A 3-year record of ecosystem-atmosphere carbon exchange from an 'ideal'* woodland site: ~~controls,~~ corrections and uncertainties

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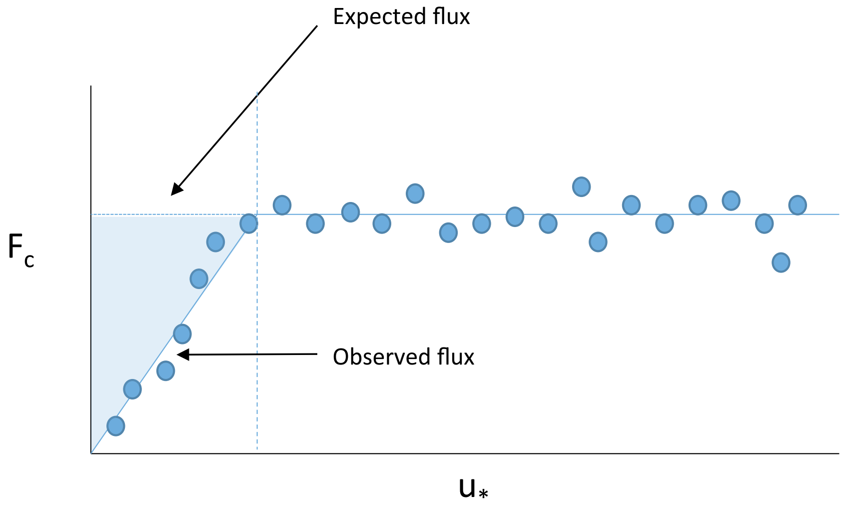
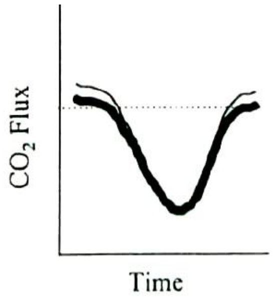
* Horizontally homogeneous infinite flat plain!

The nocturnal problem

- Occurs primarily under stable conditions
- Manifests as low-u* dependency of F_c
- Since insolation is driver of turbulent activity, occurs primarily nocturnally
- Since insolation is also a driver of photosynthesis, nocturnal NEE is respiratory flux only
- Hence risk of bias at diurnal and longer time scales





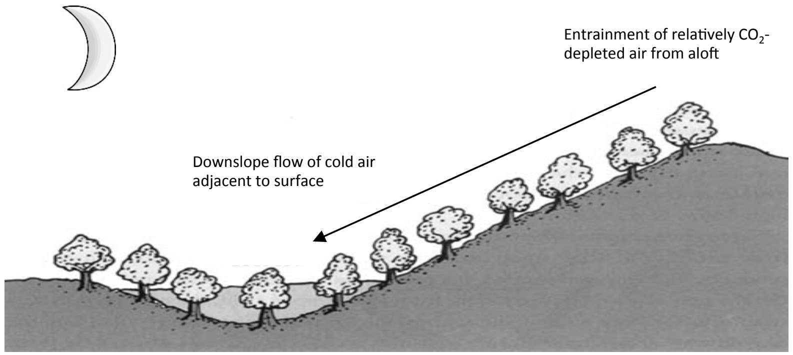
Selective-Systematic

e.g. under-reading of night-time fluxes because of drainage flows, different turbulence spectra

Key potential causes

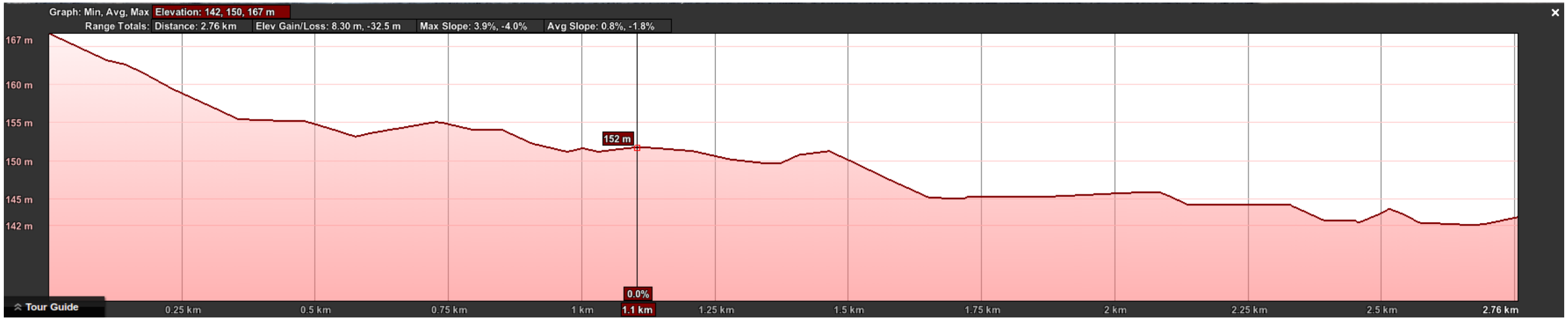
- Development of sublayers so measurement system is decoupled from surface (can be addressed by measuring storage)
- Intermittent turbulence (can be addressed by imposing stationarity criterion)
- Underestimation of storage term
- Unrepresentative fluxes due to extension of footprint
- Horizontal and/or vertical advection terms significant

Key mechanism

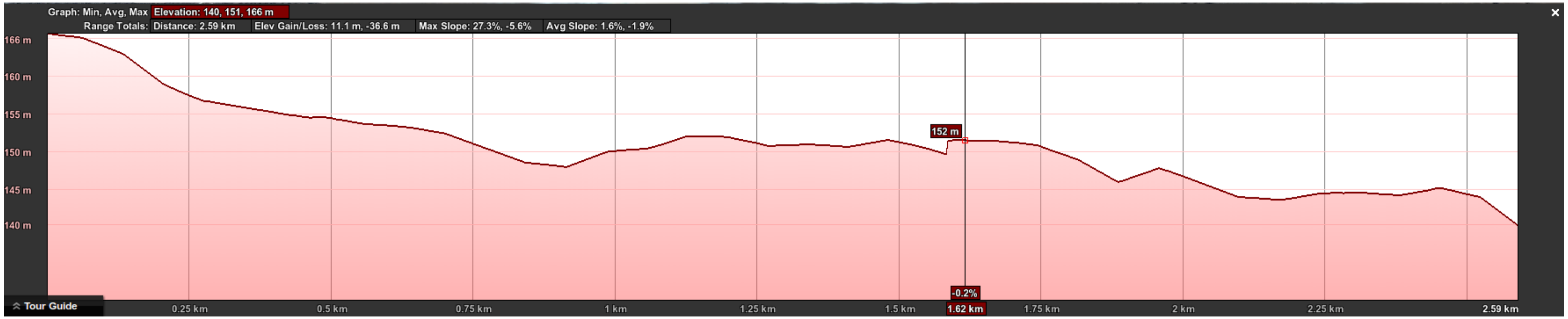


$$NEE = \underbrace{\overline{w'c'}(h_m)}_{I} + \underbrace{\int_0^{h_m} \overline{\frac{\partial c(z)}{\partial t}} dz}_{II} + \underbrace{\int_0^{h_m} \left(\bar{u}(z) \frac{\partial \bar{c}(z)}{\partial x} + \bar{v}(z) \frac{\partial \bar{c}(z)}{\partial y} \right) dz}_{III} + \underbrace{\int_0^{h_m} \left(\bar{w}(z) \frac{\partial \bar{c}(z)}{\partial z} \right) dz}_{IV} \Rightarrow R_e = F_c + S_c + Ah_c + Av_c$$

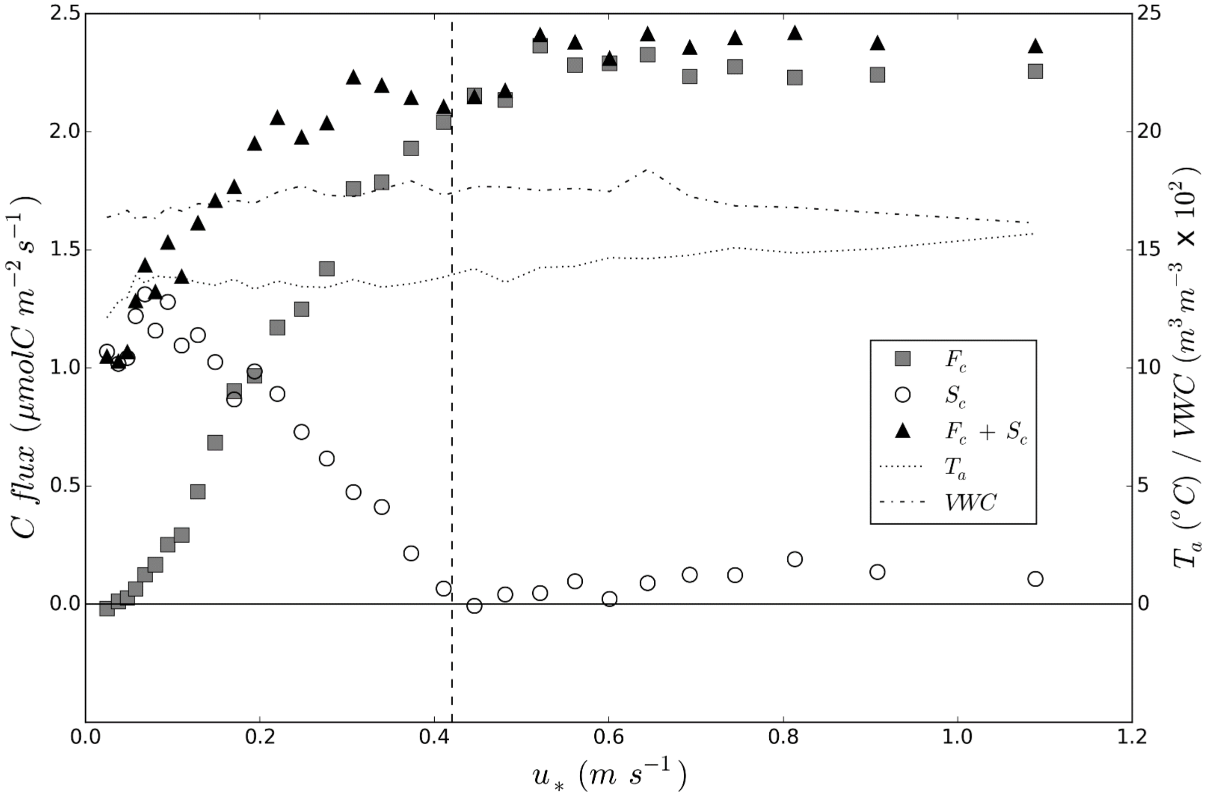
East-West profile at Whroo



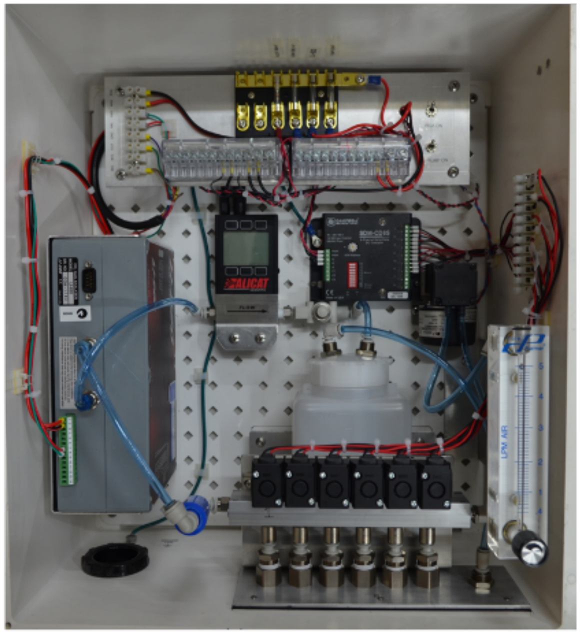
North-South profile at Whroo



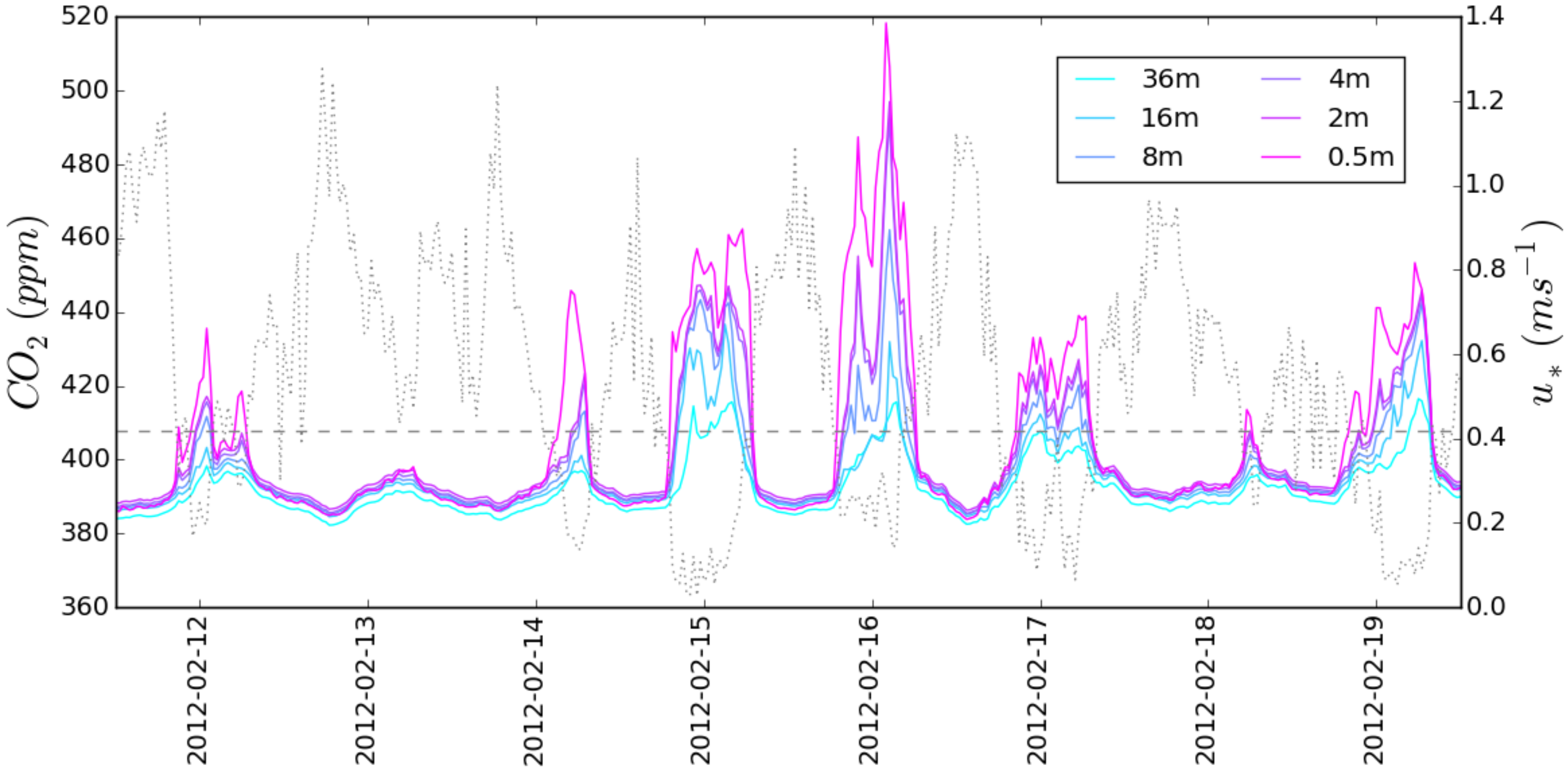
Response of F_c, S_c & controls to u_*



Whroo profile system



Sensitivity of profile CO_2 to u_*



Inferring nocturnal advection

1) Nocturnal carbon budget

$$R_e = F_c + S_c + Ah_c + Av_c$$

2) Change point analysis used to determine u_{*th}

$$R_e \approx \begin{cases} F_c, & u_* > u_{*th} \\ F_c + S_c + Ah_c + Av_c, & u_* < u_{*th} \end{cases}$$

3) Estimate R_e from TRF[t] optimised for F_c where $u_* > u_{*th}$

$$\widehat{R_e} = rb.\,\mathrm{e}^{E_0\left(\frac{1}{T_{ref}-T_0}-\frac{1}{T-T_0}\right)}$$

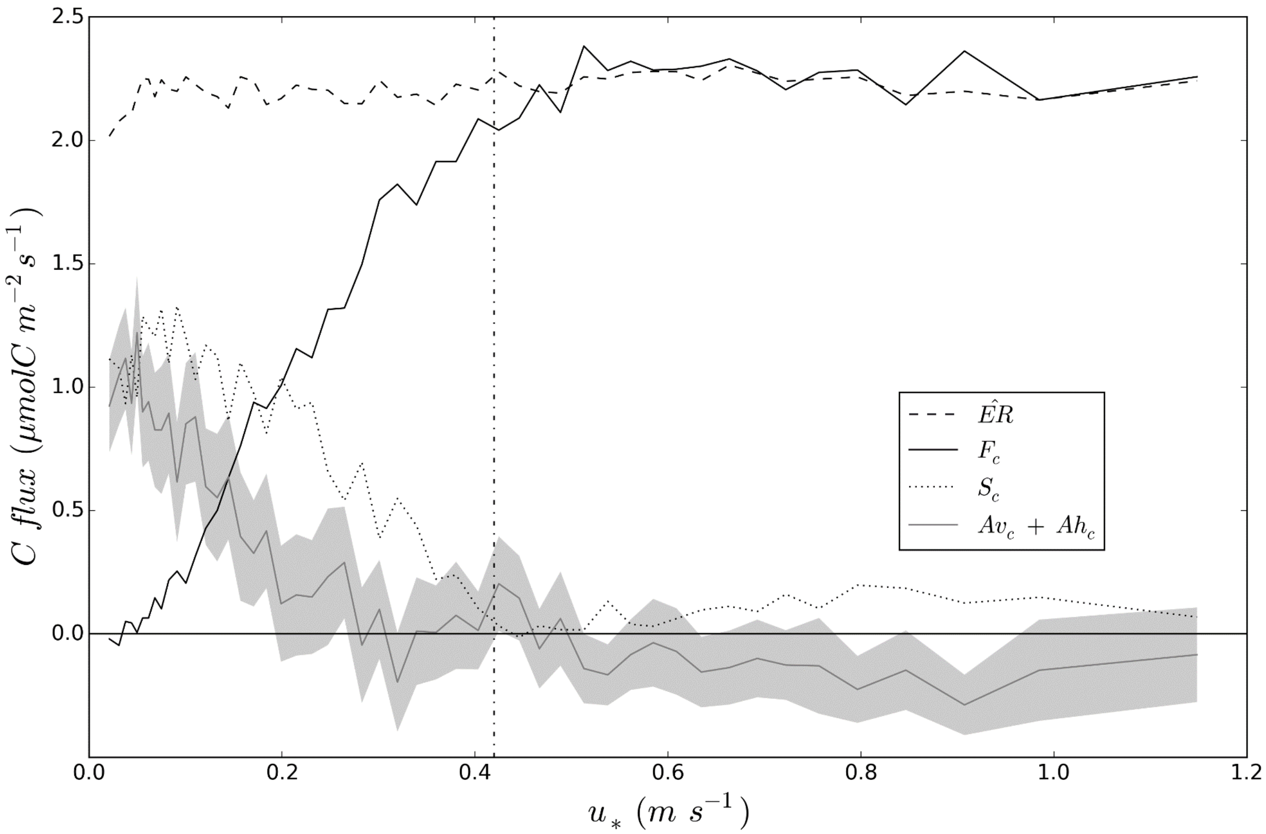
4) Infer collective advection terms for $u_* < u_{*th}$

$$\widehat{R_e} - F_c - S_c = Ah_c + Av_c$$

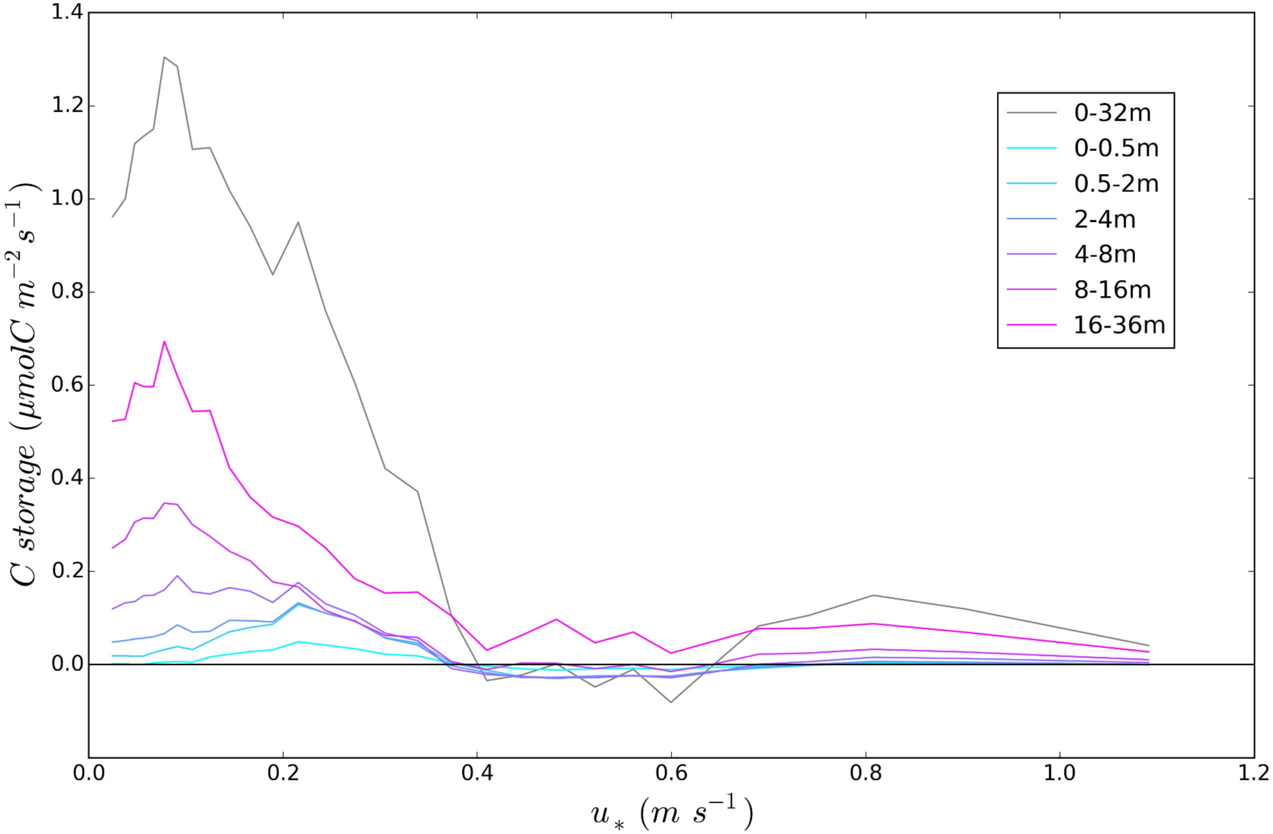
Assumed: 1) sufficient data to yield accurate estimate of R_e (60th percentile)
2) empirical model accurately captures signal
3) measurements are accurate, including F_c where $u_* < u_{*th}$
4) additional terms in the mass balance (flux divergences) are negligible

[t]Lloyd and Taylor, 1994

Apparent advection on 1-2^{o} slope

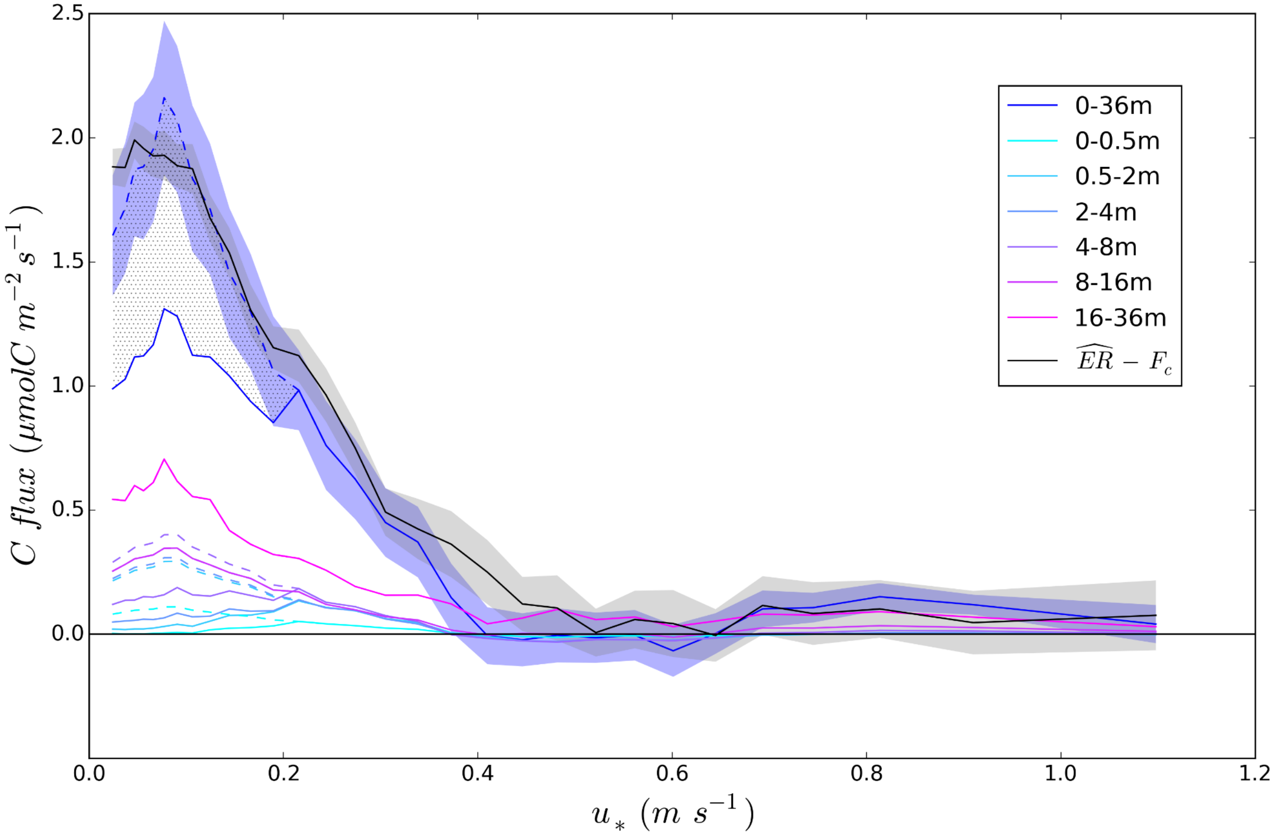


S_c by layer



- Drainage induced advection should have most noticeable effect on S_c rather than F_c
- Mean tree height at Whroo: 15.3±6.4m
- Drainage flows generally confined to depths < 10m
- Confined to trunk space due to drag imposed by canopy
- At u_* < 0.22, decline in storage below 8m

‘Correcting’ S_c decline

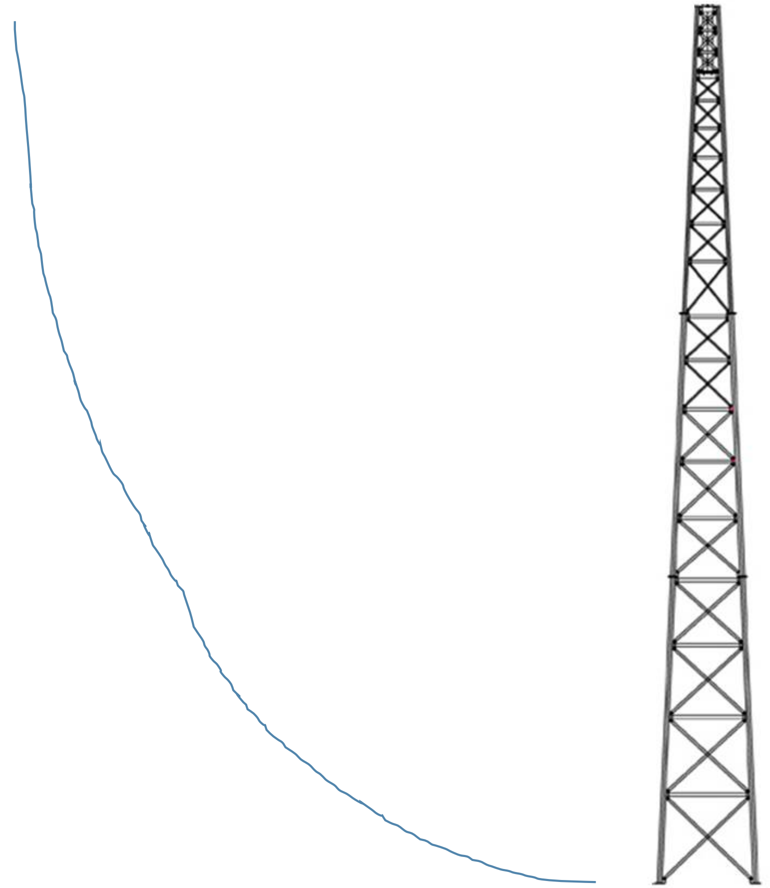


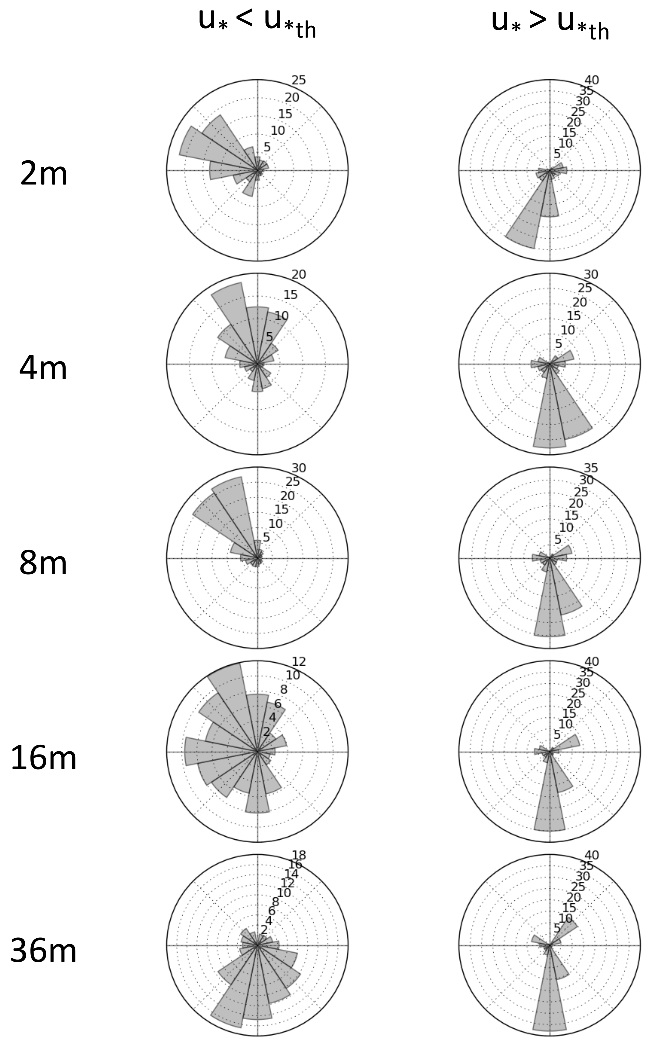
- Can extrapolate from linear relationship between upper and lower layers observed in interval $0.22 < u_* < 0.42$
- If this removes effects of advection then $Av_c + Ah_c = 0$ and therefore $\widehat{ER} - F_c = S_c$
- This ‘works’ (*i.e.* gives the answer we want)
- But implicit assumptions are almost certainly wrong
- But says something interesting about vertical source distribution

Estimating ΔC/ Δt for layers

Previous assumption almost certainly a bad one

Interested in modelling effects of changes in u* on





Measuring drainage flows

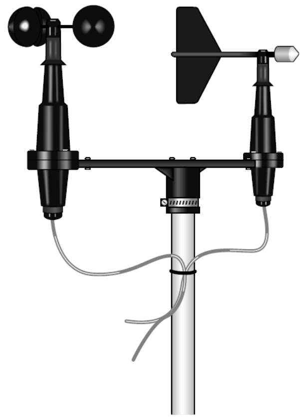
- Should be apparent in wind profiles
- Drainage flow velocities typically 0.1-0.2m s^{-1}
- Looks may be deceiving!

Wind Speed (Anemometer) Specifications

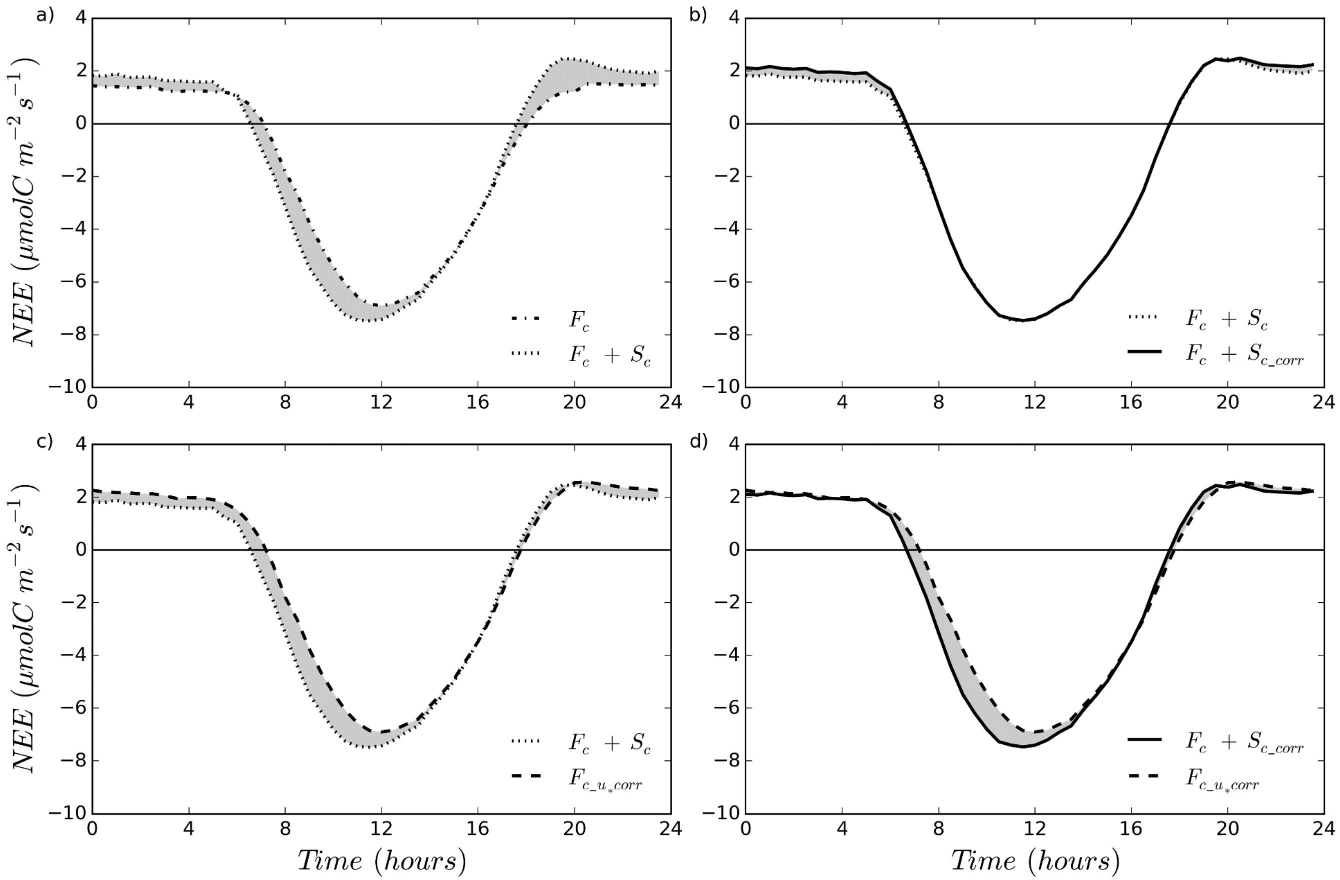
Range:	0 to 50 m s-1 (112 mph), gust survival 60 m s-1 (134 mph)
Sensor:	12 cm diameter cup wheel assembly, 40 mm diameter hemispherical cups
Accuracy:	±0.5 m s-1 (1.1 mph)
Turning Factor:	75 cm (2.5 ft)
Distance Constant (63% recovery):	2.3 m (7.5 ft)
Threshold:	0.5 m s-1 (1.1 mph)

Wind Direction (Vane) Specifications

Range:	360° mechanical, 355° electrical (5° open)
Sensor:	Balanced vane, 16 cm turning radius
Accuracy:	±5°
Damping Ratio:	0.2
Delay Distance (50% recovery):	0.5 m (1.6 ft)
Threshold:	0.8 m s-1 (1.8 mph) at 10° displacement 1.8 m s-1 (4 mph) at 5° displacement



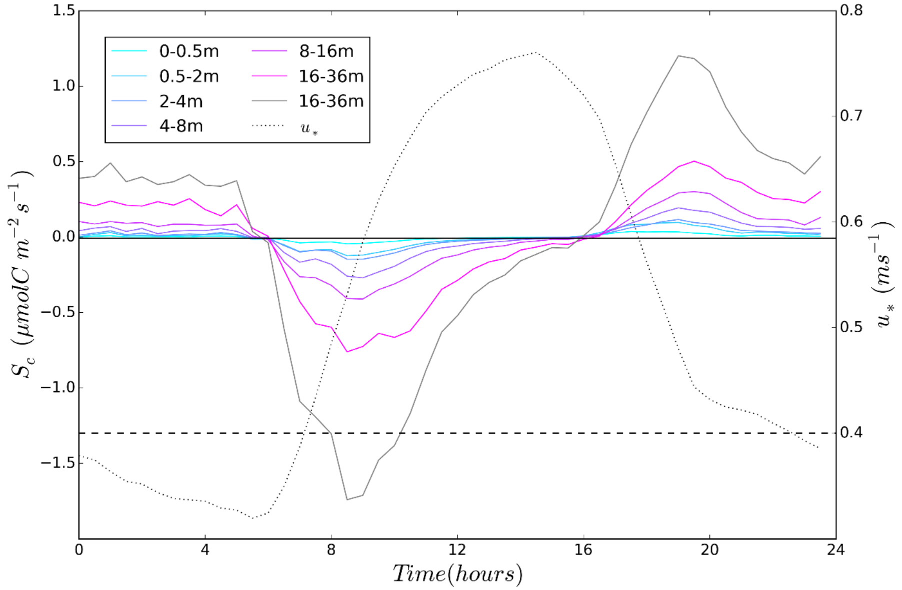
Effects on diurnal NEE dynamics

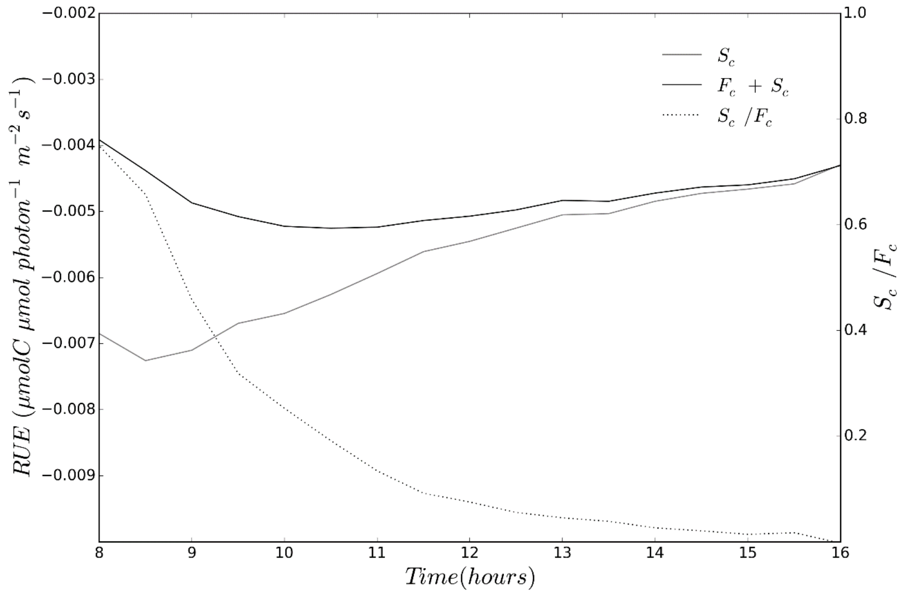


- $F_c + S_c$ inadequate nocturnally
- u_* filtered and gap-filled F_c increases nocturnal mean NEE
- u_*-dependent linear correction almost equivalent
- Storage term is not negligible during the day
- Most important before midday

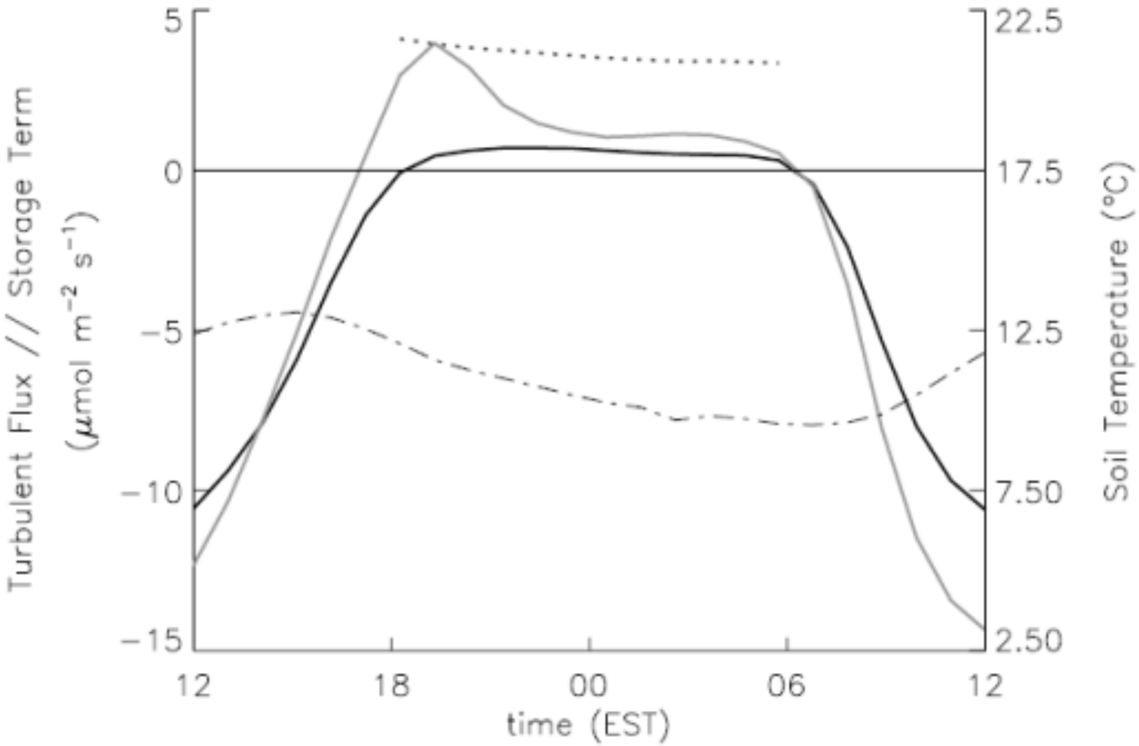
Implications of neglect of daytime storage

- For tall sites with no profile system… you need a profile system.
- Where $\sum_{i=1}^{n} A_c < \sum_{i=1}^{n} S_c$, lower bias will likely be obtained if nocturnal data is *un*corrected
- Profound effect on ecological interpretation





Also evident at Tumbarumba!



Uncertainty

Primary sources in summed NEE:

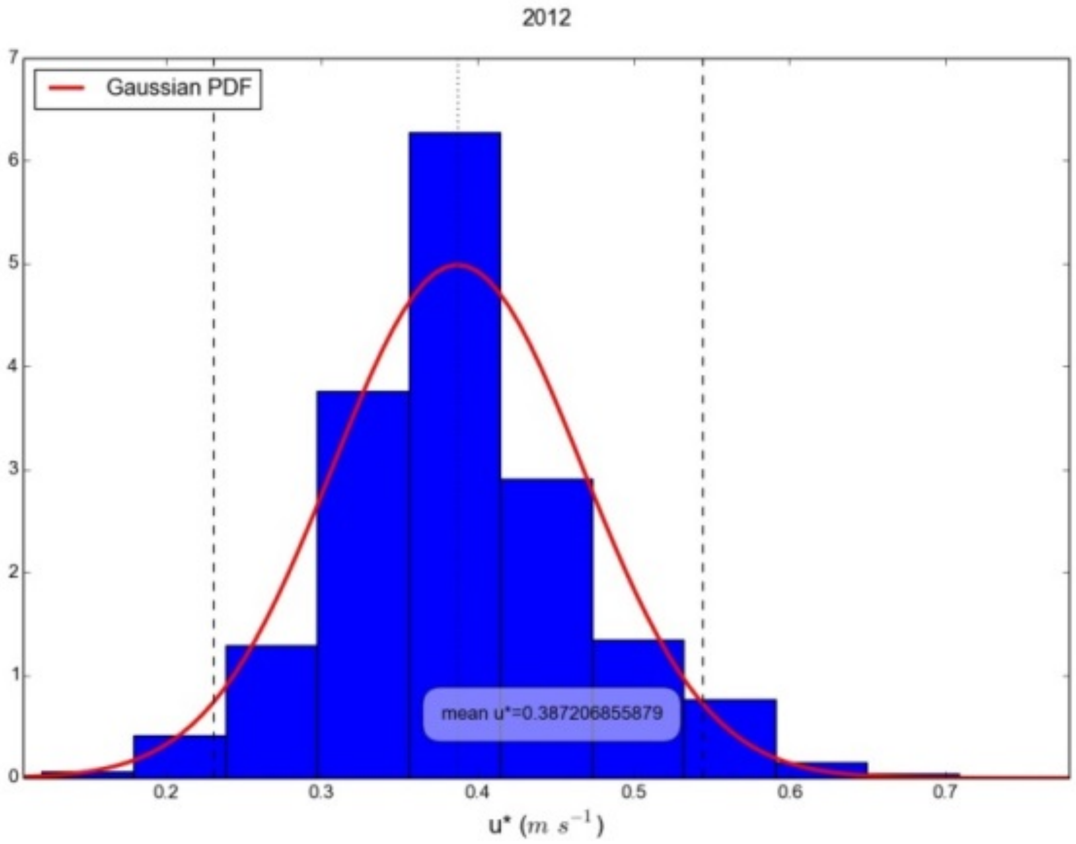
- systematic measurement error
- random measurement error
- imputation error

'There are known knowns. These are things we know that we know'. → Corrections

'There are known unknowns. That is to say, there are things that we know we don't know'. → Uncertainties

'But there are also unknown unknowns. There are things we don't know we don't know.' → Things that Ian Harman always tries to warn us about

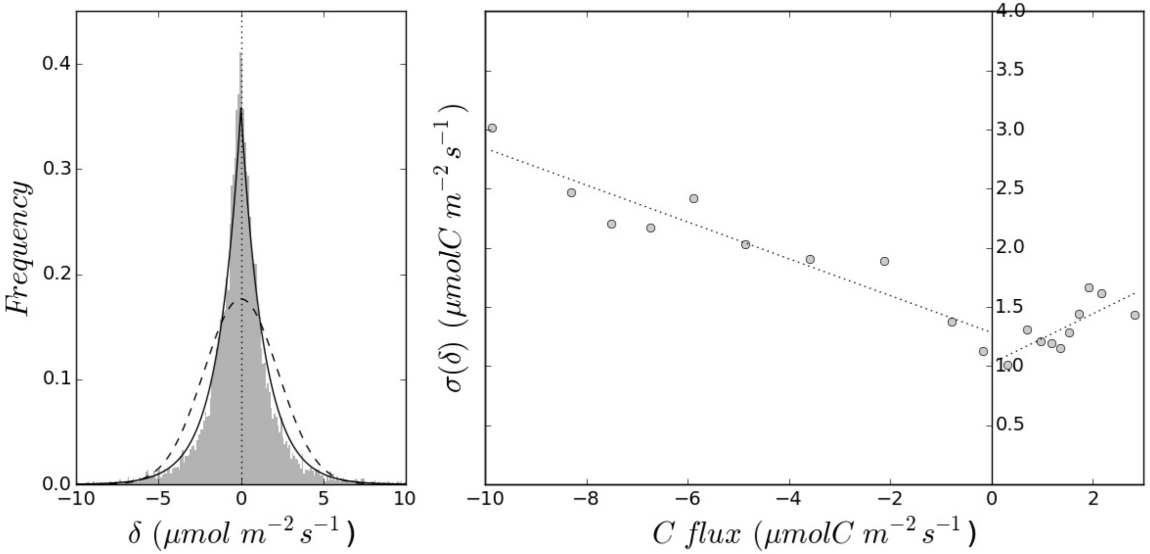
Uncertainty – systematic error



- Use change point detection to determine u_{*th} uncertainty
- Filter, gap fill and sum using upper and lower bounds of CI for u_{*th}

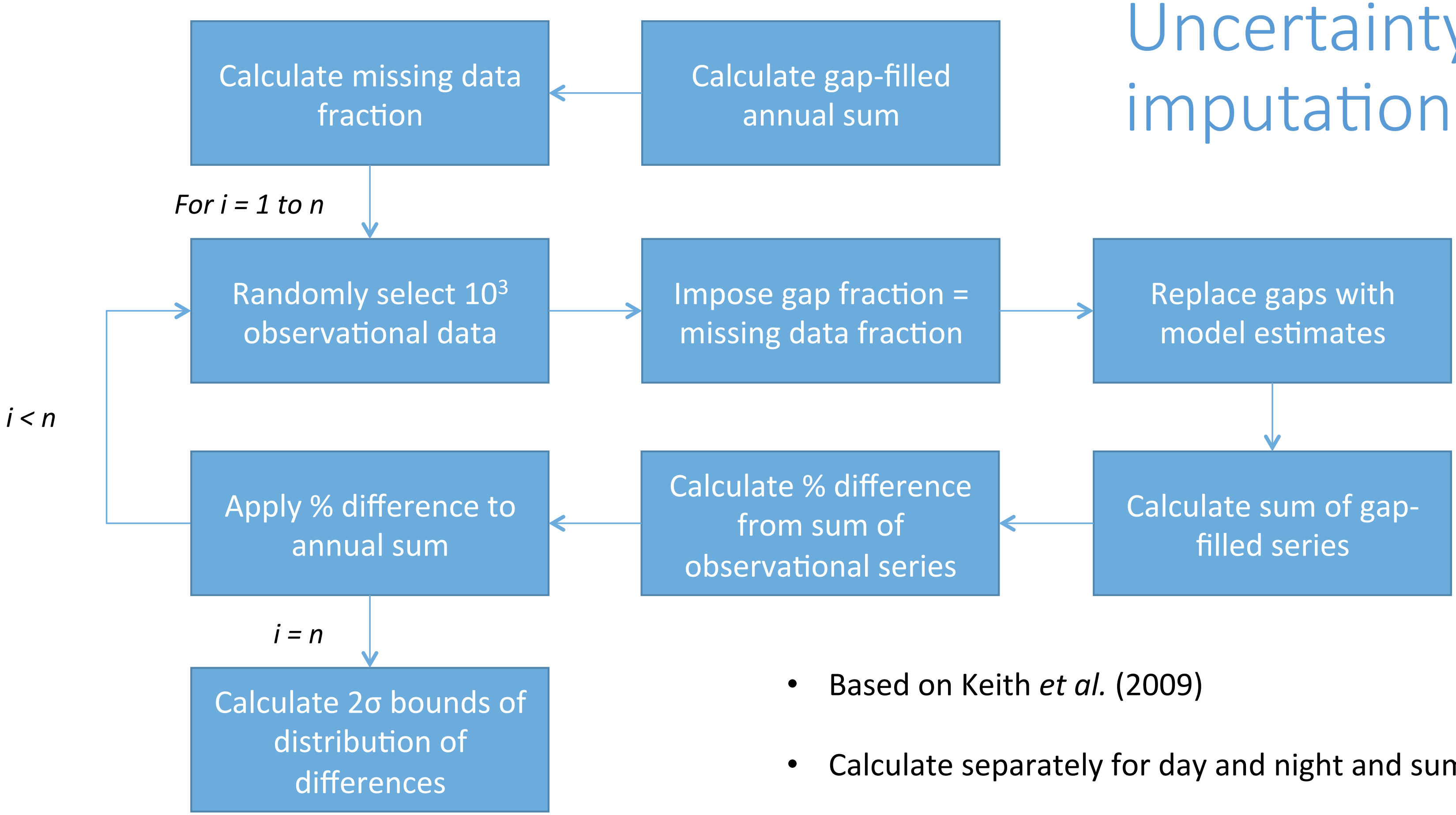
Uncertainty – random error

- Daily differencing method – random error (δ) estimated as difference between F_c pairs separated by 24 hrs
- Standard deviation of δ (σ[δ]) binned as a function of flux magnitude
- Random error estimates calculated for each observational datum from regression of σ(δ) on F_c
- Monte Carlo simulation - model-generated perfect NEE time series is degraded by noise (random draw from Laplace distribution) x 10^4
- 10^4 time series summed annually – uncertainty is 2σ bounds of distribution
- Inevitably includes footprint uncertainty and classifies signal as noise, therefore overestimates



Year	Day			Night			All
	n, %	Random	Model	n, %	Random	Model	Total
2012	8013, 91.9	7.83	8.34	2787, 31.5	5.15	11.73	17.17
2013	7776, 89.7	7.40	8.98	2795, 31.6	4.98	12.57	17.84
2014	7723, 88.9	7.91	9.57	2783, 31.5	5.03	12.10	18.05

Uncertainty – imputation error



- Based on Keith *et al.* (2009)
- Calculate separately for day and night and sum
- Necessarily includes some random error effects

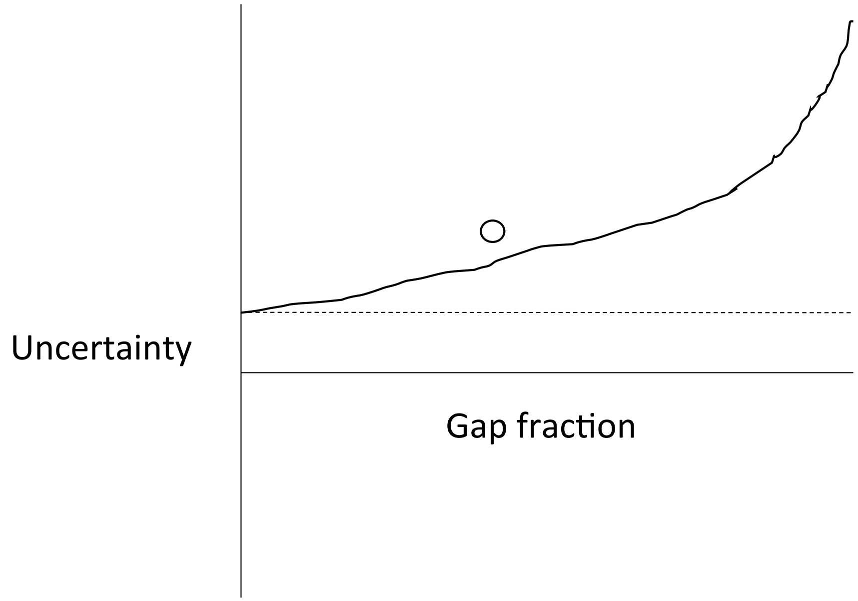
Uncertainty - partitioning error

- Generate model ER series (model parameterised from observations)

- Baseline uncertainty due to random error:
  - Superimpose noise and sum (10^4 trials)
  - Calculate 2σ of distribution of sums

- Combined uncertainty due to random error and filtering:
  - Random removal of 5, 10, 15, 20... % data
  - Superimpose noise and sum (10^4 trials)
  - Calculate 2σ of distribution of sums

- Combined uncertainty due to random error and long gaps:
  - Impose gaps
  - Superimpose noise and sum (10^4 trials)
  - Calculate 2σ of distribution of sums



Combined error

- For systematic, random, and model uncertainty, summed as:

$$\sqrt{\varepsilon_s + \varepsilon_r + \varepsilon_m}$$

- Many other unquantified uncertainties (some known and some unknown unknowns!)
- Need approaches for sites where u_{*th} not useful
- Includes effects not only of gap fraction but also gap length and timing
- Reasoning and available literature suggests we are underestimating
- If we include profile data, we need a way to characterise and propagate random error
- Uncertainties will be MUCH larger due to nature of profile measurements