The surface energy imbalance problem

Why is (H + λE) < (R_n – G_0) at most FluxNet sites?

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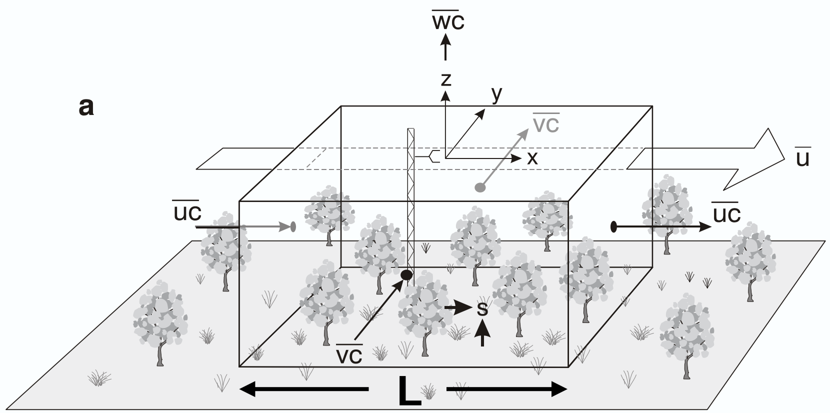
Basics: mass/energy balance on a control volume



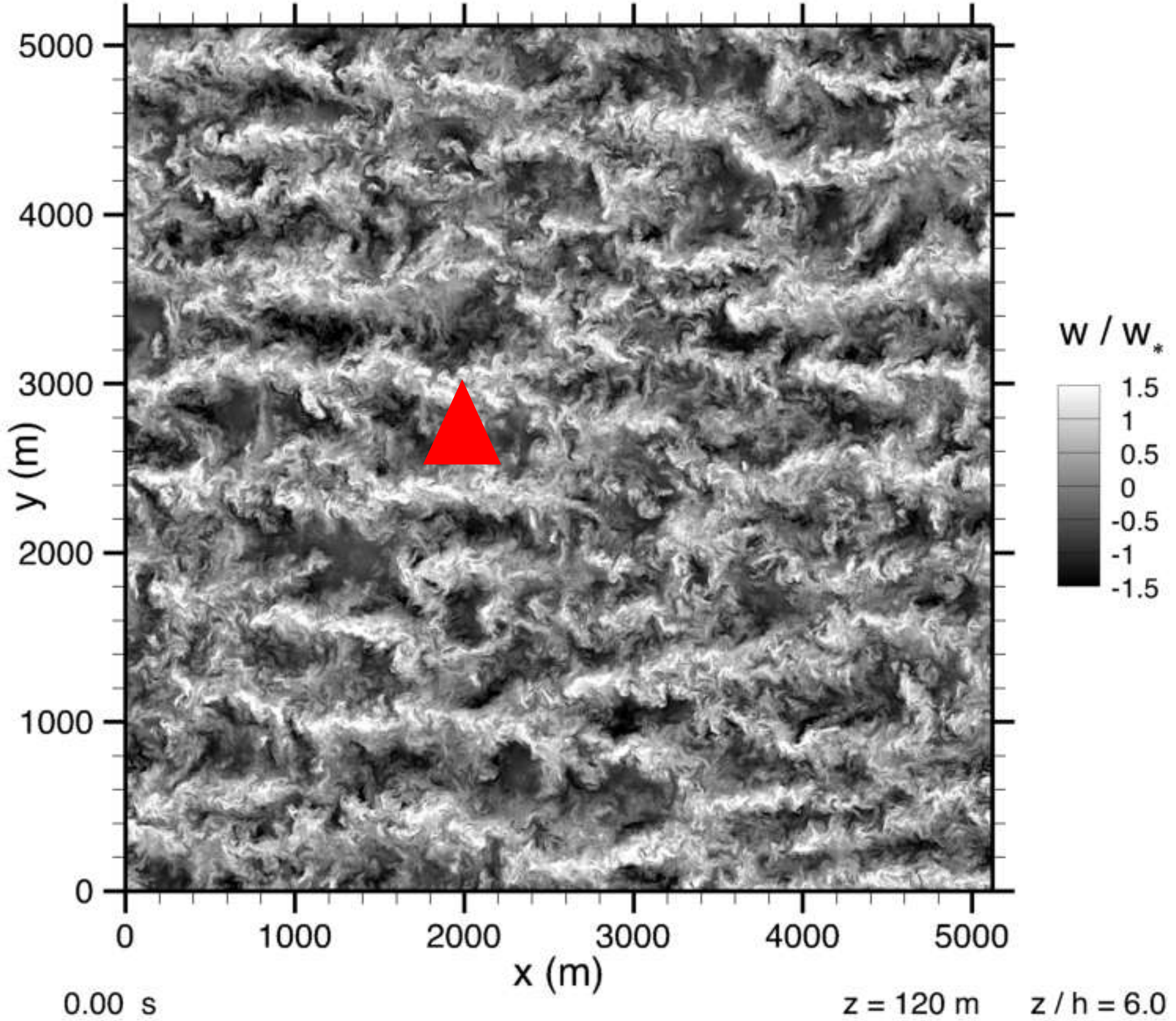
$$\overline{F_c} = \overline{F_0} + \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{S}\, dxdydz = \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{c_d}\, \overline{\frac{\partial \chi_c}{\partial t}}\, dxdydz$$

$$+ \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{uc_d}\frac{\partial \overline{\chi_c}}{\partial x} + \overline{vc_d}\frac{\partial \overline{\chi_c}}{\partial y} + \overline{wc_d}\frac{\partial \overline{\chi_c}}{\partial z} \right] dxdydz$$

$$+ \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\frac{\partial \overline{c_d}\, \overline{u'\chi_c'}}{\partial x} + \frac{\partial \overline{c_d}\, \overline{v'\chi_c'}}{\partial y} + \frac{\partial \overline{c_d}\, \overline{w'\chi_c'}}{\partial z} \right] dxdydz$$

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

$$\overline{H} = \overline{\rho_a}\, c_p \overline{w'T'} \qquad \lambda\overline{E} = \lambda M_w \overline{c_d}\, \overline{w'\chi_w'}$$

Available energy

$$\overline{A} = \overline{R_n} - \overline{G_0} - \overline{J_a} - \overline{J_b} - \overline{J_w} - \overline{J_p}$$

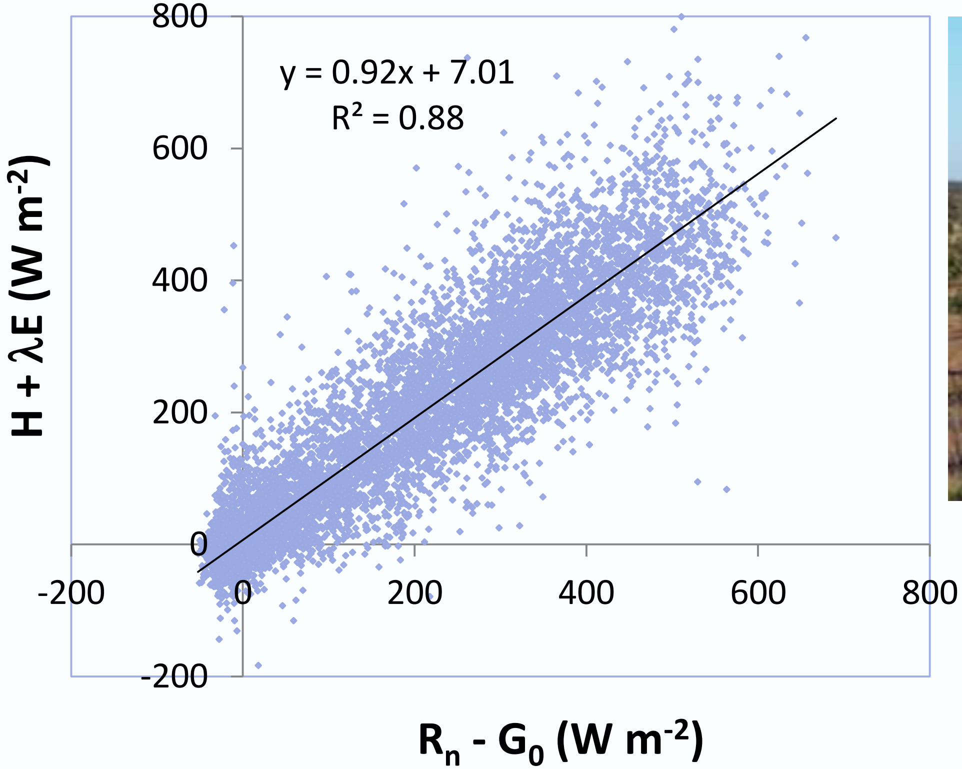
Storage terms

$$G_0 = G_{z_m} + \int_0^{z_m} C_s \frac{dT_s}{dt} dz = G_{z_m} + J_s \qquad \overline{J_x} = \int_0^h \overline{\rho_a} c_p \overline{\frac{dT_x}{dt}} dz$$

The problem:
Most flux sites report *H* + *λE* < *A*: *Why?*

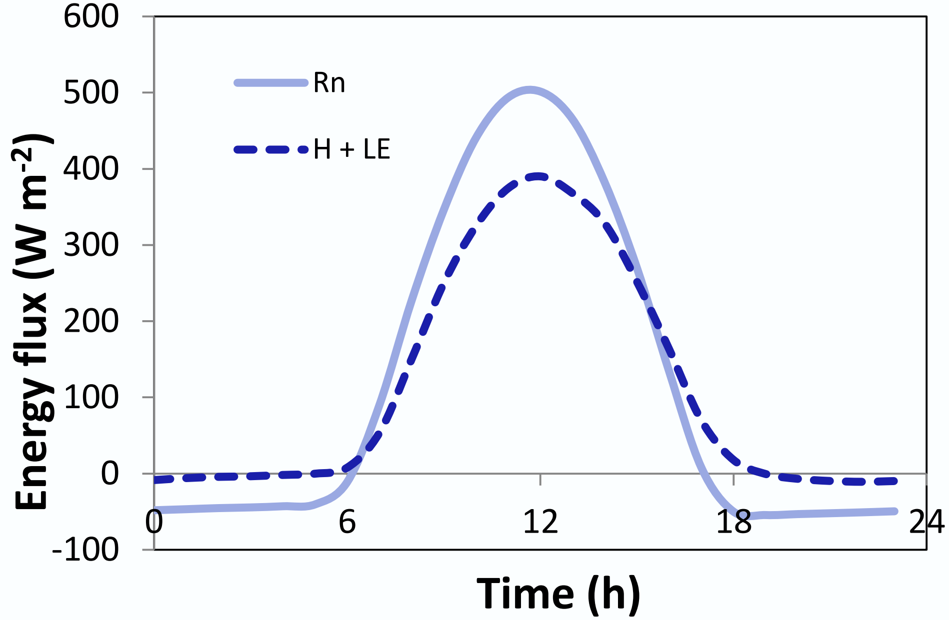
- Available energy too high?
  - Incorrect radiation measurements (R_n)
  - Incorrect storage terms (G_0, J_x)
- System design?
  - Incorrect coordinate rotation
  - Loss of high-frequency covariance (high-cut filter)
  - Averaging times too short (low-cut filter)
- Measurement Site?
  - Advective flux divergence

Hourly-average $H + \lambda E$ vs $R_n - G_0$

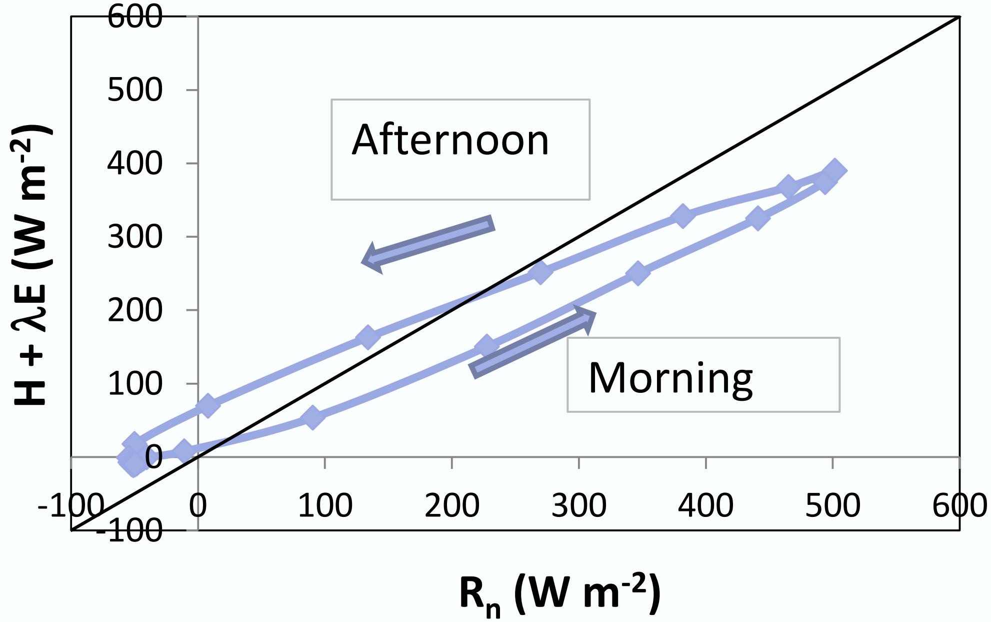


Virginia Park, Queensland

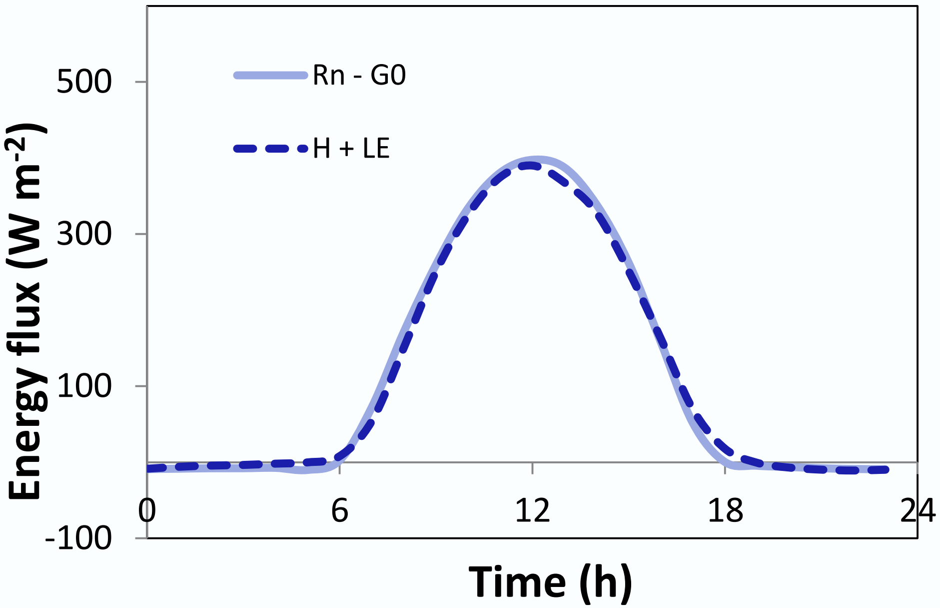
Ignore storage term G_0



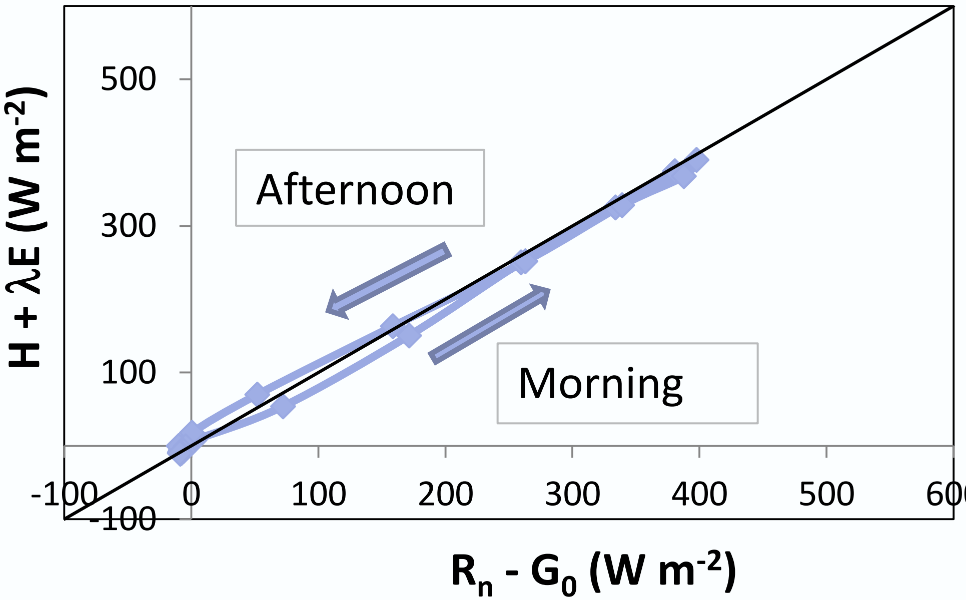
- Peak $H + \lambda E < R_n$
- Hysteresis
- Slope *always* < 1
- Intercept > 0



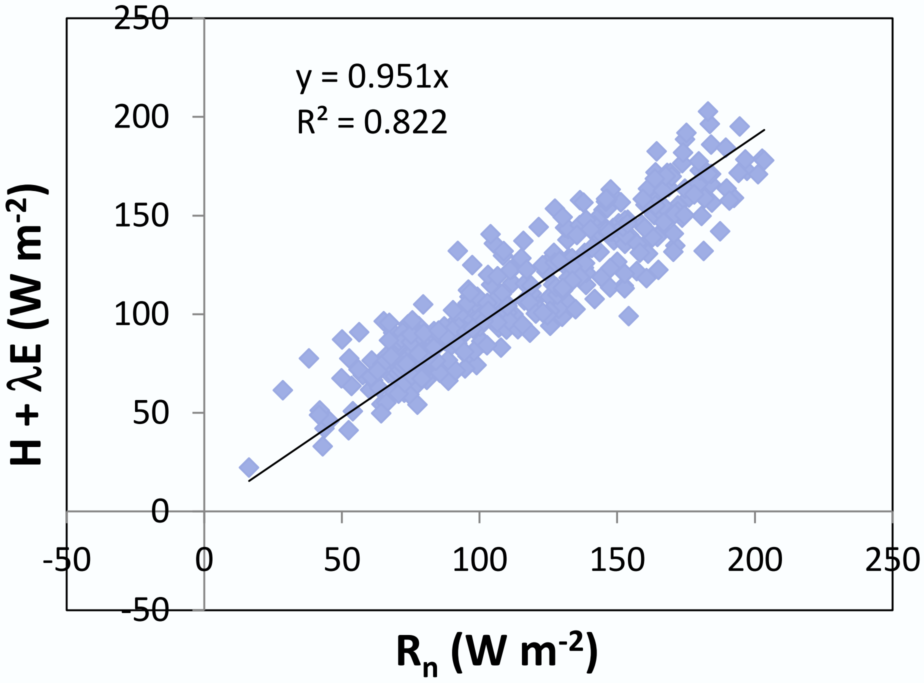
Include ‘correct’ storage term G_0

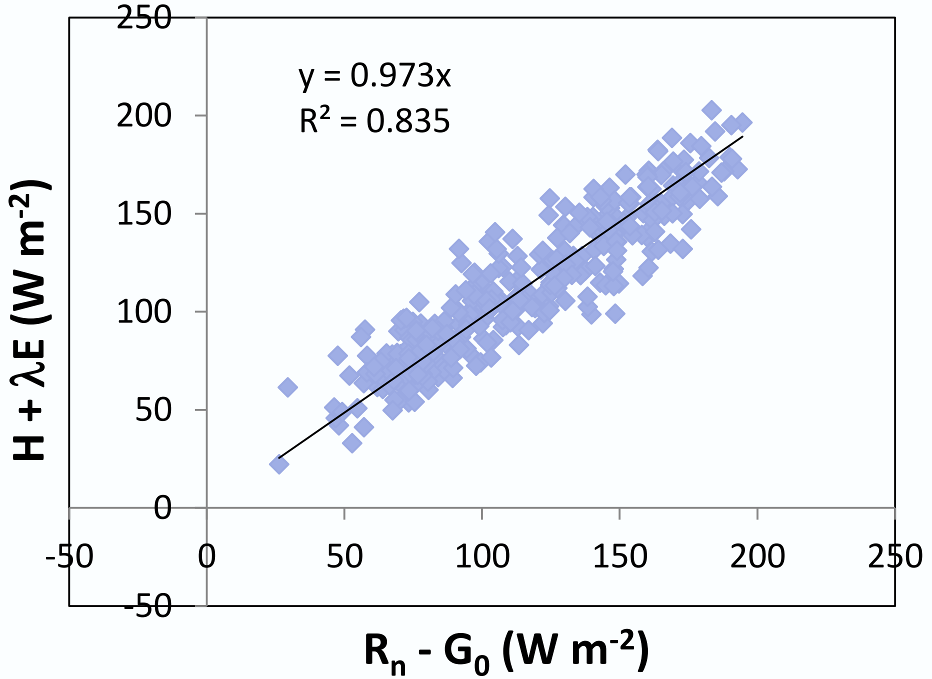


- Peak $H + \lambda E \sim R_n - G_0$
- Little hysteresis
- Slope ~ 1
- Intercept = 0



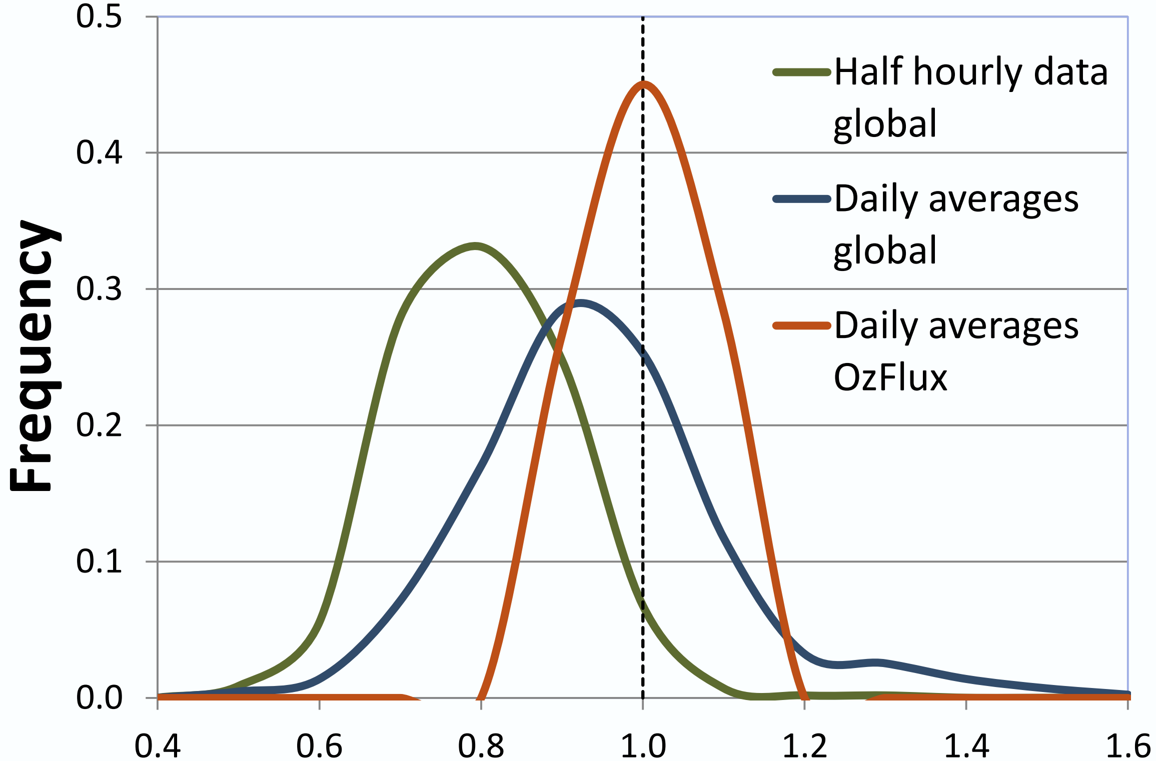
24-h averages of $H + \lambda E$ vs R_n & $R_n - G_0$





- Slope is same for both

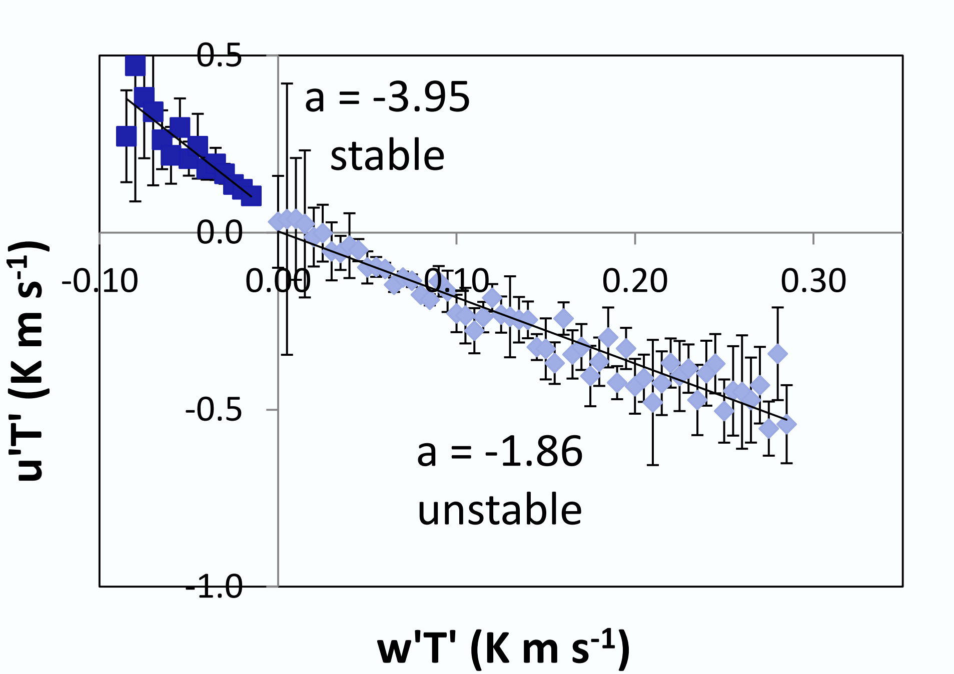
La Thuile & OzFlux datasets:
PDFs of half hourly & daily averages

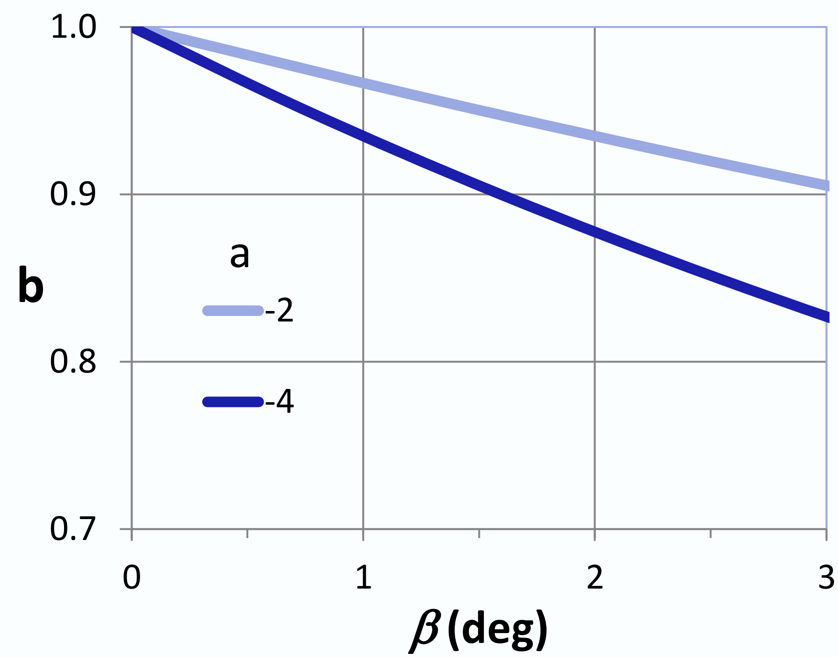


$$slope = \frac{H + \lambda E}{R_n - G_0}$$

La Thuile	
Median slope	
Half hourly	Daily
0.75	0.90

Tilt error:
u'T' cross-contamination of *w'T'*

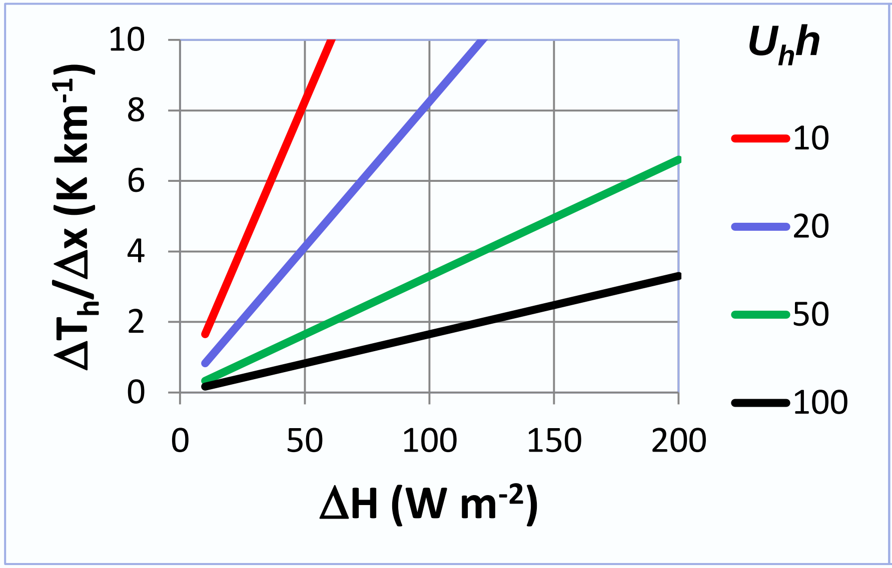




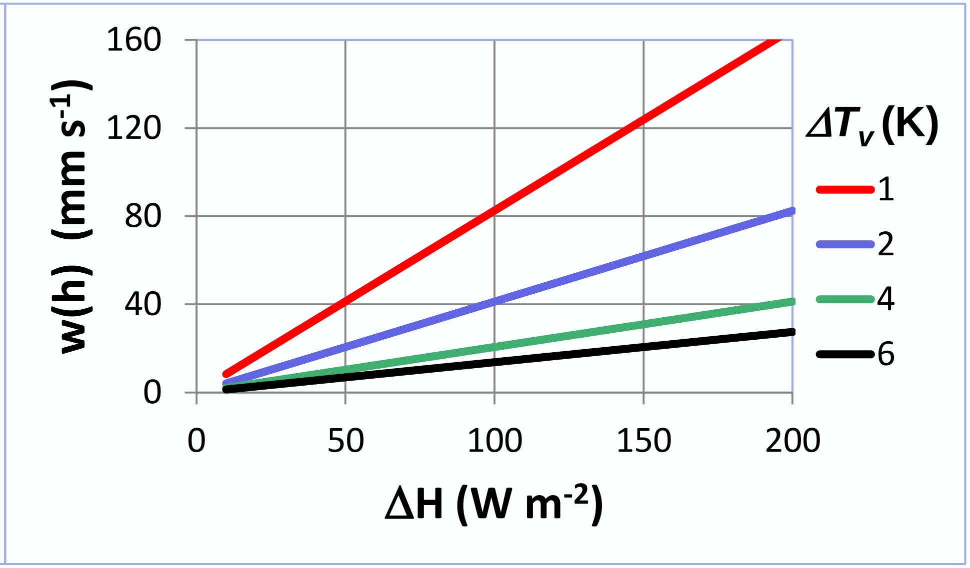
$$b = \frac{\overline{w'T'}_{measured}}{\overline{w'T'}_{true}} = \frac{1}{1 - a\sin(\beta)}$$

Advective flux divergence

- Horizontal *T* gradients



- Vertical velocity, *w*(*h*)



$$\Delta\overline{H} = \overline{\rho}c_p \int_0^h \overline{u}\frac{d\overline{T}}{dx}dz \approx \overline{\rho}c_p h \frac{\overline{u_h}}{2}\frac{\Delta\overline{T_h}}{\Delta x}$$

$$\Delta\overline{H} = \overline{\rho}c_p \int_0^h \overline{w}\frac{\partial\overline{T}}{\partial t}dz \approx \overline{\rho}c_p \overline{w}(h)\left[\overline{T}(h) - \frac{1}{h}\int_0^h \overline{T}dz\right]$$

$$\frac{\Delta\overline{T}}{\Delta x} \approx \frac{2\Delta\overline{H}}{\overline{\rho}c_p \overline{u_h}h}$$

$$\overline{w}(h) = \frac{\Delta\overline{H}}{\overline{\rho}c_p \Delta\overline{T_v}}$$

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.

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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

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