A possible explanation for energy balance non-closure in an eastern Siberian larch forest: Advection associated with 3-D atmos. mixing

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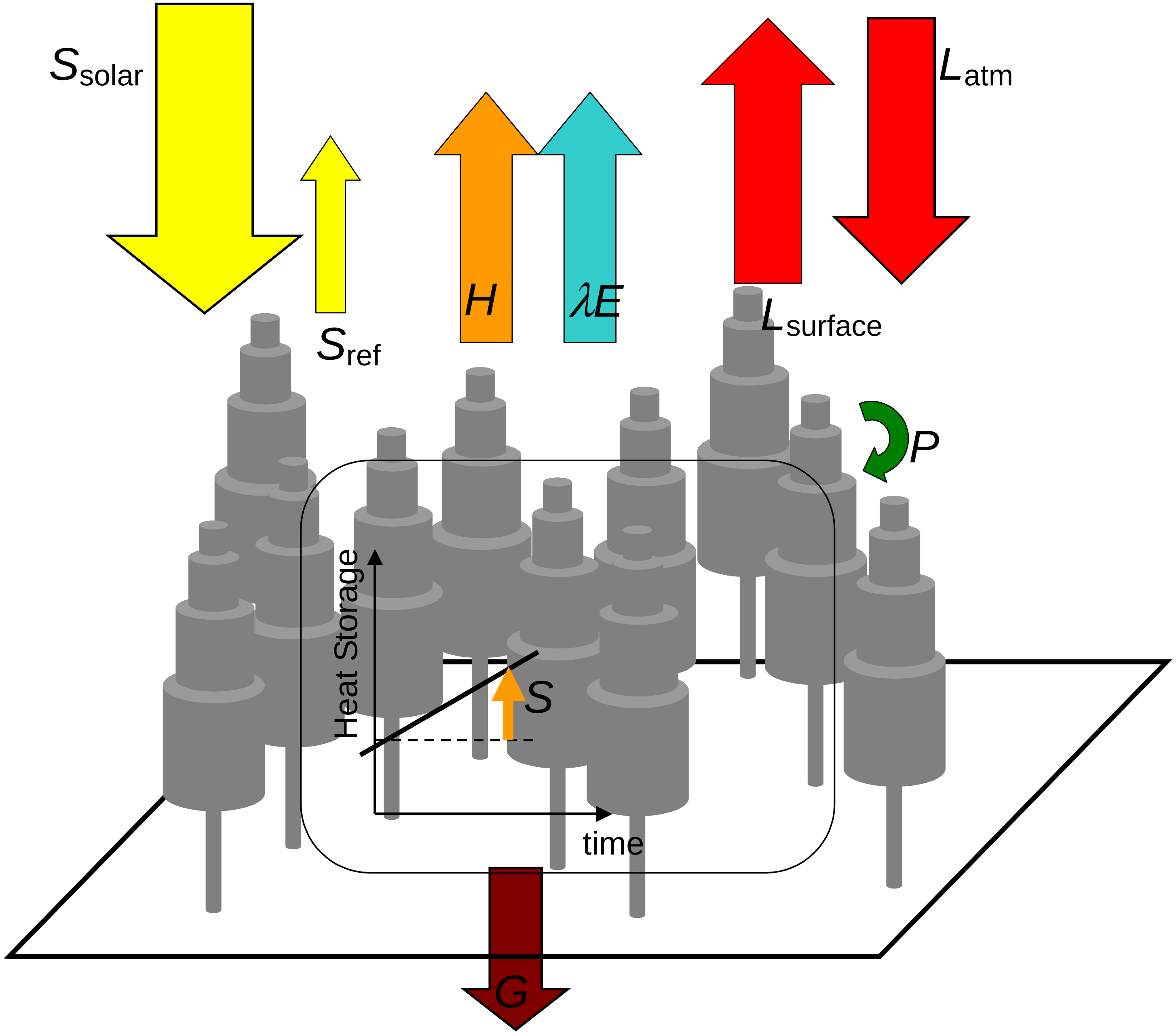
Energy balance in forest

$$R_{\mathrm{NET}} = S_{\mathrm{solar}} - S_{\mathrm{ref}} + L_{\mathrm{atm}} - L_{\mathrm{surface}} = H + \lambda E + G + S + P$$



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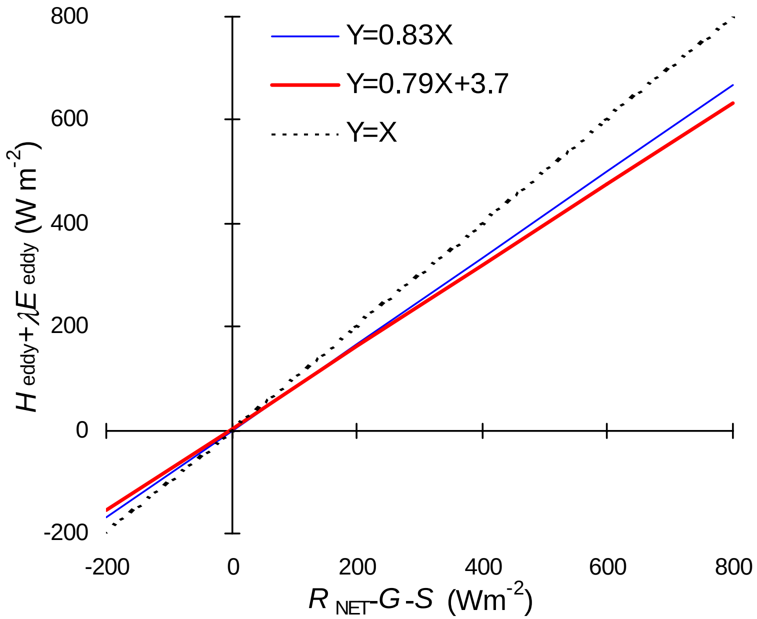
Energy non-closure

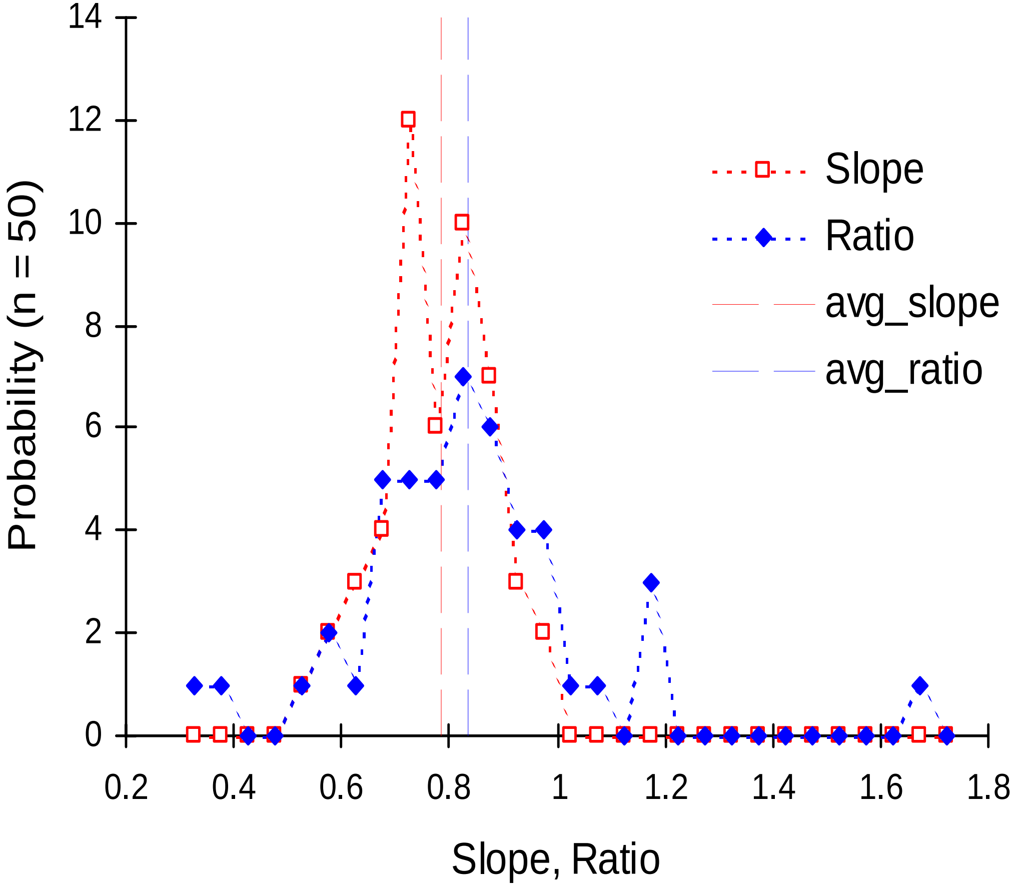
$$H_{\text{eddy}} + \lambda E_{\text{eddy}} \neq R_{\text{NET}} - G - S$$

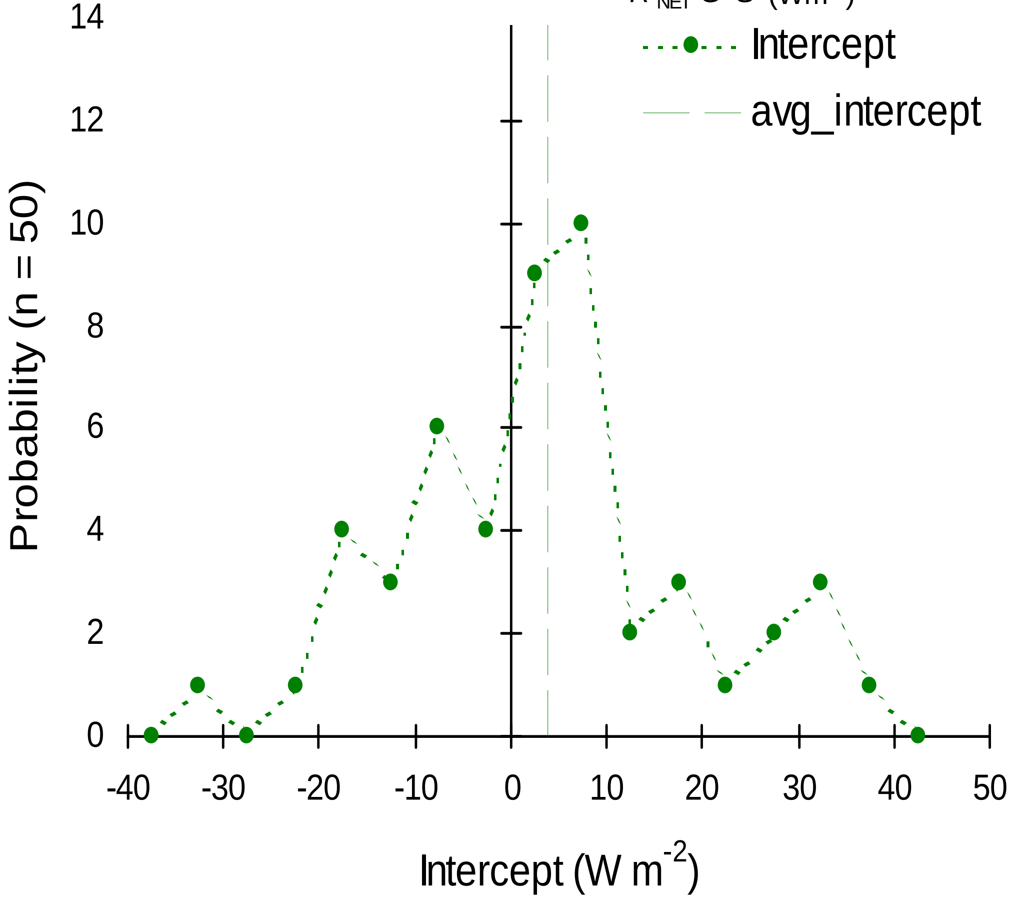
Ex: Result from 50 site year of FLUXNET;

On the average, heat flux is **20% less**

than available energy (Wilson *et al.*, 2002)







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Source of non-closure $(H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} \leq R_{\mathrm{NET}} - G - S)$

Ⅰ. Estimation errors

(1) Errors on R_{NET}, G, and S; Wilson *et al.*(2002)

(2) Errors on heat fluxes; Wilson *et al.*(2002)

(3) Sensor response for high frequency; Wilson *et al.*(2002)

Ⅱ. 3-D atmospheric flow's effect

(4) Missing for low frequency; Wilson *et al.*(2002) Sakai et al.(2002)

(5) Advection at night; Wilson *et al.*(2002)

(6) Vertical massflow; Lee(1998)

(7) 3-D structured large scale mixing; Finnigan(1999)

From review for results of FLUXNET site; Wilson *et al.*(2002):

"Complex small sources → Under-estimation for heat fluxes"

Analytical suggestion from LES; Watanabe and Kanda(2002):

"Stationary flows →Negative imbalance for point-measured flux"

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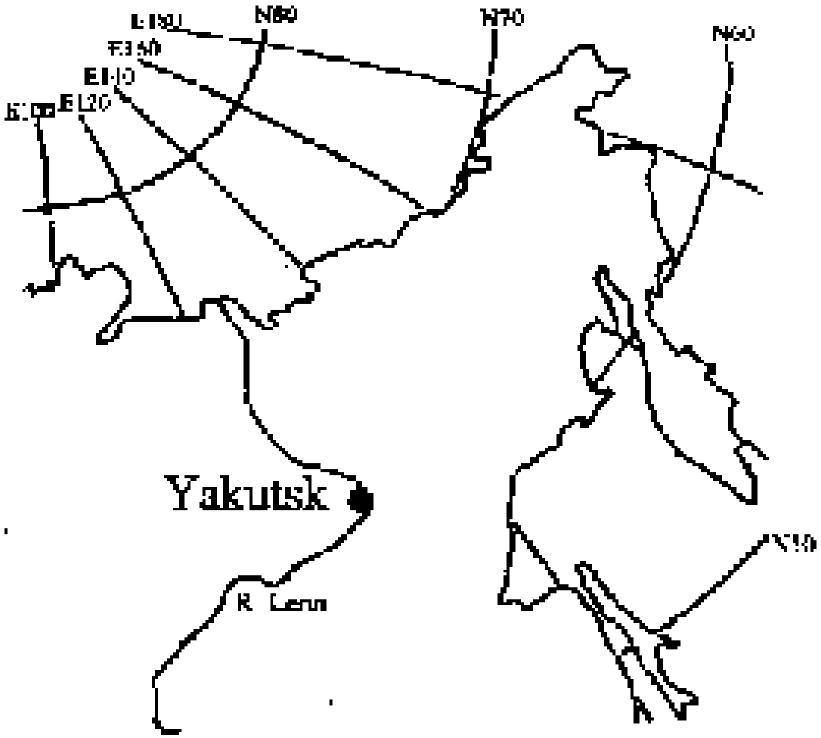
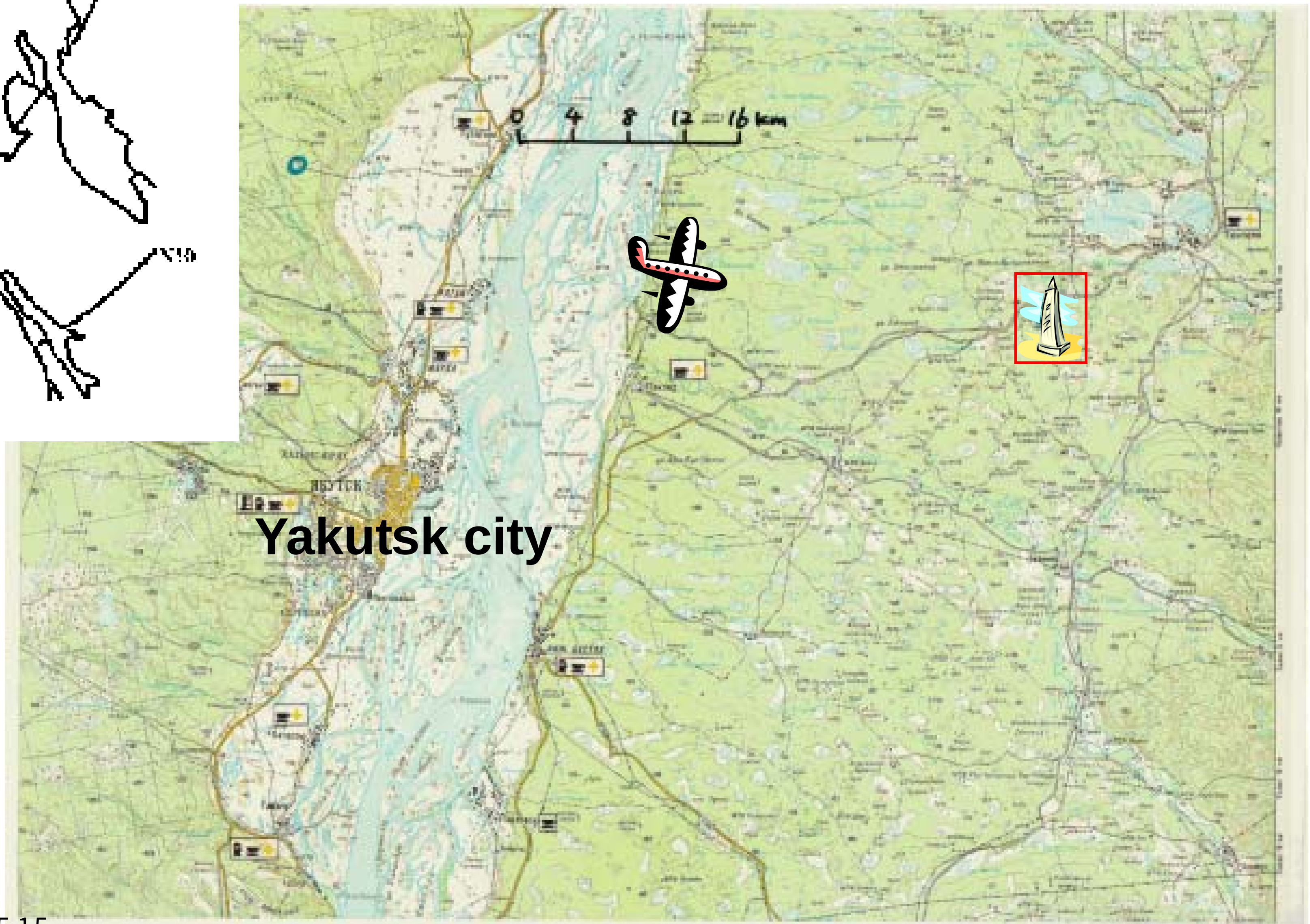
Observations

East Siberia 62.15°N、130.51°E

15APR2000～14SEP2000

Larch forest (GAME-Siberia site)



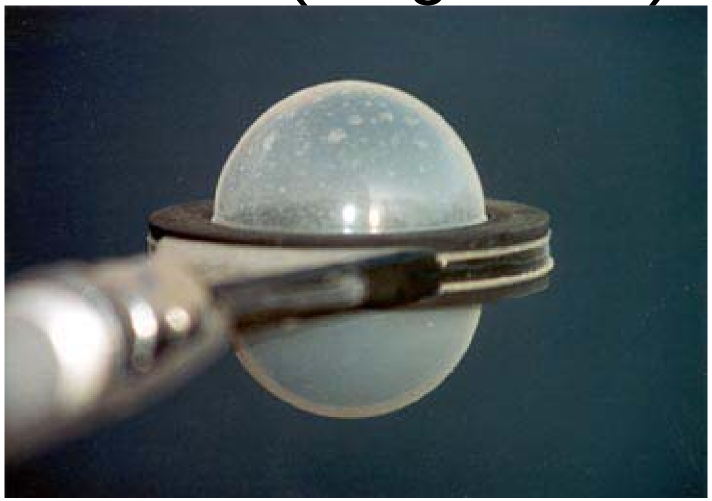


Net radiation: $R_{\mathrm{NET}} = S_{\mathrm{solar}} - S_{\mathrm{ref}} + L_{\mathrm{atm}} - L_{\mathrm{surface}}$

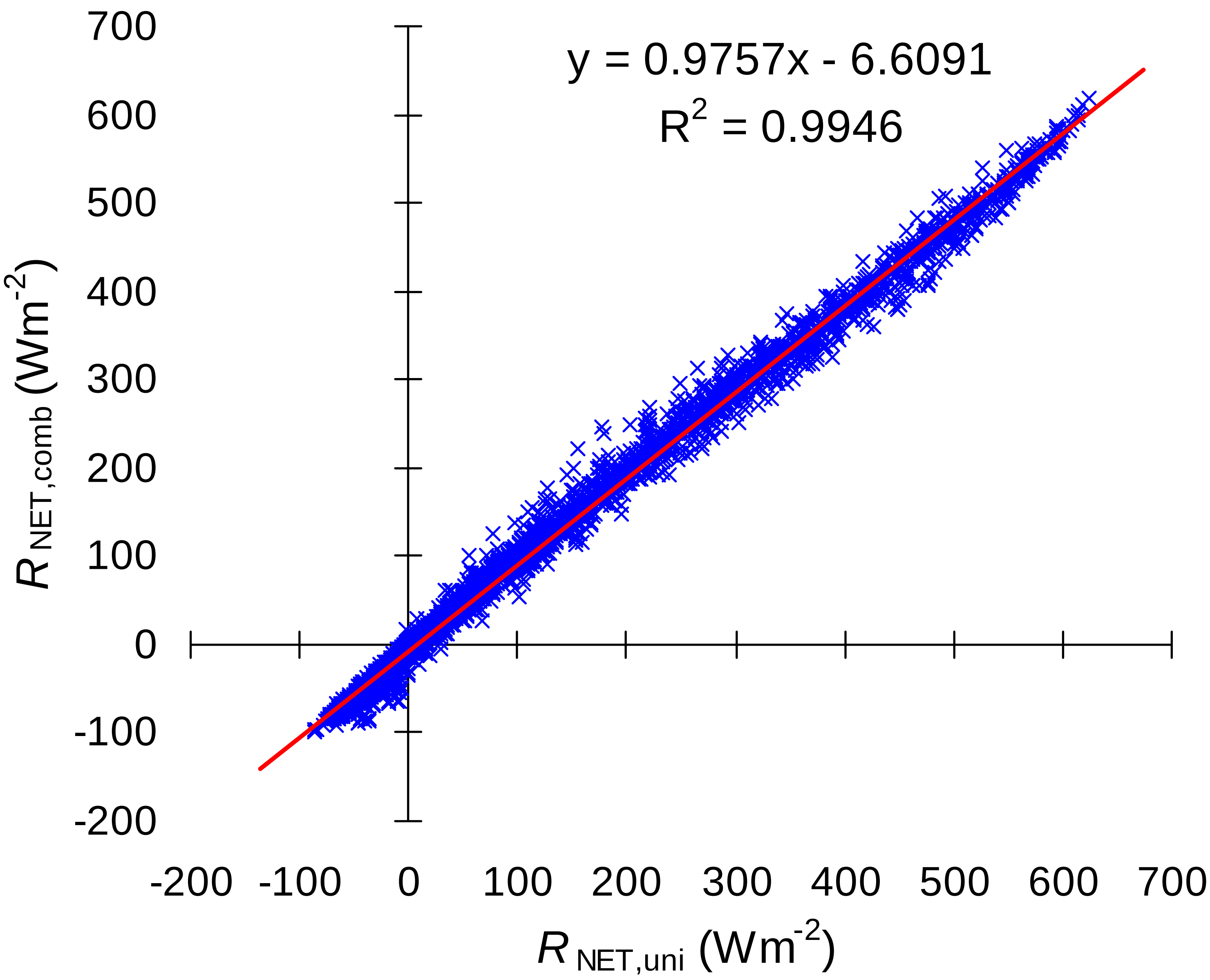

Solar (Short-wave)


Infrared (long-wave)

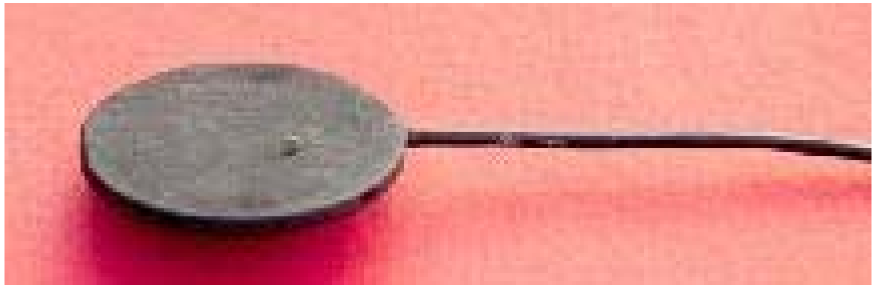

4-component budget

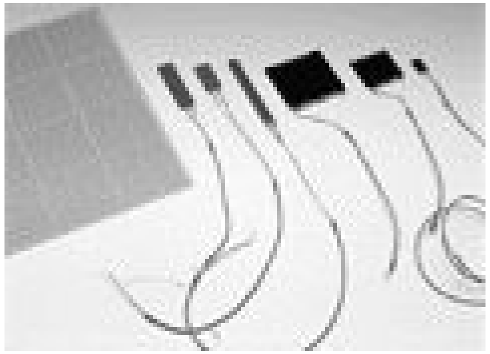

Net radiometer

Observed net radiation: $R_{\mathrm{NET}} = S_{\mathrm{solar}} - S_{\mathrm{ref}} + L_{\mathrm{atm}} - L_{\mathrm{surface}}$



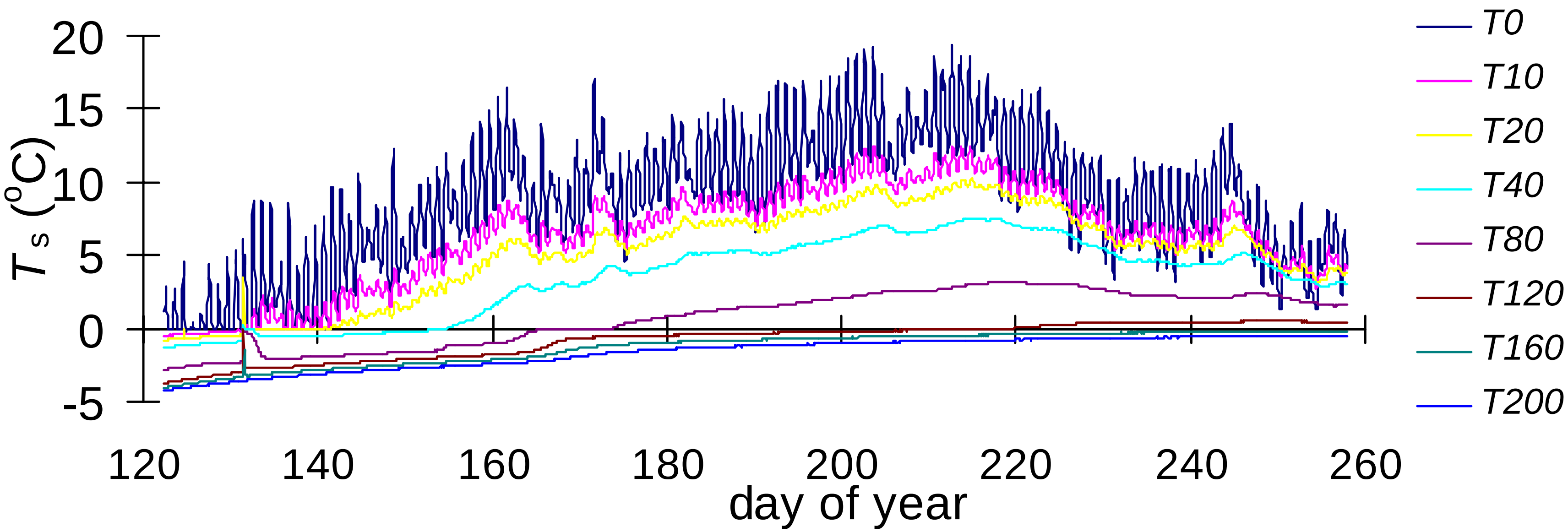
Ground heat flux: *G*



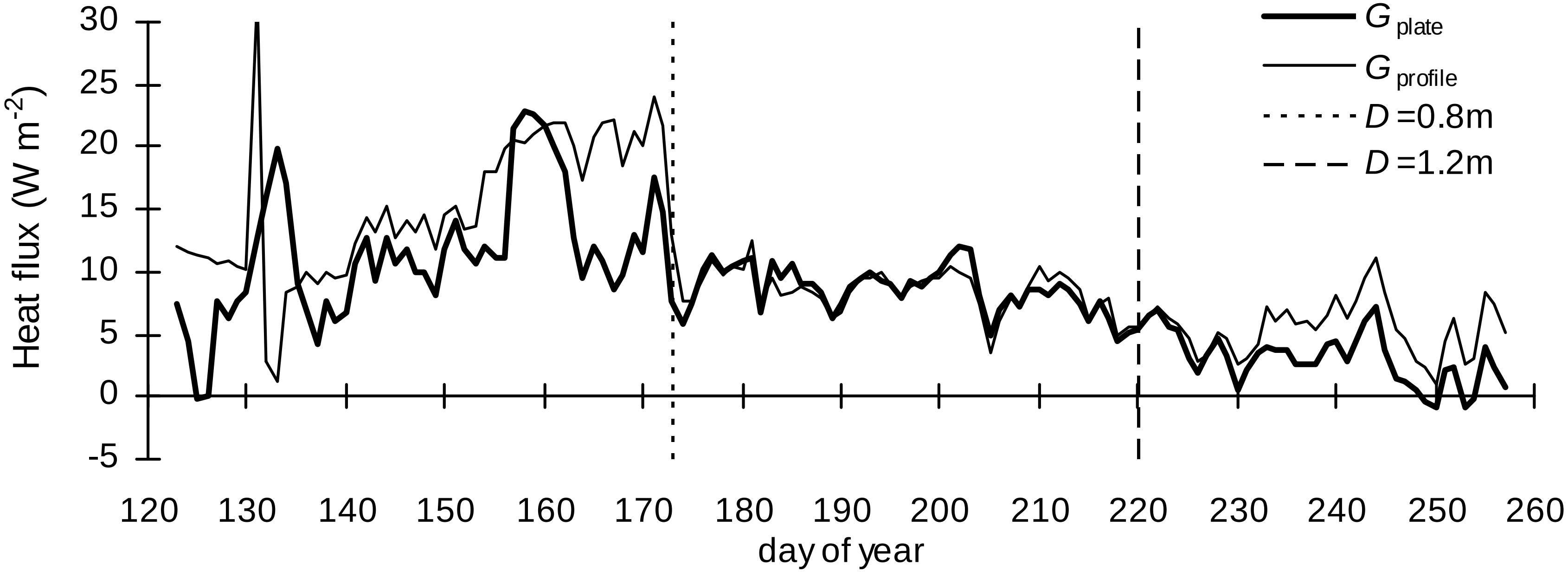


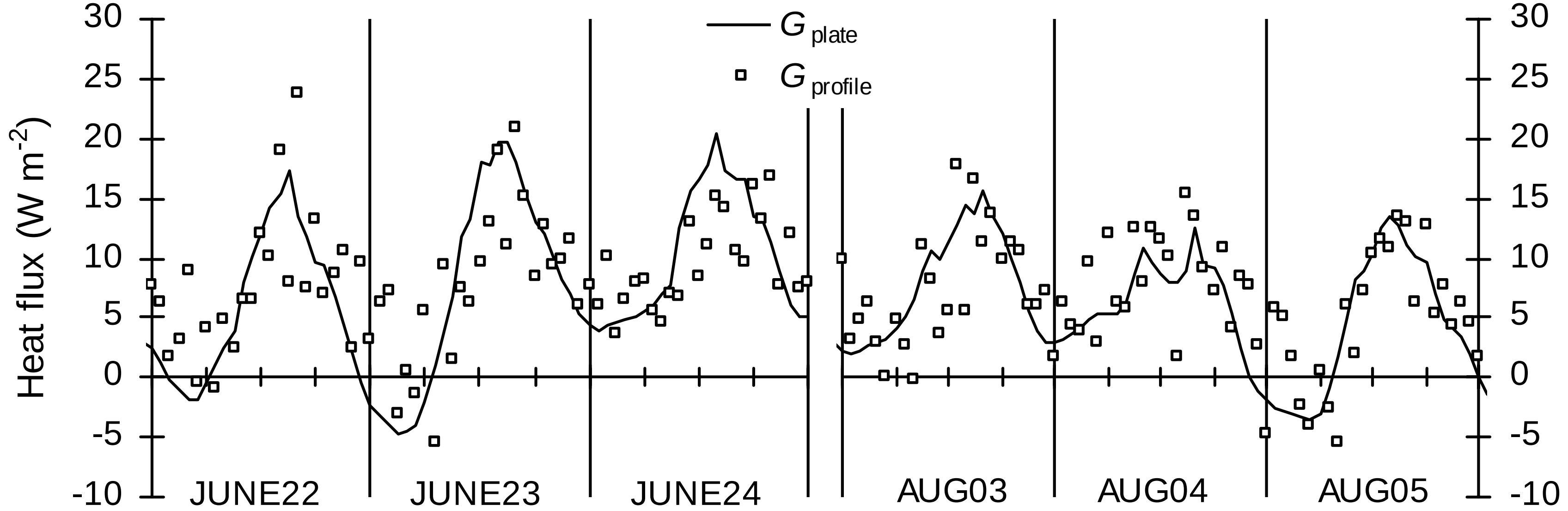
G_{plate}

$$G_{\text{profile}} = \int_0^2 \left(\rho_s c_s + \theta(z)\rho_w c_w + \theta_F(z)\rho_I c_I\right)\frac{\partial T_s(z)}{\partial t}dz + \lambda_F \rho_I \theta_F(z)\frac{\partial D}{\partial t}$$



Observed ground heat flux: G_{plate}、 $G_{profile}$





6/21～8/6: D=0.8→1.2m: $\Sigma G_{plate} = \Sigma G_{profile}$ =35.0MJm^{-2} (=7.2+27.9)

Heat storage change: $S = S_{\text{atmosphere}} + S_{\text{biomass}}$

$$S_{\text{atmosphere}} = \int_0^r \left[\rho C_{\mathrm{P}} \frac{\partial T_{\mathrm{a}}(z)}{\partial \mathrm{t}} + \lambda \frac{\partial q_{\mathrm{a}}(z)}{\partial \mathrm{t}} \right] dz$$

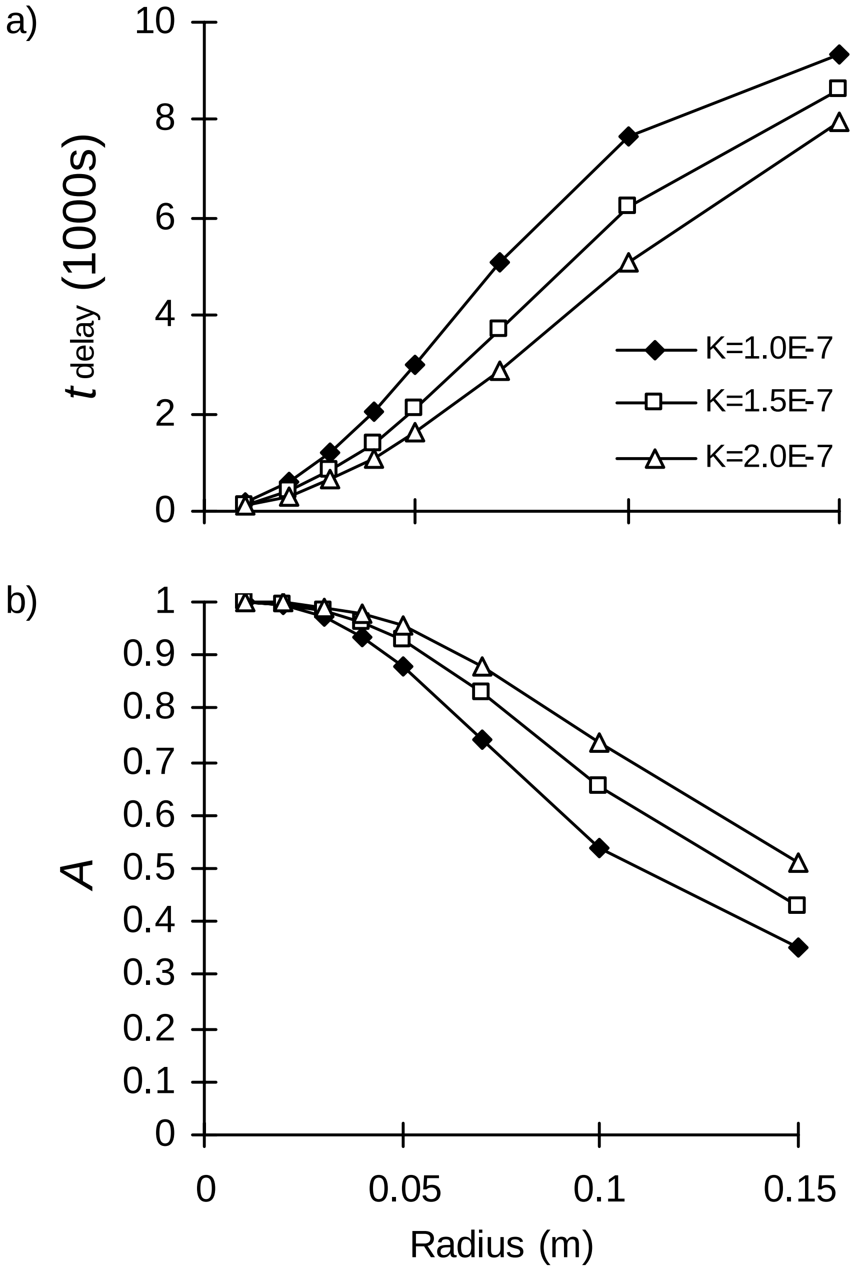
$$S_{\text{biomass}} = A c_{\mathrm{m}} M_{\text{biomass}} \frac{\partial T_{\mathrm{a}}(t - t_{\text{delay}})}{\partial t}$$

Amplitude : $A = \dfrac{\partial \overline{T_{\mathrm{b}}(t)}}{\partial T_{\mathrm{a}}(t - t_{\text{delay}})}$

Heat transfer equation within stem (cylindrical material):

$$\frac{\partial T_{\text{stem}}(t,r)}{\partial t} = K \left(\frac{\partial^2 T_{\text{stem}}(t,r)}{\partial r^2} + \frac{1}{r} \frac{\partial T_{\text{stem}}(t,r)}{\partial r} \right)$$

Simulation for stem heat transfer, and $S = S_{atmosphere} + S_{biomass}$



Items	Variables
Forest type	Young larch
Location	62.15°N, 130.51°E
Maximum melting depth of soil	1.5m
Biolocial rearch area	1600m^2
Stand density	0.42trees m^{-2}
Mean diameter at breast height	0.076m
Stand stem volume	0.02m^3 m^{-2}
Mean stand height	7.6m
Mean stand height for ten top trees	17.3m
Canopy height	10.6m

$$S_{\mathrm{biomass}} = A c_{\mathrm{m}} M_{\mathrm{biomass}} \frac{\partial T_{\mathrm{a}}(t - t_{\mathrm{delay}})}{\partial t}$$

Phase shift: t_{delay}=1800 sec

Amplitude: A=1.0

Available energy: $R_{\mathrm{NET}} - G - S = H + \lambda E$

Items	R_{NET}	G	S	$S_{atmosphere}$	$S_{biomass}$
Number of data (hours)	3624	3253	3624	3624	3624
when S_{solar} >10 Wm^{-2}	2474	2243	2474	2474	2474
when S_{solar} <10 Wm^{-2}	1150	1010	1150	1150	1150
Average value ($W\ m^{-2}$)	115.3	8.1	0.0	0.0	0.0
when S_{solar} >10 Wm^{-2}	168.4	11.1	11.3	4.3	7.0
when S_{solar} <10 Wm^{-2}	-42.3	1.5	-24.1	-9.1	-15.0
Standard deviation ($W\ m^{-2}$)	176.3	8.8	32.9	12.8	21.6
when S_{solar} >10 Wm^{-2}	168.4	8.8	31.9	12.6	21.4
when S_{solar} <10 Wm^{-2}	24.1	3.8	19.2	7.7	12.6

P : negligibly small

R_{NET}: major part of available energy

G S in daytime

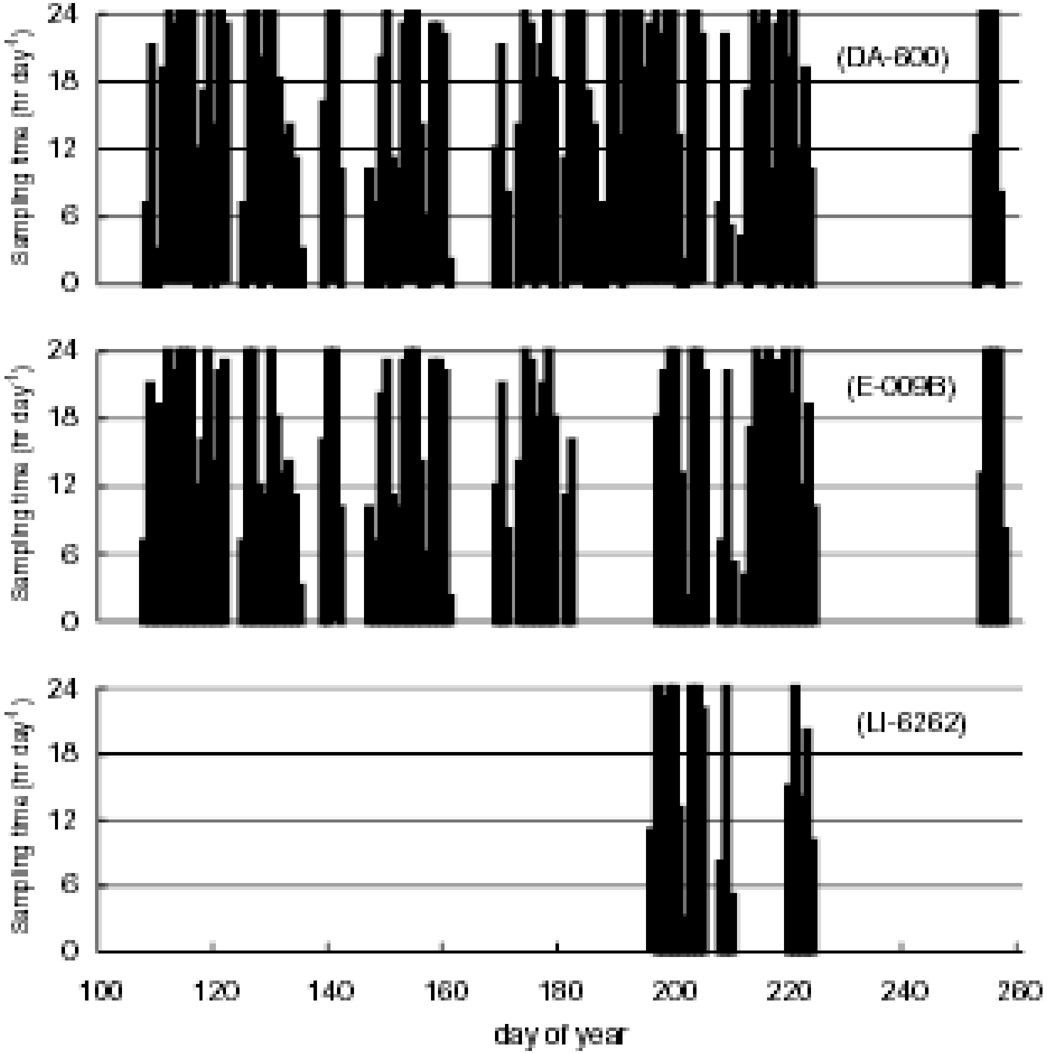
$|S| > |G|$

$|S_{atmosphere}| < |S_{biomass}|$

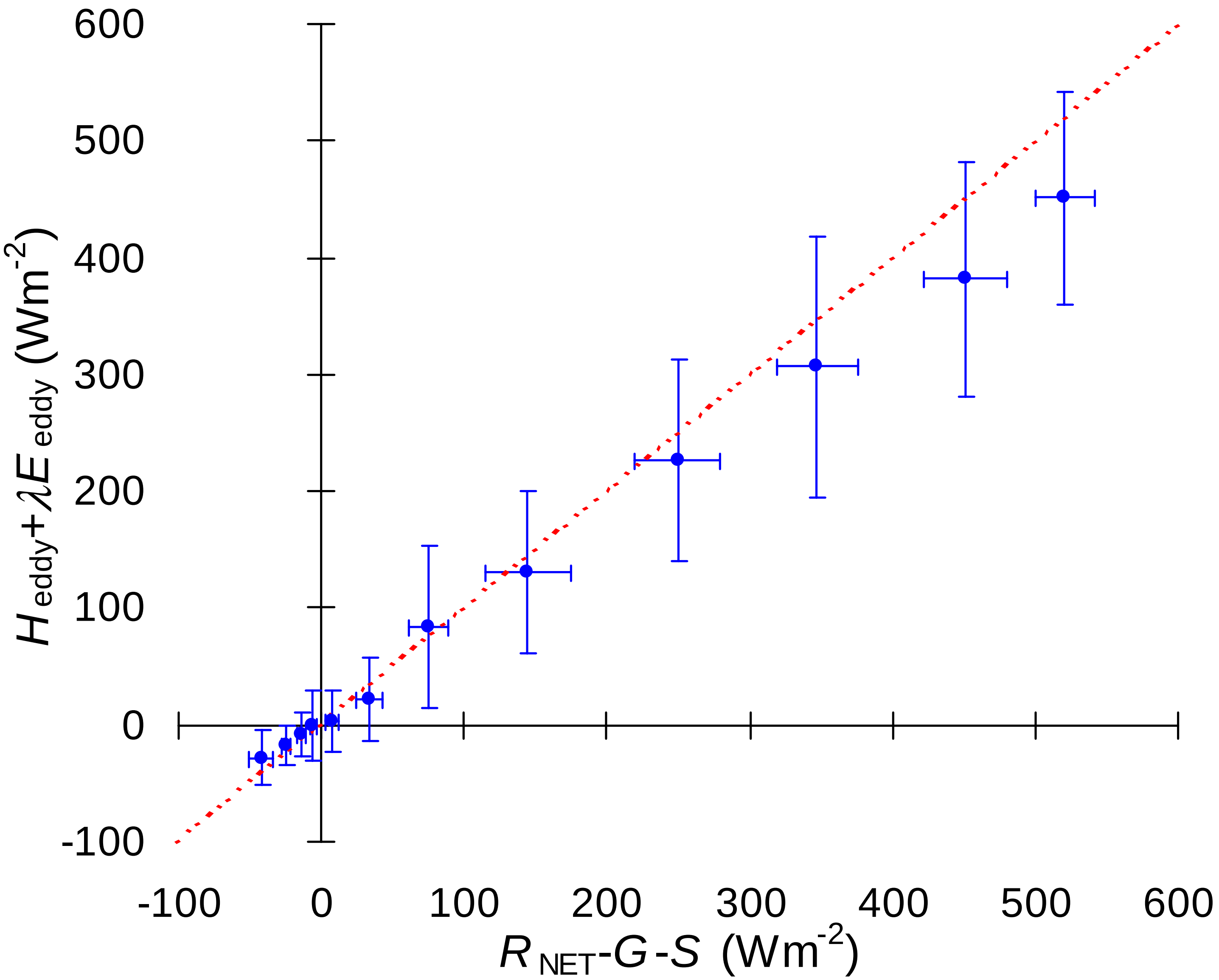
Eddy fluxes

Sensible heat: $H_{\mathrm{eddy}} = \rho C_{\mathrm{P}} \overline{w'\theta'}$

Latent heat: $\lambda E_{\mathrm{eddy}} = \lambda \overline{w'q'}$



Observed energy non-closure $H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} \leq R_{\mathrm{NET}} - G - S$



$$H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} = 0.858(R_{\mathrm{NET}} - G - S) + 5.09$$

Sources of non-closure

Ⅰ． Estimation errors

$R_{NET,uni}$ ： positive bias ← Small transparency of upper dome

$R_{NET,comb}$ ： at least 16.8Wm^{-2} smaller than $R_{NET,uni}$ on average

→R_{NET}= $R_{NET,comb}$; No positive bias. Acceptable.

$G_{profile}$ G_{plate} in summer. Errors occured by re-freezing or draught

→G = $G_{profile}$ ： No bias and minor for available enegy. Acceptable.

$S_{biomass}$＞$S_{atmosphere}$

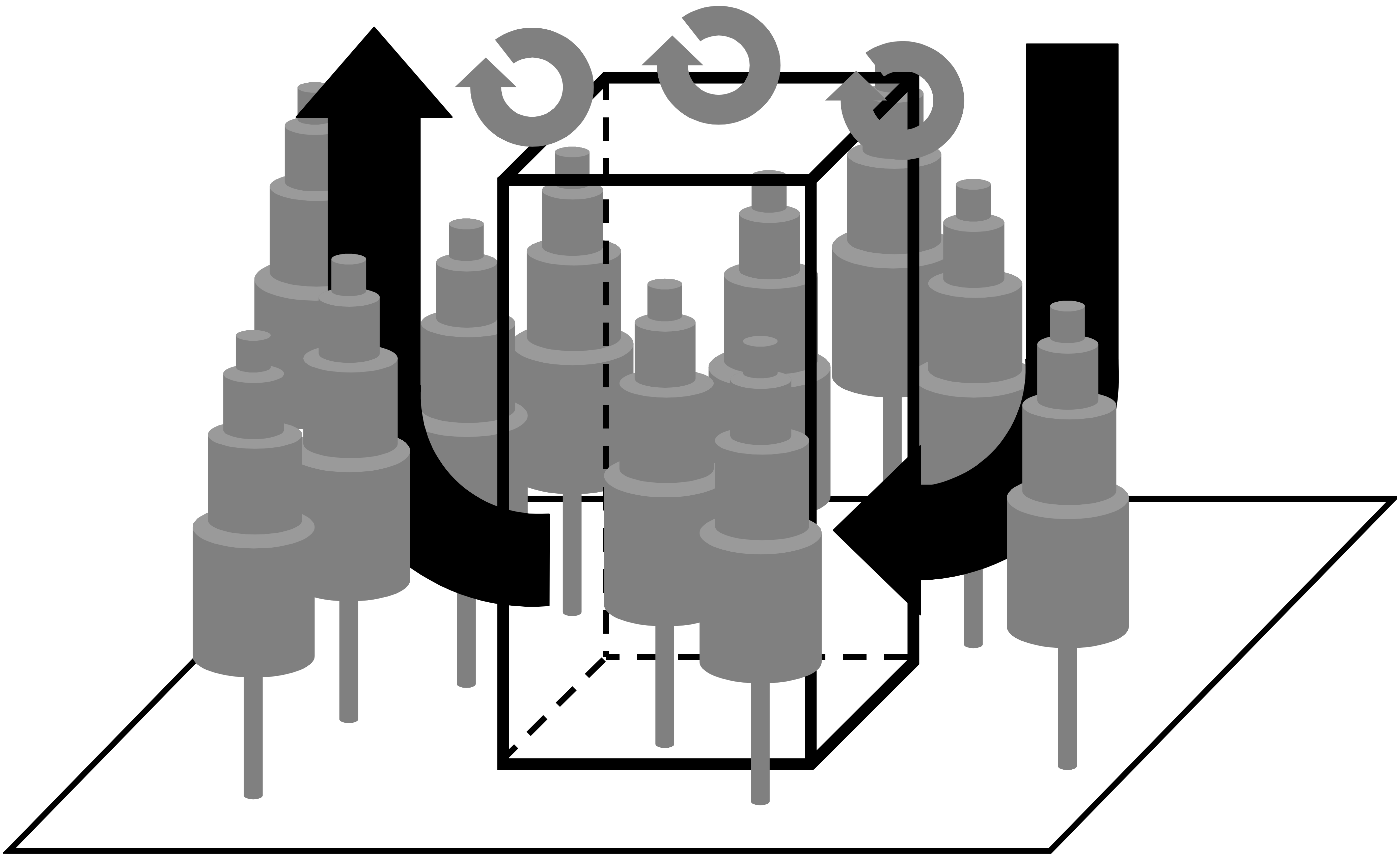
S G in daytime, S＞G at night.

→S : Possible to be major source at night.

Ⅱ． 3-D flow's effect （low-freq. loss, large eddy & advection)

3-D flow should be major source, at least in daytime.

Advection fluxes



Basic Equations

Energy conservation：

$$R_{\mathrm{NET}} - G - S = H_{\mathrm{eddy}} + H_{\mathrm{adv}} + \lambda E_{\mathrm{eddy}} + \lambda E_{\mathrm{adv}}$$

Sensible heat：$H_{\mathrm{adv}} = \rho C_{\mathrm{P}} T_{\mathrm{out}} V - \rho C_{\mathrm{P}} T_{\mathrm{in}} V$

Latent heat ：$\lambda E_{\mathrm{adv}} = \lambda q_{\mathrm{out}} V - \lambda q_{\mathrm{in}} V$

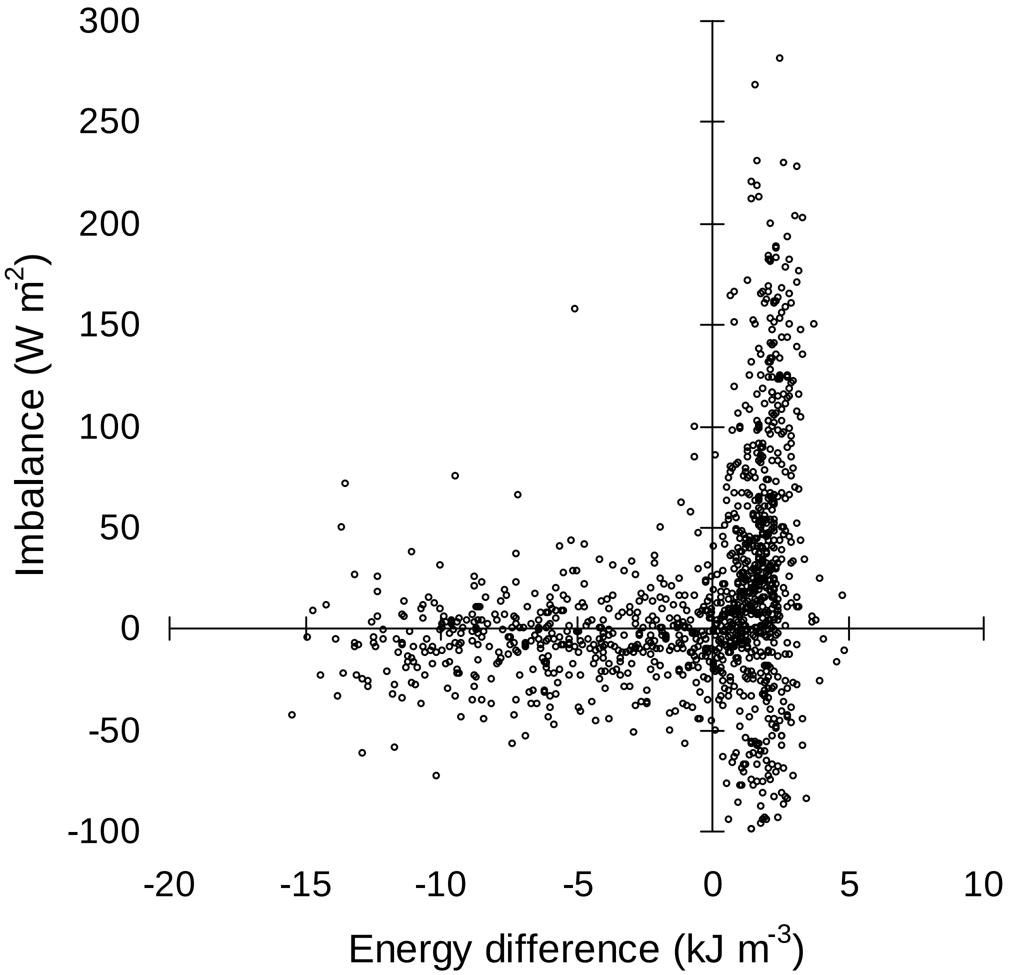
Volume [$m^3 m^{-2} s^{-1}$]：$V = \dfrac{R_{\mathrm{NET}} - G - H_{\mathrm{eddy}} - \lambda E_{\mathrm{eddy}}}{\rho C_{\mathrm{P}} T_{\mathrm{out}} - \rho C_{\mathrm{P}} T_{\mathrm{in}} + \lambda q_{\mathrm{out}} - \lambda q_{\mathrm{in}}}$

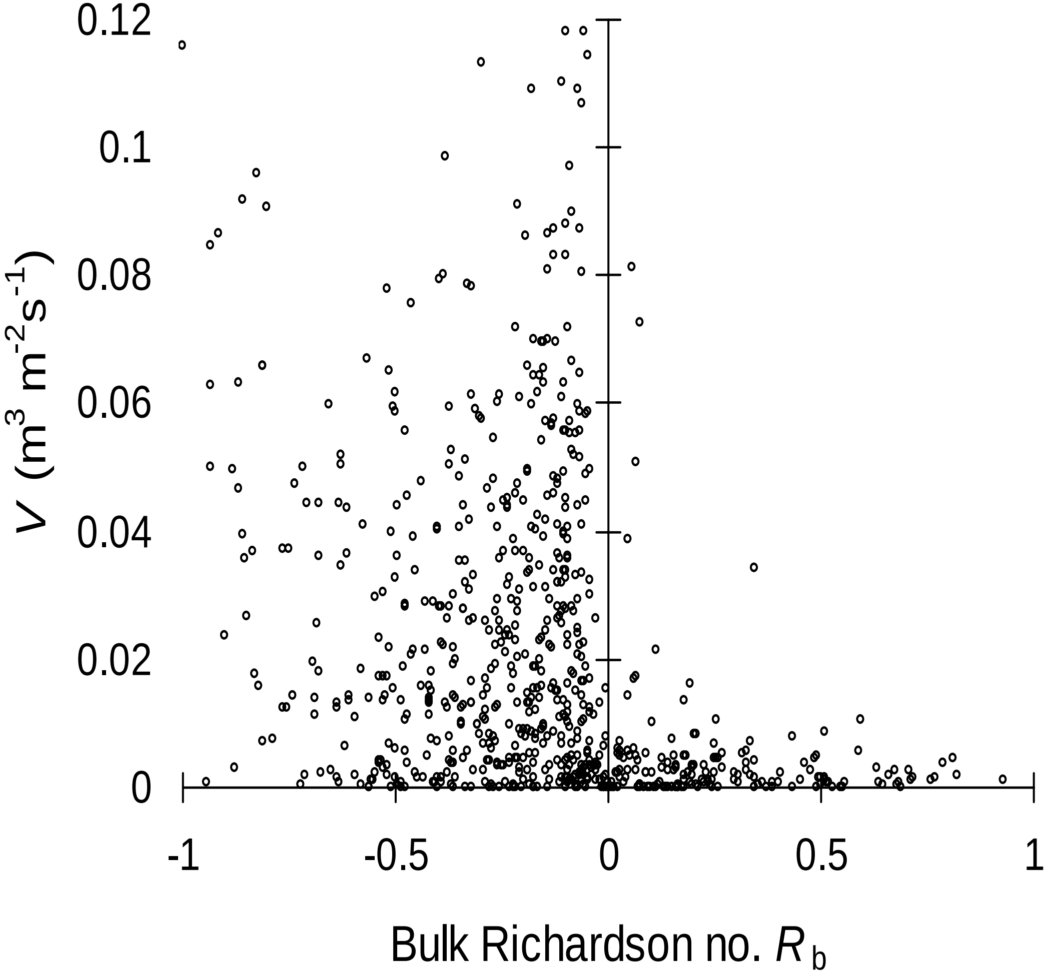
Energy difference between above and below canopy is important.

ex., in Japan: wet soil & dense canopy→ $q_{\mathrm{out}} > q_{\mathrm{in}}$ but $T_{\mathrm{out}} \approx T_{\mathrm{in}}$

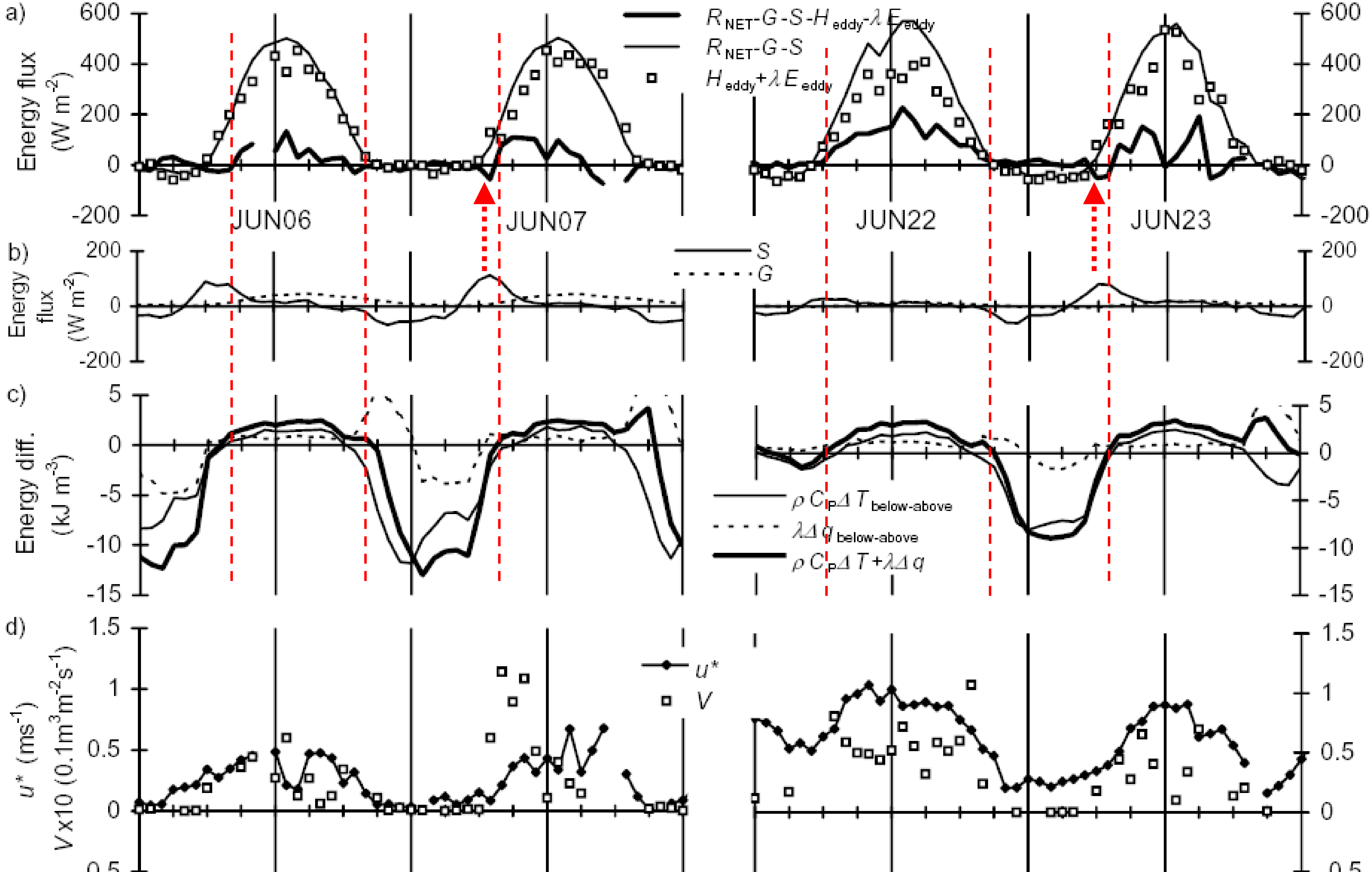
in Siberia: wet soil & sparse canopy→ $q_{\mathrm{out}} > q_{\mathrm{in}}$ and $T_{\mathrm{out}} > T_{\mathrm{in}}$

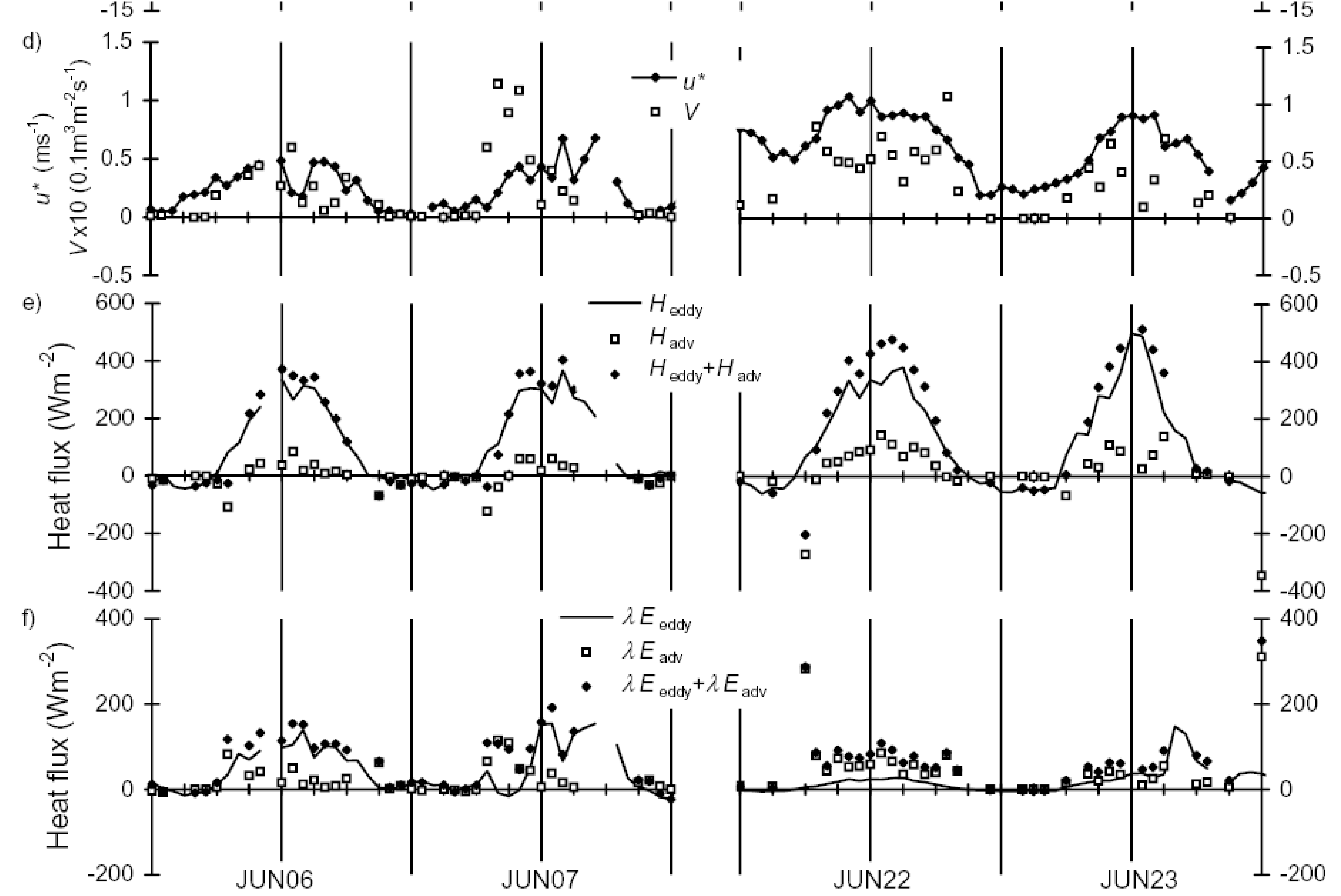
Trial computation



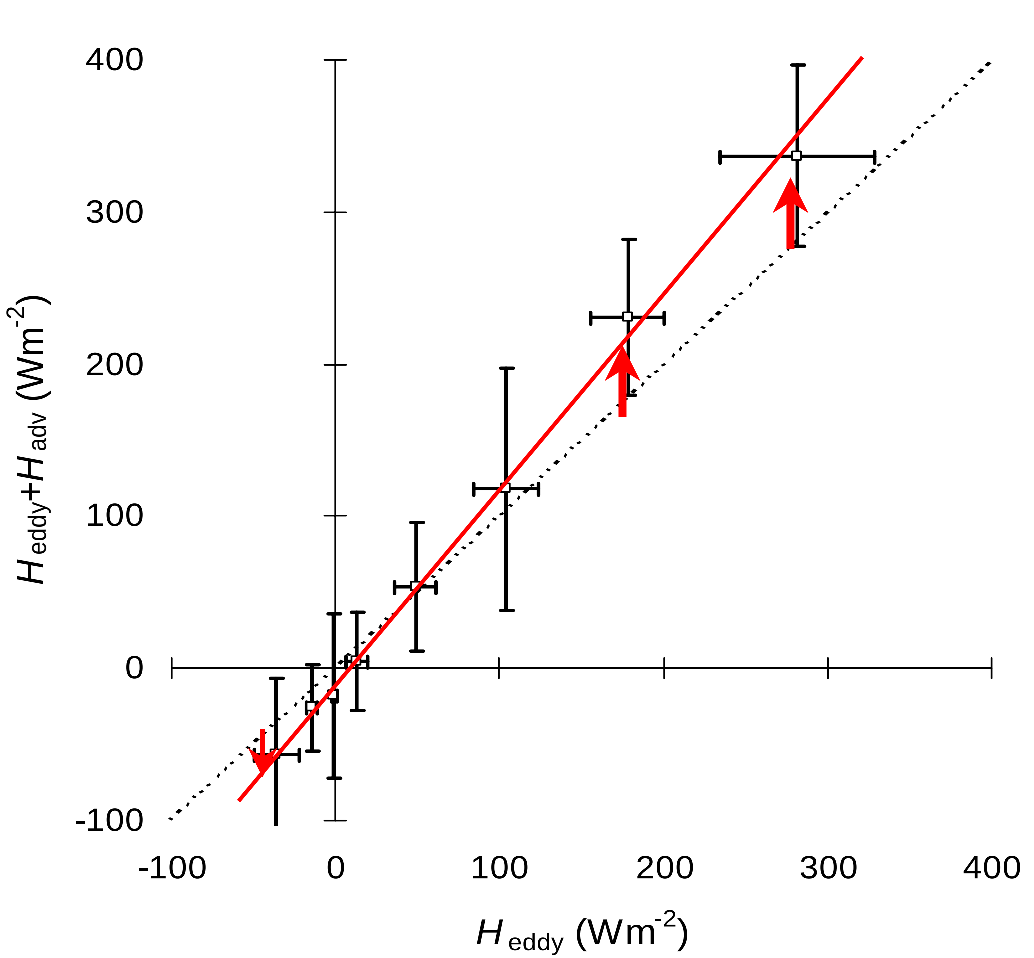


Results : diurnal courses

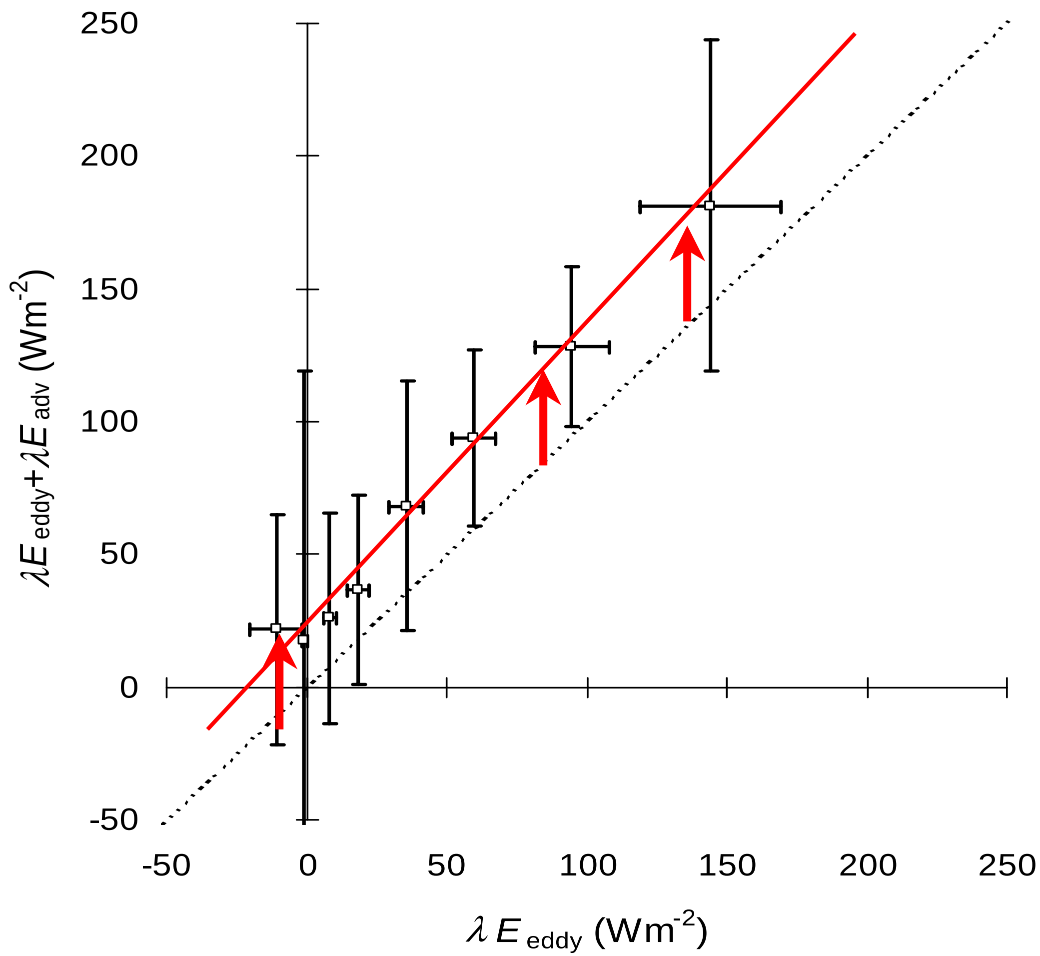



d)
e)
f)
u^* (ms^{-1})
Vx10 (0.1m^{3}m^{-2}s^{-1})
u^*
V
H_{eddy}
H_{adv}
$H_{eddy}+H_{adv}$
Heat flux (Wm^{-2})
λE_{eddy}
λE_{adv}
$\lambda E_{eddy}+\lambda E_{adv}$
JUN06
JUN07
JUN22
JUN23

Results - heat fluxes



Sensible heat fluxes

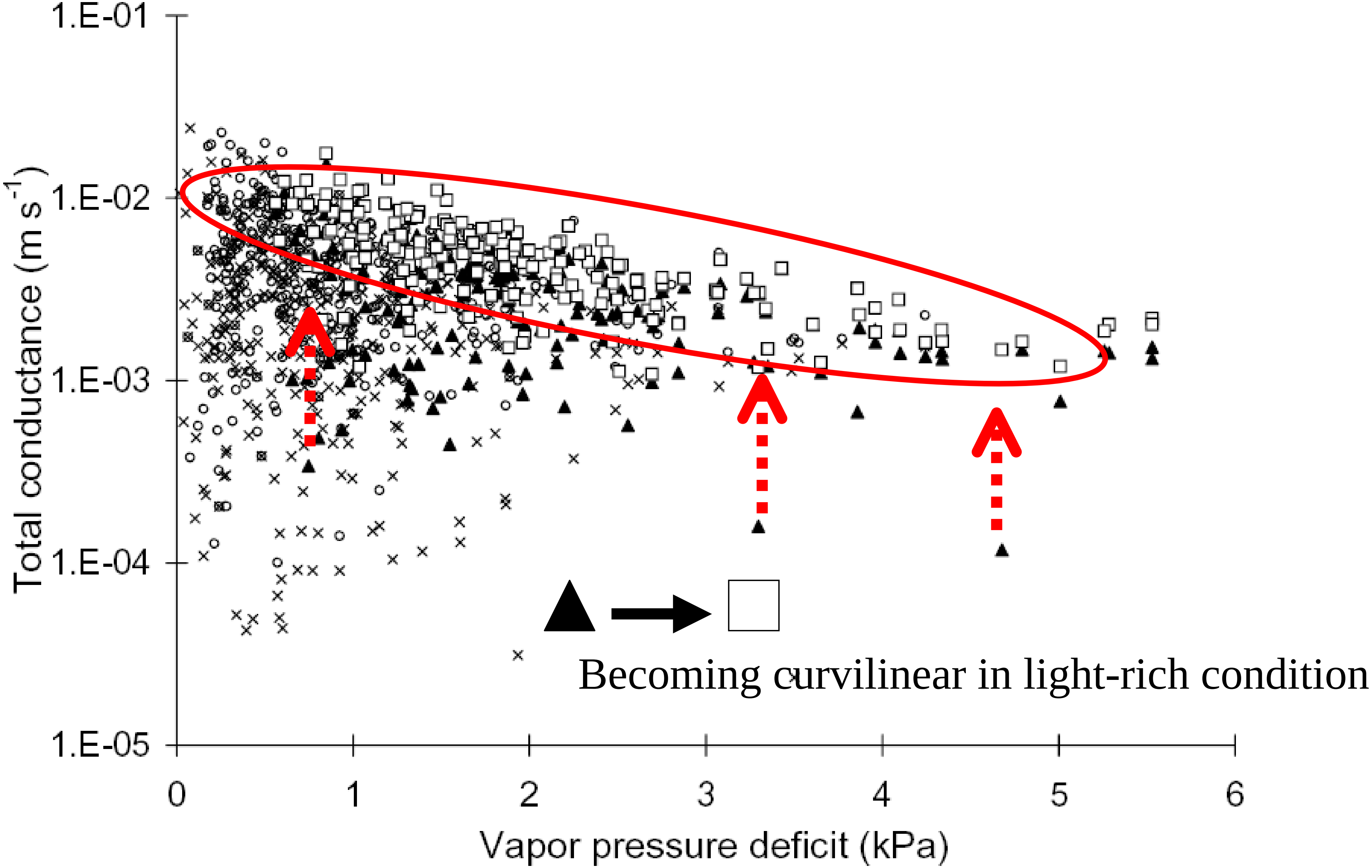


Latent heat fluxes

H_{adv} ：4.4 ± 58.6Wm^{-2}、 positive in day、negative at night

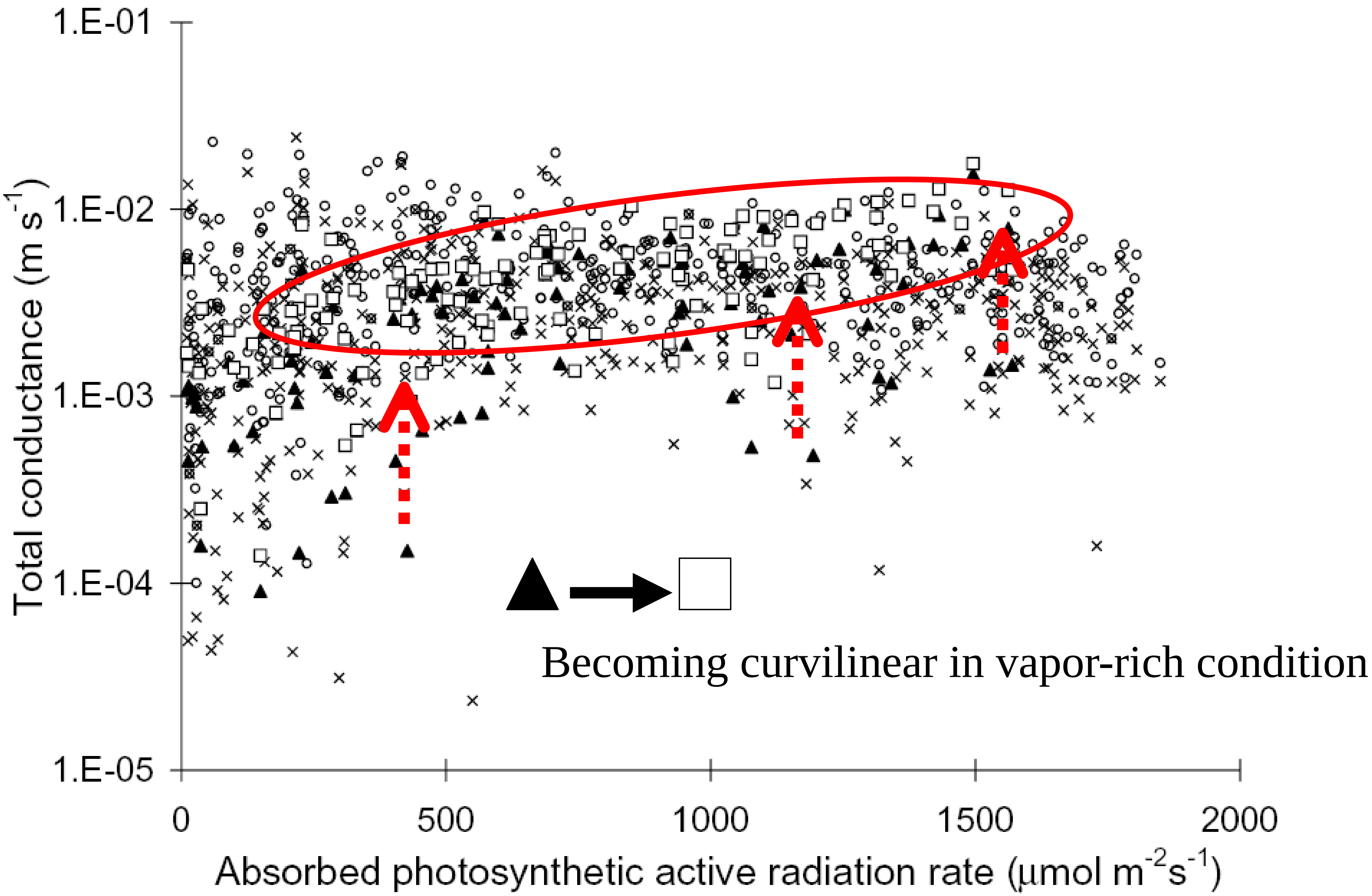
λE_{adv} ：25.5 ± 51.5Wm^{-2}、mostly positive

Total conductance vs Vapor deficit



g_t derived from λE_{eddy} (crosses for aPAR<1000; filled triangles for aPAR>1000)
and $\lambda E_{eddy}+\lambda E_{adv}$ (empty circles for aPAR<1000; empty rectangles for aPAR>1000)

Total conductance vs Absorbed PAR



g_t derived from λE_{eddy} (crosses for *VPD*<0.8 or *VPD*>1.2; **filled triangles** for 0.8<*VPD*<1.2) and $\lambda E_{eddy}+\lambda E_{adv}$ (empty circles for *VPD*<0.8 or *VPD*>1.2; **empty rectangles** for 0.8<*VPD*<1.2)

Concluding remarks

Growing season 2000, at larch forest in east Siberia,
Obs. results of available energy & eddy fluxes:

$$H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} = 0.858(R_{\mathrm{NET}} - G - S) + 5.09$$

Source of non-closure:

Ⅰ. Estimation errors

R_{NET} : No positive bias. Acceptable

G : No bias and minor for available enegy. Acceptable

S : Possible to be major source at early morning

Ⅱ. 3-D flow's effect（low-freq. loss, large eddy & advection)

3-D flow should be major source, at least in daytime.

→ Trial estimation from 1-D observation system.

Two major postulates：

(1) T and q are horizontally homogeneous in distribution.
(2) The measured eddy flux is representative within the field.
→Trial computation

V ：$0.025 \pm 0.034 m^3 m^{-2} s^{-1}$

H_{adv} ：$4.4 \pm 58.6 Wm^{-2}$、 positive in day、negative at night

λE_{adv} ：$25.5 \pm 51.5 Wm^{-2}$、mostly positive

λE greatly changed to clearly explain transpiration property.

Future works：

Many case that P-(1) is false. → True of representative T and q ?

No verification of P-(2) →3-D observation or simulation is required.