Land/Atmosphere Interface: Importance to Global Change

Chuixiang Yi
School of Earth and Environmental Sciences
Queens College, City University of New York
Outline

- Land/atmosphere interface
- Fundamental problems
- Progresses
Why land-atmosphere interactions are important to global change?
An example
Atmospheric CO₂ rectifier effect

- **Deep mixing**
  - Low CO₂
  - Photosynthesis

- **Shallow layer**
  - High CO₂
  - Respiration

- **Mixed Layer**
  - CO₂

- **SBL**

**Boundary layer dynamics and terrestrial CO₂ fluxes**

- Sunset
- Sunrise
Why land-atmosphere interactions are important?

ABL = Atmospheric boundary layer

(ABL= Atmospheric boundary layer)

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(Denning et al., 1995)

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Measuring CO$_2$ by eddy flux tower

- WLEF tall tower (447m)
  - Complex at night
  - Simple in day

(Yi et al., JGR 2000)
Measuring boundary layer evolution by 915-MHz ABL profiling radar

\[ Z_i = a + b \Gamma \]

\[ \Gamma = \sqrt{\int_0^t (\theta_w)_s \, dt'} \]

\[ \text{(Yi et al., JGR 2004)} \]

\[ \text{(Yi et al., JAS 2001)} \]
Canopy layer is more complex and important!

Photosynthesis, respiration

\[ \text{CO}_2 \quad \text{H}_2\text{O} \quad \text{VOC} \quad \text{CH}_4 \]

Absorber and producer

Aerodynamics

Classic theories do not work

No transport theory within canopy

Turbulence nature affects reaction rate

Canopy layer is more complex and important!
Why classic turbulent theories do not work within canopies?
\[ \tau \rho^{-1} = -uw' = u_*^2 \]

- Fundamental Characteristics

\[ \frac{\partial \tau}{\partial z} = \frac{\partial p}{\partial x} \approx 0 \]

- K-theory, proposed by Boussinesq in 1877,

\[ K_m \frac{\partial u}{\partial z} \]

- Mixing length theory, developed by Prandtl in 1925,

\[ \ell^2 \left| \frac{\partial u}{\partial z} \right| \frac{\partial u}{\partial z} \]

\[ c_D u^2, \text{ proposed by Prandtl in 1932 based on the velocity-squared law.} \]

Yi, 2007
Von Karman’s similarity hypothesis

\[ \ell = K \left| \frac{\overline{d\bar{u}} / dz}{d^2\overline{u} / dz^2} \right| \]
\[ \ell = \kappa \left| \frac{d\bar{u}}{dz} \right| \frac{d^2\bar{u}}{dz^2} \]

\[ \ell = KZ \]

\[ \bar{u}(z) = \frac{u_*}{\kappa} \ln \left( \frac{z}{Z_0} \right) \]

\[ \kappa \approx 0.4 \]

\( Z_0 \) is roughness
Velocity-Squared Law

\[ \text{Drag} = C_D \rho S V^2 \]

Edme Mariotte 1673
Christiaan Huygens 1699
Sir Issac Newton 1687
Navier in 1822
Stokes in 1845
Prandtl in 1905
The friction velocity is the artificial but related velocity for which the square law holds exactly”-Sutton (1953, pp.76)

Taylor (1916) was first to test the validity of the velocity-squared law on the earth’s surface and estimated its drag coefficient values.

The mixing length theory has achieved remarkable success. Thom (1971) rationalized the physical connection between length scale and velocity scale.
Exponential flux layer

Constant flux layer

\[ \bar{u}(z) \]

\[ -u'w'(z) \]

\[ \frac{\partial \tau}{\partial z} = \frac{\partial p}{\partial x} \approx 0 \]

\[ \frac{\partial \tau}{\partial z} \approx F_D, \]

\[ F_D = \rho c_D a \bar{u}^2 \]

Yi, 2007
Why classic theories do not work within canopy.

\[ \ell = 0 \]

Negative viscosity

\[ -u'w' = K_m \frac{\partial \bar{u}}{\partial z} \]

Yi, 2007
New developments in canopy flow theory
\[ \tau = -\rho u' w' \]

\[ \left[ \tau \right] \equiv \frac{\text{MLT}^{-1}}{L^2 T} \quad \frac{\text{mass} \cdot \text{velocity}}{\text{area} \cdot \text{time}} \quad \frac{\text{momentum}}{\text{area} \cdot \text{time}} \]

\textbf{Momentum Transfer Rate}

Yi, 2007
\( \tau = -\rho \overline{u}' \overline{w}' \propto \rho \overline{u}^2 \)

**momentum loss rate**

**momentum** = \( \rho \overline{u} \)

**average velocity** = \( \overline{u} / 2 \)

**flow deceleration**

\( \rho \overline{u} \times \overline{u} / 2 = \rho \overline{u}^2 / 2 \)

\( \tau = c_D \rho \overline{u}^2 \)

Yi, 2007
Local Equilibrium Hypotheses

momentum transfer rate = momentum loss rate

\[-\rho u'w'(z) = \rho c_D(z)\bar{u}^2(z)\]

\[-\frac{\partial u'w'\,}{\partial z} = c_D(z)\alpha(z)u^2(z)\]

\(\tau = -\rho u'w'(z)\)

(Yi, 2007)
Momentum Equations are closed

\[ \frac{\partial u'w'}{\partial z} = c_D(z)a(z)u^2(z) \]

\[ -u'w'(z) = c_D(z)\bar{u}^2(z) \]

\[ \frac{d}{dz} \left( c_D(z)\bar{u}^2(z) \right) = a(z)c_D(z)\bar{u}^2(z) \]

\[ -\frac{du'w'(z)}{dz} + a(z)\bar{u}'w'(z) = 0 \]

(Yi, 2007)
Uniform Vegetation

\[ c_D(z) = c_D \]
\[ a(z) = a \]
\[ -\frac{\partial u'w'}{\partial z} = ac_Du^2(z) \]

\[ q(z) = c_D\overline{u^2}(z) = \overline{-u'w'}(z) \quad \Rightarrow \quad \frac{dq(z)}{dz} = aq(z) \]

\[ \overline{u}(z) = \overline{u}_h e^{\alpha \left( \frac{z}{h} - 1 \right)} \quad \Leftrightarrow \quad \text{Inoue's model} \]

(Yi, 2007)
\[ \tilde{\tau} = e^{\text{LAI}(\zeta - 1)} \]

\[ \zeta = z / h, \quad \tilde{\tau} = \tau(z) / \tau_h \]

(Yi, 2007)
\[-u'w'(z) = -u'w'(0)e^{L(z)} = u_*^2(h)e^{-(LAI - L(z))}\]

\[L(z) = \int_0^z a(z')dz'\]

\[LAI = \text{leaf area index} = \text{entire leaf area per m}^2 \text{ ground}\]

\[a(z) = \text{leaf area density (m}^2/\text{m}^3)\]

\[\text{Yi, 2007}\]
\[ \tau_h = -u'w'(h) \]

\[ \tau_0 \big/ \tau_h = e^{-LAI} \]

\[ \tau_0 = -u'w'(0) \]

LAI = leaf area index = entire leaf area per m² ground
For example, 90% of $T_h$ is absorbed by the whole canopy at LAI = 2.3.
Dimensional Analysis
(Buckingham Pi theorem)

\[ \tau = f_1(\text{Re}, \text{LAI}) \rho \bar{u}^2 \]

(Yi, 2007)
Comparison with the High-Order Closure

The high-order closure simulations

Observed leaf area density

Observations

CMT model

\[ \frac{\langle u'w'(z) \rangle}{u^2_*(h)} = e^{-(LAI-L(z))} \]

Requirement

<table>
<thead>
<tr>
<th></th>
<th>High-order model</th>
<th>CMT model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computing cost</td>
<td>A super-computer</td>
<td>A calculator</td>
</tr>
<tr>
<td>Adjustable constants</td>
<td>Produced from one dataset cannot be used for another</td>
<td>No constants universal</td>
</tr>
</tbody>
</table>
CMT predictions versus observations

- Shaw 1977
- Wilson 1988
- Amiro 1990
- Baldocchi & Meyers 1988

- Katul & Albertson 1998
- Amiro 1990
- Kelliher et al. 1998

(Yi, 2007)
The robust agreements between the theoretical predictions and observations indicate that the nature of momentum transfer within canopies can be well understood by the CMT theory.

What are canopy MASS and ENERGY transfer theories?
Super-Stable Layer Theory
Advection issues on eddy flux measurements

Super-stable layer, flow separation (Yi et al., 2005)

Courtesy to Jielun Sun
A super stable layer

(1) Slow mean airflow; (2) Maximum drag elements; (3) Minimum vertical exchange;
(4) Maximum horizontal CO2 (or other scalar) gradient; (5) Maximum ratio of wake and shear production rate.

\[ Ri = \frac{g \frac{\partial T}{\partial z}}{\frac{T}{\partial z} \left( \frac{\partial u}{\partial z} \right)^2} \Rightarrow \infty \]

(Yi, 2007; Yi et al., 2005)
SF₆ experiments

Yi et al. 2005

0146–0504 MST 8 August 2002

0000–0500 MST 8 August 2002

Yi et al. 2005
Horizontal CO$_2$ gradient in summer

Yi et al. 2007

Super stable layer

Yi et al. 2007
Keeling Plot

Metolius, Oregon ponderosa pine forest

\[ y = -25.01 + 6039x \]
\[ R^2 = 0.993 \]

Carbon isotope ratio of atmospheric CO\(_2\), \% vs. \(1/[CO_2]\), ppmV\(^{-1}\)
Apply the computational fluid dynamics (CFD) approach to simulate canopy flow
Renormalization-group $k-\varepsilon$ turbulence model

Leaf area density and drag coefficient profile derived from the analytical model were used.
‘S’-shaped wind profile

\[ \theta < \theta_r \quad \text{Cold inflow} \]

Yi et al. 2005
Chimney phenomenon

\[ \theta \geq \theta_r \quad \text{Warm inflow} \]

Yi et al. 2007b
Oscillation

\[ \theta \approx \theta_r \]

Yi et al. 2007b
Steady States

\[
\begin{align*}
\frac{du_0}{dt} &= 0 = f_u(u_0, \theta_0), \\
\frac{d\theta_0}{dt} &= 0 = f_\theta(u_0, \theta_0).
\end{align*}
\]

\[
\begin{align*}
 u_0^\pm &= \pm \sqrt{\frac{g}{c_D \ell} \left( \frac{\theta_r - \theta_0}{\theta_r} \right)}, \\
\theta_0 &= \theta_r \left( 1 - \frac{c_D \ell L_c^2}{g \gamma^2 \sin^2 \alpha} \right),
\end{align*}
\]

Steady States

Stable

Unstable

Yi et al. 2007b
Synopsis

\[ \theta_r - \theta_0 \geq \theta_c = \frac{\gamma \sin \alpha}{c_D \ell} \approx 0.194 \text{ K} \]

\[ (u_+^0, \theta_0) \quad \text{stable.} \]

\[ (u_0^-, \theta_0) \quad \text{unstable.} \]

\[ 0 \leq \theta_r - \theta_0 \leq \theta_c \approx 0.194 \]

Oscillation.

Yi et al. 2007b
Acknowledgements to

Monson lab, University of Colorado
Davis lab, Penn State University
Dean Anderson, USGS
Andrew Turnipseed, NCAR
Peter Bakwin, NOAA/CMDL
Zhiqiang Zhai, University of Colorado
Lamb lab, Washington State University
Denning lab, Colorado State University
\[ w'(z) = c_D(z)\overline{u}^2(z) \]

\[ \frac{d}{dz} \left( c_D(z)\overline{u}^2(z) \right) = a(z)c_D(z)\overline{u}^2(z) \]

\[ -\frac{du'w'(z)}{dz} + u(z)\overline{u}'w'(z) = 0 \]

Thank you!
Science stops
Faith begins

You cannot ask why.

The holy property of science appears

Logic Provable

You can ask why.

Law

Deductions
Contact information

Chuixiang Yi
Assistant Professor
School of Earth and Environmental Sciences
Queens College, City University of New York
65-30 Kissena Blvd
Flushing, New York 11367
Phone: 718-997-3366
Fax: 718-997-3299
Email: cyi@qc.cuny.edu
http://www.essc.psu.edu/~cxyi
http://qcpages.qc.edu/EES/pep/yi.html