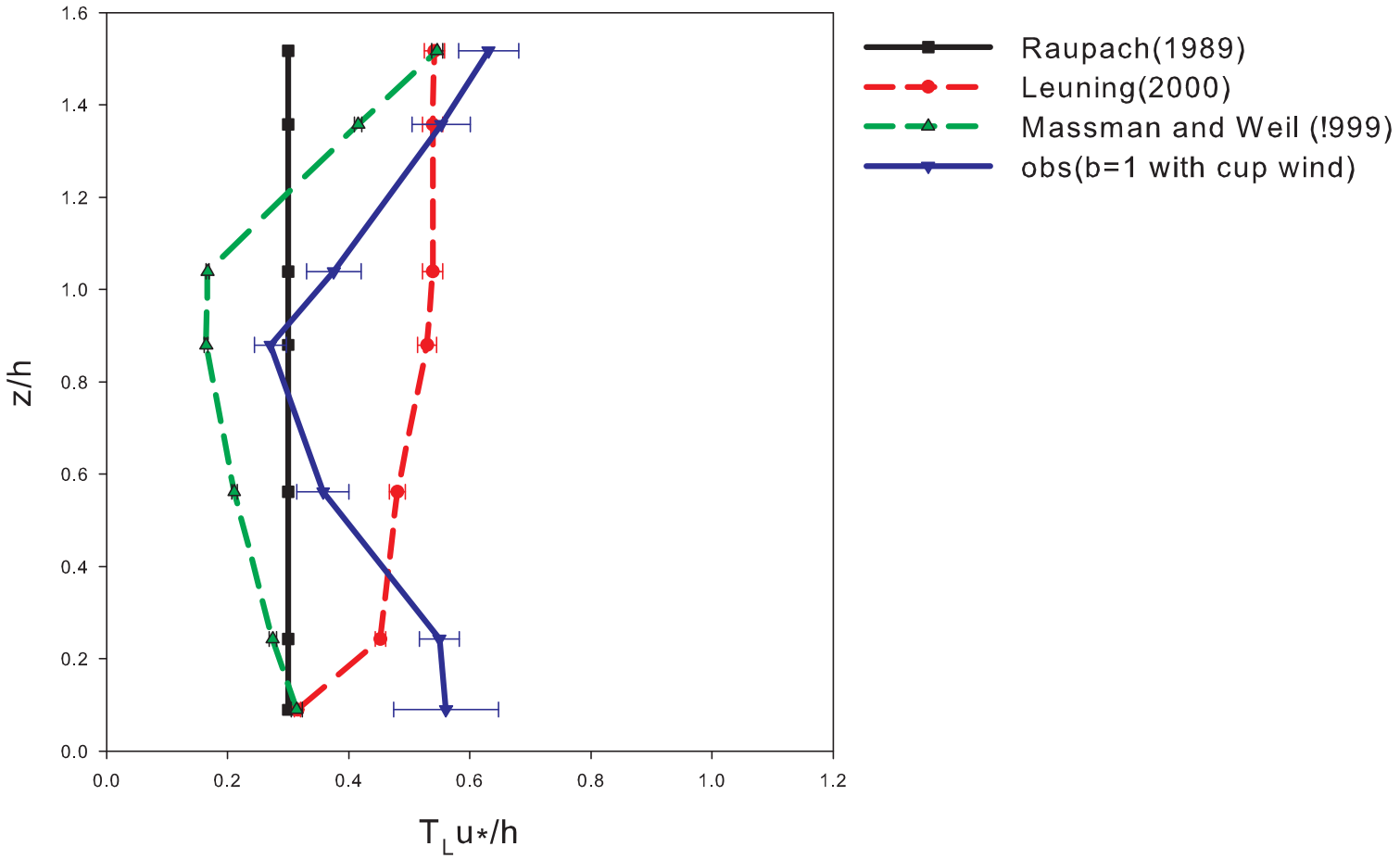
L_L is constant with height. ($L_L = \sigma_w T_L$)

Lagrangian Time Scale: Unstable condition



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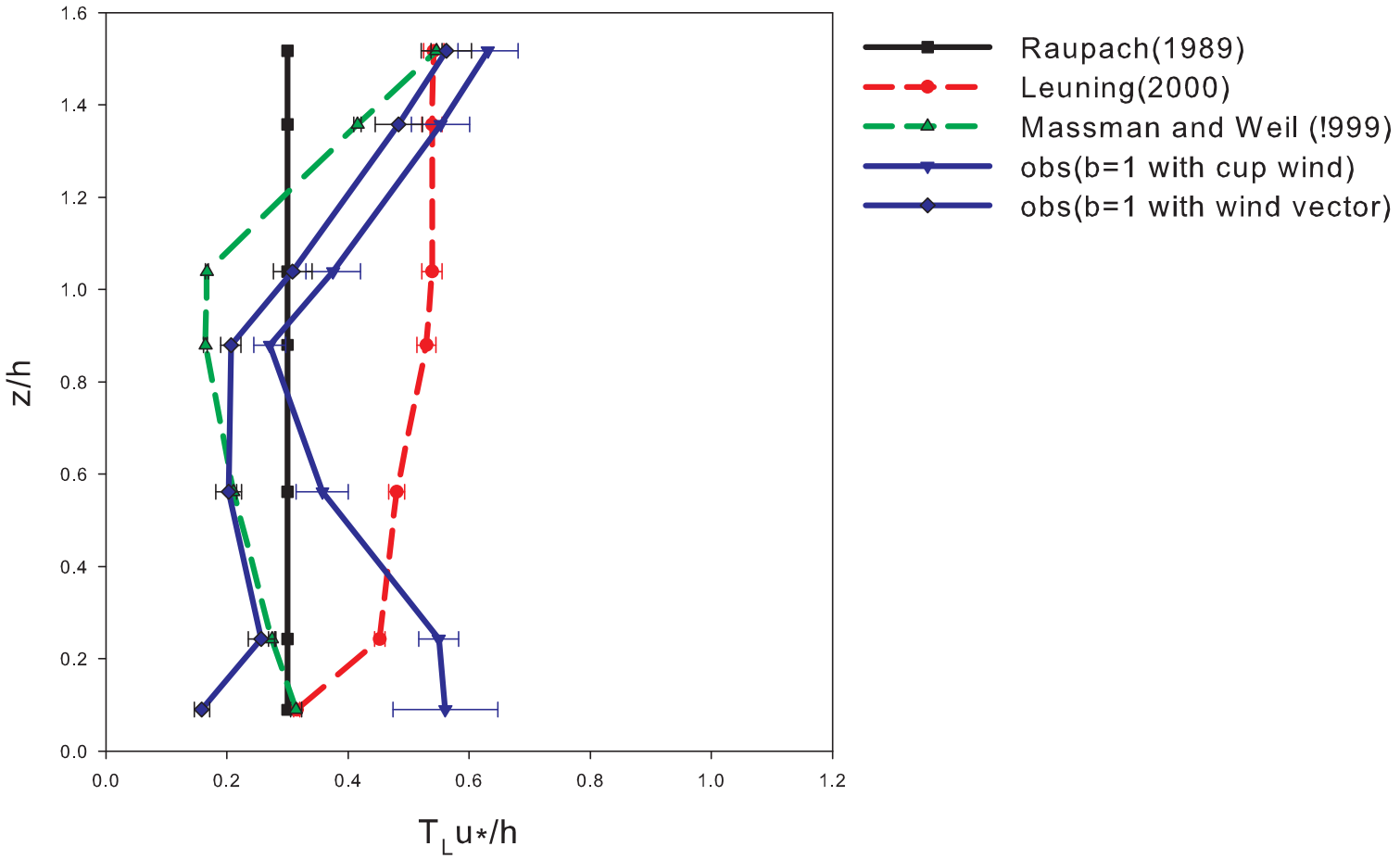

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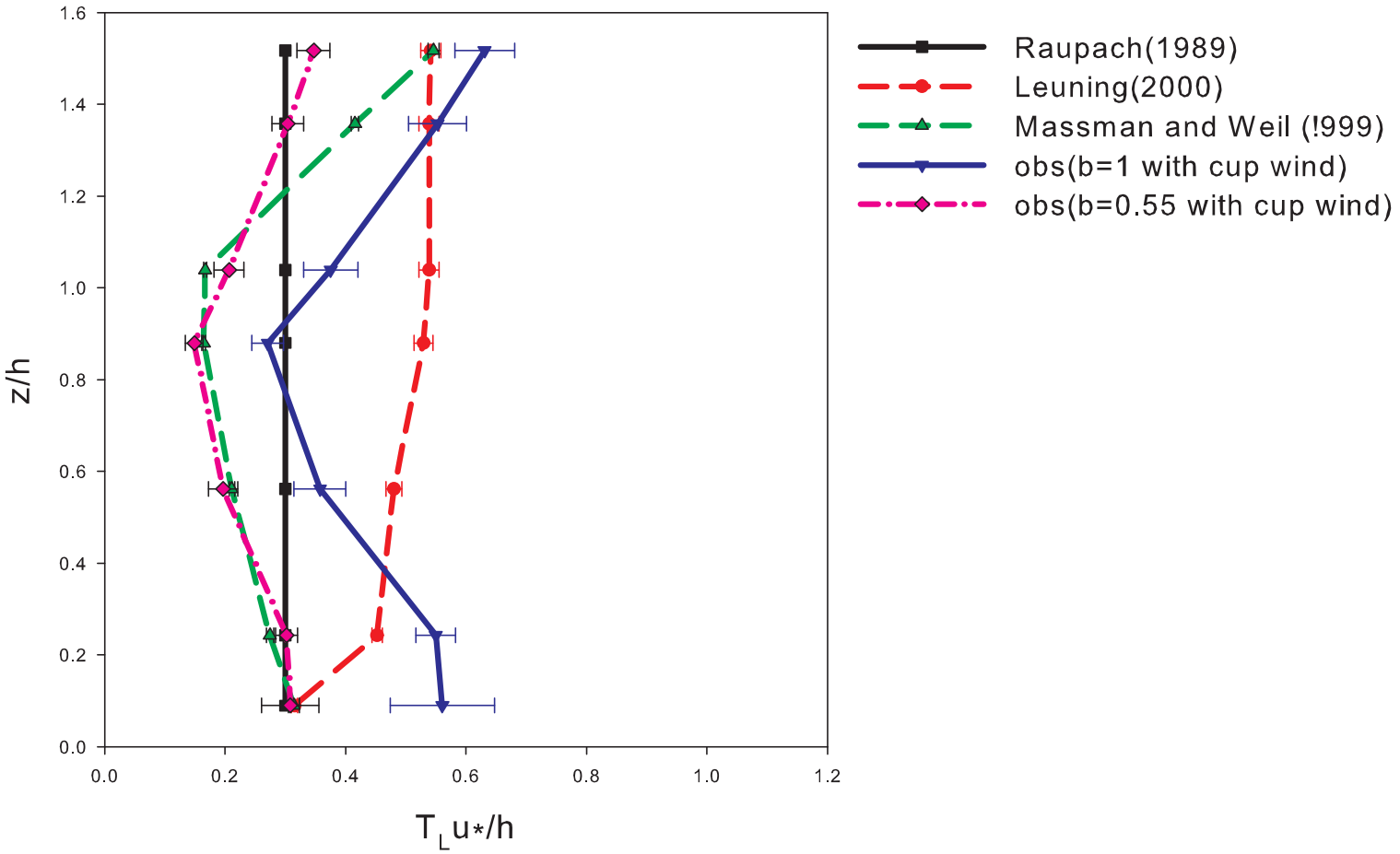

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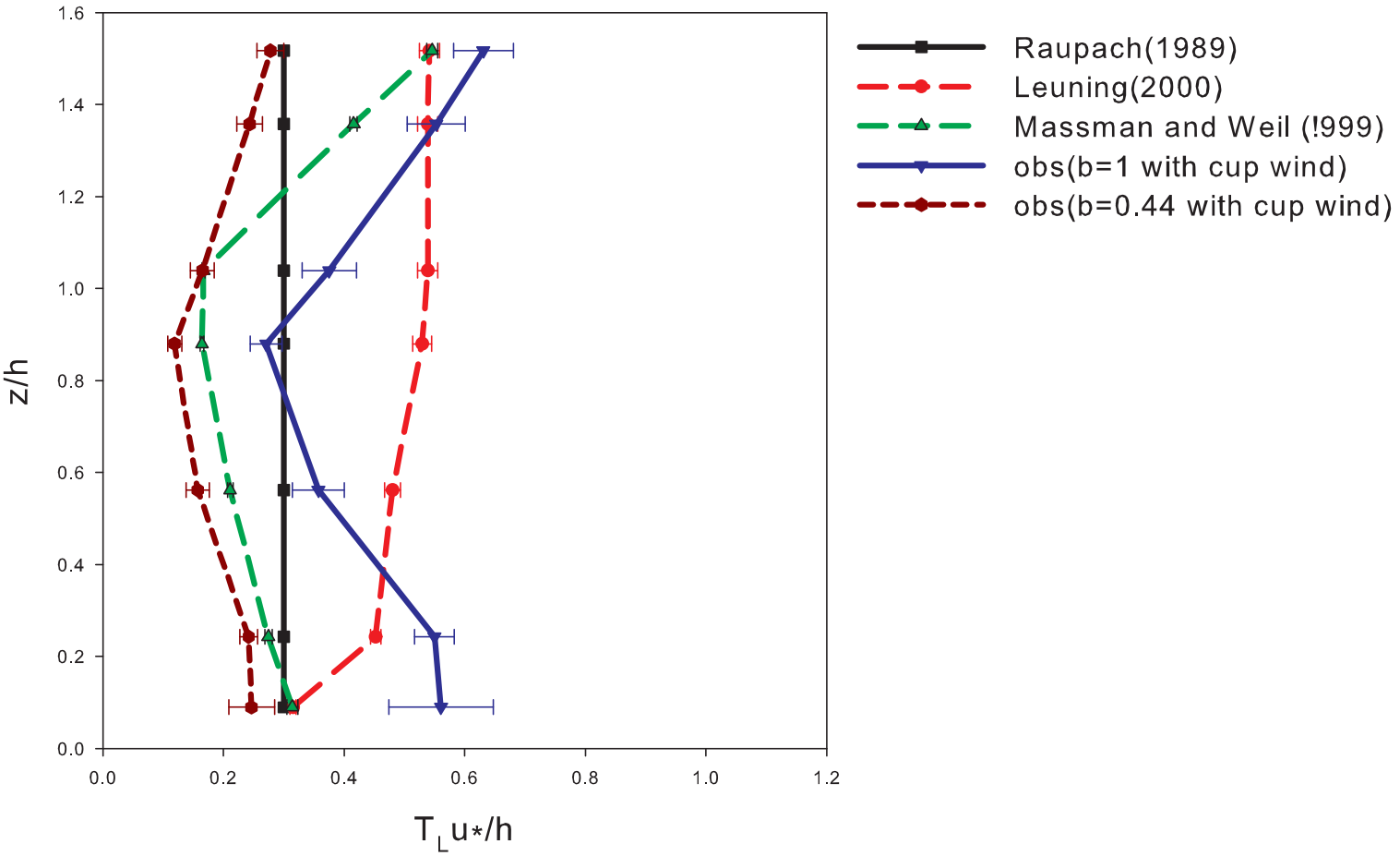
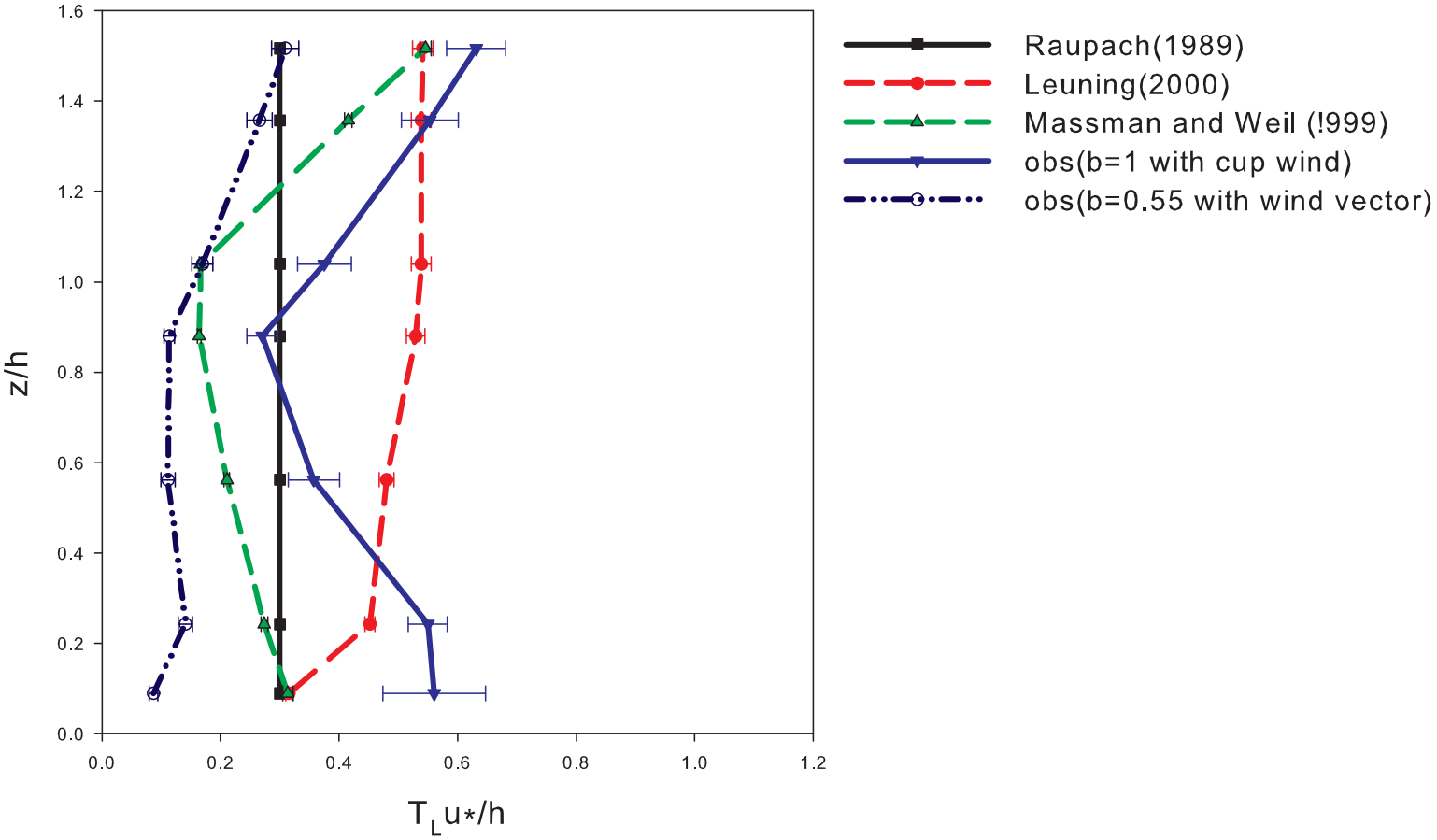
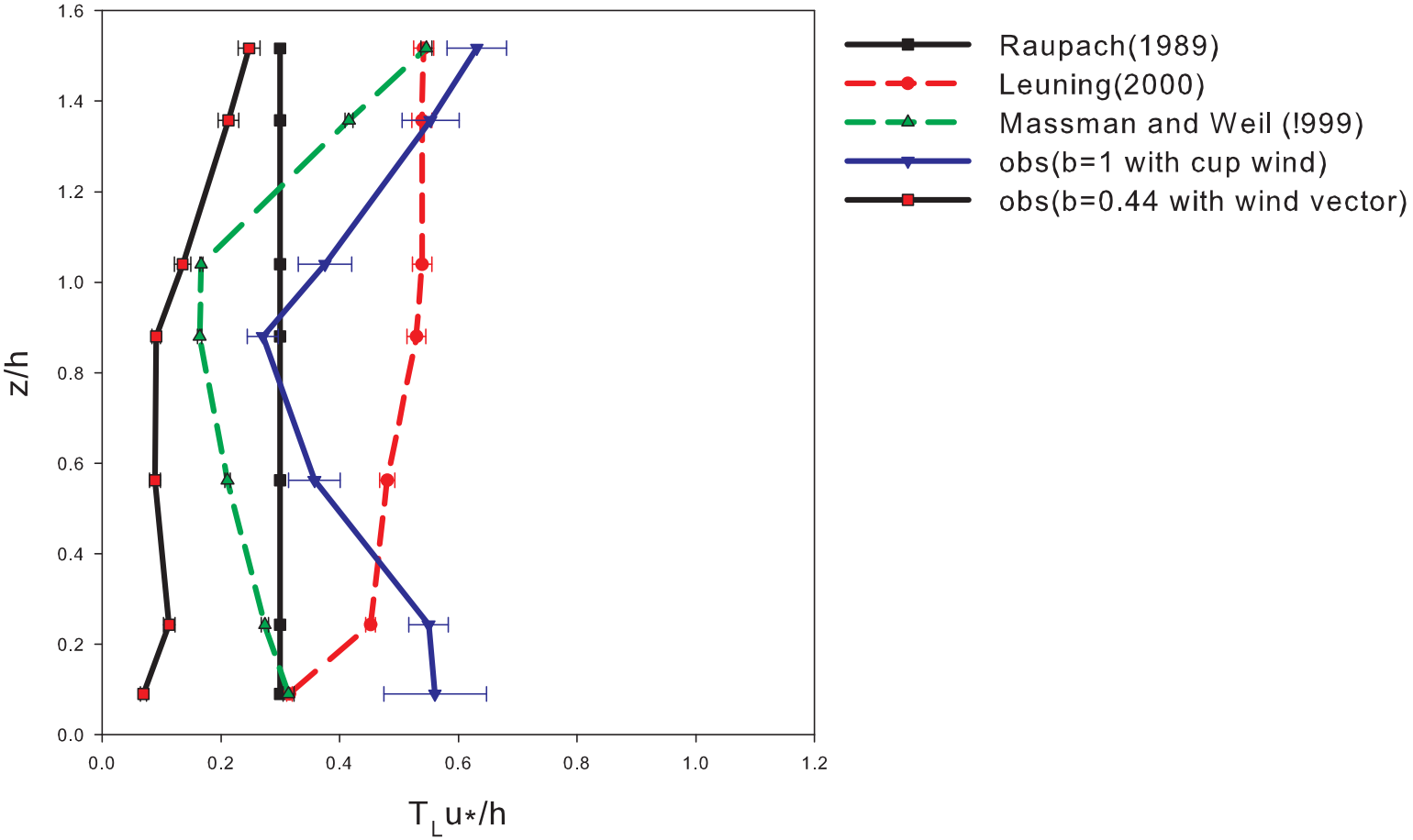


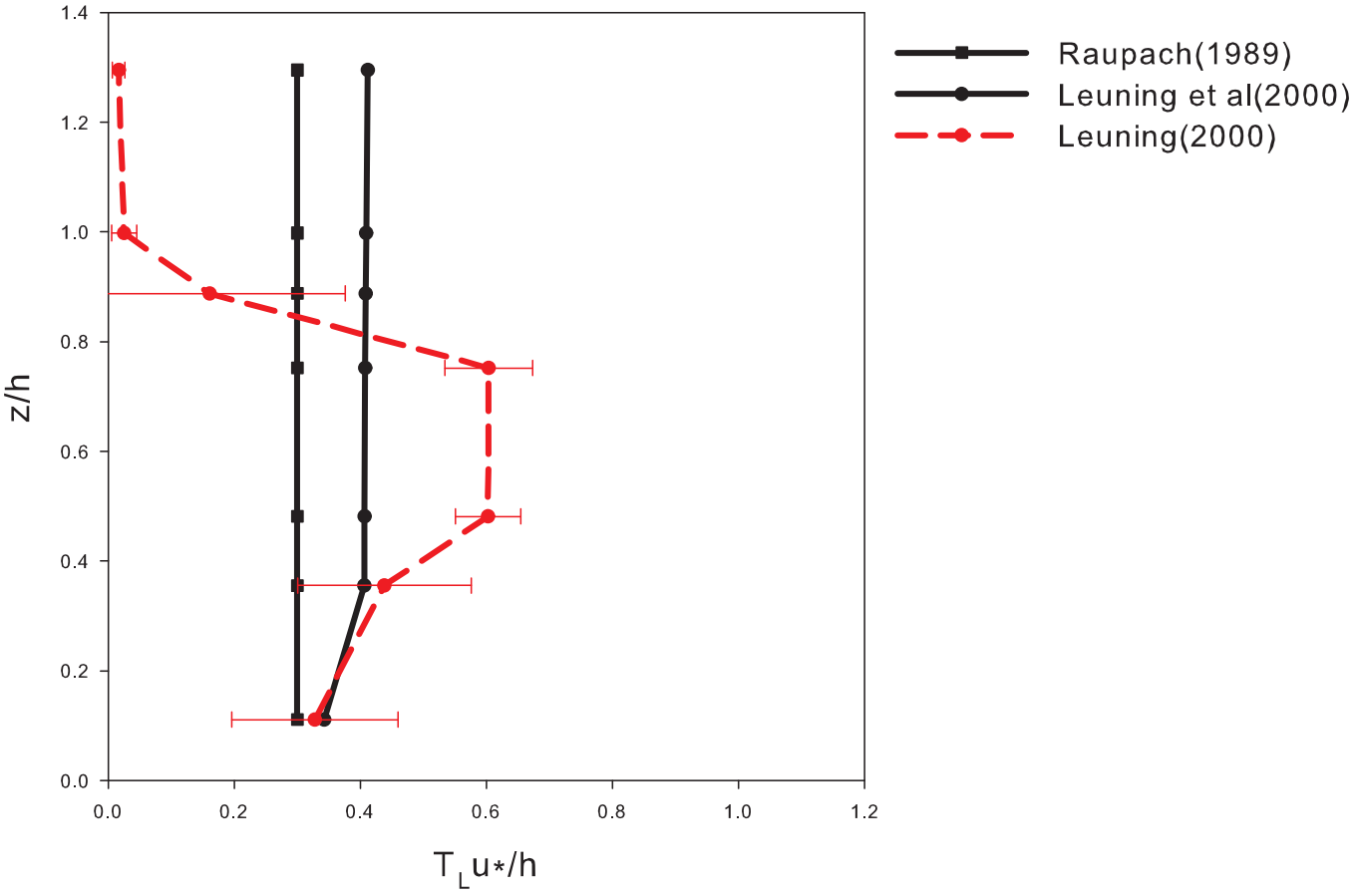
Lagrangian Time Scale: Unstable condition



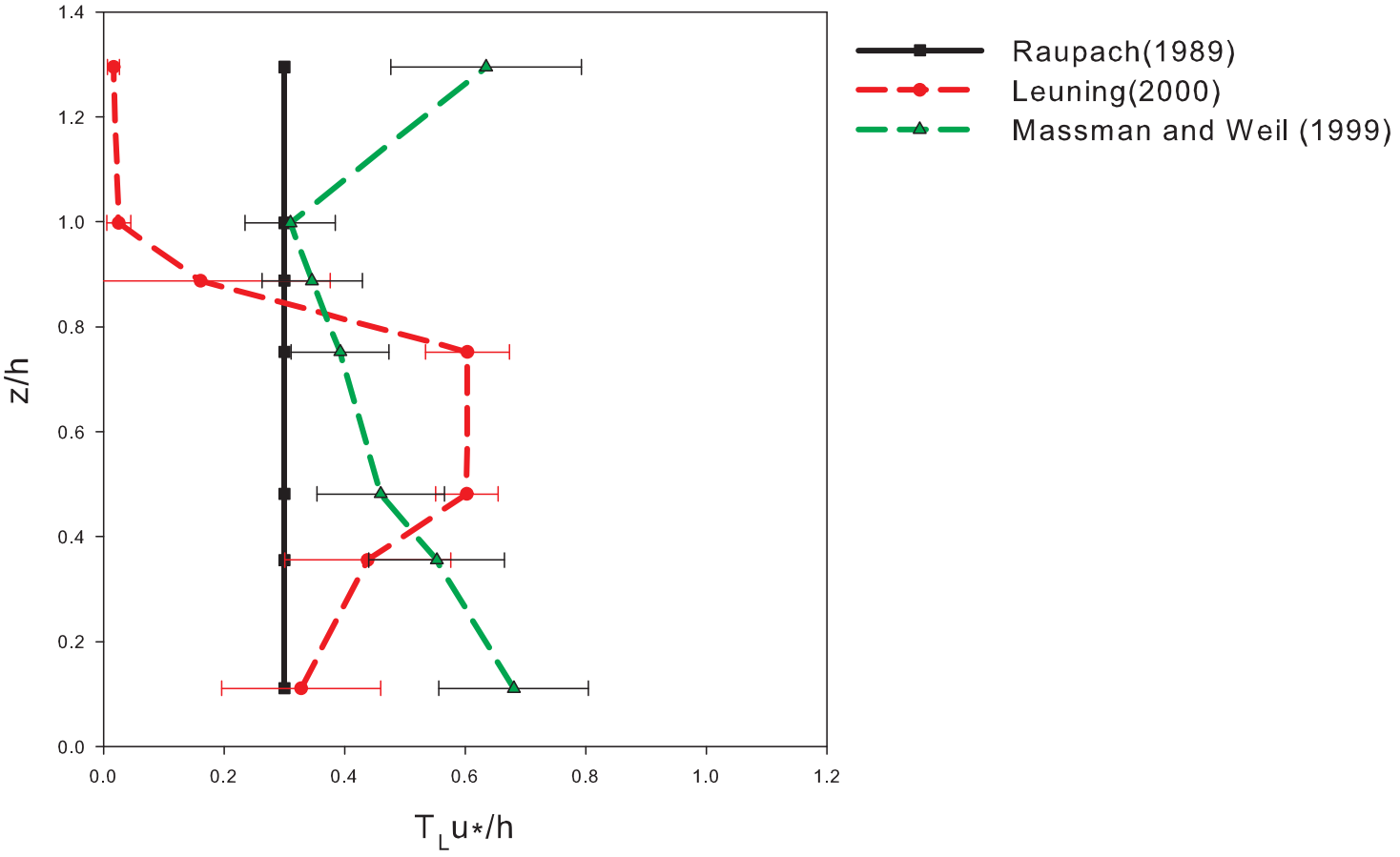
Lagrangian Time Scale: Unstable condition



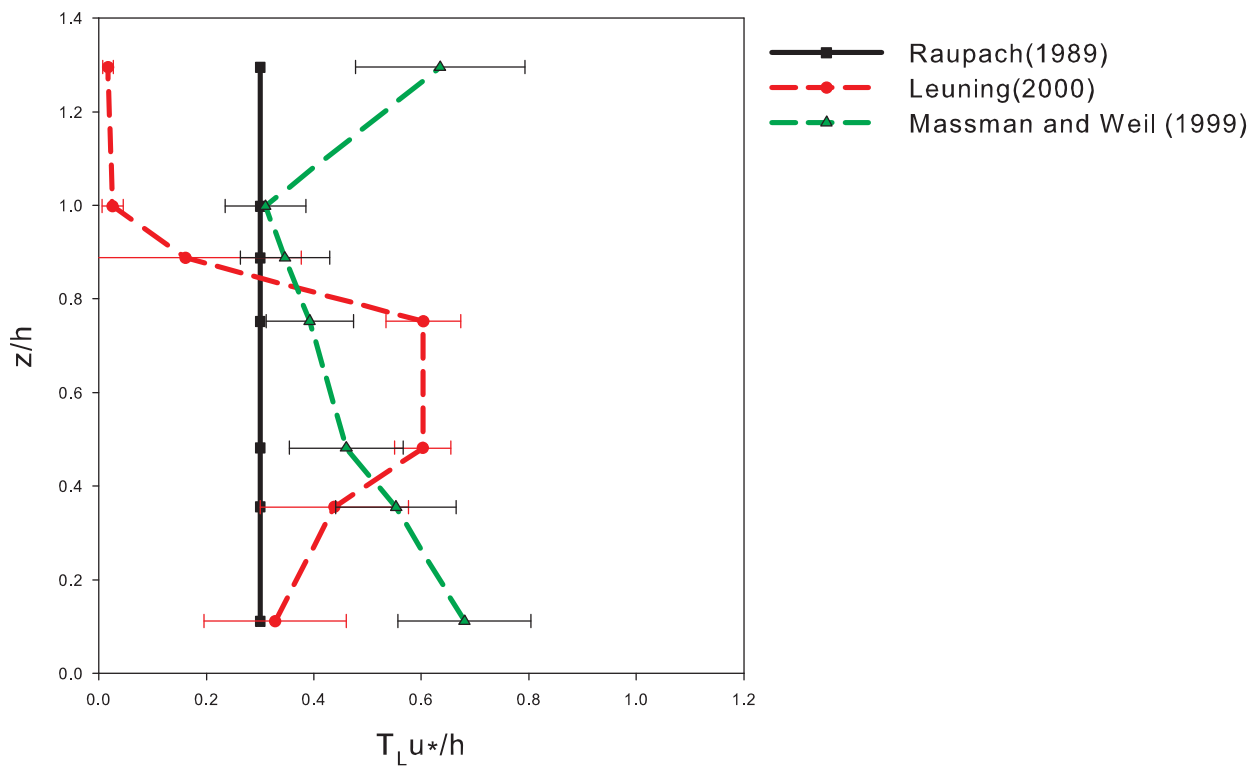
Lagrangian Time Scale: Stable condition



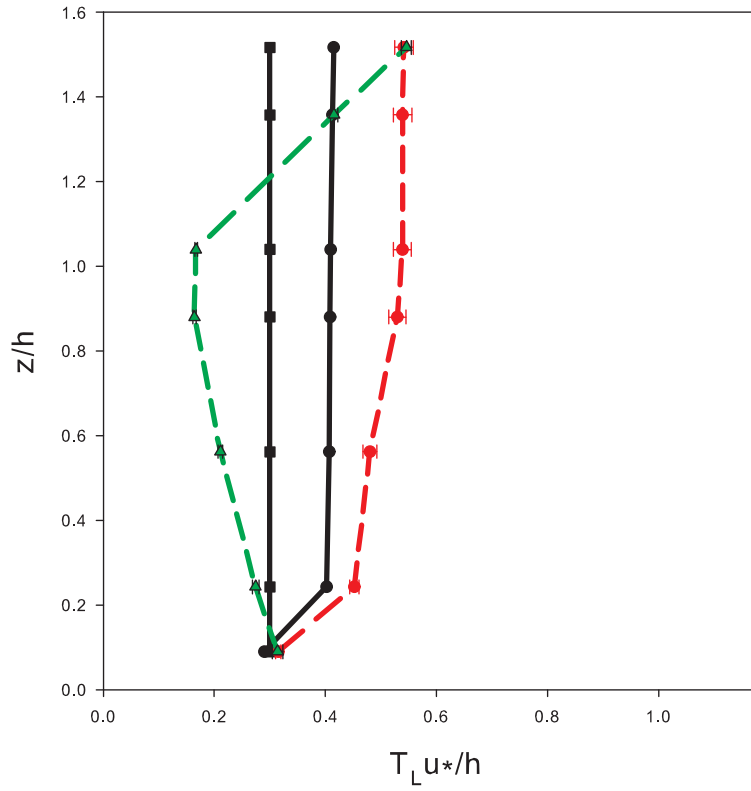
Lagrangian Time Scale: Stable condition



Lagrangian Time Scale: Stable condition



Stable conditions

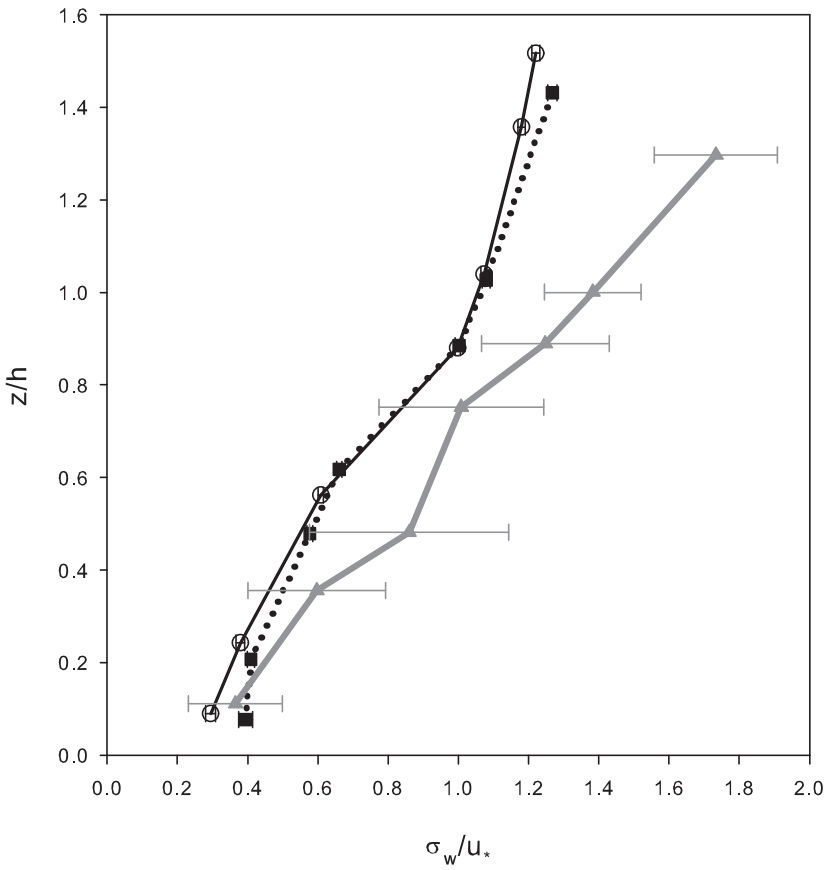


Unstable conditions

Stability Correction in MW profile?

$$\frac{T_L u_*}{h} = \begin{cases} A_1(1-d/h)\gamma_3/(\sigma_w(z)/u \\ A_1(z-d)/h \end{cases}$$

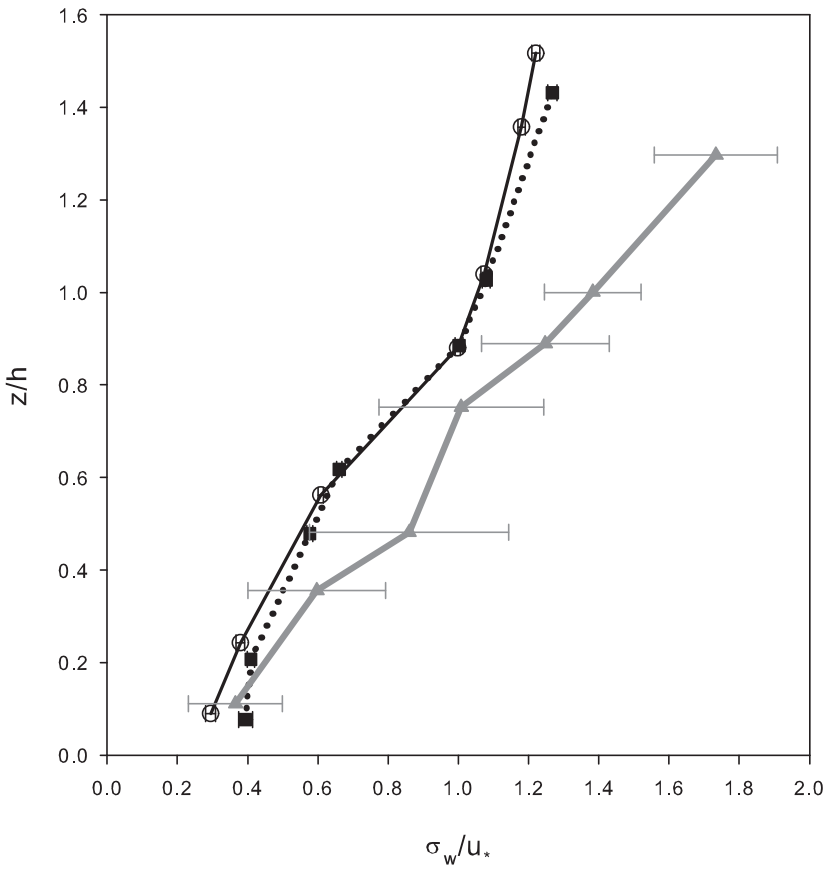
$$A_1 \propto (\sigma_w(z)/u_*\gamma_3)^{1/2}(1-d/h)^{-1/2}$$



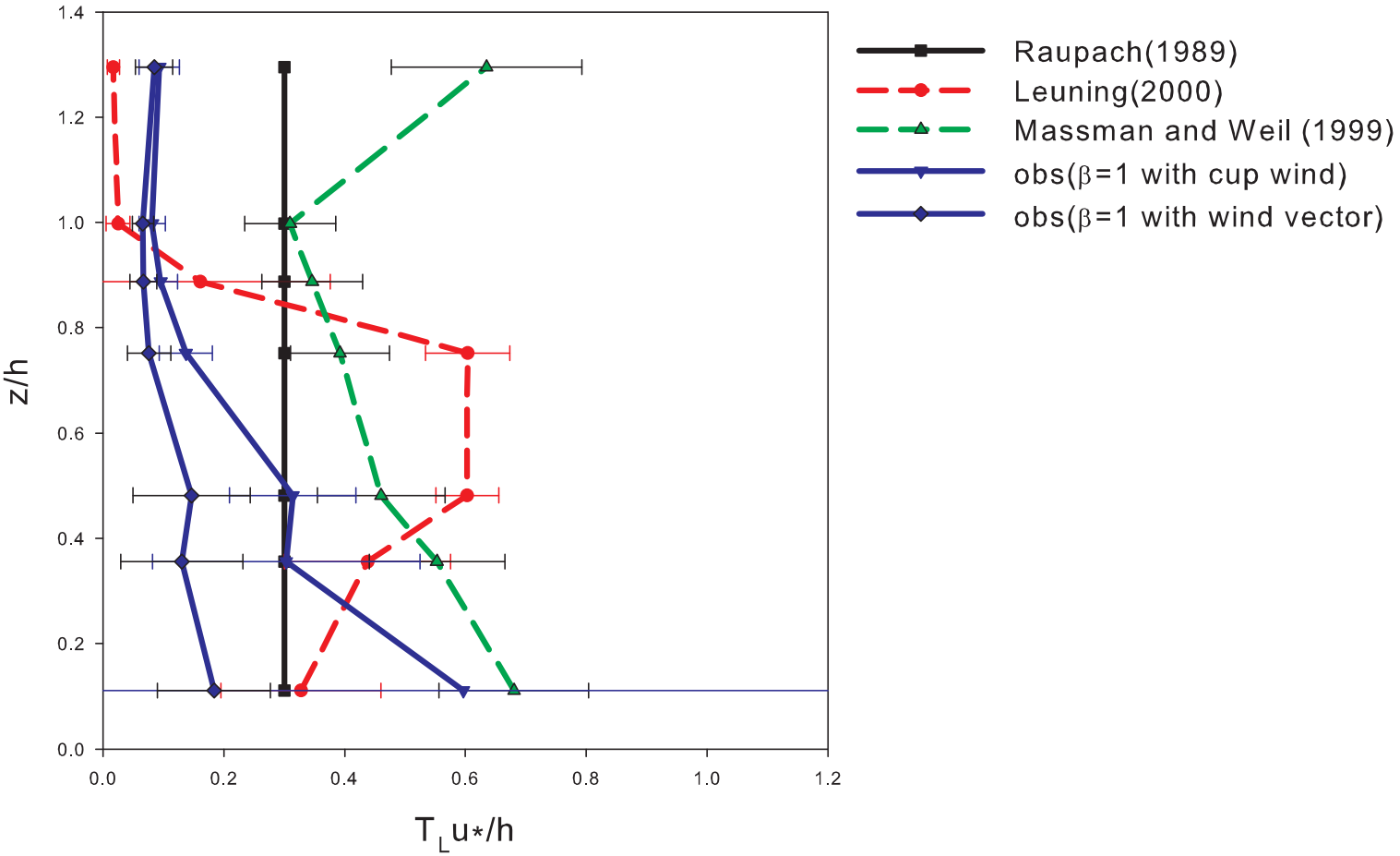
Stability Correction in MW profile?

$$\frac{T_L u_*}{h} \propto \frac{\gamma_3^{3/2}}{\sqrt{\sigma_w(z)/u_*}}$$

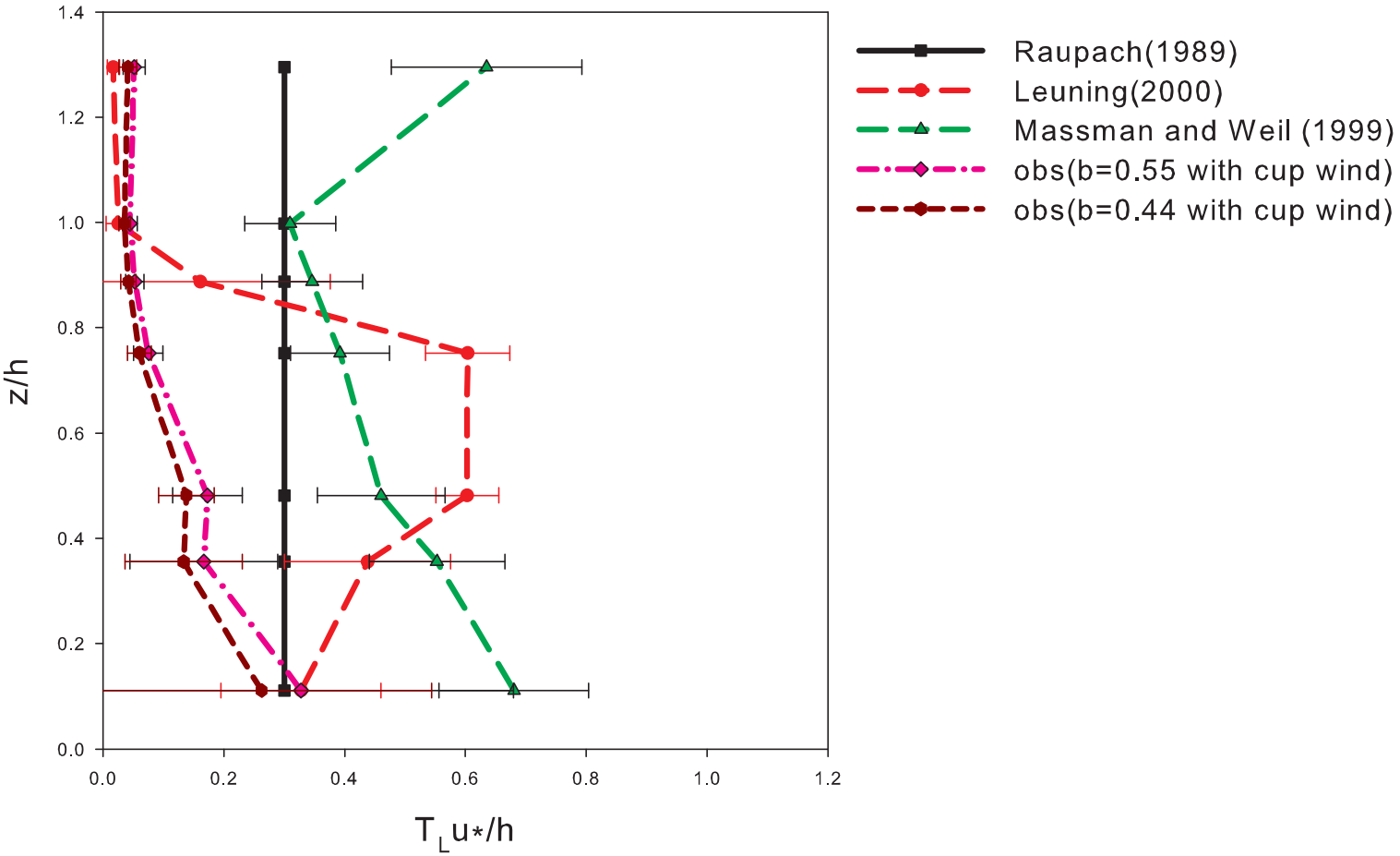
$$\gamma_3 = (\sigma_w/u_*)_{\text{above the canopy}}$$



Lagrangian Time Scale: Stable condition



Lagrangian Time Scale: Stable condition



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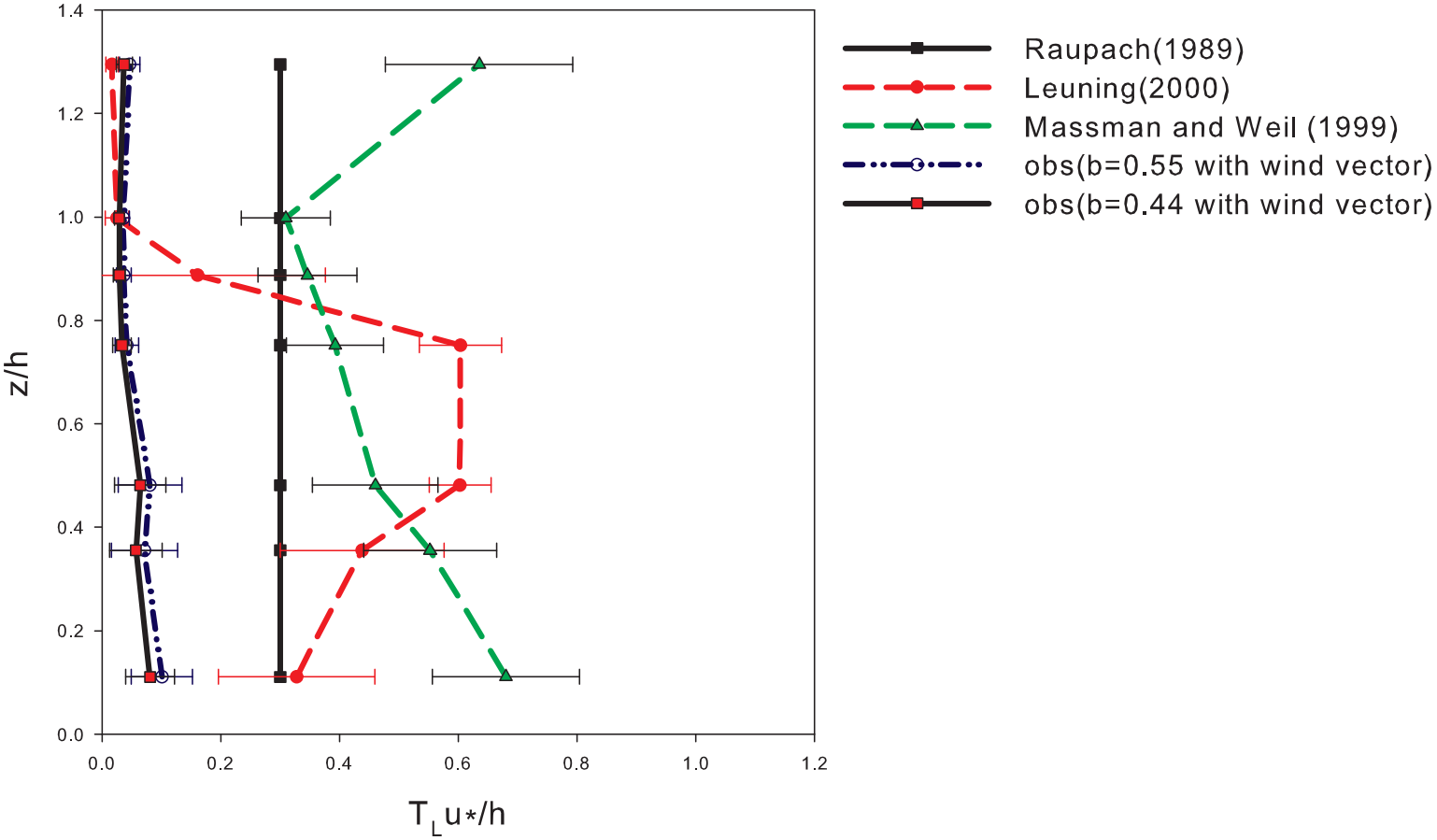
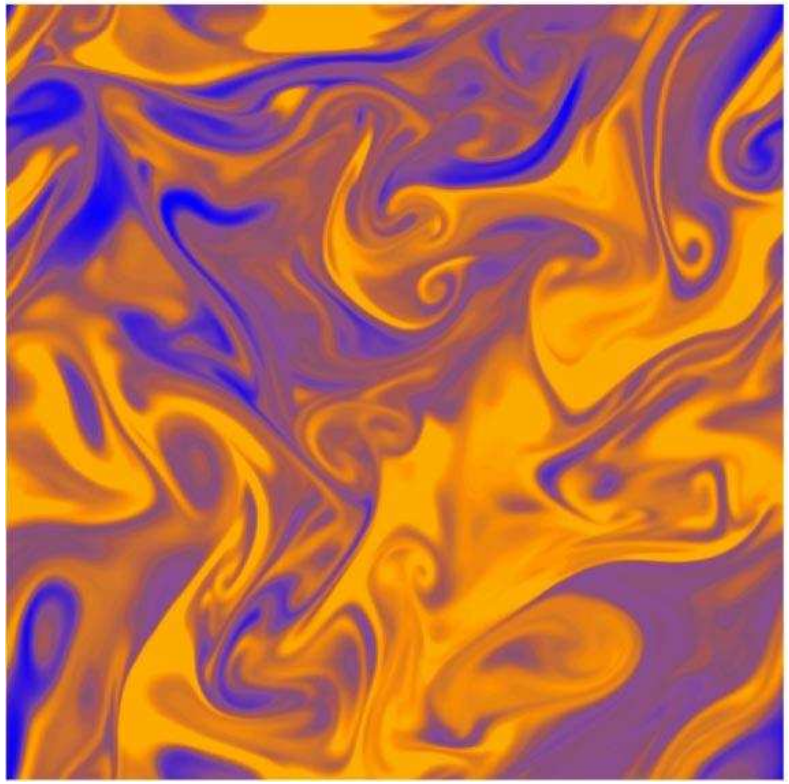
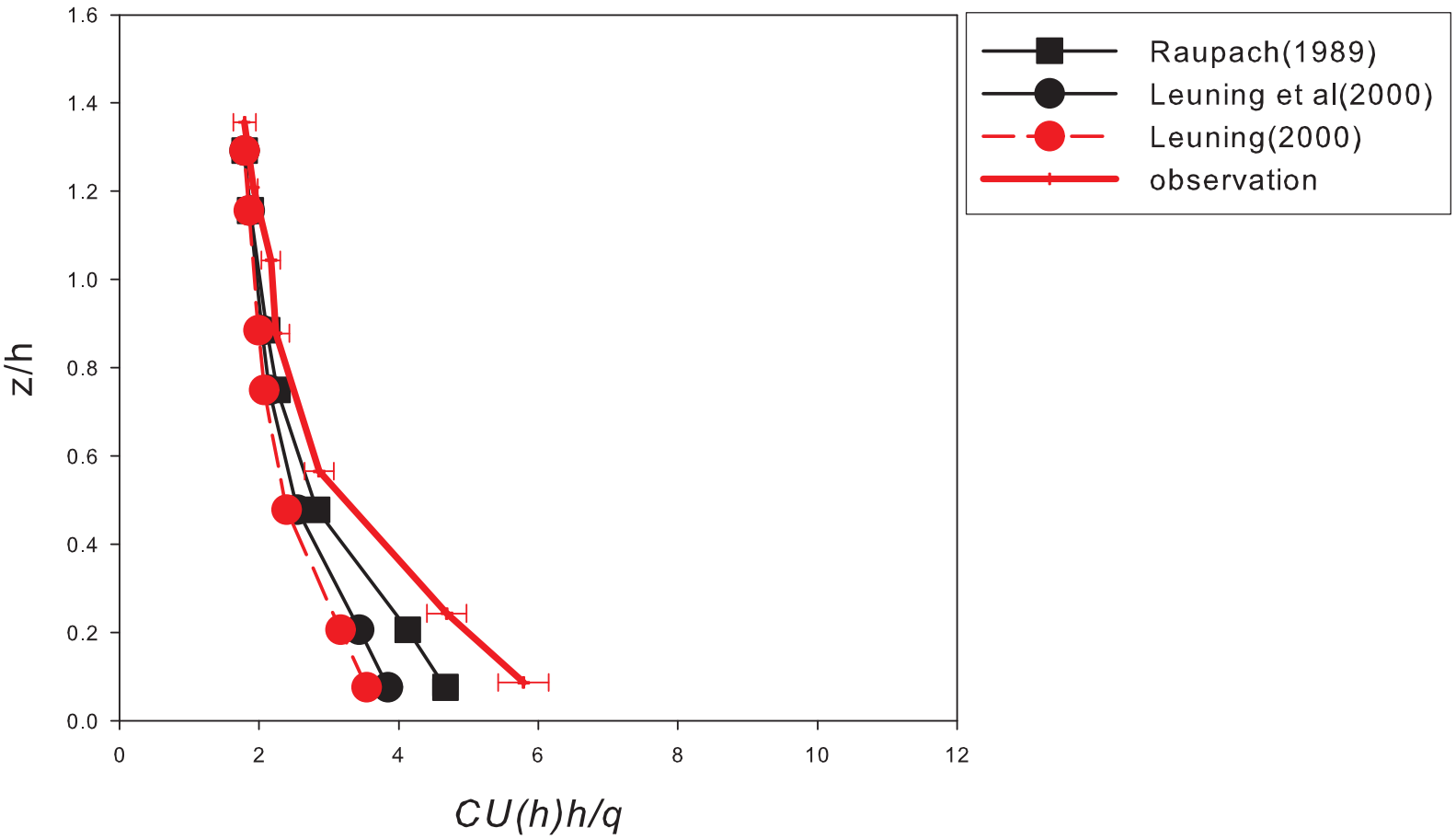


Comparison of Model with observed tracer concentration profile



Unstable Conditions: $x/h = 1.87, h/h_s = 0.1$



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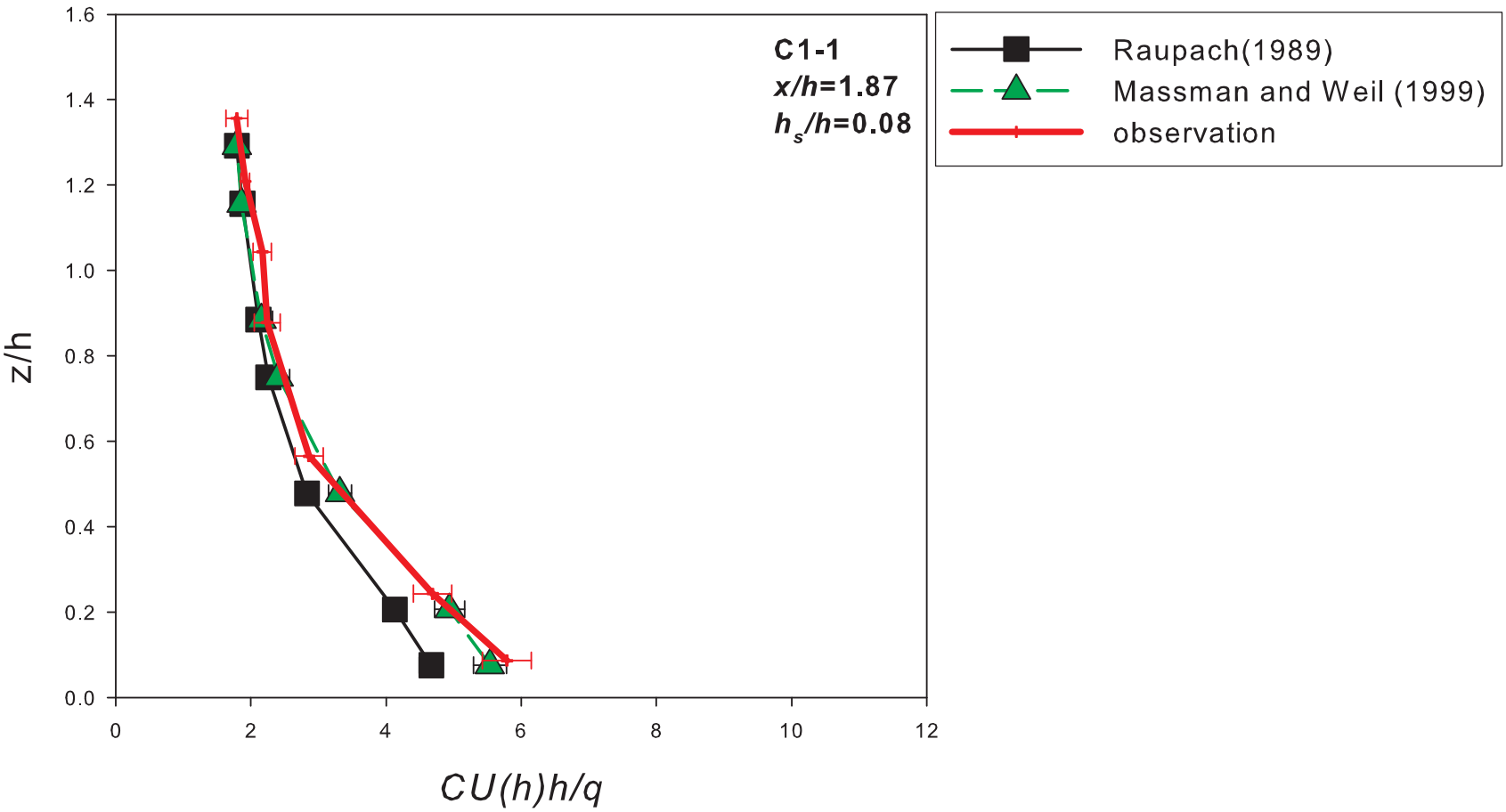

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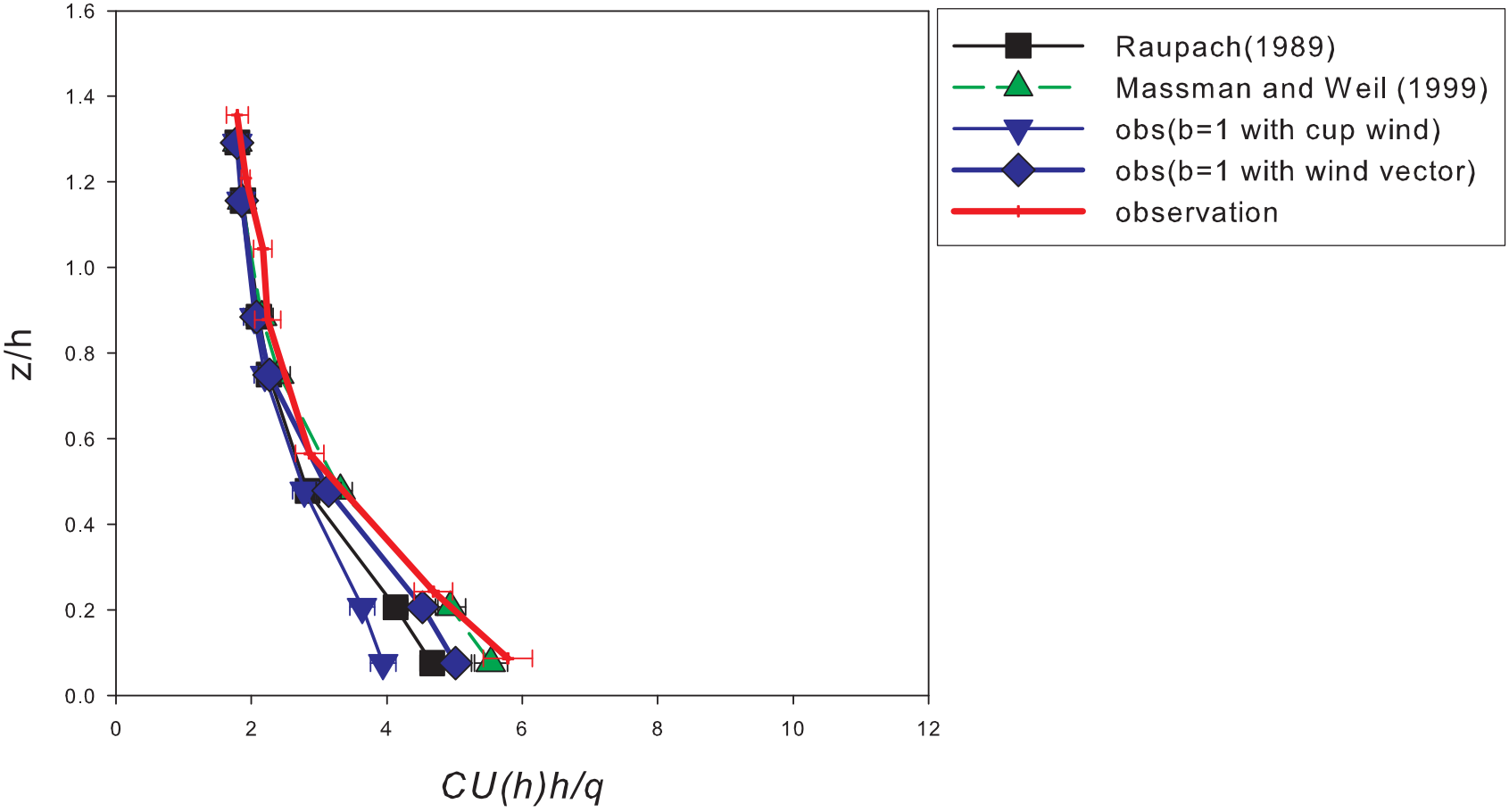

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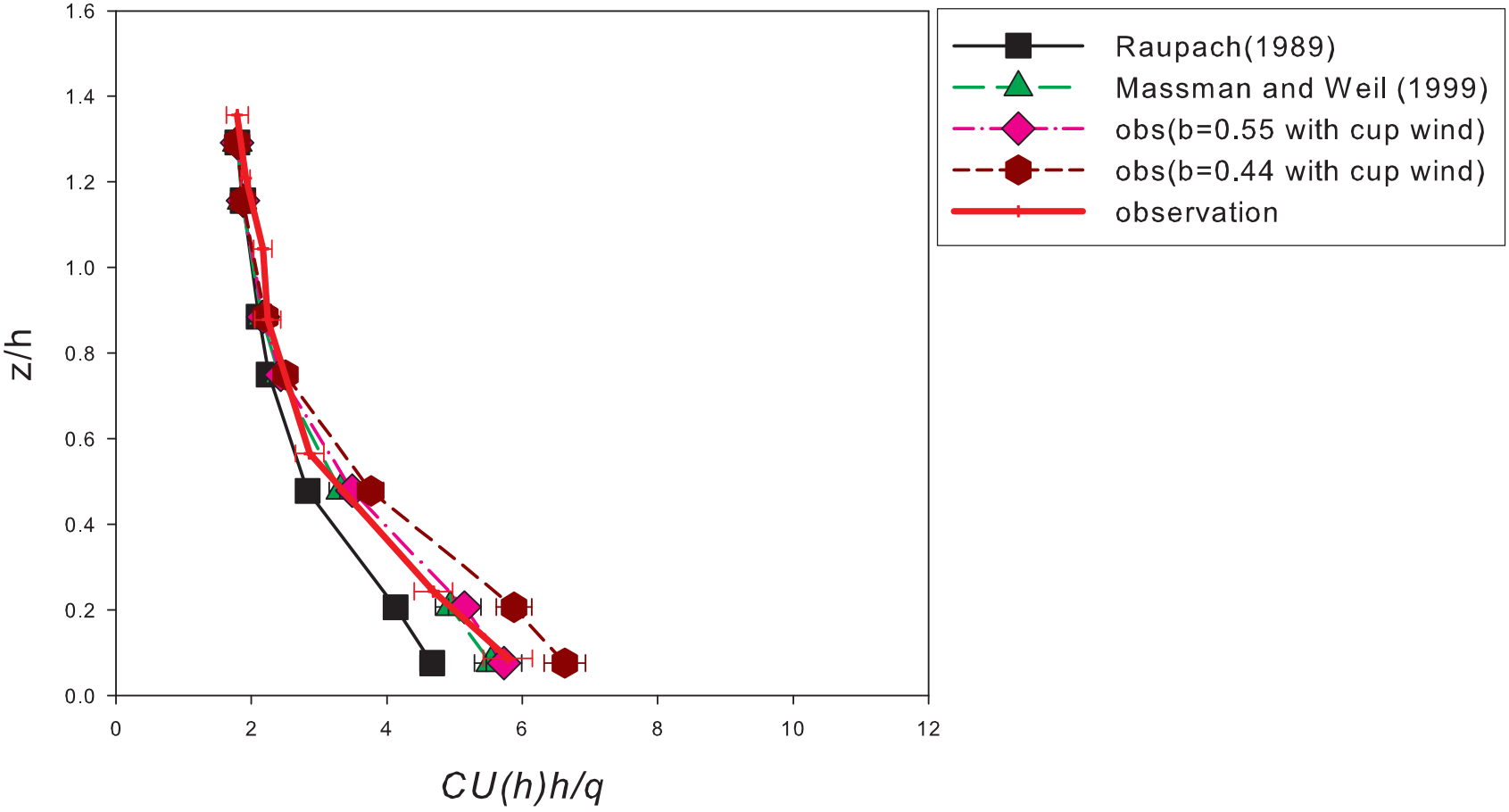

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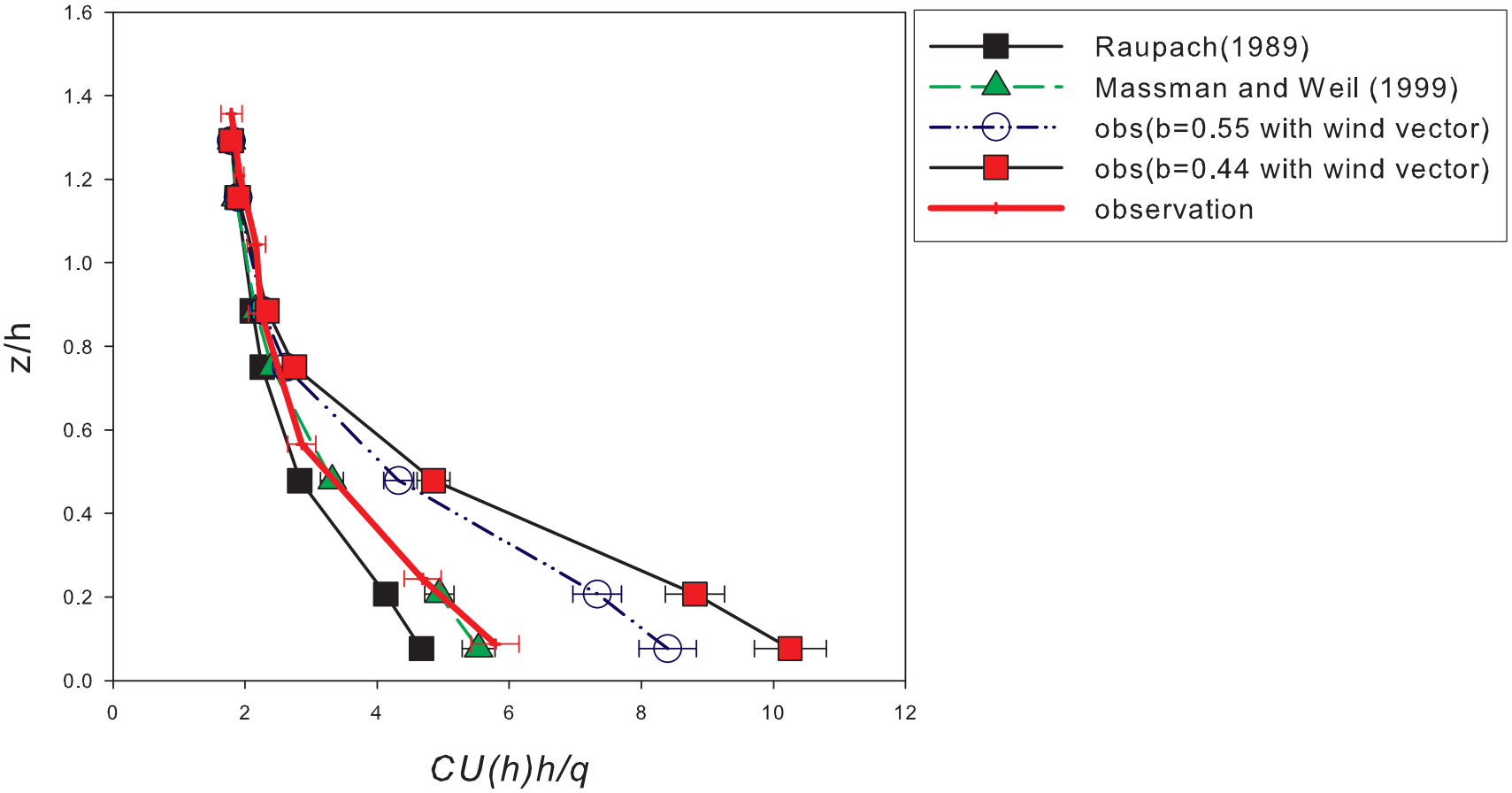
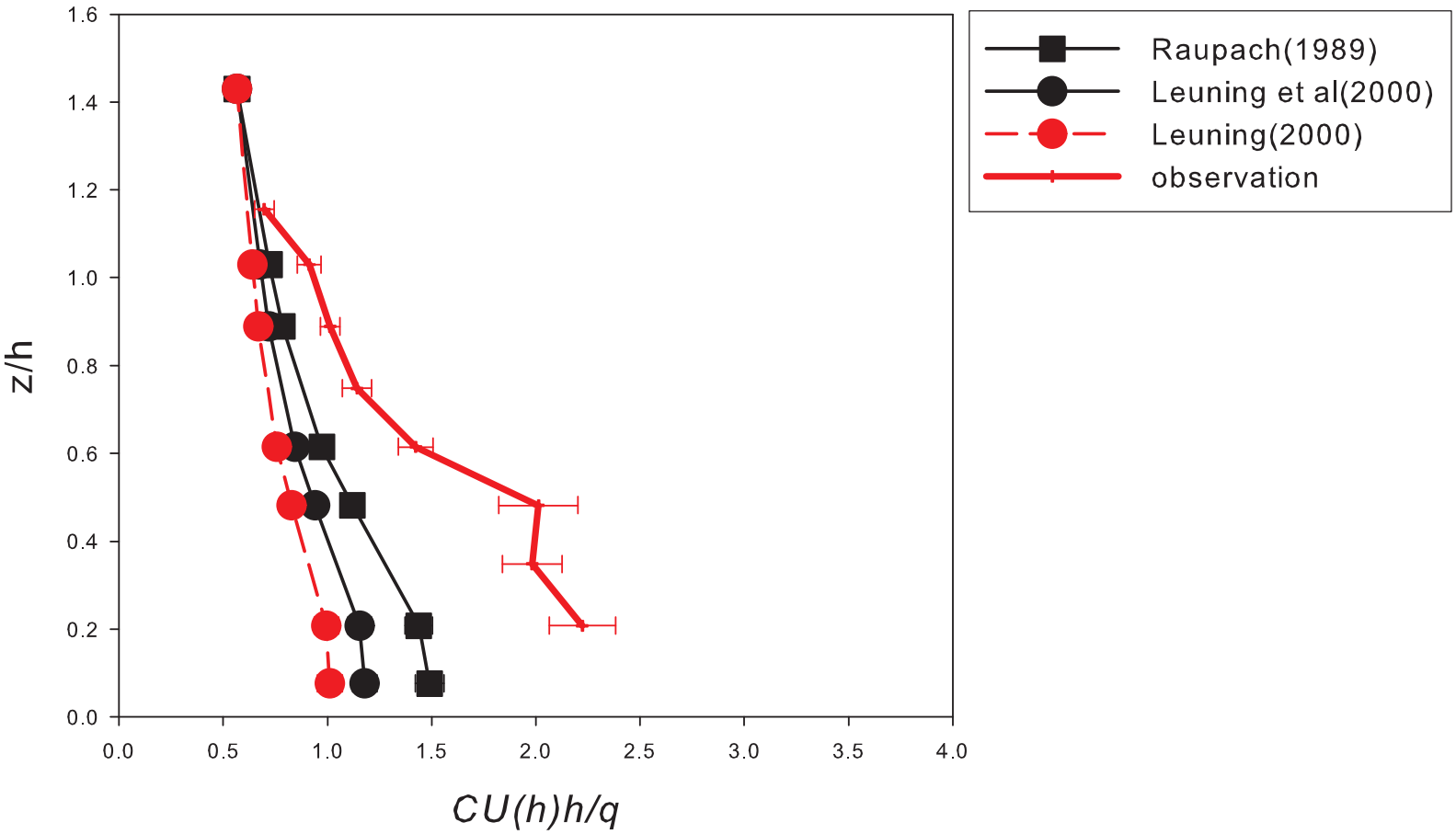


Unstable Conditions: $x/h = 3.70, h/h_s = 0.1$



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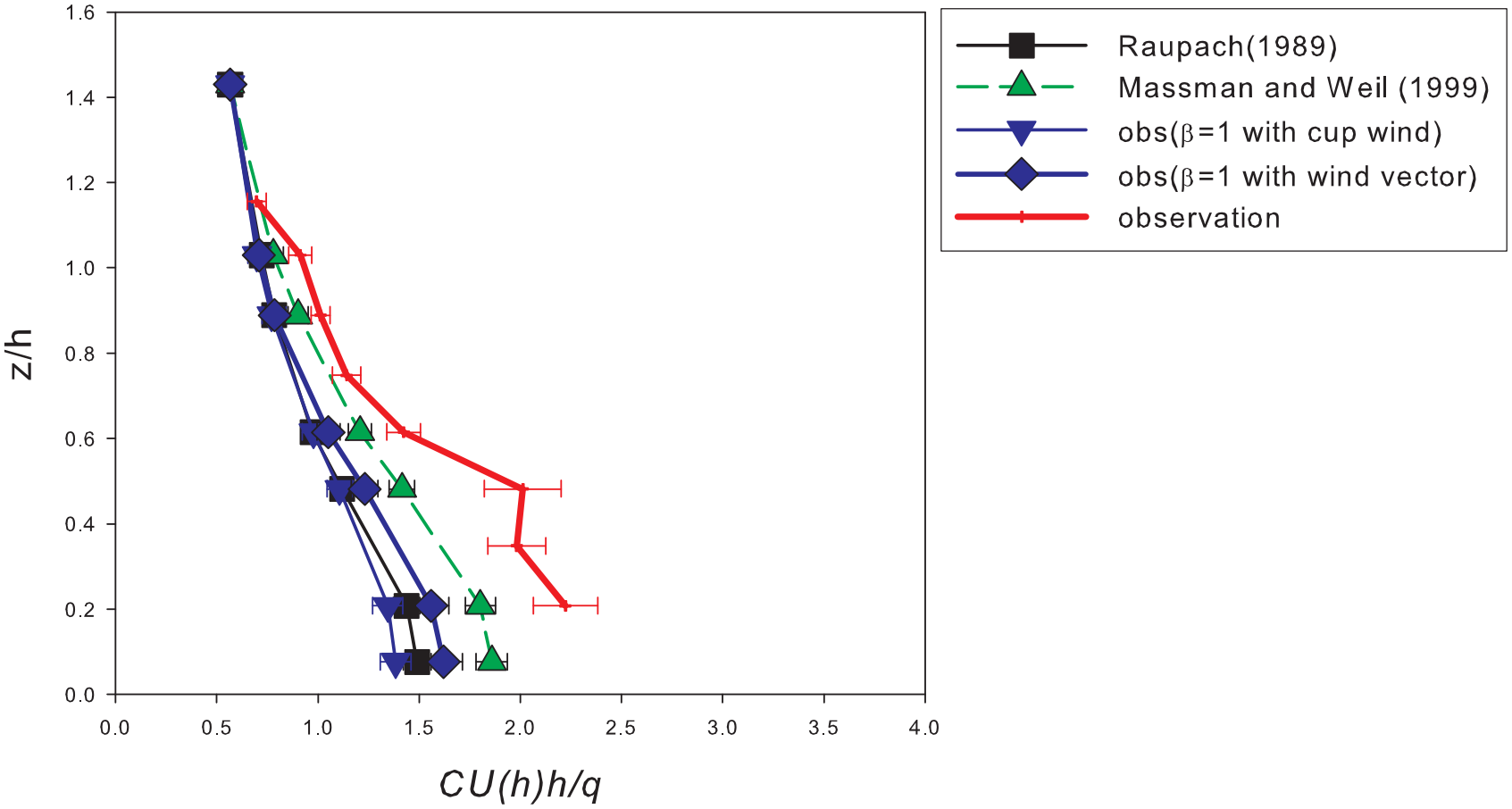

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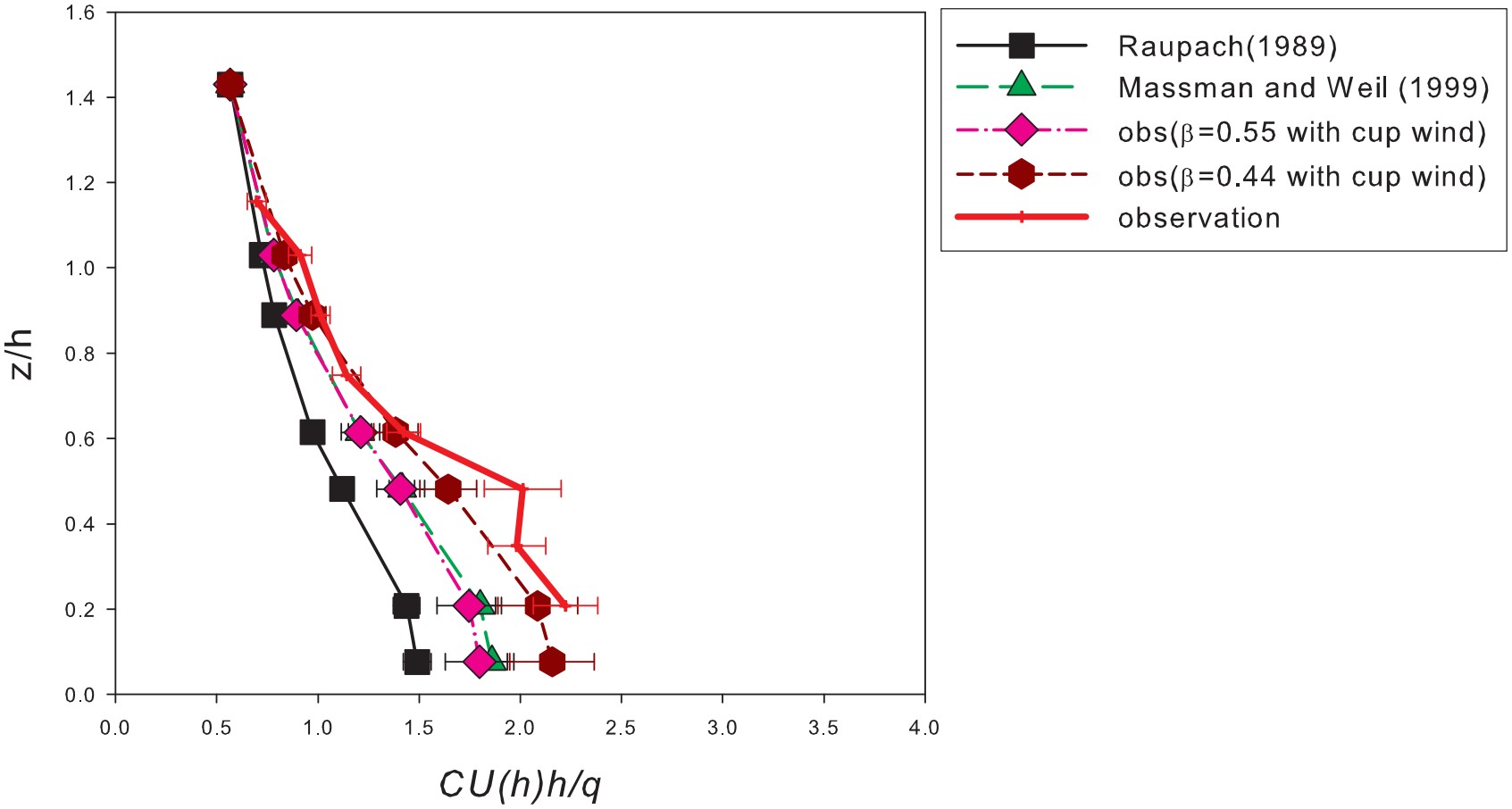

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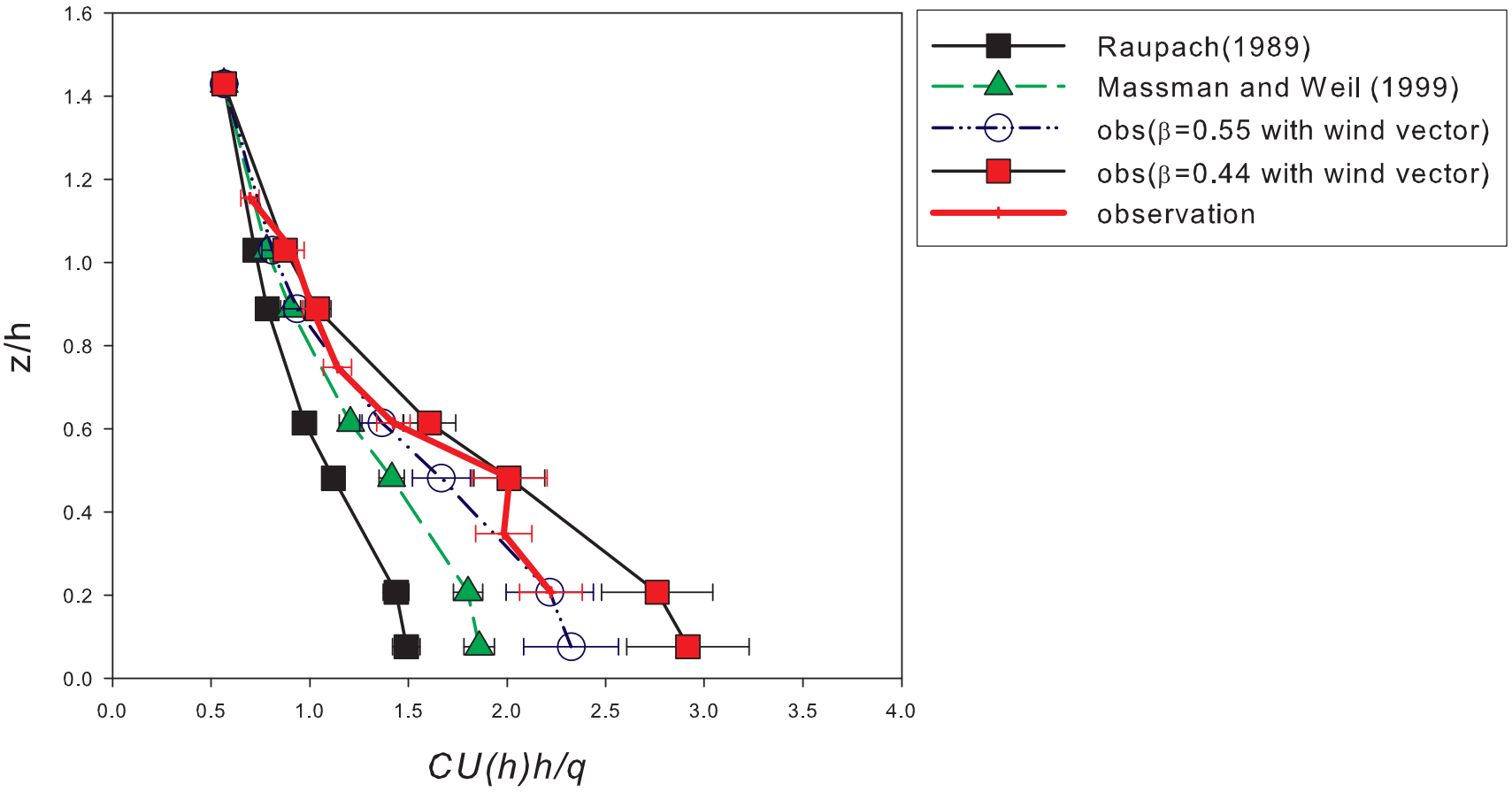

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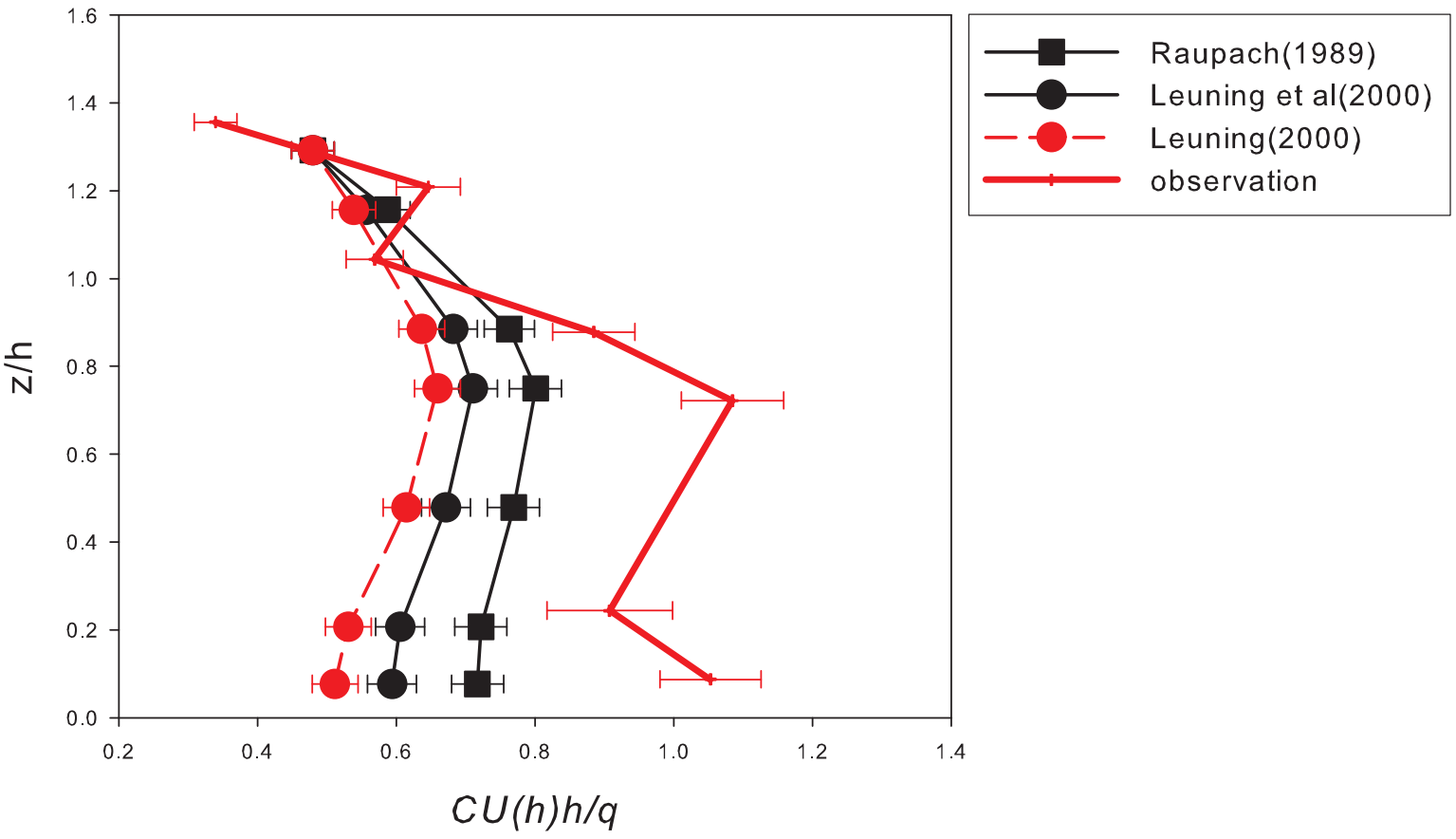

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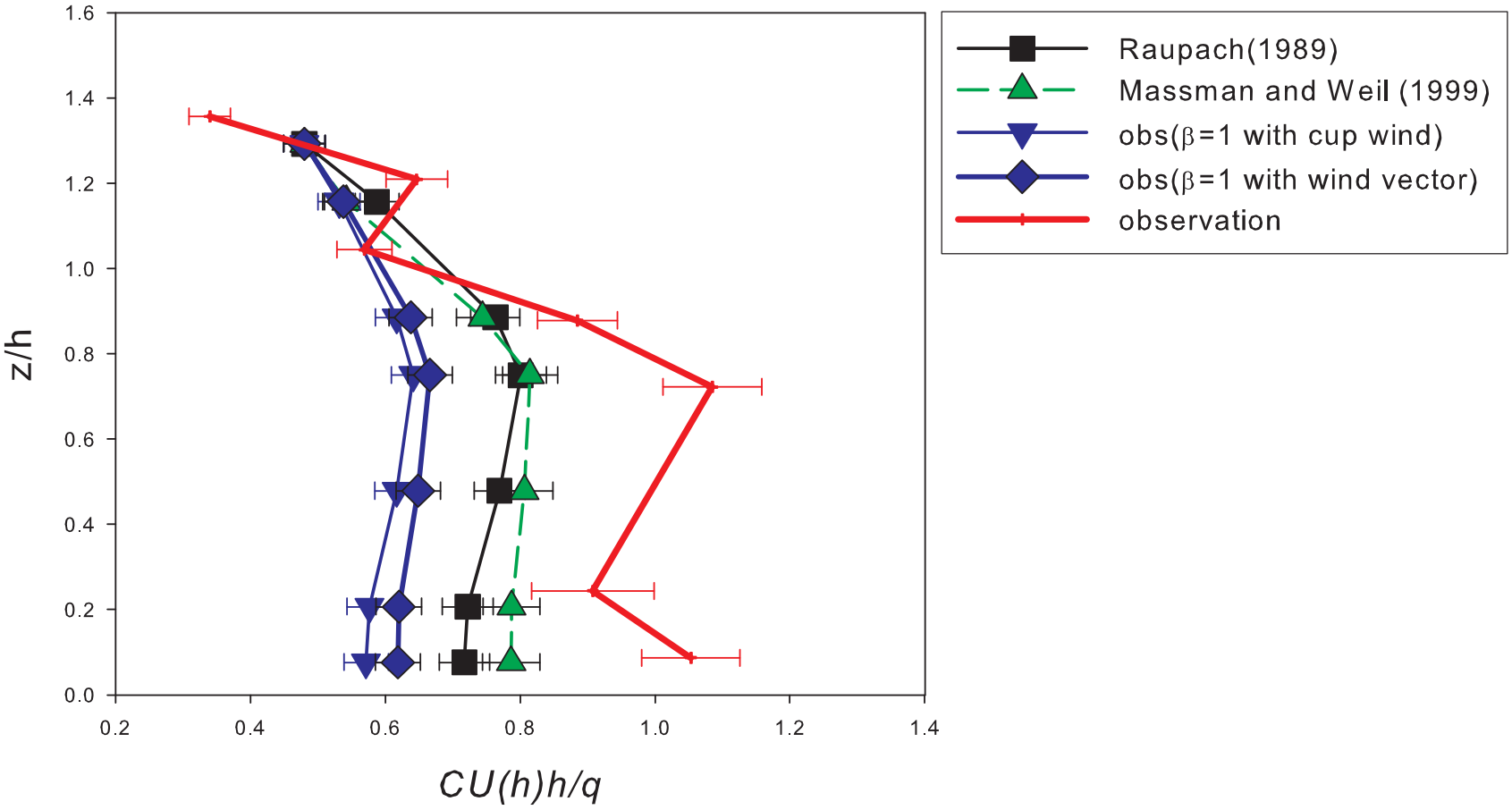

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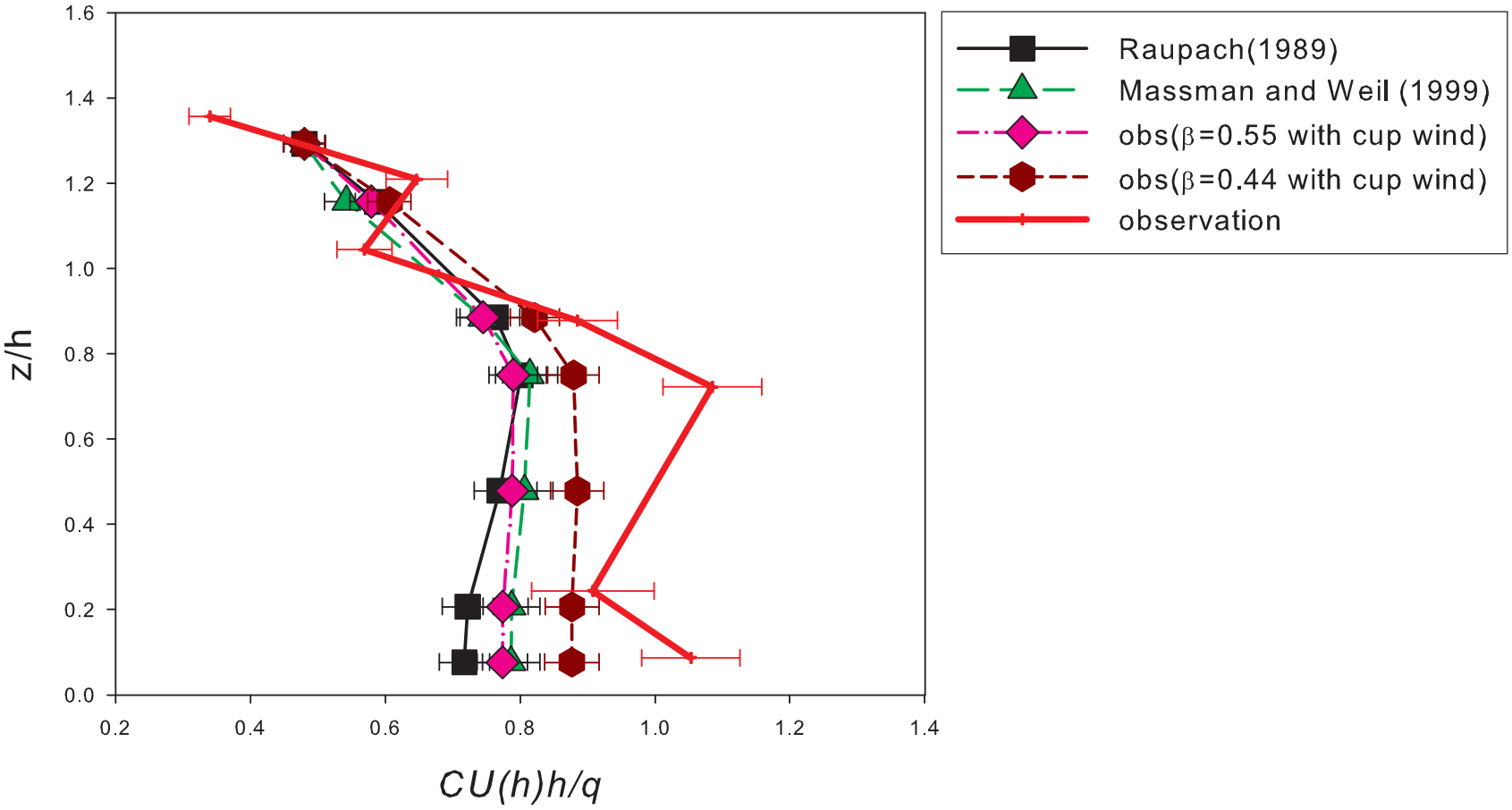

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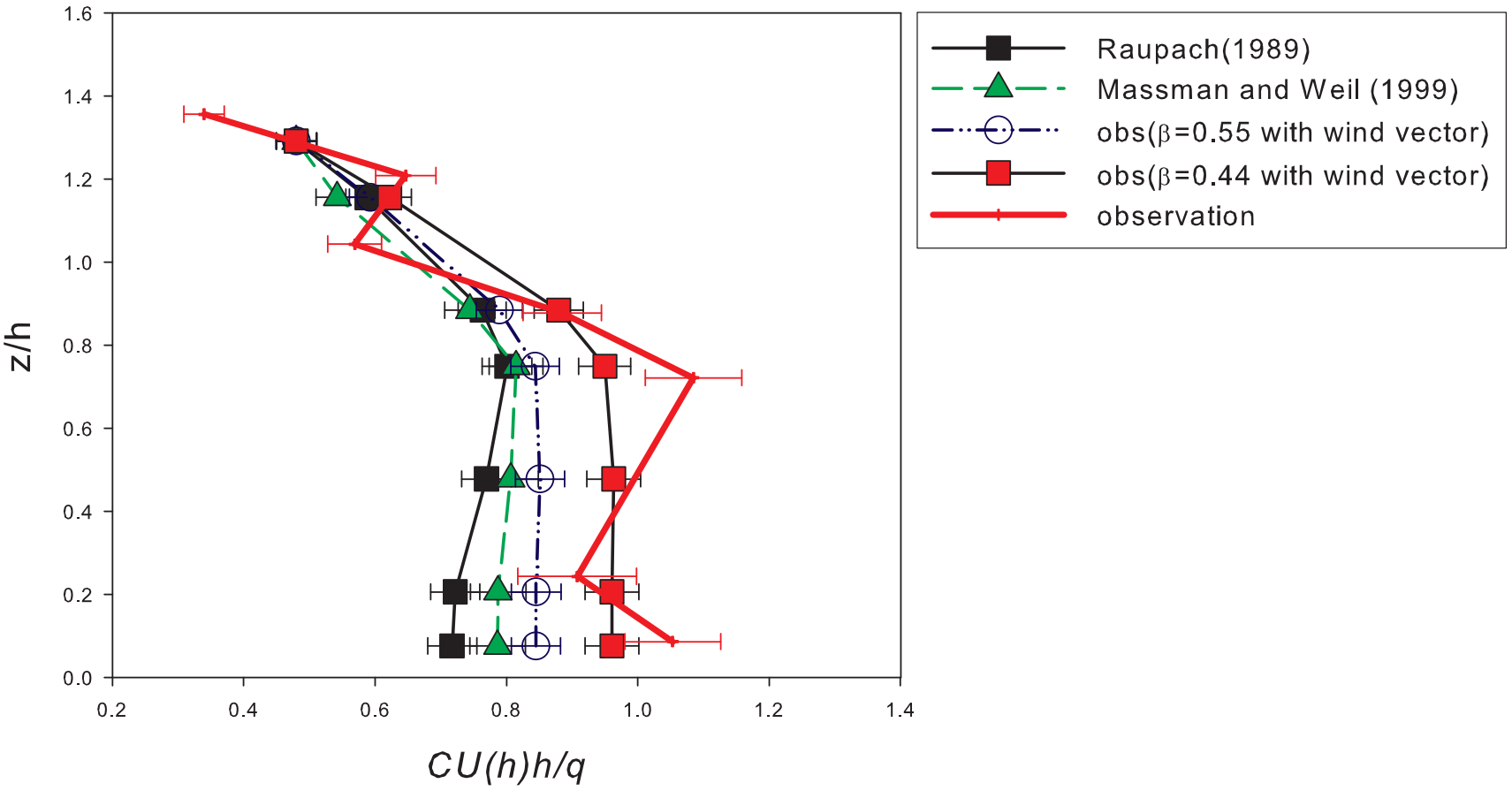
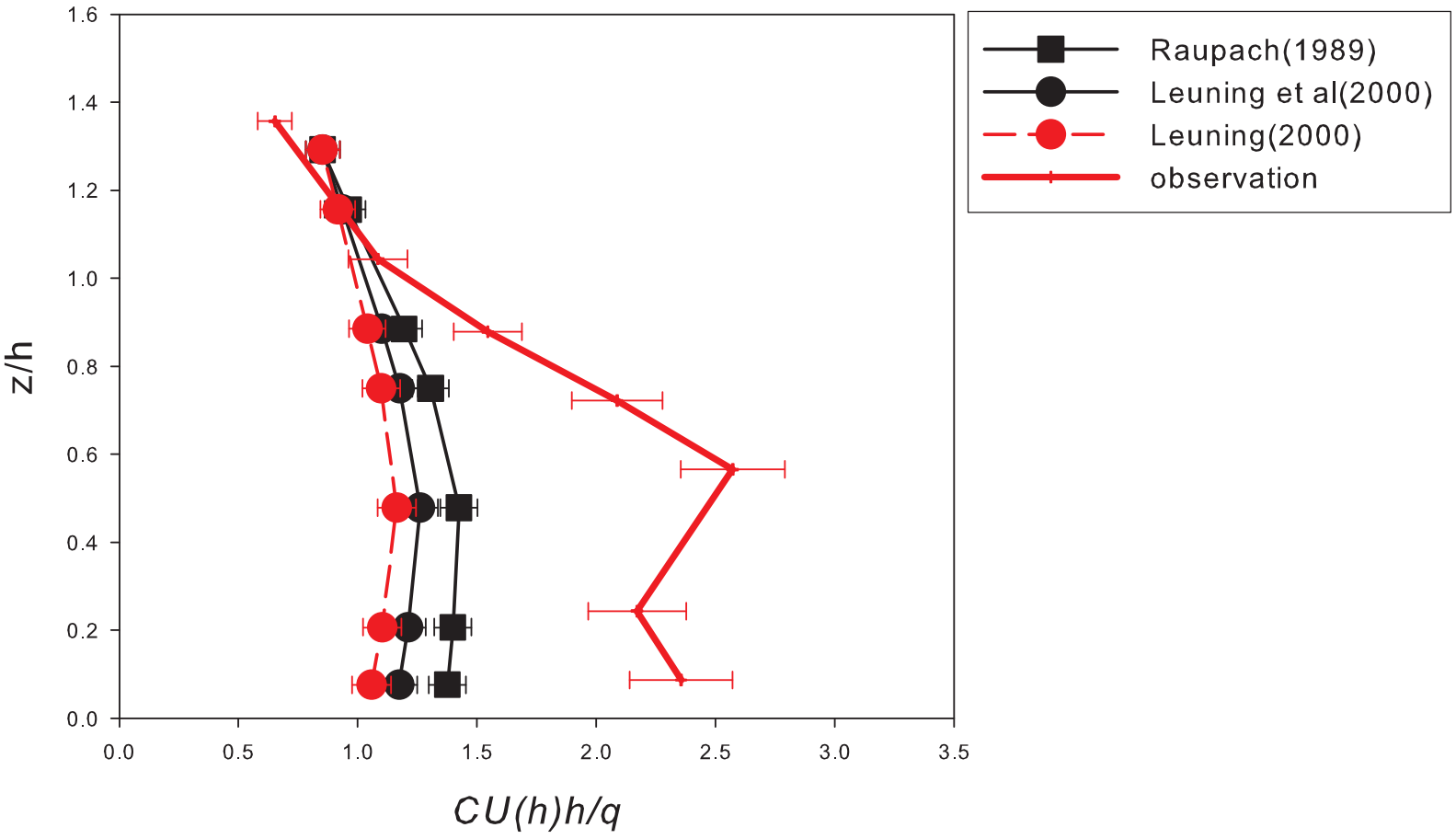


Unstable Conditions: $x/h = 1.87, h/h_s = 0.56$



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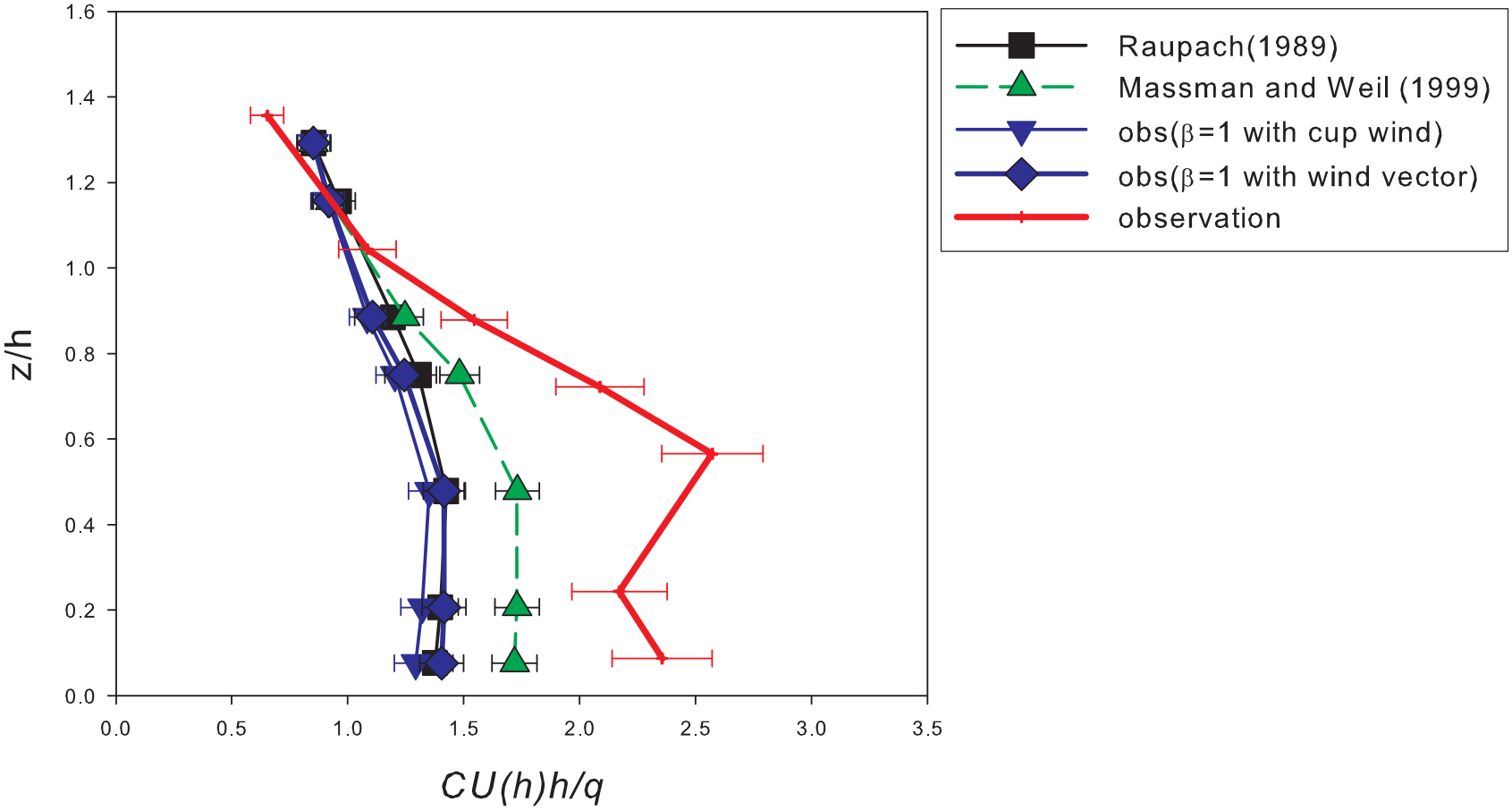

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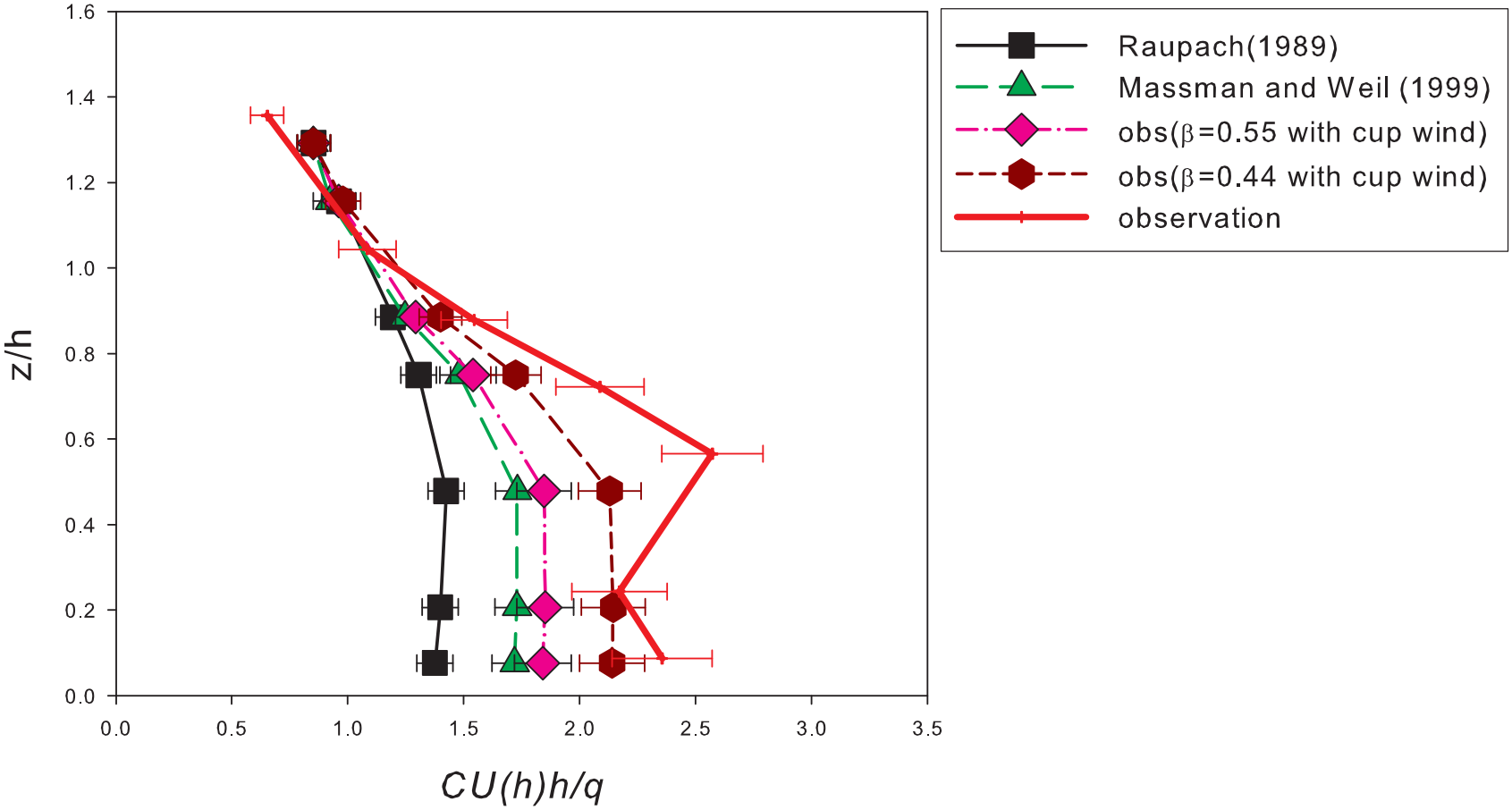

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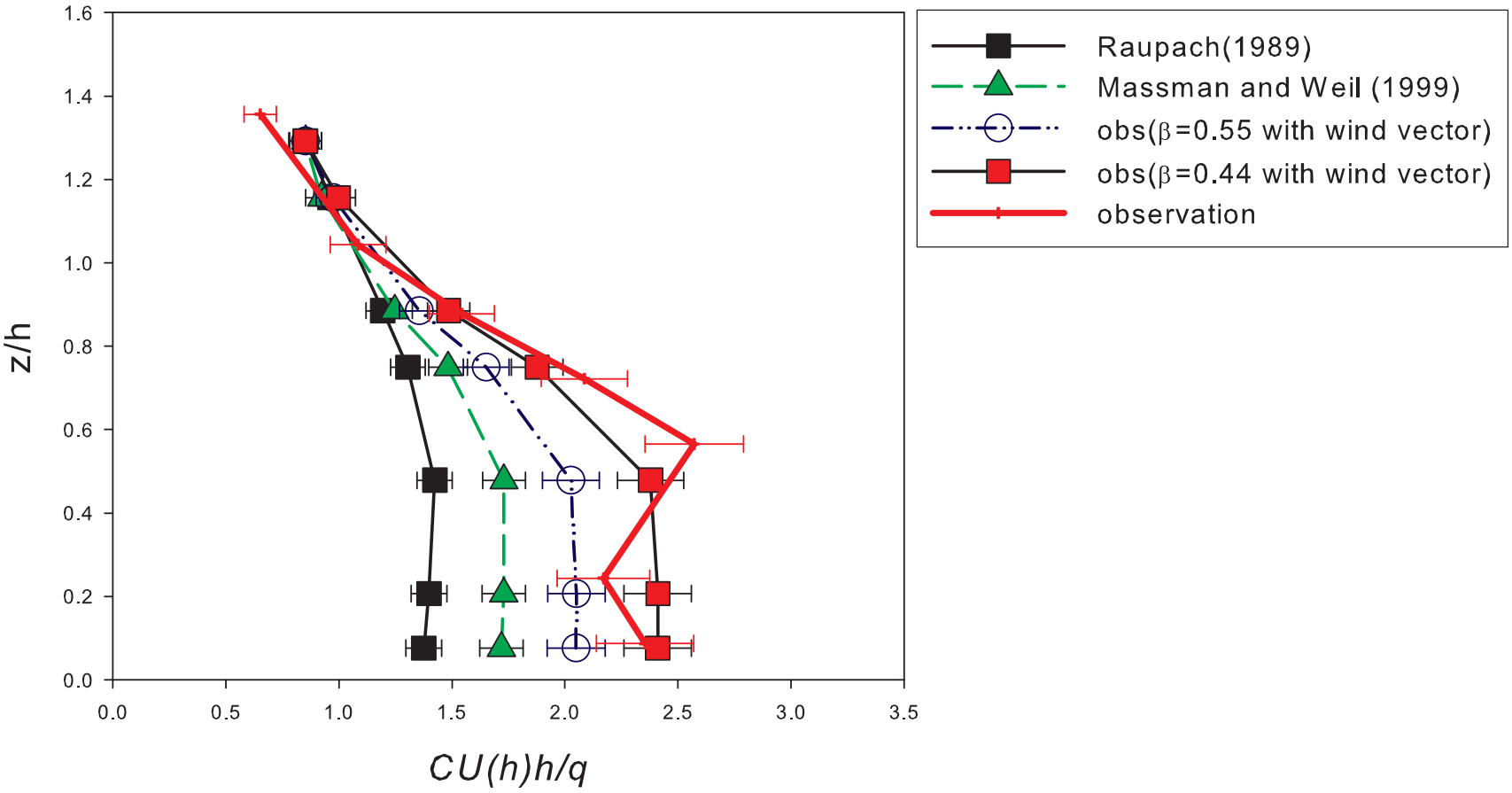
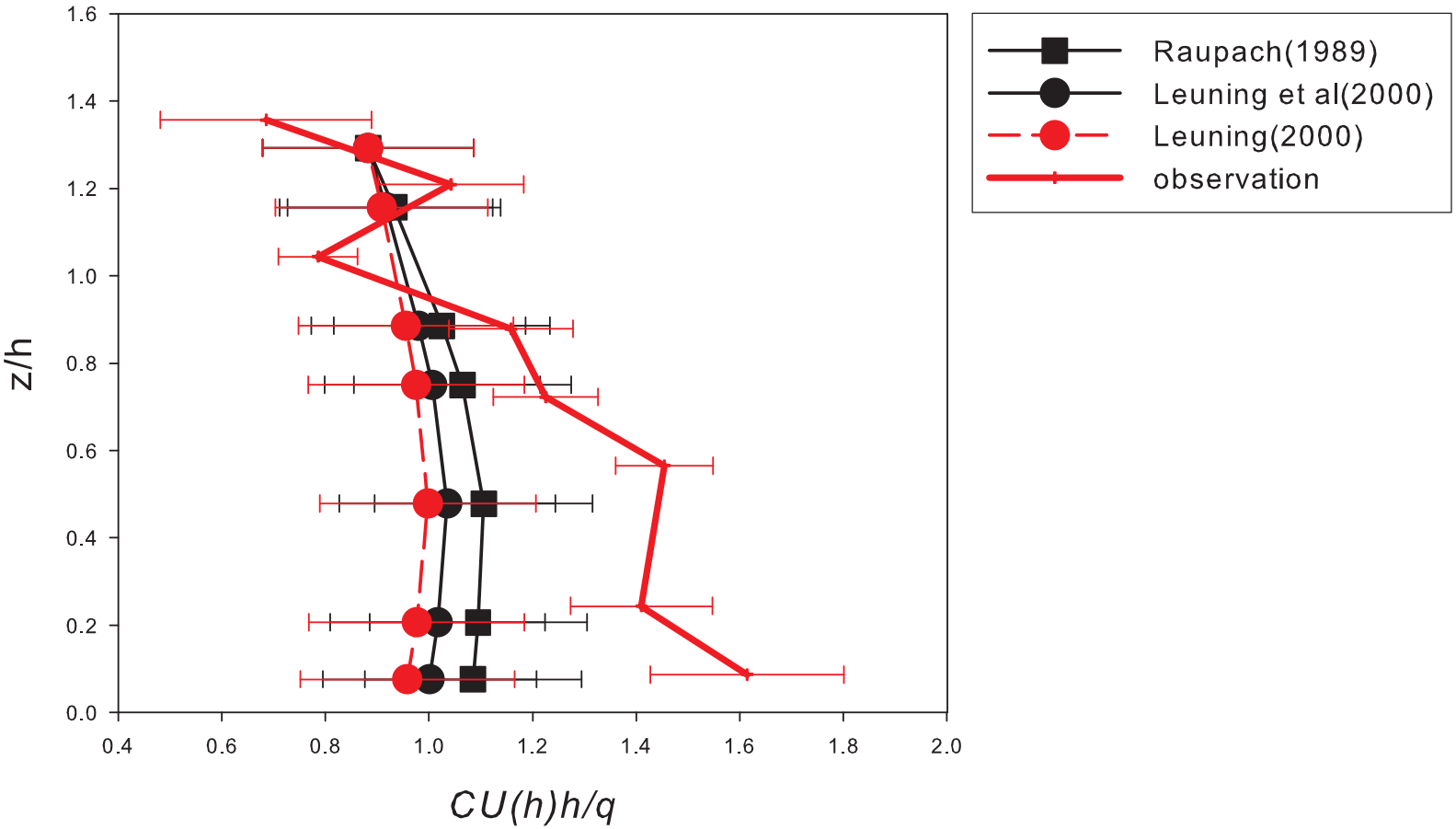


Unstable Conditions: $x/h = 3.74, h/h_s = 0.56$



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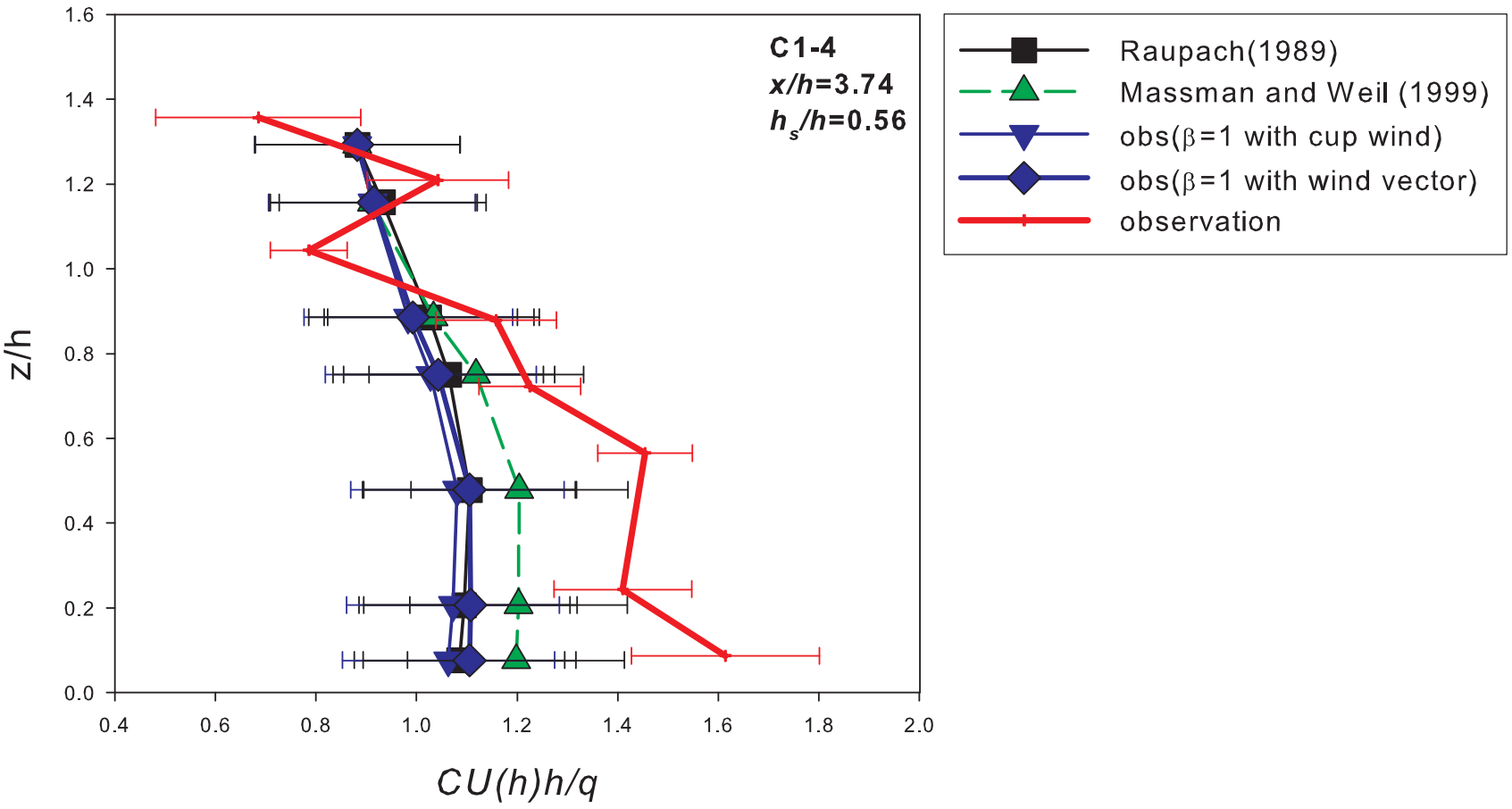

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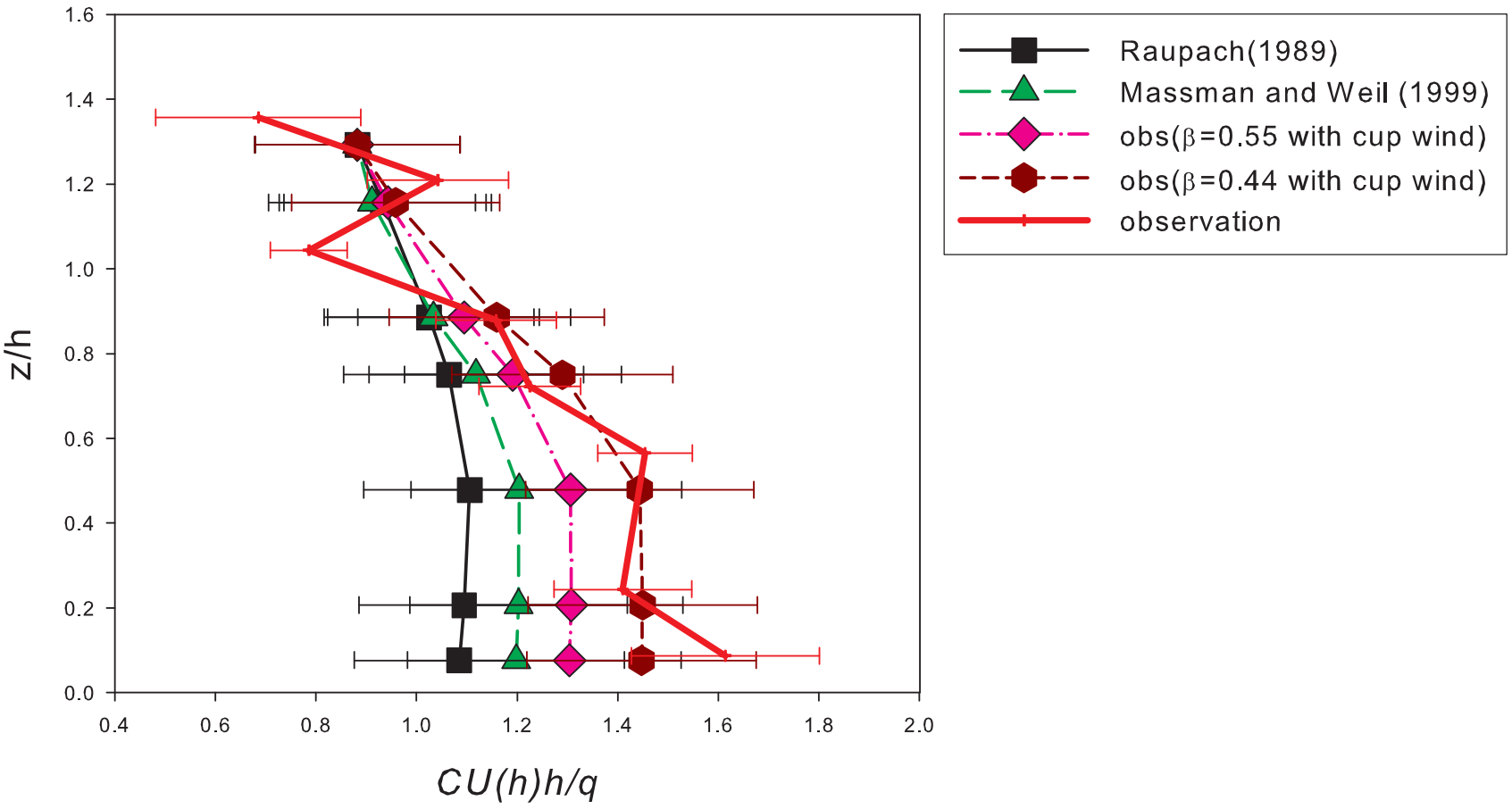

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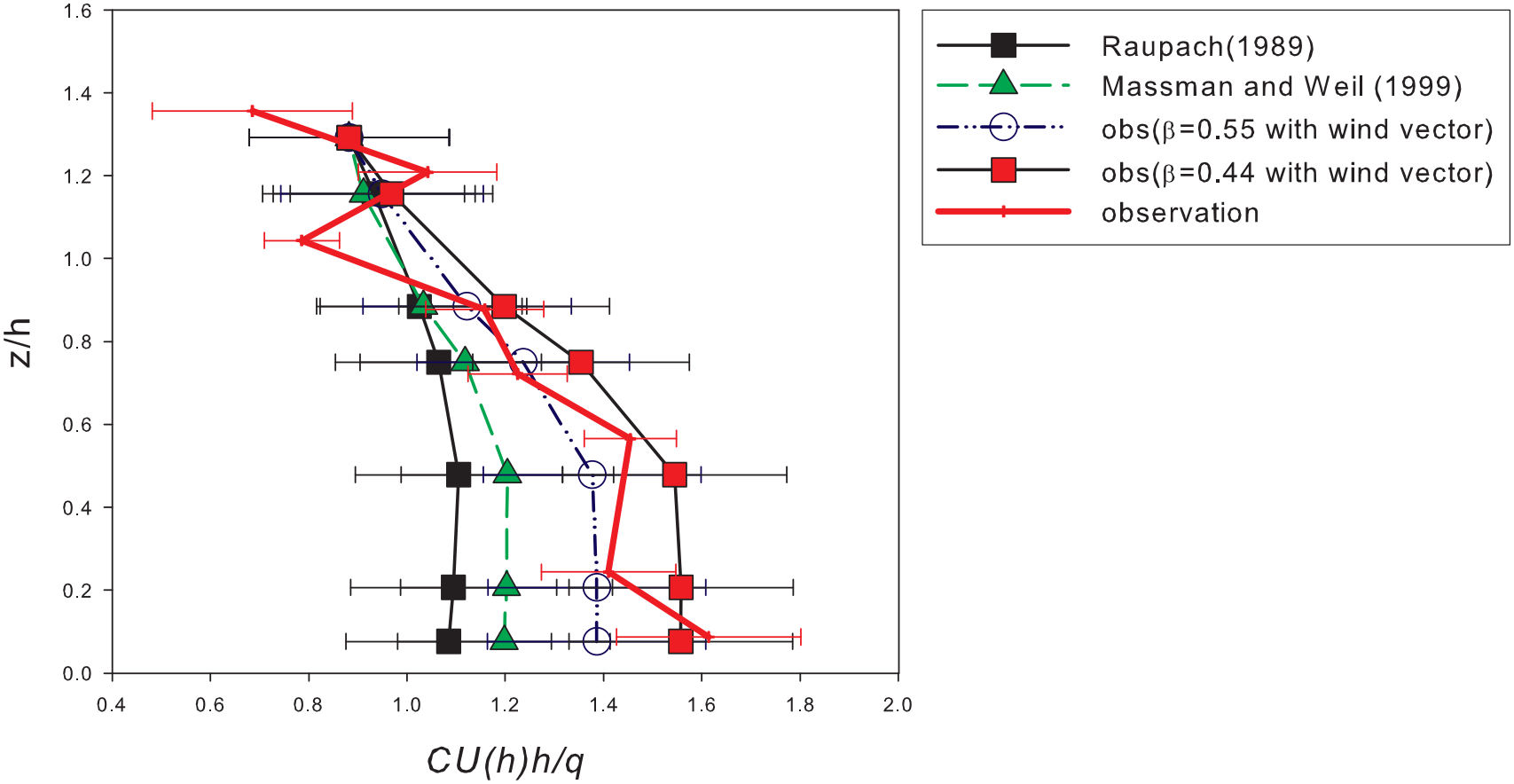
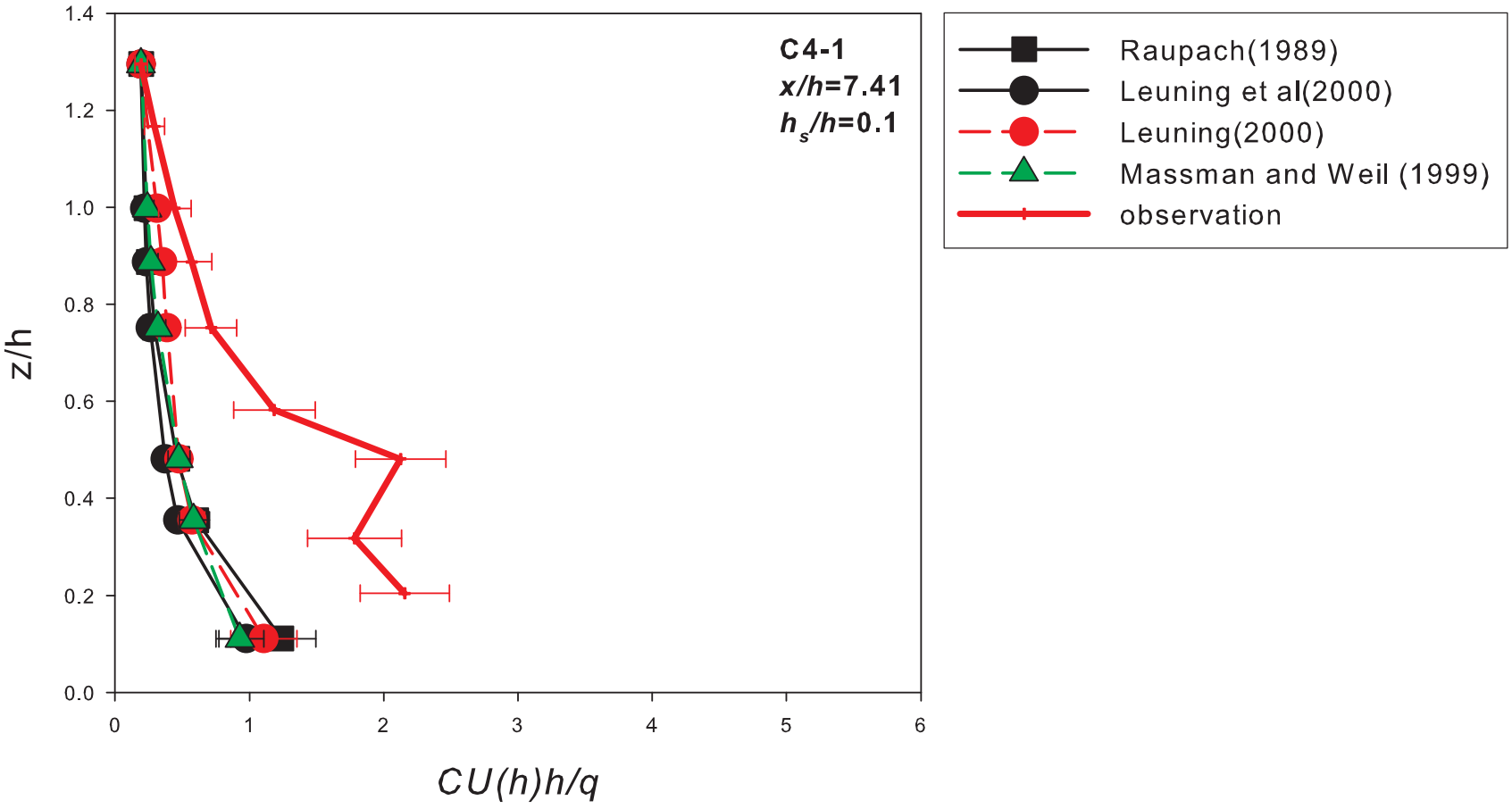


Weakly Stable Conditions: $x/h = 7.4, h/h_s = 0.1$



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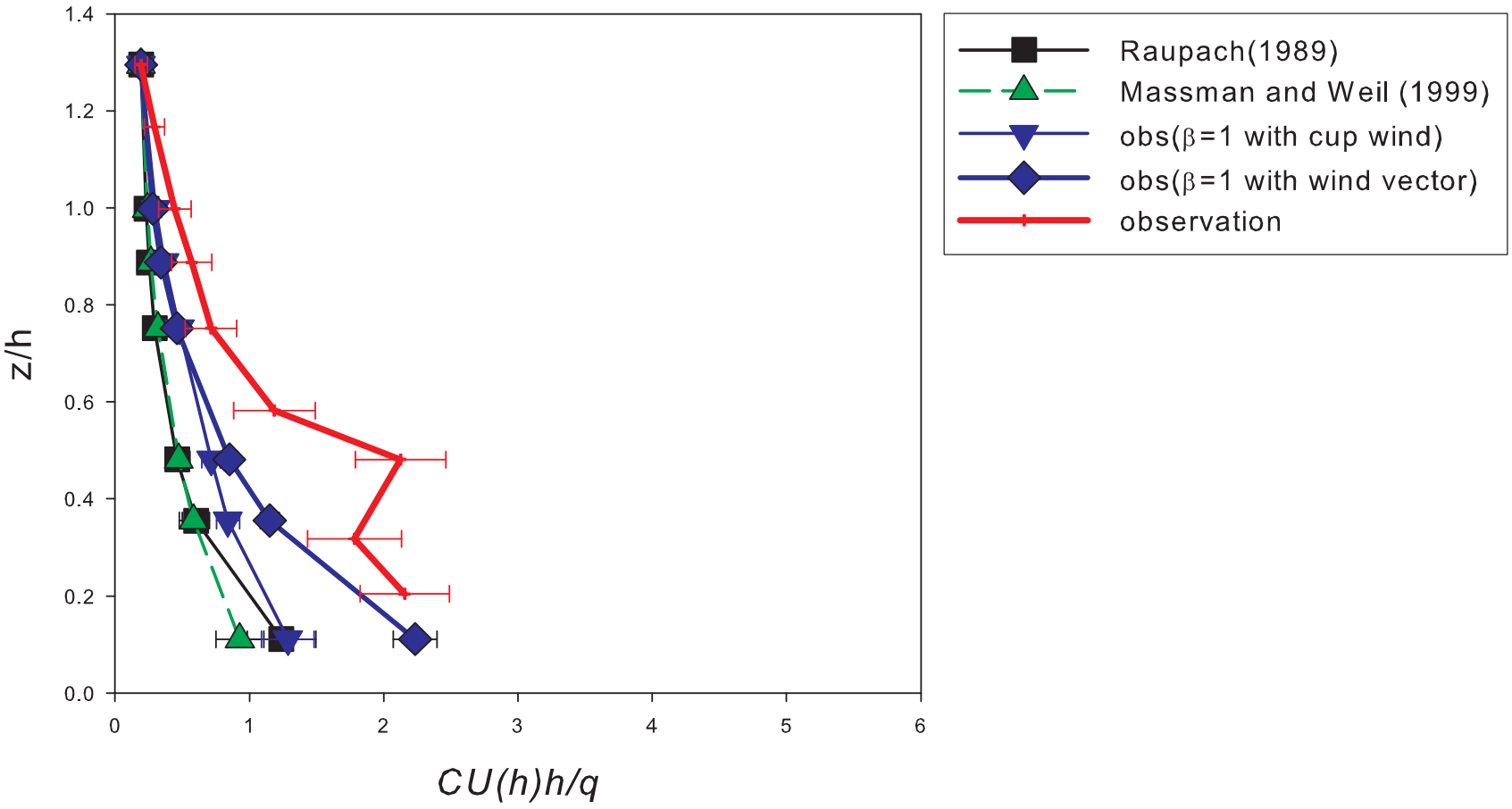

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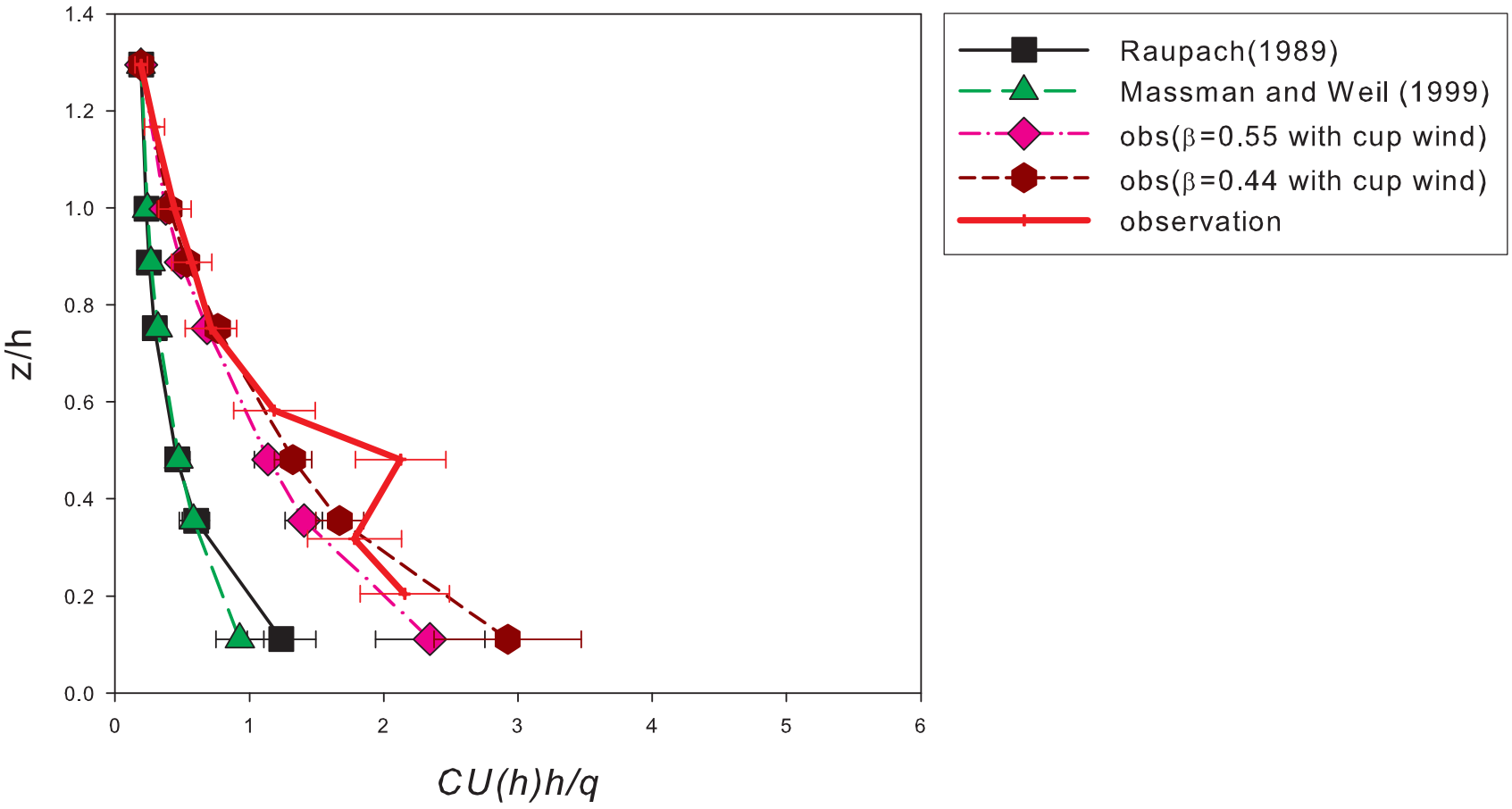

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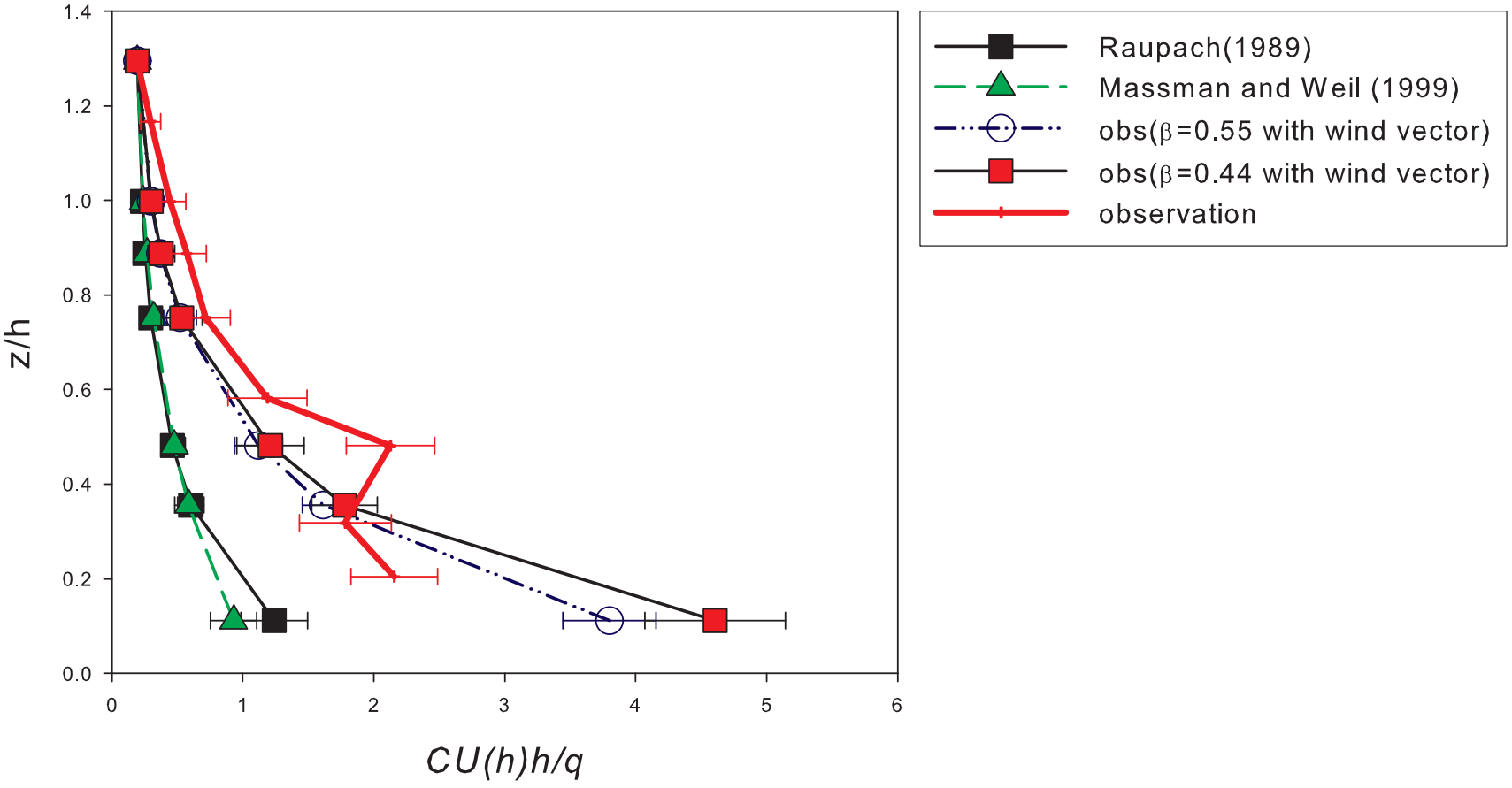
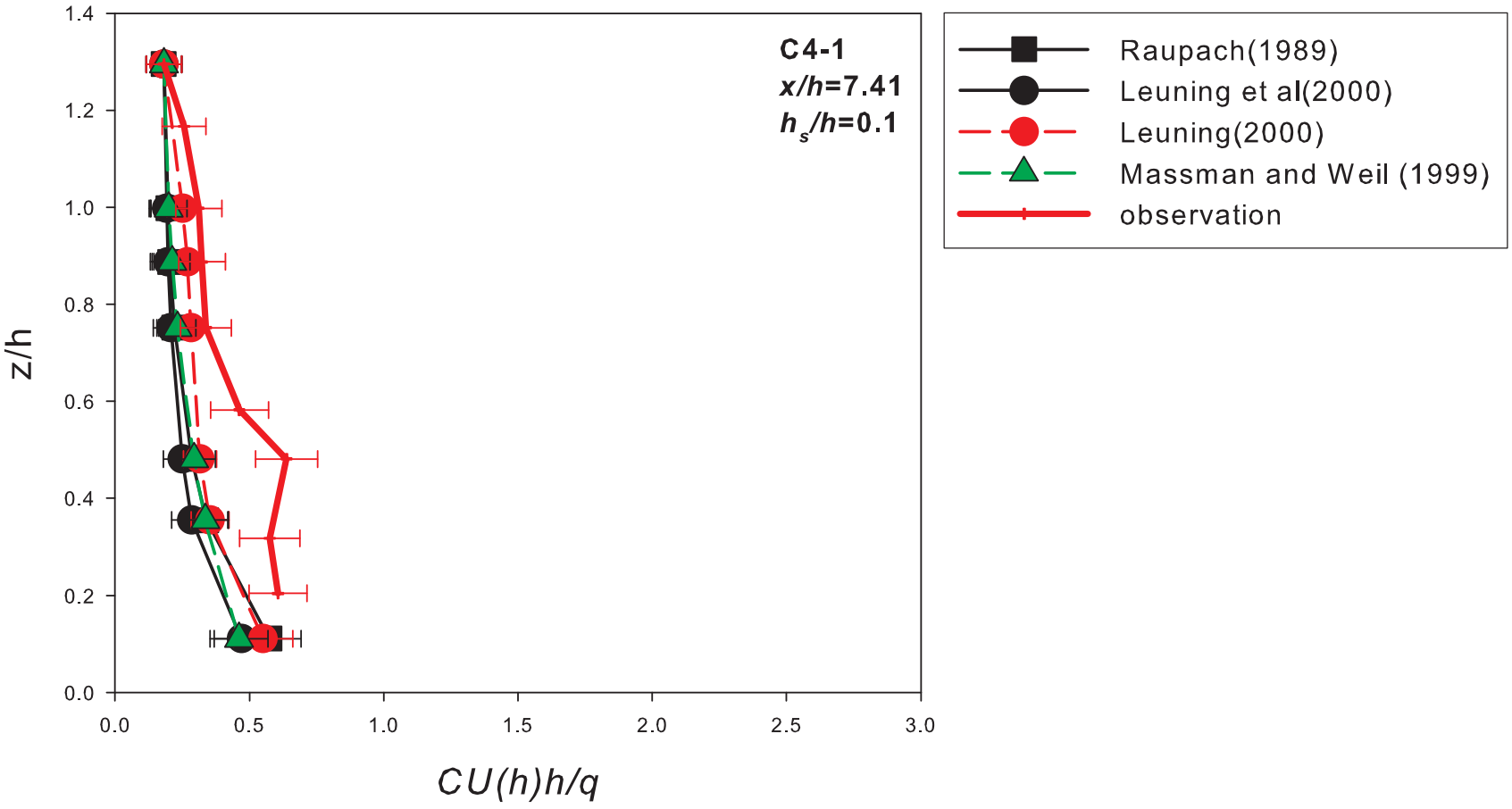
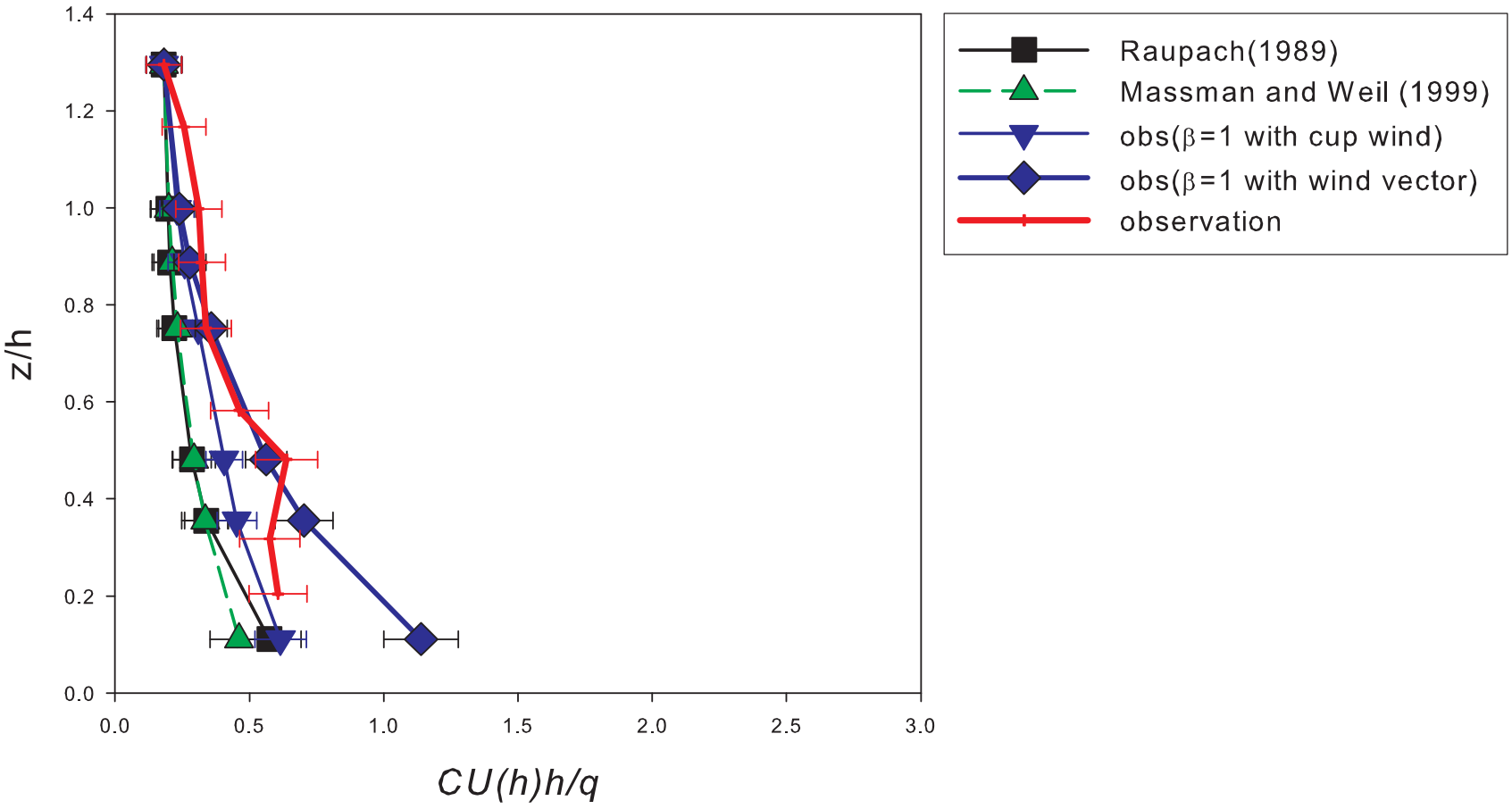


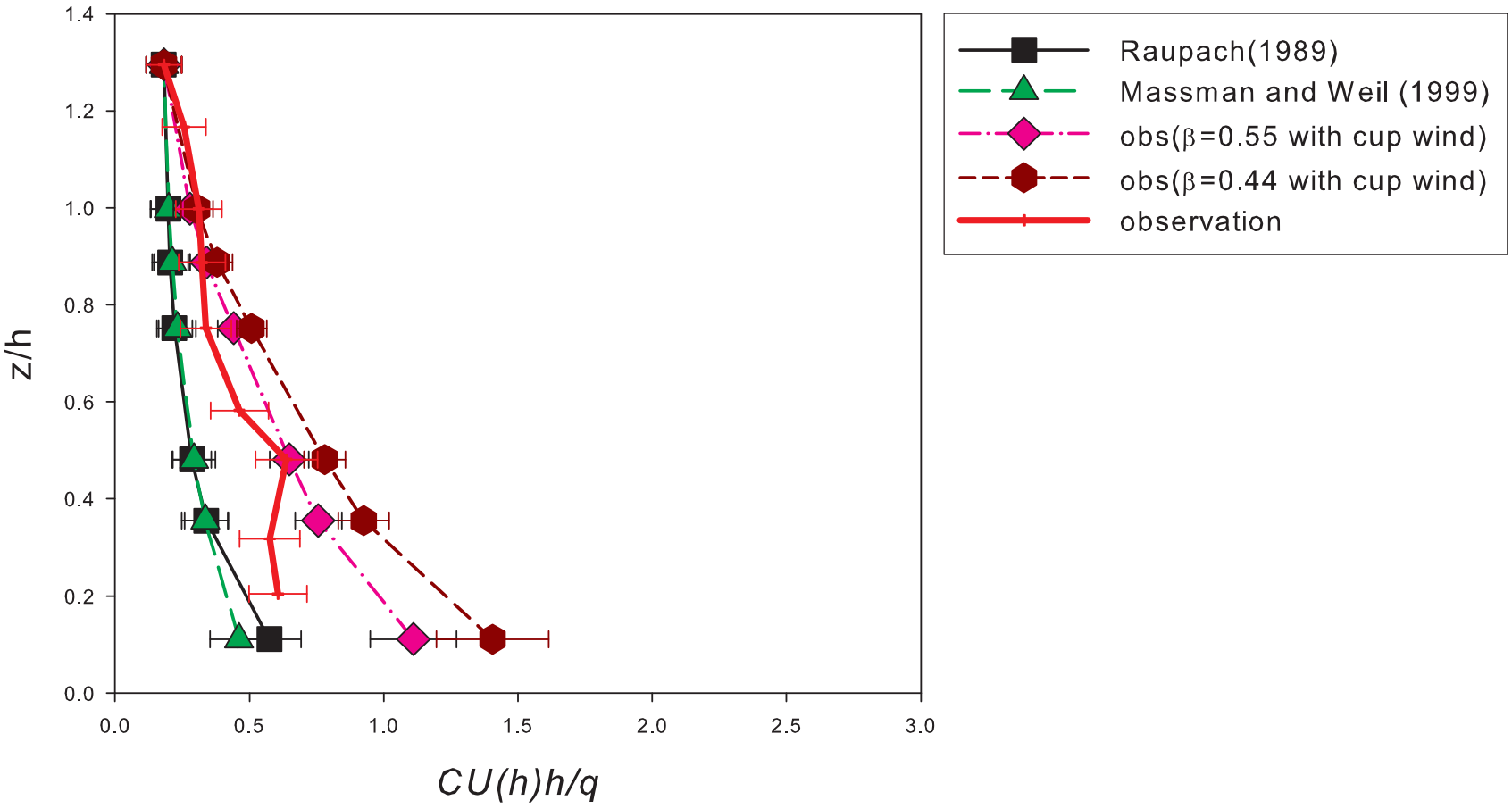
Weakly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



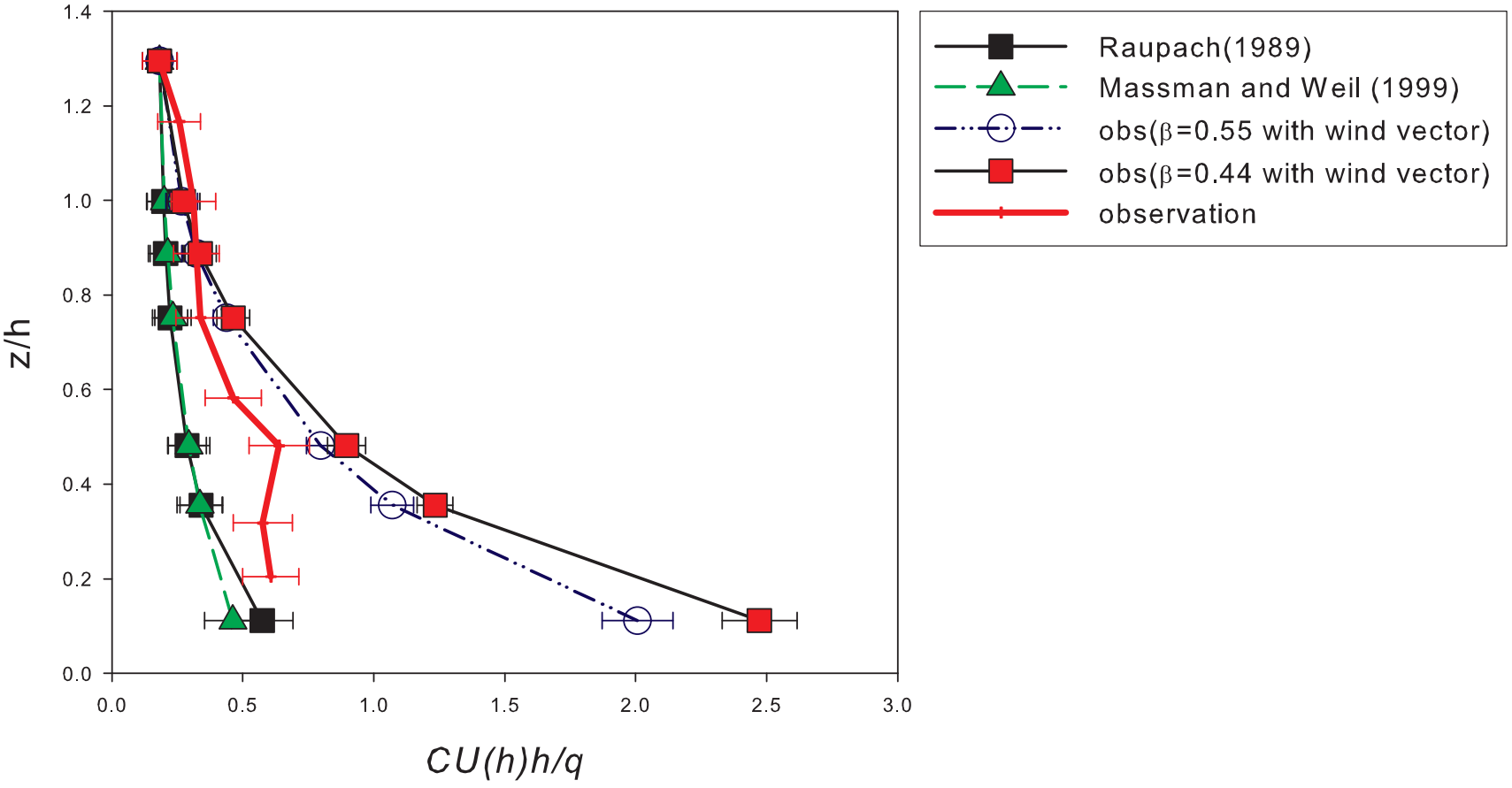
Weakly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



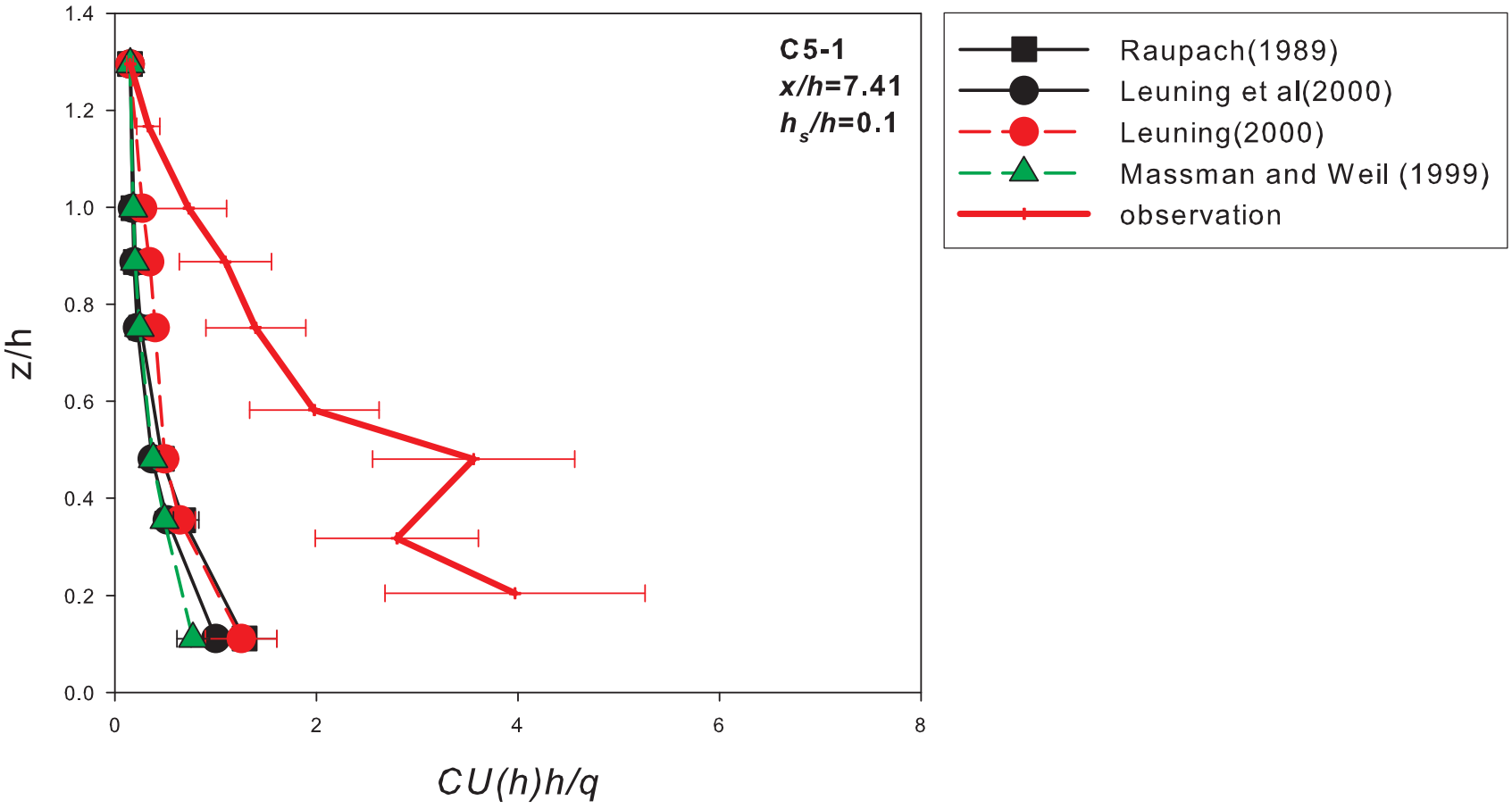
Weakly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



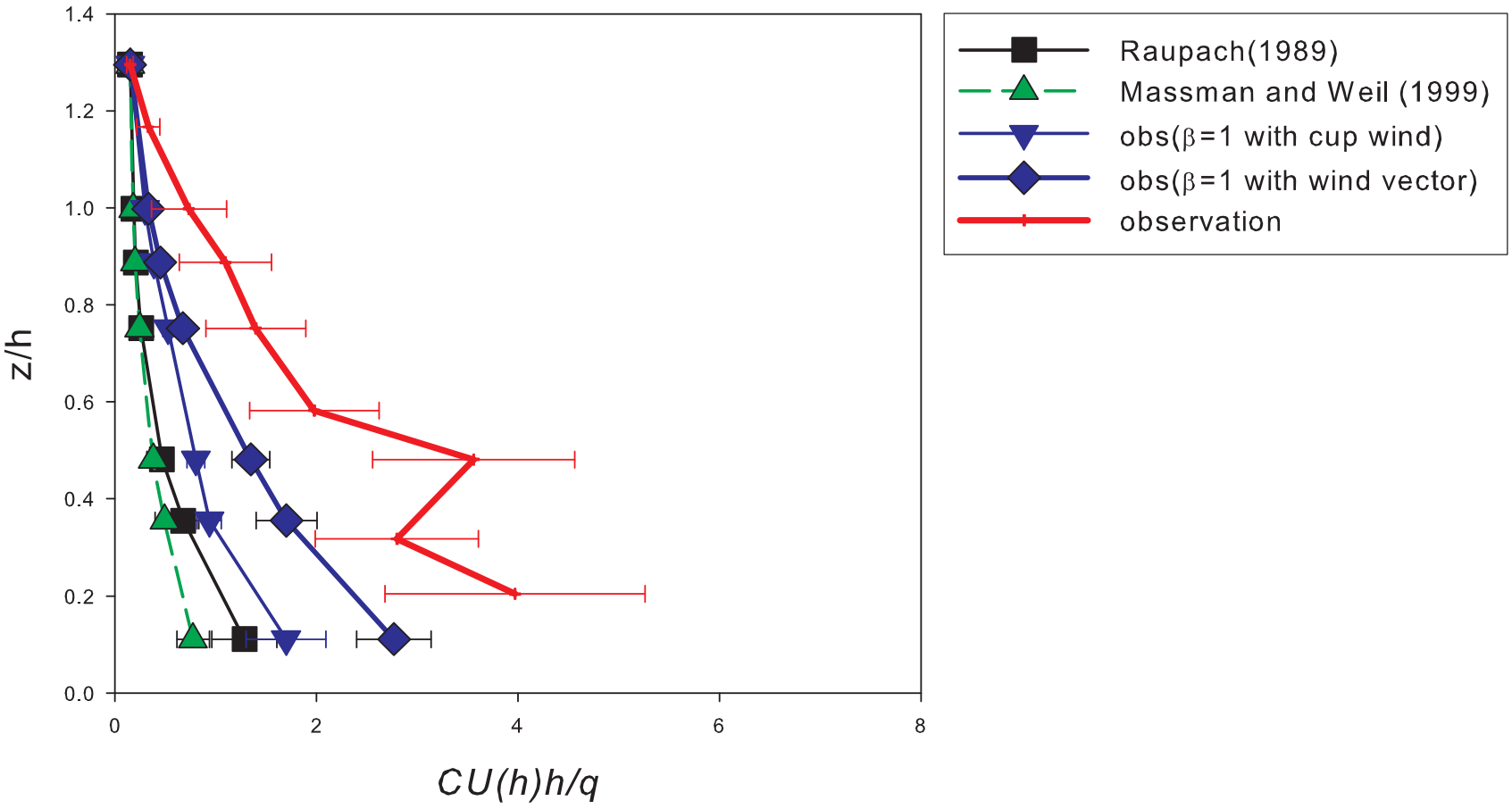
Weakly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



Strongly Stable Conditions: $x/h = 7.4, h/h_s = 0.1$



Strongly Stable Conditions: $x/h = 7.4, h/h_s = 0.1$



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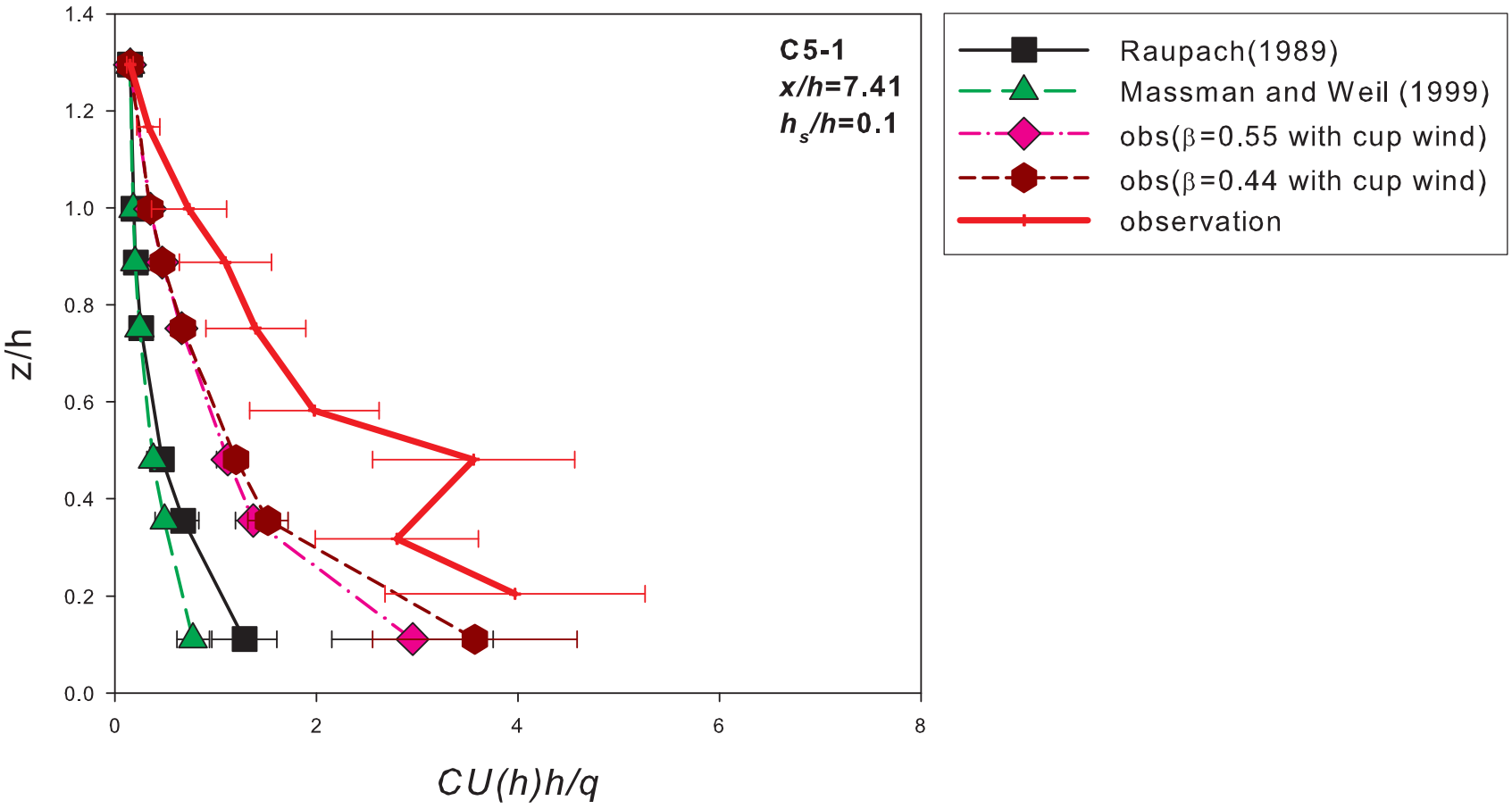

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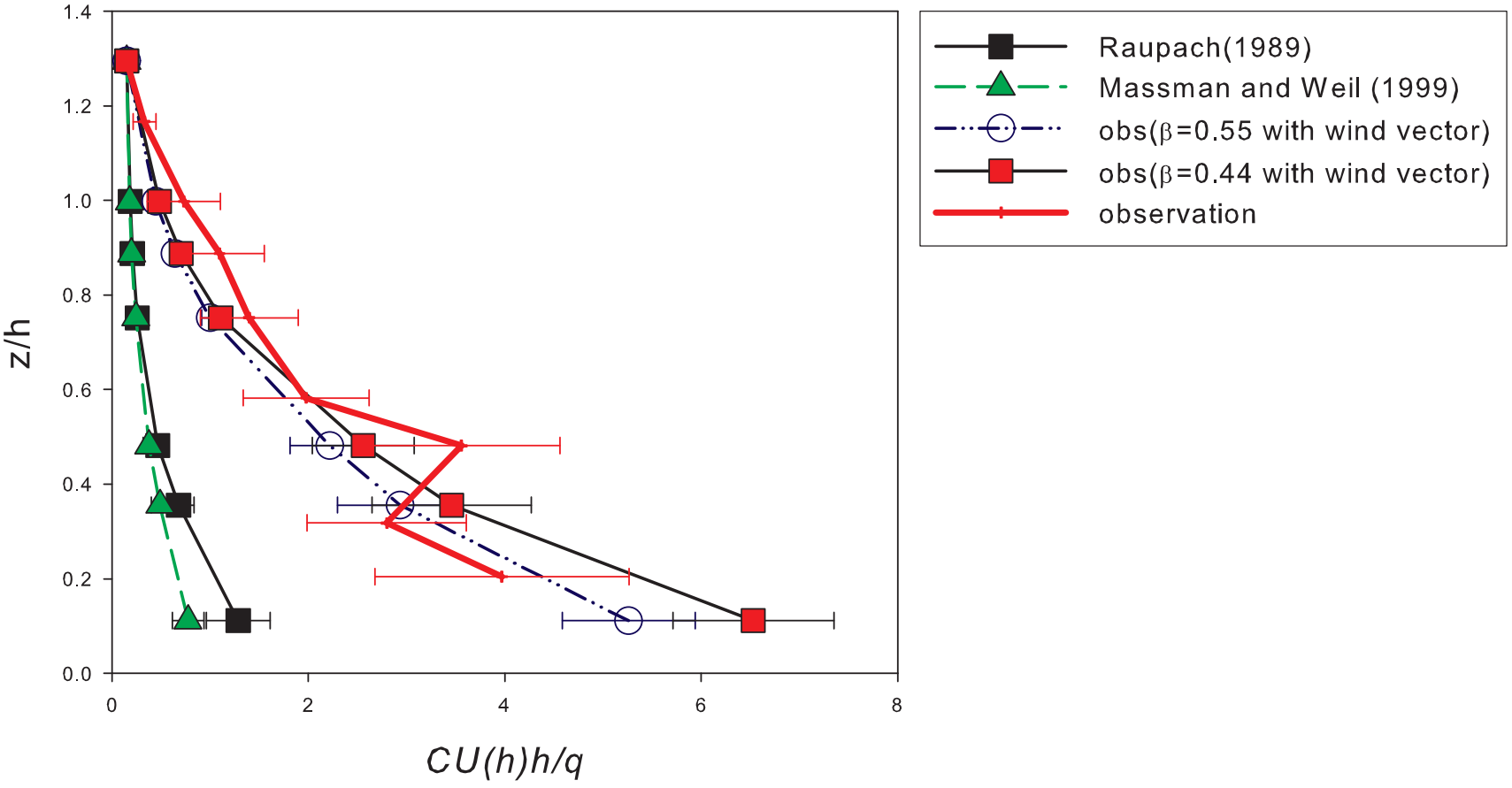
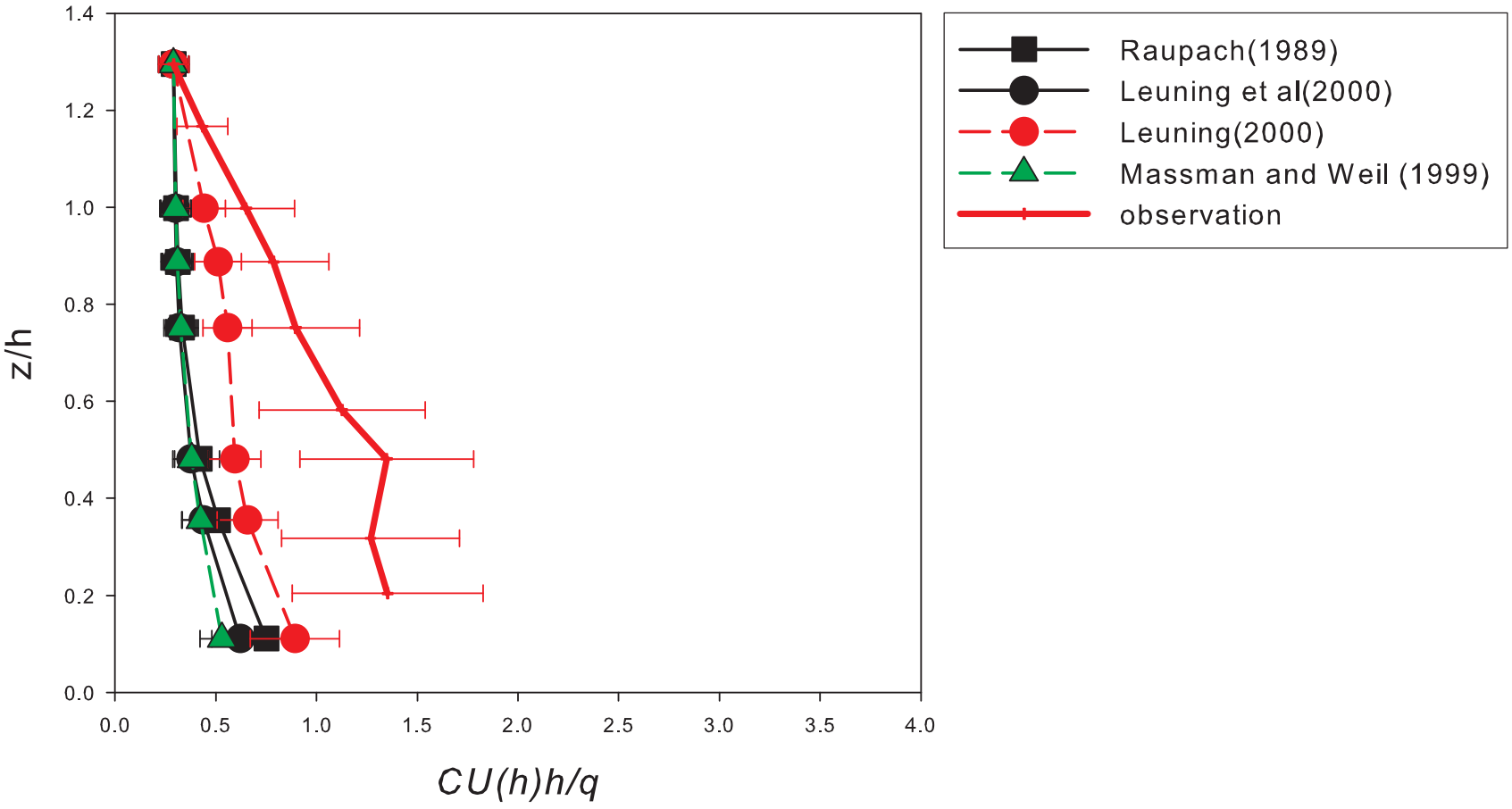
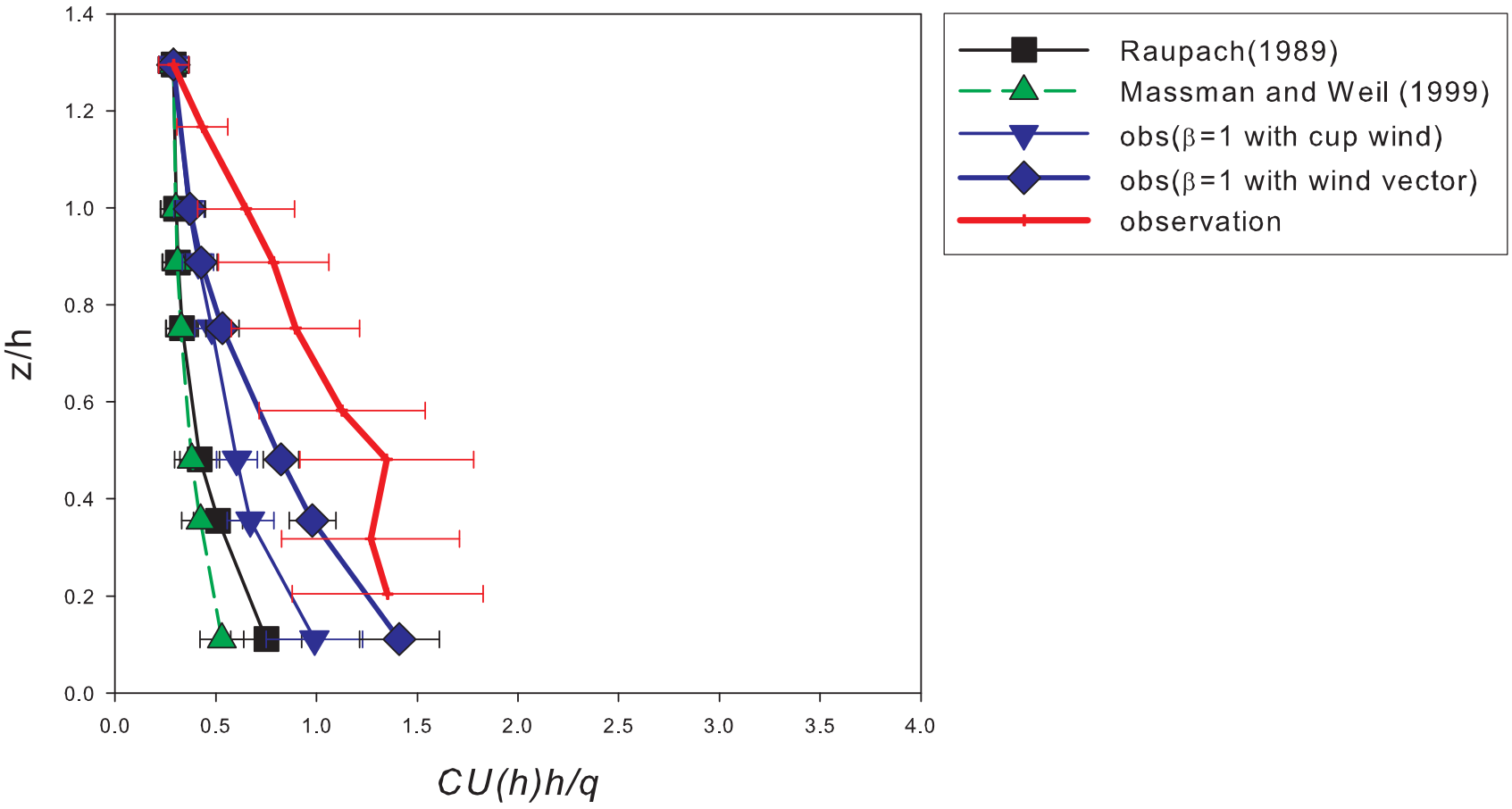


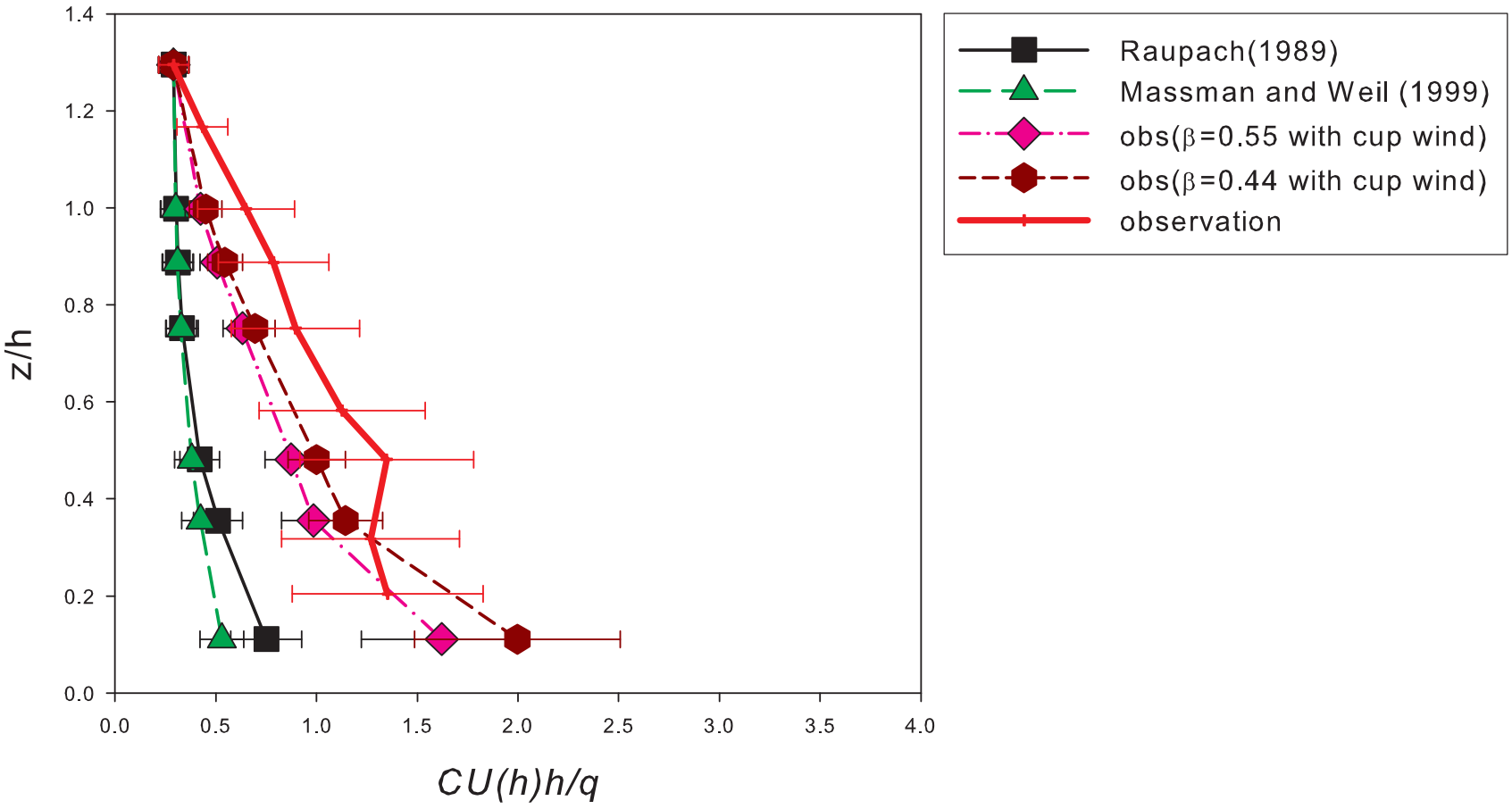
Strongly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



Strongly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



Strongly Stable Conditions: $x/h = 14.8, h/h_s = 0.1$



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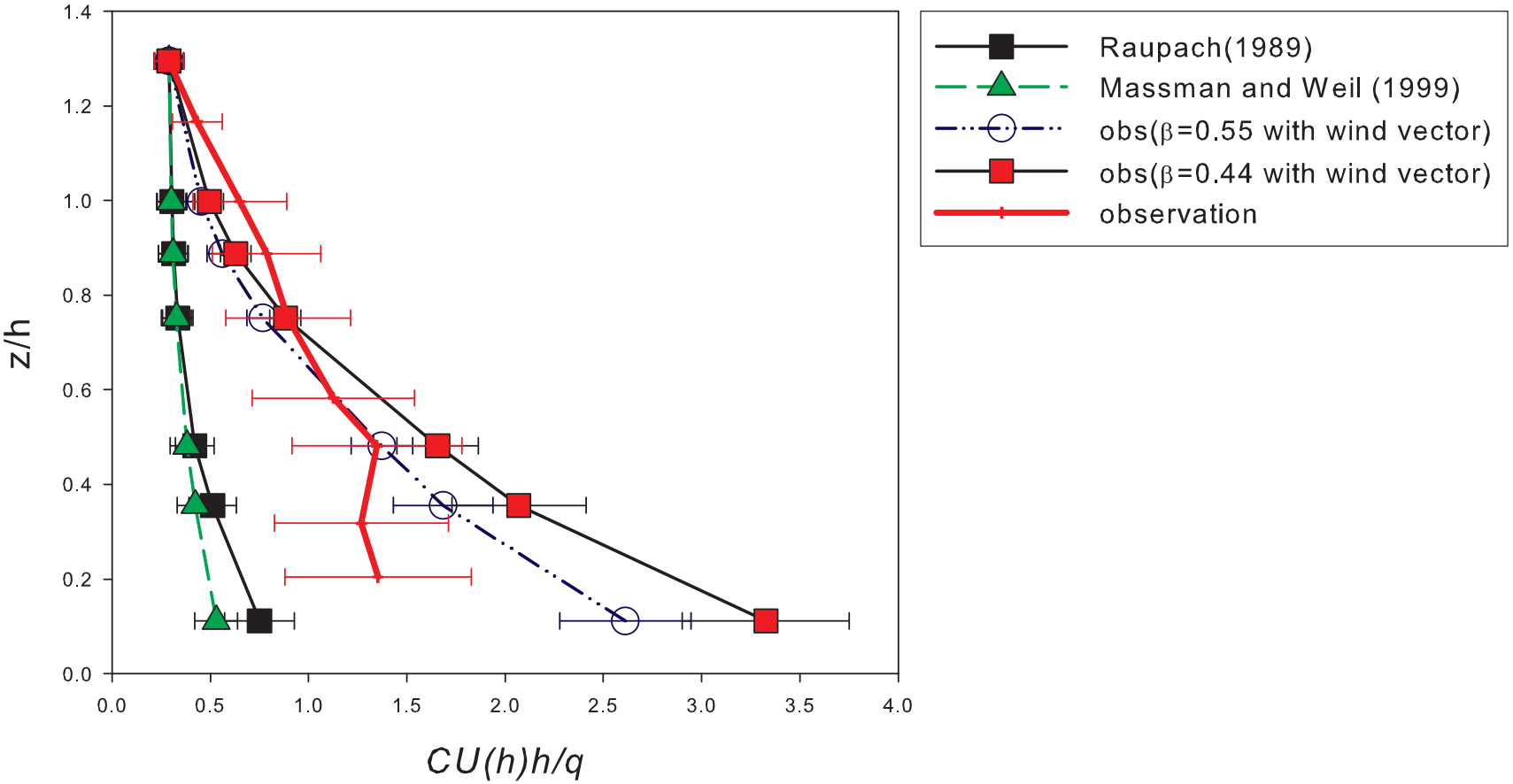


Conclusions

1. Artificial tracers were released at several heights and distance from a tower with turbulence measurements.

Conclusions

1. Artificial tracers were released at several heights and distance from a tower with turbulence measurements.
2. A Lagrangian analytic solution was derived for a (ground/elevated) line source.
   - Considering advection makes smaller $(\partial c/\partial z)$ for given source strength in a forward problem. In a inverse problem, larger source strength is estimated for given $(\partial c/\partial z)$.

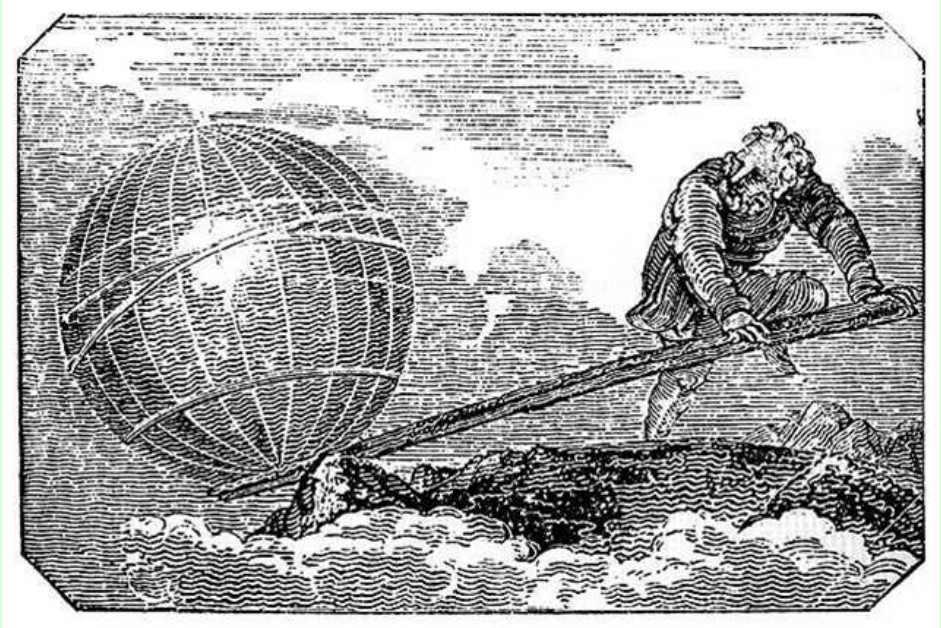
Conclusions

1. The model performance substantially depended on the Lagrangian time scale parameterizations.
   - The observed time scales were proportional to σ_w^{-1} within the canopy.
   - Massman and Weil (1999) parameterization gives the increase time scales in stable conditions.
   - The effect of understories on Lagrangian time scales is not negligible.
   - The model results are sensitive to Lagrangian time scales and so Stability correction is important.

Conclusions

1. The model successfully predicted the observed tracer concentrations, especially the Lagrangian time scales were calculated from the observation.
   - $\beta \sim 0.5$ gives the best model performances.
2. In nighttime, the model gives less diffusion inside the canopy but stronger mixing above the canopy.
   - Convection velocity inside the canopy may be larger than local mean wind speed.
   - Horizontal dispersion becomes important compared to the mean mass transport in calm night.

Thank you so much!



Give me a place ***(Data)*** to stand on and I can move ***(Save)*** the earth. - Archimedes (Scientists in the AmeriFlux Meeting)

This study was supported by the U.S. Dept. of Energy, Terrestrial Carbon Processes Program.