A possible source for the non-closure of the energy balance at a larch forest of eastern Siberia: the advection due to 3-D associated atmospheric mixing

by Hiro-Ki TANAKA

INTRODUCTION

Energy balance equation;

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

R_{NET}: Net radiation flux,
S_{solar}: Solar radiation flux,
S_{ref}: Reflective radiation flux,
L_{atm}: Atmospheric radiation flux,
L_{surface}: long-wave radiation flux from the surface,
G: Ground heat flux,
S: Heat storage change rate,
P: Photosynthetic energy flux (negligible),
H: Sensible heat flux,
λE: Latent heat flux.

Non-closure of the energy balance, Imbalance ratio;

$$I_{\mathrm{BR}} = \frac{(R_{\mathrm{NET}} - G - S) - (H + \lambda E)}{R_{\mathrm{NET}} - G - S} \approx 0.2 \sim 0.3$$

Possible sources for non-closure;

I. Estimation errors:
(1) Estimation errors for R_{NET}, G, and S,
(2) Estimation errors for H and λE,
(3) High frequency loss of turbulent fluxes,

II. Effect of large scale atmospheric mixing:
(4) Low frequency loss of turbulent fluxes,
(5) Advection especially in nighttime,
(6) Effect of mass flow flux from non-zero w,
(7) Effect of 3-D mean velocity fields.

MATERIALS and METHODS

Site was a flat young larch forest located at 62.15°N、130.51°E, the middle reaches of the Lena river, in a permafrost region. The distance from the river is 30 km. The nearest grassland was lying more than 1km far.

Observation was from April 15 through September 14, 2000 using ACOS with storage batteries charged by solar cells. Eddy fluxes measurements were with an engine-driven-generator at 23.8m high on the top of tower, intermittently.

Radiation fluxes: two ways; $R_{\mathrm{NET,comb}}$ and $R_{\mathrm{NET,uni}}$

Ground heat flux: two ways; G_{plate} and G_{profile}

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

Heat Storage change rates: $S_{\mathrm{atmosphere}}$ and S_{biomass}

$$S_{\mathrm{atmosphere}} = \int_0^r \left[\rho C_P \frac{\partial T_a(z)}{\partial t} + \lambda \frac{\partial q_a(z)}{\partial t}\right]dz$$

$$S_{\mathrm{biomass}} = A c_m M_{\mathrm{biomass}} \frac{\partial T_a(t - t_{\mathrm{delay}})}{\partial t}, \quad A = \frac{\partial \overline{T_b(t)}}{\partial T_a(t - t_{\mathrm{delay}})}$$

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

Eddy fluxes: partly two ways; H_{eddy} and $\lambda E_{\mathrm{eddy}}$

Basic equations for Advection fluxes:

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

$$H_{\mathrm{adv}} = \rho C_P T_{\mathrm{out}} V - \rho C_P T_{\mathrm{in}} V, \quad \lambda E_{\mathrm{adv}} = \lambda q_{\mathrm{out}} V - \lambda q_{\mathrm{in}} V$$

RESULTS

Available energy flux: R_{NET}-G-S
R_{NET}: major contributed,
G: minor contributed,
S: similar to G during daytime, while larger at night.

Net radiation fluxes:

$$R_{\mathrm{NET,comb}} = 0.976 R_{\mathrm{NET,uni}} - 6.61 \quad (n = 3584, r^2 = 0.995)$$

Mean $R_{\mathrm{NET,uni}}$ > Mean $R_{\mathrm{NET,comb}}$ by 9.6Wm^{-2}
Root mean square difference = 19.3Wm^{-2}

Ground heat flux:
$G_{\mathrm{profile}} = G_{\mathrm{plate}}$ during the mid summer
$G_{\mathrm{profile}} > G_{\mathrm{plate}}$ in the spring and the autumn

Energy imbalance:

$$H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} = 0.858(R_{\mathrm{NET}} - G - S) + 5.09 \quad (n = 1250, r^2 = 0.841)$$

Daily $H_{\mathrm{eddy}}+\lambda E_{\mathrm{eddy}}$ < Daily R_{NET}-G-S by 16.1±25.9 Wm^{-2}
Daily $I_{\mathrm{BR,daily}}$ =0.14. Hourly $I_{\mathrm{BR,hourly}}$ =0.13

DISCUSSION

Possible sources for non-closure

R_{NET} had little random errors. $R_{\mathrm{NET,uni}}$ had positive bias errors due to less transparency of the upper dome of the net radiometer, while $R_{\mathrm{NET,comb}}$ was smaller than $R_{\mathrm{NET,uni}}$, at least.

G and S were not so large and could not be major source for the non-closure. Positive bias of S might explain the small negative peaks of the imbalance in the early morning.

Although it was not deny that the estimation errors of R_{NET}-G-S contributed to minor part of the non-closure, the major source was due to the advection effect rather than the estimation errors expect in the early morning.

Estimation of Advection fluxes

Two important postulates;
(1) Air temperature and humidity can be treated as horizontally homogeneous, since the horizontal variability could be much less than the vertical variability.
(2) Obtained eddy flux can be regarded as the representative flux, which appears by the highest incidence rate within the objective field.

Trial calculation for H_{adv}, λE_{adv} and V was made with substituting the air temperature at 22.8m high to T_{in}, the humidity at 22.8m to q_{in}, the temperature at 1.1m to T_{out} and the humidty at 1.1m to q_{out}.

V of 69.4% (868hours) was resulted $0.0 \le V \le 0.3$ m^{3}m^{-2}s^{-1}, while 30.1% (376hours) were below zero. Averaged V when $0.0 \le V \le 0.3$ was 0.025±0.034. The magnitudes were clearly divided by stability R_b=0.

H_{adv}: 4.4±58.6Wm^{-2}, daytime: H_{adv}>0, night: H_{adv}<0
λE_{adv}: 25.5±51.5Wm^{-2}, generally: λE_{adv}>0

Evapotranspiration property

The physiological responses of trees toward the change of *VPD* with light-rich condition, and toward the change of *aPAR* with vapor-rich condition were more clearly appeared after considering λE_{adv}.

A possible source for the non-closure of the energy balance at a larch forest of eastern Siberia: the advection due to 3-D associated atmospheric mixing

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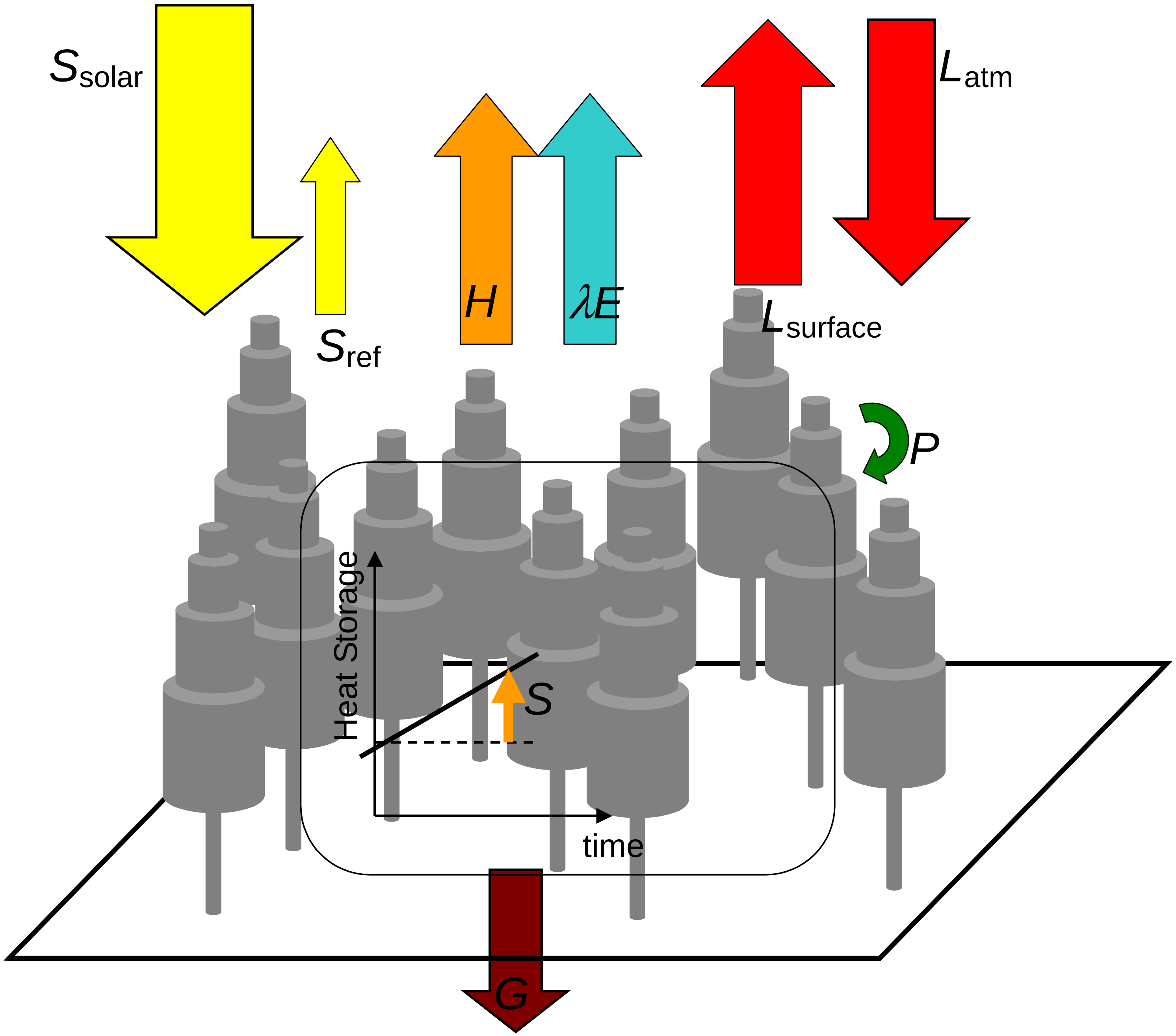
# Abstract

The non-closure of the energy balance has been recognized among lots of recent flux observations as the imbalance problem. The sum of the daily heat fluxes observed with the eddy covariance over a young larch forest canopy in eastern Siberia was around 86%, showing same tendency as reported results. After we discussed the estimation errors for the available energy fluxes including the net radiation flux, the ground heat flux, and the heat storage change rates, we concluded that the estimation errors were too small to be major sources for the non-closure, that the imbalance was caused mainly by the advection effect due to the 3-D associated large-scale atmospheric flows. The definition for the advection heat fluxes was proposed. It was suggested that the heat energy differences between above and below canopy played important role for the advection fluxes. Under two postulates including the horizontally homogeneous of the air temperature and the vapor density and the representative eddy fluxes within the objective field, we made a trial computation for the advection fluxes. As the results, the advection volume par unit area and unit time was calculated as $0.025 \pm 0.034 m^3 m^{-2} s^{-1}$, and the advection fluxes were $4.4 \pm 58.6 Wm^{-2}$ for the sensible heat and $25.5 \pm 51.5 Wm^{-2}$ for the latent heat. The estimated values of the heat fluxes were much varied by counting the advection fluxes from only the eddy fluxes, especially for the latent heat. Considering advection latent heat flux made the environmental response properties of forest evapotranspiration clear.

Keywords: Non-closure of energy balance, Advection flux, Forest, Siberia, GAME

森林樹冠上のエネルギー収支

$$R_{\mathrm{NET}} - G - S - P = H + \lambda E$$



インバランス（$H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} \le R_{\mathrm{NET}} - G - S$）の要因

Ⅰ．見積り誤差

(1)R_{NET}, G, S**の見積り誤差**　Wilson *et al.*(2002)

(2)**熱フラックスの測定誤差**　Wilson *et al.*(2002)

(3)**渦相関法における高周波減衰**　Wilson *et al.*(2002)

Ⅱ．3次元構造をもつ組織流の効果

(4)**低周波変動の採り逃し**　Wilson *et al.*(2002) Sakai et al.(2002)

(5)**夜間の移流**　Wilson *et al.*(2002)

(6)**鉛直平均流の効果**　Lee(1998)

(7)**３次元構造をもった大規模大気混合の効果**　Finnigan(1999)

FLUXNET**サイトの結果のレビュー**　Wilson *et al.*(2002)

「小さな原因が複雑に複合→熱フラックスの過小評価」

LES**を用いた解析結果**　Watanabe and Kanda(2002)

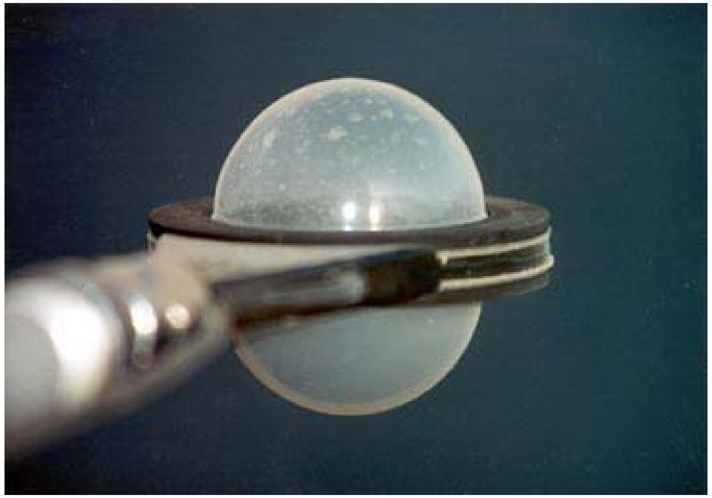
「定常流の存在→点計測フラックスで系統的に負のインバランス」

正味放射量　$R_{\mathrm{NET}} = S_{\mathrm{solar}} - S_{\mathrm{ref}} + L_{\mathrm{atm}} - L_{\mathrm{surface}}$

日射計(短波放射計)

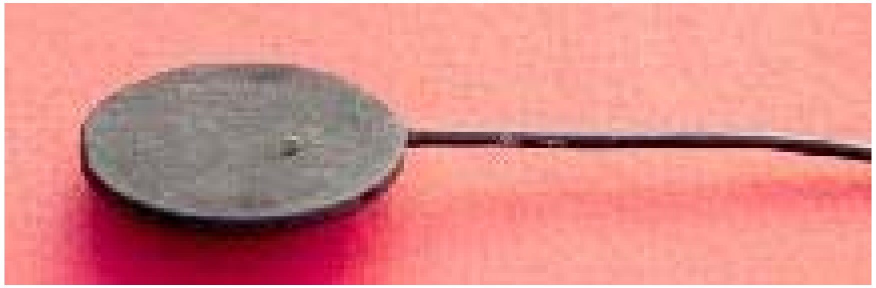
赤外放射計(長波放射計)

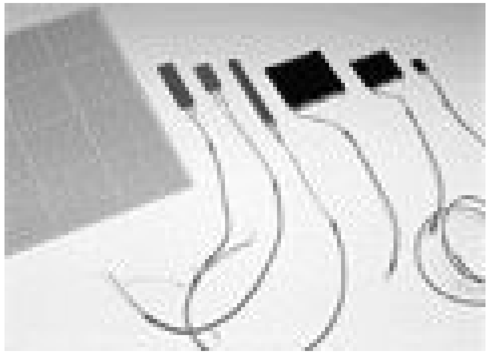
４成分放射収支計



正味放射計

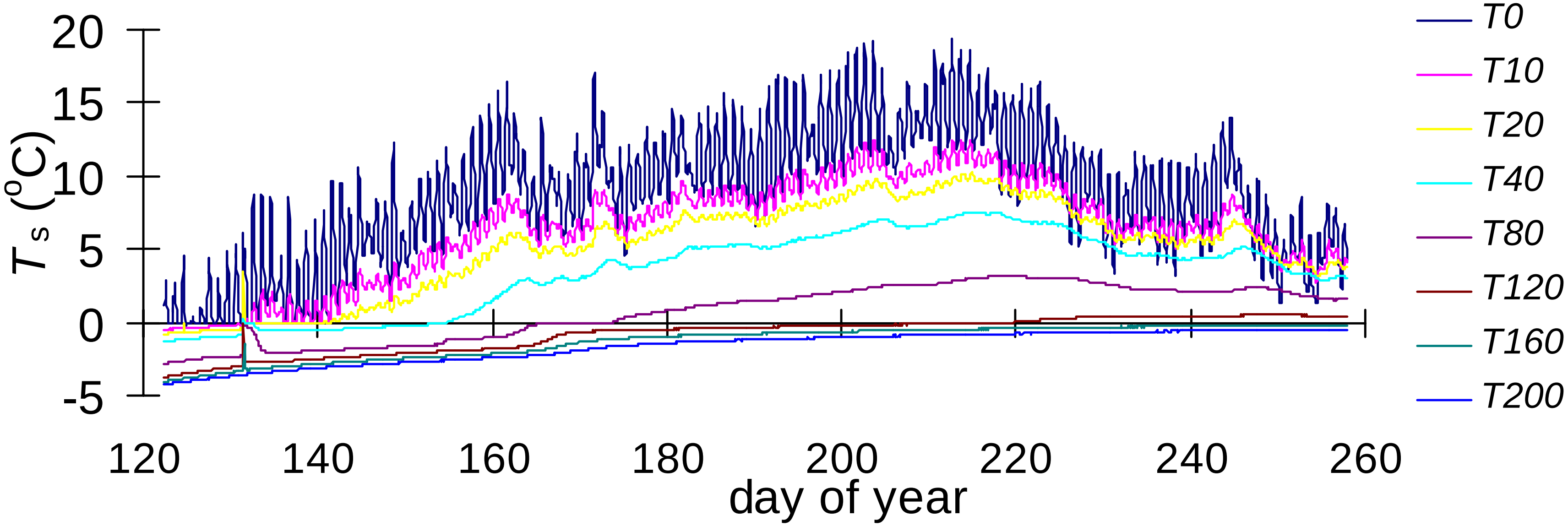
地中熱留量 *G*





G_{plate}

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



貯熱変化量　$S = S_{\mathrm{atmosphere}} + S_{\mathrm{biomass}}$

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

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

温度変化追従性： $A = \dfrac{\dfrac{\partial t}{\partial T_{\mathrm{b}}(t)}}{\partial T_{\mathrm{a}}(t - t_{\mathrm{delay}})}$

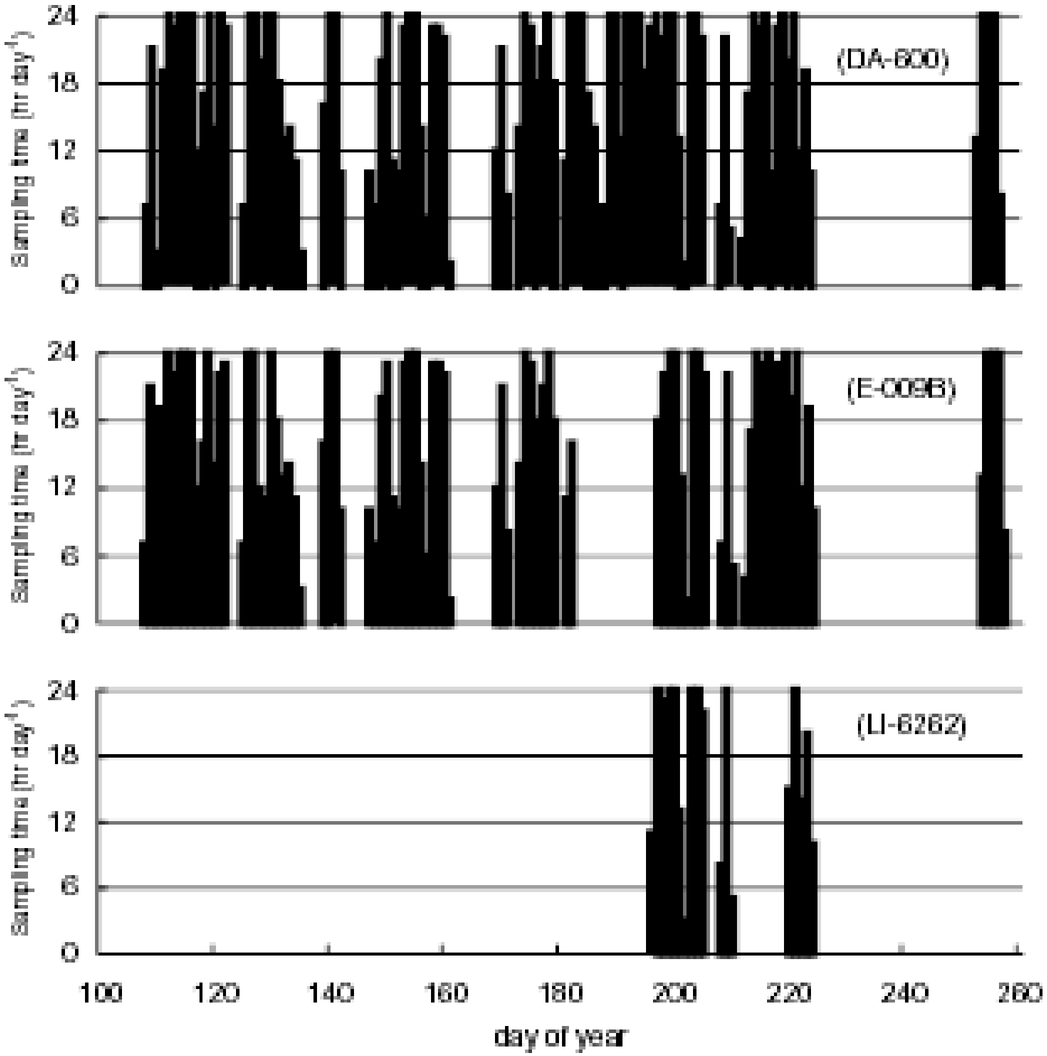
樹幹(円筒)内の熱伝導方程式：

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

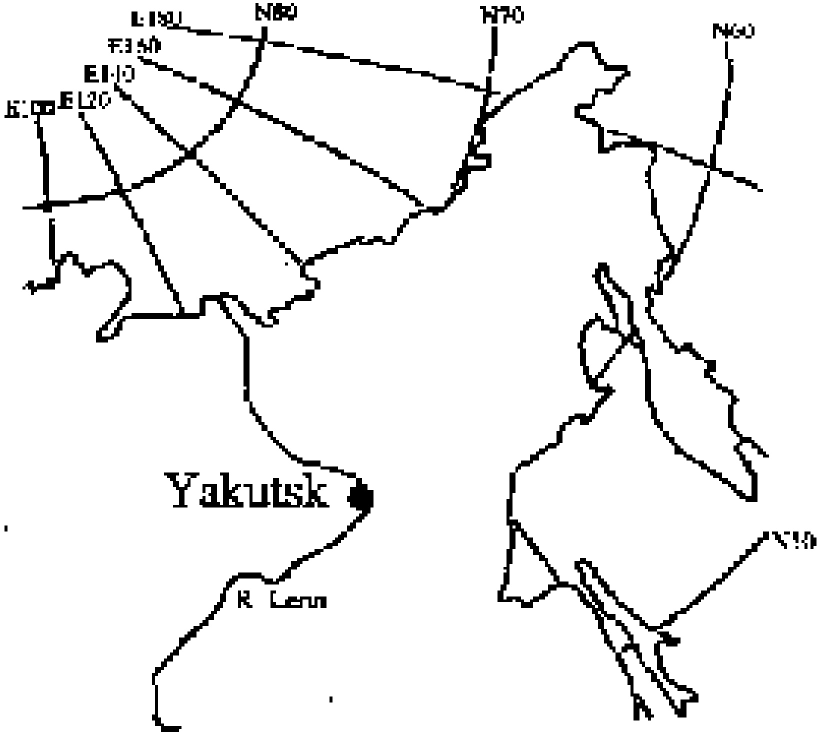
渦相関フラックス

顕熱フラックス $H_{\mathrm{eddy}} = \rho C_{\mathrm{P}} \overline{w'\theta'}$

潜熱フラックス $\lambda E_{\mathrm{eddy}} = \lambda \overline{w'q'}$



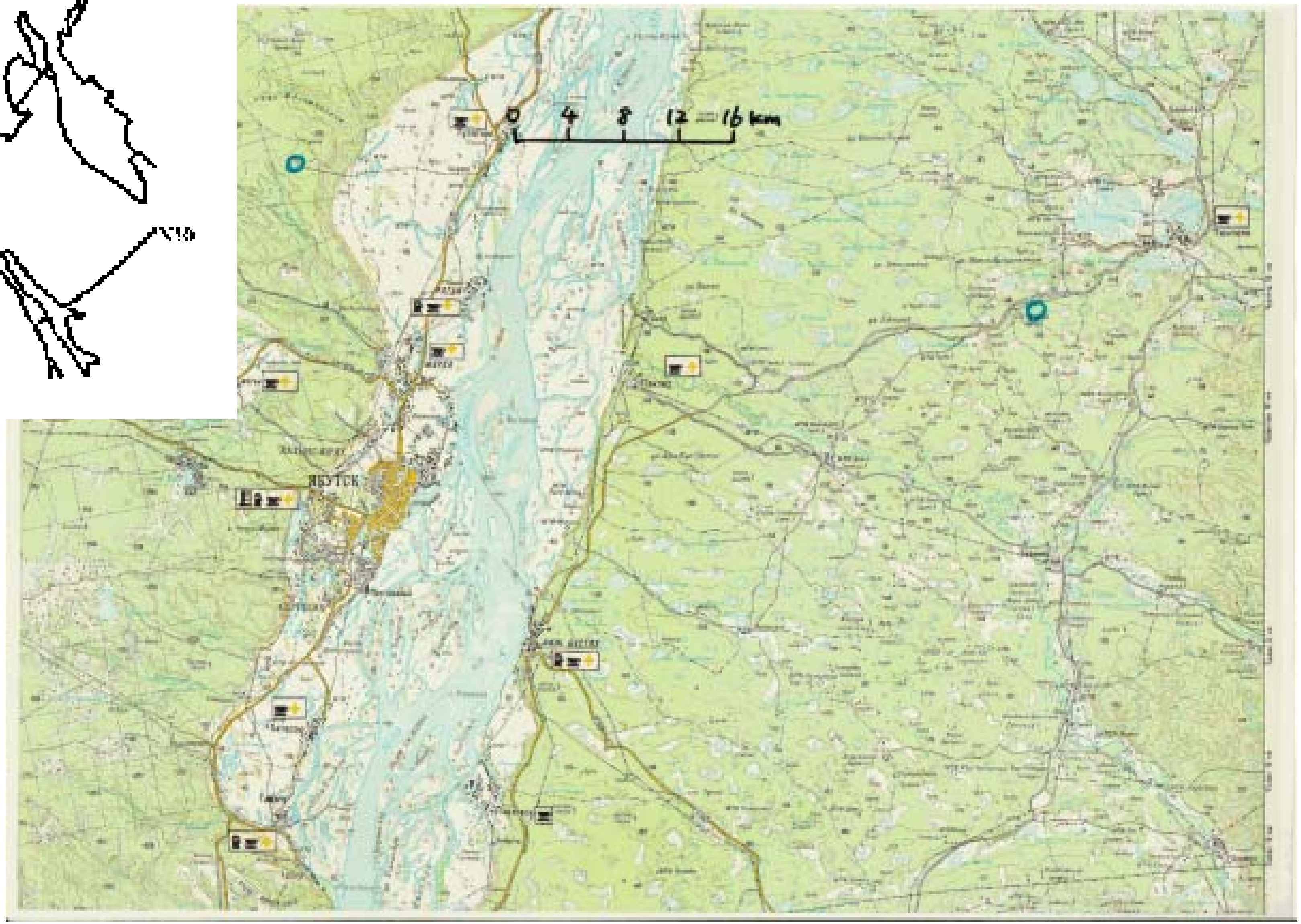
観測



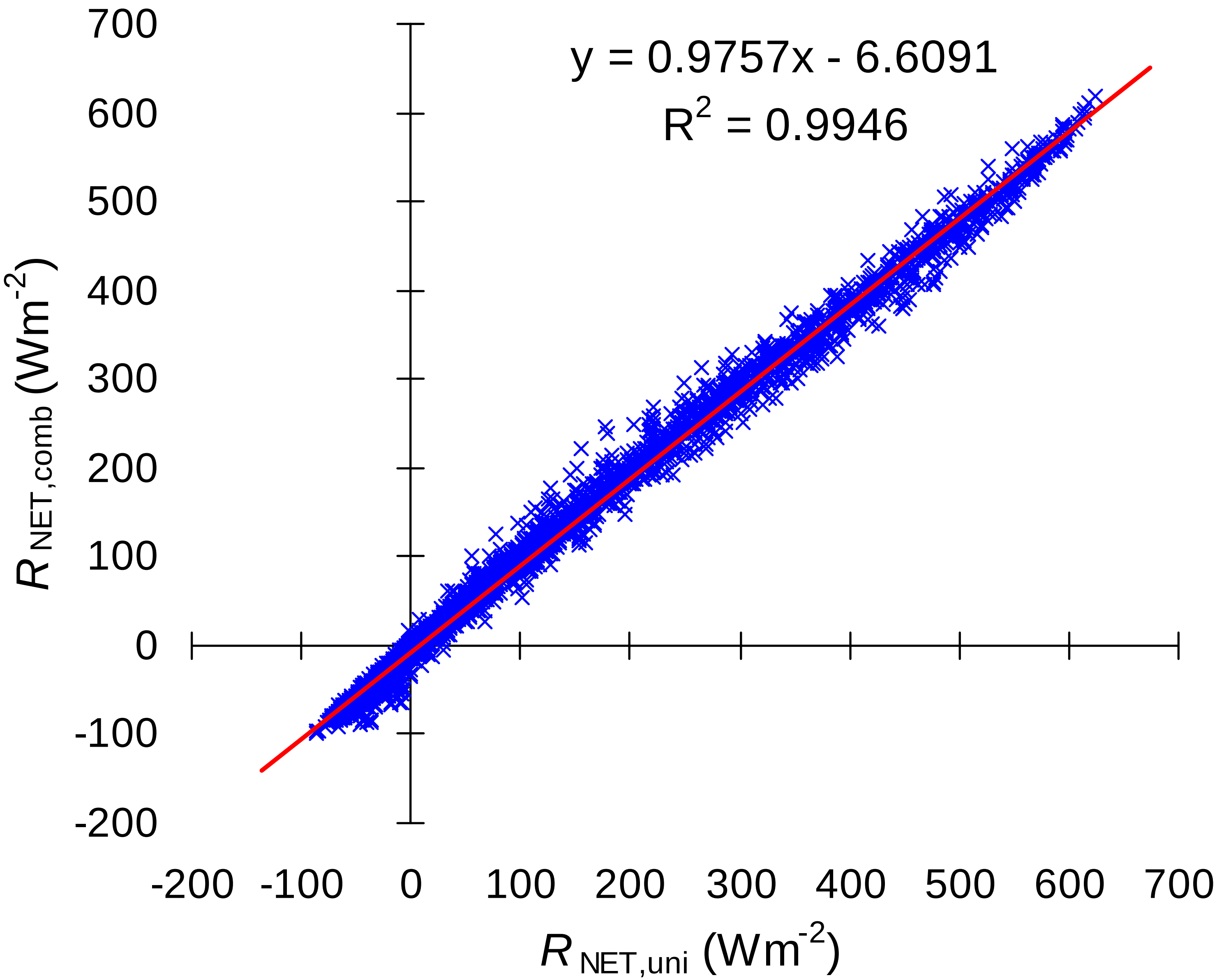
東シベリア　62.15°N、130.51°E

2000 **年** 4 **月** 15 **日〜**9 **月** 14 **日**

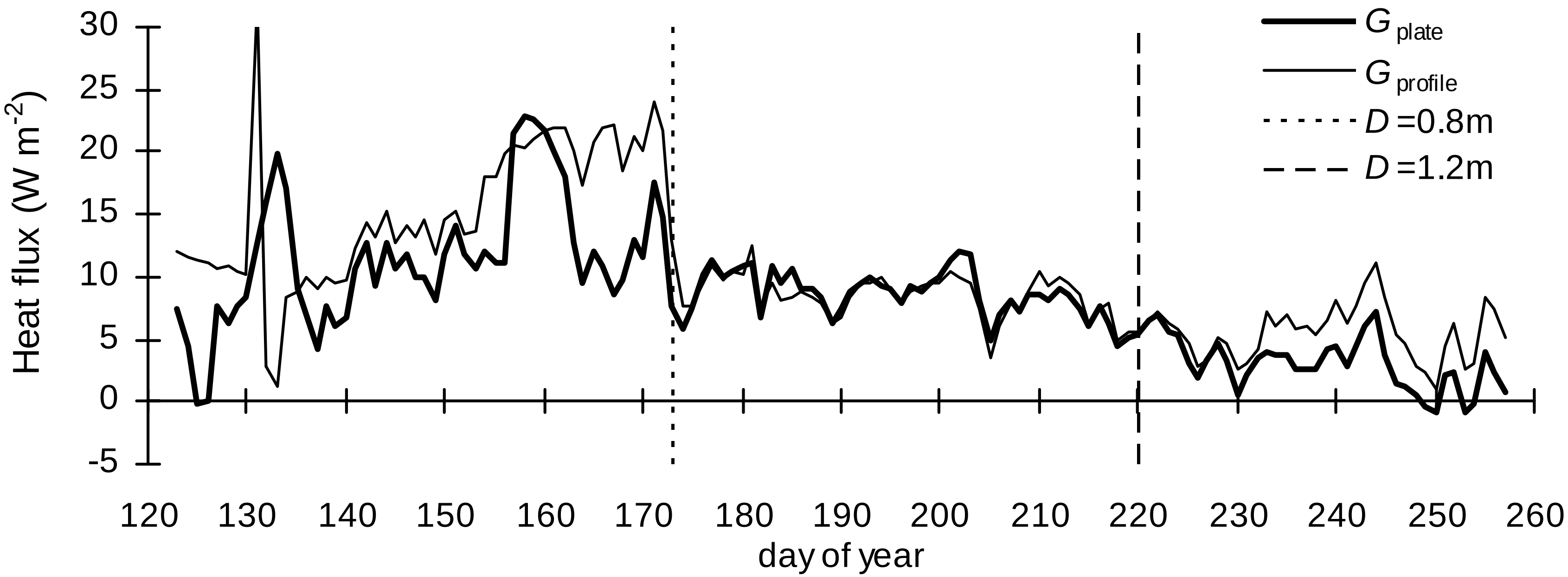
カラマツ林(GAME-Siberia **右岸サイト**)

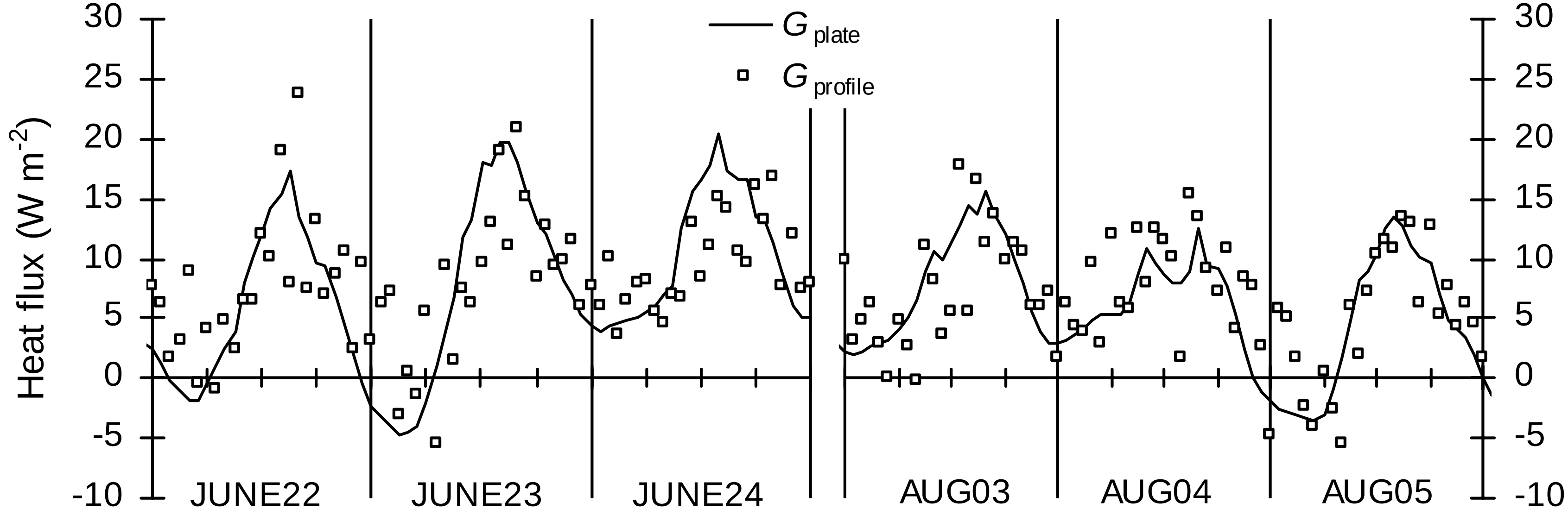


正味放射量 $R_{\mathrm{NET}} = S_{\mathrm{solar}} - S_{\mathrm{ref}} + L_{\mathrm{atm}} - L_{\mathrm{surface}}$



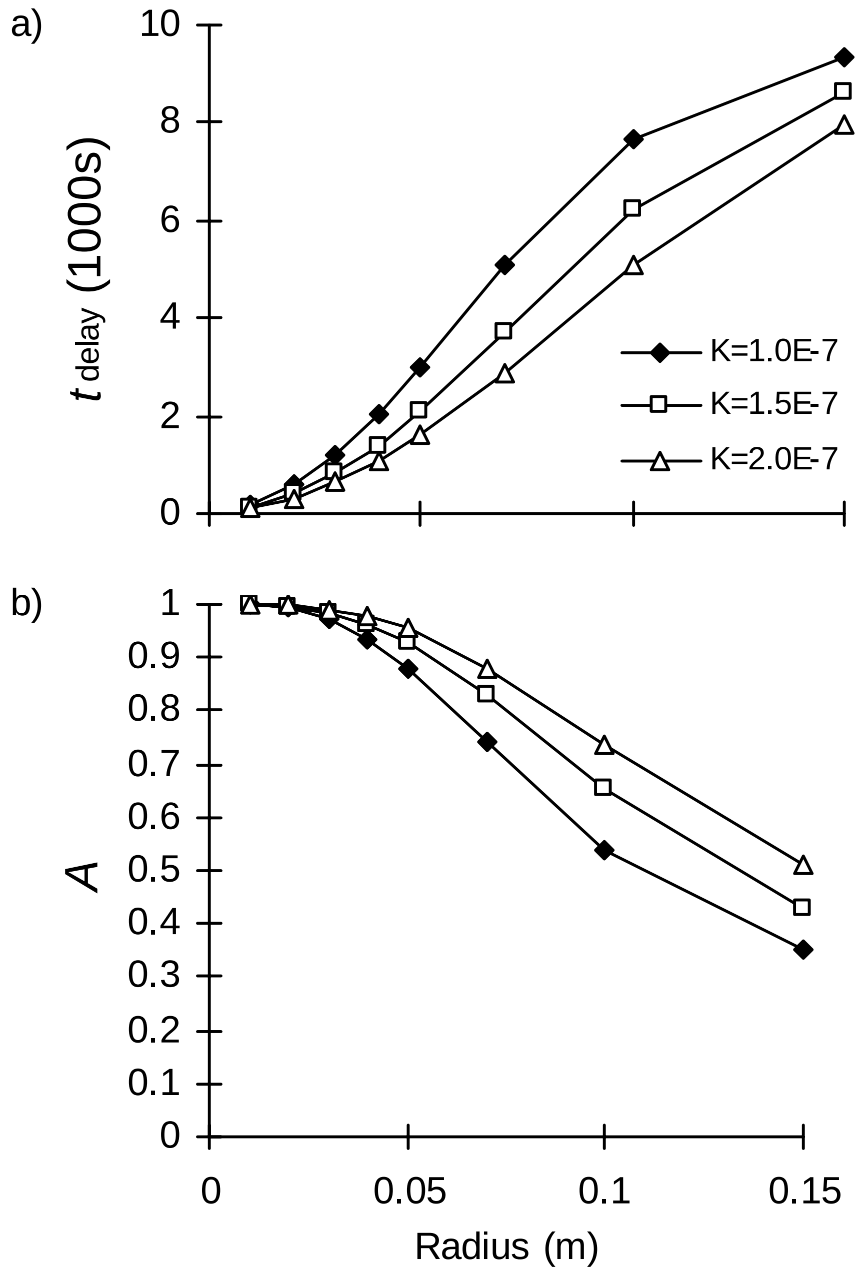
地中熱留量　G_{plate}、$G_{profile}$





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

貯熱変化量　$S=S_{atmosphere}+S_{biomass}$



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

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

位相差　t_{delay}=1800 sec

追従性(振幅比)　A=1.0

有効エネルギー　$R_{\mathrm{NET}} - G - S - P = H + \lambda E$

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

P は微小で無視できると仮定。

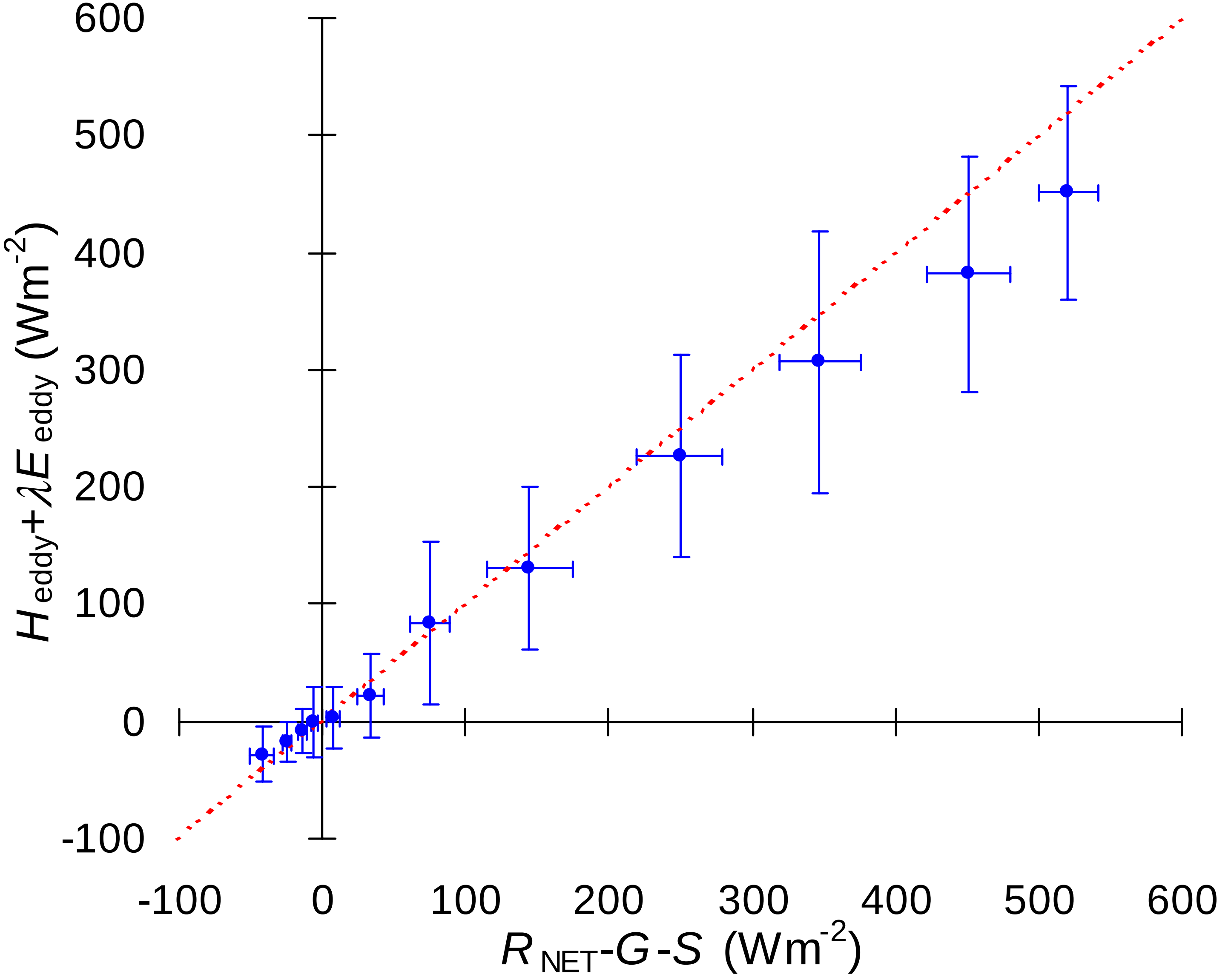
R_{NET} は有効エネルギーの大部分を占める。

日中、G と S の寄与は同程度。

夜間、S の寄与が比較的大きい。

$S_{\mathrm{atmosphere}}$ よりも、S_{biomass} の寄与が大きい。

エネルギーインバランス　$H_{\mathrm{eddy}} + \lambda E_{\mathrm{eddy}} \leq R_{\mathrm{NET}} - G - S$



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

インバランスの要因

Ⅰ．見積り誤差

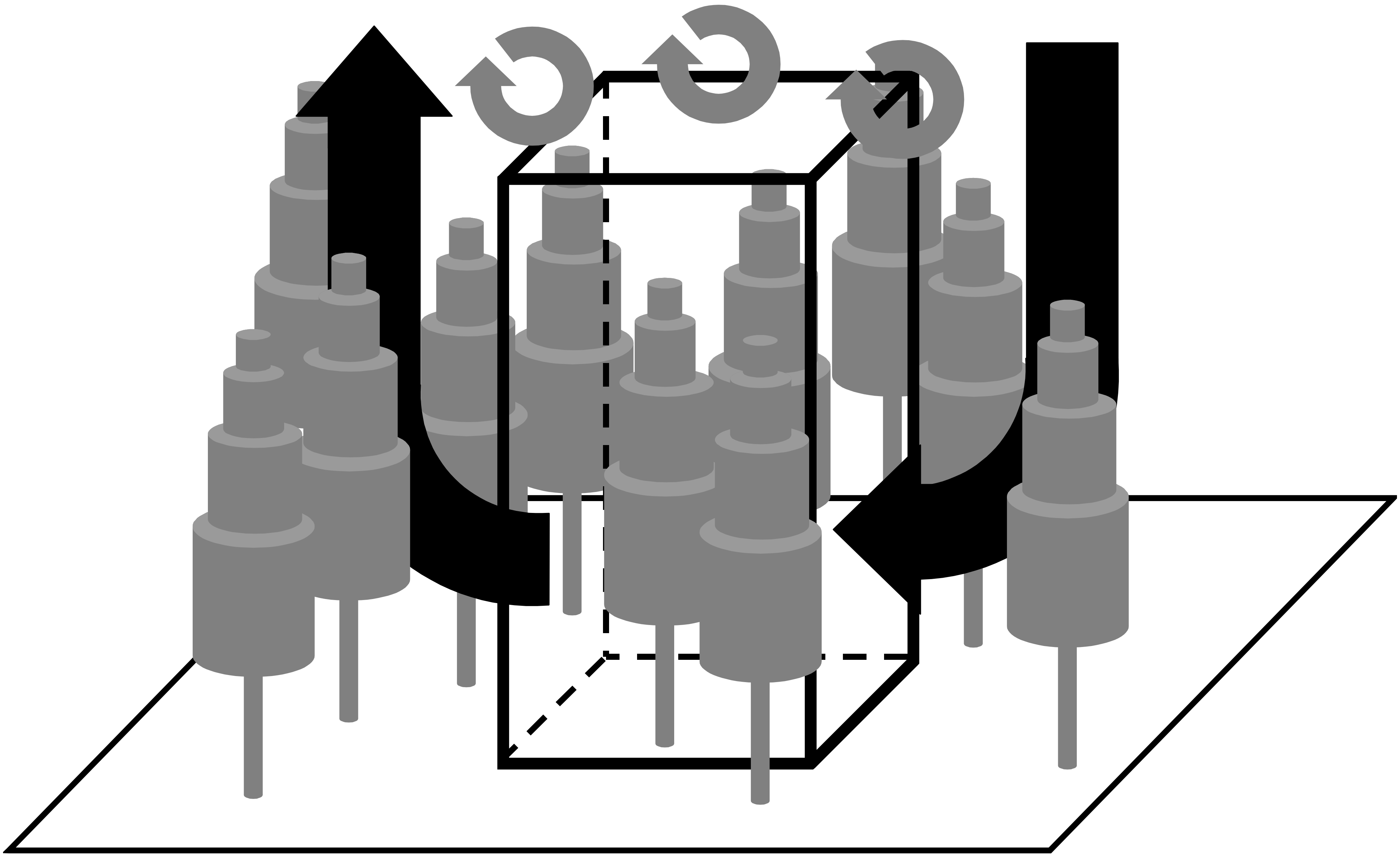
$R_{NET,uni}$：正のバイアスあり←上部ドームの透過性が小。
$R_{NET,comb}$：少なくとも $R_{NET,uni}$ より平均 16.8Wm^{-2} 小。
→R_{NET}：変化は良好に計測。正のバイアスとなる可能性は小。

$G_{profile}$：夏期は G_{plate} と良好に一致。再凍結・乾燥による誤差あり
→G：バイアス誤差は小さい。有効エネルギーへの寄与も小さい。

$S_{biomass}$：$S_{atmosphere}$ より寄与が大きい。
S：日中は G と同程度、夜間は寄与が大きい。
→日中の主要因ではないが、インバランスの要因となり得る。

Ⅱ．３次元構造をもつ組織流（低周波変動、大規模渦、移流）による熱輸送の効果→鉛直熱フラックスの見積り誤差

移流フラックス



基礎式

エネルギー収支式：

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

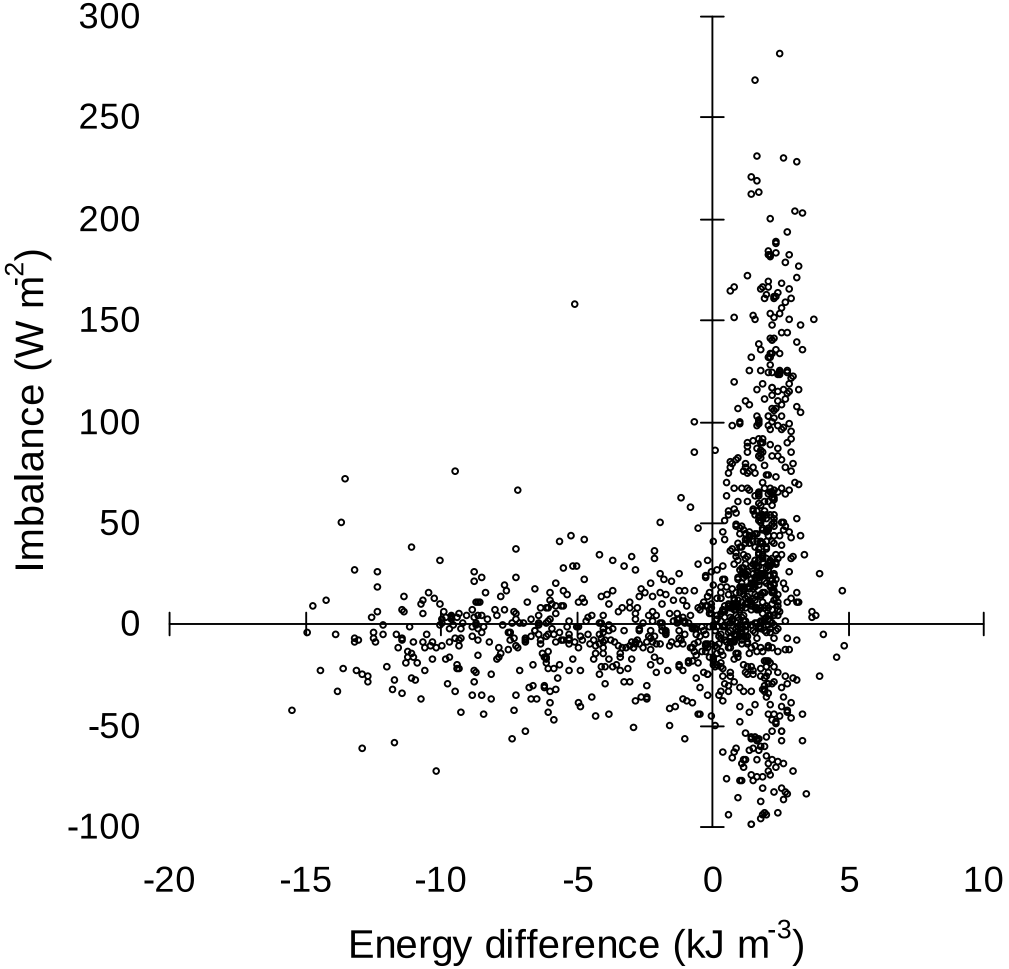
顕熱フラックス： $H_{\mathrm{adv}} = \rho C_{\mathrm{P}} T_{\mathrm{out}} V - \rho C_{\mathrm{P}} T_{\mathrm{in}} V$

潜熱フラックス： $\lambda E_{\mathrm{adv}} = \lambda q_{\mathrm{out}} V - \lambda q_{\mathrm{in}} V$

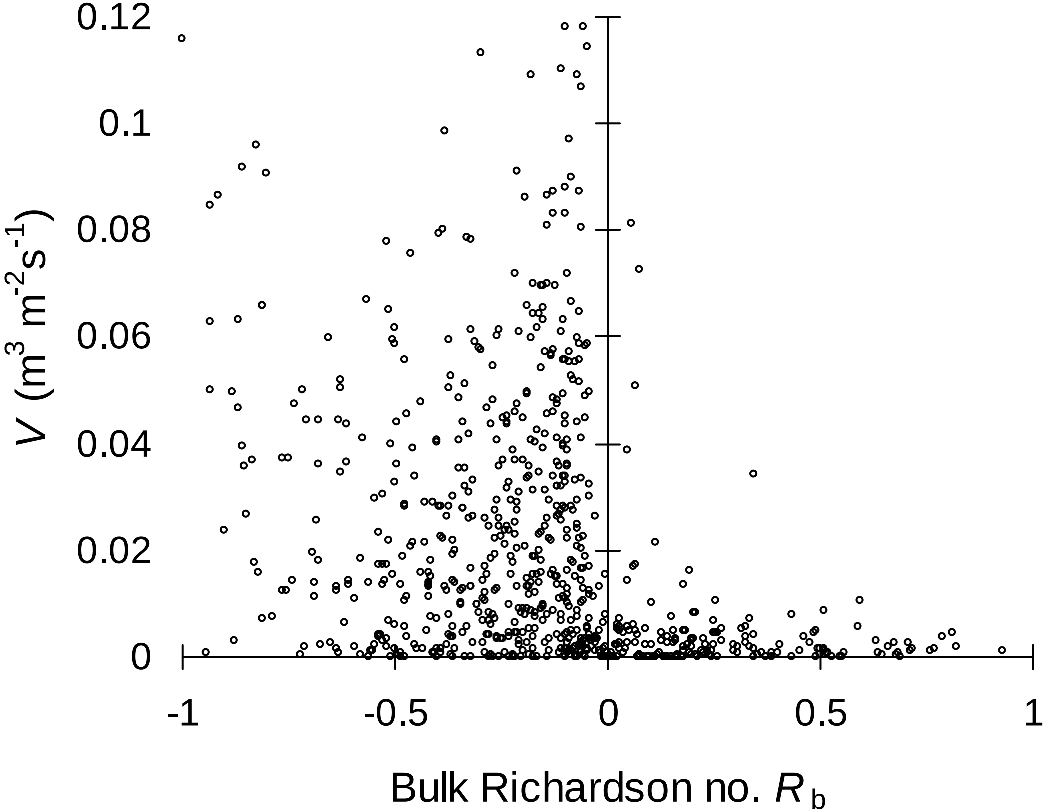
移流体積[$m^3 m^{-2} s^{-1}$]**：** $V = \dfrac{R_{\mathrm{NET}} - G - H_{\mathrm{eddy}} - \lambda E_{\mathrm{eddy}}}{\rho C_{\mathrm{P}} T_{\mathrm{out}} - \rho C_{\mathrm{P}} T_{\mathrm{in}} + \lambda q_{\mathrm{out}} - \lambda q_{\mathrm{in}}}$

→樹冠上と林幹空間の温度差・湿度差が移流熱フラックスに重要
一般的な温帯林：土壌が湿潤、樹冠が閉鎖→温度差小、湿度差大
シベリアの森林：土壌湿潤、樹冠が粗→温度差・湿度差ともに大

試算結果その１

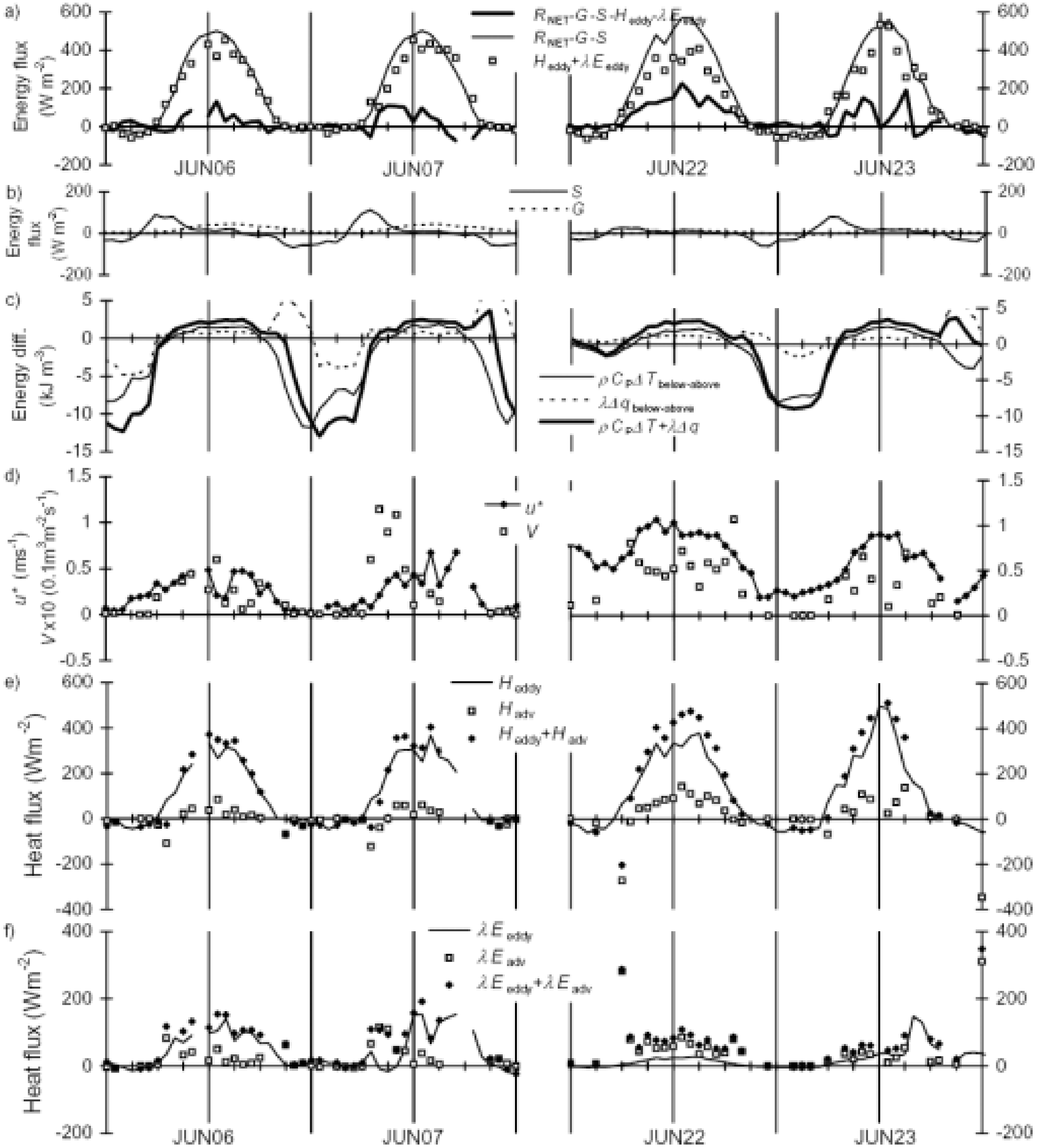


Imbalance (W m-2)
300
250
200
150
100
50
0
-50
-100
-20
-15
-10
-5
0
5
10
Energy difference (kJ m-3)



V (m3 m-2s-1)
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.5
0
0.5
1
Bulk Richardson no. R b

試算結果



インバランス

G と S

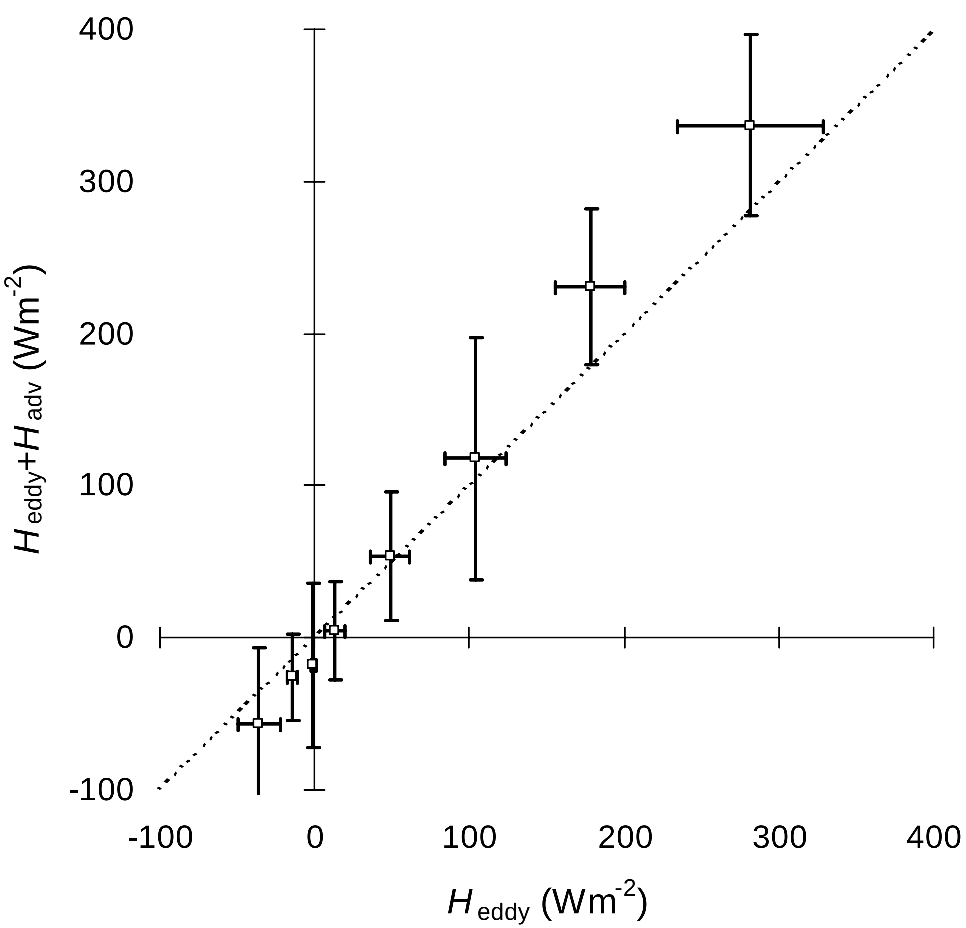
上下エネルギー差

移流体積

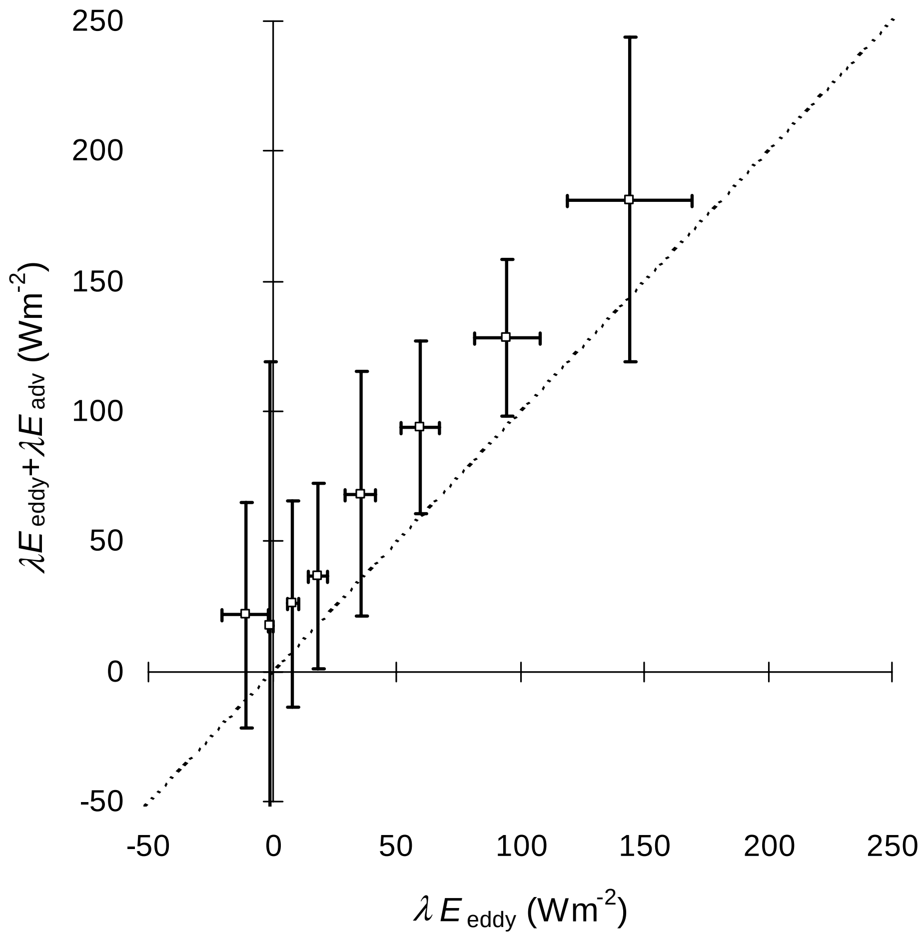
顕熱フラックス

潜熱フラックス

試算結果その２

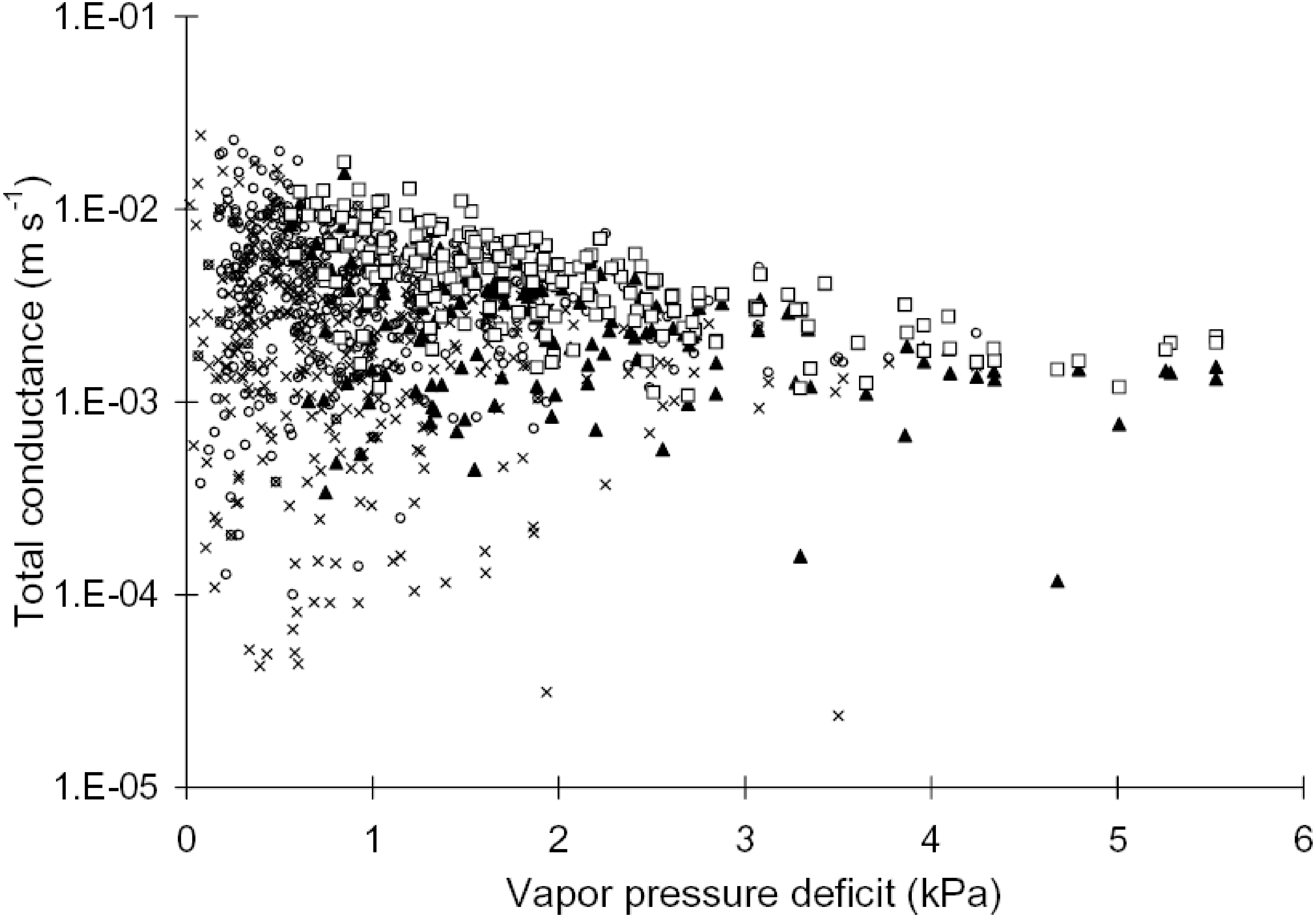


顕熱フラックス



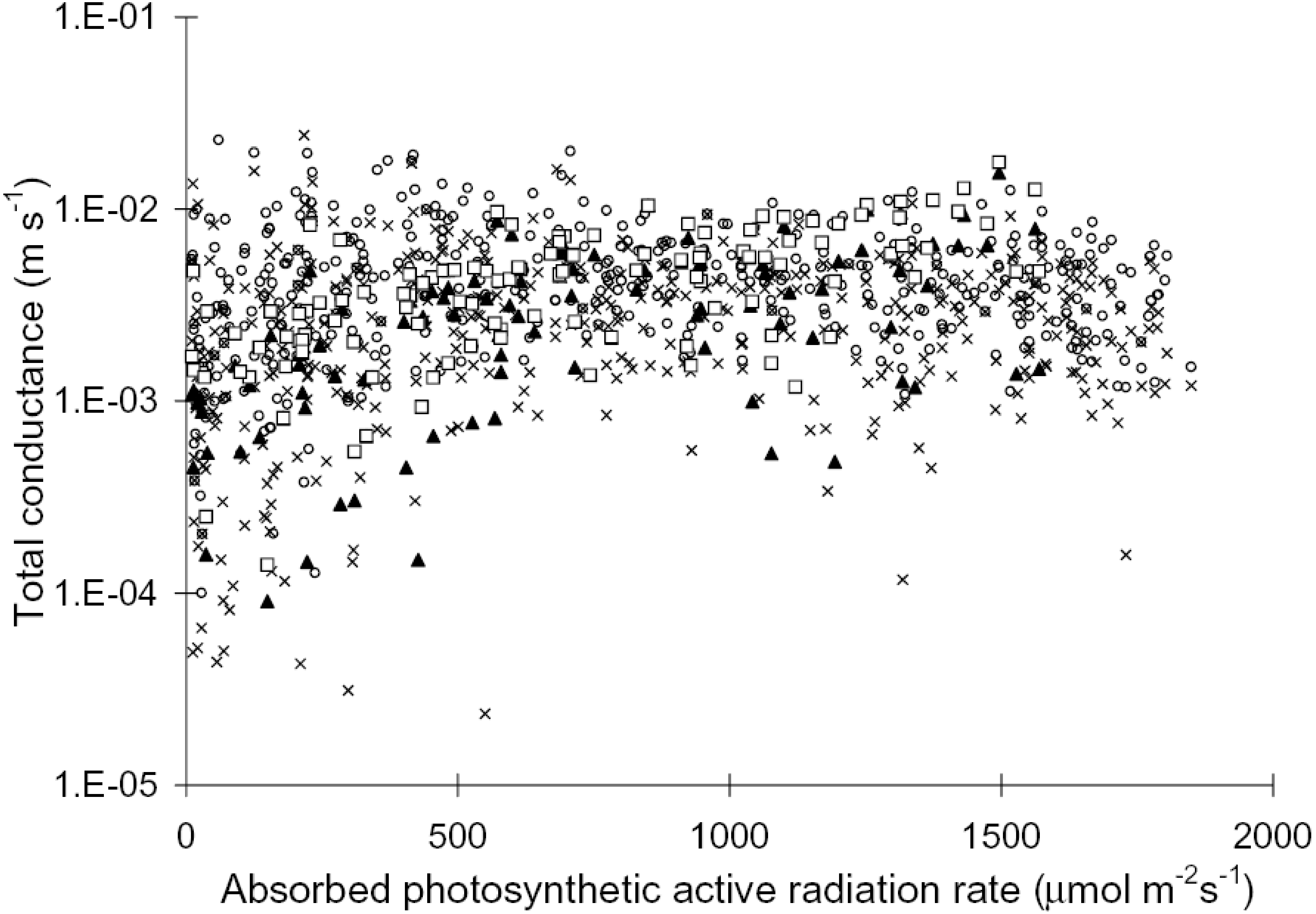
潜熱フラックス

全コンダクタンス vs 飽差



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)

全コンダクタンス vs 吸収光合成有効放射



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)

結論

東シベリア・カラマツ林、2000年生長期
有効エネルギー・渦相関熱フラックス測定結果：

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

インバランスの要因

Ⅰ．見積り誤差

R_{NET}：変化は良好に計測。正のバイアスとなる可能性は小。

G：バイアス誤差は小さい。有効エネルギーへの寄与も小さい。

S：日中の主要因ではないが、インバランスの要因となり得る。

Ⅱ．3 次元構造をもつ組織流（低周波変動、大規模渦、移流）による熱輸送の効果→１次元観測から試算

２つの仮定：

(1)　**温度と絶対湿度は水平方向で均一に分布**

(2)　**計測された渦相関フラックスは、対象領域を代表**

→移流フラックスの試算

V　　：0.025±0.034m^{3}m^{-2}s^{-1}

H_{adv}　　：4.4±58.6Wm^{-2}、**日中に正、夜間に負**

λE_{adv}　：25.5±51.5Wm^{-2}、**ほとんどの場合、正**

特にλEが大きく変化　蒸発散の環境応答特性が明瞭化

課題：

仮定(1)不成立時多し→代入する温度・湿度の精度向上

仮定(2)の検証不足→３次元的観測・数値計算による検証