The surface energy imbalance problem

Why is $(H + \lambda E) < (R_n - G_0)$ at most FluxNet sites?

Ray Leuning  |  Chief Research Scientist
23 April 2012
Basics: mass/energy balance on a control volume

\[ F_c = F_0 + \frac{1}{L^2} \int_0^L \int_0^L \int_0^h S \, dx \, dy \, dz = \frac{1}{L^2} \int_0^L \int_0^L \int_0^h c_d \frac{\partial \chi_c}{\partial t} \, dx \, dy \, dz \]

\[ + \frac{1}{L^2} \int_0^L \int_0^L \int_0^h \left[ uc_d \frac{\partial \chi_c}{\partial x} + vc_d \frac{\partial \chi_c}{\partial y} + wc_d \frac{\partial \chi_c}{\partial z} \right] \, dx \, dy \, dz \]

\[ + \frac{1}{L^2} \int_0^L \int_0^L \int_0^h \left[ \frac{\partial u}{\partial x} \frac{\partial \chi_c}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial \chi_c}{\partial y} + \frac{\partial w}{\partial z} \frac{\partial \chi_c}{\partial z} \right] \, dx \, dy \, dz \]
Turbulent transport

- At a single tower
- Replace space & time average of mass balance of CV
- by time average alone

- Large-eddy simulation: Dr Ned Patton, UCAR, Boulder, CO
Horizontally homogeneous site

Eddy fluxes

\[ \bar{H} = \rho_a c_p \bar{w}' \bar{T}' \quad \lambda \bar{E} = \lambda M_w c_d \bar{w}' \bar{\chi}' \]

Available energy

\[ A = R_n - G_0 - J_a - J_b - J_w - J_p \]

Storage terms

\[ G_0 = G_{z_m} + \int_0^{z_m} C_s \frac{dT_s}{dt} \, dz = G_{z_m} + J_s \]
\[ \bar{J}_x = \int_0^h \rho_a c_p \frac{dT_c}{dt} \, dz \]
The problem:
Most flux sites report $H + \lambda E < A$: Why?

• Available energy too high?
  • Incorrect radiation measurements ($R_n$)
  • Incorrect storage terms ($G_0, J_x$)

• System design?
  • Incorrect coordinate rotation
  • Loss of high-frequency covariance (high-cut filter)
  • Averaging times too short (low-cut filter)

• Measurement Site?
  • Advective flux divergence
Hourly-average $H + \lambda E$ vs $R_n - G_0$

$y = 0.92x + 7.01$
$R^2 = 0.88$

Virginia Park, Queensland
Ignore storage term $G_0$

- Peak $H + \lambda E < R_n$
- Hysteresis
- Slope always < 1
- Intercept > 0
Include ‘correct’ storage term $G_0$

- Peak $H + \lambda E \sim R_n - G_0$
- Little hysteresis
- Slope $\sim 1$
- Intercept $= 0$
24-h averages of $H + \lambda E$ vs $R_n$ & $R_n - G_0$

- Slope is same for both
La Thuile & OzFlux datasets:
PDFs of half hourly & daily averages

The surface energy imbalance problem            23 April 2012

\[
slope = \frac{H + \lambda E}{R_n - G_0}
\]

<table>
<thead>
<tr>
<th></th>
<th>La Thuile</th>
<th>Median slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half hourly</td>
<td>0.75</td>
<td>0.90</td>
</tr>
<tr>
<td>Daily</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

La Thuile
Median slope
Half hourly 0.75    Daily 0.90
Tilt error: 

$u'T'$ cross-contamination of $w'T'$

\[ a = -3.95 \quad \text{stable} \]
\[ a = -1.86 \quad \text{unstable} \]

\[ b = \frac{w'T'_{\text{measured}}}{w'T'_{\text{true}}} = \frac{1}{1 - a \sin(\beta)} \]
Advective flux divergence

- Horizontal $T$ gradients

\[ \Delta H = \bar{\rho} c_p \int_{0}^{h} u \frac{dT}{dx} \, dz \approx \bar{\rho} c_p \, h \, \frac{\Delta T_h}{\Delta x} \]

\[ \frac{\Delta \bar{T}}{\Delta x} \approx \frac{2 \Delta \bar{H}}{\rho c_p \, u_h \, h} \]

- Vertical velocity, $w(h)$

\[ \Delta H = \bar{\rho} c_p \int_{0}^{h} w \frac{\partial T}{\partial t} \, dz \approx \bar{\rho} c_p \, w(h) \left[ \bar{T}(h) - \frac{1}{h} \int_{0}^{h} \bar{T} \, dz \right] \]

\[ w(h) = \frac{\Delta \bar{H}}{\rho c_p \Delta \bar{T}_v} \]
Conclusions (1)

• Half-hourly averages of $H + \lambda E$ systematically underestimate $R_n - G_0$ at most flux sites

• Advective flux divergences cannot explain imbalance:
  • needs unrealistically large and systematically positive horizontal $T$ gradients and vertical velocities

• Advection can import and export energy!

• Leuning et al. (2012) AgForMet 156:65-74.
Conclusions (2)

• Imbalance partially explained by:
  • Phase lags due to incorrect estimates of energy storage in soils, air & biomass below the measurement height
  • 24-hour averages remove much of bias
  • Incorrect coordinate rotation: $u'T'$ contamination of $w'T'$

• Well-designed eddy flux systems on horizontally homogeneous sites can measure fluxes accurately
  • Do not force $H + \lambda E = R_n - G_0$ on hourly timescales
  • Do not adjust scalar fluxes

• Leuning et al. (2012) AgForMet 156:65-74.
Thank you

CSIRO Marine and Atmospheric Research
Ray Leuning
Chief Research Scientist

+61 2 6246 5557
ray.leuning@csiro.au