Physical and Biological Processes that Controls Water Vapor Exchange between Vegetation and the Atmosphere

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Contributions from the Biometeorology Lab

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Josh Fisher
Siyan Ma
Xingyuan Chen
Gretchen Miller
Matthias Falk
Kevin Tu
Outline

• Processes, Supply vs Demand, Short and Long Time scales
  – Short
    • Energy
    • Meteorology
  – Long
    • Leaf area index
    • Nutrition
    • Plant Functional type
  – Short to Long
    • Surface Conductance
    • Soil Moisture
• Time
  – Day/Night
  – Seasonal
  – Interannual
• Space
  – Land Use
  – PBL/Landscape
  – Globe
Water and the Environment: Biogeophysical-Ecohydrological View

- Transpiration/Evaporation
- Available Energy
- Sensible Heat
- Photosynthesis/Respiration
- Carbon
- Soil Moisture
- Litter
- Nutrients
Processes and Linkages: Roles of Time and Space Scales

- Weather model
- Ecosystem Dynamics
- Biogeochemistry
- Biophysical model

- continent
- region/biome
- landscape
- canopy

- seconds
- days
- years
- centuries

- ppt, Ta, P, e_a, u, R_g, L
- \( \lambda \)E, H
- A_c, G_c
- Leaf Area, N/C, Ps capacity

Species, Functional Type
Penman Monteith Equation

\[ \lambda E = \frac{s(R_n - S) + \rho \cdot C_p \cdot G_H \cdot D}{s + \gamma + \gamma \frac{G_H}{G_s}} \]

Function of:

- Available Energy (Rn-S)
- Vapor Pressure Deficit (D)
- Aerodynamic Conductance (Gh)
- Surface Conductance (Gs)
Eco-hydrology: ET, Functional Type, Physiological Capacity and Drought
Effects of Functional Types and $R_{\text{Sfc}}$ on Normalized Evaporation

$R_c$ is a $f$(LAI, N, soil moisture, $P_s$ Pathway)
Stomatal Conductance Scales with N, via Photosynthesis

Stomatal Conductance Scales with Photosynthesis

Photosynthetic Capacity Scales with Nitrogen

Stomatal Conductance scales with Nitrogen

after Schulze et al (1994)

Wilson et al. 2001, Tree Physiology
Integrated Stomatal Conductance Scales with Photosynthetic Capacity and LAI

![Graph showing the relationship between stomatal conductance ($G_s$) and maximum carboxylation rate ($V_{cmax}$) for different LAI values.](image)

**CANVEG Computations**
Effects of Leaf Area and Photosynthetic Capacity on Normalized Evaporation: Well-Watered Conditions

\[ \frac{Q_E}{Q_{E,eq}} = 1.3 \]

\[ V_{c,\text{max}} \]

\[ LAI \]

Canveg Model, Baldocchi and Meyers, 1998 AgForMet
Effects of Leaf Area and Photosynthetic Capacity on Normalized Evaporation: Watered-Deficits

Boreal Forest

\[ \frac{Q_E}{Q_{E,eq}} \]

- \( k=10 \)
- \( k=8.0 \)
- \( k=7.0 \)

\( V_cmax \times LAI \)

\( Q_{E,eq} \)
LAI and Ps Capacity also affects Soil vs Total Evaporation
Canopy Surface Conductance does not equal the Canopy Stomatal Conductance

Be Careful about using $G_{can}$ to compute isotopic discrimination
Forest Biodiversity is Negatively Correlated with Normalized Evaporation

Use Appropriate and Root-Weighted Soil Moisture

\[ \langle \theta \rangle = \frac{\int_0^z \theta(z) \, dP(z)}{\int_0^z dP(z)} \]

Chen, Baldocchi et al., in prep.
ET and Soil Water Deficits: Root-Weighted Soil Moisture

Grassland

Oak Savanna

Baldocchi et al., 2004 AgForMet
ET and Soil Water Deficits: Water Potential

Root-Weighted Soil Moisture Matches Pre-Dawn Water Potential

ET of Annual Grass responds to water deficits differently than Trees

Baldocchi et al., 2004 AgForMet
Leaf Area Index scales with Water Balance Deficits

various functional types:
- Baldocchi and Meyers (1998)
- savanna:
  - Eamus et al. 2001
  - Oak Savanna, CA

LAI

\[ b[0]: -0.68 \]
\[ b[1]: 0.84 \]
\[ r^2: 0.69 \]
Nocturnal Transpiration from Blue Oak

Fisher et al. 2006, Tree Physiology
Seasonal and Annual Time Scales

Potential and Actual Evaporation are Decoupled in Semi-Arid System
Interannual Variation ET

Vaira 2004

- 2001: 301 mm
- 2002: 292 mm
- 2003: 353 mm
- 2004: 284 mm

Oak Savanna

- 2002: 389 mm
- 2003: 422 mm
- 2004: 340 mm
- 2005: 484 mm

E (mm d⁻¹) vs. Day

ET (mm d⁻¹) vs. Day
Annual ET of Annual Grassland varies with Hydrological Growing Season

Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, submitted
Growing Season Length and ET, Temperate Forest

Oak Ridge, TN

Year with Longer Growing Season (13 days) Evaporated More (27 mm).

Other Climate Factors could have confounded results, but \( R_g \) (5.43 vs 5.41 GJ m\(^{-2}\)) and \( T_{air} \) (14.5 vs 14.9 C) were similar and rainfall was ample (1682 vs 1435 mm)

Wilson and Baldocchi, 2000, AgForMet
Year to Year differences in ET is partly due to differences in Growing Season Length

Field data show that ET decreases by 2.07 mm for each day the start of the growing season is delayed
ET: Spatial Scale
Landscape Differences
On Short Time Scales, Grass ET > Forest ET

Monthly Averages

LE/LE$_{eq}$ vs. Gs (mm s$^{-1}$)

Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, submitted
Role of Land Use on ET:
On Annual Time Scale, Forest ET > Grass ET

California Savanna

Evaporation (mm y⁻¹)

Hydrological Year

Oak Woodland
Annual Grassland

Ryu, Baldocchi et al, JGR-Atmos, submitted
• Savanna Uses More Water than Grassland
• Savanna Soil holds about 78 mm more Water
• Annual ET Decreases with Rg
• Rg is negatively correlated with Rain and Clouds
• System is Water not Radiation Limited

Ryu, Baldocchi, Ma, Hehn, JGR-Atmos, submitted
Stand Age also affects differences between ET of forest vs grassland

Marc and Robinson, 2007 HESS
Assessing Spatial Averages with Subgrid Variability

\[
E[\lambda E] = \frac{\bar{s} A + s' \bar{A}' + \rho C_p (\bar{D} g_a + \bar{D}' g_a ')}{(s + \gamma + \gamma (g_a / g_s + g_a r_s '))}
\]
Sub-Grid Variability: MODIS and IKONOS

Use Power Law scaling to Estimate small scale Variance

\[ E[f(x)] = f(x) + \frac{1}{2} \frac{\partial^2 f(x)}{\partial x^2} \sigma(x)^2 \]

Baldocchi et al 2005 Tellus
Errors in ET Scaling

$$E[f(x)] = f(\bar{x}) + \frac{1}{2} \frac{\partial^2 f(\bar{x})}{\partial x^2} \sigma(\bar{x})^2$$

Baldocchi et al 2005 Tellus
Linking Water and Carbon: Potential to assess $G_c$ with Remote Sensing

**Annual Grassland**

Regr. Coef:
- $b[0]$: 0.117
- $r^2$: 0.793

**Oak Savanna**

Regr. Coef:
- $b[0]$: 8.53e-3
- $b[1]$: 8.97
- $b[2]$: 736.0
- $r^2$: 0.812

Xu + DDB, 2003 AgForMet
Gc Exhibits Scale ‘Invariance’

FLUXNET Data

Stomatal Conductance Survey
Dennis Baldocchi; UC Berkeley

Processed by M. Falk
Fisher et al Global ET Model

<table>
<thead>
<tr>
<th>Total Latent heat flux</th>
<th>( LE_s + LE_c + LE_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy Transpiration</td>
<td>((1 - f_{\text{wet}}) f_g f_T \alpha - \frac{\Delta}{\Delta + \gamma} R_{nc} )</td>
</tr>
<tr>
<td>Soil Evaporation</td>
<td>((f_{\text{wet}} + f_{\text{SM}} (1 - f_{\text{wet}})) \alpha - \frac{\Delta}{\Delta + \gamma} (R_{nc} - G) )</td>
</tr>
<tr>
<td>Intercepted Evaporation</td>
<td>( f_{\text{wet}} \alpha - \frac{\Delta}{\Delta + \gamma} R_{nc} )</td>
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| \( f_{\text{wet}} \) | \( RH^{10} \) |
| \( f_g \) | \( \frac{f_{\text{APAR}}}{f_{\text{IPAR}}} \) |
| \( f_{\text{APAR}} \) | \( m_1 SAVI + b_1 \) |
| \( f_{\text{IPAR}} \) | \( m_2 NDVI + b_2 \) |
| \( f_c \) | \( f_{\text{IPAR}} \) |
| \( f_T \) | \( \exp \left(-\left(\frac{T_c - T_{\text{opt}}}{\Delta}\right)^2\right) \) |
| \( f_{\text{SM}} \) | \( RH^{VPD} \) |
| \( T_{\text{opt}} \) | \( T_c \text{ at max}\{f_{\text{wet}} T_c RH^{VPD}\} \) |
$RH^{VPD}$

A measure for downscaling ET with Drought???

Fisher, Tu and Baldocchi, RSE in press
Global ET, 1989, ISLSCP

<table>
<thead>
<tr>
<th>ET (mm/y)</th>
<th>reference</th>
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<tbody>
<tr>
<td>613</td>
<td>Fisher et al</td>
</tr>
<tr>
<td>286</td>
<td>Mu et al. 2007</td>
</tr>
<tr>
<td>467</td>
<td>Van den Hurk et al 2003</td>
</tr>
<tr>
<td>649</td>
<td>Bosilovich 2006</td>
</tr>
<tr>
<td>560</td>
<td>Jackson et al 2003</td>
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</table>

Fisher et al, in press
Global ET pdf, 1989, ISLSCP

Fisher et al.
Conclusions

- Biophysical data and theory help explain powerful ideas of Budyko and Monteith that provide framework for upscaling and global synthesis of ET
  - ET scales with canopy conductance, which scales with LAI and Ps capacity, which scales with precipitation and N
Be Careful

- Short-Term Differences in Potential and Actual ET may not hold at Annual Time Scales
  - Grass has greater potential for ET than Savanna
- Sub-Grid Variability in surface properties can produce huge errors in upscaled ET at the 1 km Modis Pixel Scale
Present and Past
Biometeorology ET Team

Funding: US DOE/TCP; NASA; WESTGEC; Kearney; Ca Ag Expt Station
FluxNET WUE

FLUXNET 2007

GPP (gC m$^{-2}$ y$^{-1}$) vs. LE (mm y$^{-1}$)
Global ET

July

Fisher et al, in press
Photosynthesis > Respiration

CO₂

Limited Lear Area and Sparse Canopy Reduce ET, too

Ps Capacity must be Great, For Short Period

Leaf N and Leaf Thickness must support Ps Machinery

Photosynthesis

CO₂

Limited Lear Area and Sparse Canopy Reduce ET, too

Ps Capacity must be Great, For Short Period

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Photosynthesis

CO₂
Interannual Variation ET: Grassland

Vaira 2004

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Inter annual Water Balance

Oak Savanna

ET (mm d⁻¹)

Day

0 50 100 150 200 250 300 350

0 1 2 3 4 5

2002: 389 mm
2003: 422 mm
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$RH_{VPD}$

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Fisher et al. Remote Sensing Environment, in press