Transport across the air-water interface with emergent vegetation

INTECOL
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UC Berkeley
Civil and Environmental Engineering

Outline

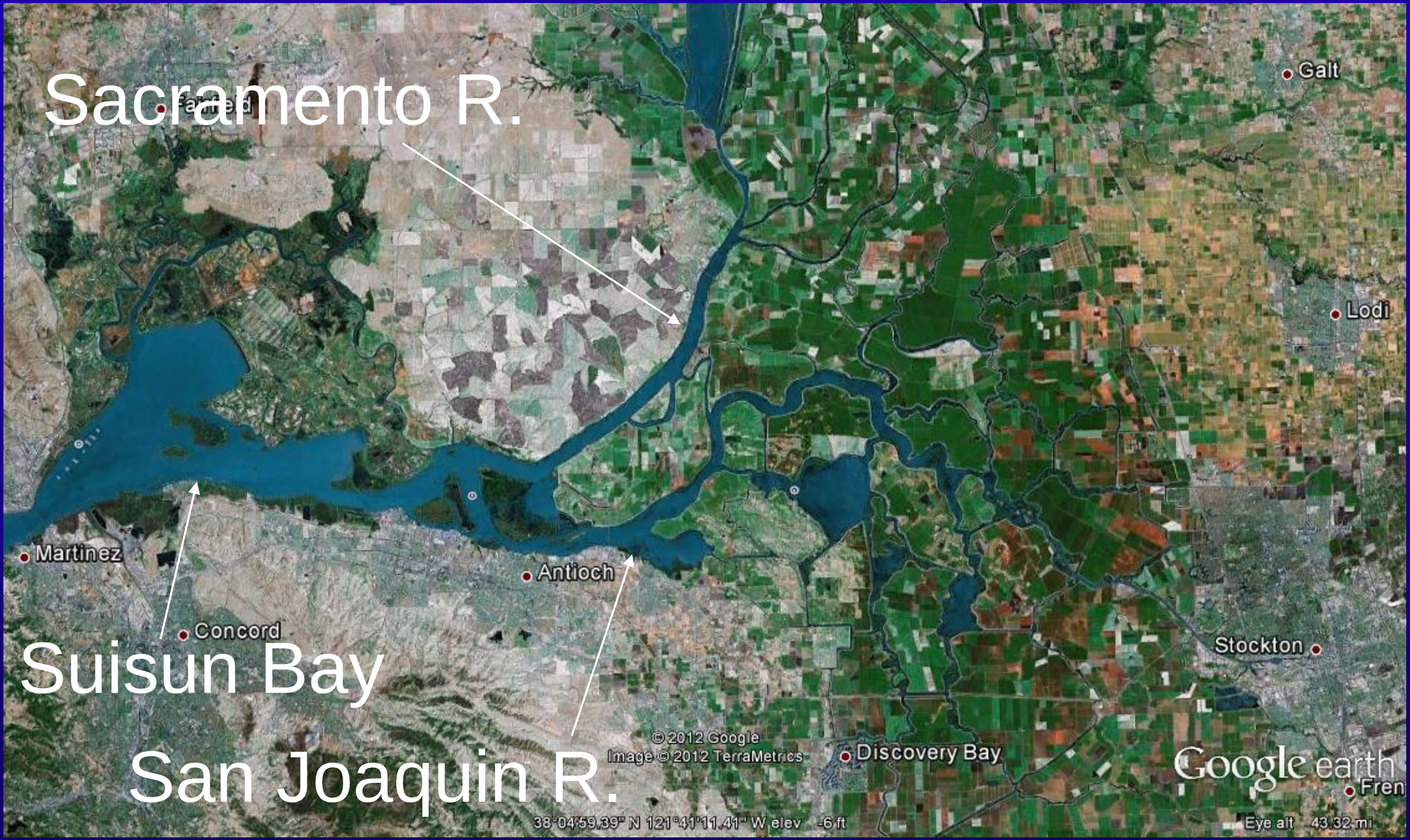
- Motivating example: the Sacramento-San Joaquin Delta
- Background
  - Wetland gas fluxes
  - Transport models
  - Causes of wetland mixing
- Lab measurements of gas fluxes
- A gas transport model for wetlands
  - Empirical gas transfer velocity (*k*) model
  - Universal k model

Sacramento-San Joaquin Delta

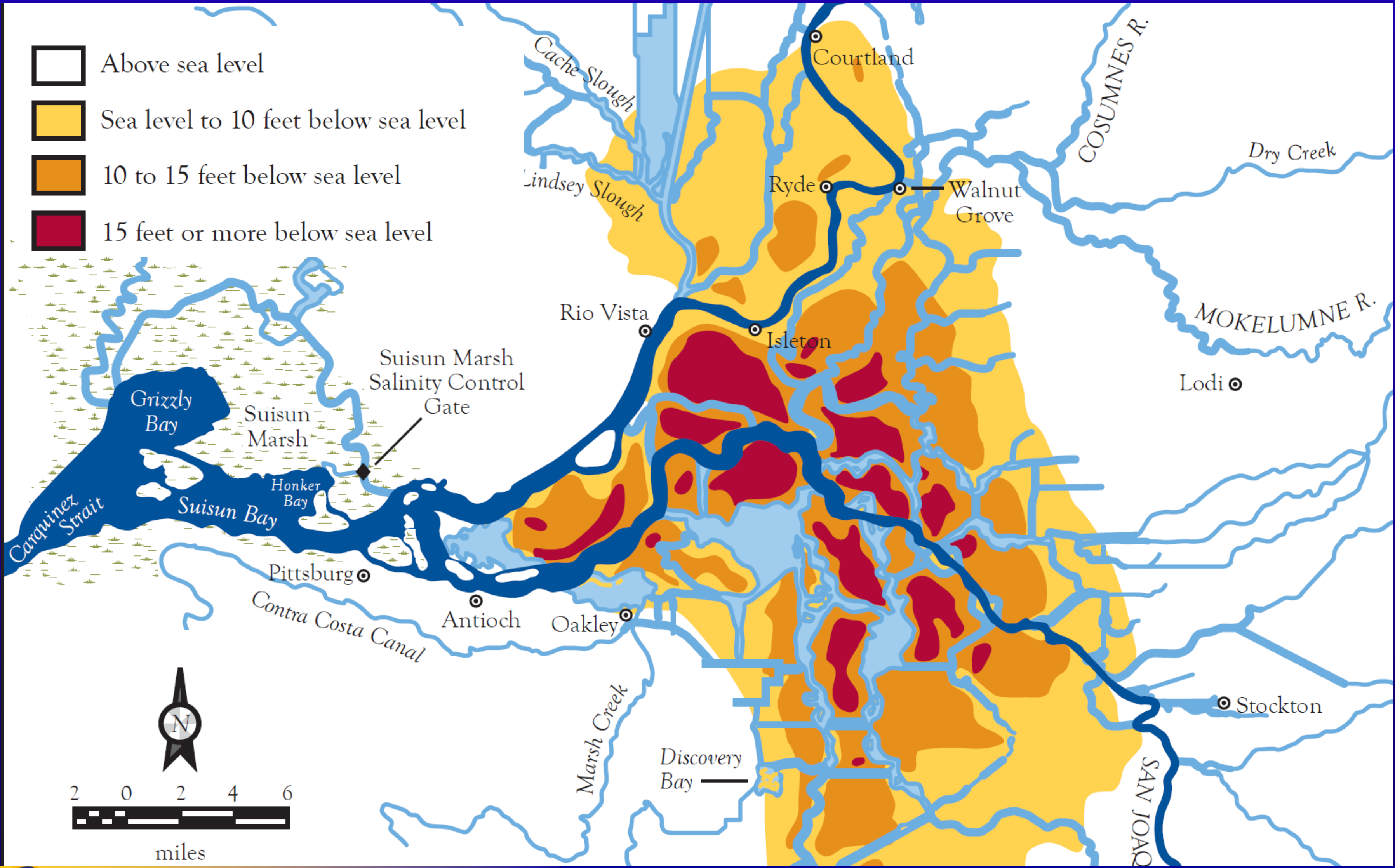
Sacramento-San Joaquin Delta

Sailing to Stockton in a *Night Scene on the San Joaquin River (Hutchins, 1857)*

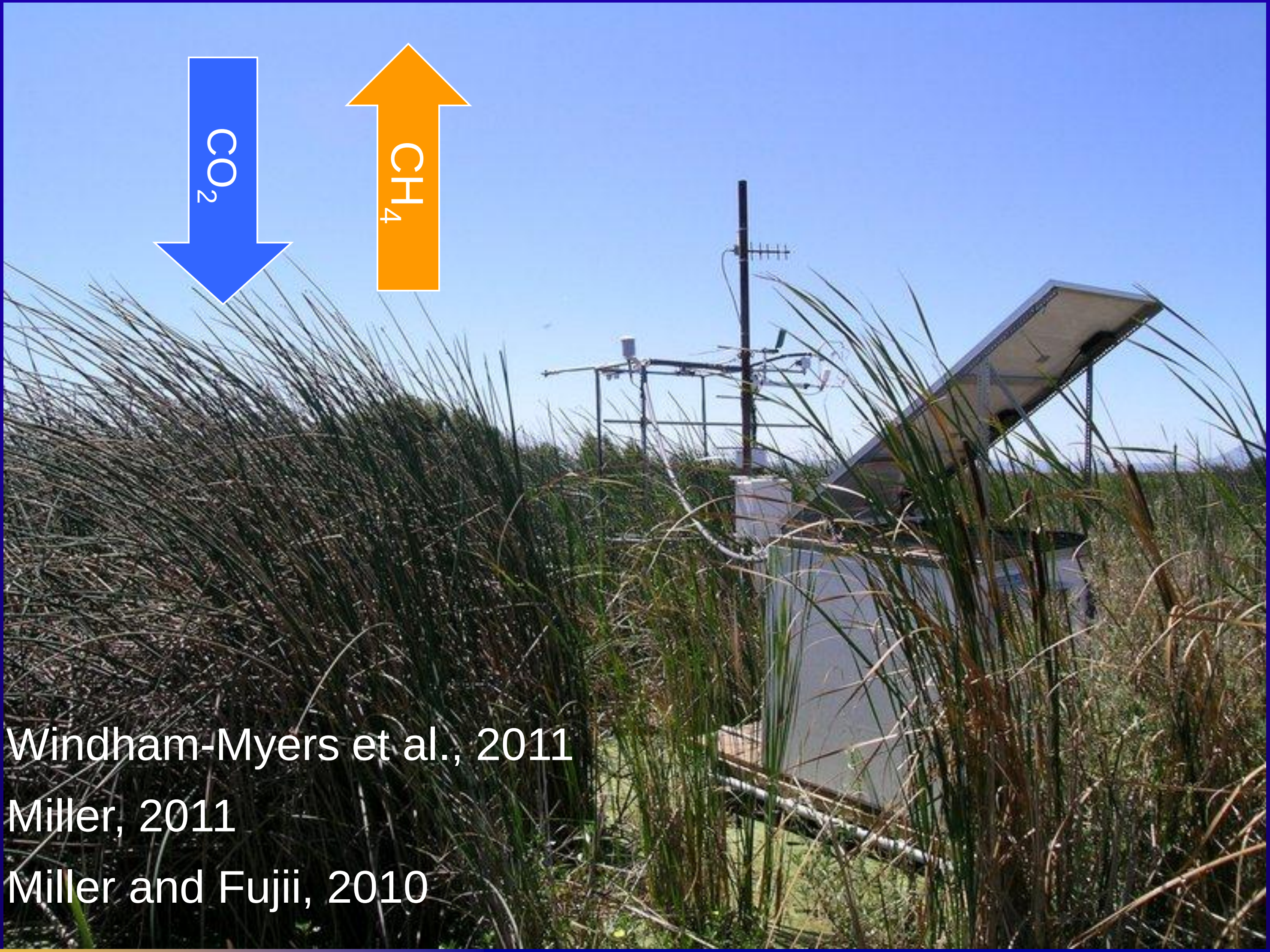
Sacramento-San Joaquin Delta



Sacramento-San Joaquin Delta



Restored wetlands in S-SJ Delta



Restored wetlands in S-SJ Delta

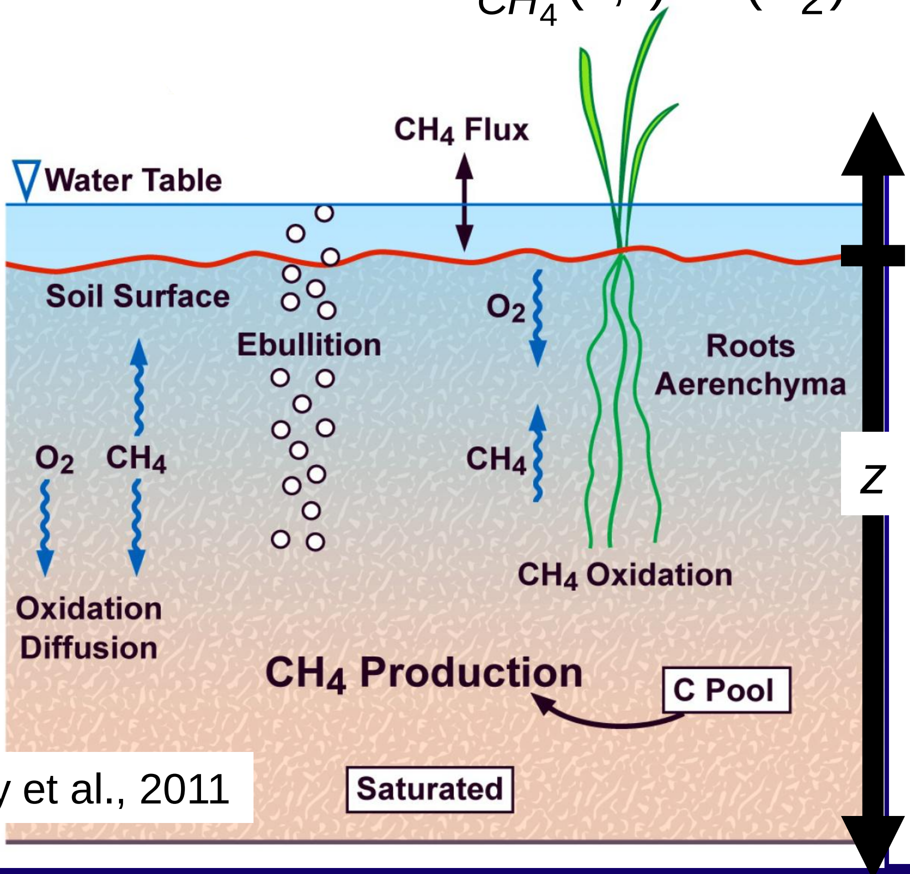
How can **restored wetlands** be managed to capture **more CO_2** and release **less CH_4**?

Wetland models (e.g. CLM4Me)

1. $$\frac{\partial CH_4}{\partial t} = P(z,t) - C_{CH_4}(z,t) - A_{CH_4}(z,t) + \frac{\partial F_{CH_4}}{\partial z} - E(z,t)$$

$$C_{CH_4}(z,t) = f(O_2)$$

2. $$\frac{\partial O_2}{\partial t} = -C_{O_2}(z,t) - A(z,t) + \frac{\partial F_{O_2}}{\partial z}$$



Riley et al., 2011

Definitions:

- F = Diffusive flux
- C = Consumption
- P = Production (CH_4)
- E = Ebullition (CH_4)
- A = Aerenchyma (plant-mediated) transport

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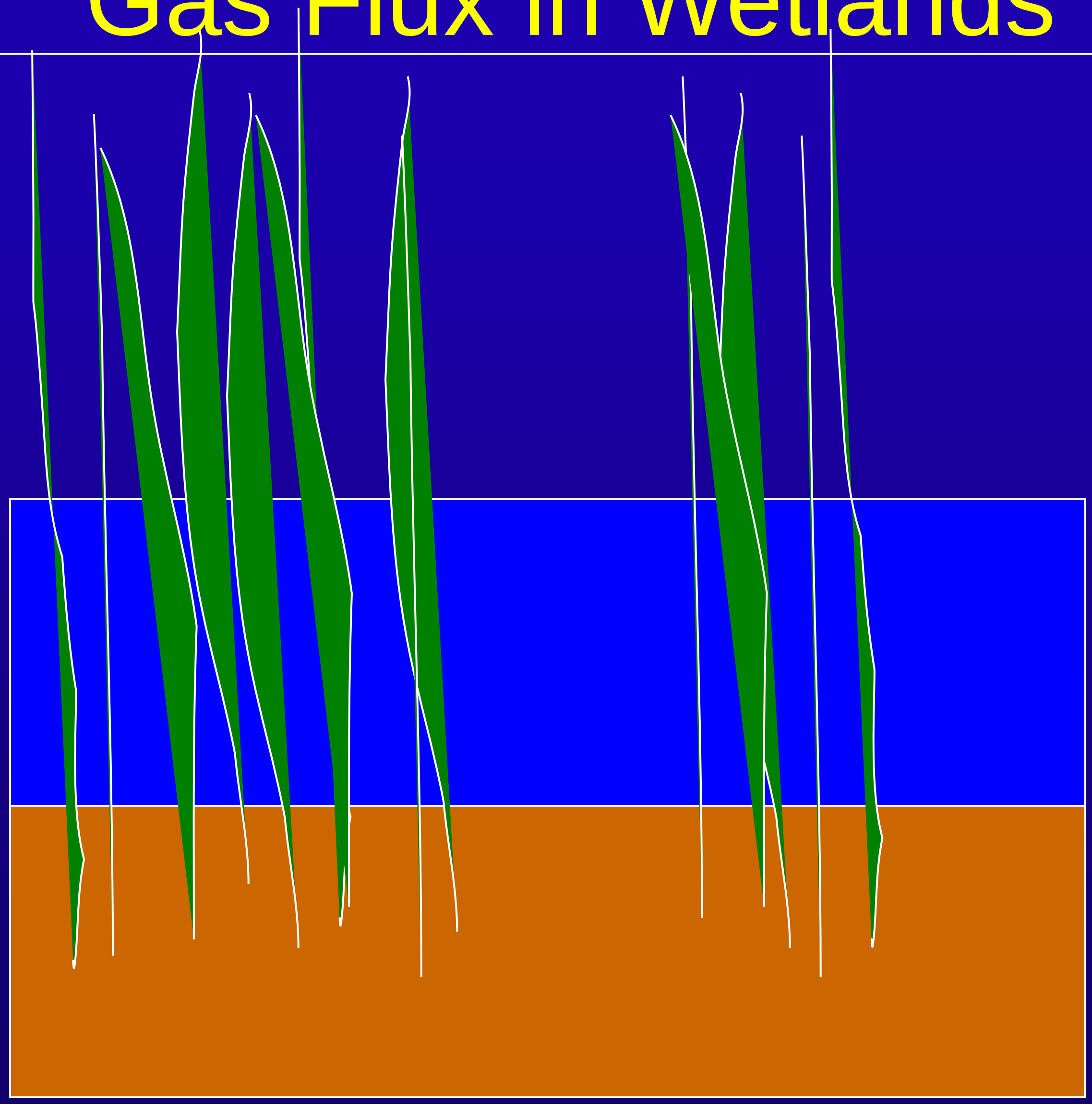
Gas Flux in Wetlands



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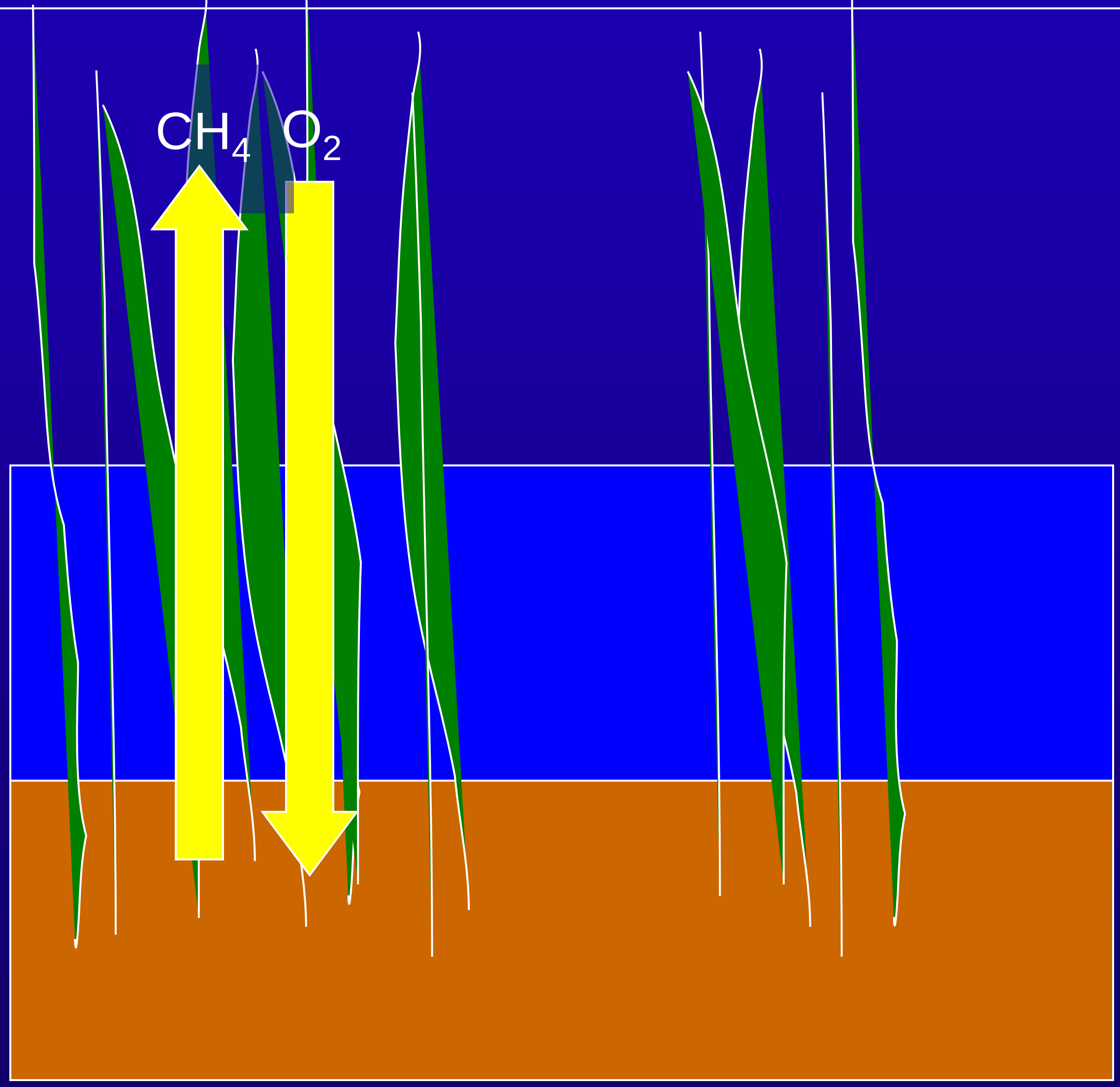

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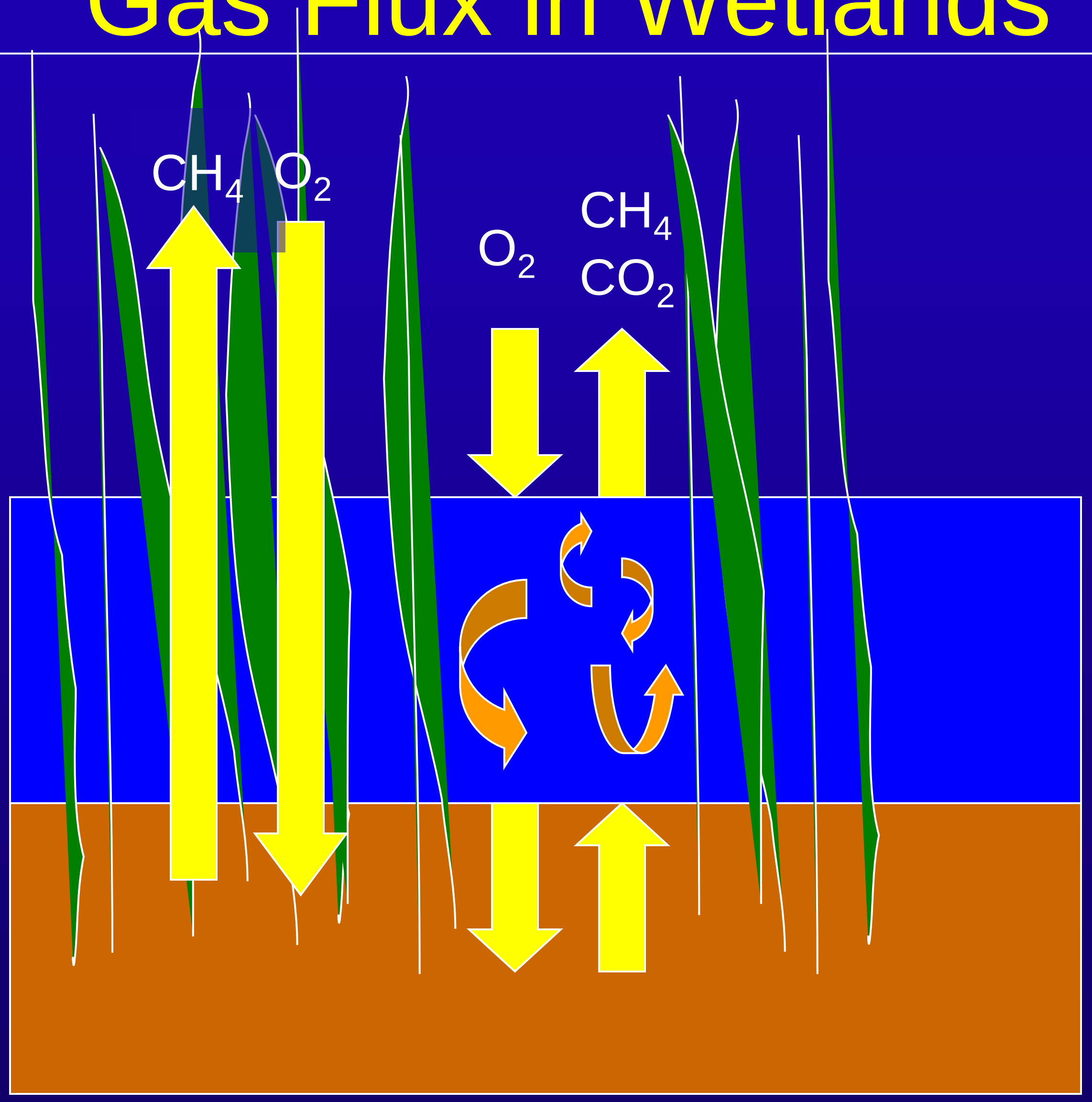

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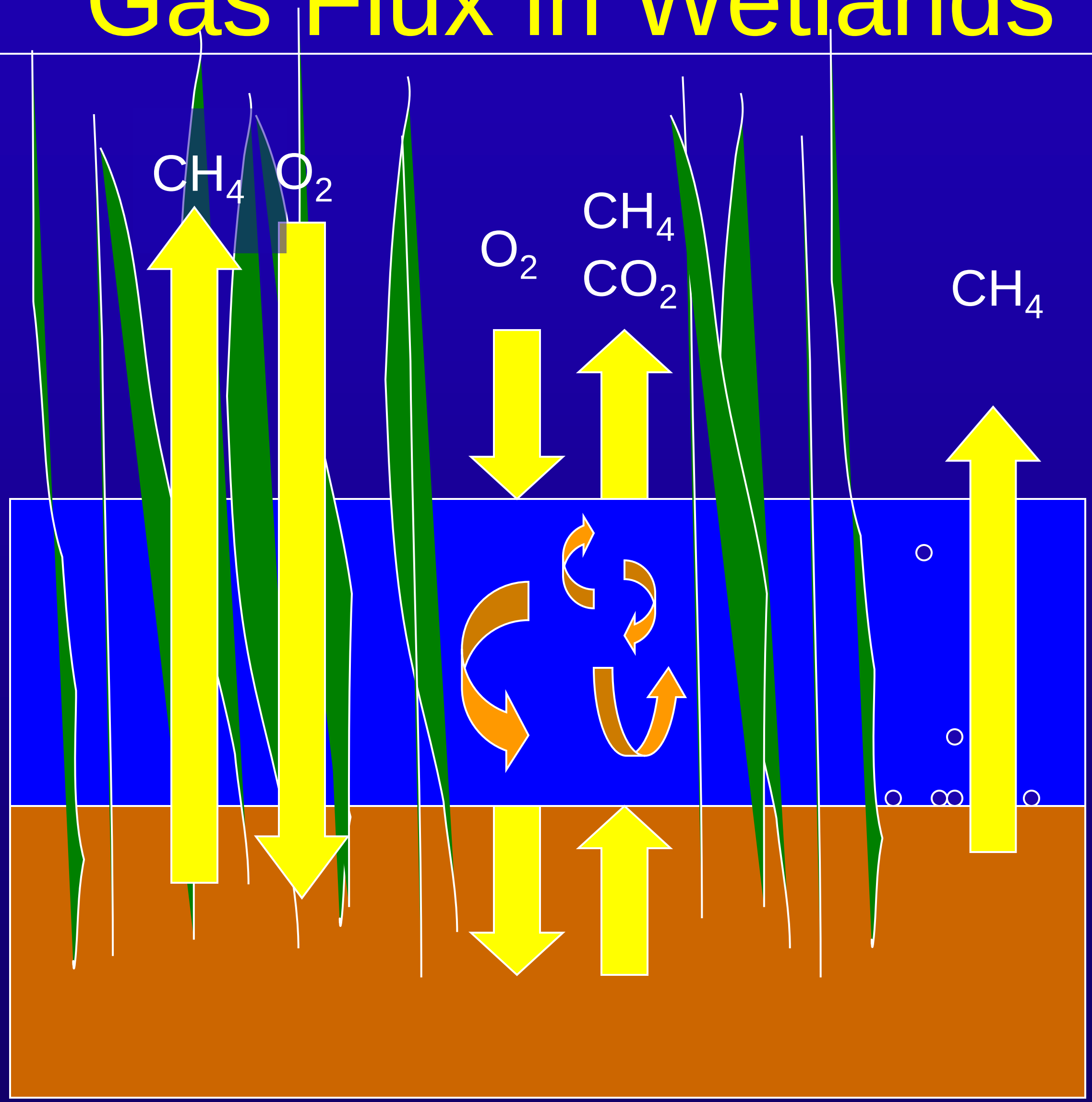
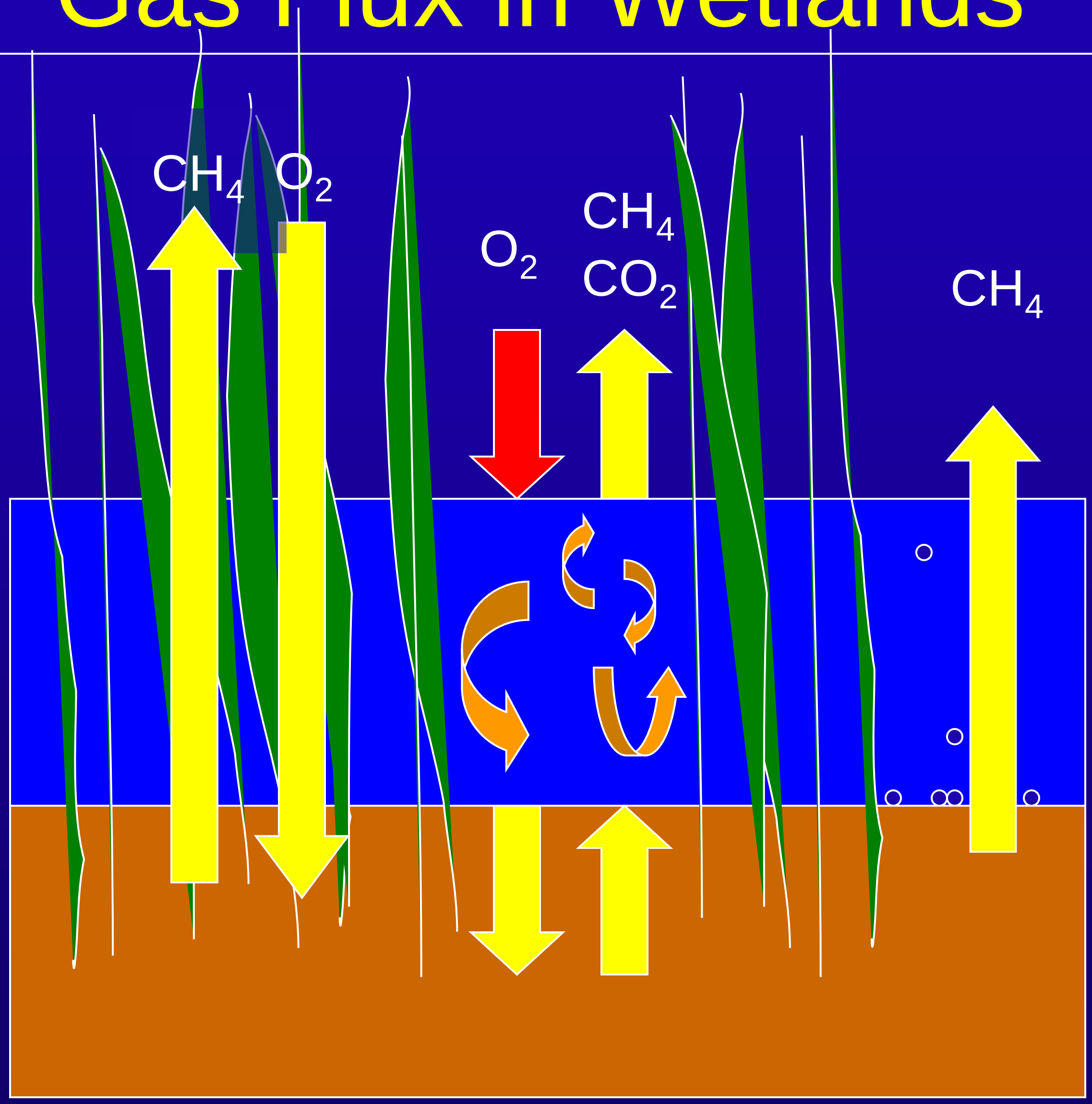


Gas Flux in Wetlands

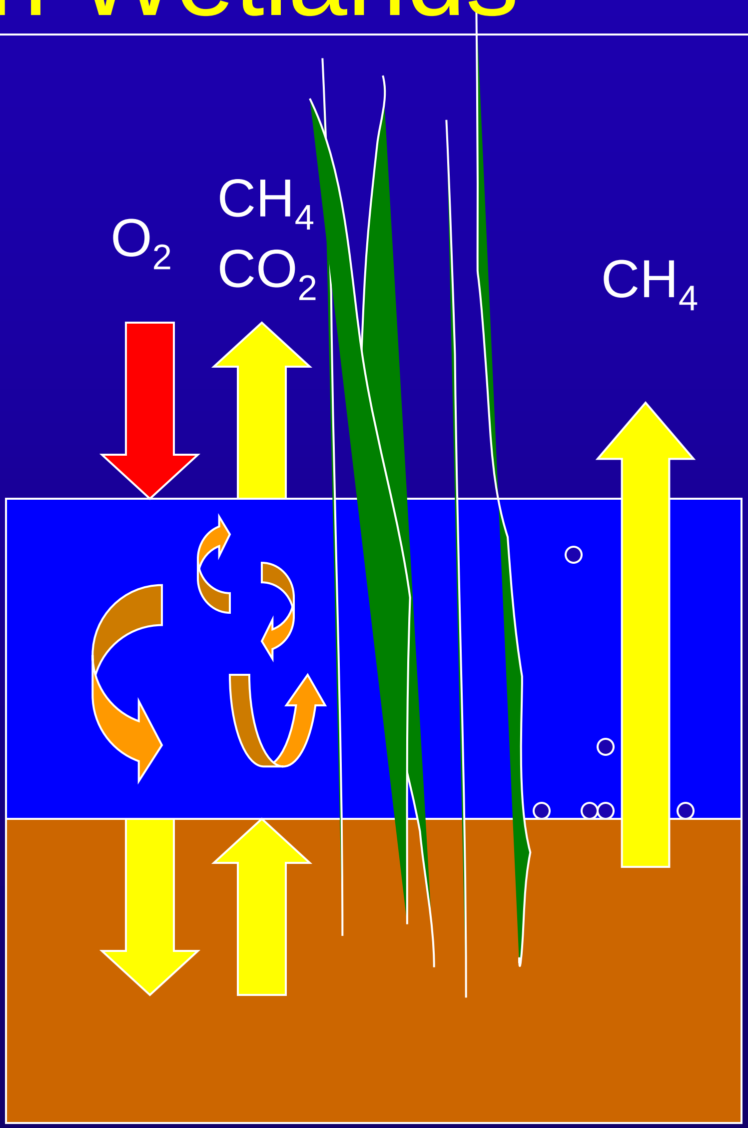


Gas Flux in Wetlands

DO is the best indicator or redox status in wetland surface waters (Reddy and DeLaune, 2008)

Oxygen fluxes into the water column

•Enhance methanotrophy
•Inhibit methanogenesis



Wetland models (e.g. CLM4Me)

$$1.\ \frac{\partial CH_4}{\partial t} = P(z,t) - C_{CH_4}(z,t) - A_{CH_4}(z,t) + \frac{\partial F_{CH_4}}{\partial z} - E(z,t)$$

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$$F_{CH_4} = -D_m \frac{\partial CH_4}{\partial z}$$

$$2.\ \frac{\partial O_2}{\partial t} = -C_{O_2}(z,t) - A(z,t) + \frac{\partial F_{O_2}}{\partial z}$$

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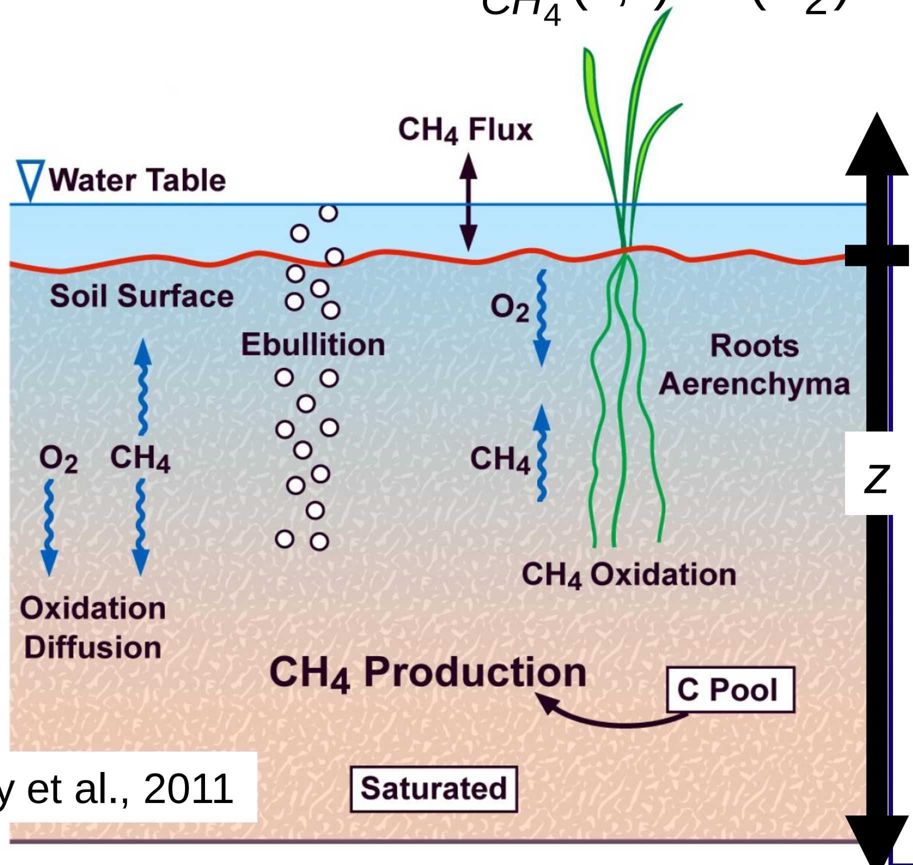

Riley et al., 2011

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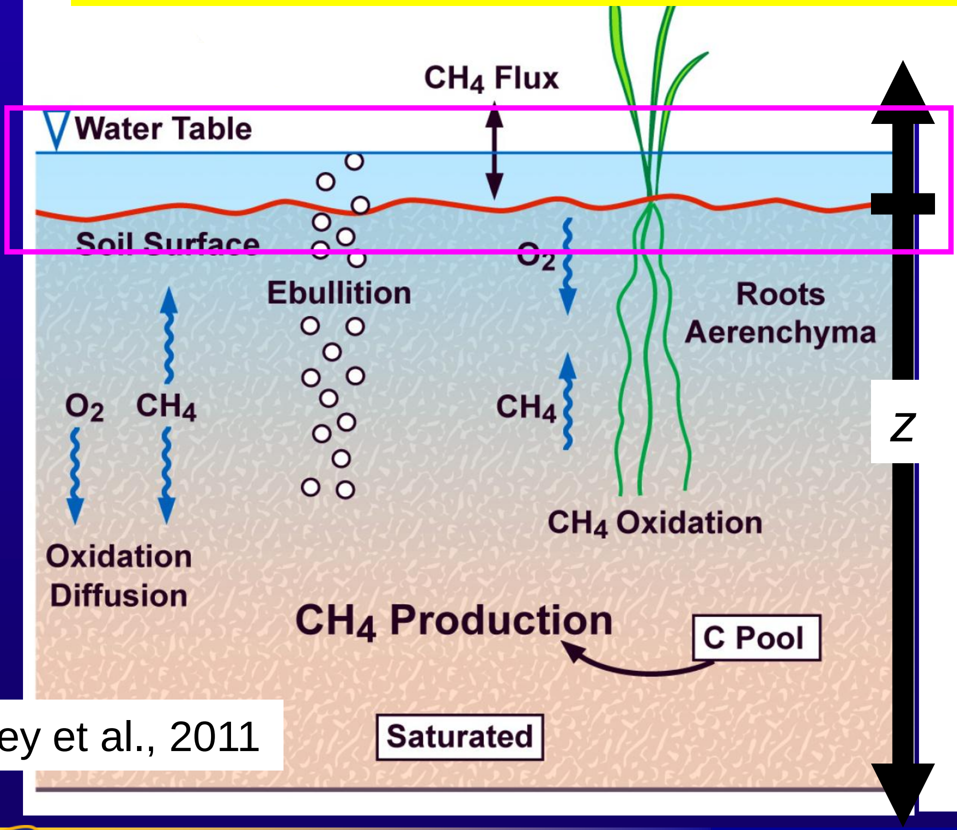
Wetland models (e.g. CLM4Me)

How are gas fluxes through the wetland water column best modeled?



Riley et al., 2011

$$F_{O_2} = -D_m \frac{\partial O_2}{\partial z}$$

$$F_{CH_4} = -D_m \frac{\partial CH_4}{\partial z}$$

Transport Model Options

Molecular diffusion

$$Flux = -D_m \left.\frac{\partial \langle C \rangle}{\partial z}\right|_{interface}$$

Fickian Model and Film Simplification

$$\underset{\text{(at interface)}}{Flux} = \overbrace{-D_T \left.\frac{\partial \langle C \rangle}{\partial z}\right|_{interface}}^{\text{Fickian Model}} \approx \overbrace{k\left(\langle C_{surf} \rangle - \langle C_{bulk} \rangle\right)}^{\text{Film Simplification}}$$

Transport Model Options

Molecular diffusion

$$Flux = -D_m \frac{\partial \langle C \rangle}{\partial z}\bigg|_{interface}$$

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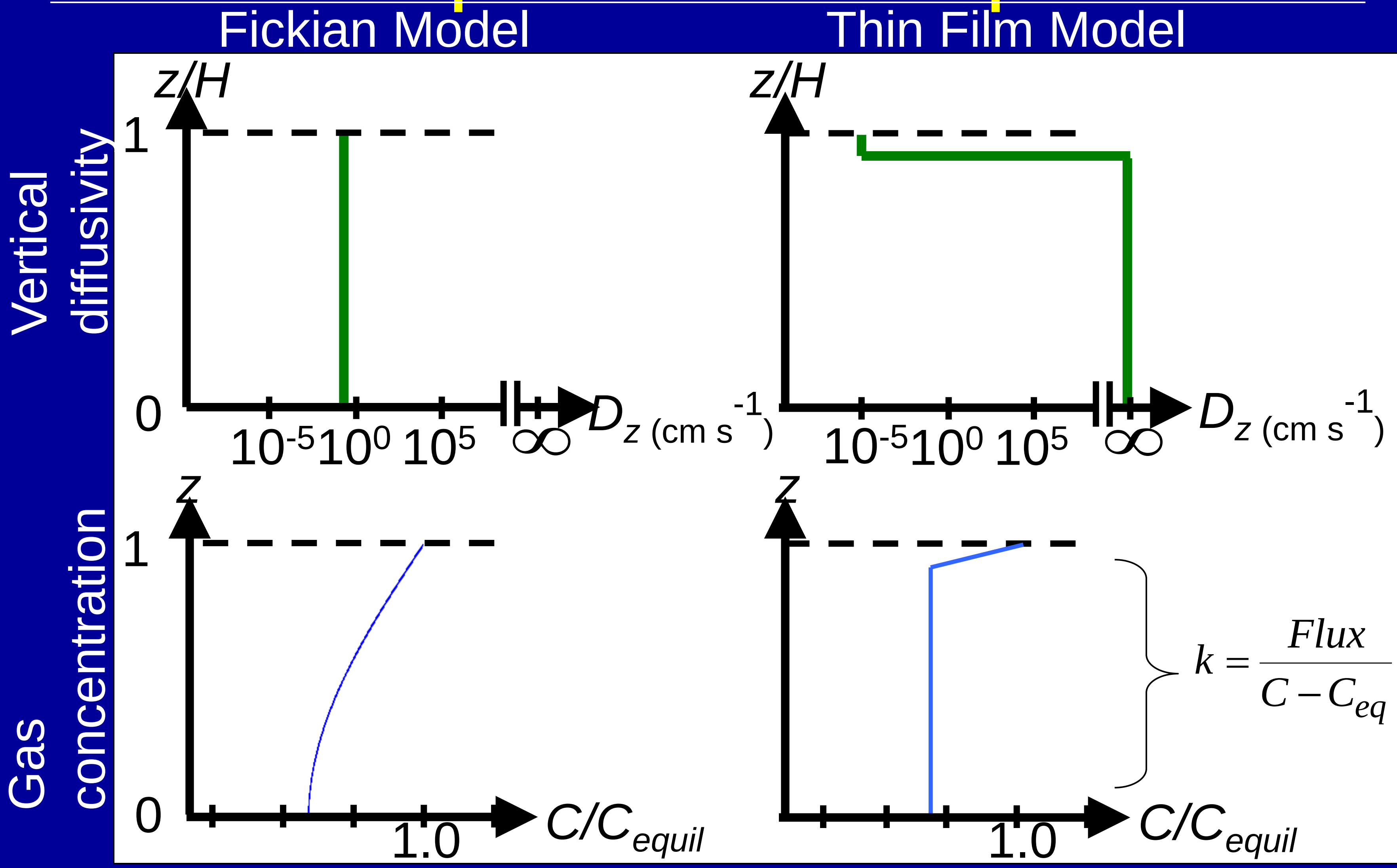
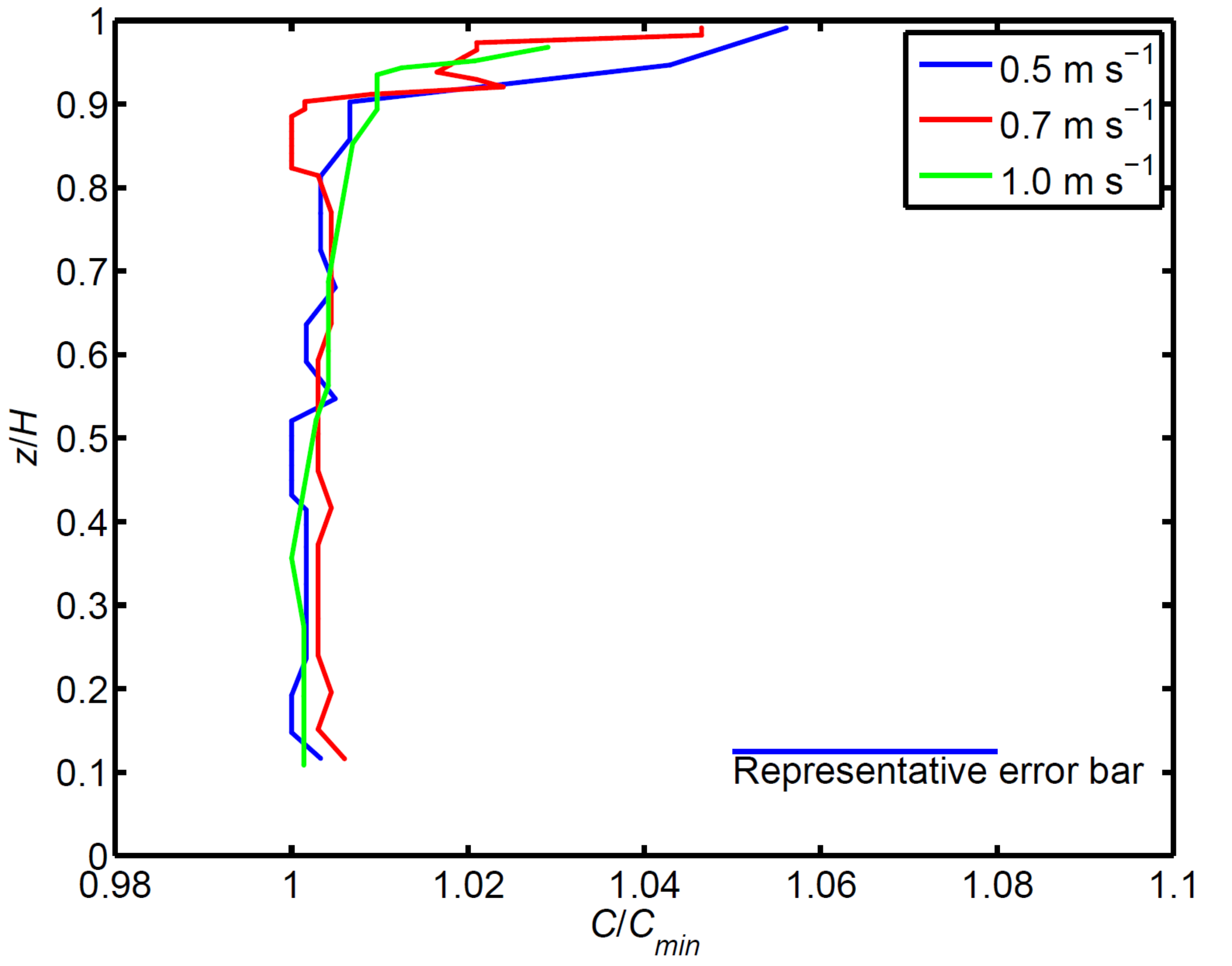
(at interface)

Transport Model Options



Transport Model Selection



Transport Model Selection

Fickian Model and Film Simplification

$$Flux = -D_T \frac{\partial \langle C \rangle}{\partial z}\bigg|_{interface} \approx k(\langle C_{surf} \rangle - \langle C_{bulk} \rangle)$$

(at interface)

We're going to find flux using *k*

But what is k?

k in wetlands

- Field studies
  - k_{600}=0.3-1.8 cm hr^{-1} (Everglades RSL)
  - k_{600}=0.8 cm hr^{-1} (hardwood swamp)
  - k_{600}=0.2-0.7 cm hr^{-1} (flooded boreal forest)
- Empirical function of forcings

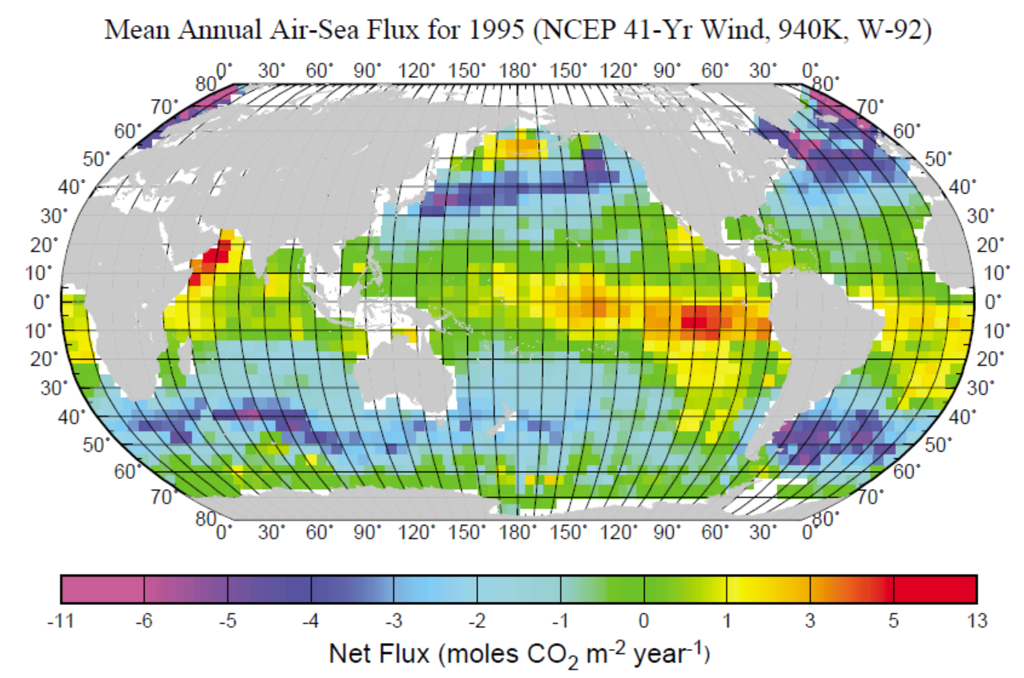
  not yet known
- Universal divergence model

  not yet tested

Empirical k models in other flows

- Rivers k=f(u*)
- Oceans k=f(U_{10})
- Lakes k=f(U_{10}, thermal stratification)

Example: $k \sim (U_{10})^2$
[Wanninkof 1992]
used to calculate global patterns in air-sea CO_2 flux
[Takahashi et al, 2001]



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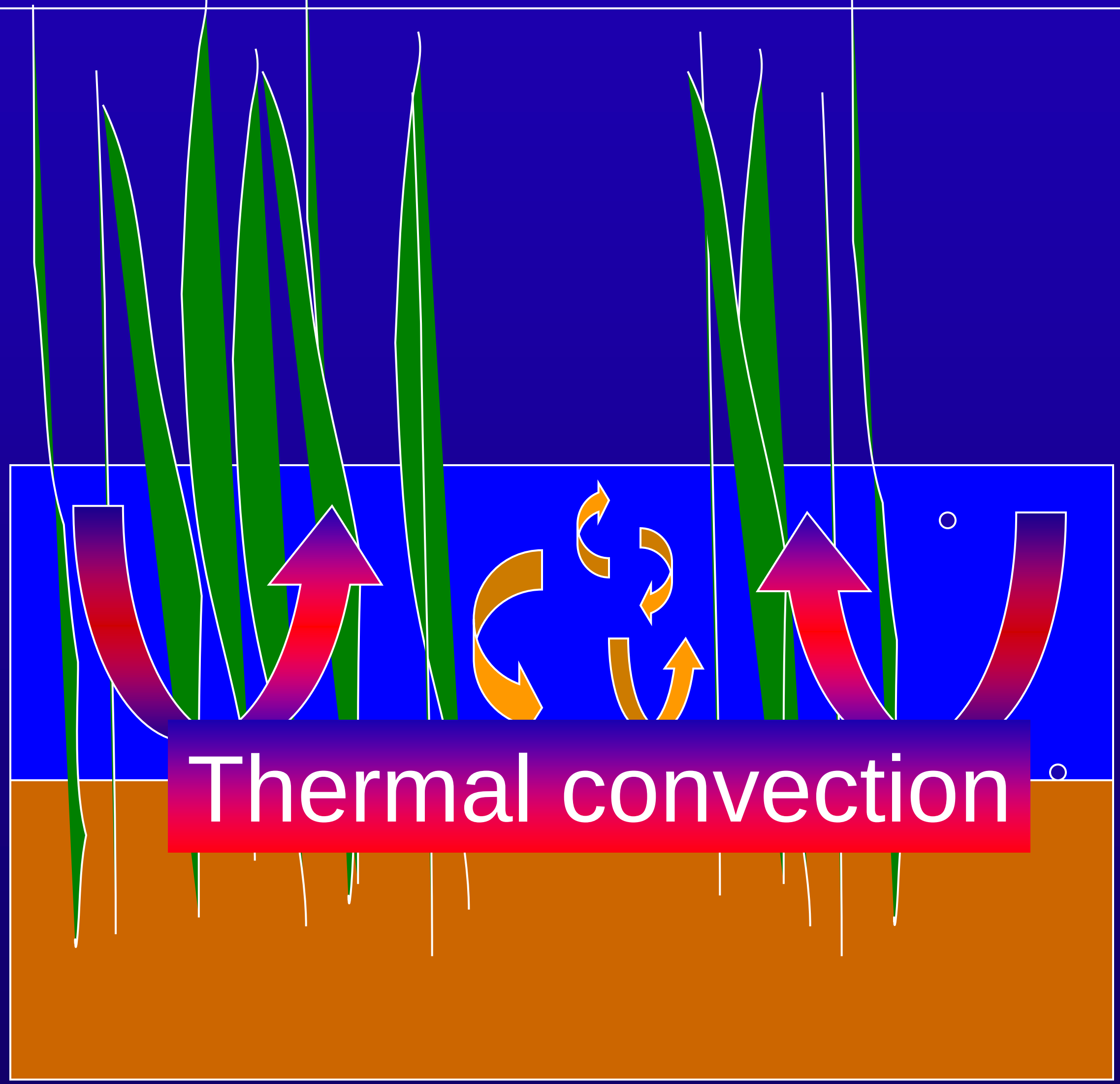
Causes of Wetland Mixing



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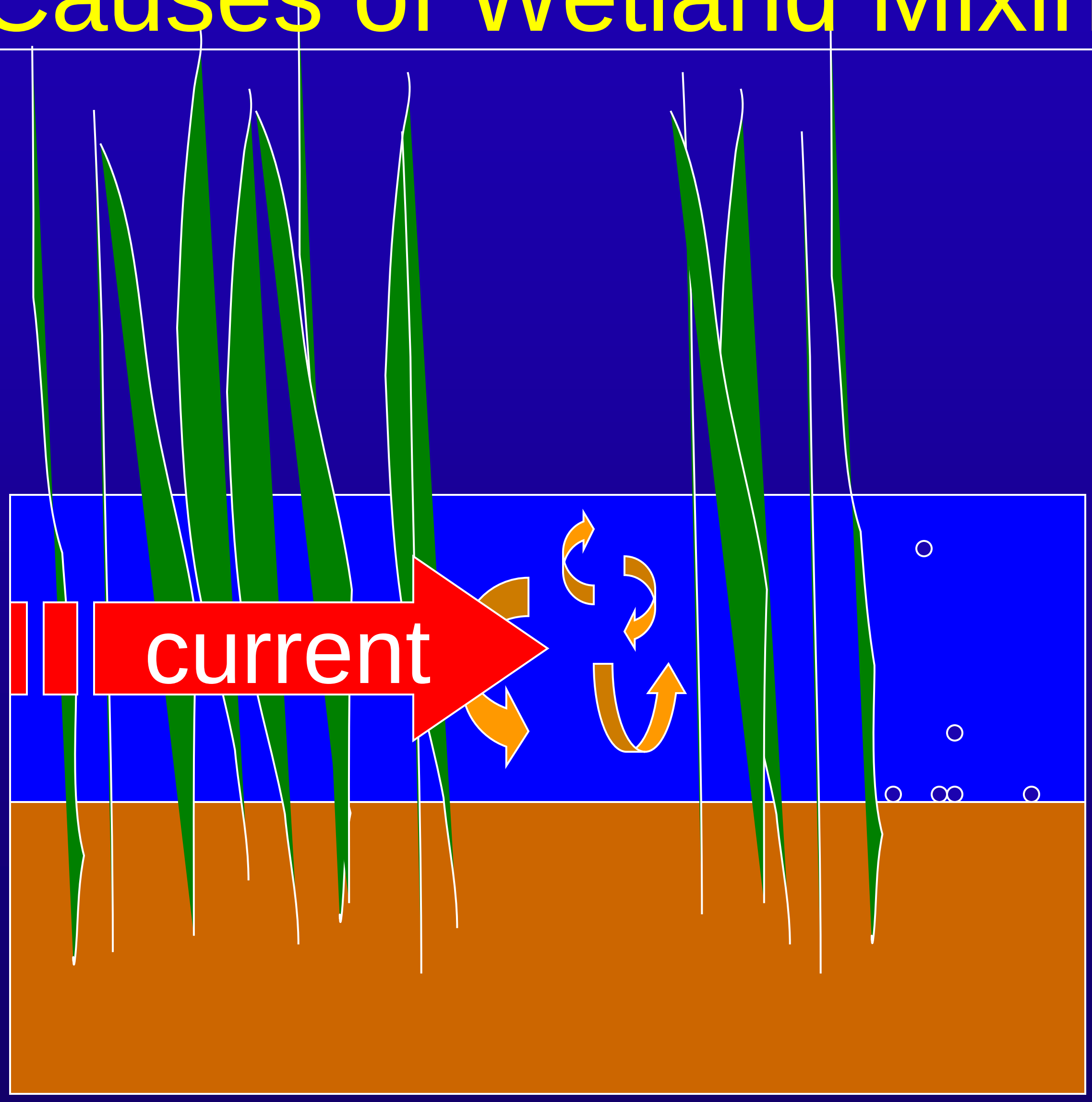

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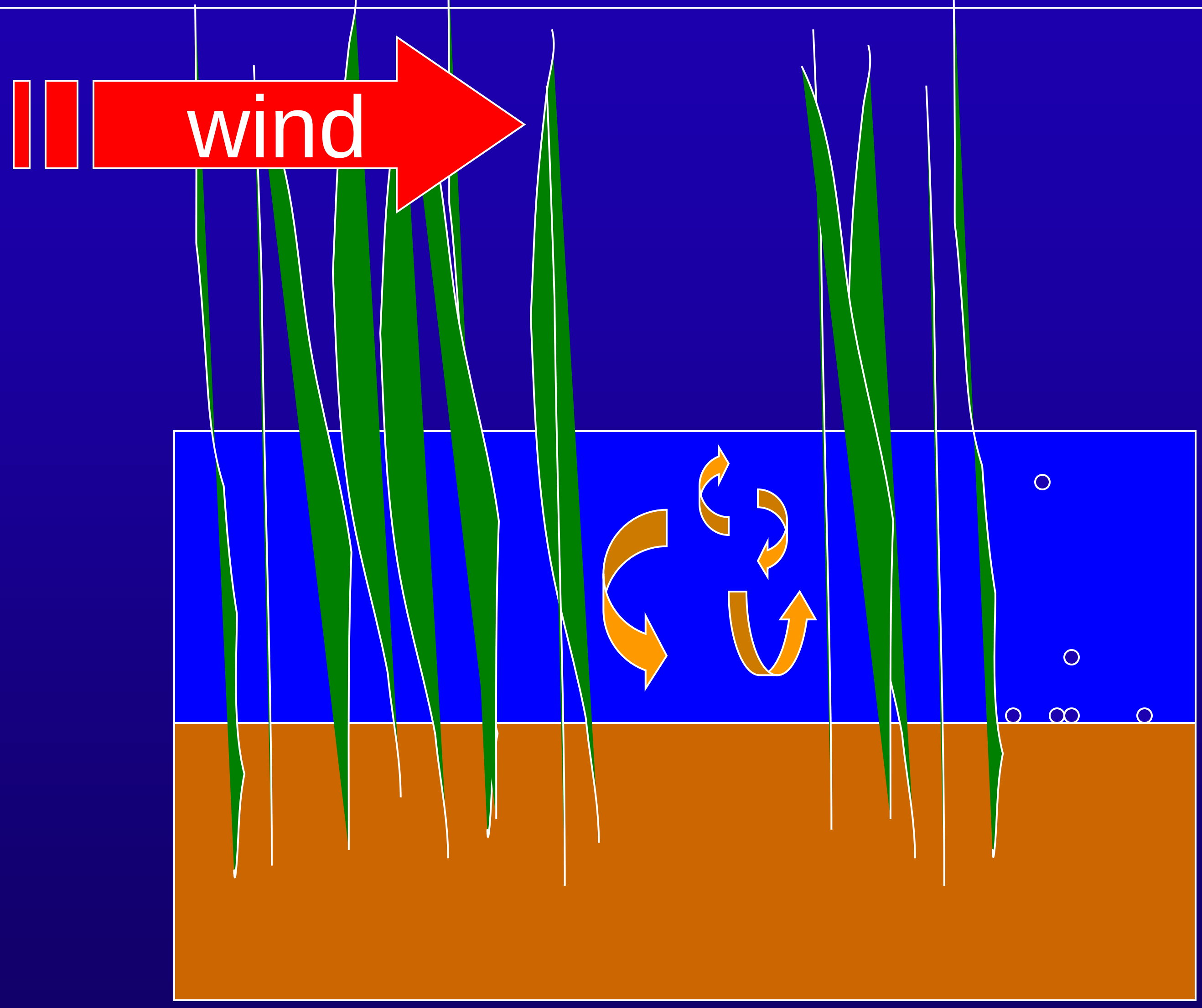
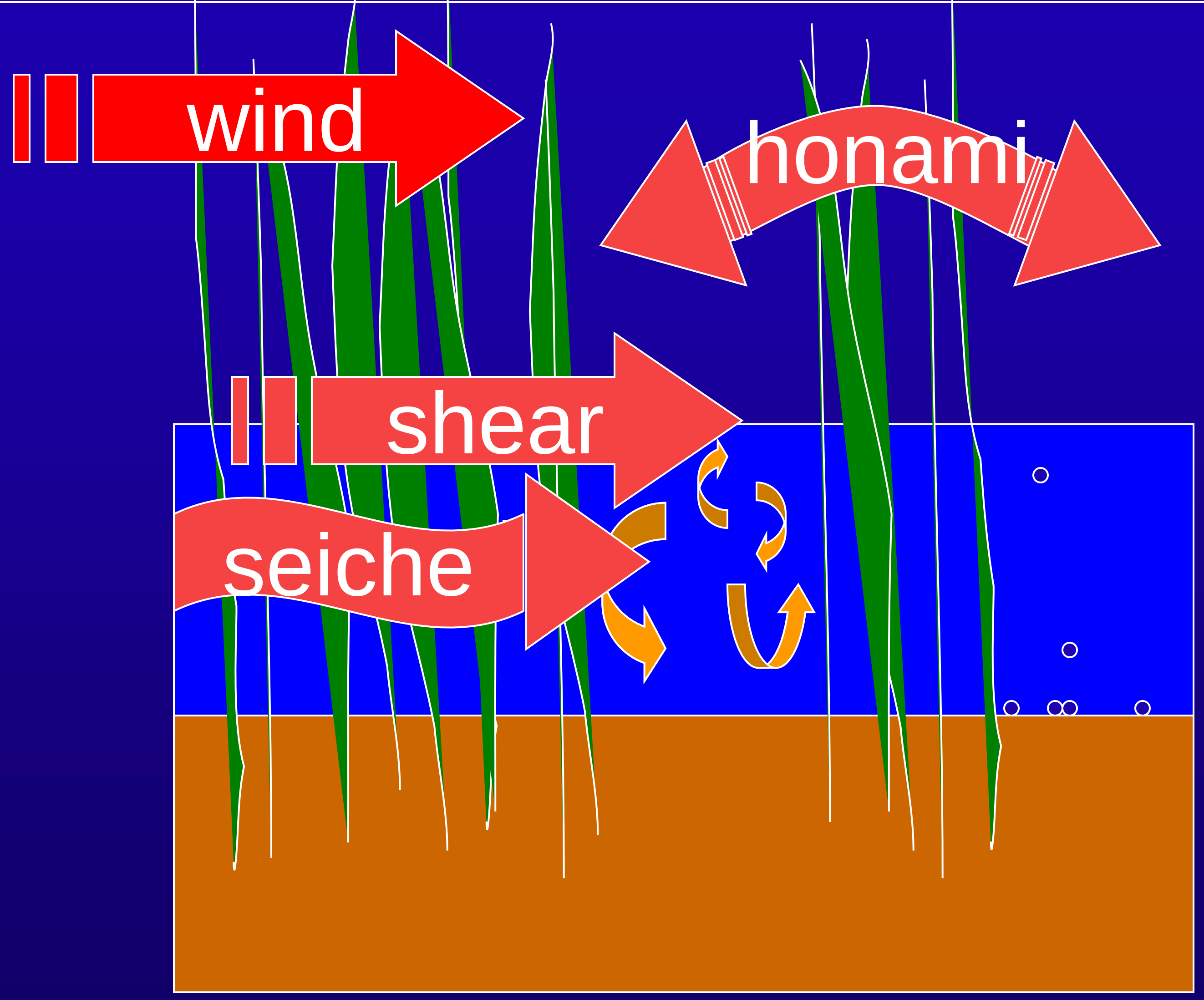
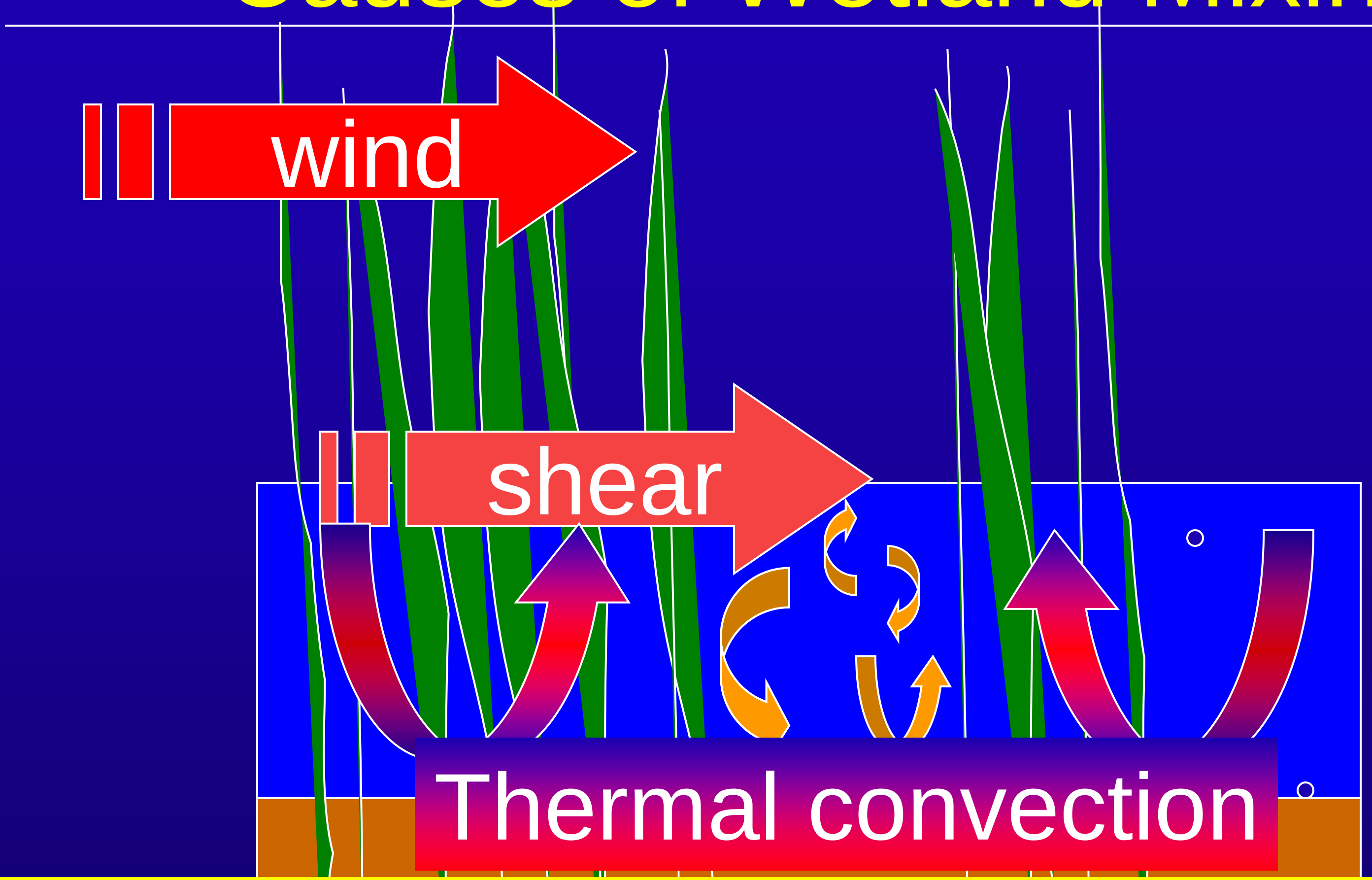


Causes of Wetland Mixing



Causes of Wetland Mixing



How does *k* vary with wind shear and thermal convection in wetlands?

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Measuring flux and *k* in laboratory

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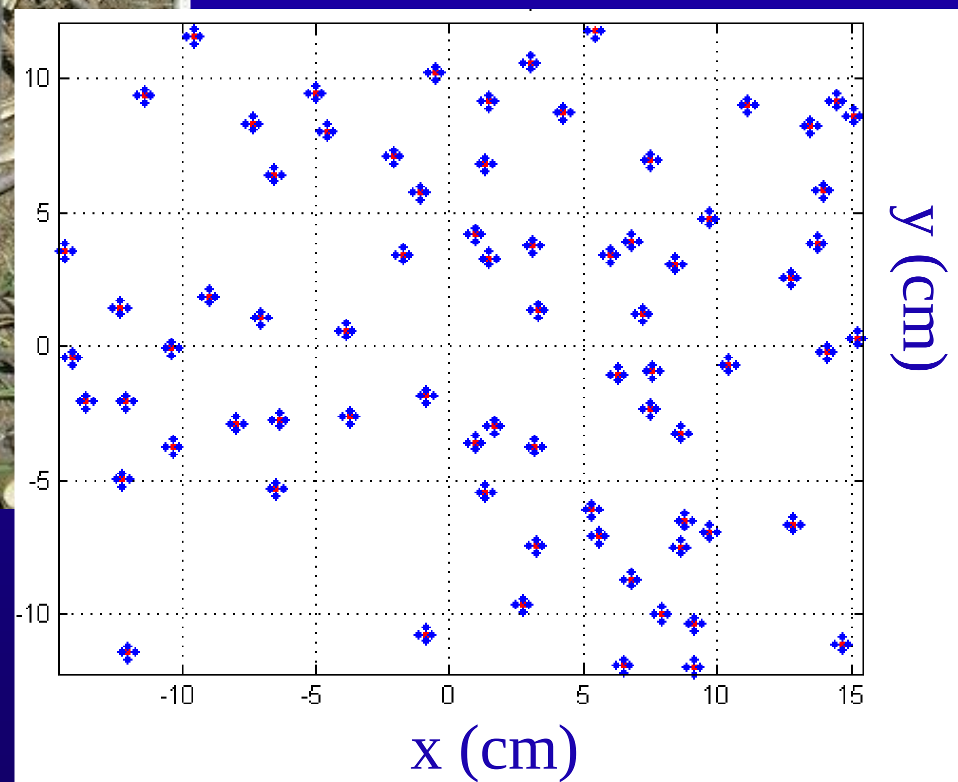
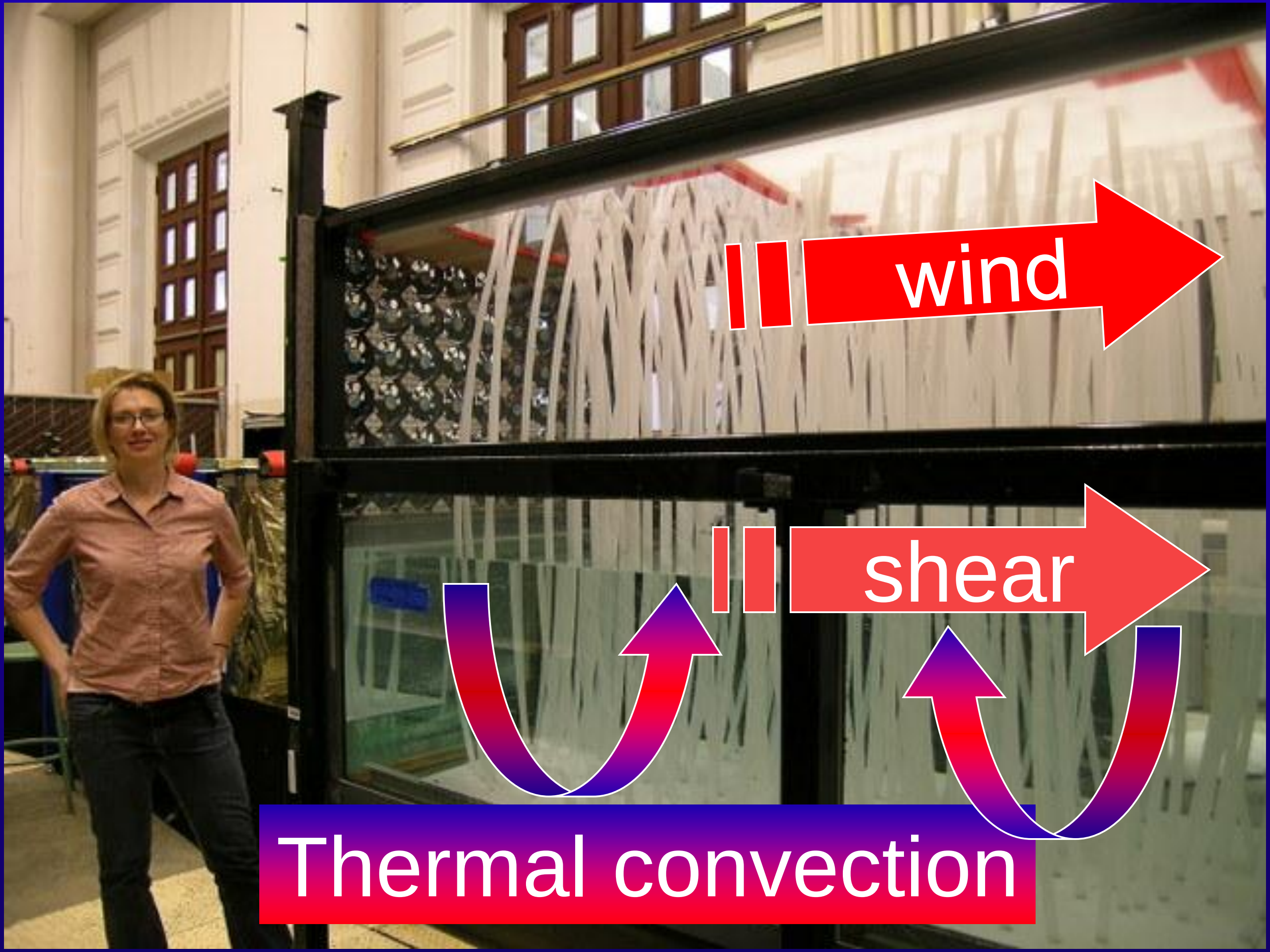
Measuring flux and *k* in laboratory

Schoenoplectus acutus (tule) density and spatial pattern

Simulated stem pattern



Measuring flux and *k* in laboratory



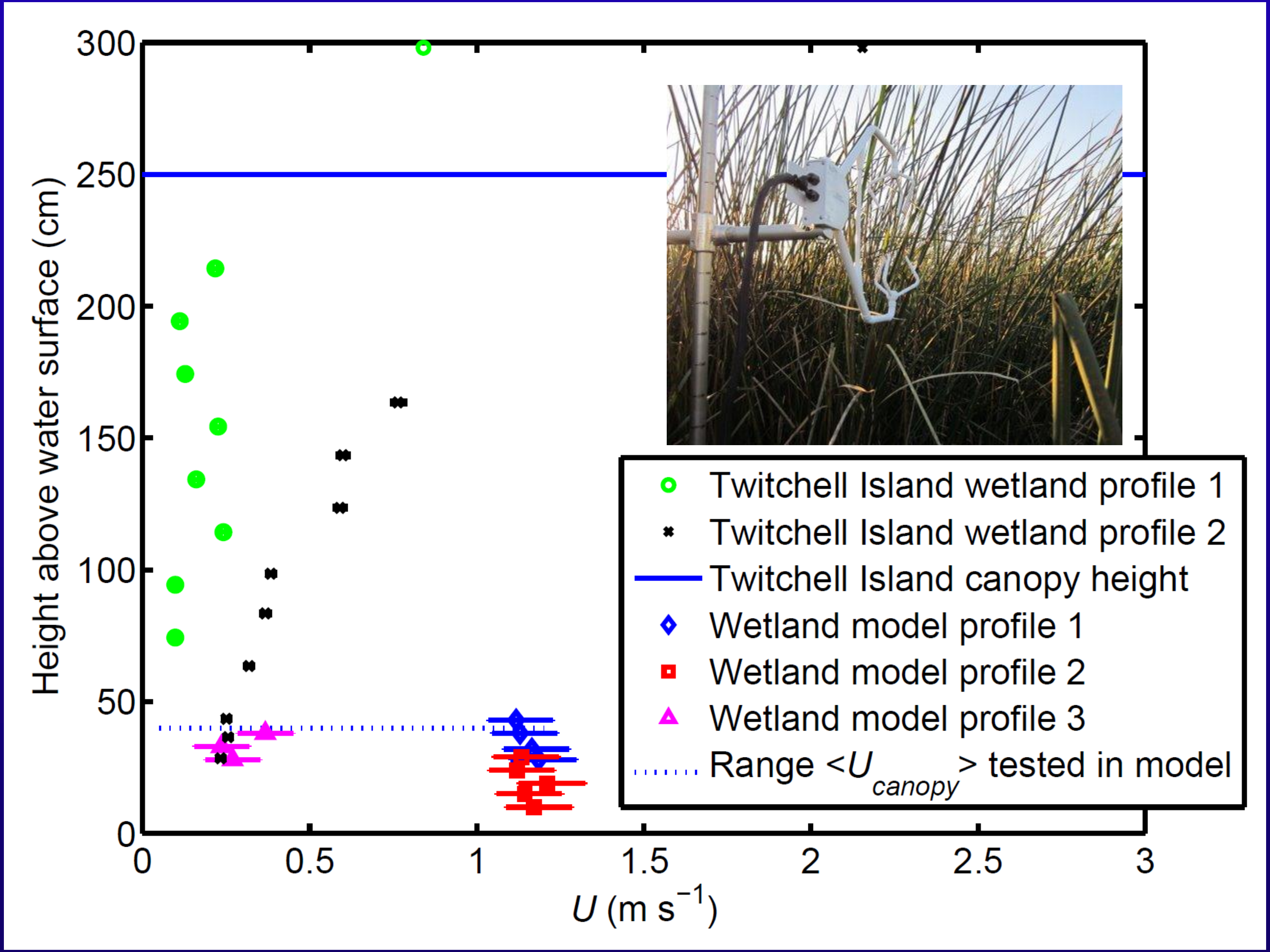
Wind, thermal stratification levels

$\langle U_{canopy} \rangle$ between 0.05 m s^{-1} and 1.1 m s^{-1}

Thermal stratification

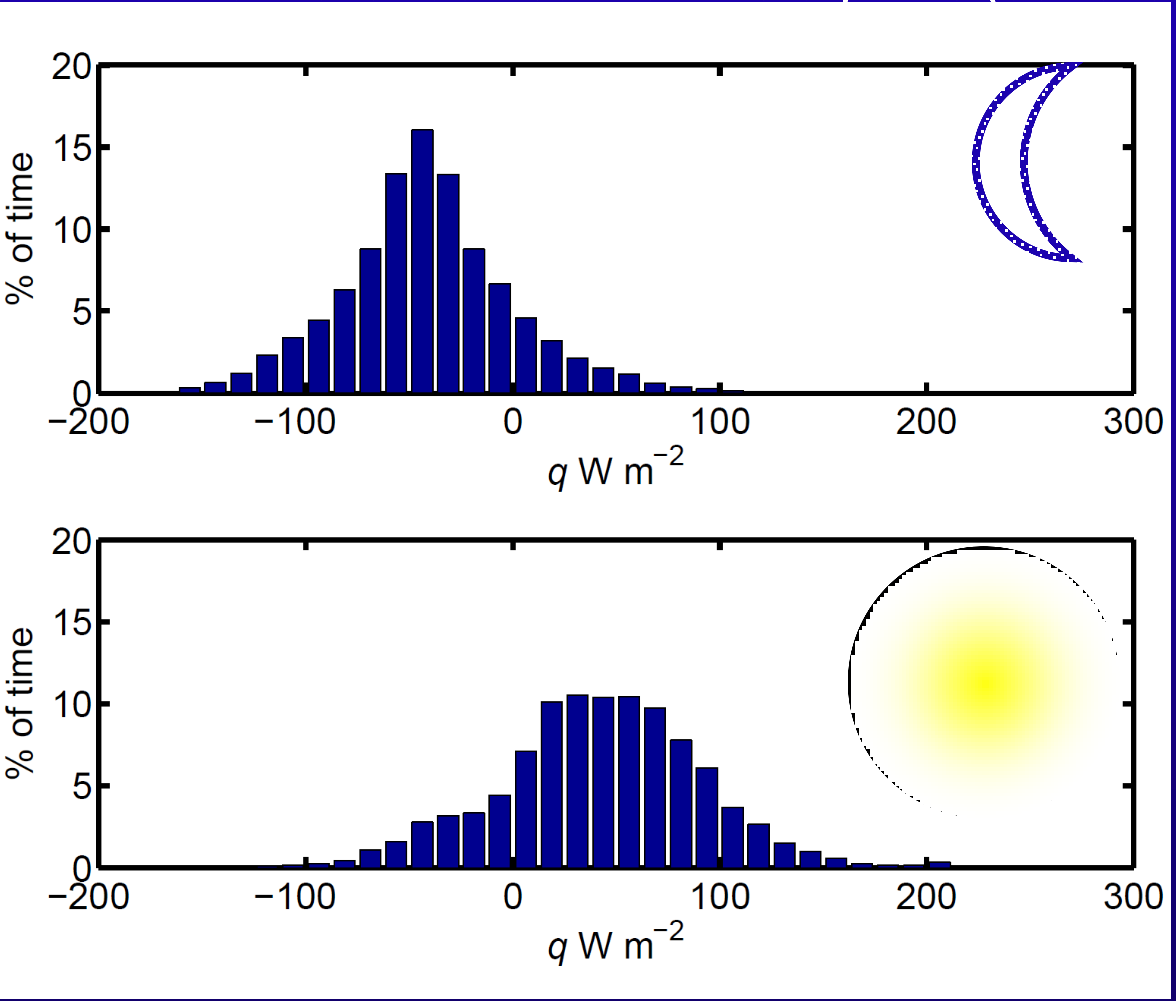
q between -300 W m^{-2} and 115 W m^{-2}

Choice of wind speeds to measure



Choice of stratification cases

Twitchell Island wetlands heat flux histograms (June-Sep, 2010)



Data source: Bryan Downing (USGS)

Wind, thermal stratification levels

wind

$\langle U_{canopy} \rangle$ between 0.05 m s^{-1} and 1.1 m s^{-1}

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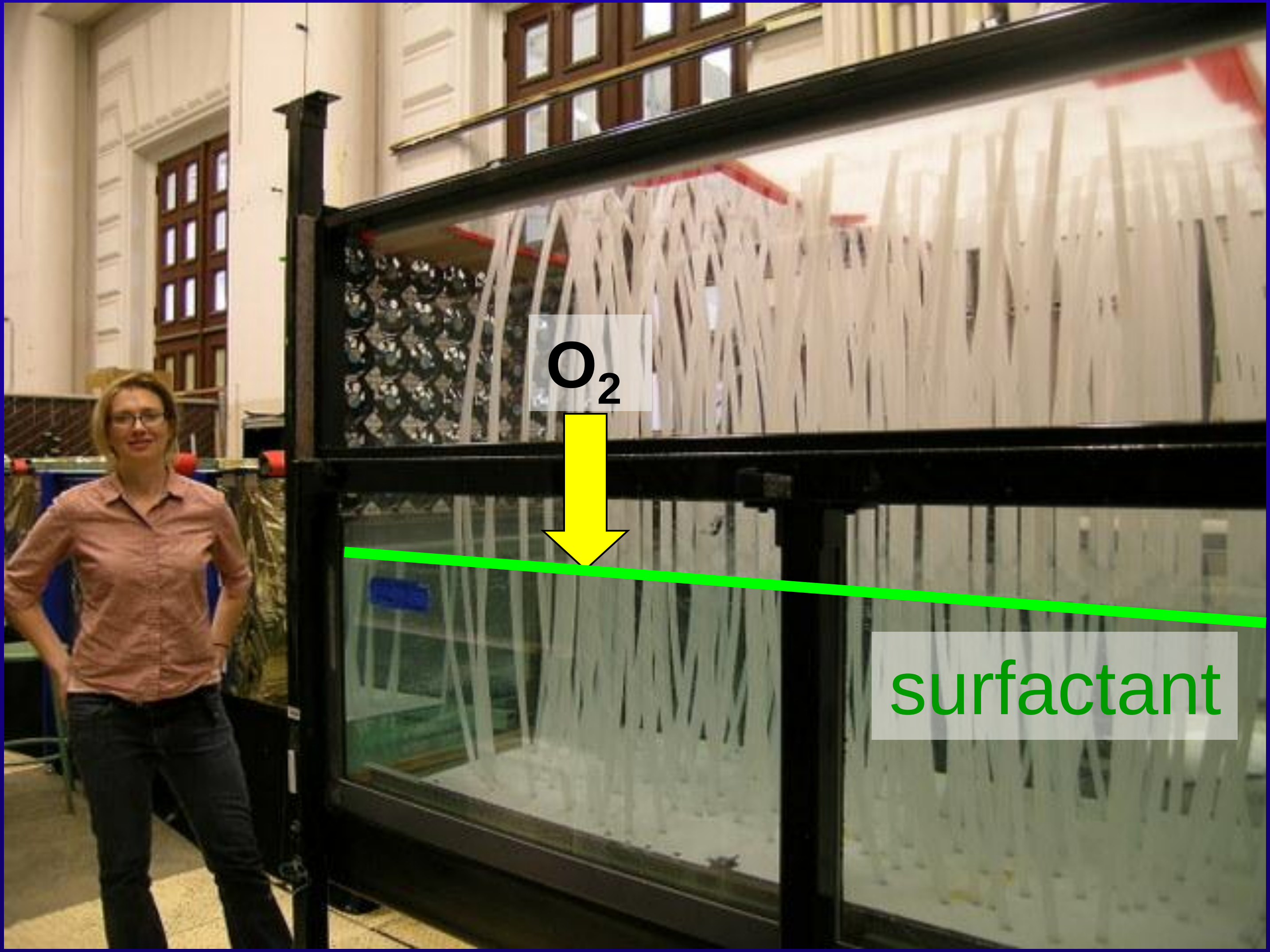
q between -300 W m^{-2} and 115 W m^{-2}

Measuring flux and *k* in laboratory



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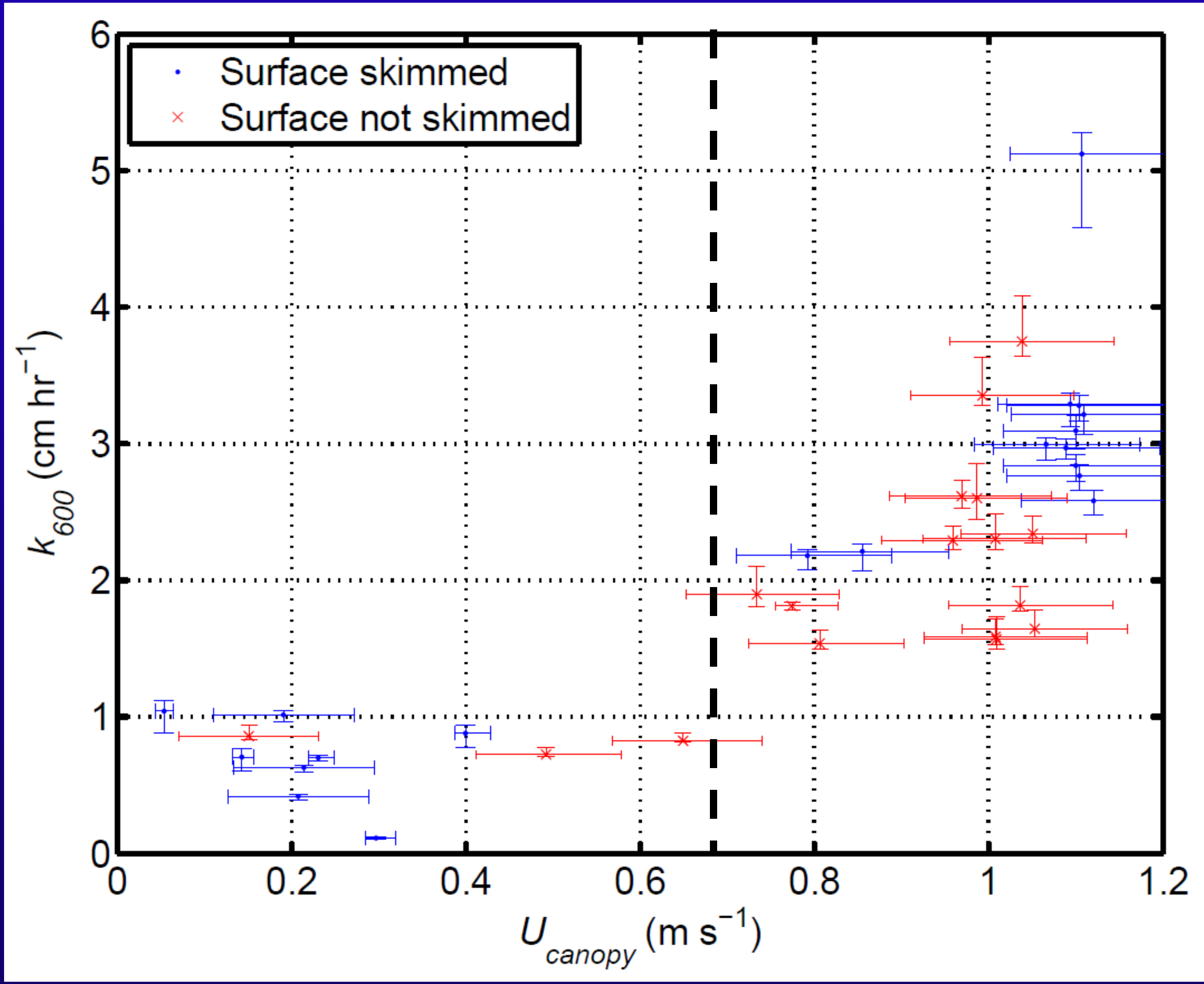
k as an empirical model of forcings



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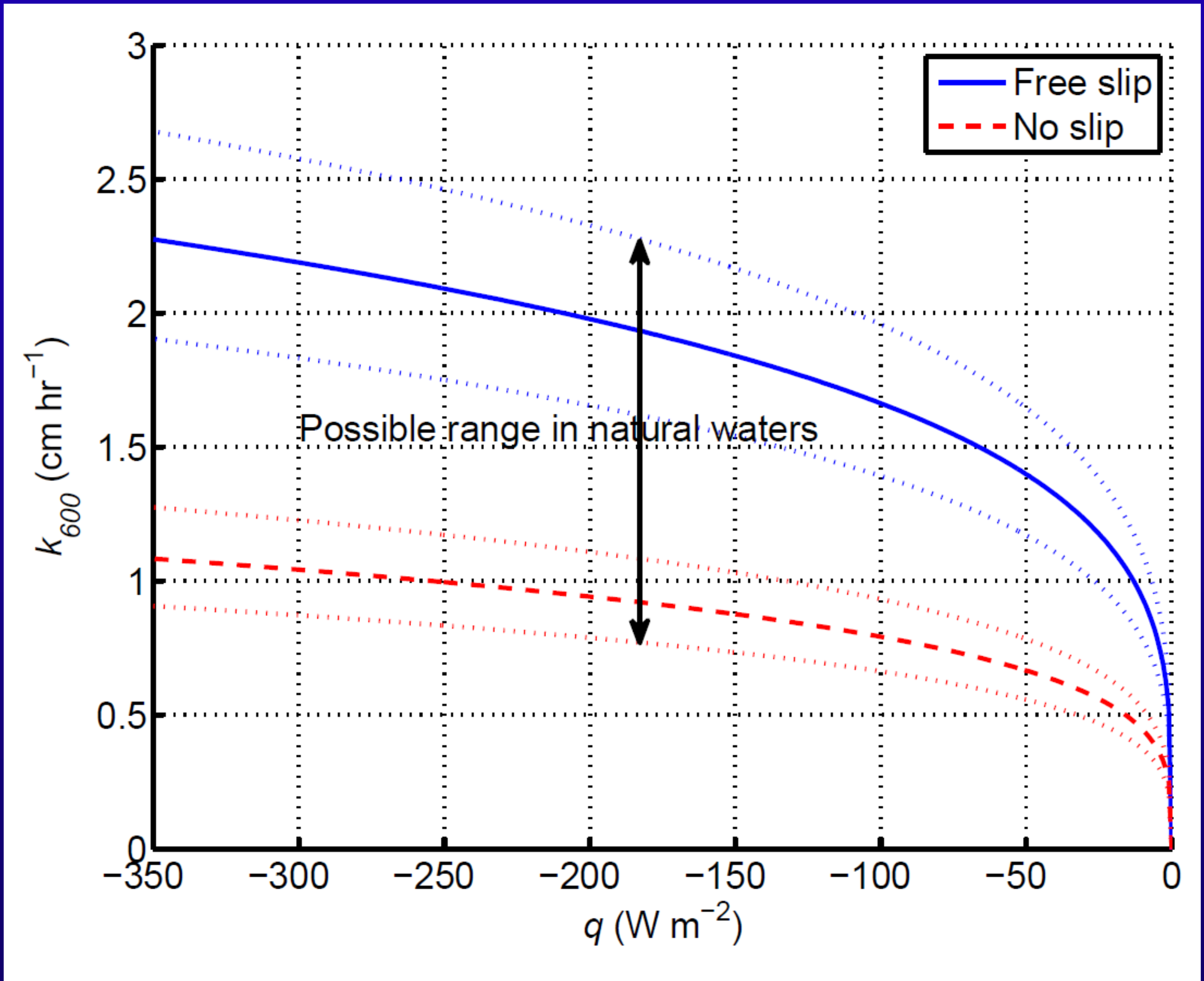

$$q = \frac{dT}{dt}\rho c_p H$$

Semi-empirical relationships

$$k_h \propto (-q)^{1/4} \quad q < 0$$

scaling heat transfer coeff. to gas transfer coeff.

$$k_{600} = k_h \left(\frac{600}{\mathrm{Pr}}\right)^{-n}$$

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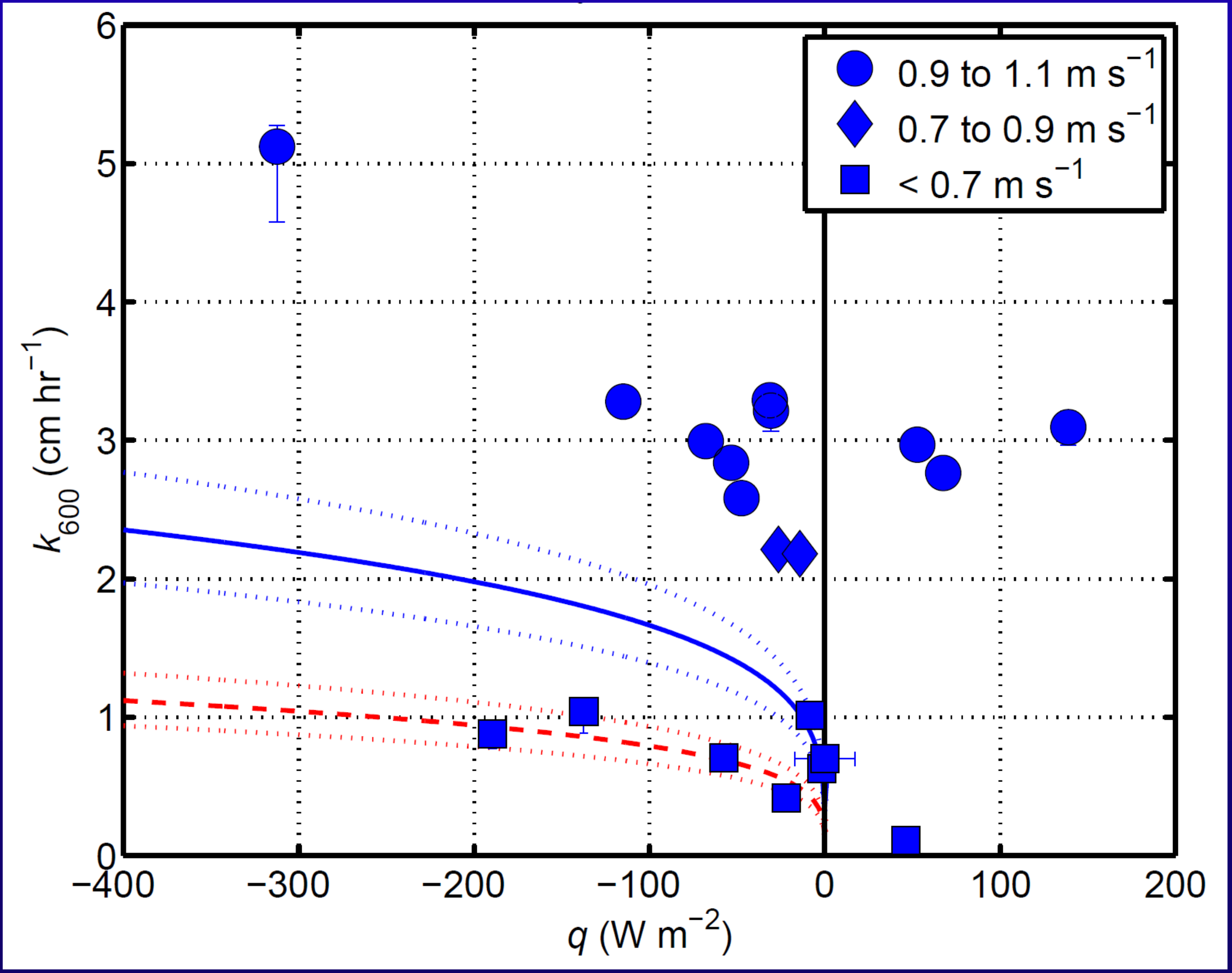

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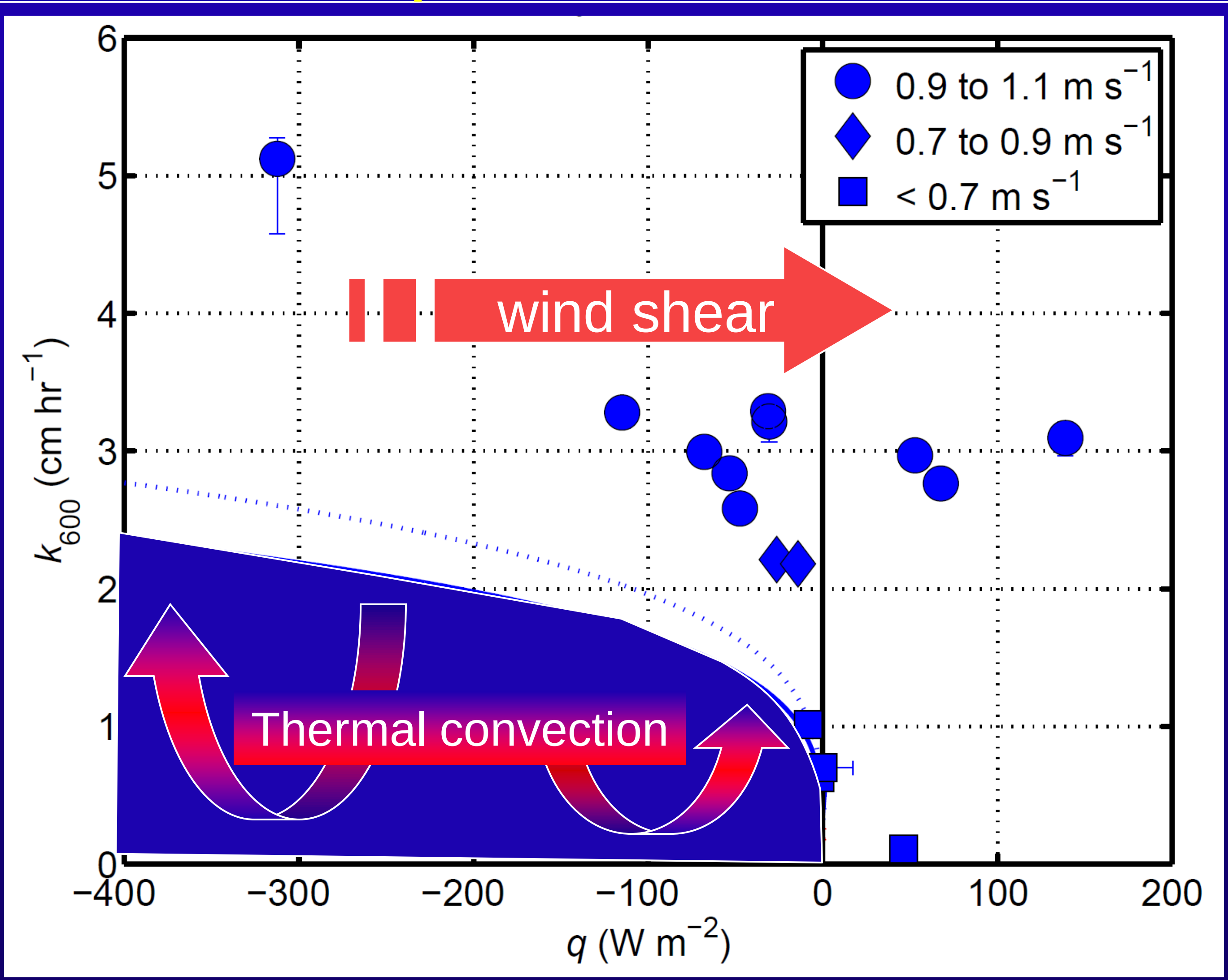
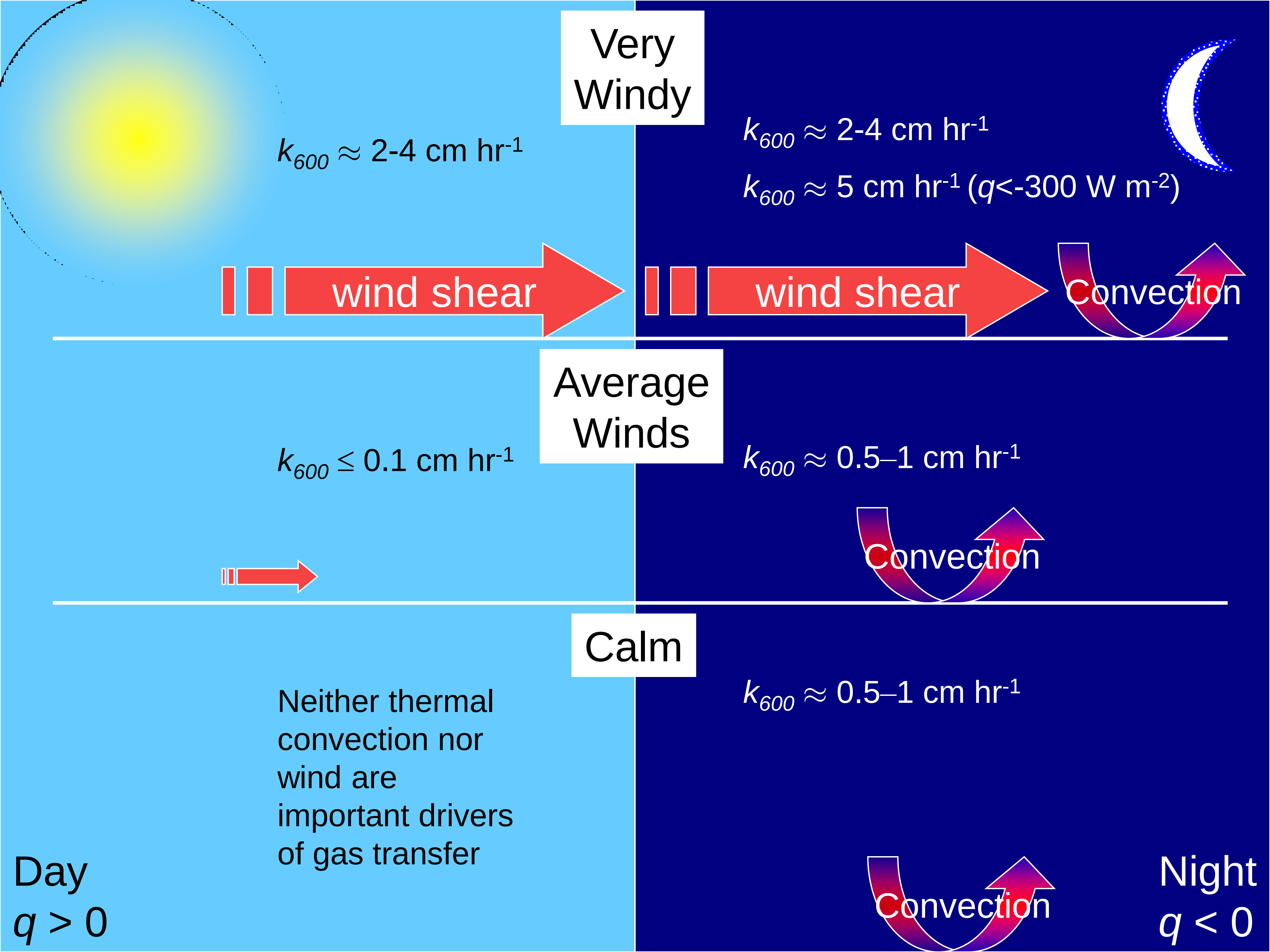
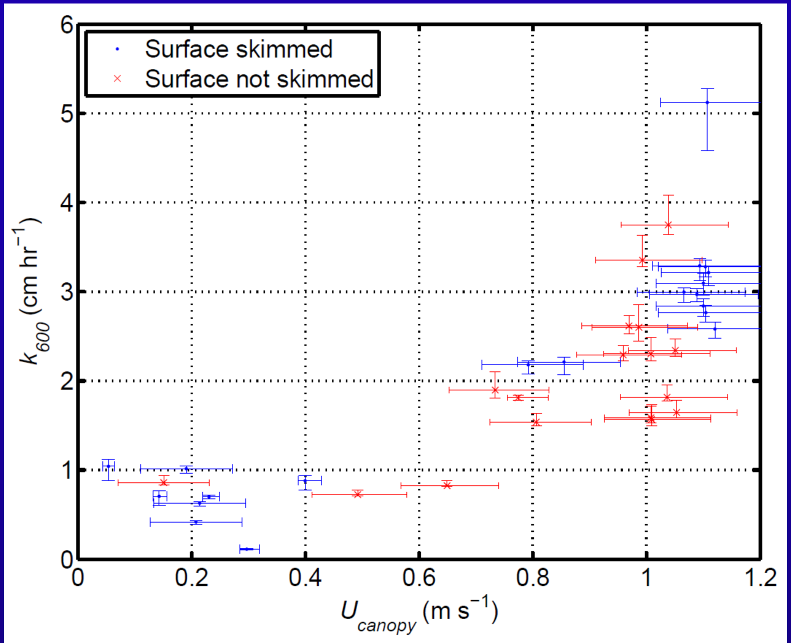
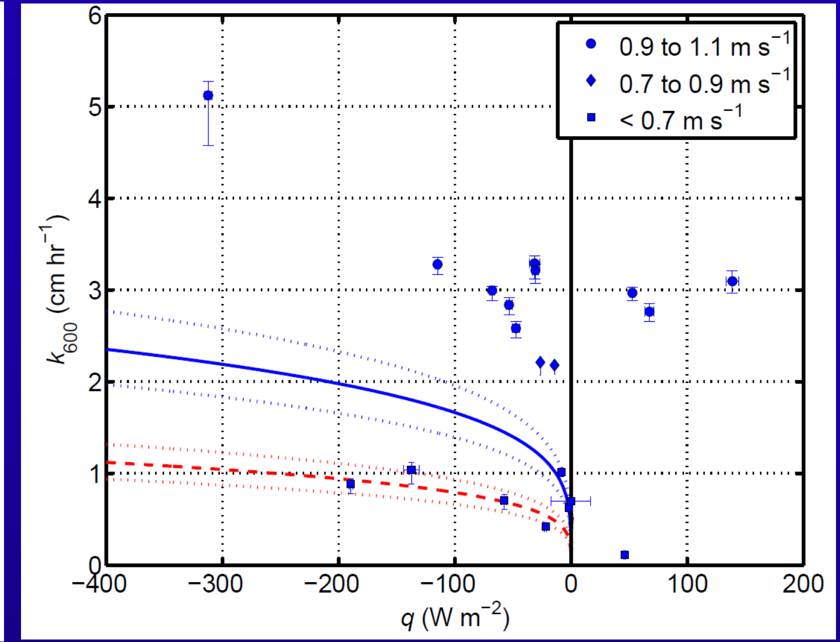



Very Windy
$k_{600} \approx$ 2-4 cm hr^{-1}
$k_{600} \approx$ 2-4 cm hr^{-1}
$k_{600} \approx$ 5 cm hr^{-1} (q<-300 W m^{-2})
wind shear
wind shear
Convection
Average Winds
$k_{600} \leq$ 0.1 cm hr^{-1}
$k_{600} \approx$ 0.5–1 cm hr^{-1}
Convection
Calm
Neither thermal convection nor wind are important drivers of gas transfer
$k_{600} \approx$ 0.5–1 cm hr^{-1}
Convection
Day
$q > 0$
Night
$q < 0$

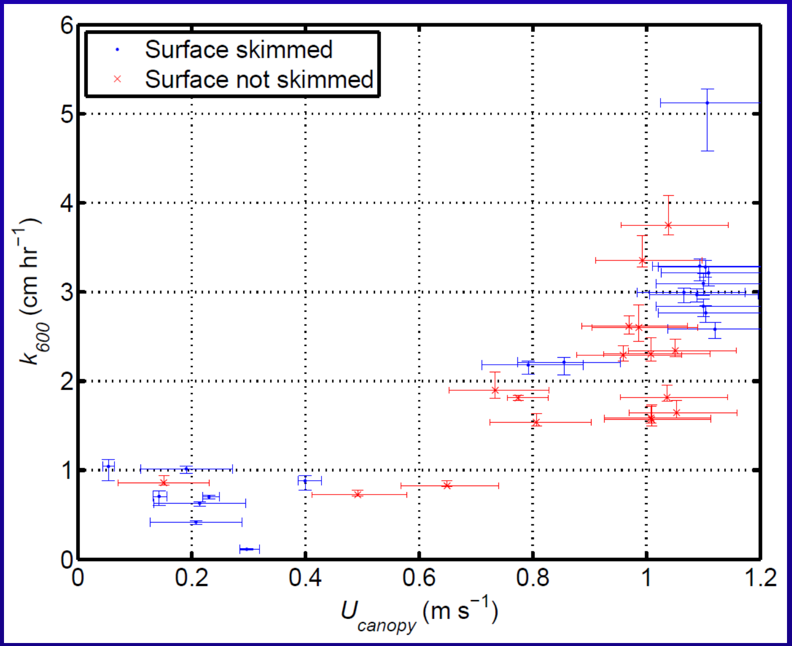
k as an empirical model of forcings

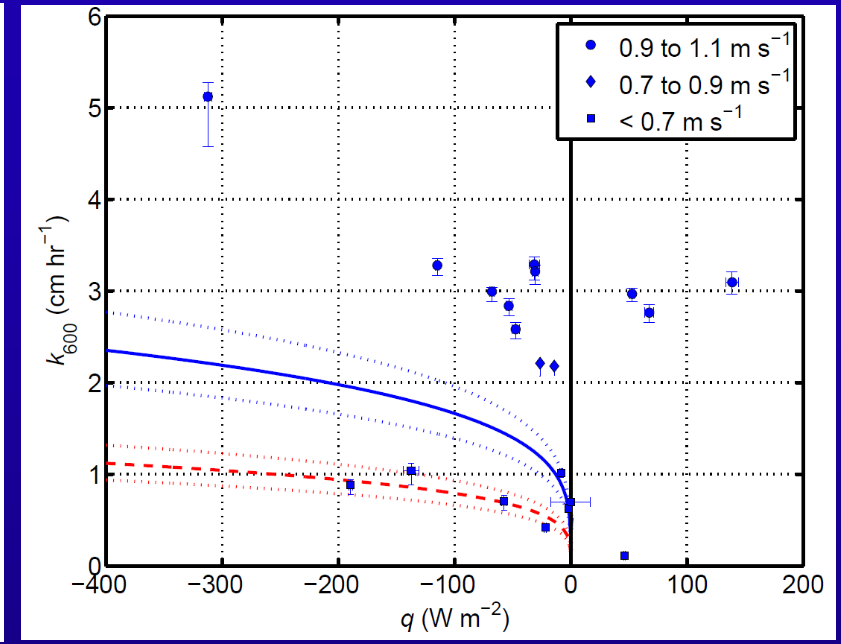




How does this vary with plant geometry and canopy structure?

k as an empirical model of forcings





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**** universal mechanistic model for k ****

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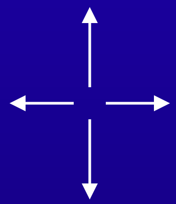
Universal mechanistic model for *k*

$$k = \square \sqrt{\nu \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)_0} \, Sc^{-n}$$

(Turney et al., 2005)

surface
velocity
divergence



$$\square \approx 0.5$$

(McKenna and McGillis, 2004)

Universal mechanistic model for *k*

plant geometry & canopy structure

↓

surface velocity field

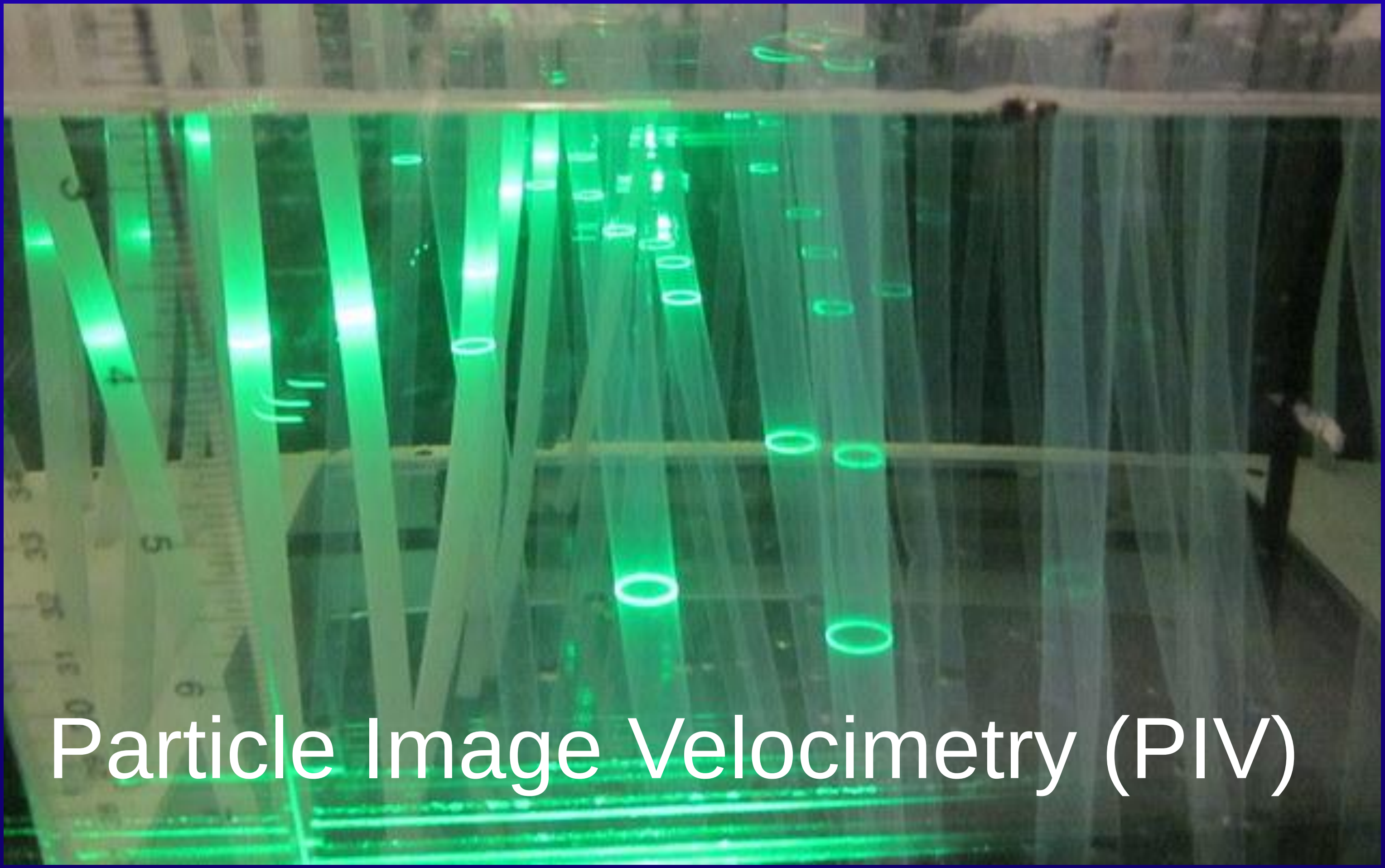
↓

surface velocity divergence

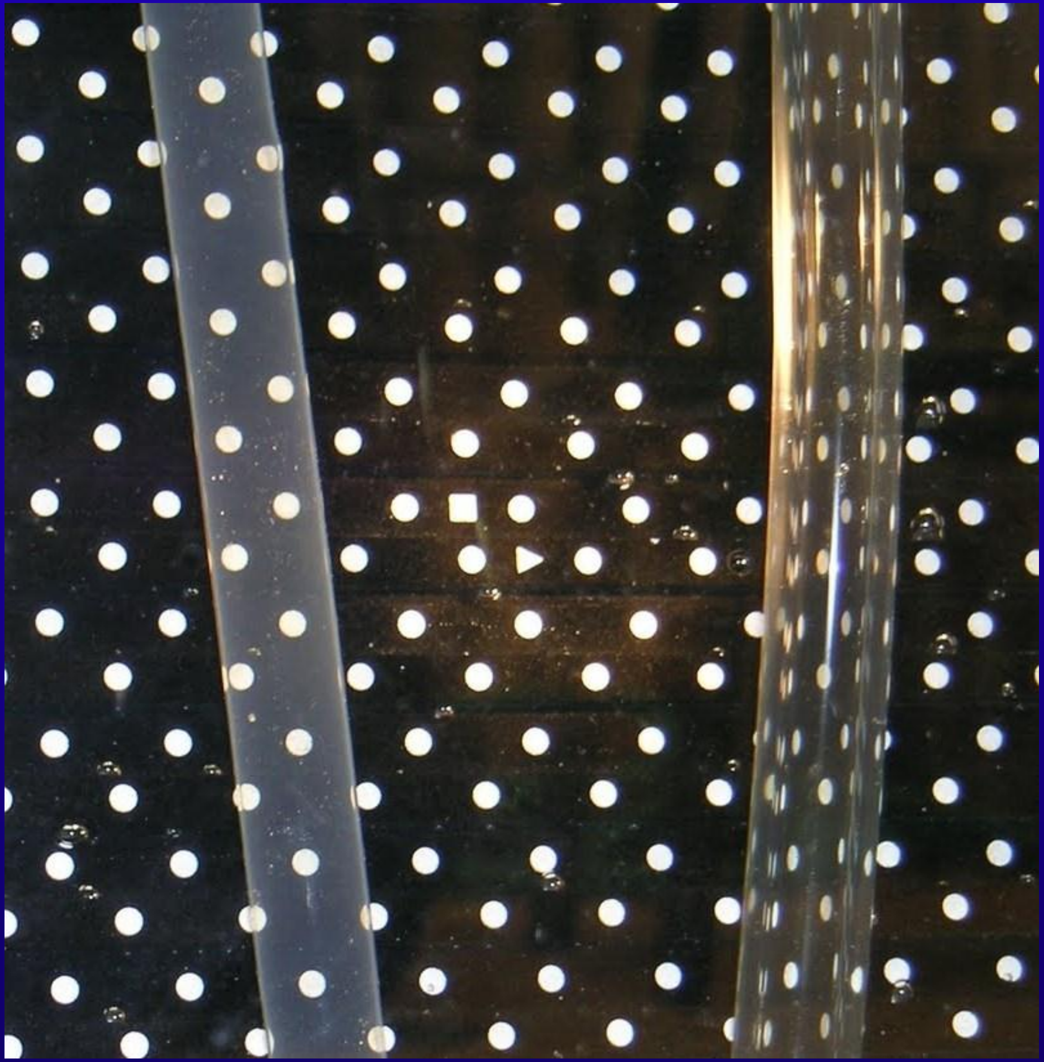
↓

k ← - - - - empirical method (from plant geometry & canopy structure)

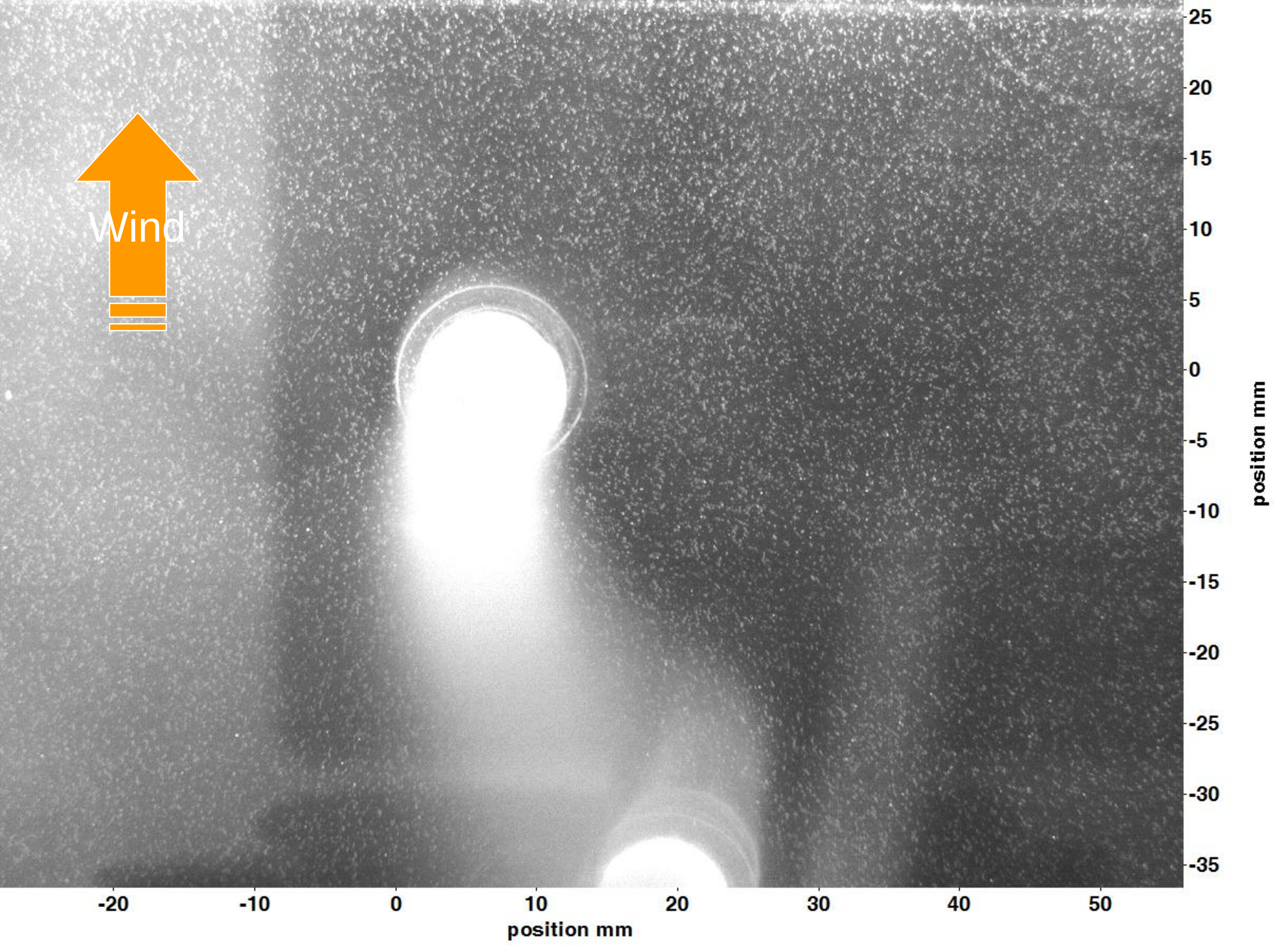
Flow in laboratory wetland model



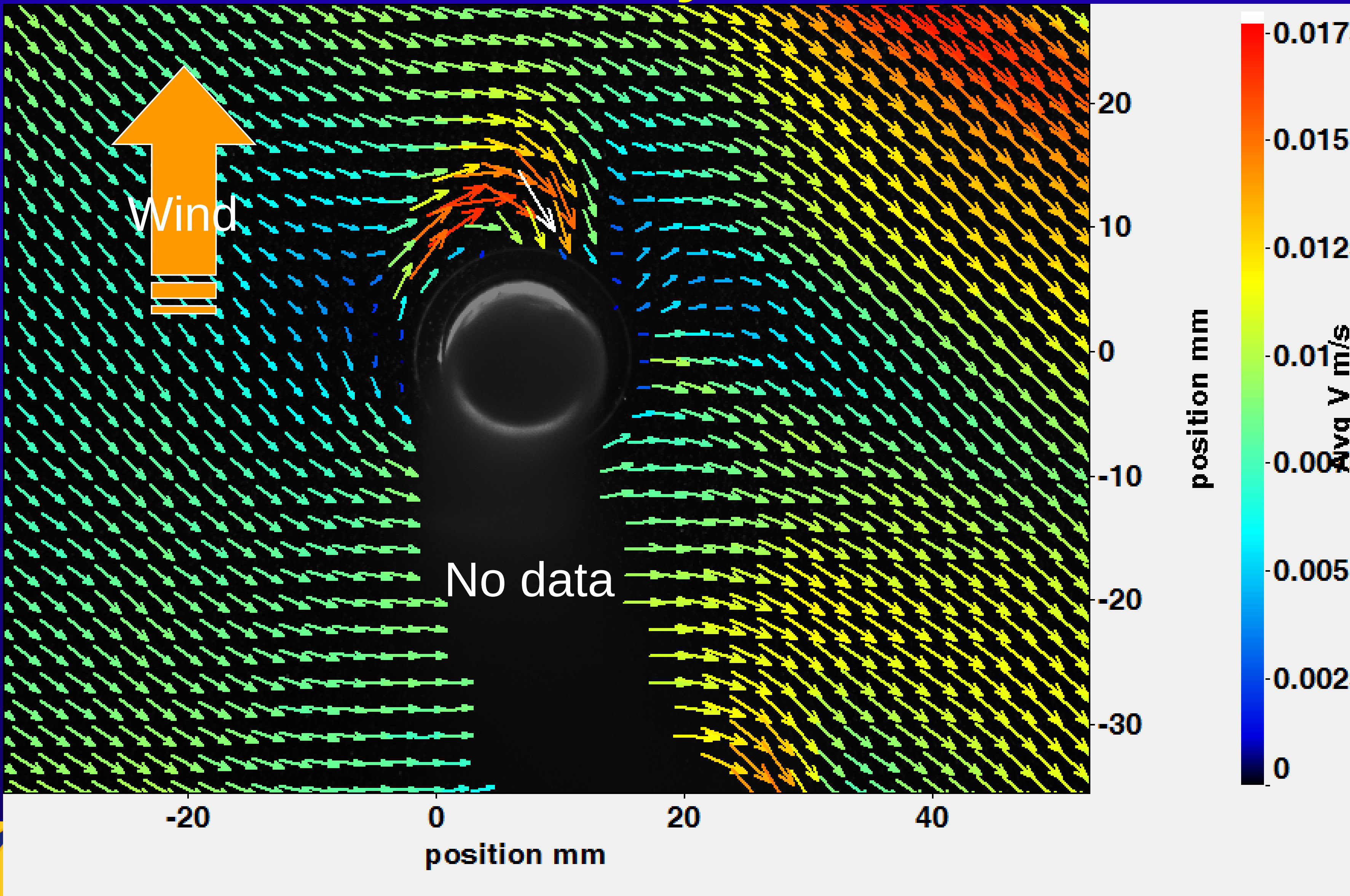
Refractive Index Matching



Wind
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
position mm
-20
-10
0
10
20
30
40
50
position mm


Wind
position mm
-20
-10
0
10
20
30
40
50
position mm
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35

Velocity Field



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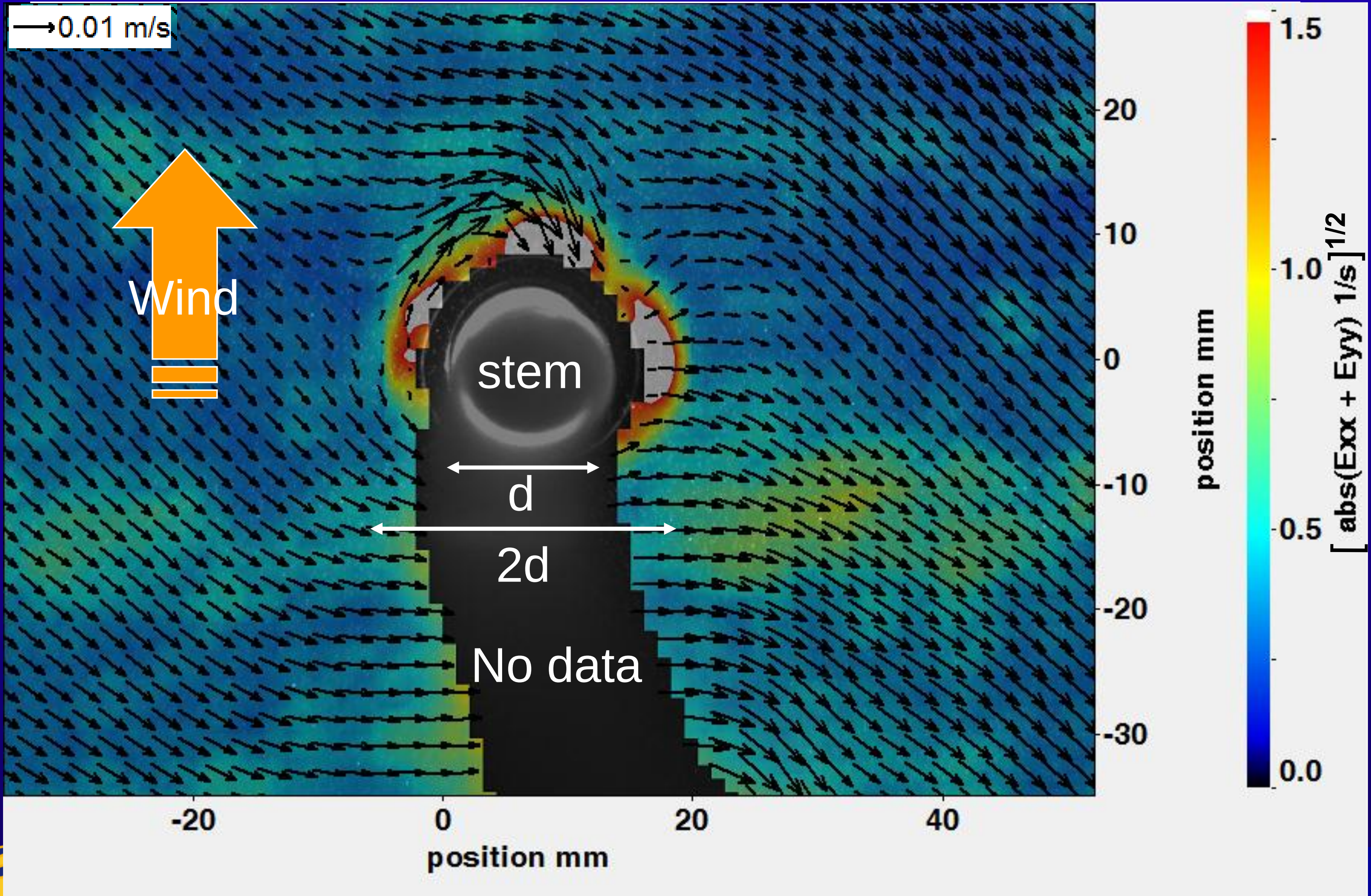

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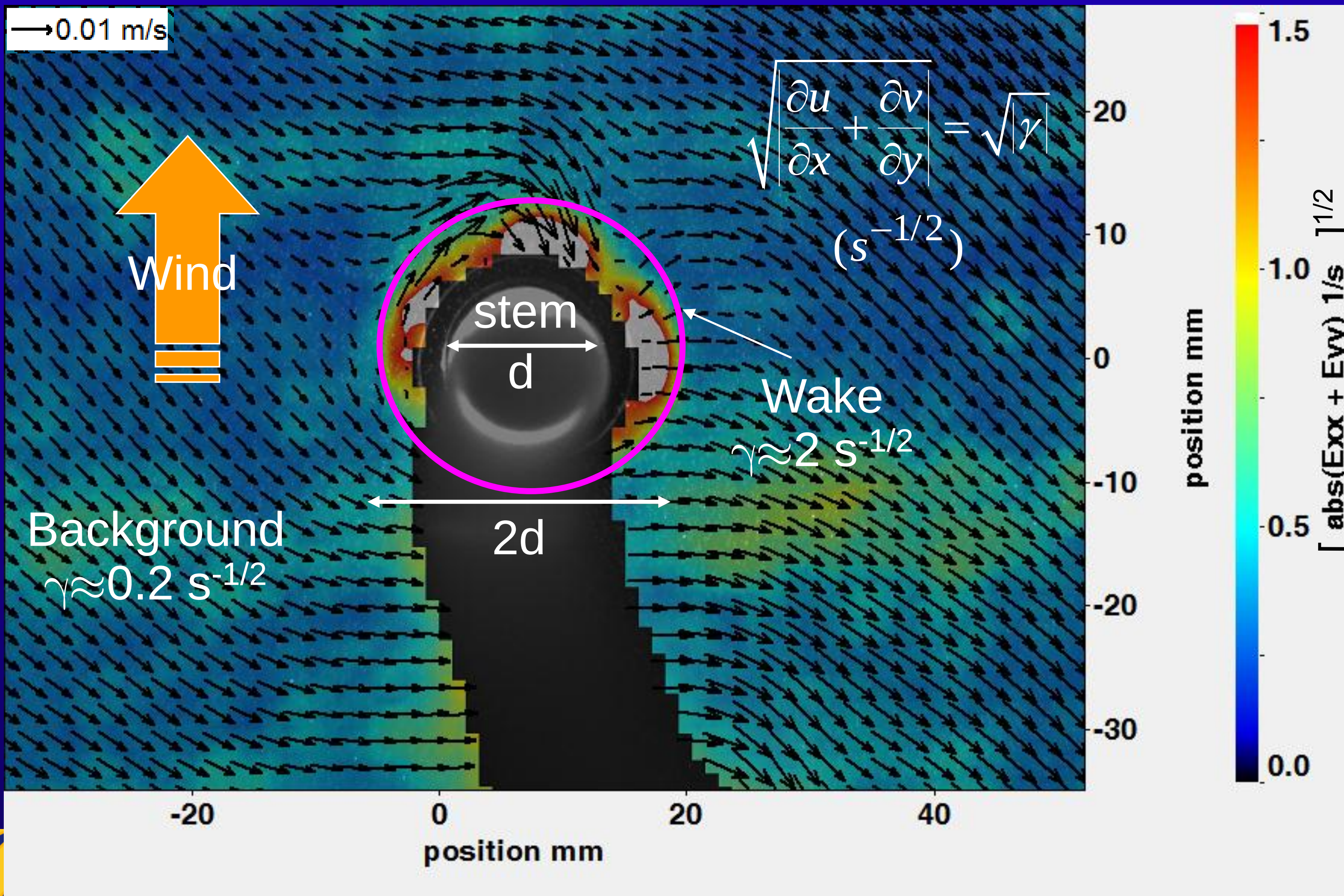

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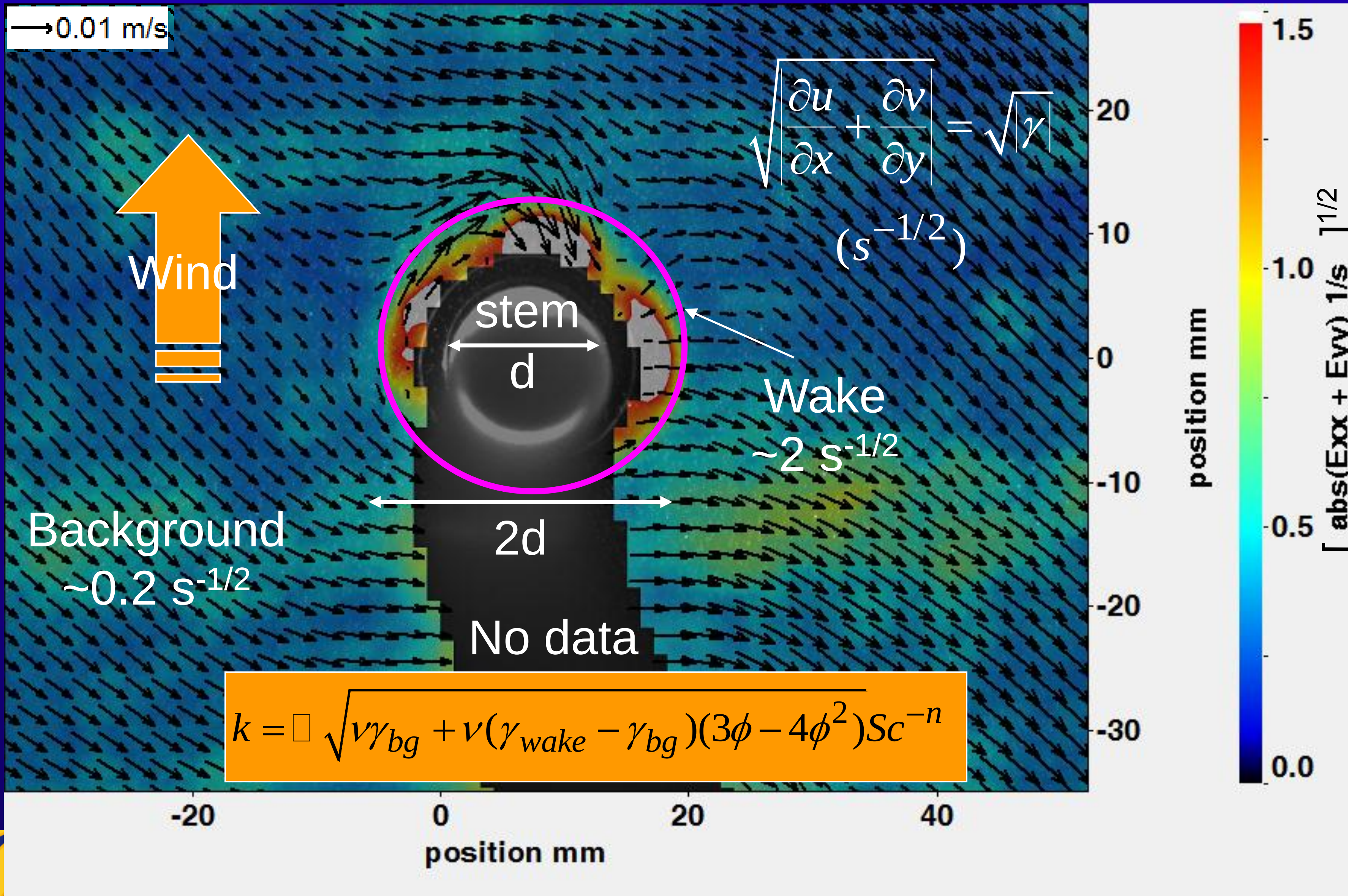
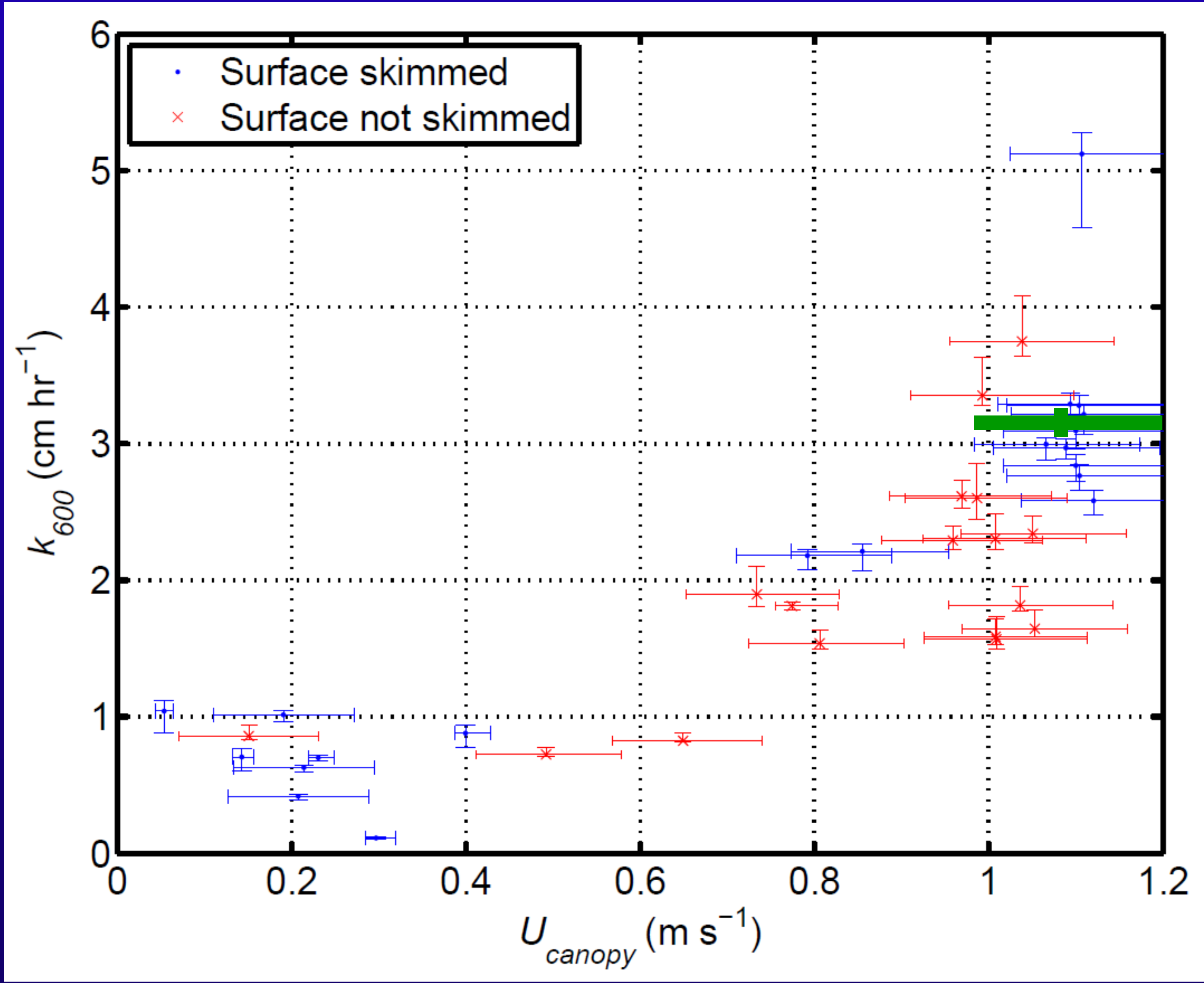


$$\sqrt{\left|\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right|}=\sqrt{|\gamma|}$$

$$k = \square \sqrt{\nu\gamma_{bg} + \nu(\gamma_{wake} - \gamma_{bg})(3\phi - 4\phi^2)}\, Sc^{-n}$$

k as an empirical model of forcings



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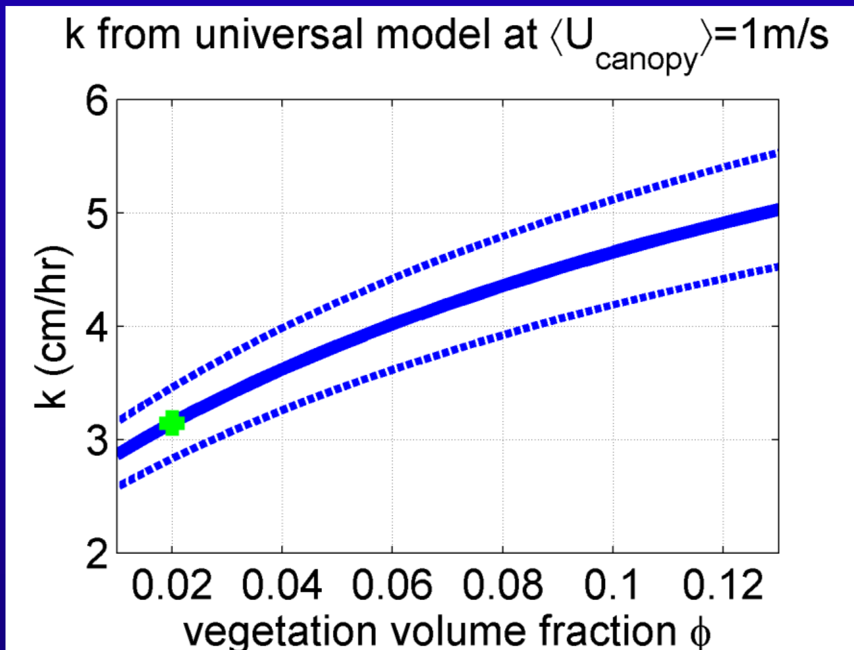

$$k = \Box \sqrt{\nu\gamma_{bg} + \nu(\gamma_{wake} - \gamma_{bg})(3\phi - 4\phi^2)}Sc^{-n}$$

k fits into wetland models

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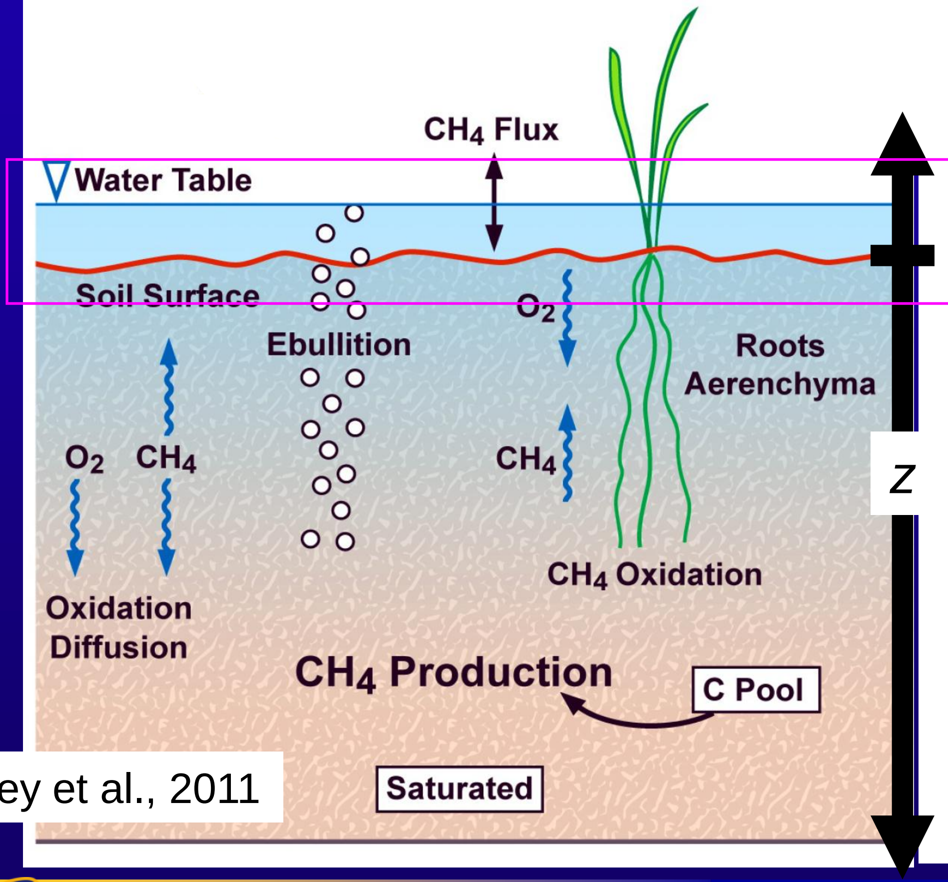
$$F_{CH_4} = k(CH_4 - CH_{4,surf})$$

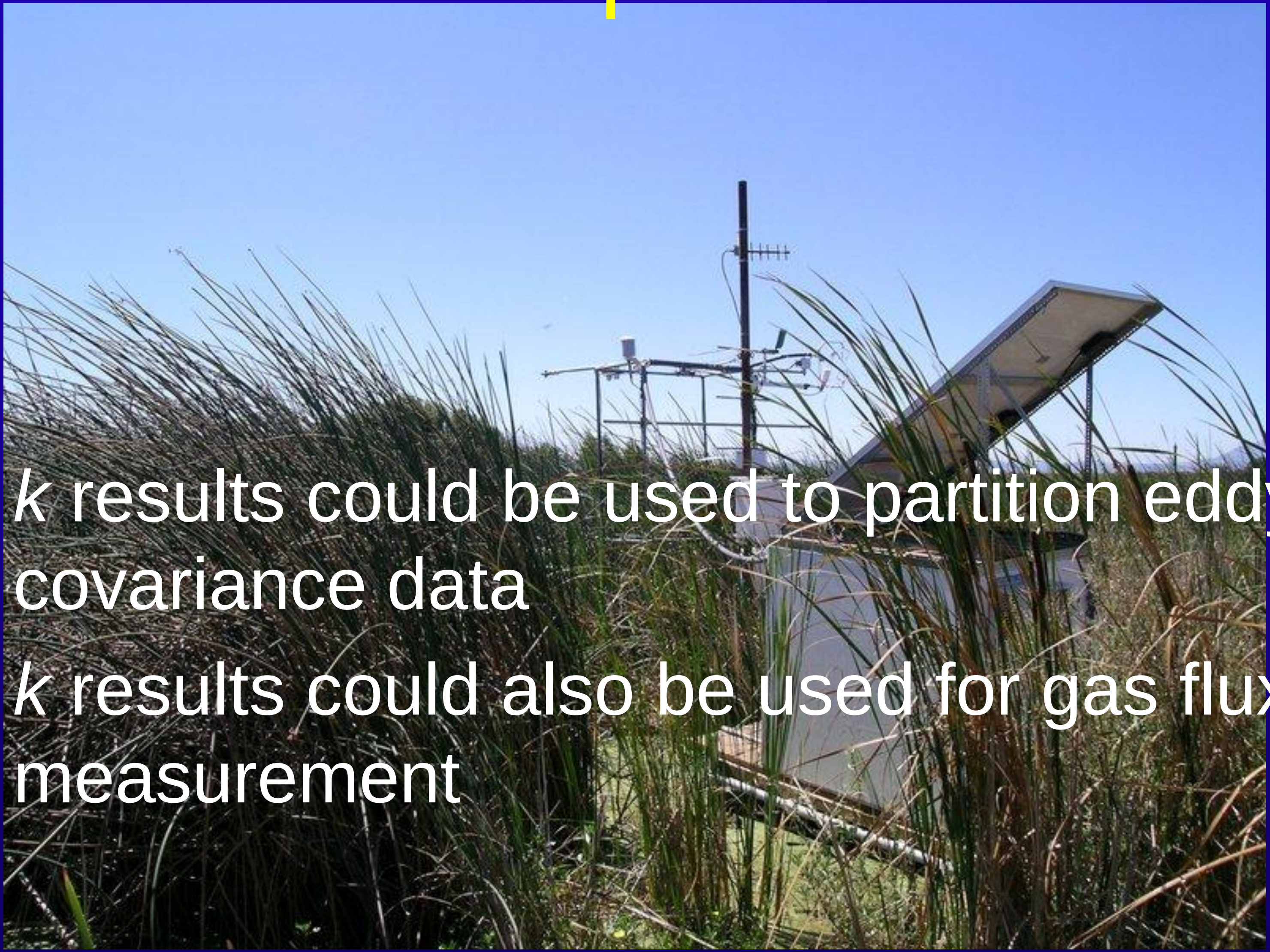


Riley et al., 2011

$$2.\ \frac{\partial O_2}{\partial t} = -C_{O_2}(z,t) - A(z,t) + \frac{\partial F_{O_2}}{\partial z}$$

$$F_{O_2} = k(O_2 - O_{2,surf})$$

Other Implications:



- *k* results could be used to partition eddy covariance data
- *k* results could also be used for gas flux measurement

References

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