Sub-canopy measurements in Hyytiälä, SMEAR II station

Samuli Launiainen's Master thesis

"Turbulenssista ja turbulenttisista pystyvoista mäntymetsän latvuston alapuolella"

TKE-yhtälö latvuston sisällä

$$0 = -\left\langle \overline{u'w'} \right\rangle \frac{\partial \left\langle \overline{u} \right\rangle}{\partial z} - \left\langle \overline{u_i'u_j'}'' \frac{\partial \overline{u_i}''}{\partial x_j} \right\rangle - \frac{\partial}{\partial z}\left(\frac{\left\langle \overline{p'w'} \right\rangle}{\rho} + \frac{1}{2}\left\langle \overline{w'u_i'u_j'} \right\rangle + \frac{1}{2}\left\langle \overline{w}''\overline{u_i'u_j'} \right\rangle \right) - \left\langle \varepsilon \right\rangle + \frac{1}{\rho}\left\langle \overline{v_i'd_i'} \right\rangle$$

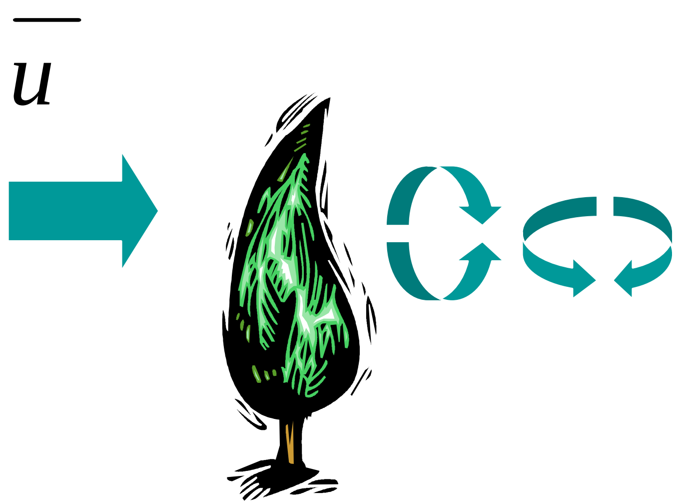
1 2 3 4 5 6 7 (16)

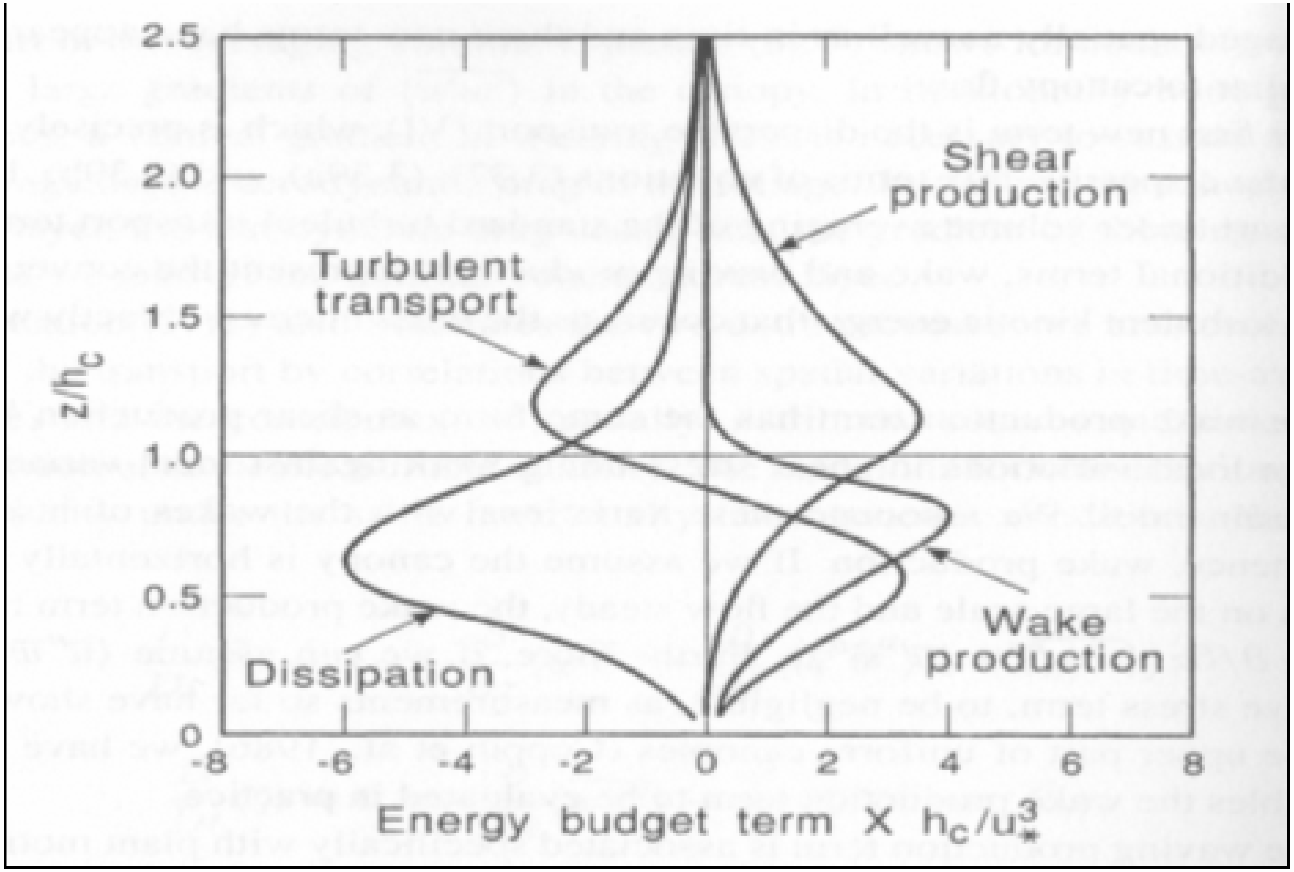
Terms 1,3,4,6 as in constant flux layer:

Term 2: ”wake effect”; production

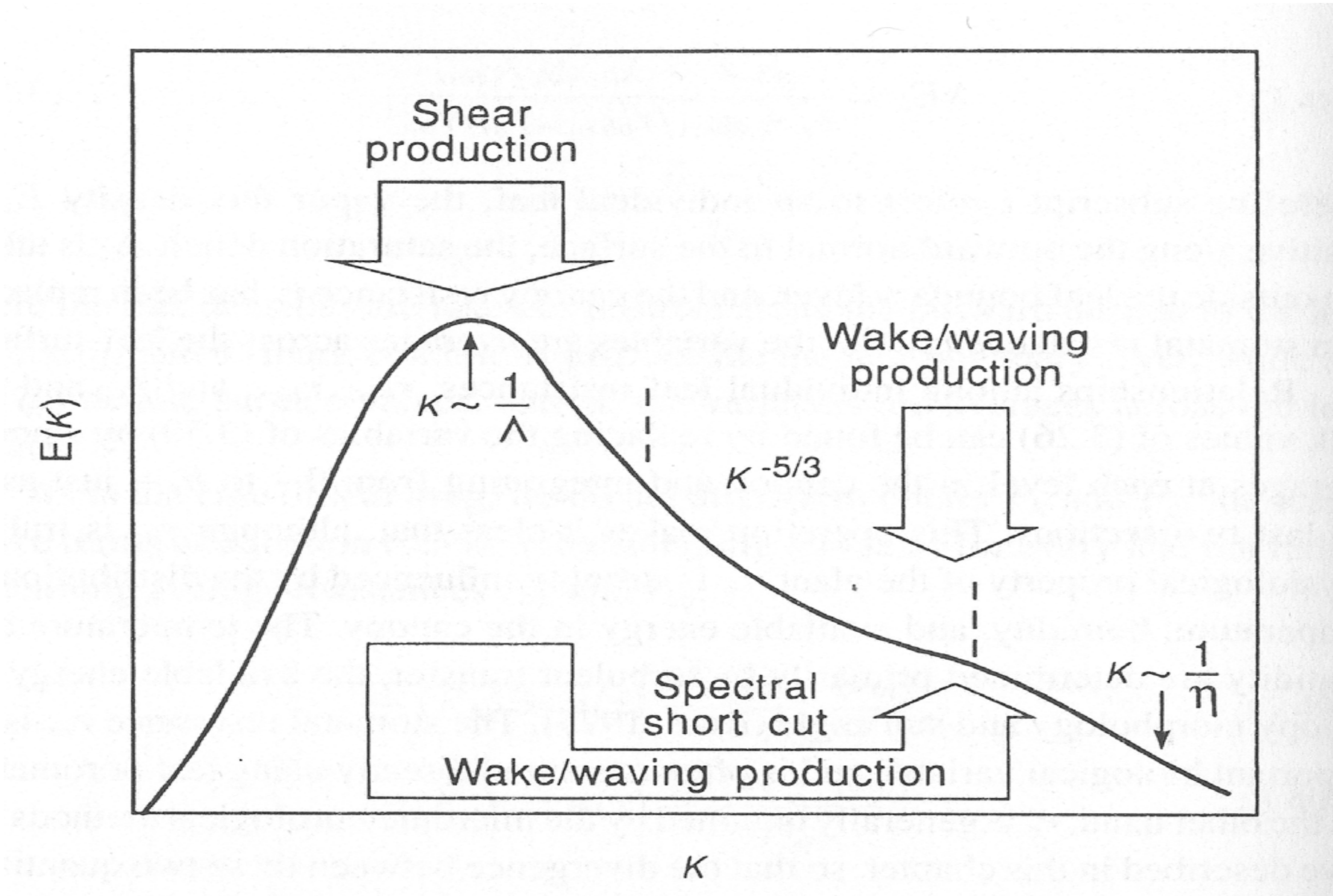
Termi 5: ”dispersive flux”; upward transport

Term 7: waving; net sink





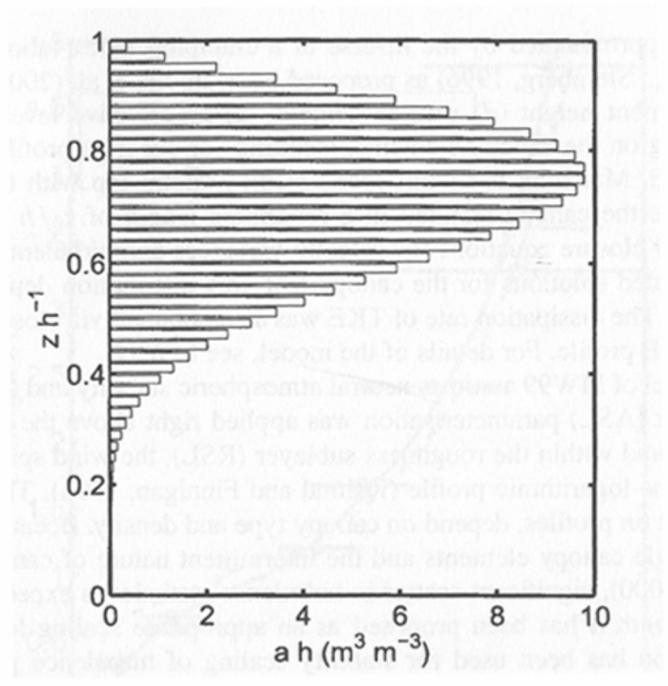
Kuva 3: Turbulenssin kineettisen energian (TKE) taseen suurimpien termien merkitys latvuston sisällä ja yläpuolella. Tuuliväänne (shear production) ja vanavesiefekti (wake production) tuottavat turbulenssin kineettistä energiaa, jota turbulenttinen kuljeustermi (turbulent transport) siirtää latvuston alaosiin, missä dissipaatio on voimakasta. Pystyakseli on normitettu latvuston korkeudella (Kaimal ja Finnigan 1994).



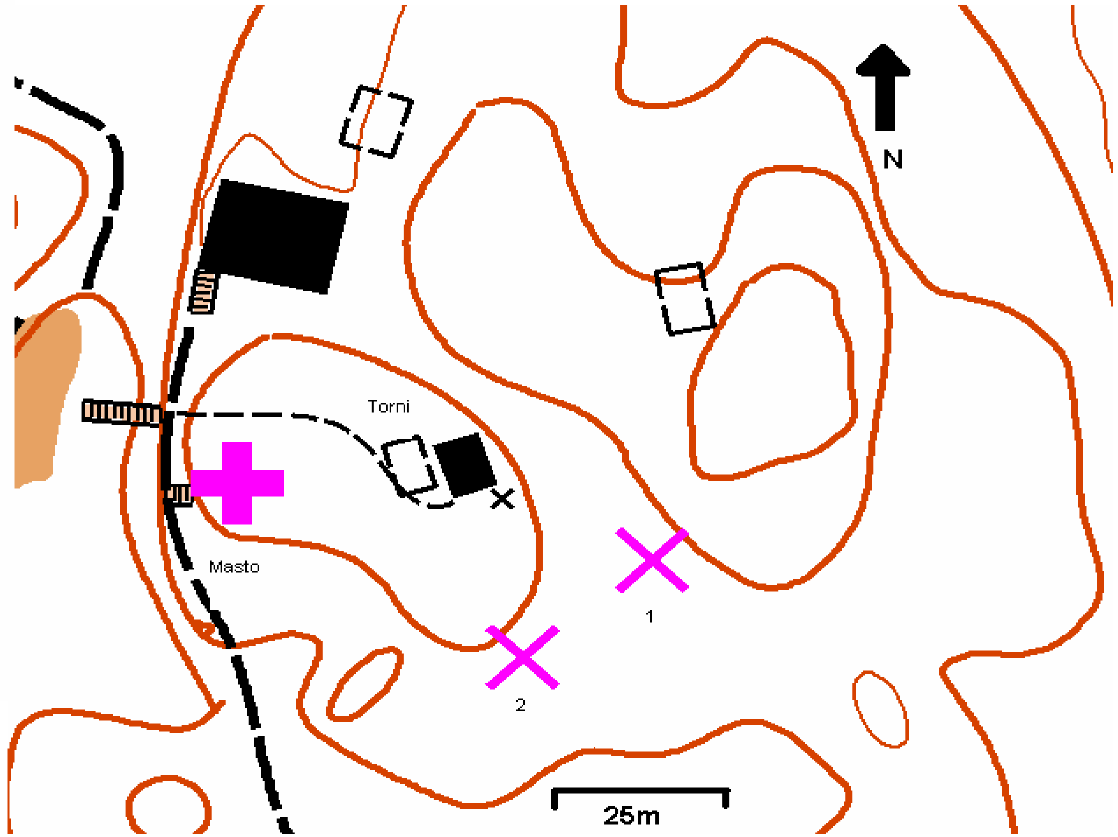
(Kaimal ja Finnigan (1994): Turbulent boundary-layer flows: Their structure and measurement, Oxford Univ. Press)

Measurement site and methods

- Hyytiälä SMEAR II –station in Juupajoki, Southern Finland
- Measurements at 3m heigth above ground in a sub-canopy trunk space
- height of the trees (scots pine) h=14m:
  - measurement height z=0,2h
- foliage consentrated to the upper part of the canopy: measurements in trunk space
- continuous measurements from september 2003→
- supporting measurements: all mast measurements, soil temperature, PAR and R_n 1m above ground (august 2004→)



vertical distribution of LAI
in Hyytiälä scots pine canopy
(Rannik et al. 2003)



Map of the SMEAR II –site. Large cross is 73m main tower, small crosses places where EC-measurements were made. Contour interval 2-3 meters.

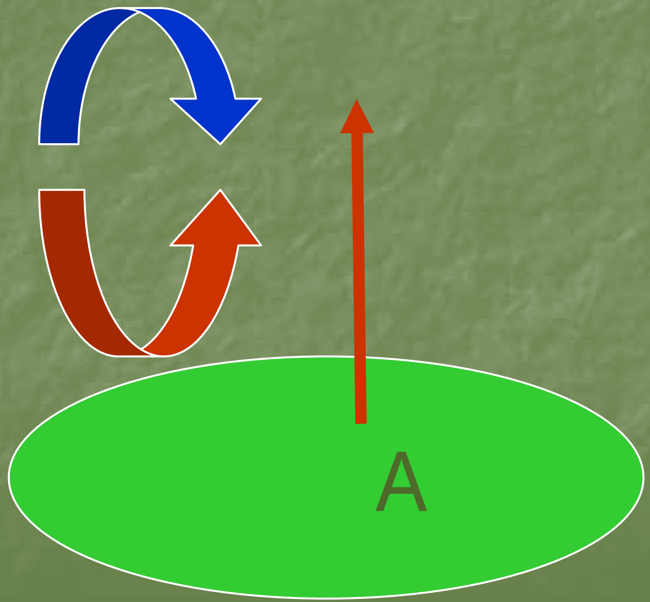
EC-systems

- Consists of a fast ultrasonic anemometer and a closed-path infrared gas analyzer connected by a sampling tube
- sampling frequency 10Hz, 3-D co-ordinate rotation, 30min ave., stationarity check & vertical mixing criterium
- 2 different setups:
  - results are compareable
  - 1) Solent + LiCor 6262:
    - September 2003 – January 2004, June 2004→
  - 2) Metek + LiCor 7000:
    - February 2004 – June 2004

Eddy covariance measurements

- A flux is defined as: ”amount of substance/area/time” (typically a flux density is used: amount/unit of area/unit of time)
- EC-flux: a covariance between instant fluctuations of vertical velocity (w’) and a substance s (s’)
- typically 30min average
- signs: ”-” downwards

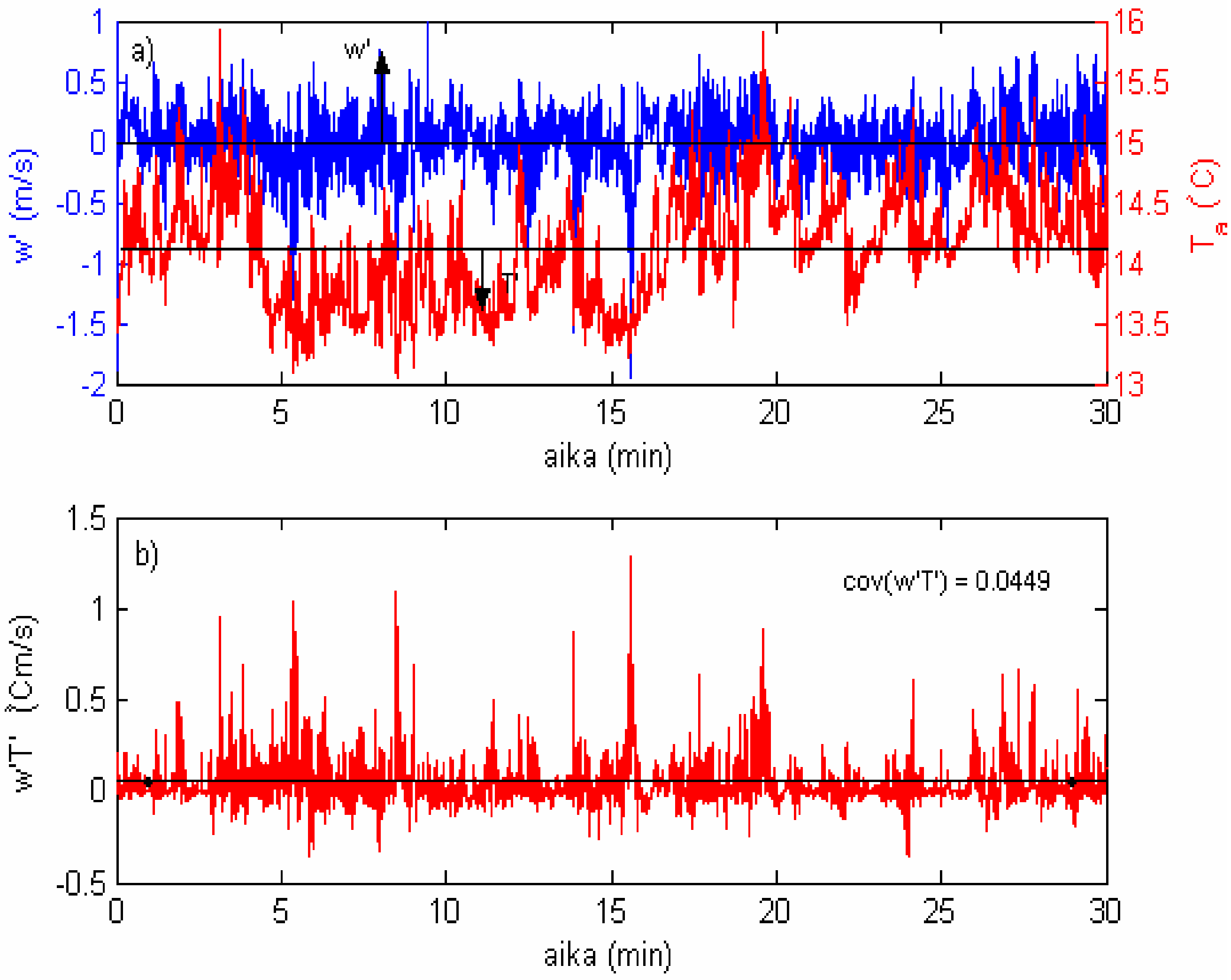
$$F = \overline{w's'}$$



- The site is heterogenious from micrometerorologial point of view:
  - stationarity? homogenity?
  - enough turbulence?
  - flux and consentration footprint?
- We measure fluxes inside roughness sub-layer: the flux is not constant with height!
- No universal similarity theories for a flow inside canopy
  - no ”valid” easy-to-use methods for flux measurements, calculation or quality check
  - friction velocity criterium doesn’t work
  - much empirical work needed!

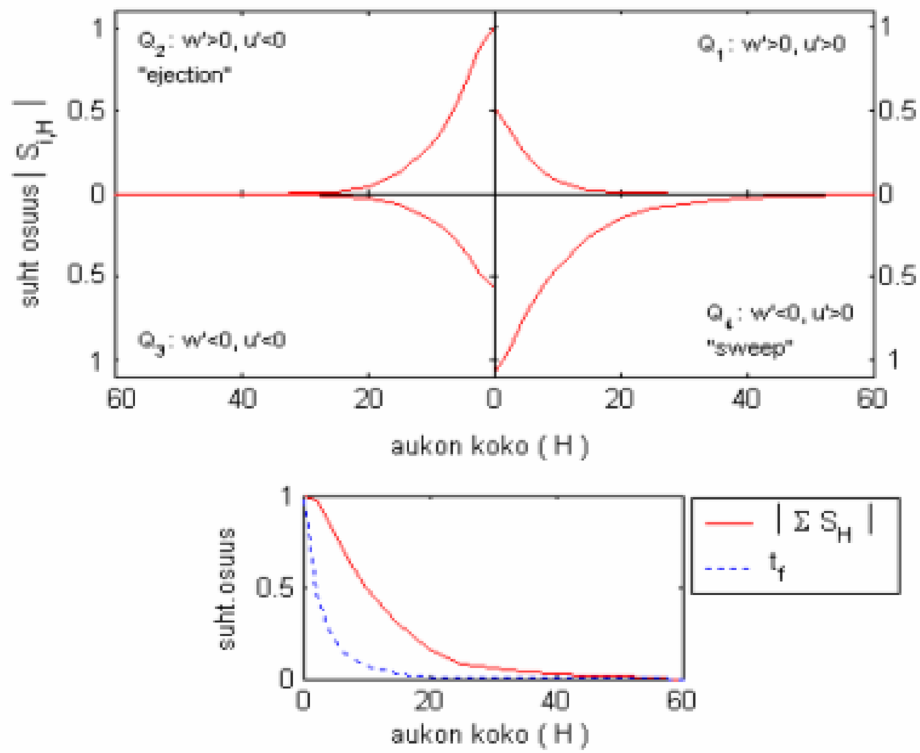
A ”constant” flux ?

- Inside a forest canopy turbulence is intermittent and the fluctuations of 3 wind components are of the same order as the mean wind (*U*):
  - turbulence intensity is high and the flow field is highly variable in time and space
  - Total flux is an average of numerous momentary products of fluctuating components w’ and s’:
    - different signs of w’ and s’ → four possible ”Quadrants” and TWO possible flux directions: up and down
    - ”flux is typically a small sum of strong opposite events”



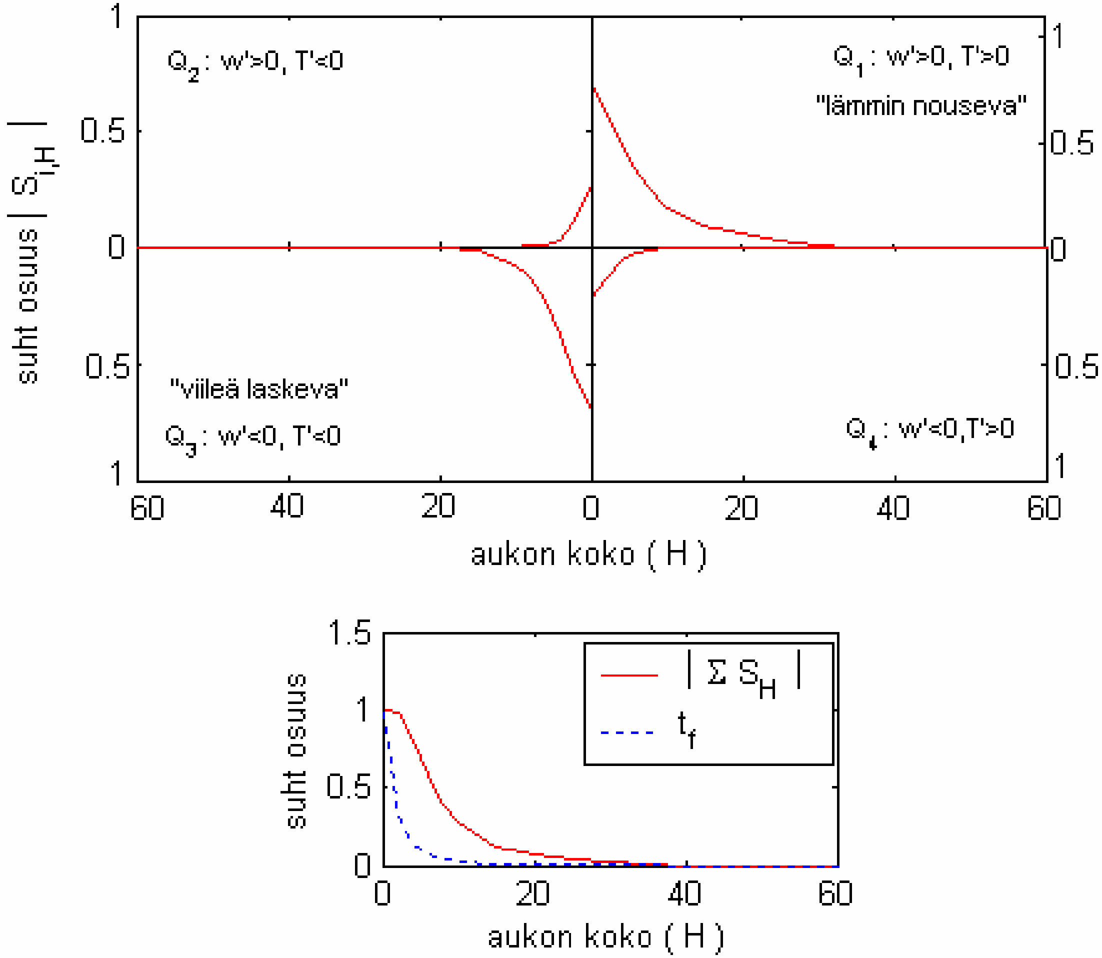
momentary values of: a) vertical wind (w) and air temperature (T_a)
b) product of w'T' with corresponding average cov(w'T')=total flux

Quadrant analysis



Kuva 18: Liikemäärävuon (τ) koostuminen eri neljänneksistä ja eri vahvuisista tapahtumista u'(t)w'(t). Alakuvassa kokonaisvuon koostuminen eri vahvuisista tapahtumista ja näihin kulunut aika t_f .

Quadrant analysis: *H* on a sunny summer day



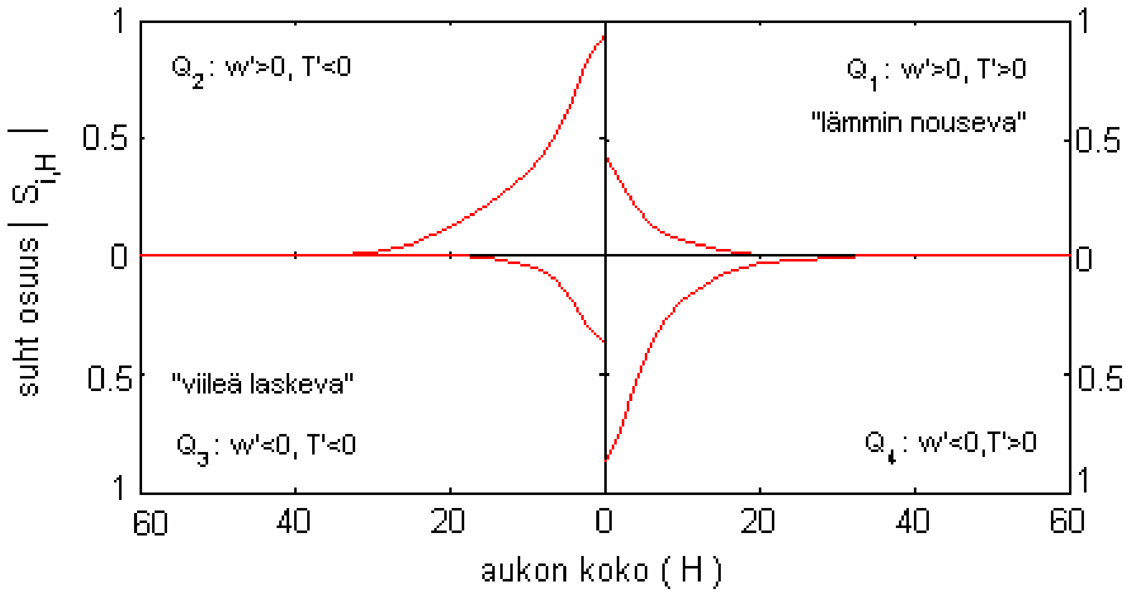
Q_1 and Q_3: upward flux

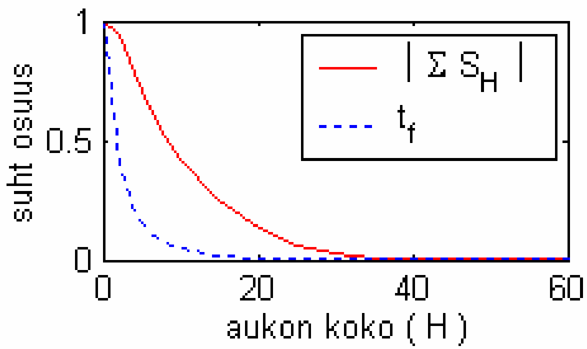
Q_2 and Q_4: downward flux

TOTAL flux is sum of these!

The formation of sensible heat flux from different quadrants (instant products w'T')

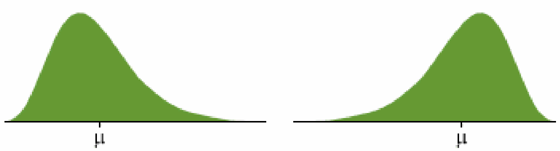
Quadrant analysis: *H* on a clear stable night





The formation of sensible heat flux from different quadrants (instant products w'T')

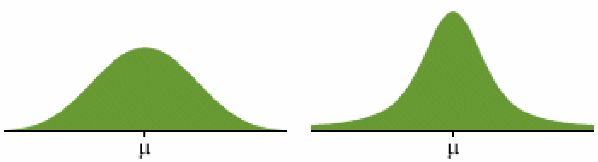
Positive vs. Negative Skewness
Exhibit 1



These graphs illustrate the notion of skewness. Both PDFs have the same expectation and variance. The one on the left is positively skewed. The one on the right is negatively skewed.

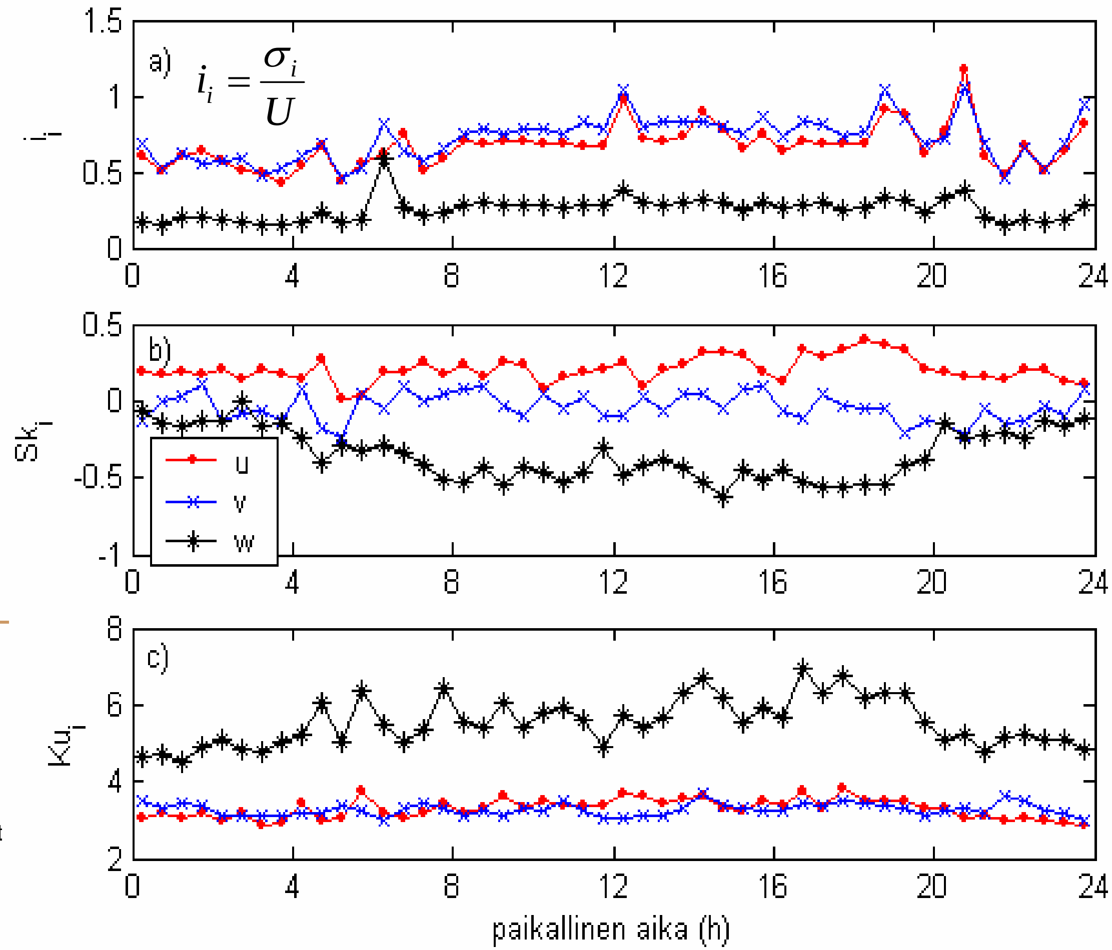
$$Sk_j = \frac{\overline{u_j'^3}}{\sigma_j^3}$$

Low vs. High Kurtosis
Exhibit 1



These graphs illustrate the notion of kurtosis. The PDF on the right has higher kurtosis than the PDF on the left. It is more peaked at the center, and it has fatter tails.

$$Ku_j = \frac{\overline{u_j'^4}}{\sigma_j^4}$$



Normaalijakaumalle:
Sk_i=0, Ku_i=3
(vakiovuokerroksen turbulenssi!)

(jakaumat: http://www.riskglossary.com/articles/kurtosis.htm)

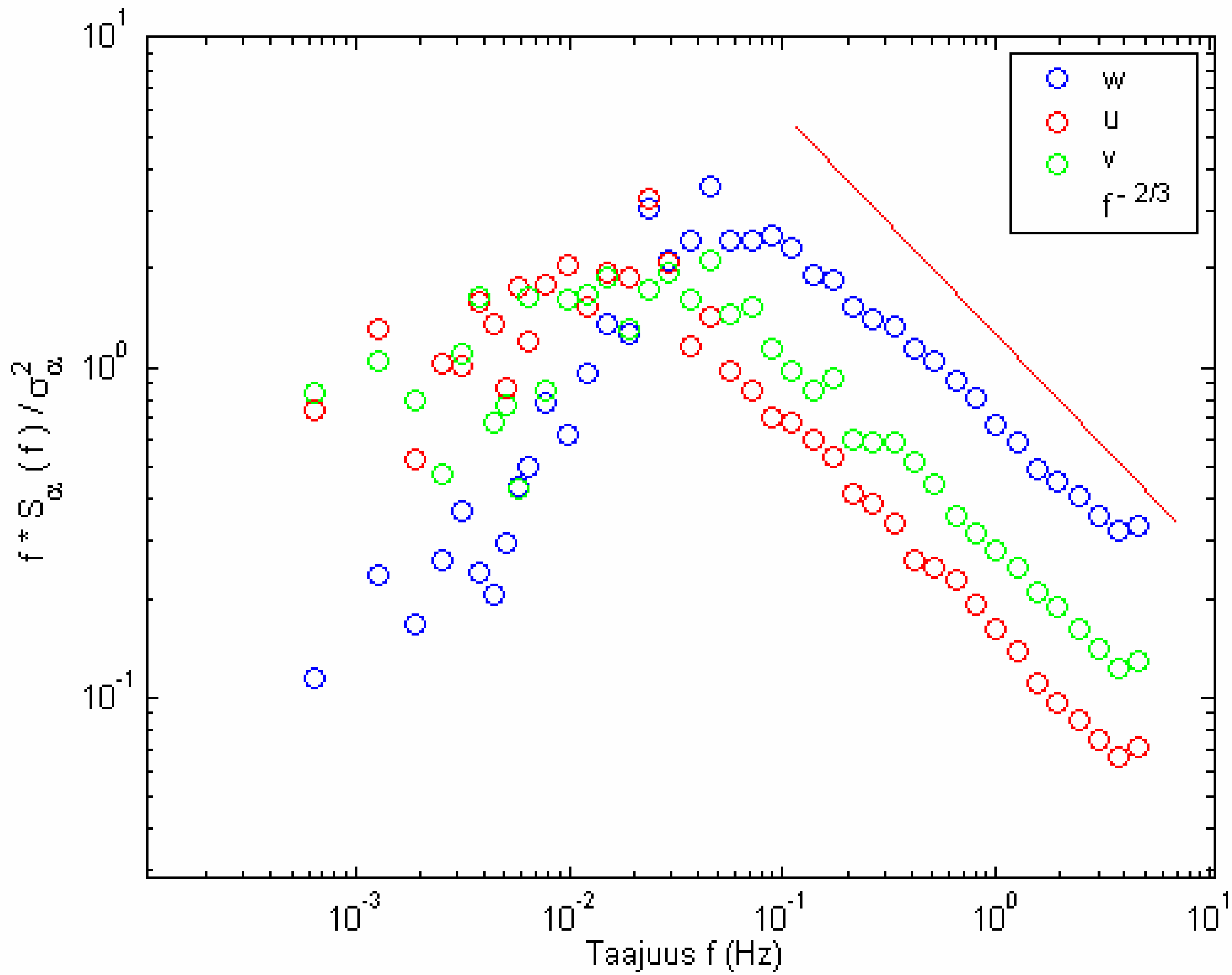
The structure of turbulent vertical fluxes in sub-canopy

- The turbulence and thus the fluxes are intermittent; large part of the flux is ”delivered” in short time (5-15% of total time)
- Small sum of strong events with different signs (different direction): especially H_2O and CO_2 –fluxes
- So, the large eddies dominate the mass and energy transfer (?)

Turbulence spectra

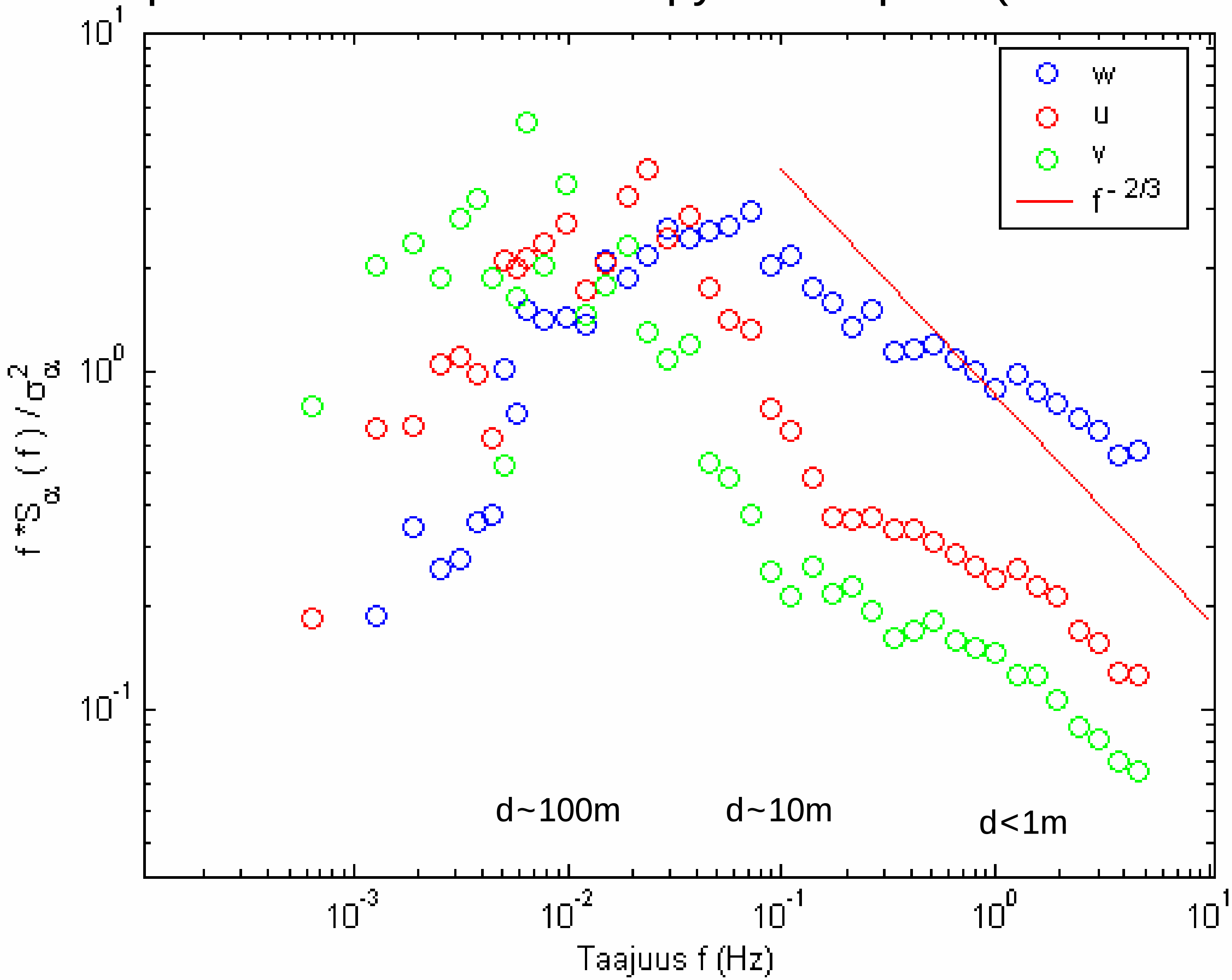
- Any time serie can be transformed into frequency domain by Fourier-transform: this means that any time serie can be represented as a sum of n sinus or cosinus functions.
- Power spectrum: each Fourier-component shows how much of the total variance is located in that frequency
- Cospectrum: an integral of the cospectrum = total flux; each Fourier-component shows the contribution of that frequency to total flux

Power specra of u, v and w above canopy (23m)



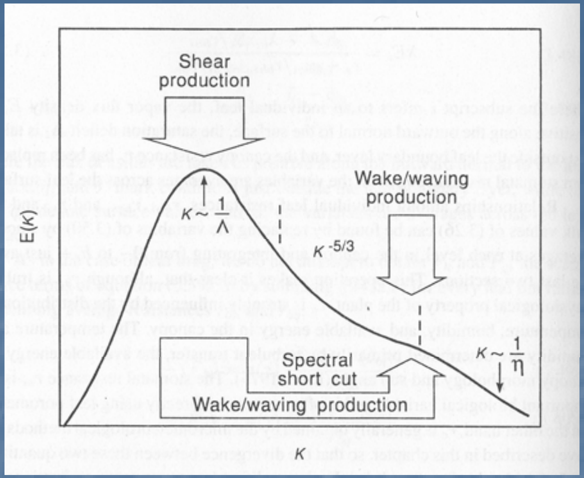
Frequency weighted power spectra normalized by total variance and plotted as a function of frequency(Hz). Red line represents inertial subrange behaviour suggested by Kolmogorov.

Same as previous but in sub-canopy trunk space (3m above ground)

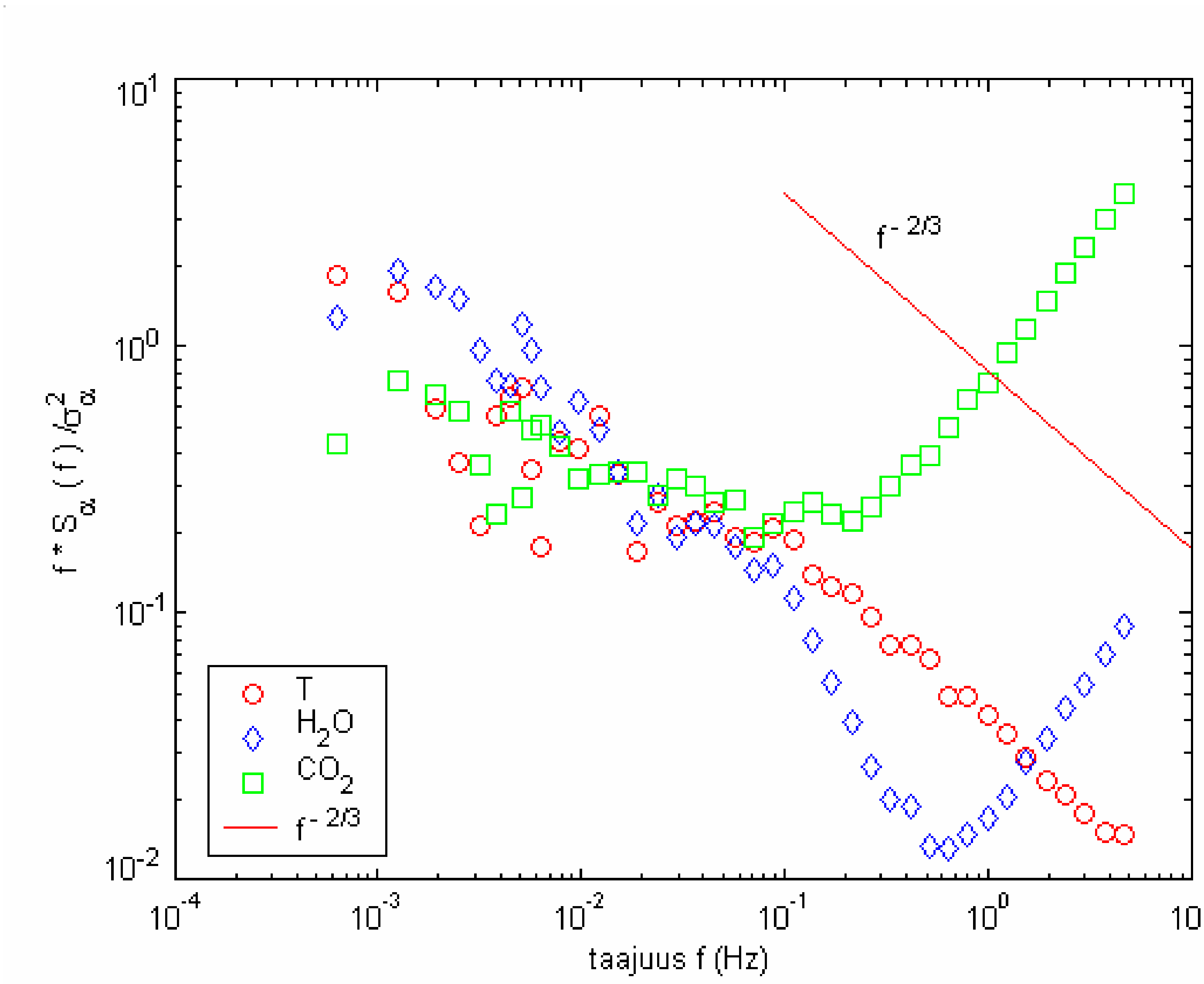


Note that the slope of u and v components are more than -2/3 in low frequency end and less than -2/3 in high frequency end of the inertial subrange

”The spectral short cut”

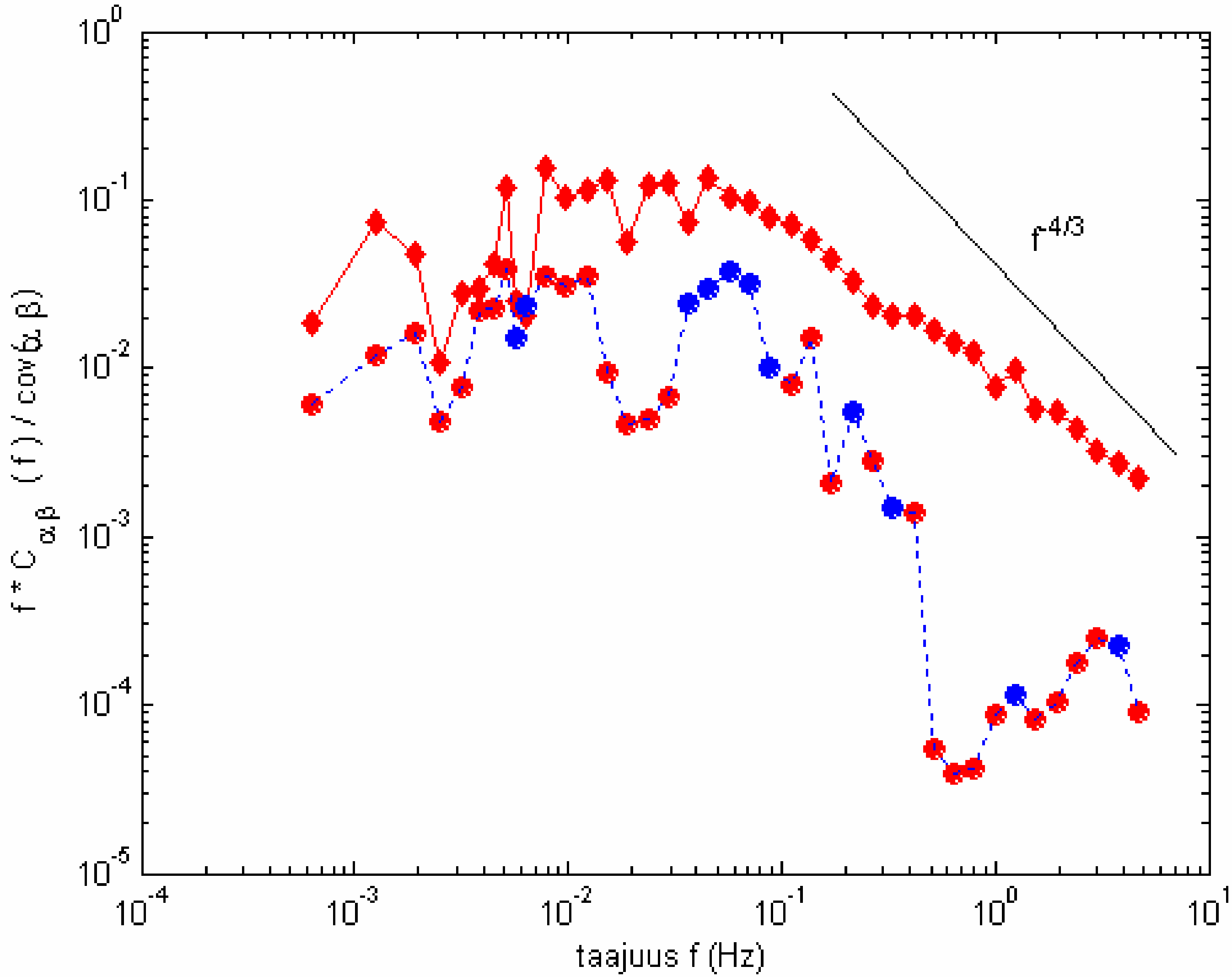


- Mean flow kinetic energy (MKE) is transformed into turbulent kinetic energy (TKE) especially in turbulent wakes formed behind individual roughness elements.
  - large mechanical creation of turbulence
- Also large eddies (30-100m) are affected the same way: TKE converted directly into smaller eddies in turbulent wakes
  - high dissipation rate of TKE, ”spectral short cut” → TKE is feeded into smaller eddies (size under 10m, note ”a kink” in power spectra + slope less than -2/3 at high frequencies)



Frequency-weighted power spectra of temperature, H_2O and CO_2

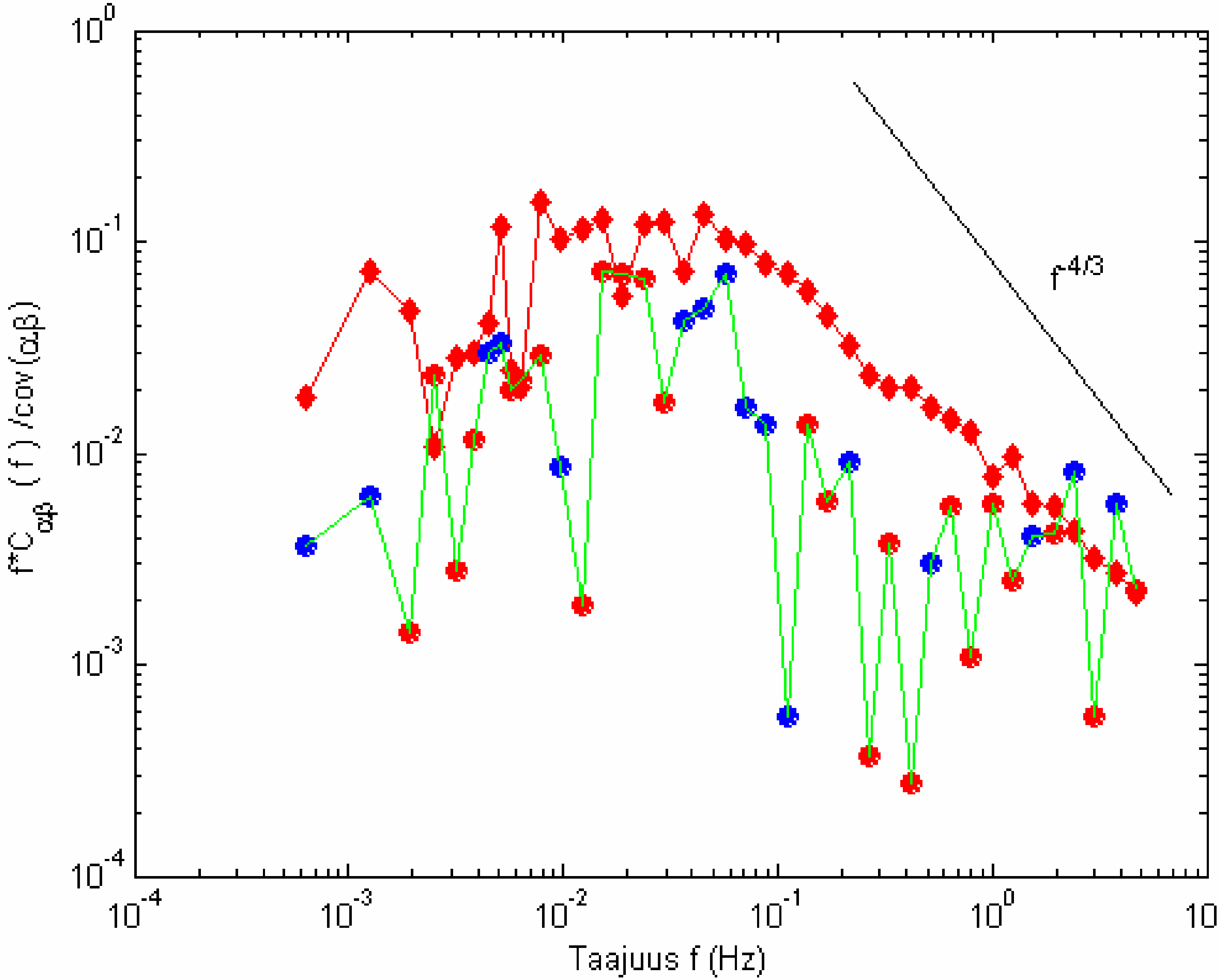
Frequency weighted cospectra of w'T' and w'q' (water vapour flux) normalized by total covariance and plotted against frequency



red markers: contribution to total flux is positive; (upward flux).
blue markers: negative (downward) flux. Total fluxes are positive.

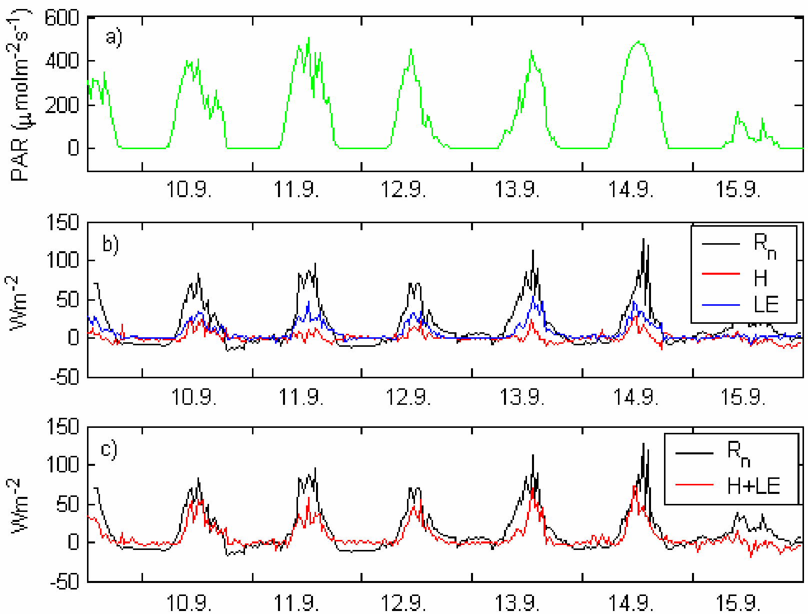
Cospectra: which frequencies contribute most to the flux?

- Spectral maximum typically at frequencies 10^{-2} → eddy size ~100m.
- For water vapour flux: downward flux at frequencies 3-8x10^{-2} → 30-15m eddies transport humidity downwards → ”mixing air inside canopy” (large H_2O source in foliage-layer daytime) → co-gradient flux
- Large eddies (>~30m) transport moisture away from canopy to atmosphere and dry the canopy air → positive, upward flux → counter-gradient (?) flux.
- Smallest eddies (<5m) transport moisture from surface upwards: no connection with the foliage
- NET TRANSPORT OF H_2O UPWARDS because LARGE EDDIES DOMINATE THE TRANSFER.



CO_2 flux: more variability → random variation in flux direction; total flux small daytime. Uncertainty of each Fourier component is large.

Energy balance closure

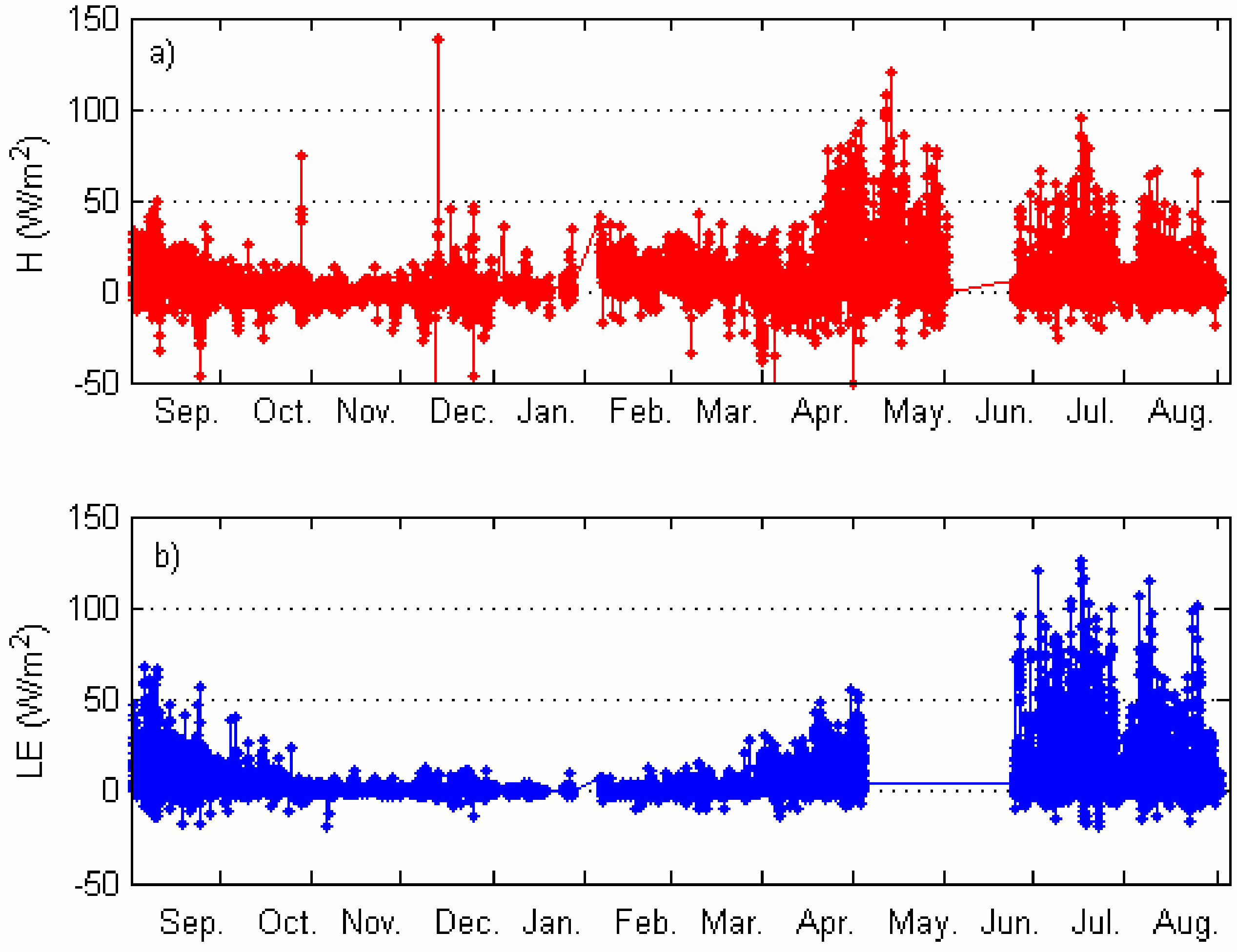


a) PAR (23m), b) $R_{n(1m)}$, H and LE
c) $R_{n(1m)}$ and H+LE

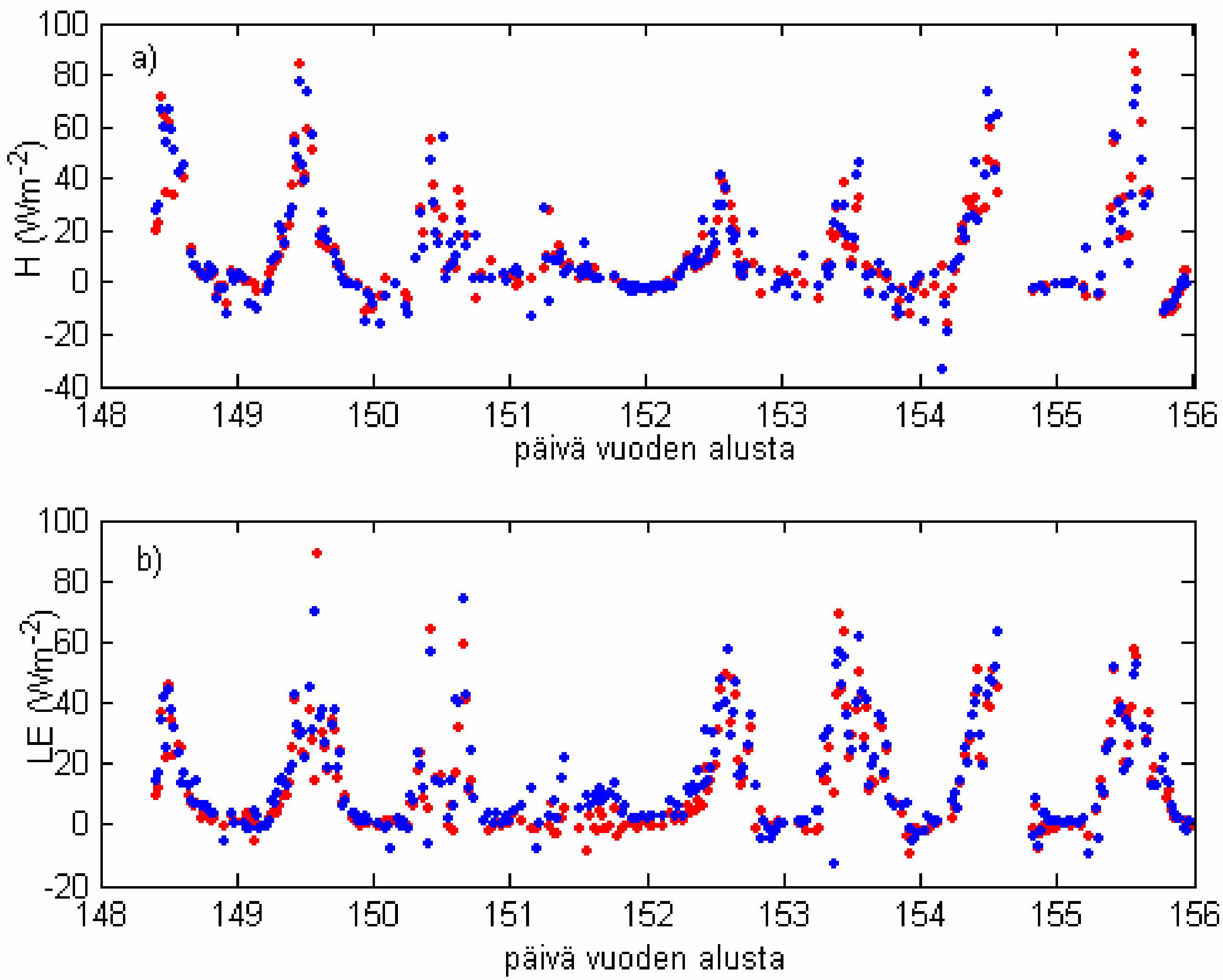
figure from september 2004

- Energy balance closure above soil surface: cumulative $H+LE=0,5R_n$
  - no ground heat flux measured; should improve the balance
  - fixed R_n sensors
  - R_n only slightly negative on nighttime (back-radiation from the canopy crown)

Annual variability of H and LE

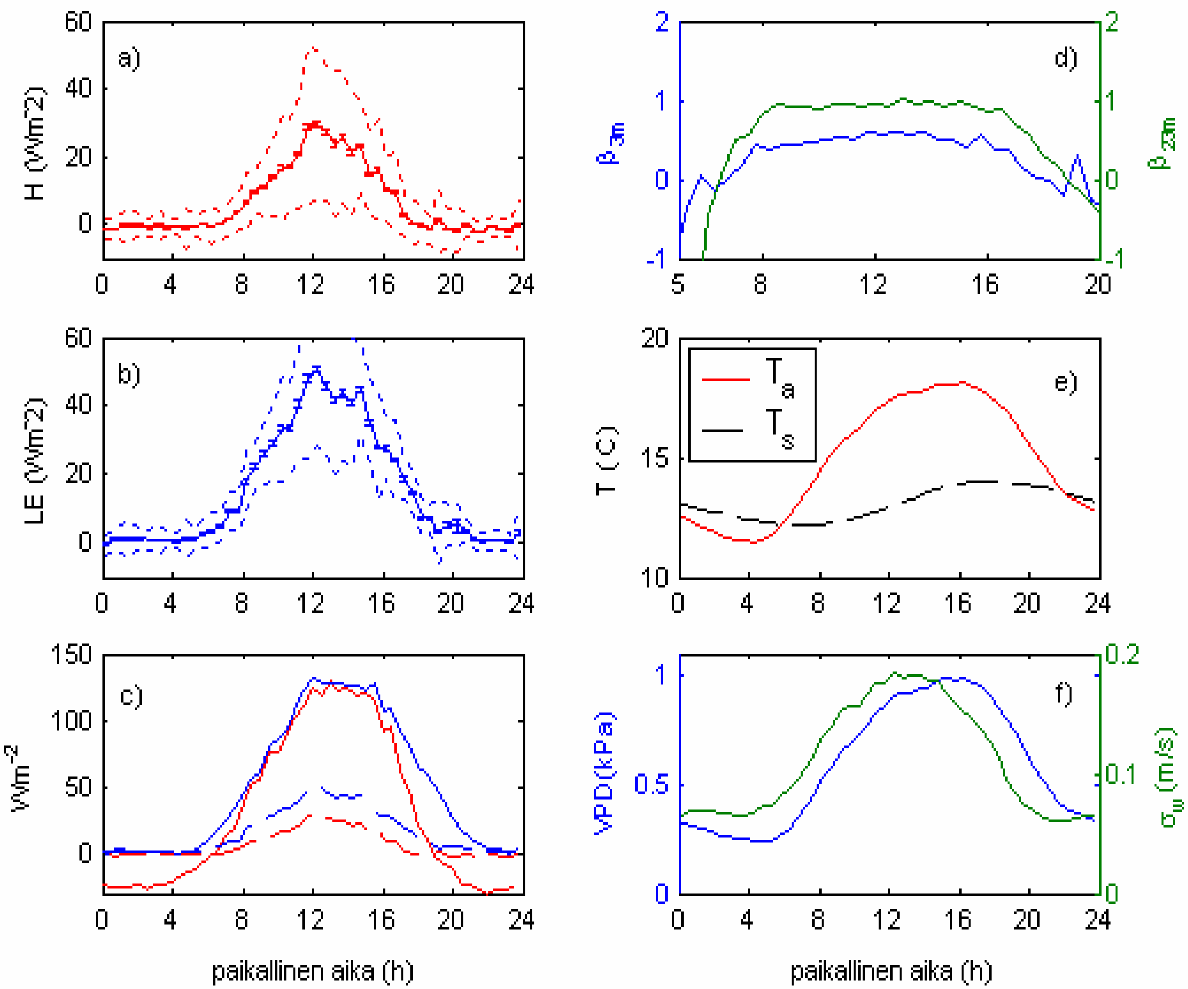


Typical diurnal variation of H and LE for 8-day-period in the beginning of June.



a) sensible heat flux (H) and b) latent heat flux (LE) in May-June 2004: intercomparison of the measurement systems. (Solent=red, Metek=blue)

Diurnal variability of H and LE



a) H, b) LE at 3m, c) H and LE 23m and 3m,
d) Bowen ratio 23m and 3m, e) Ta, Ts, f)VPD and std(w)

Heat fluxes: H and LE

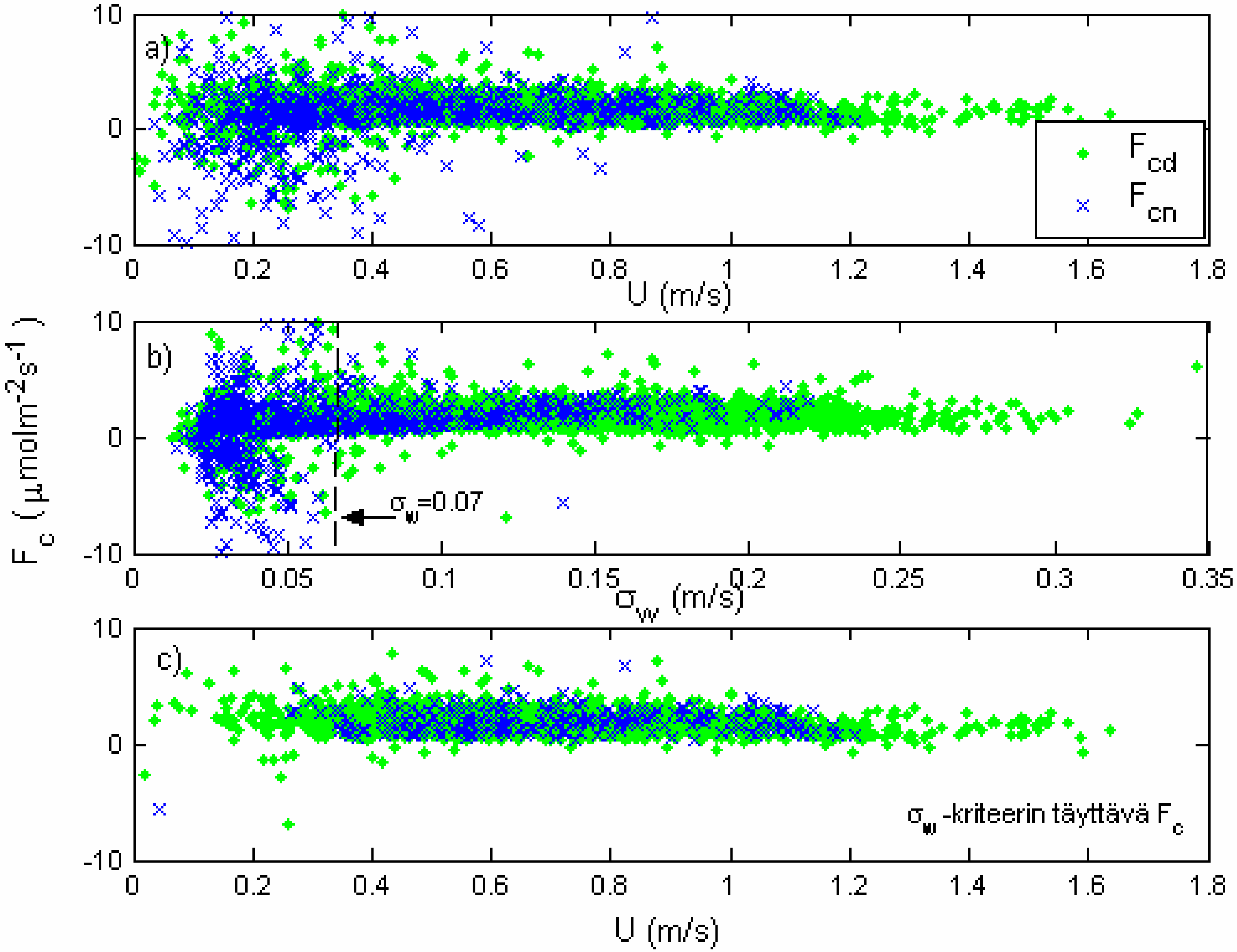
- Clear diurnal and annual variations
- typically: H<+80Wm^{-2}, LE<+100Wm^{-2}
- mean midday Bowen ratio at 3m: ~0,4-0,5
- July-August: mean maximum H~ +20 Wm^{-2}
  - about 20% of above canopy H
  - on summer: only slightly negative nighttime
- mean maximum LE~ +40Wm^{-2}
  - about 30% of above canopy LE; soil & understory responsible for

  ~1/3 of total evapotranspiration(?)
  - note: different footprints
- Not only H but also evaporation measurements seem to be OK!

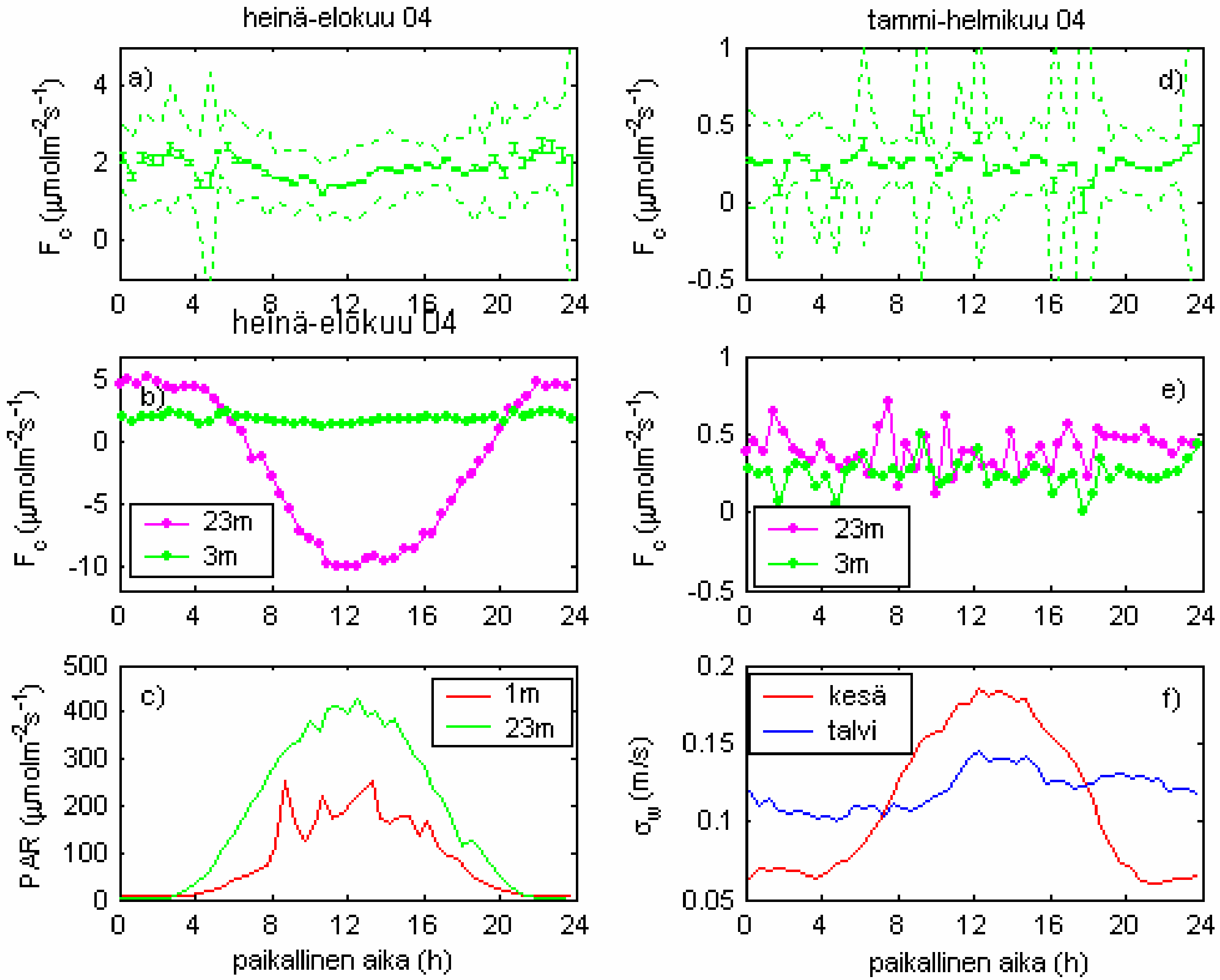
Sub-canopy CO_2 -flux

- Important to ensure the quality of each 30min observation:
  - Non-stationarity test (Foken & Wichura 1996) (FS<100% has been used, totally empirical limit)
  - standard deviation of vertical velocity (std(w)) has been used as ”mixing criterium”; there has to be enough turbulence because:
    - basic assumption when using EC-method
    - we want to measure net exchange between soil & understory and atmosphere:
      - minimum storage of CO_2 below measurement height:

      → specially important when no profile measurements
- std(w) criterium: analogy to friction velocity
- Soil and air temperature control CO_2-flux:clear annual variation
  - relationship between F_c and T_s, T_a can be used for gap-filling
  - $F_c = aT_s + b\exp(cT_a)$

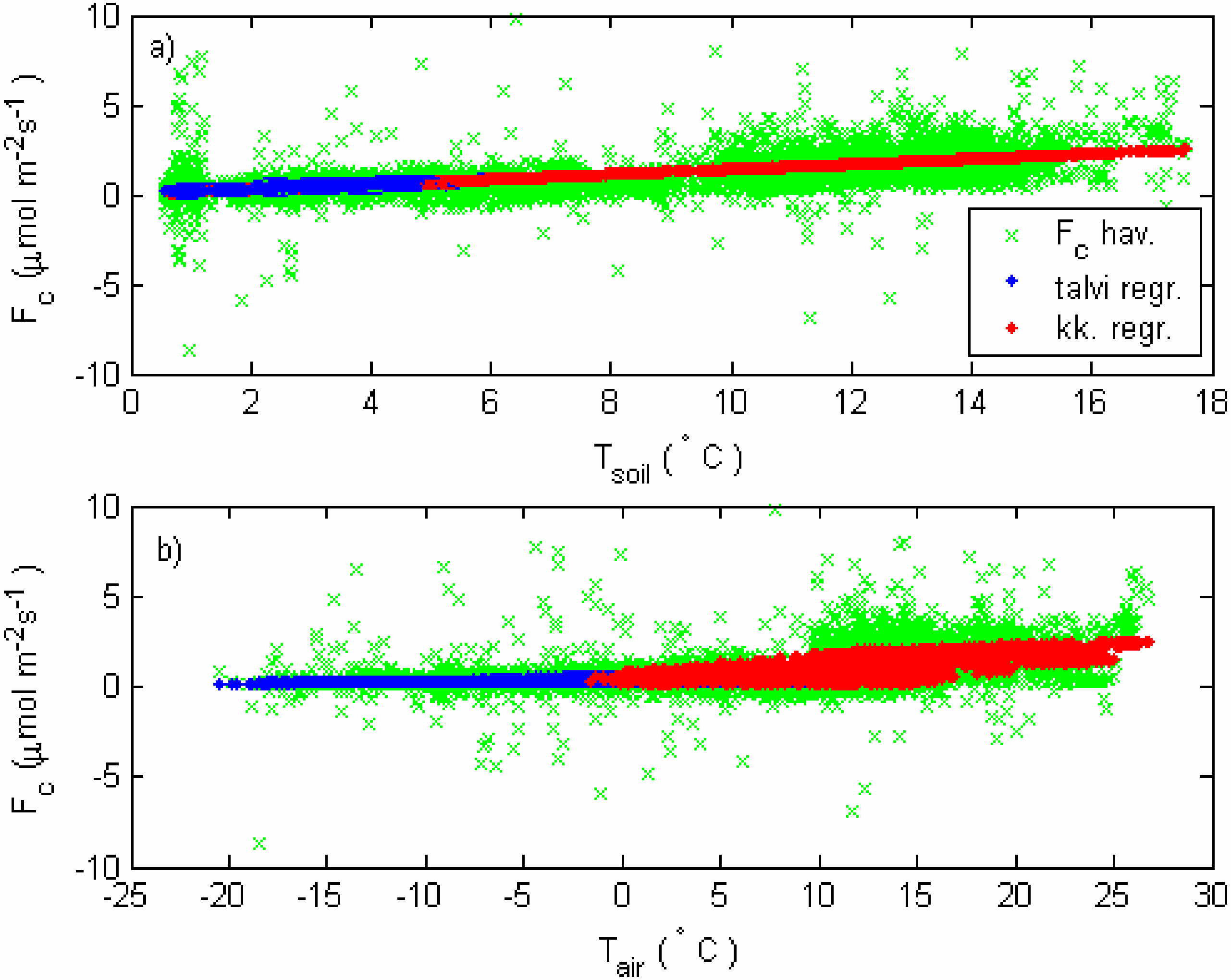


CO_2-flux as a function of a) mean wind speed (U), b) std(w) and c) U when data has filtered by std(w) criterium. x represents nighttime observations



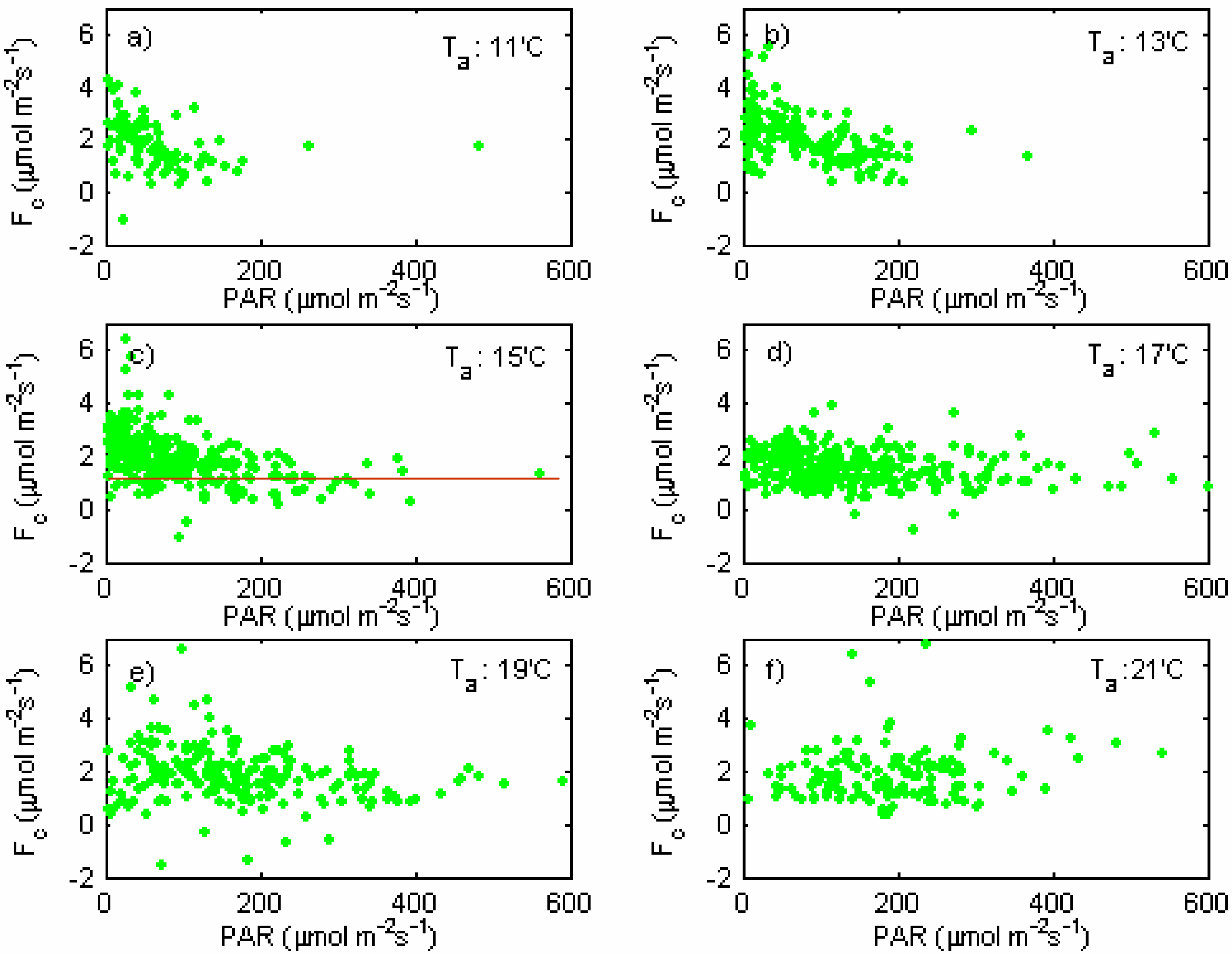
Average diurnal variation of CO_2-flux in july-august: a)F_c (3m), S.E. and std(F_c), b)F_c (3m and 23m) and in january-february: d) and e)

Figs. c and f show the variability of PAR (1m and 23m) and std(w)



$$F_c = aT_s + b\exp(cT_a)$$

CO2-flux as a function of a) soil temperature Ts , b) air temperature Ta
Red: regression estimates for Fc (growing season)
Blue: -”- (wintertime)



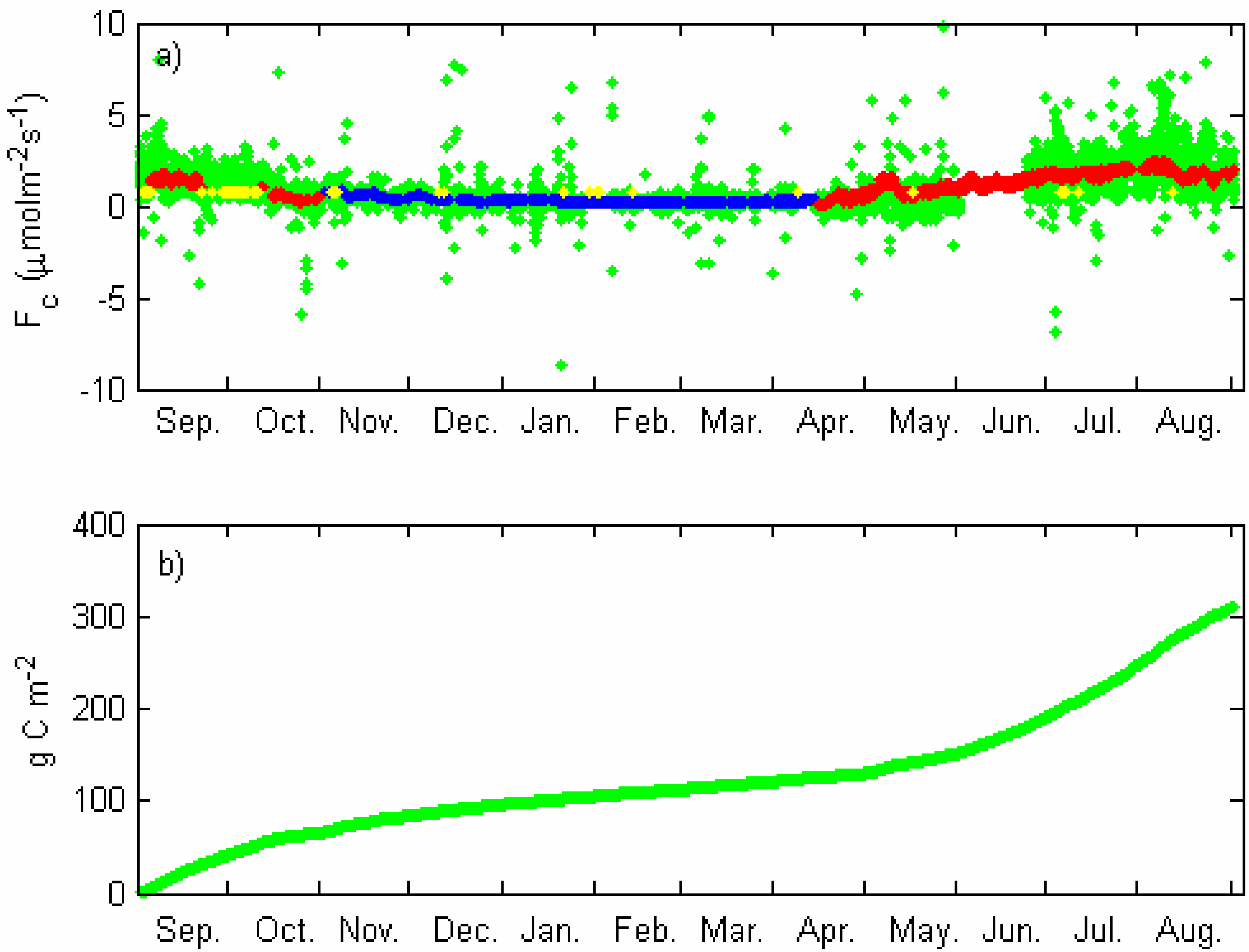
Päiväaikaisen F_c:n PAR-riippuvuus 2'C lämpötilaluokittain. Kuvassa välin keskilämpötila.

CO_2-flux as a function of photosyntetically active radiation (PAR) in 2´C air temperarture classes.

Diurnal variability of sub-canopy CO_2-flux:

- July-August:
- R ~ 2 µmolm^{-2}s^{-1} nighttime (maximum on the morning when sun rises → more mixing
- Minimum at noon:
  - photosynthesis of understory
  - time lag in soil temperature
- Rises again on afternoon:
  - soil temperature increases
    - soil respiration increases?
  - air temp. increases
    - effect on photosynthesis?
- ”clear diurnal variation”
- T_s+T_a explains 40% of variation

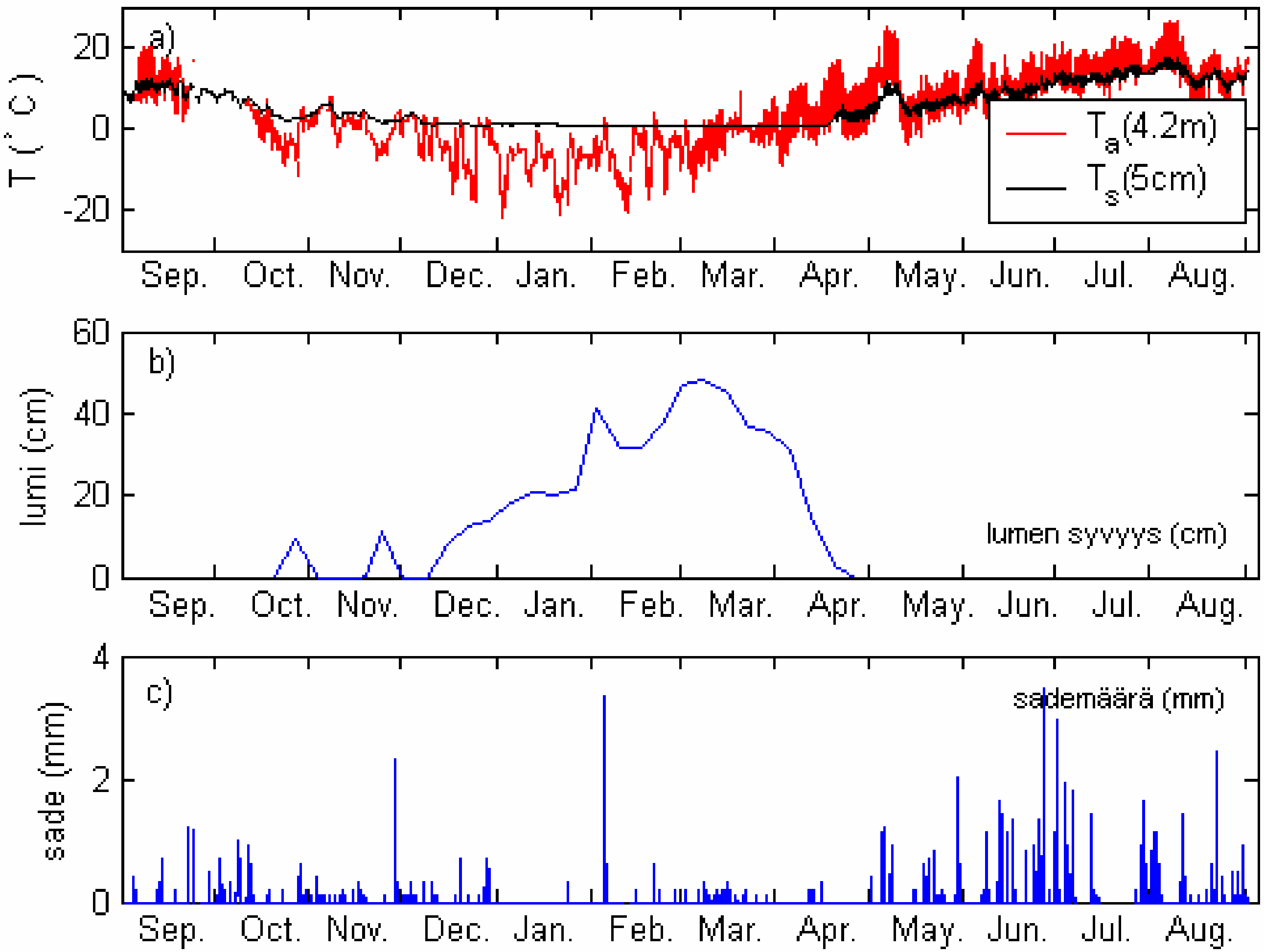
- January-February:
- R ~ 0,2-0,4 µmolm^{-2}s^{-1}
- ”random variation”
- T_s+T_a explains only 10% of variation



a) Gap-filled 30min CO2-flux 3m above ground below a scots pine canopy.
Green: observations, blue: regression estimates (winter), red: regression estimates (growing season), yellow: filled by average
b) Cumulative NEE over measurement year

Sub-canopy F_c compared to F_c above canopy

- Summertime: 35-45% or total ecosystem respiration below 3m level
- Wintertime: R_{sub} ~ 0,55-0,65R_e
- Photosynthesis of understory
  - CO_2 –uptake 1,0-2,0 µmolm-2s-1
  - F_c still positive (on average) whole day
- Soil + understory a net source of carbon whole year
  - NEE at 3m: +311 +/- 40 g(C)m-2
  - minimum on wintertime when T_s and T_a are low
  - maximum on july-august when T_s is high
- Based on EC measurements: soil + understory responsible for ~ 35-40% of annual ecosystem respiration



a) air and soil temperature (5cm depth)
b) snow depth (cm)
c) rain (mm)

Conclusions

- Eddycovariance method can be used below a relative sparce coniferous forest canopy if
  - the site is considered ”homogenious”
  - fluxes are stationary
  - there is enough turbulence present
    - enough vertical mixing

- Results comparable with earlier results from other sites measured by EC.
- Turbulence structure and the structure of turbulent fluxes inside canopy are different from those typically observed above forest
- Structures similar to those represented earlier and by ”theories”. Changes in turbulence spectra indicate the interaction effects between canopy elements ant the flow. (e.g. Raupach and Thom 1981, Kaimal and Finnigan 1994, Finnigan 2000)
- Values of H_2O and CO_2 –fluxes can be underestimations up to 10-20% because no correction for high-frequency losses has been made.

Future work?

- The use of stationary and std(w) mixing criteria is encouraged
- Ground heat flux measurements → energy balance closure below and above canopy
- Profile measurements of CO_2, H_2O and T_a below EC-measurement height
  - possible storage flux below measurement height
- Temporal and spatial variability inside canopy
  - momentum flux; turbulence structure
  - CO_2 and H_2O -fluxes
- Spectral correction for scalar fluxes
  - low-pass filtering caused by measurement system
    - difficult task: no ”reference spectra” or universal theories
    - ”first assumption” should be made
- Comparison of EC-results to chamber, cuvette and different evaportanspiration measurements
- Articles: BER (spring 2005, CO_2 and H_2O), Turbulence article (summer-august 2005)