Parameterization of free and forced convection in the atmospheric boundary layer based on large-eddy simulations

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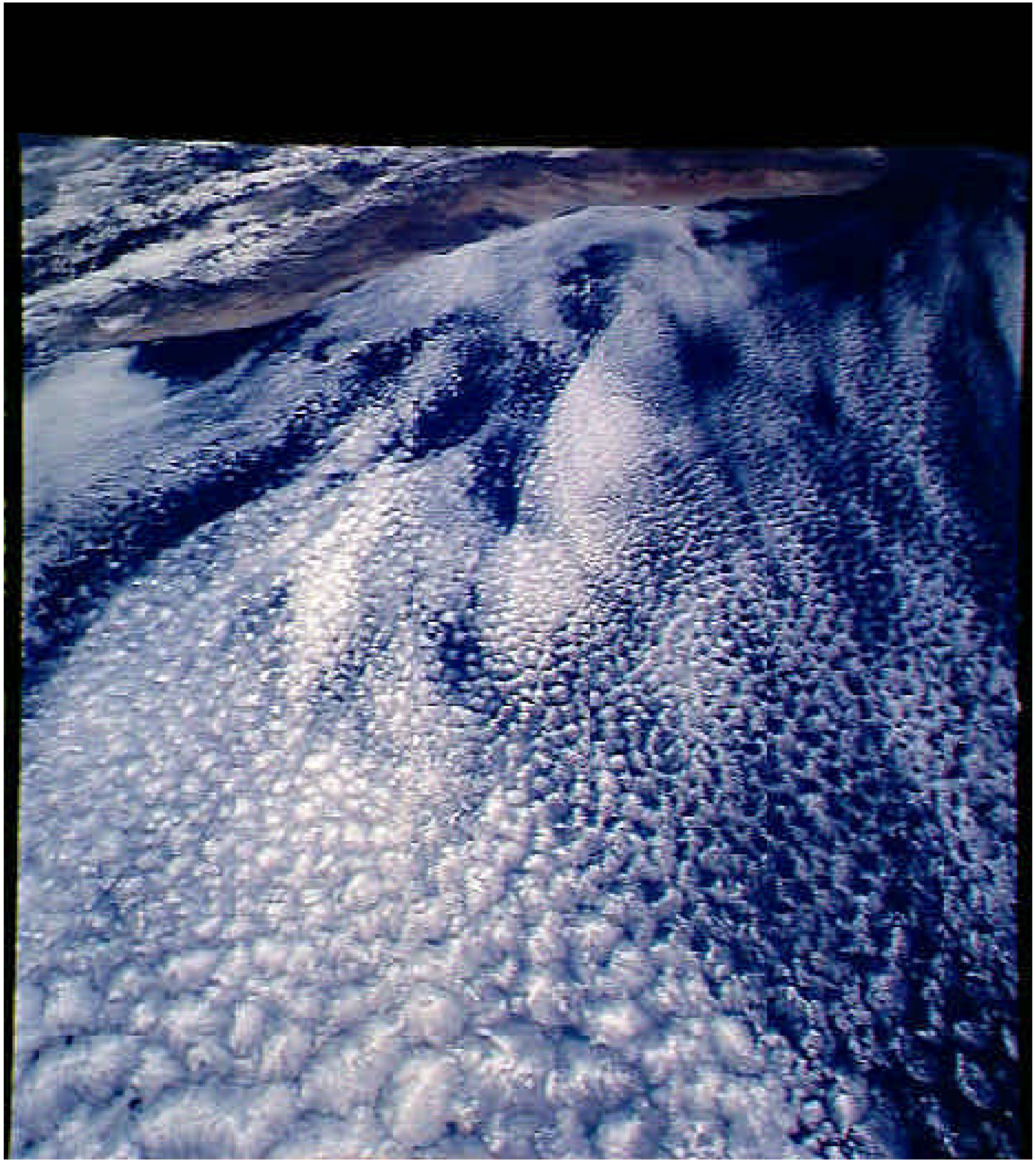
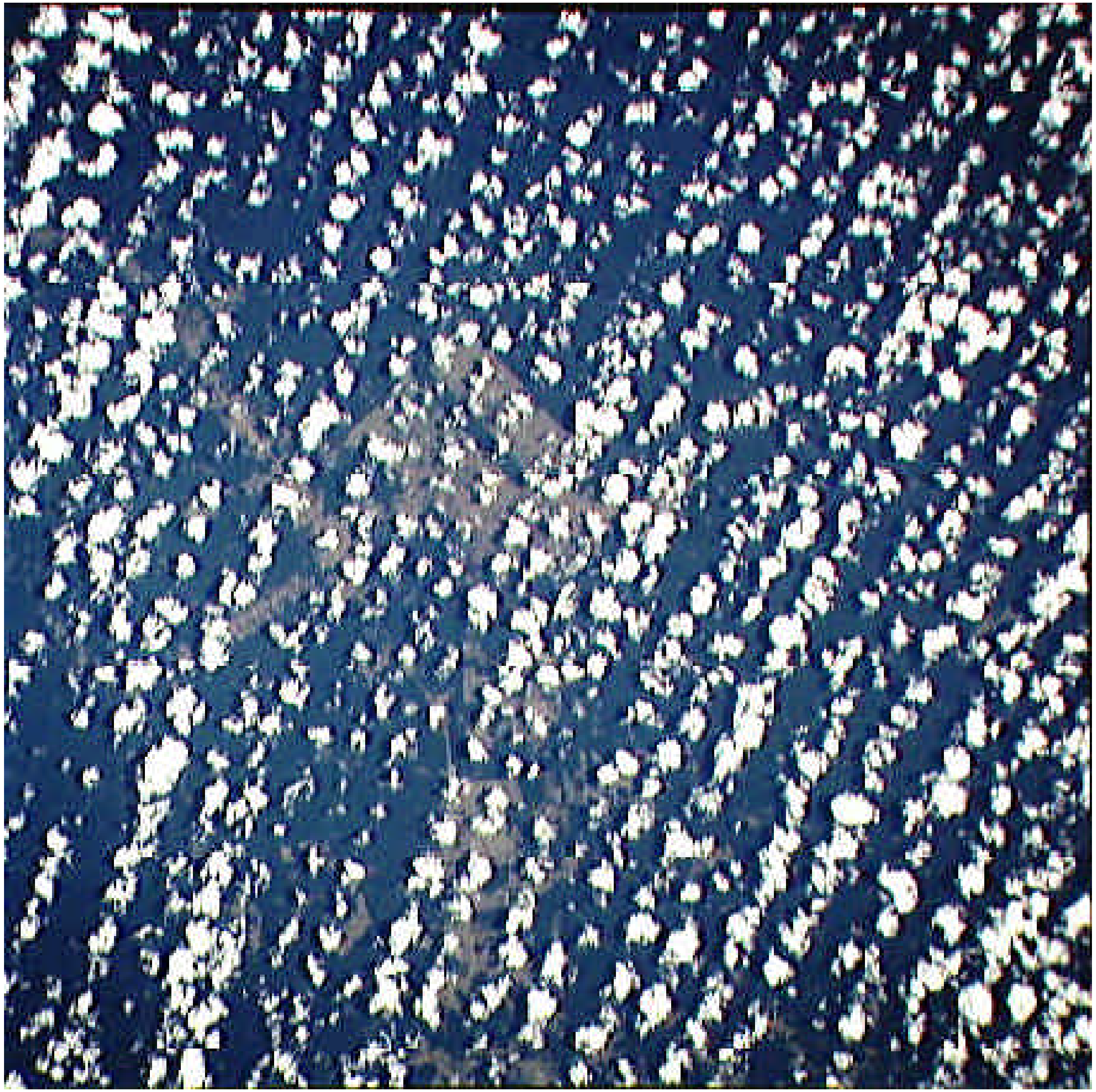
Forms of atmospheric convection:

- 1. Cloudless free convection (clear cells)
- 2. Cloudless forced convection (clear rolls)

- 3. Cu-topped free convection (open cells)
- 4. Cu-topped forced convection (open rolls)

- 5. Sc-topped free convection (closed cells)
- 6. Sc-topped forced convection (closed rolls)





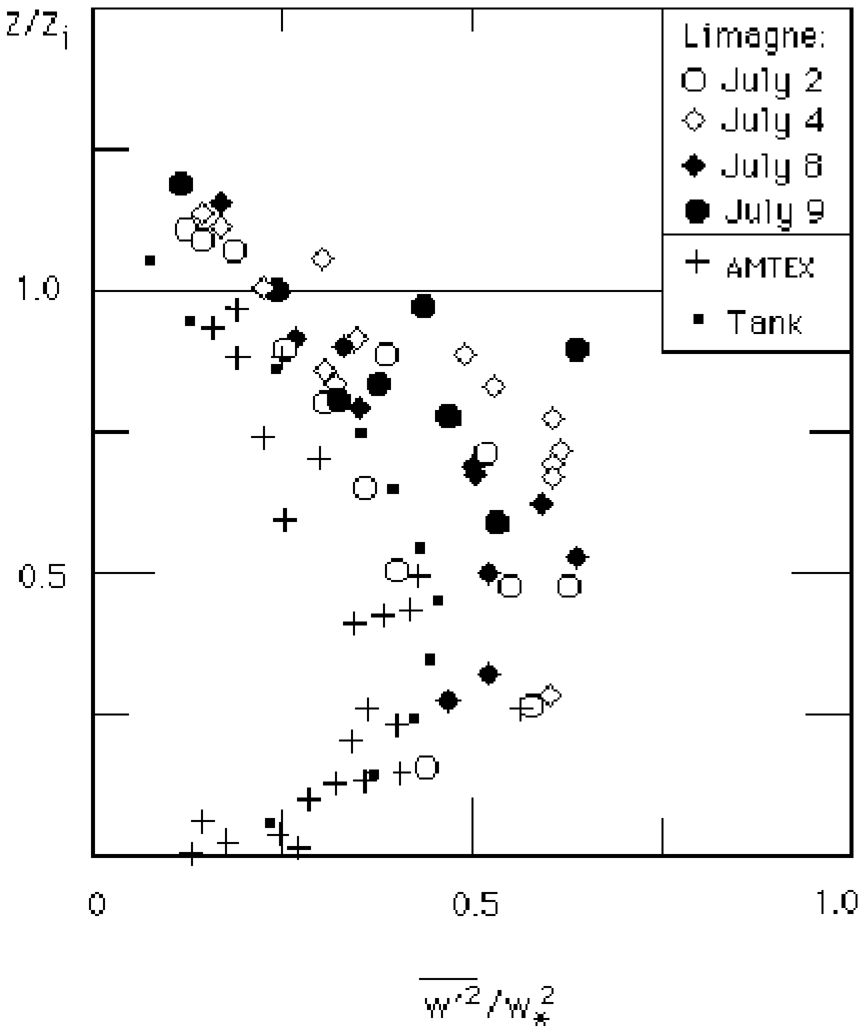
$w_* = (\beta\, z_i\, H_o)^{1/3}$ for vertical velocity,

$\Theta_* = H_o/w_*$ for temperature ,

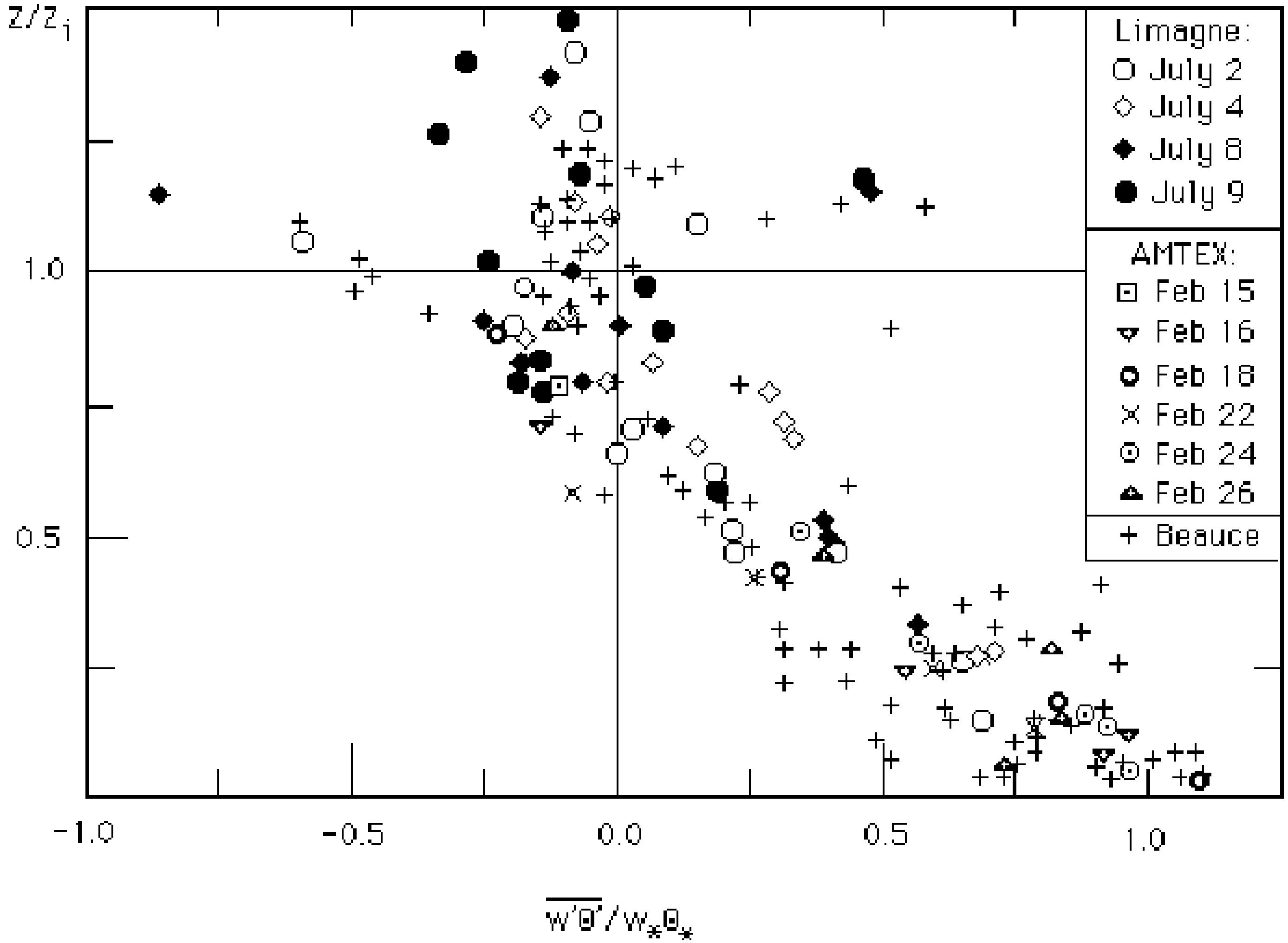
$q_* = Q_o/w_*$ for a passive scalar,

z_i for height,

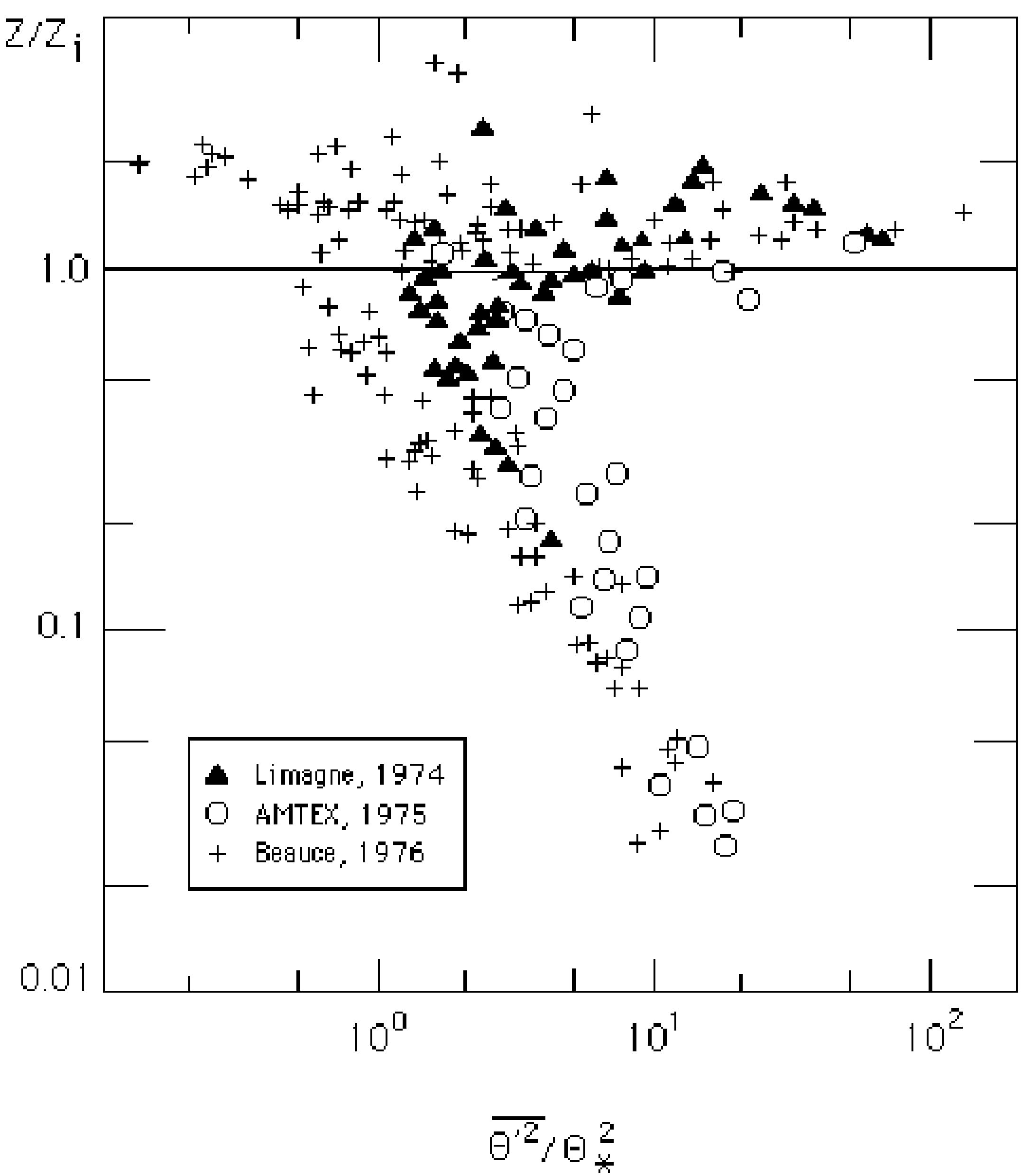
$\tau_* = w_*/z_i$ for time,



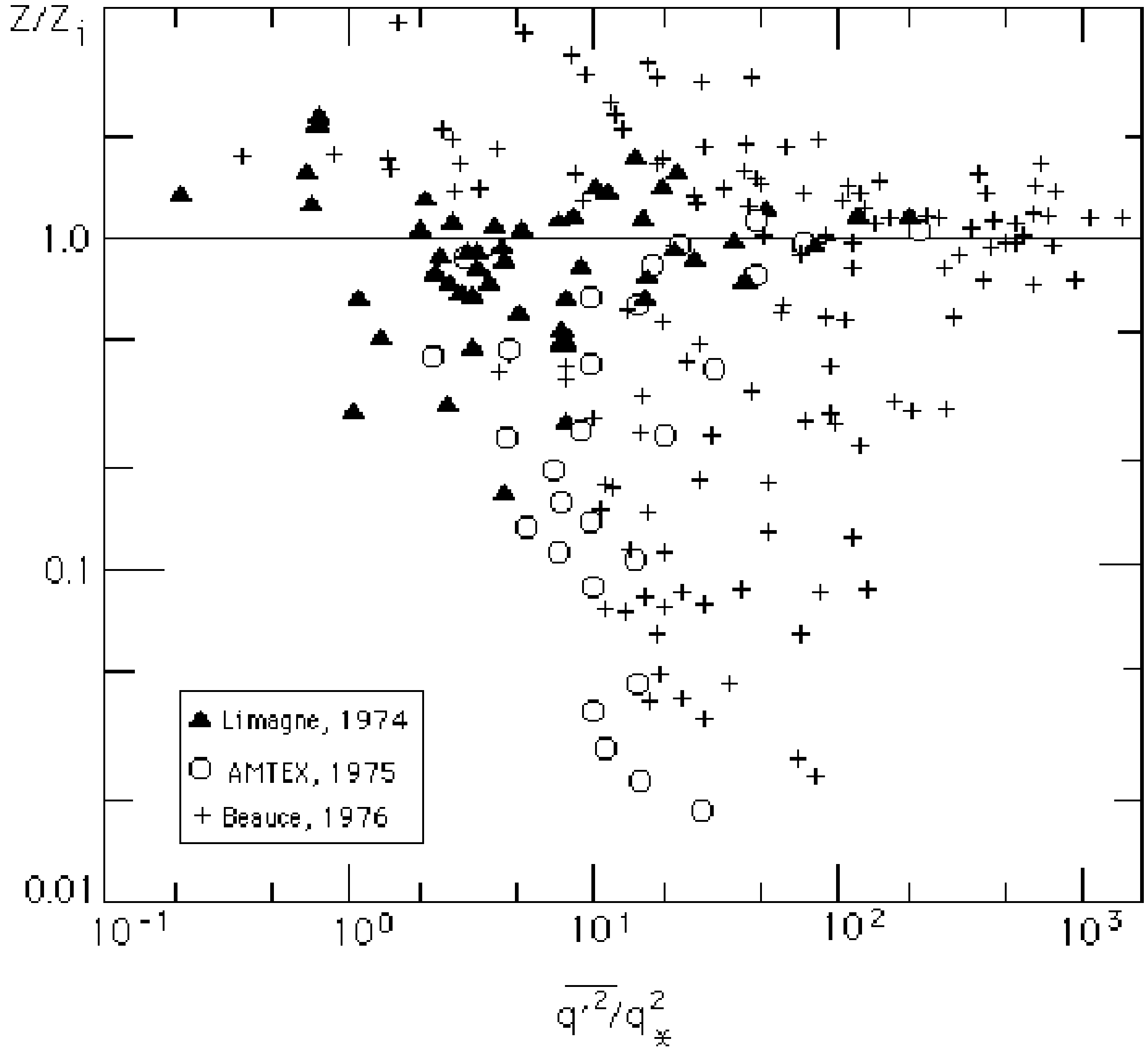
z/z_i
1.0
0.5
0
0.5
1.0
Limagne:
July 2
July 4
July 8
July 9
AMTEX
Tank
w'^2/w_*^2



z/z$_i$
1.0
0.5
-1.0
-0.5
0.0
0.5
1.0
$\overline{w'\theta'}/w_*\theta_*$
Limagne:
July 2
July 4
July 8
July 9
AMTEX:
Feb 15
Feb 16
Feb 18
Feb 22
Feb 24
Feb 26
Beauce



Z/Z_i
1.0
0.1
0.01
Limagne, 1974
AMTEX, 1975
Beauce, 1976
10^0
10^1
10^2
$\overline{\Theta'^2}/\Theta_*^2$

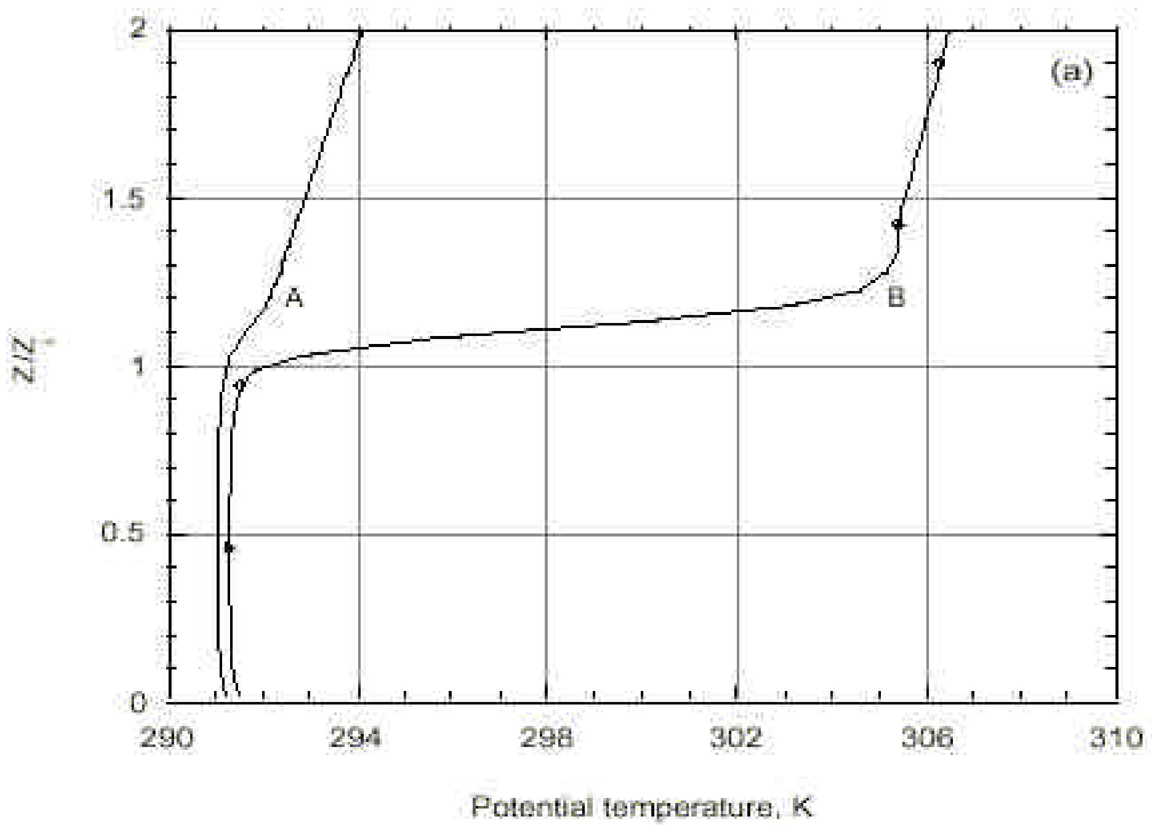


Z/Z_i
1.0
0.1
0.01
10^-1
10^0
10^1
10^2
10^3
q'^2/q_*^2
Limagne, 1974
AMTEX, 1975
Beauce, 1976

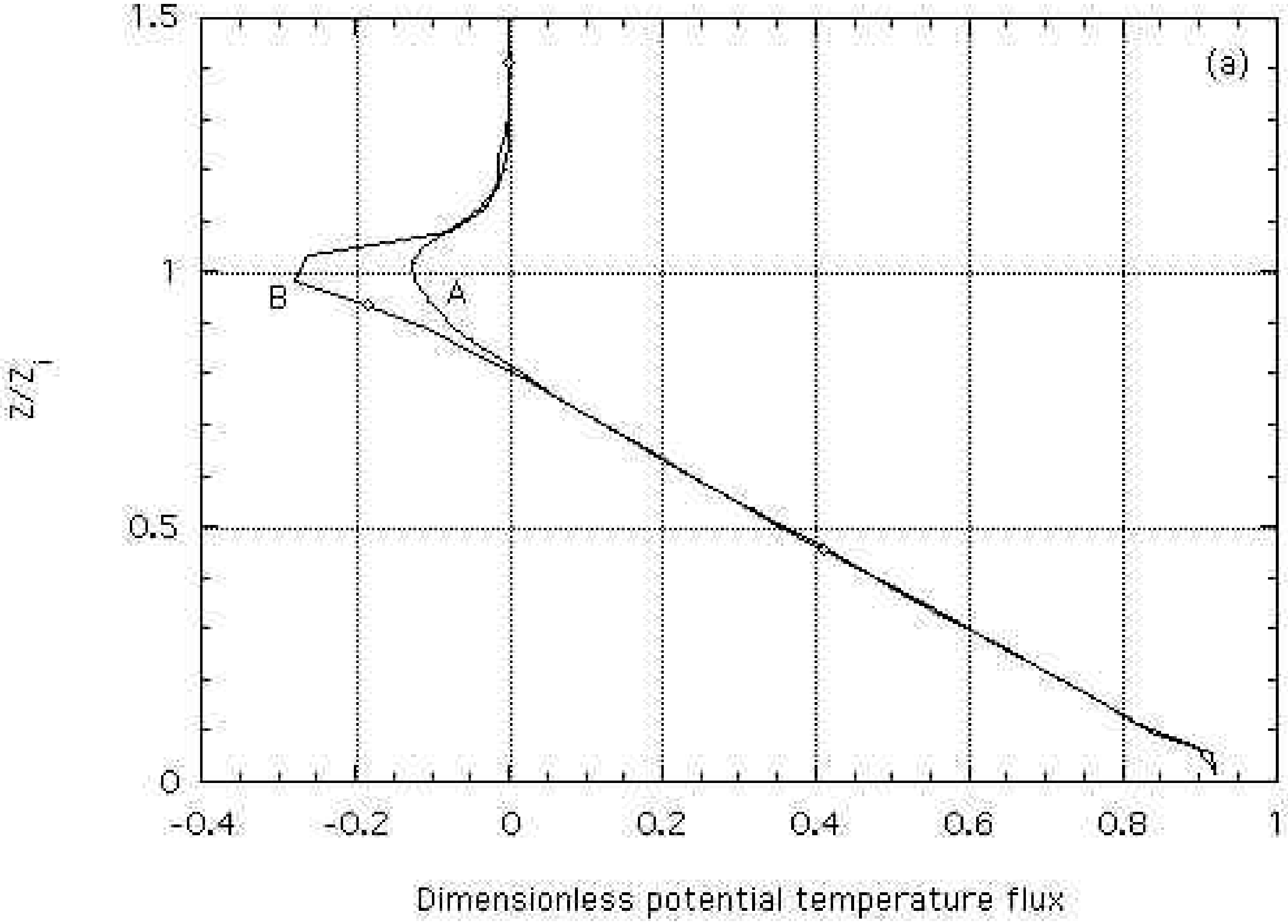
LES experiments:

- 1. Free convection
- 2. Forced convection (barotropic)
- 3. Forced convection (baroclinic)

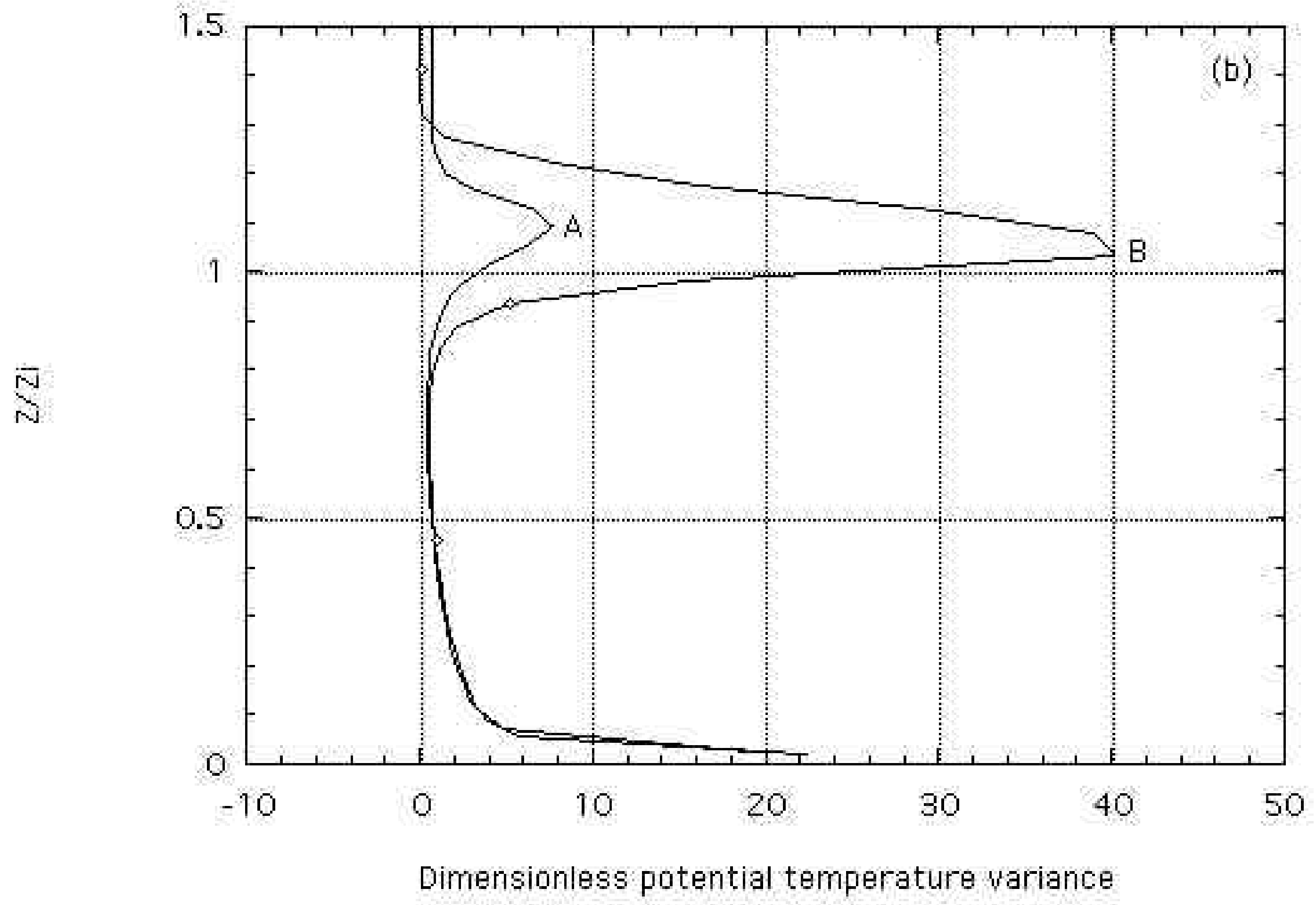
Free-convection experiments

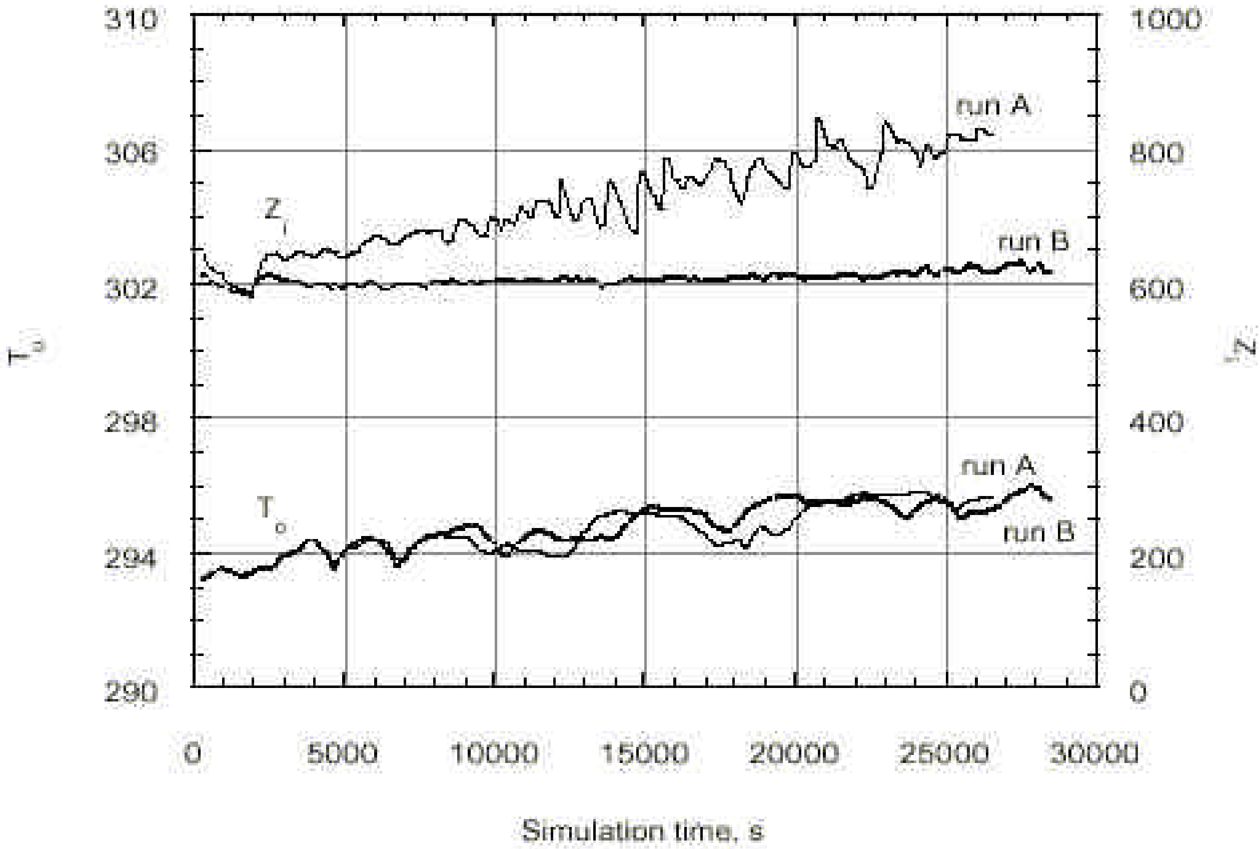


(a)
A
B
Z/Z_i
2
1.5
1
0.5
0
290
294
298
302
306
310
Potential temperature, K



1.5
1
0.5
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
(a)
B
A
z/z$_i$
Dimensionless potential temperature flux


1.5
1
0.5
0
Z/Zi
-10
0
10
20
30
40
50
Dimensionless potential temperature variance
(b)
A
B



310
306
302
298
294
290
1000
800
600
400
200
0
run A
run B
run A
run B
Z_i
T_o
T_o
Z_i
0
5000
10000
15000
20000
25000
30000
Simulation time, s

$S_w = w_*$ for vertical velocity,

$S_\theta = w_* N_i / \beta$ for temperature ,

$S_q = g_i \; w_* / N_i$ for humidity (or other scalar),

$S_h = w_* / N_i$ for height,

$S_t = 1/N_i$ for time,

where N_i is the Brunt-Vaisala frequency

$$N_i = (\beta \gamma_i)^{0.5}$$

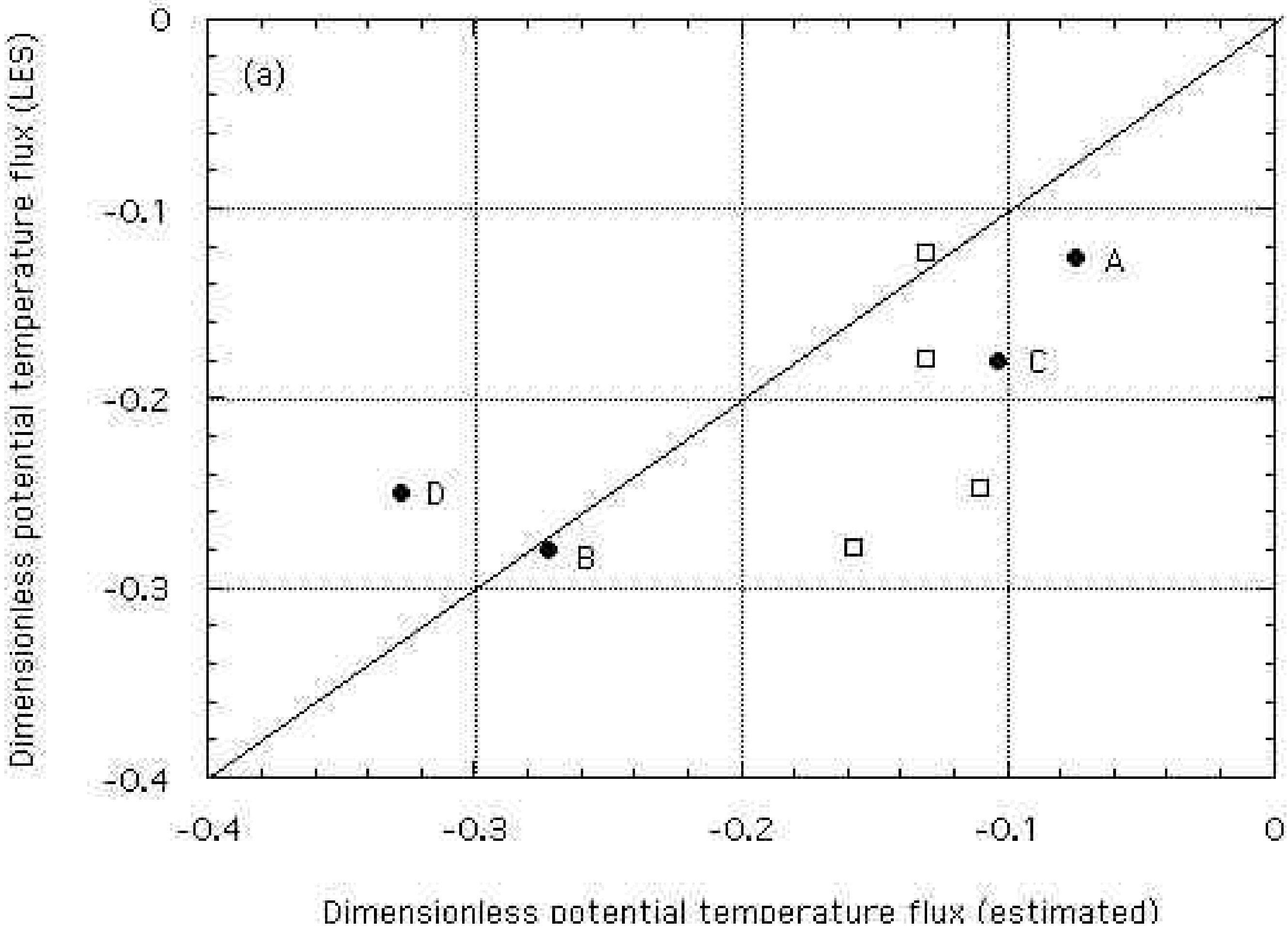
$$H_i = - c_H \quad {}_w S \, S_\theta$$

$$Q_i = - c_Q \quad {}_w S \, S_q$$

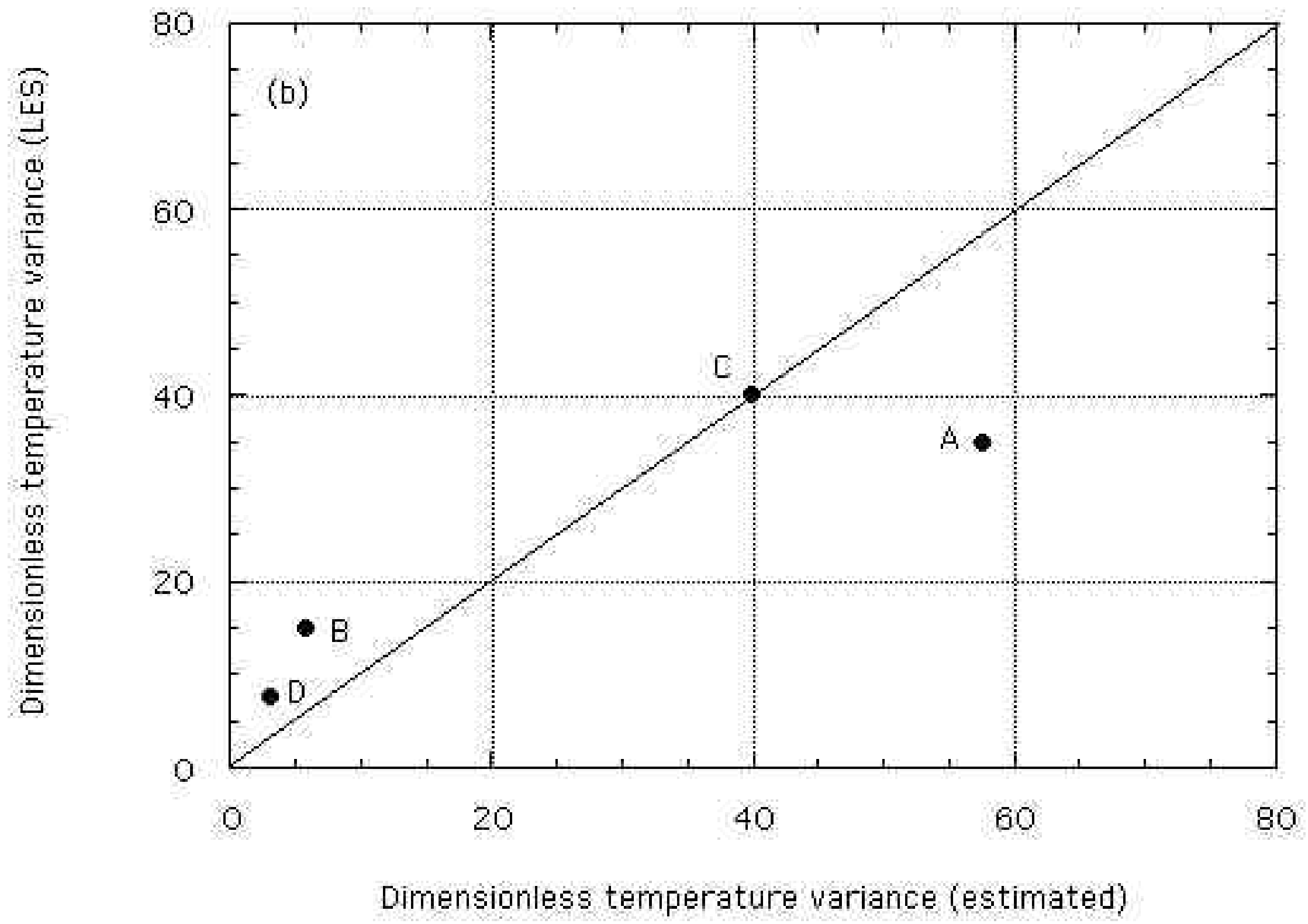
$$\sigma_{\theta i}^2 = \quad {}_\theta \quad c_\theta^2 S$$

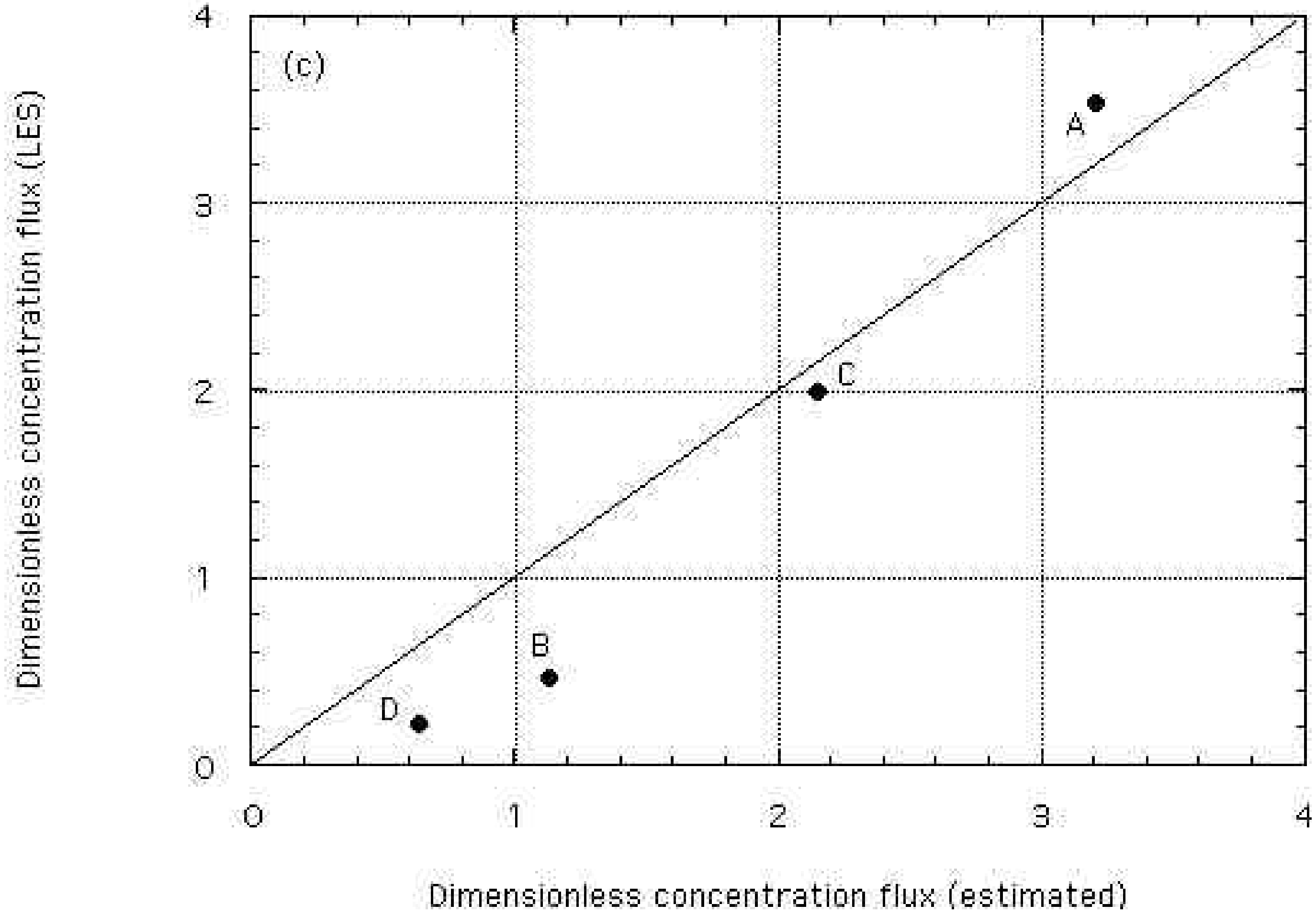
$$\sigma_{qi}^2 = \quad {}_q \quad c_q^2 S$$

$$C_{\theta q i} = \quad {}_{\theta q} \quad c_\theta S S_q$$

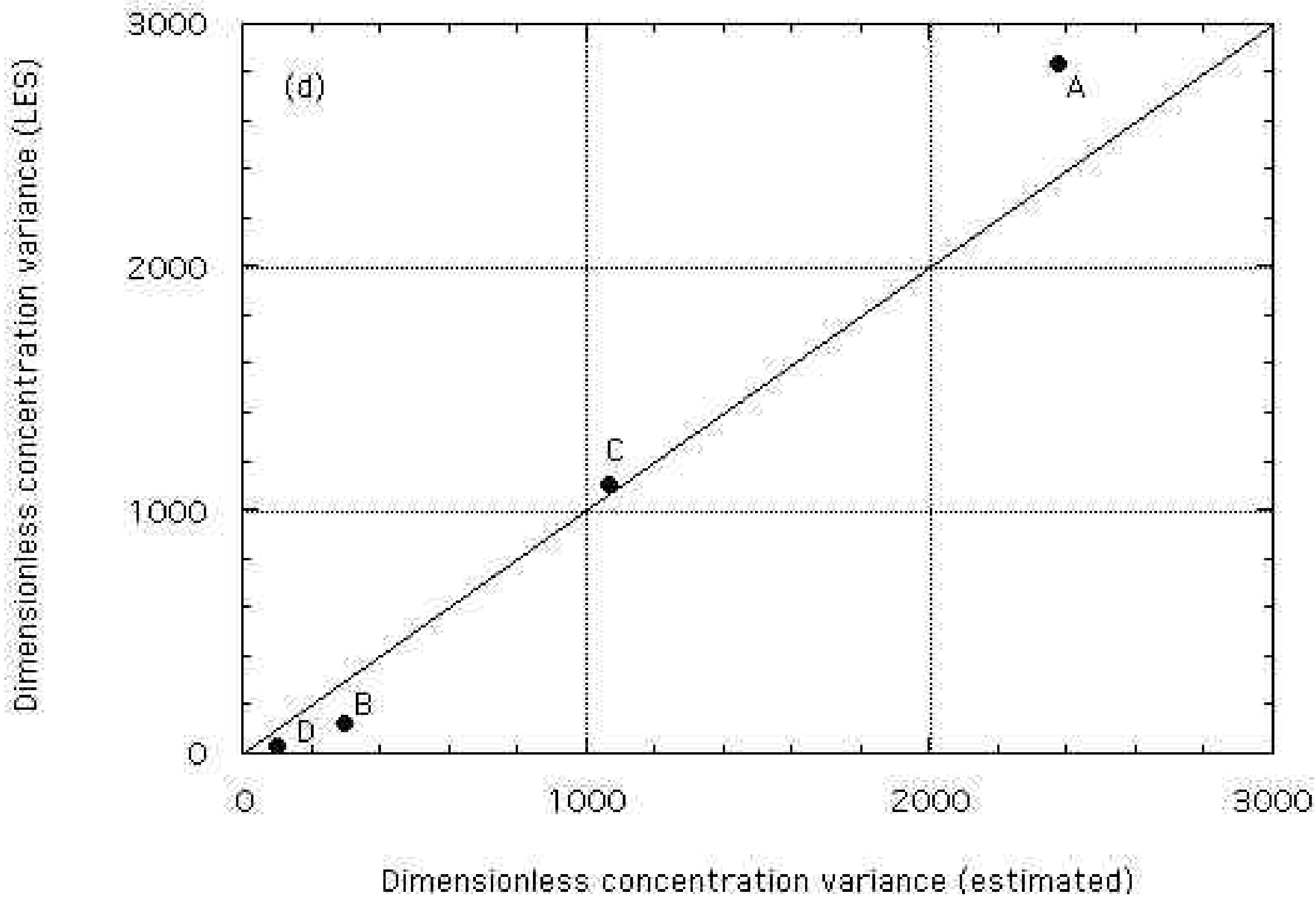


(a)
A
B
C
D
0
-0.1
-0.2
-0.3
-0.4
-0.4
-0.3
-0.2
-0.1
0
Dimensionless potential temperature flux (LES)
Dimensionless potential temperature flux (estimated)

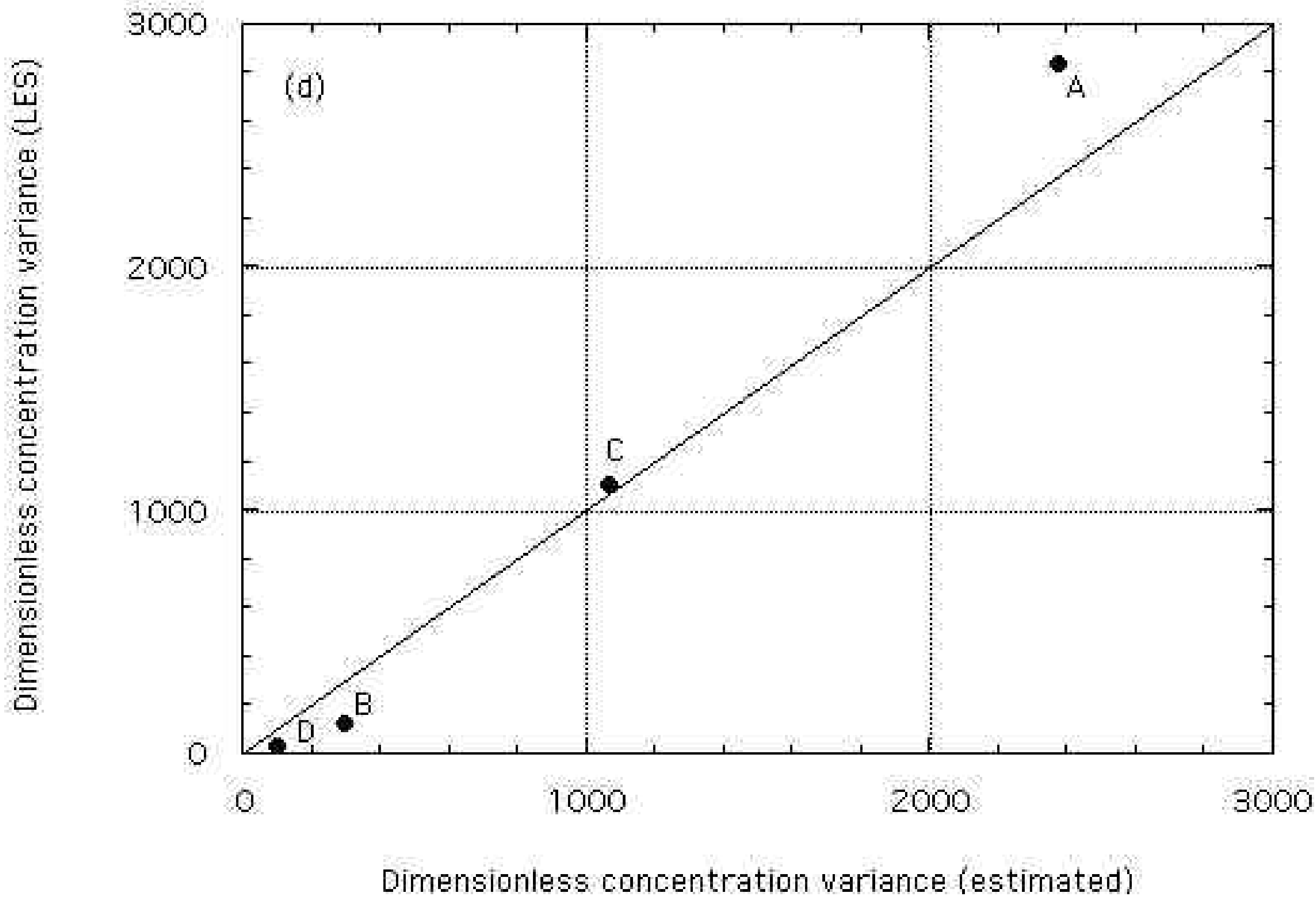

(b)
A
B
C
D
Dimensionless temperature variance (LES)
Dimensionless temperature variance (estimated)
0
20
40
60
80



(c)
A
B
C
D
0
1
2
3
4
0
1
2
3
4
Dimensionless concentration flux (LES)
Dimensionless concentration flux (estimated)

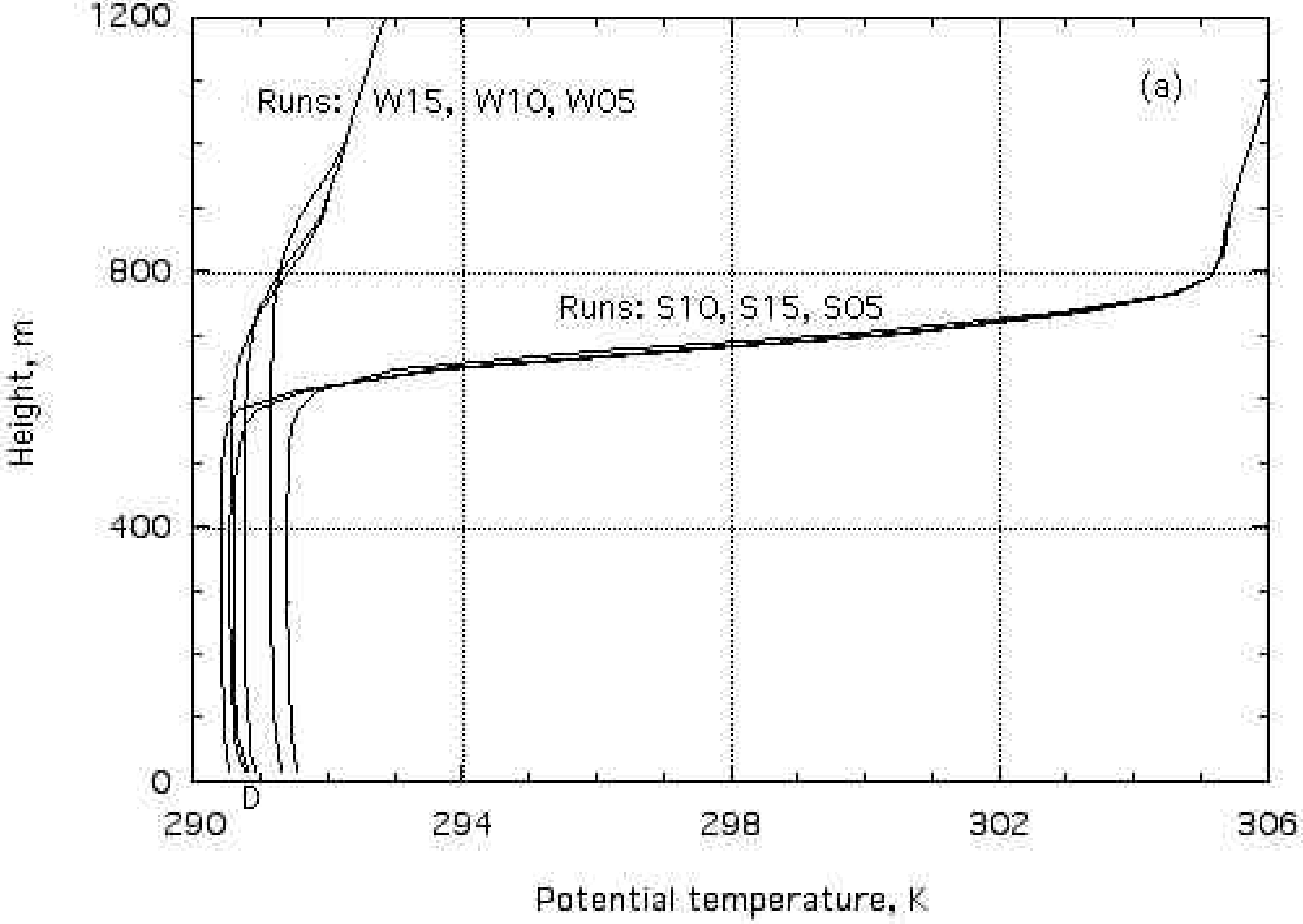


(d)
A
B
C
D
3000
2000
1000
0
0
1000
2000
3000
Dimensionless concentration variance (LES)
Dimensionless concentration variance (estimated)

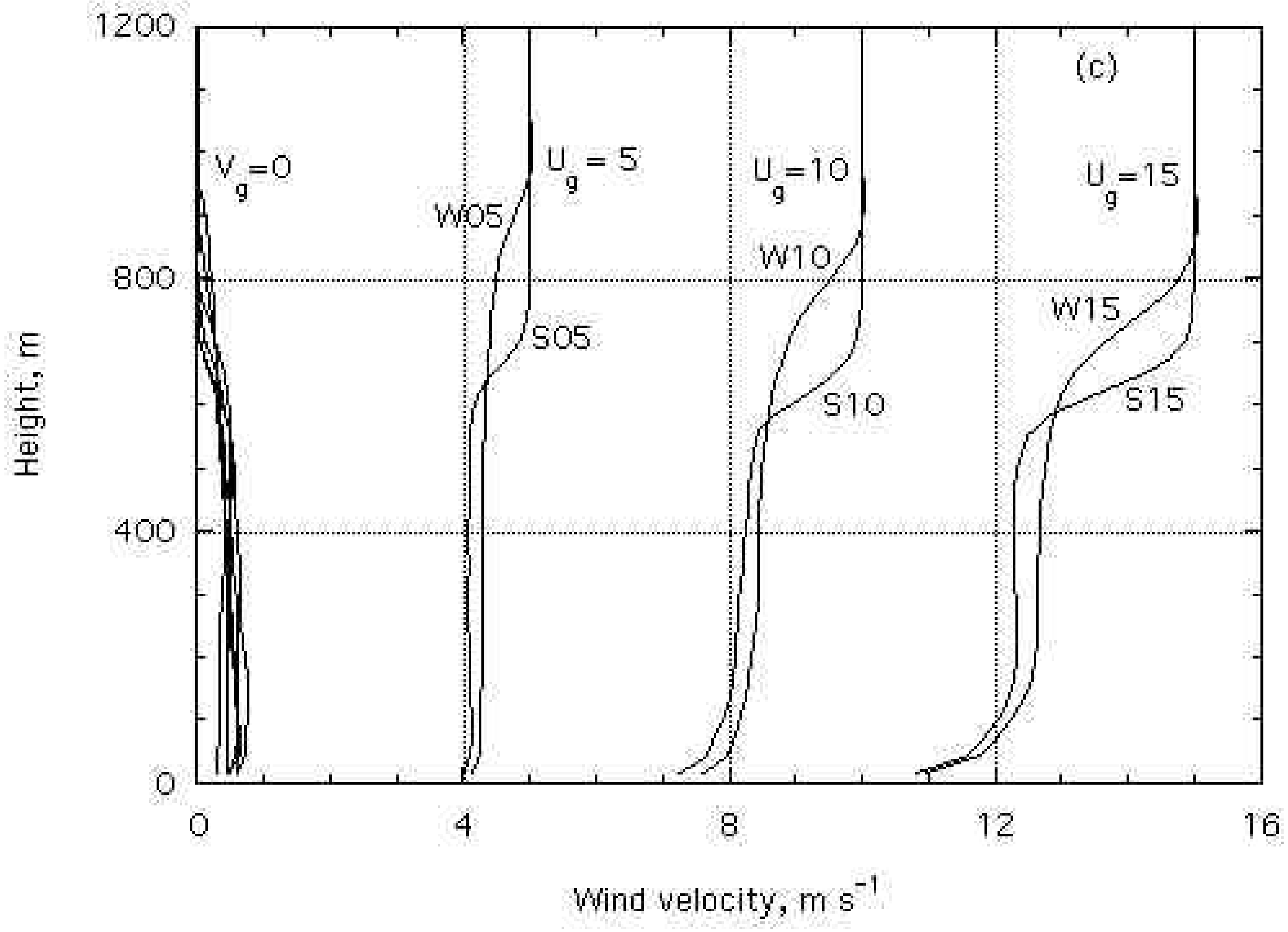


(d)
A
B
C
D
3000
2000
1000
0
0
1000
2000
3000
Dimensionless concentration variance (LES)
Dimensionless concentration variance (estimated)

Forced convection (barotropic) experiments



1200
800
400
0
290
294
298
302
306
Height, m
Potential temperature, K
Runs: W15, W10, W05
Runs: S10, S15, S05
(a)
D



(c)
V_g=0
U_g = 5
U_g=10
U_g=15
W05
S05
W10
S10
W15
S15
Height, m
Wind velocity, m s^{-1}
0
400
800
1200
0
4
8
12
16

When wind shear is present, statistics of turbulence at the top of the mixed layer are dependent not only on the temperature gradient γ_i, but also on velocity gradients $s_{xi} = du/dz|_i$ and $s_{yi} = dv/dz|_i$ in the interfacial layer, or equivalently on the interfacial dynamic Richardson number:

$$Ri = \frac{\beta \gamma_i}{s_{xi}^2 + s_{yi}^2}$$

$$H_i \quad (S_w / S_\theta) = - c_H \quad (1 + c_r \quad i) / (1 + R \quad)^{1/2} / \quad R \quad i$$

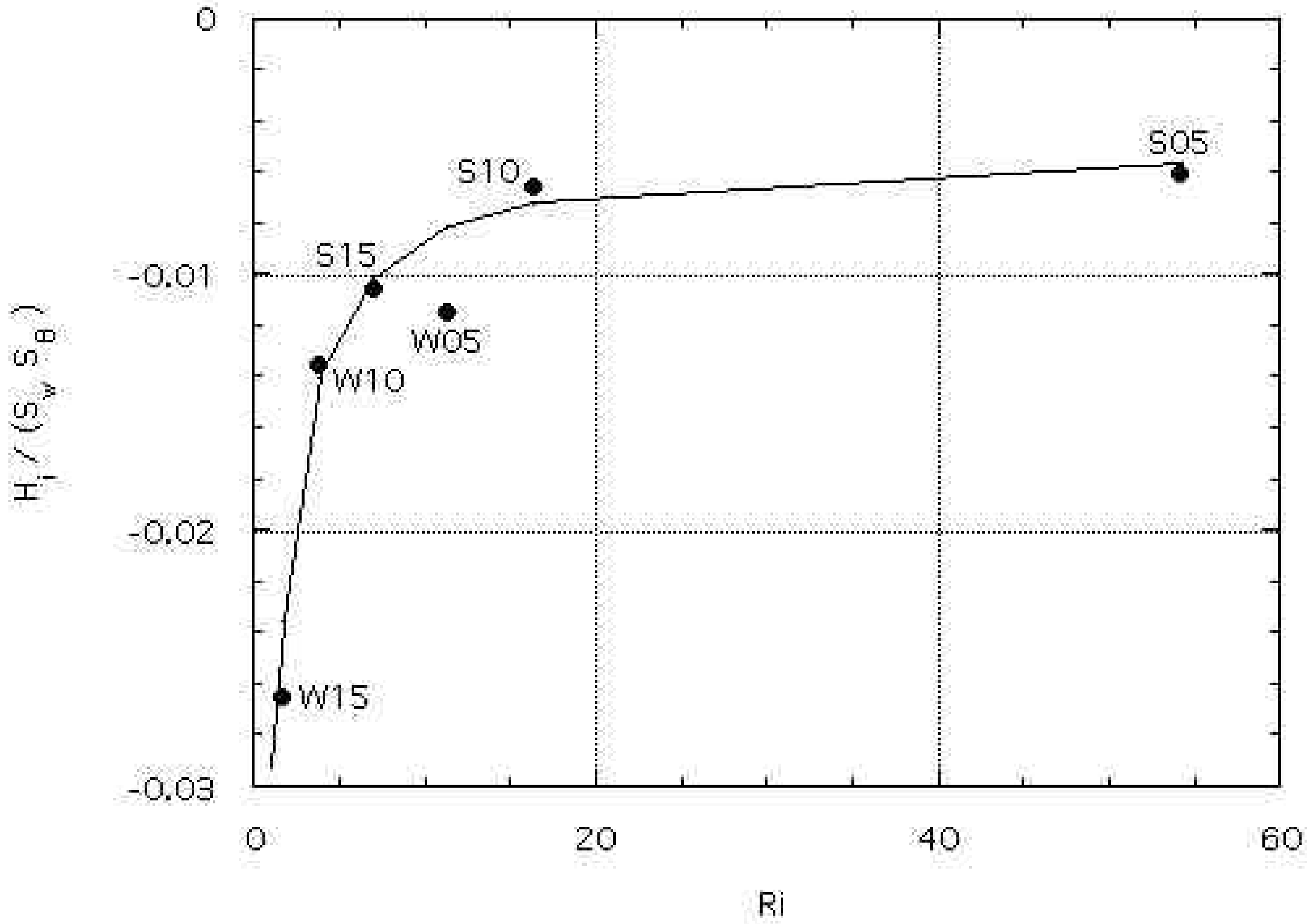
$$Q_i \quad (S_w / S_q) = - c_Q \quad (1 + c_r \quad i) / (1 + R \quad)^{1/2} / \quad R \quad i$$

$$\sigma_{\theta i}^{2} \quad S_\theta^{2} / \quad = \quad _\theta \quad (1 + c_r \quad c\, i) / (1 + R \quad) \quad / \quad R \quad i$$

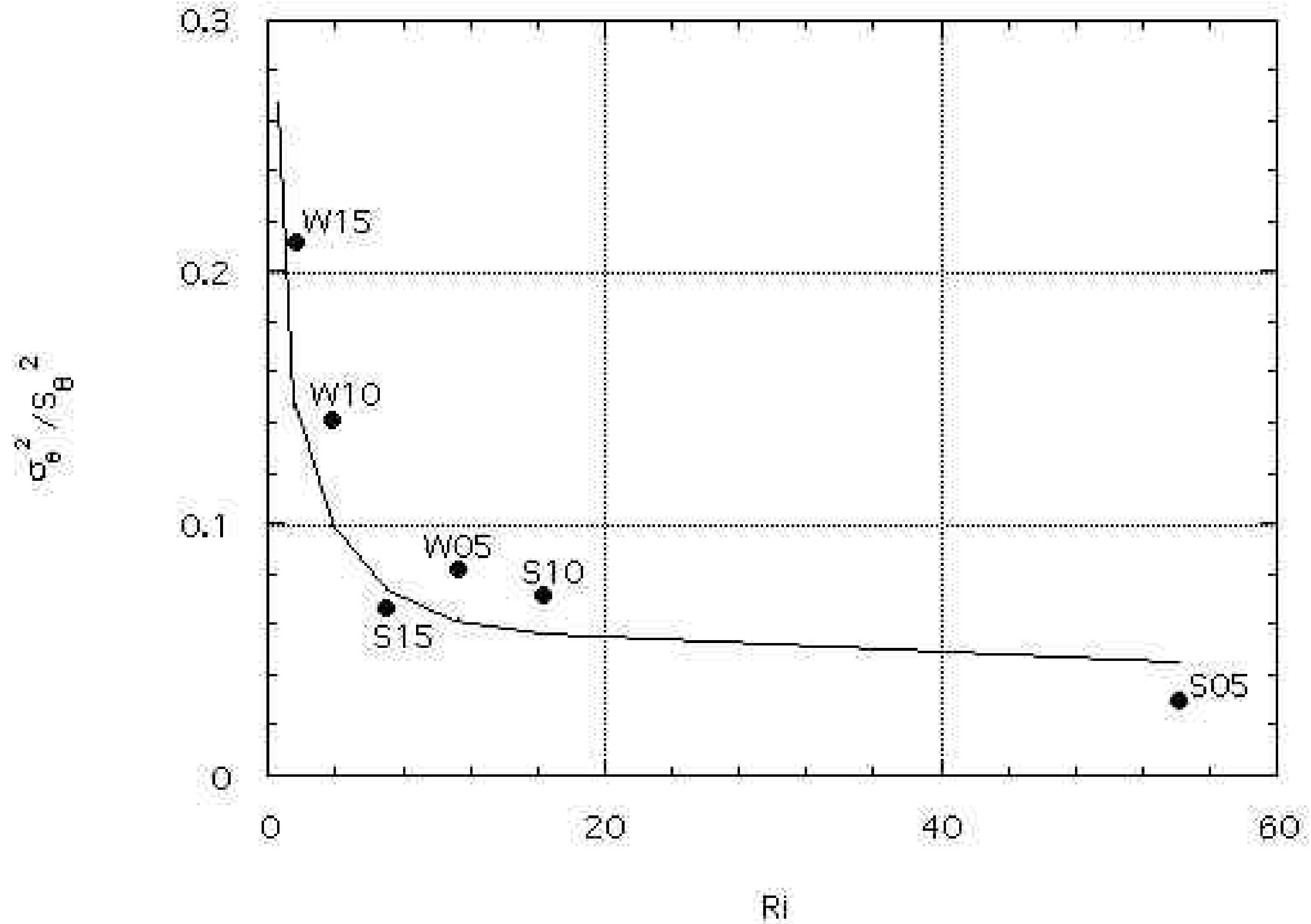
$$\sigma_{q i}^{2} \quad S_q^{2} \quad / = \quad _q \quad (1 + c\, c_r \quad i) / (1 + R \quad) \quad / \quad R \quad i$$

$$C_{\theta q i} \quad (S_\theta / S_q) = \quad _{\theta q} \quad (1 + c\, c_r \quad i) / (1 + R \quad) \quad / \quad R \quad i$$

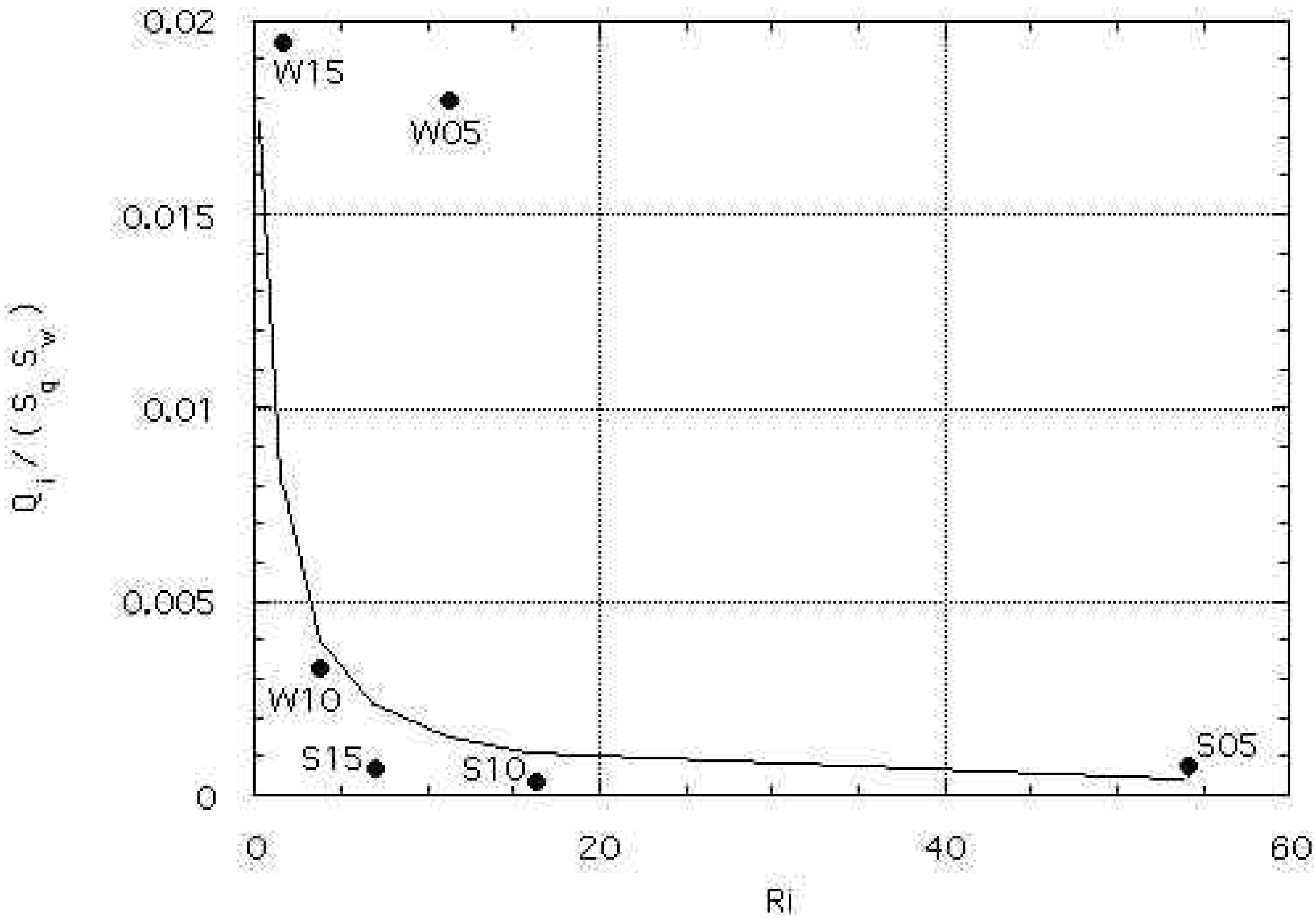
$$_{wi}^{2} \quad S_w^{2} \quad / = \quad _w \quad (1 c + c_r \quad i) \quad R$$



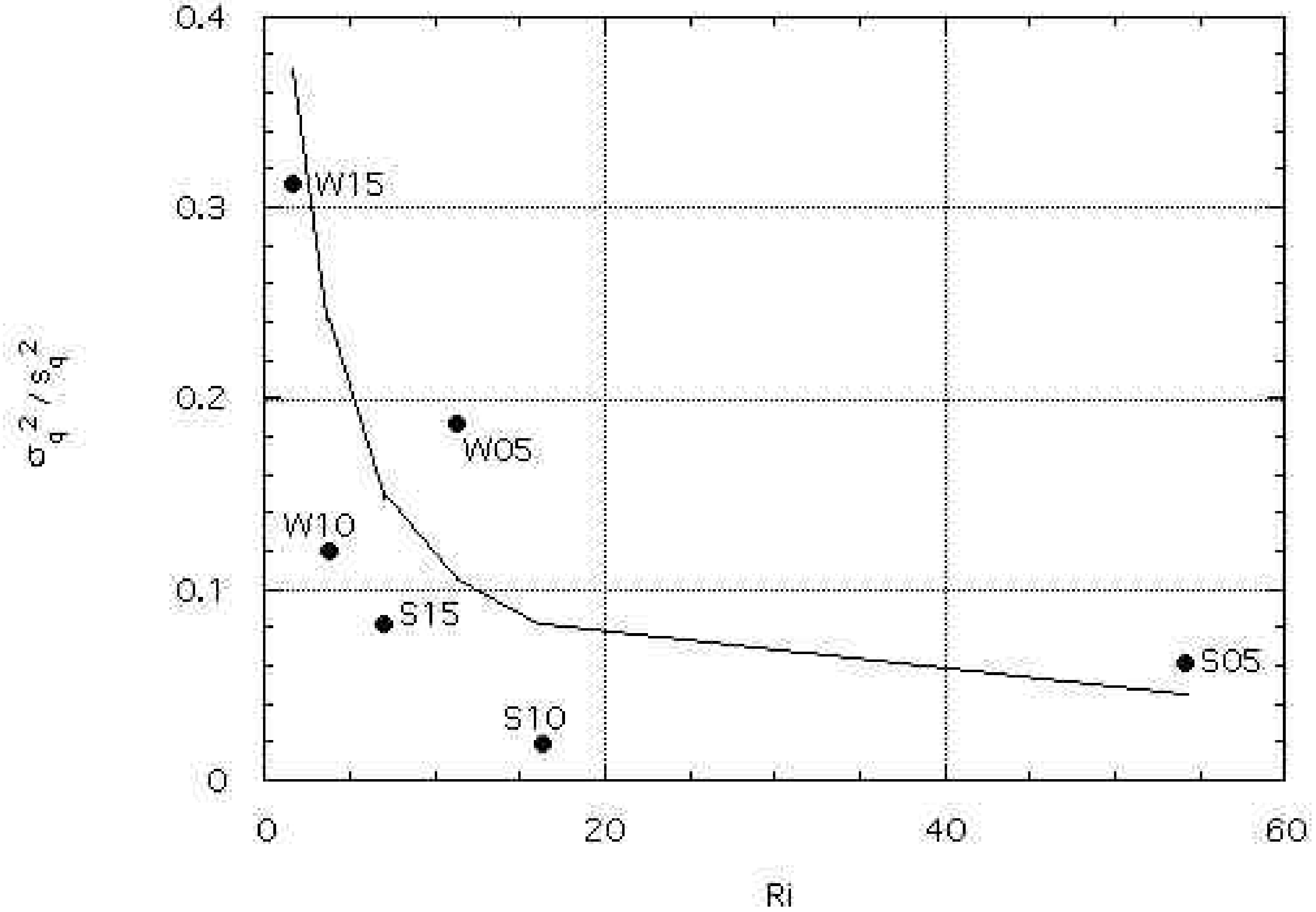
0
-0.01
-0.02
-0.03
0
20
40
60
Ri
H_i / (S_v S_θ)
S05
S10
S15
W05
W10
W15



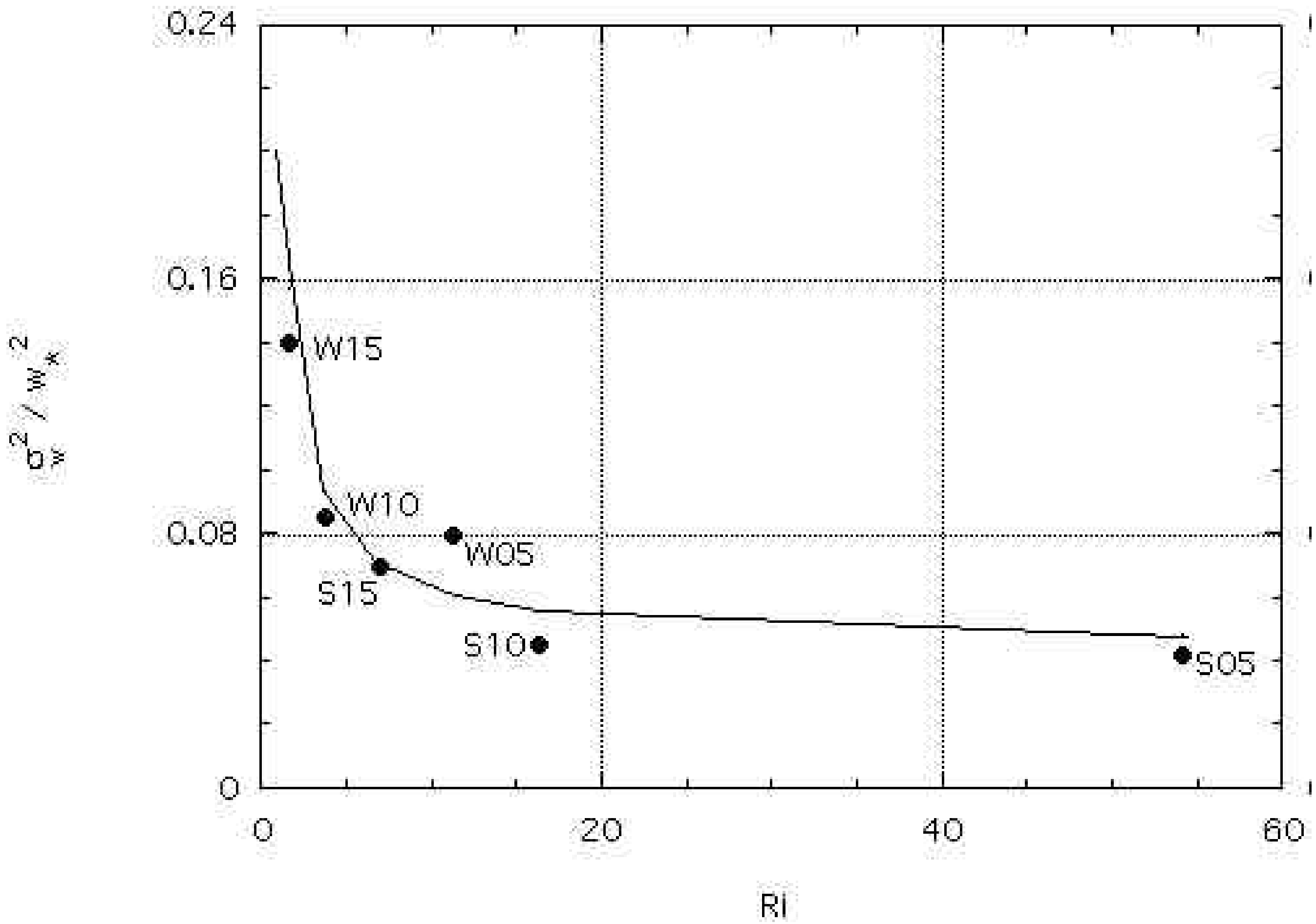
0.3
0.2
0.1
0
0
20
40
60
Ri
$\sigma_\theta^2/S_\theta^2$
W15
W10
W05
S10
S15
S05



0.02
0.015
0.01
0.005
0
0
20
40
60
Ri
$Q_i / (S_q S_w)$
W15
W05
W10
S15
S10
S05

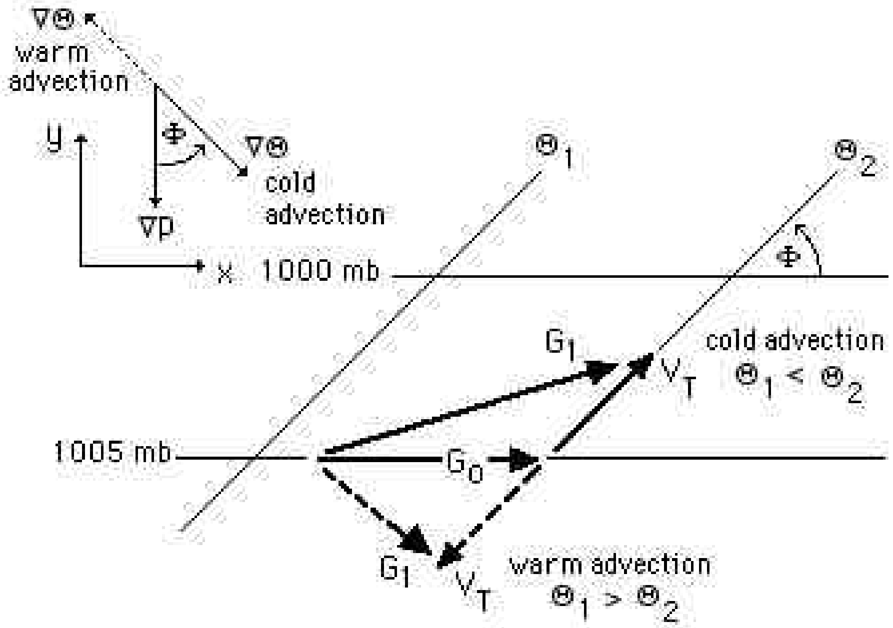


0.4
0.3
0.2
0.1
0
0
20
40
60
Ri
σq2 / sq2
W15
W05
W10
S15
S10
S05

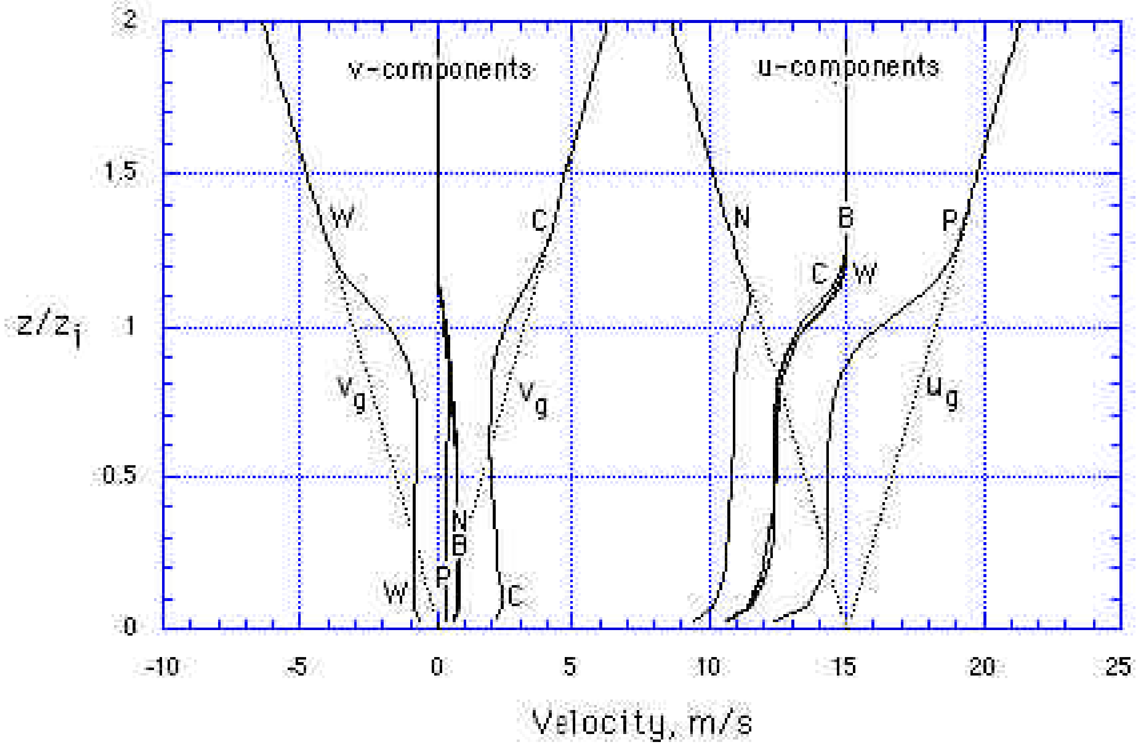


0.24
0.16
0.08
0
0
20
40
60
Ri
σ_w^2 / w_*^2
W15
W10
W05
S15
S10
S05

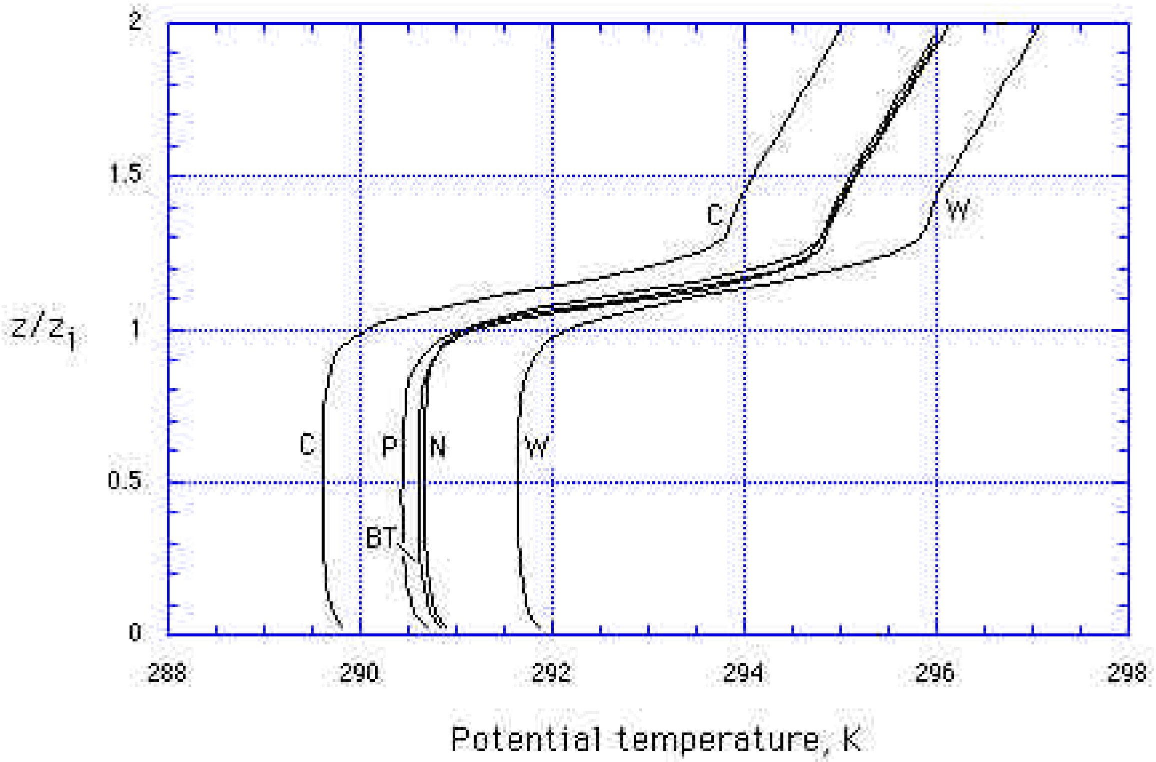
Forced convection (baroclinic) experiments



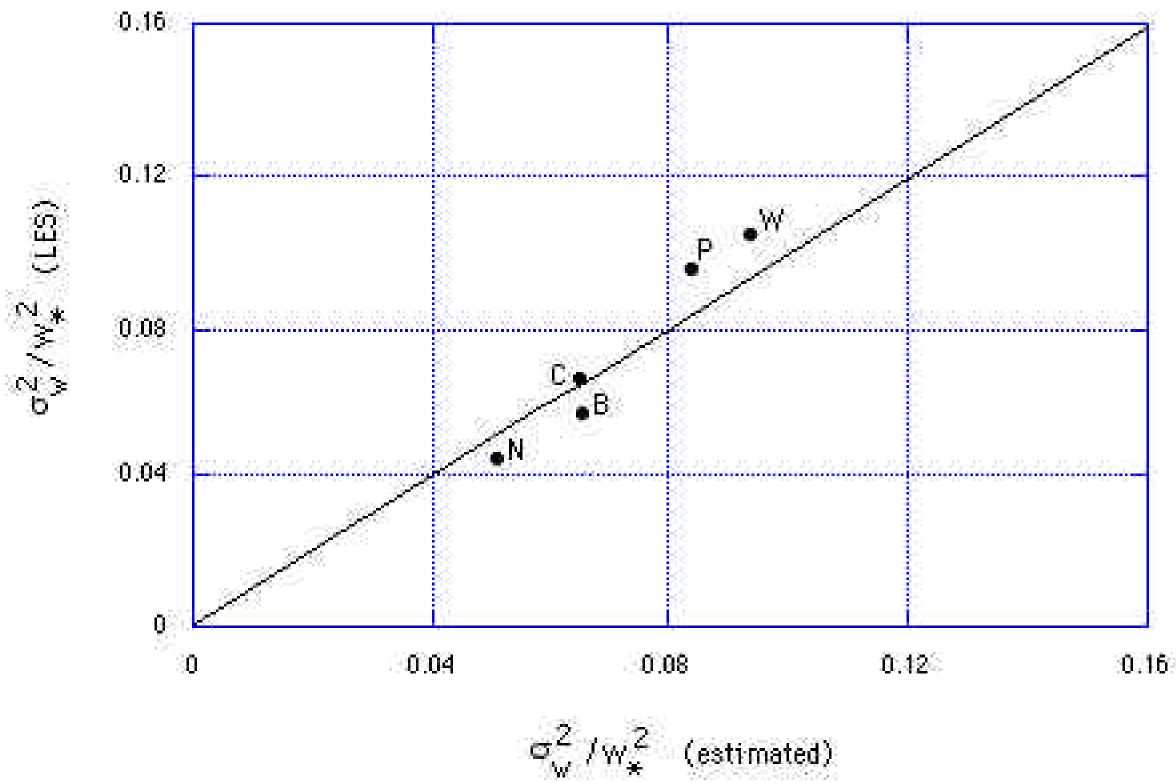
∇Θ
warm advection
Φ
∇Θ
cold advection
∇p
y
x
1000 mb
Θ1
Θ2
Φ
G1
VT
cold advection
Θ1 < Θ2
1005 mb
G0
G1
VT
warm advection
Θ1 > Θ2



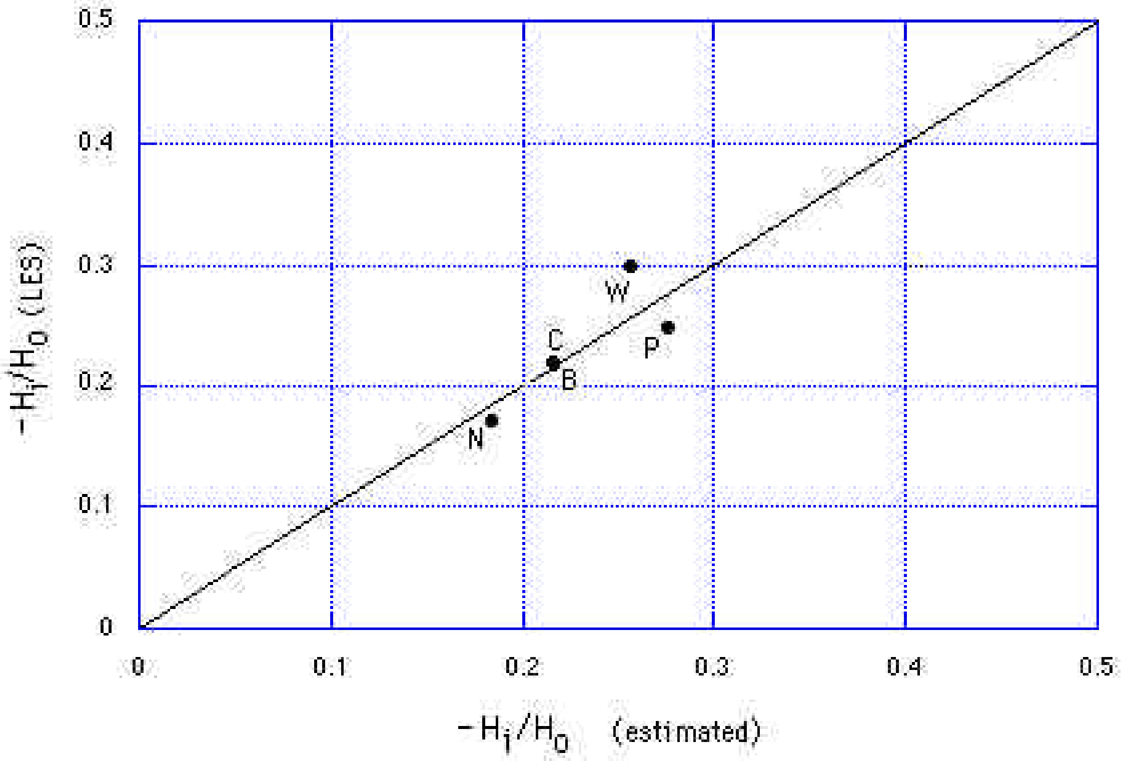
v-components
u-components
z/z_i
Velocity, m/s
W
C
N
B
P
C
W
v_g
v_g
u_g
N
B
P
W
C
-10
-5
0
5
10
15
20
25
0
0.5
1
1.5
2

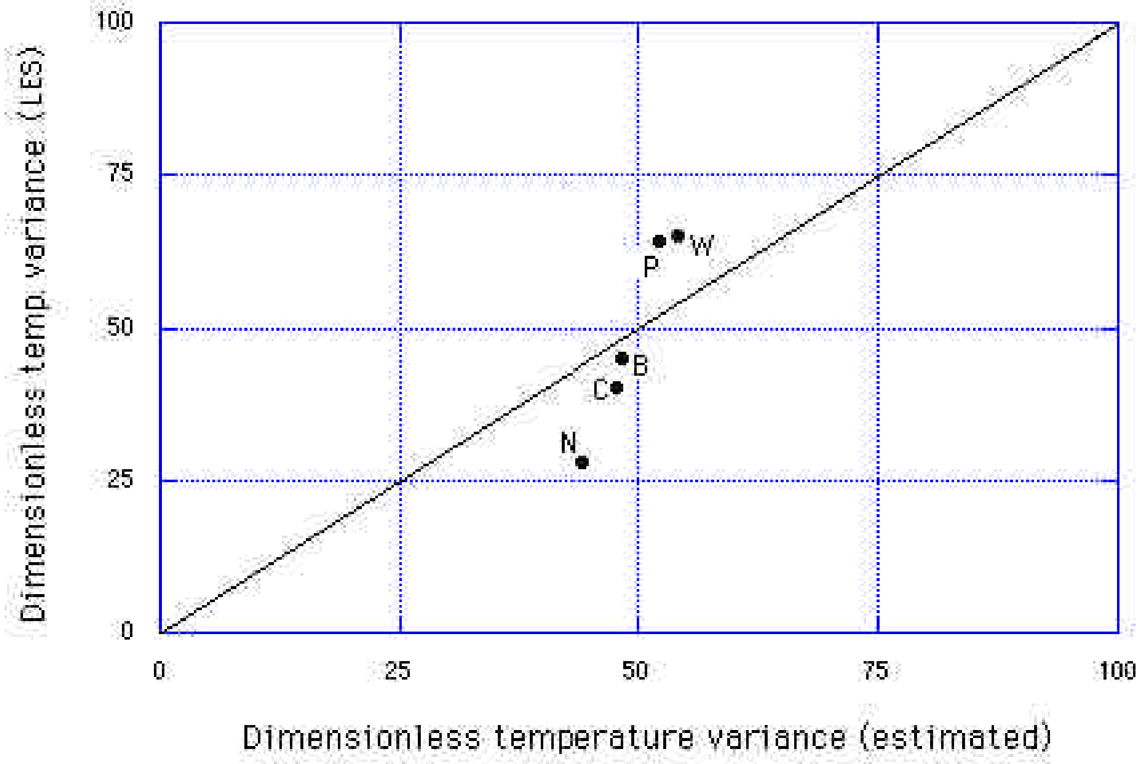


z/z$_i$
2
1.5
1
0.5
0
288
290
292
294
296
298
Potential temperature, K
C
W
C
P
N
W
BT



0.16
0.12
0.08
0.04
0
0
0.04
0.08
0.12
0.16
W
P
C
B
N
σ²_w / w*² (LES)
σ²_w / w*² (estimated)


0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
W
C
B
P
N
$-H_i/H_0$ (LES)
$-H_i/H_0$ (estimated)



100
75
50
25
0
0
25
50
75
100
P
W
B
C
N
Dimensionless temp. variance (LES)
Dimensionless temperature variance (estimated)

Conclusions:

- 1. Two different sets of convective scales are valid in the convective ABL (mixed layer scaling and interfacial scaling)

- 2. In the interfacial layer the characteristic (peak) values of moments are functions of the Richardson number:

$$m/S_i = C_m \; F_i(1/Ri)$$

- 3. Profiles of scalar variances, covariances, and gradients in the CBL can be expressed as a sum of two semi-empirical similarity functions multiplied by a combination of mixed layer scales and interfacial scales:

$$m = c_m \; S_m \; F_m(z/z_i) + C_m \; S_i \; F_i(z/z_i, 1/Ri),$$

$$H = w_* \Theta_* (1 - z/z_i) - C_H S_w S_\theta z/z_i (1 + 8/Ri)/(1 + 1/Ri)^{1/2}$$

$$Q = w_* q_* (1 - z/z_i) - C_Q S_w S_q z/z_i (1 + 8/Ri)/(1 + 1/Ri)^{1/2}$$

$$\sigma_\theta^2 = 1.8 \Theta_*^2 (1 - z/z_i) / (z/z_i)^{2/3} + C_\theta S_\theta^2 [(z/z_i)^9 / (2.1 - z/z_i)^9] [(1 + 8/Ri)/(1 + 1/Ri)]$$

$$\sigma_q^2 = 2.0 q_*^2 (1 - z/z_i) / (z/z_i)^{2/3} + C_q S_q^2 [(z/z_i)3 / (2.2 - z/z_i)^7] [(1 + 8/Ri)/(1 + 1/Ri)]$$

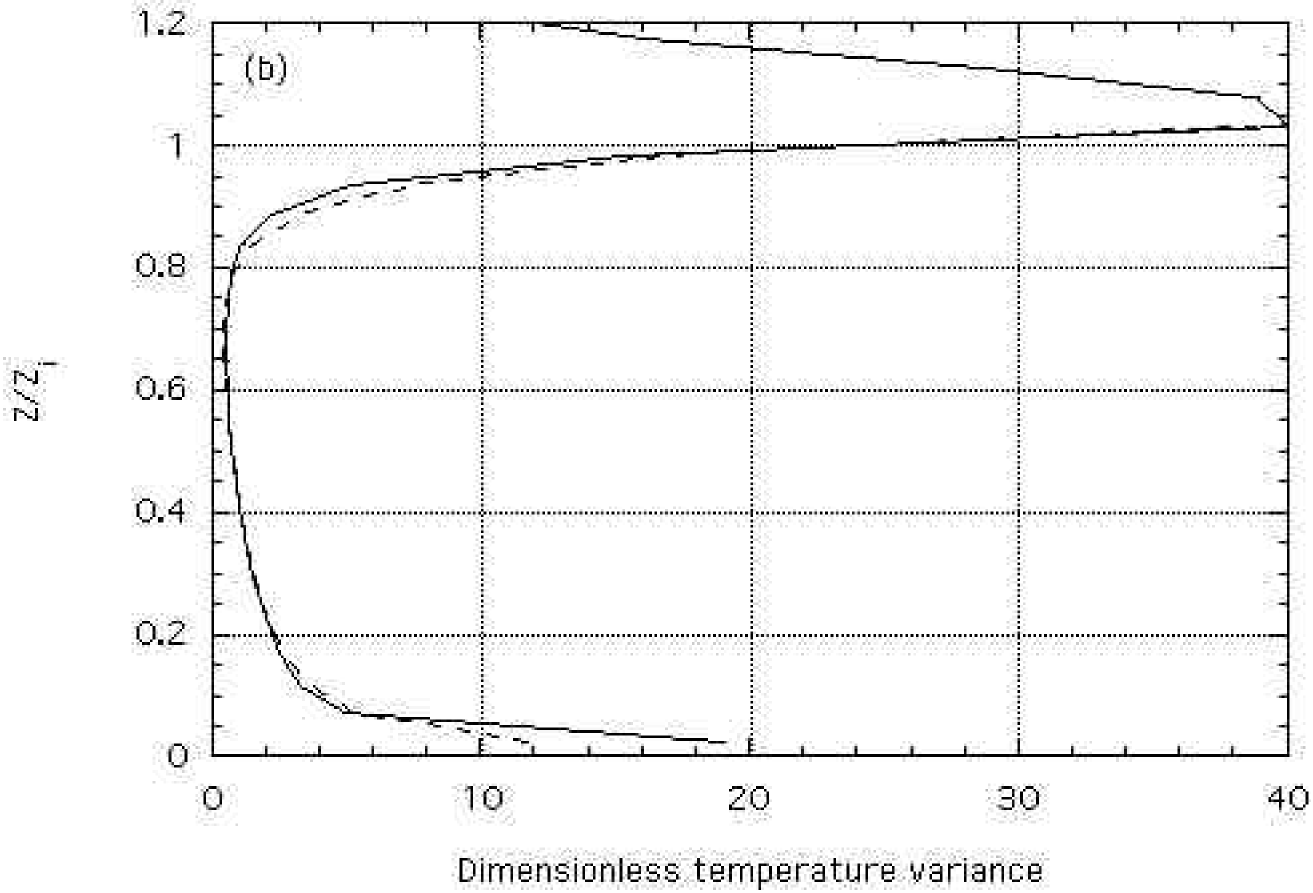
$$c_{\theta q} = 1.5 \Theta_* q_* (1 - z/z_i) / (z/z_i)^{2/3} + C_{\theta q} S_\theta S_q [(z/z_i)8 / (2.2 - z/z_i)^8] [(1 + 8/Ri)/(1 + 1/Ri)]$$

$$\sigma_w^2 = 1.4 w_*^2 (1 - z/z_i)^{4/3} (z/z_i)^{2/3} + C_w S_w 2[(z/z_i)1/2 (1.1 - z/z_i)^{1/3}] (1 + 8/Ri)$$

and also

$$d\Theta/dz = -\Theta_*/z_i (1 - z/z_i)^4 / (z/z_i)^{4/3} + \gamma_i (z/z_i)^9 / (2.23 - z/z_i)^9$$

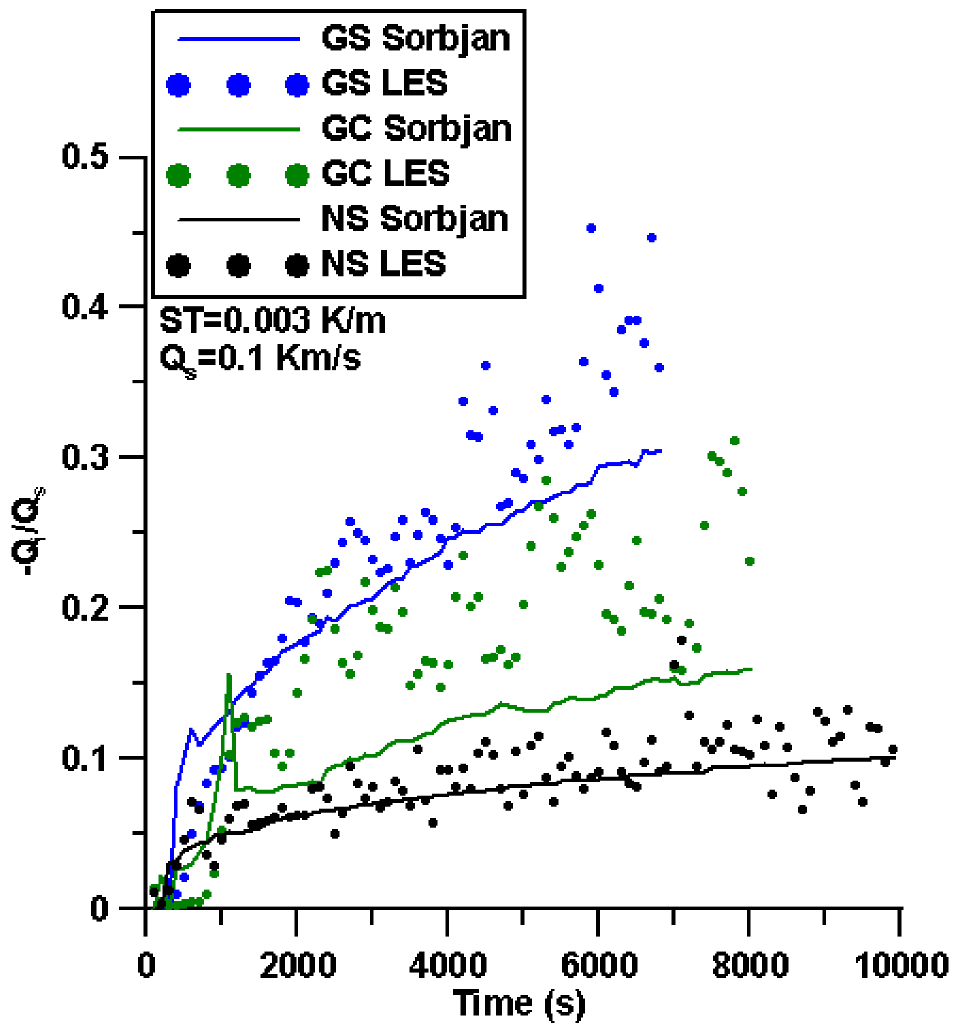
$$dq/dz = -q_*/z_i (1 - z/z_i)^4 / (z/z_i)^{4/3} + g_i (z/z_i)^9 / (2.23 - z/z_i)^9$$



(b)
1.2
1
0.8
0.6
0.4
0.2
0
z/z_i
0
10
20
30
40
Dimensionless temperature variance

The End

Thank you for your attention!


GS Sorbjan
GS LES
GC Sorbjan
GC LES
NS Sorbjan
NS LES
ST=0.003 K/m
Q_s=0.1 Km/s
-Q_i/Q_s
0.5
0.4
0.3
0.2
0.1
0
0
2000
4000
6000
8000
10000
Time (s)