Katabatic flows, advection and CO2 transport over Complex Terrain

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Outline

Paradox findings of katabatic flow

Optimal control of katabatic flows

Recirculation and CO_2 transport

Katabatic flows

- What are the major controls of katabatic flows?

- How do they work together for maximum katabatic flows?

Two opposite findings of katabatic flows

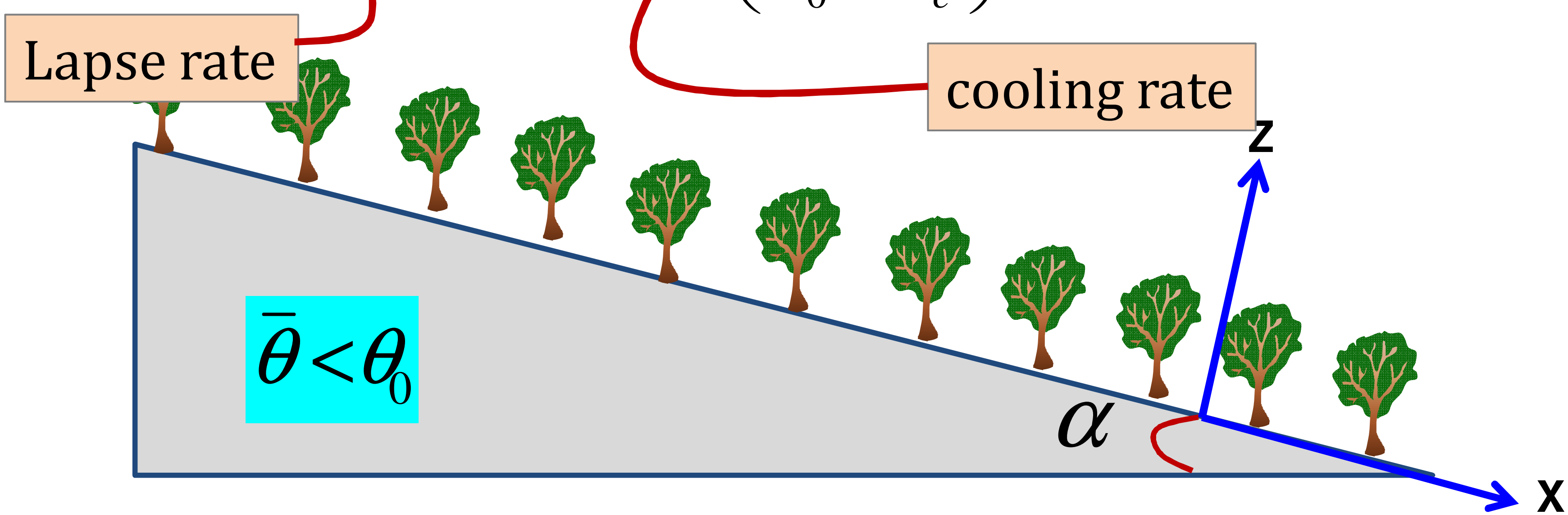
1. Katabatic flows are stronger on steep slopes.
(Horst and Doran, 1986; Nappo and Rao, 1987)

2. Katabatic flows are stronger on gentle slopes.
(McNider, 1982; England and McNider, 1993; Zhong and Whiteman, 2008; Axelsen and van Dop, 2009)

An oversimplified model

$$\frac{\partial \overline{u}}{\partial t} = g \sin\alpha \frac{\theta_0 - \overline{\theta}}{\theta_0} - c_D a |\overline{u}| \overline{u} \qquad (1)$$

$$\frac{\partial \overline{\theta}}{\partial t} = \gamma \overline{u} \sin\alpha - R_c \left(\frac{\overline{\theta} - \overline{\theta}_c}{\overline{\theta}_0 - \theta_c} \right) \qquad (2)$$



(Yi, 2009)

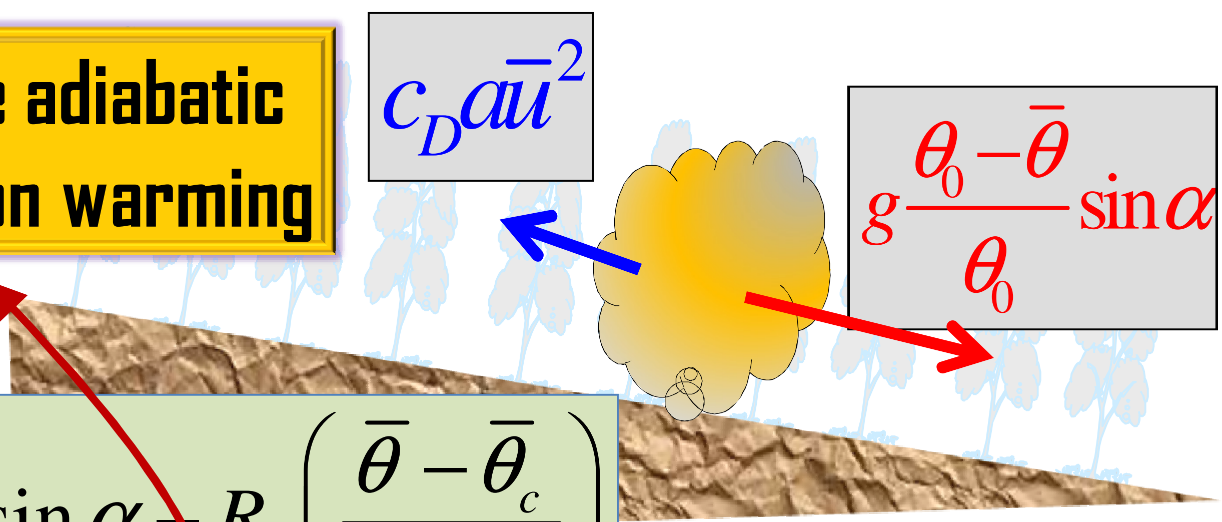
(Chen & Yi, 2012, QJRMS)

$$\frac{\partial \bar{u}}{\partial t} = g \sin\alpha \frac{\theta_0 - \bar{\theta}}{\theta_0} - c_D a |\bar{u}| \bar{u}$$

Gravity and Drag

Dominated initially by gravity and finally approach steady state

Downslope adiabatic compression warming



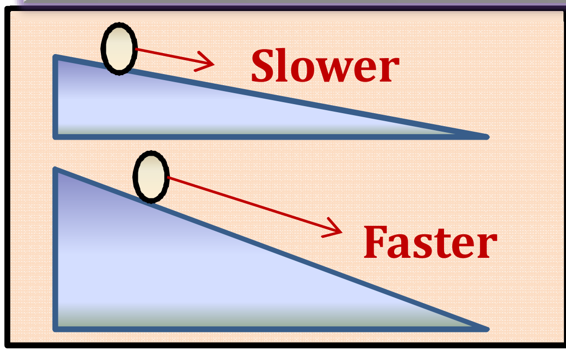
$$\frac{\partial \bar{\theta}}{\partial t} = \gamma \bar{u} \sin\alpha - R_c \left(\frac{\bar{\theta} - \bar{\theta}_c}{\bar{\theta}_0 - \theta_c} \right)$$

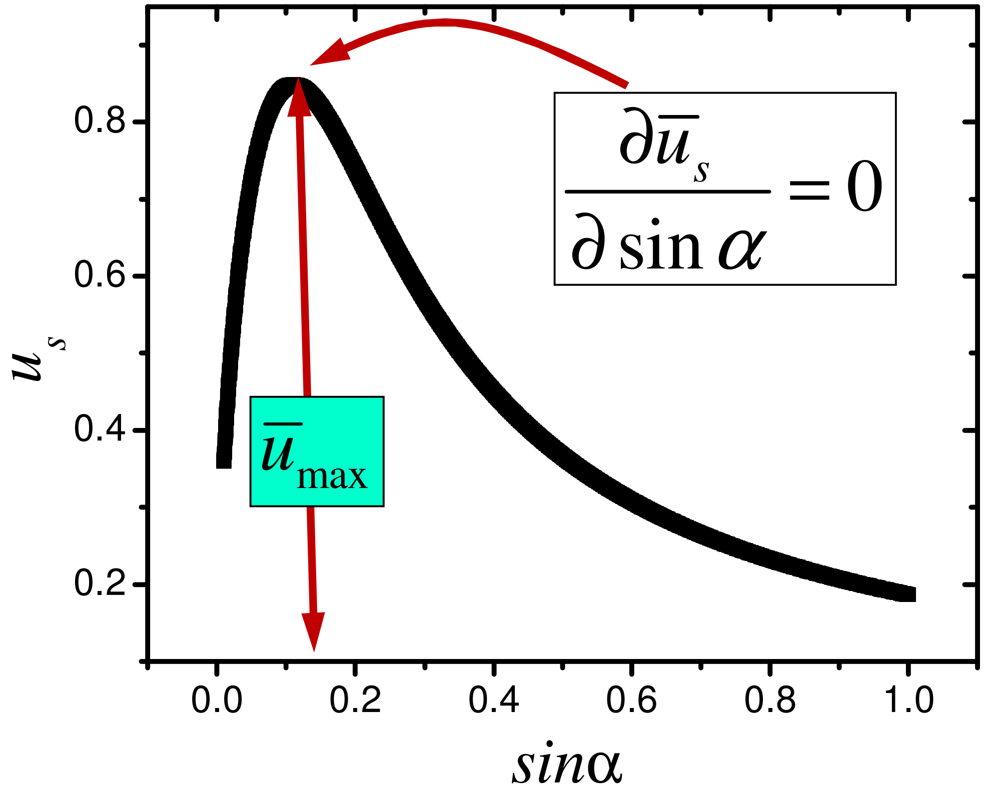
Steady State

$$\bar{u}_s = \left(-1 + \sqrt{1 + \eta \sin^{-3}\alpha}\right) \upsilon \sin^2 \alpha$$

$$\eta = \frac{4 c_D a R_c^2 \theta_0}{\gamma^2 g(\theta_0 - \theta_c)}$$

$$\upsilon = \frac{\gamma g(\theta_0 - \theta_c)}{2 c_D a R_c \theta_0}$$





Competition between gravity and buoyancy

$$\frac{\partial \bar{u}}{\partial t} = g \sin\alpha \frac{\theta_0 - \bar{\theta}}{\theta_0} - c_D a |\bar{u}| \bar{u}$$

$$\frac{\partial \bar{\theta}}{\partial t} = \gamma \bar{u} \sin\alpha - R_c \left(\frac{\bar{\theta} - \bar{\theta}_c}{\bar{\theta}_0 - \theta_c}\right)$$

(Chen & Yi, 2012)

Optimal control of katabatic flows

Katabatic flows are not determined by slope angle alone, but controlled synergistically with slope cooling, ambient stratification, and vegetation structure. The condition for maximum katabatic flows is governed by:

$$L_c(V_T)^{-2}\sin^3\alpha = b$$

α is a terrain slope; $L_c = 1/(c_D a)$ is canopy length scale; $V_T = R_c/\gamma$ is thermal velocity; c_D is drag coefficient, a is leaf area density; R_c is cooling rate, γ is lapse rate.

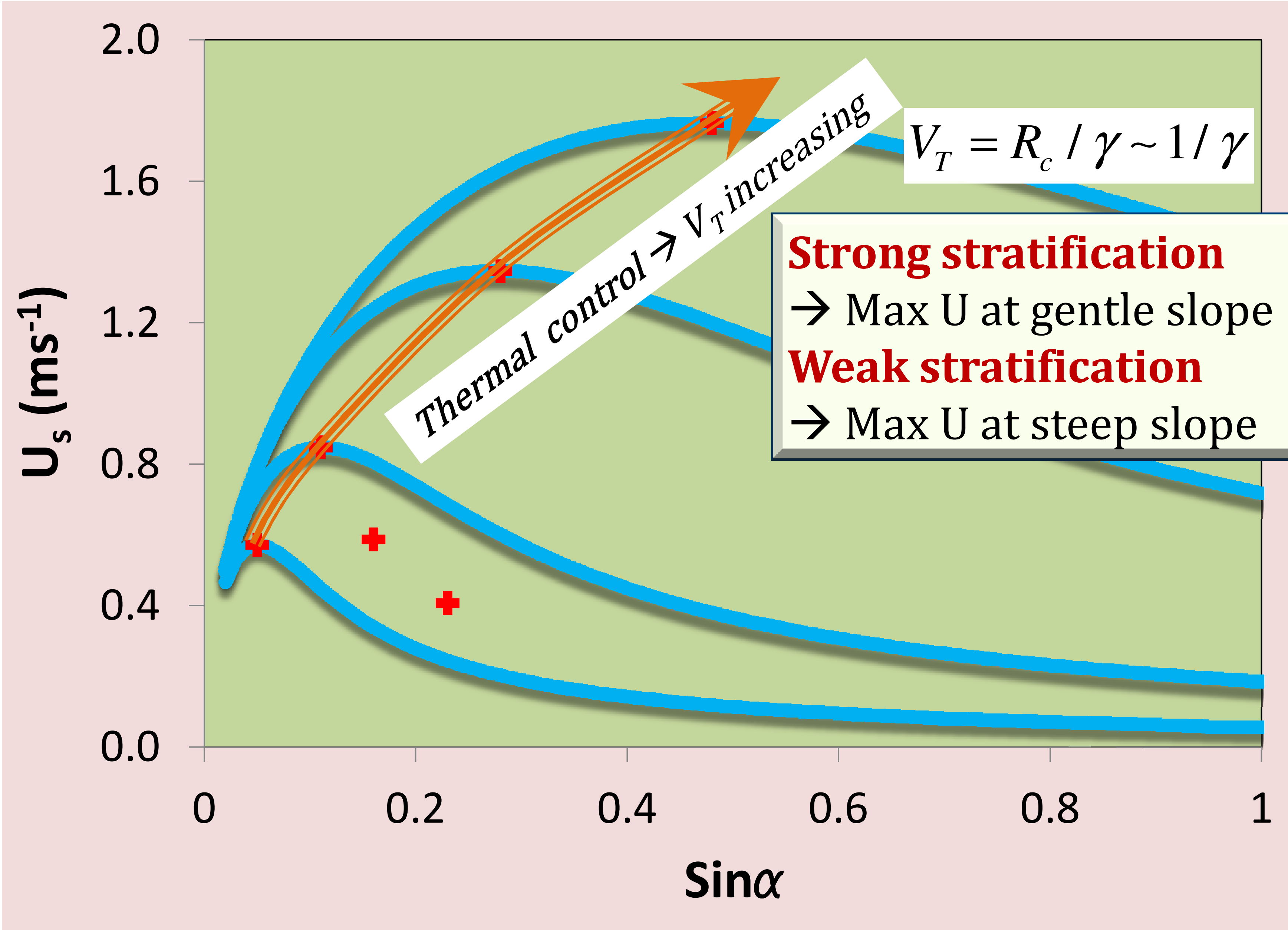
Power Law

$Sin^3\alpha$ → slope is the most important.

$(V_T)^{-2}$ → Thermal velocity is the second important.

L_c → Canopy is the third important.

(Chen & Yi, 2012, accepted by QJRMS)



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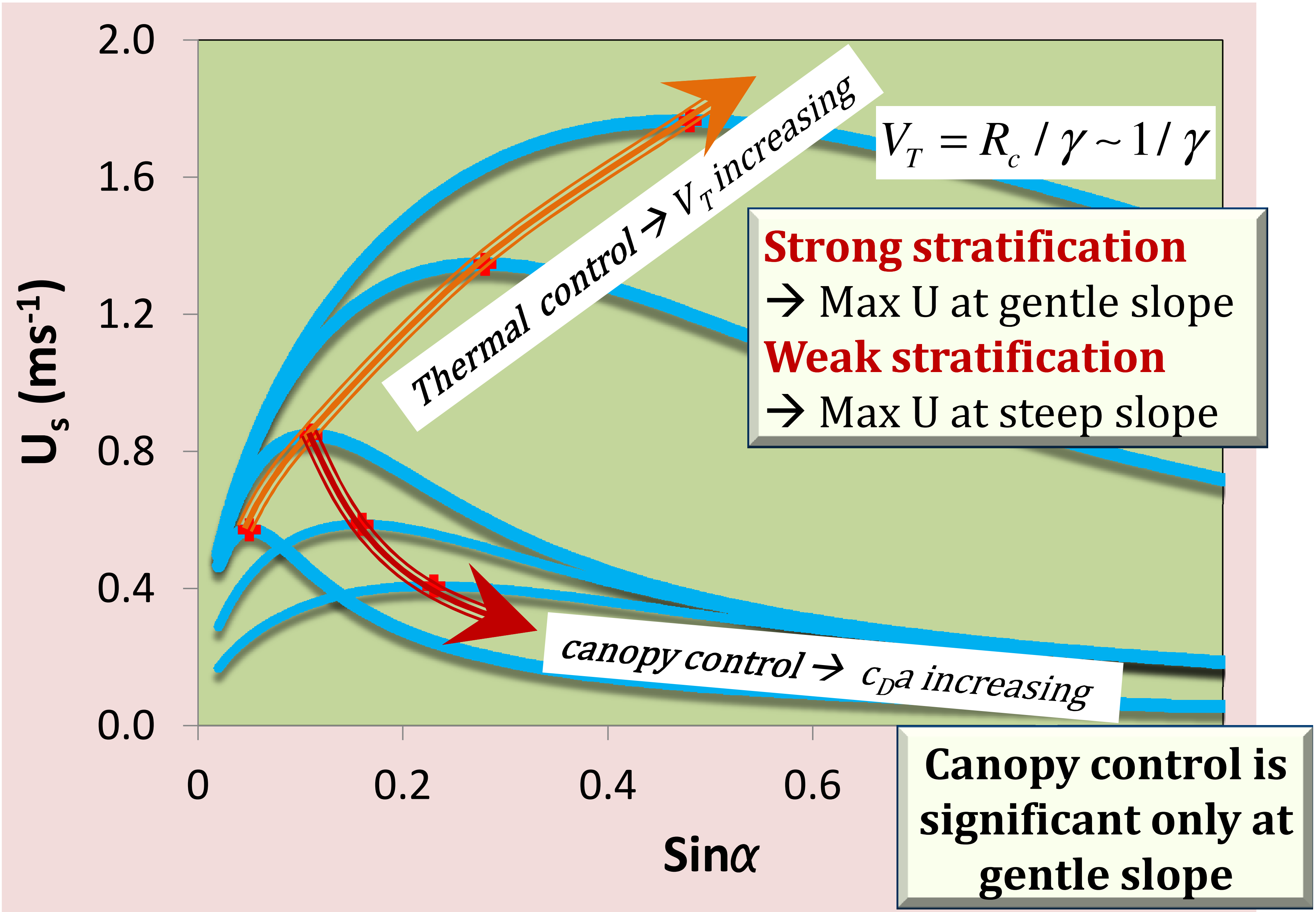
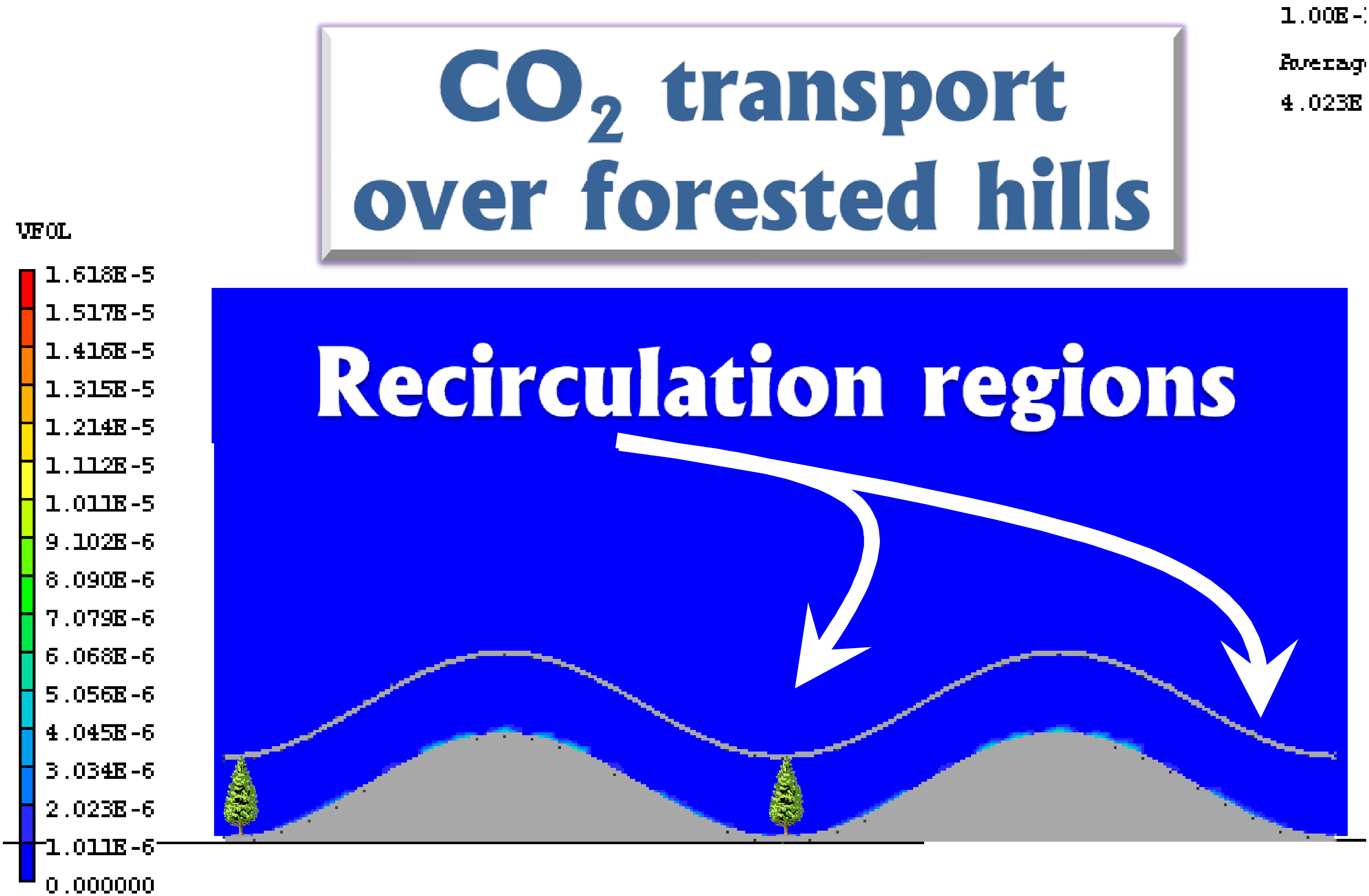


(Chen & Yi, 2012, accepted by QJRMS)

Numerical simulations of CO_2 transport over complex terrain

- **Computational Fluid Dynamics (CFD)**

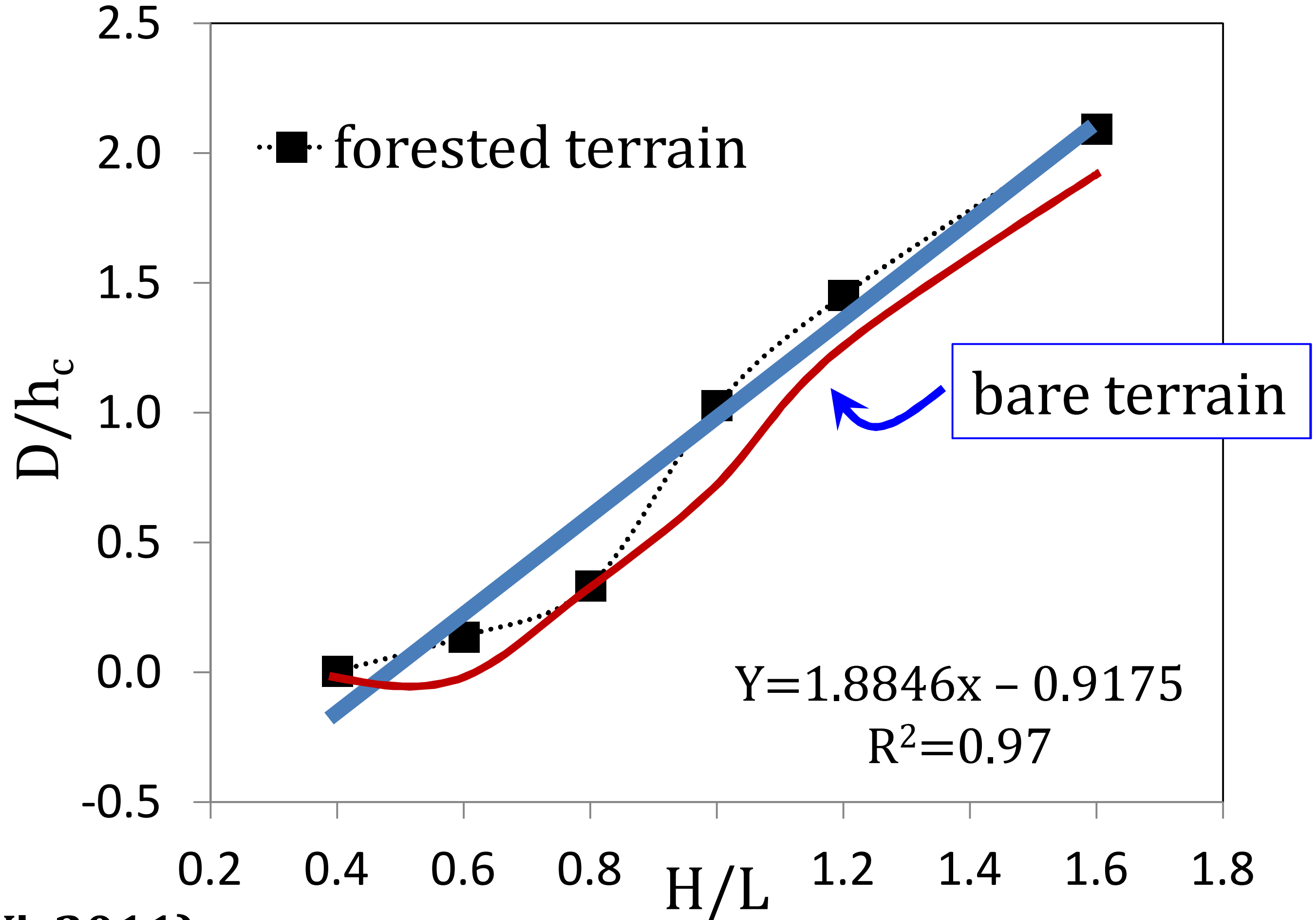
CO_2 transport over forested hills



Neutral condition with background wind from left to right.

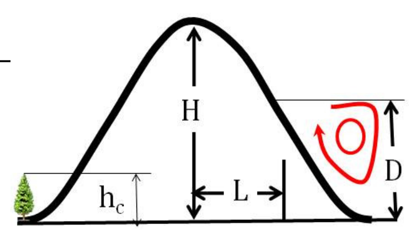
(Xu and Yi, 2012, i

Recirculation depth controlled by terrain shapes



(Xu and Yi, 2011)

D – Depth of recirculation
$\boldsymbol{h_c}$ – canopy height



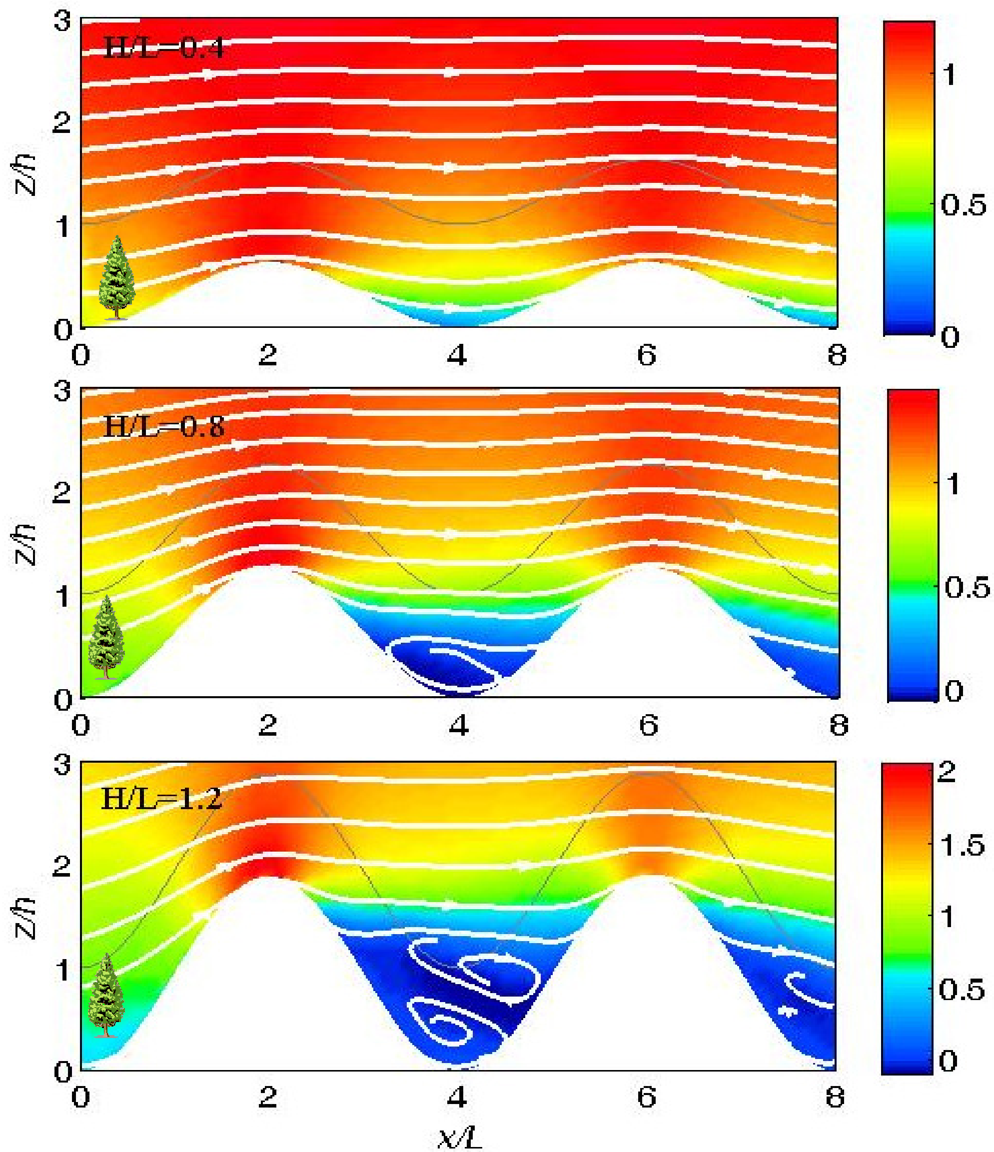
H – hill height
L – ¼ of hill width

Lee vortices controlled by terrain shapes

H/L<0.8

H/L=0.8

H/L>0.8



No vortex

Vortex formation

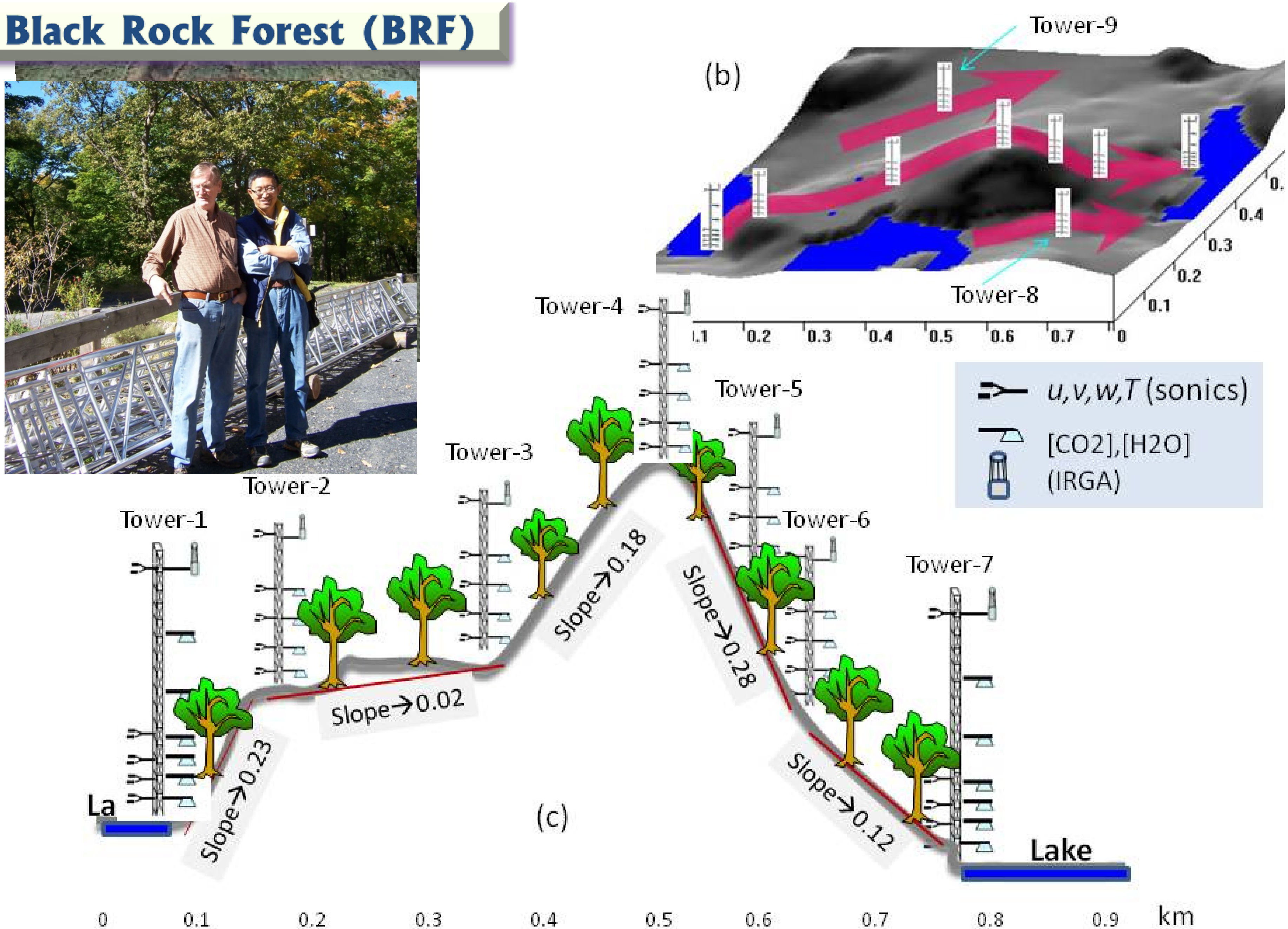
Multiple vortices

(Xu and Yi, 2012, in review)

Conclusions

- Advection issues are tough but cannot be avoided. Otherwise, your data errors cannot be explained.
- Gentle hills do not cause gentle advection errors in calm night (strong stratification).
- Forest flows and turbulent transport process are asymmetric from windward to leeward side over a forested hill. This feature has been predicted by analytical models (Finnigan and Belcher; 2004; Wang and Yi, 2012) and by tunnel experiments (Gaby Katul's group). Recirculation is an important mixing bubble of NEE.
- Our dream is a good dream and need your support!

Black Rock Forest (BRF)



Thank you!

Acknowledgements to

My funding support:

NSF AGS under Grant No. 0930015

National Science Foundation
WHERE DISCOVERIES BEGIN