EXPERIMENTAL STUDY OF TURBULENCE AND VERTICAL TEMPERATURE PROFILE IN THE URBAN BOUNDARY LAYER

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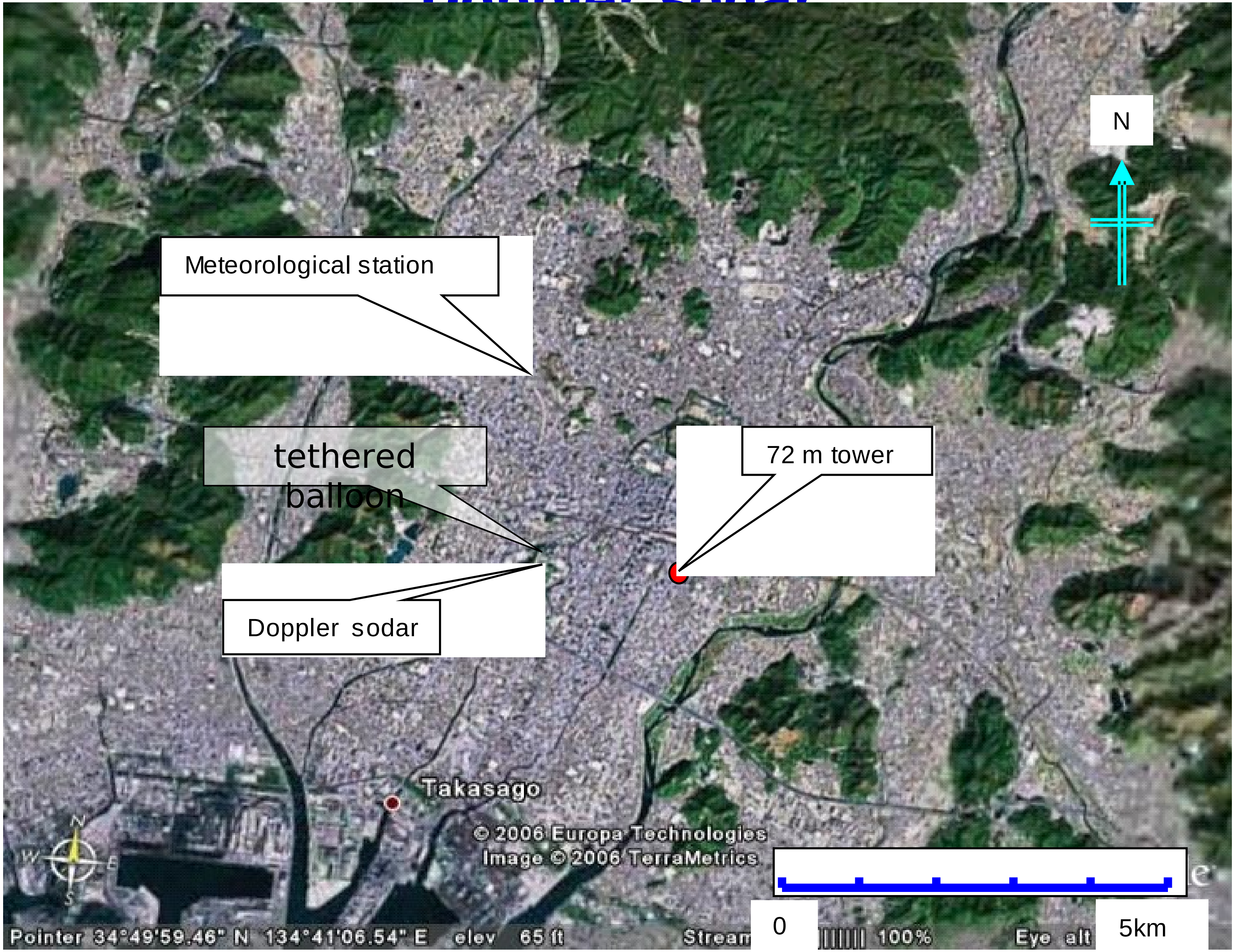
Introduction

- **Recently, the dispersion of motor vehicle exhaust gas has been predicted using the new generation models in urban areas (Valkonen et al.,1995, Werferi, 1995).**
- **The Monin-Obukhov similarity theory has often been used in the models.**
- **However, the similarity theory cannot be applied within the roughness sublayer. (Rotach, 1993).**
- **The reason why the similarity theory can not be applied in the roughness sublayer is not known.**
- **Since the mechanical turbulence generated by buildings is large in the lower part of the urban boundary layer, the turbulence in the roughness sublayer may deviate from the empirical formula at rural smooth sites.**
- **We studied the turbulence and vertical temperature profile in the lower part of the urban boundary layer by conducting the field observations in Himeji City, carrying out wind tunnel experiments and numerical simulations.**

Urban area in Himeji city the site of a microwave-tower, tethered balloon and the Doppler sodar



North

In the north of the tower is a commercial area with buildings of 10 to 45 m in height.

View from the tower looking north

South

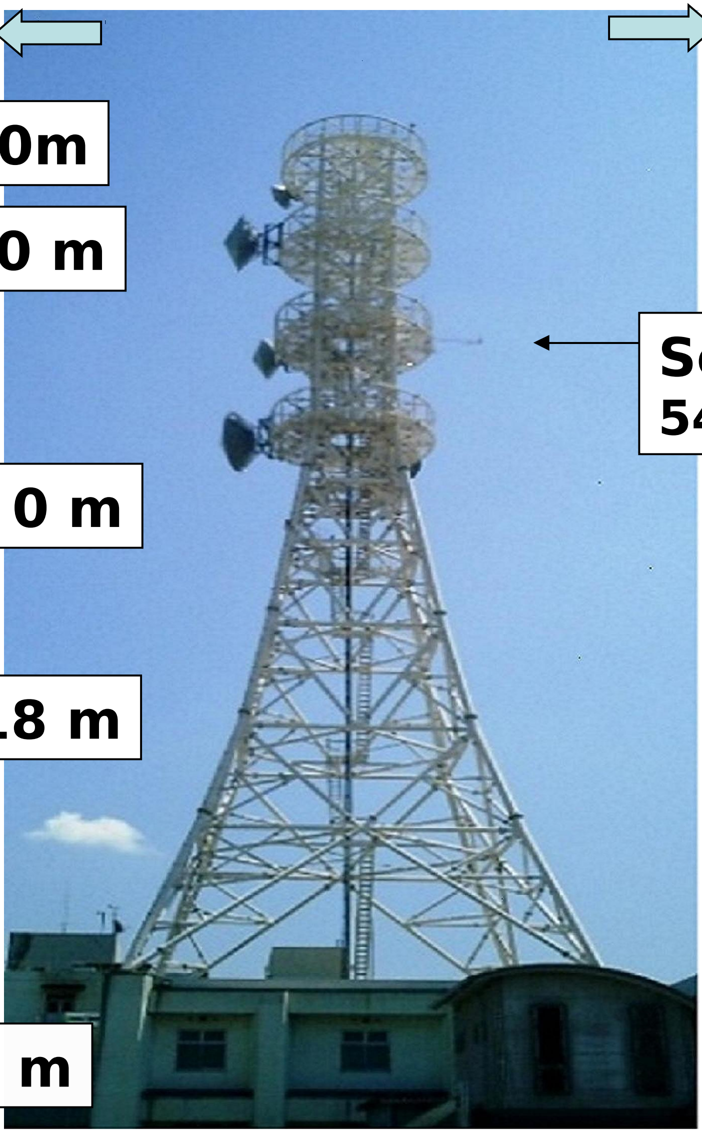
In the south and east of the tower is a commercial and residential area with buildings of 7 to 30 m in height.

View from the tower looking south

Instruments mounted on the 72 m tower

north

south



T 70m

T 60 m

T 4 0 m

T 18 m

T 4 m

Vertical temperature profile

One year

Thermistor thermometer

(Espec RT-30S)

Surface temperature

Infrared thermometer MR-40

turbulence

Sonic Anemometer 54 m

50 Hz, 60 min

46 hours

April to August, 1996

KAIJO SAT-550

Measurement of vertical temperature at heights below 300 m

Using tethered balloon

Summer

July 19, 2007

4 : 00～11 : 00

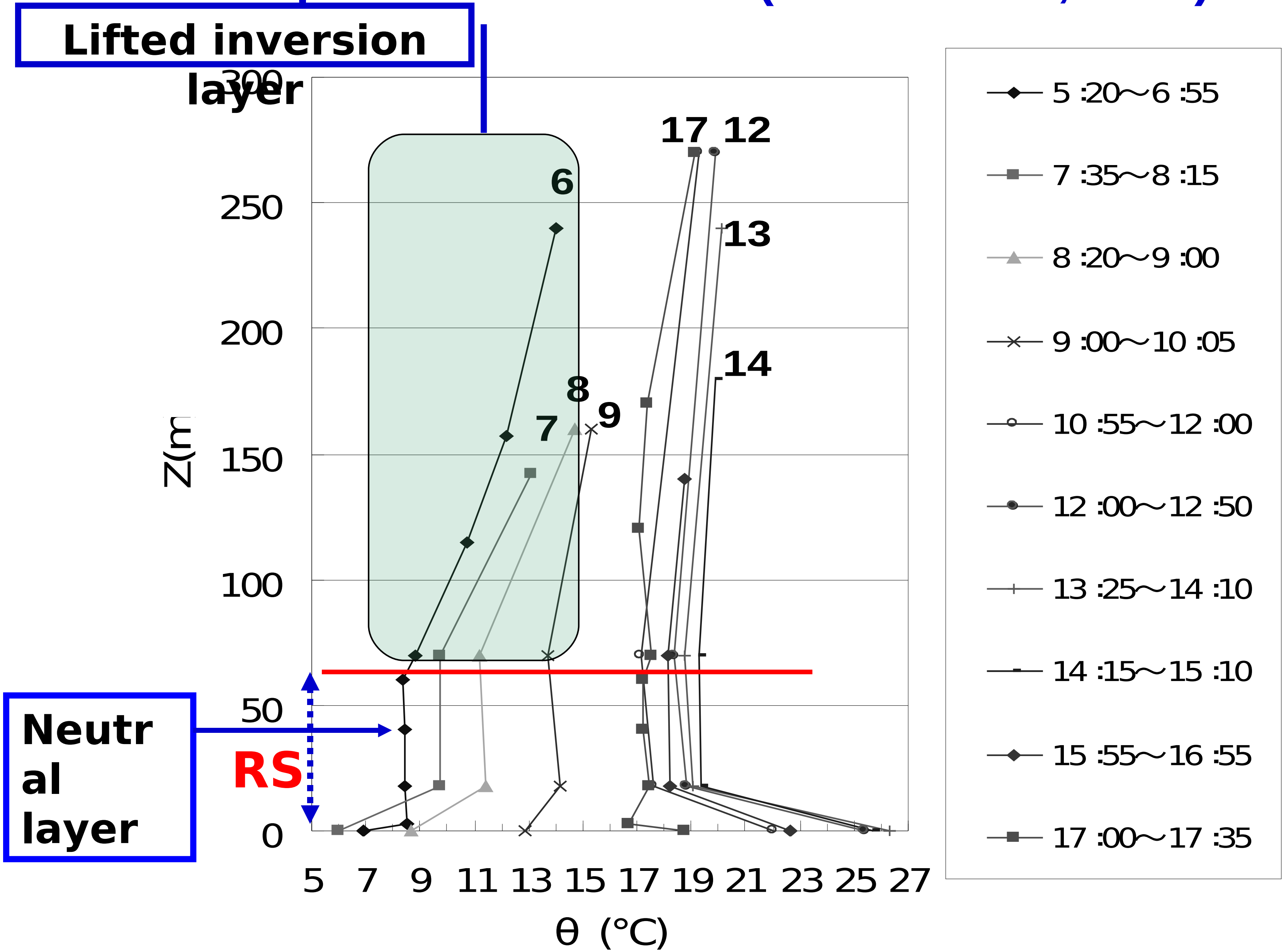
Autumn

November 8, 2007

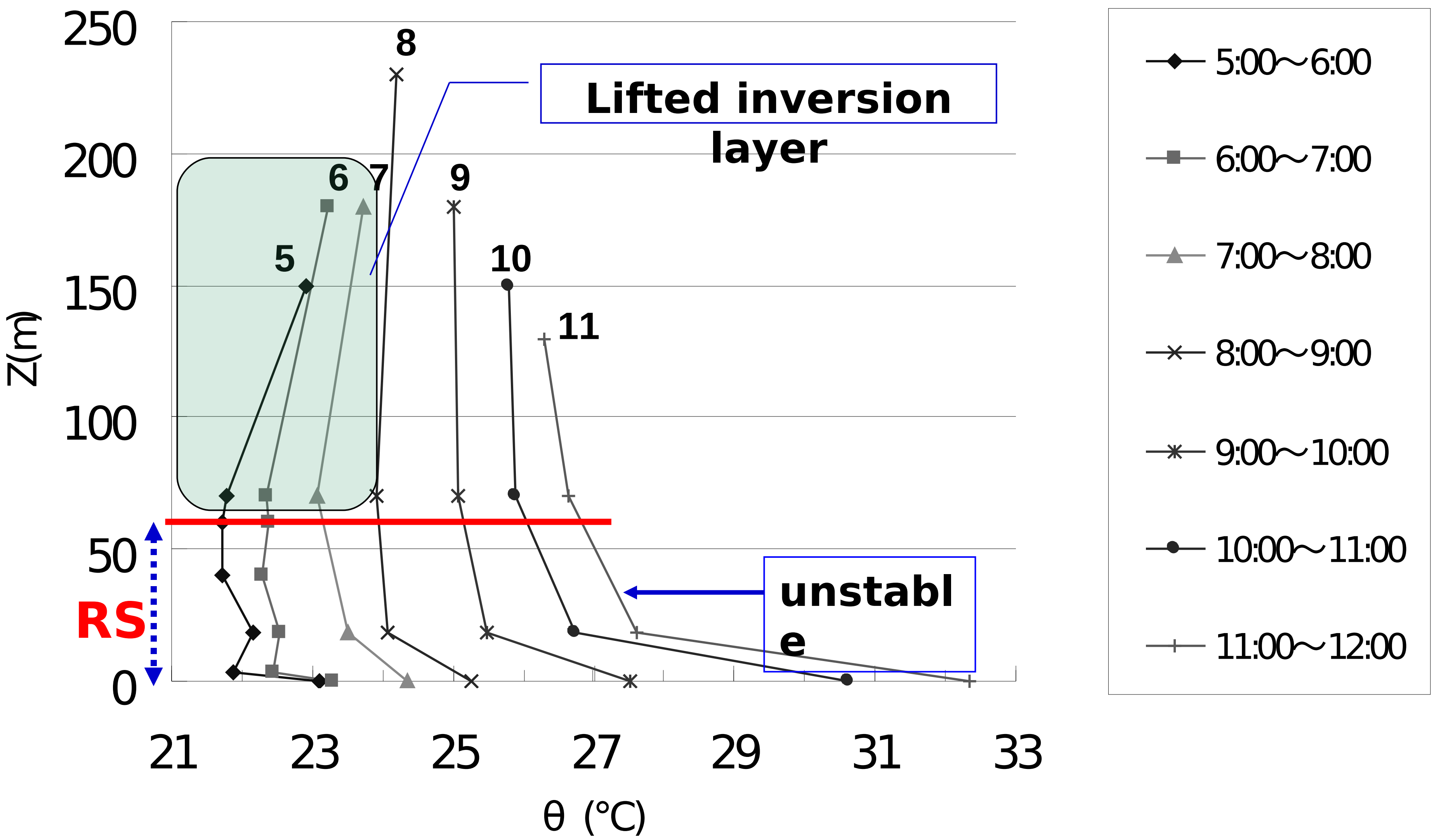
5 : 00～17 : 30

At the park in the center of the city

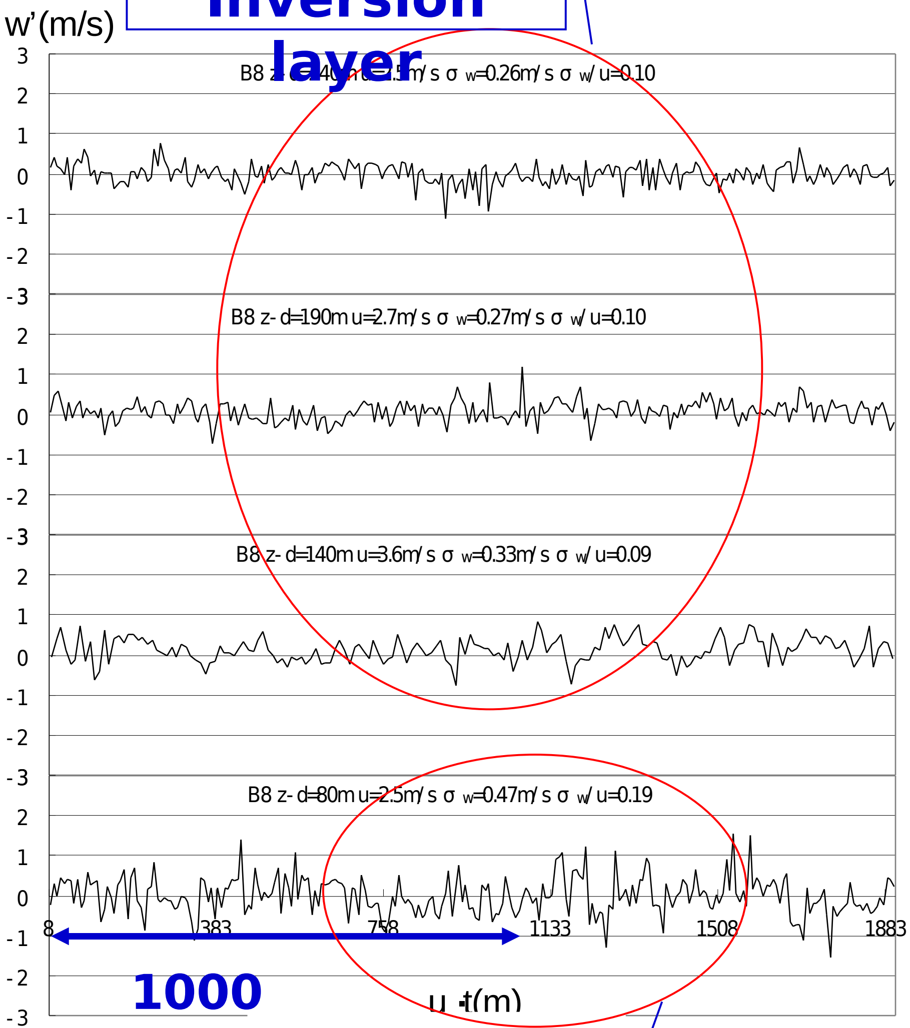
Vertical profile of potential temperature and surface temperature in autumn (8 November, 2007)

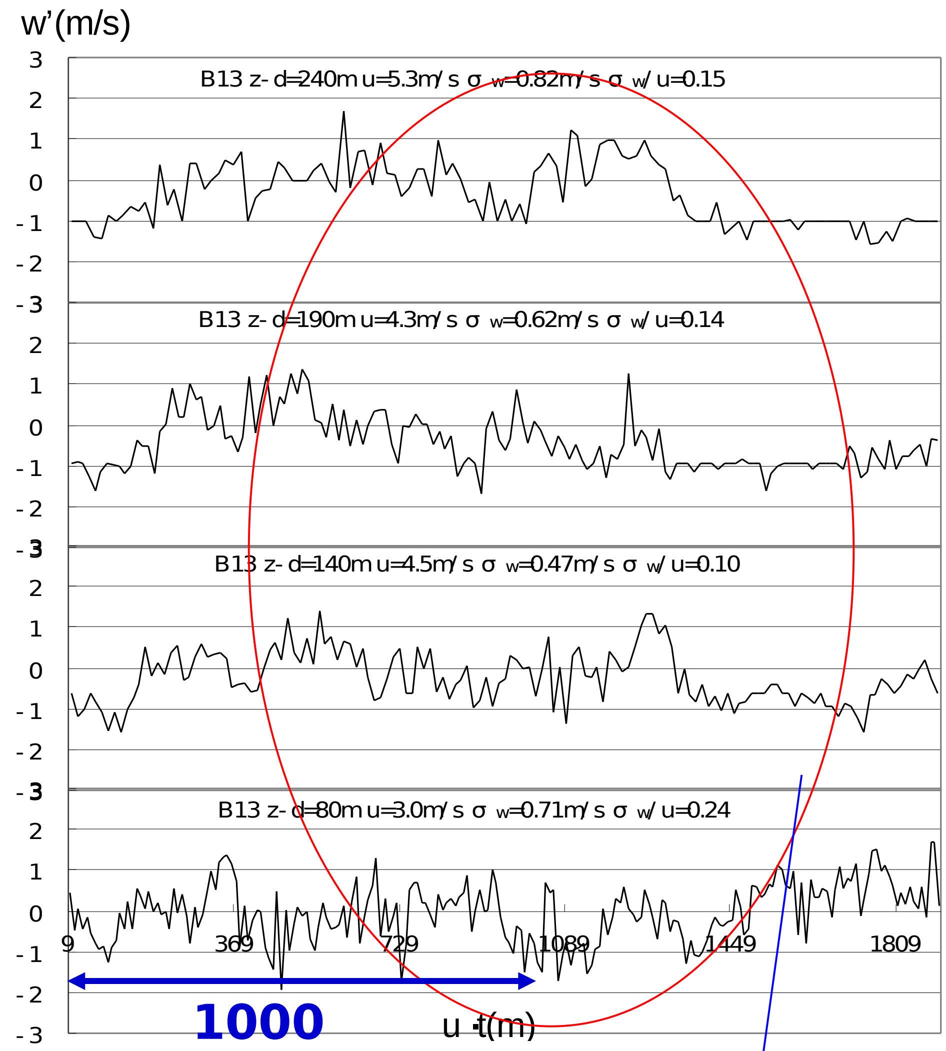


Vertical profile of potential temperature and surface temperature in summer (19 July, 2007)



w' on 19 July (2007) measured by using Doppler sodar in Himeji city





Inversion layer

1000 m

5:00 — 5:15

Neutral layer, RS

1000 m

11:00 — 11:10

Convective

Summary results of turbulence measured at the tower

at $z = 54$ m

Wind directions: southern(SW - ESE)

Observation period: Apr. 1, June 12 – 15, Aug. 21, 24, 2006, n = 46

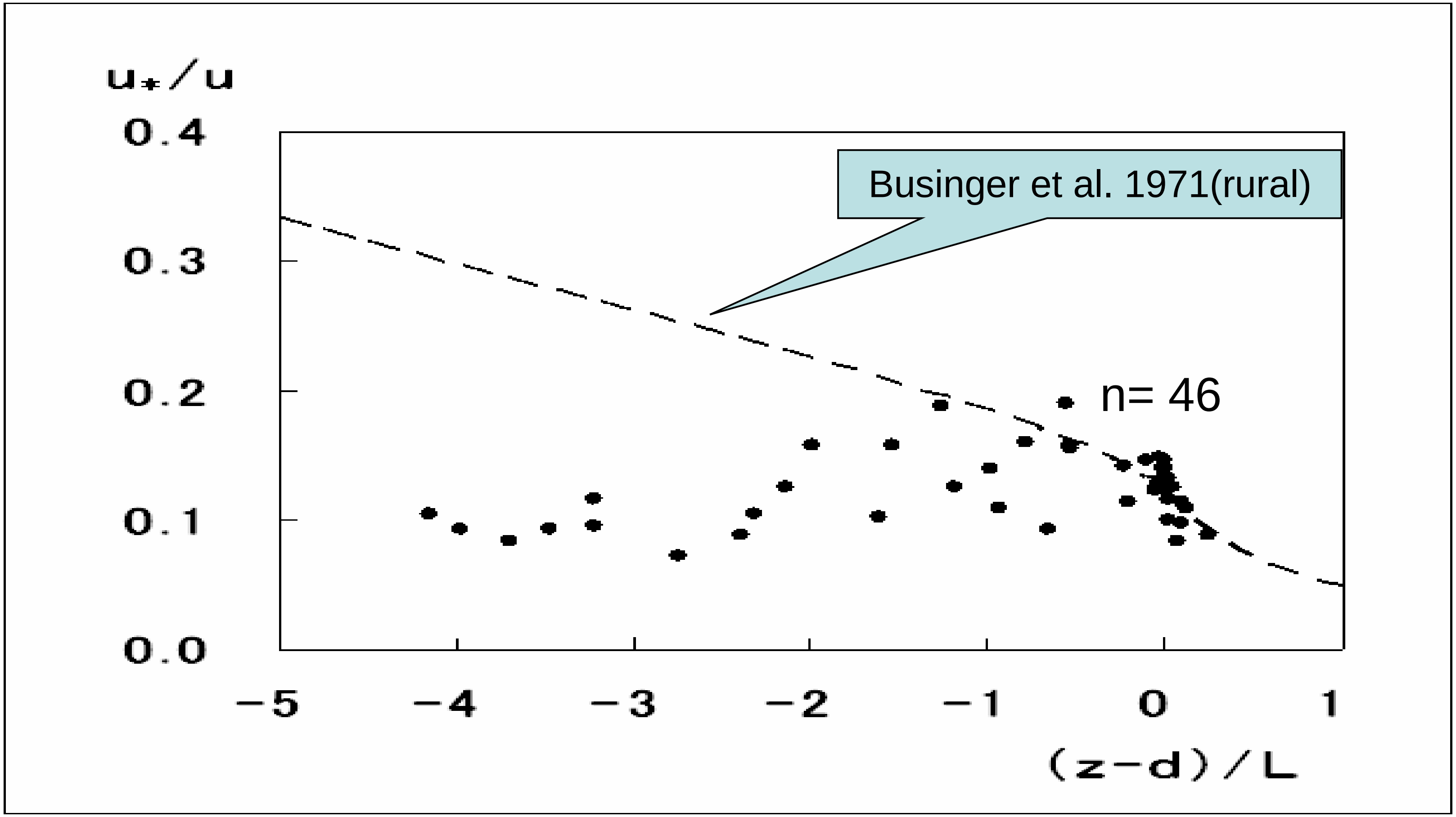
50 Hz, 60 min,

PS	n
B	5
BC	7
C	7
CD	2
D	25

	u	w	θ	$(z-d)/L$	u_*	σ_u/u_*	σ_v/u_*	σ_w/u_*
	m s^{-1}	m s^{-1}	°		m s^{-1}			
ave.	4.8	0.11	294	−0.95	0.59	2.5	2.3	1.47
max.	10.7	0.28	330	0.25	1.06	5.5	5.4	2.4
min.	1.8	−0.04	236	−4.2	0.16	1.70	1.34	1.05
σ	2.2	0.08	24	1.31	0.26	0.62	0.85	0.35
n	46							

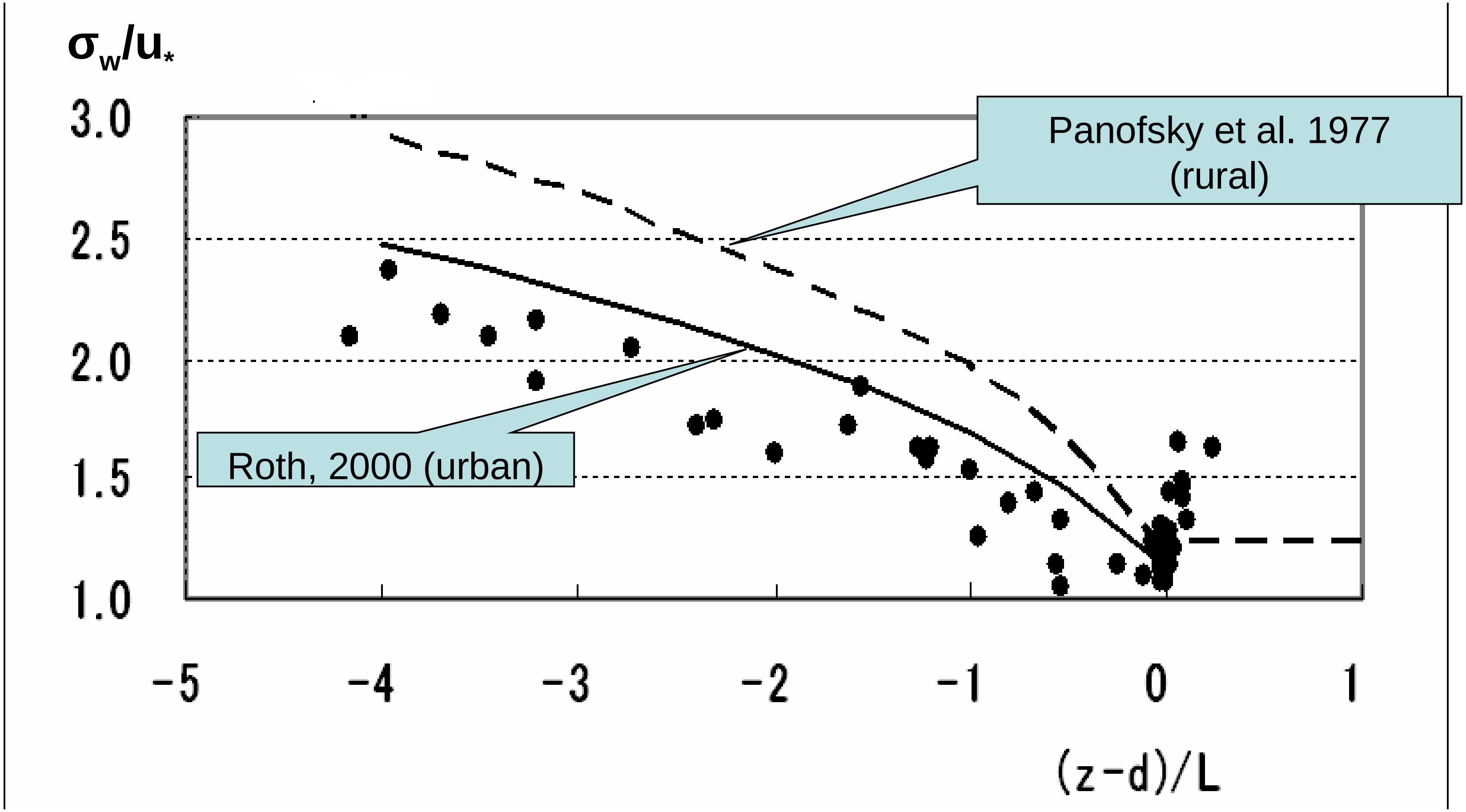
Observed u_*/u at the tower (z = 54m) in Himeji city

wind direction: SW - ESE



Under unstable conditions, turbulence transports momentum less effectively in urban areas than in rural areas.

Observed σ_w/u_* at the tower (z = 54m) in Himeji city



u_* mechanical turbulence

σ_w both mechanical and convective turbulence →

u_*/σ_w large mechanical turbulence

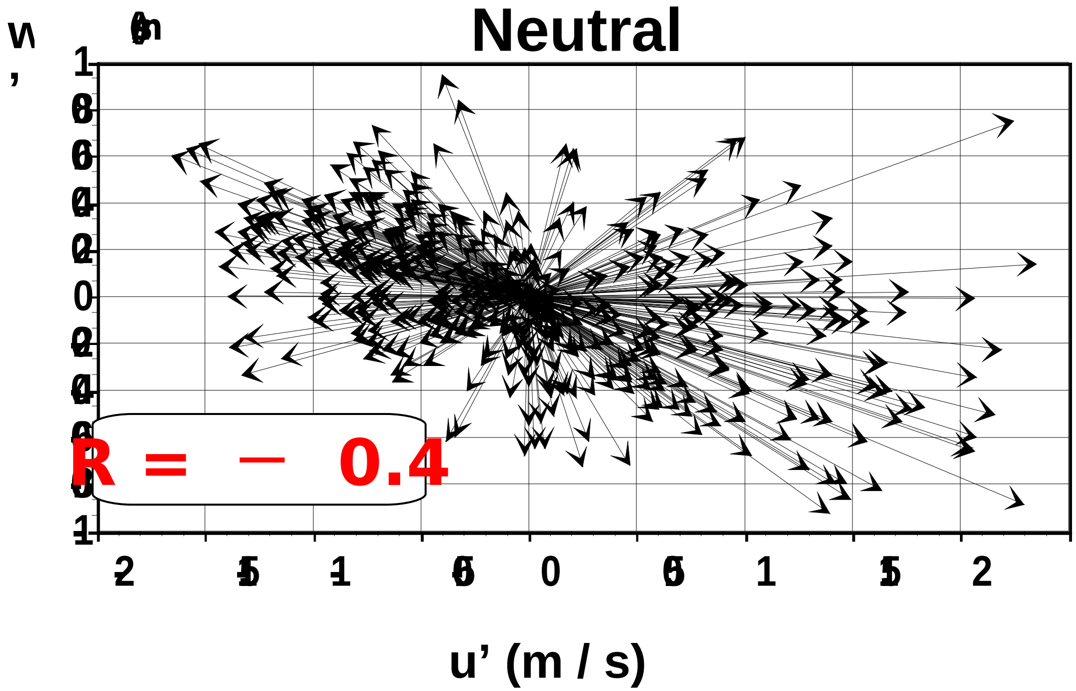
Vectors (u’, w’) observed at the tower

z=54 m

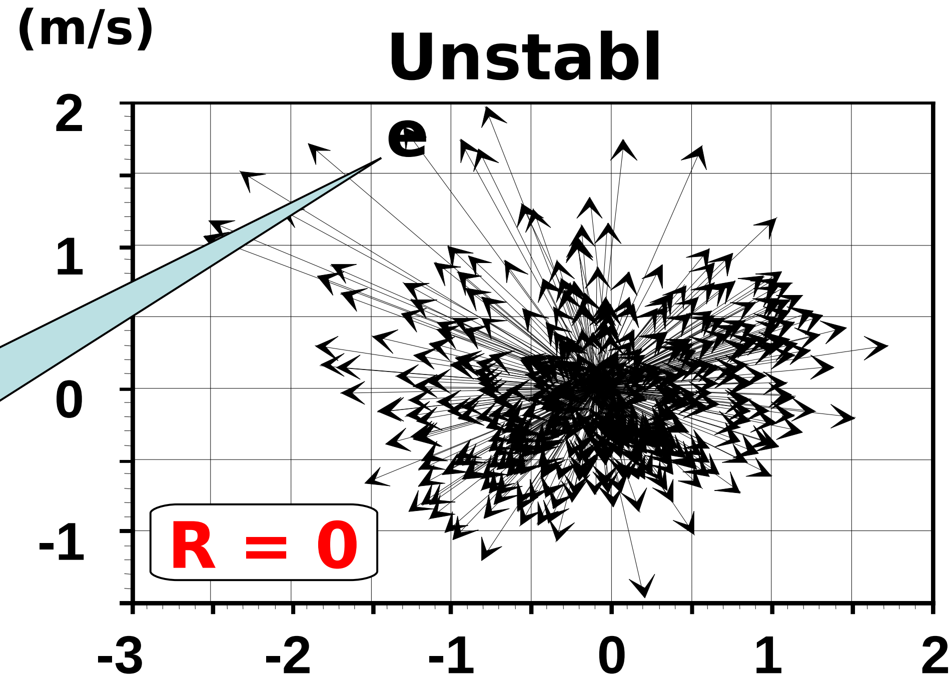
(Kono and Koyabu, 2005)

Oct. 21, 9:00 – 9:20

in 1993



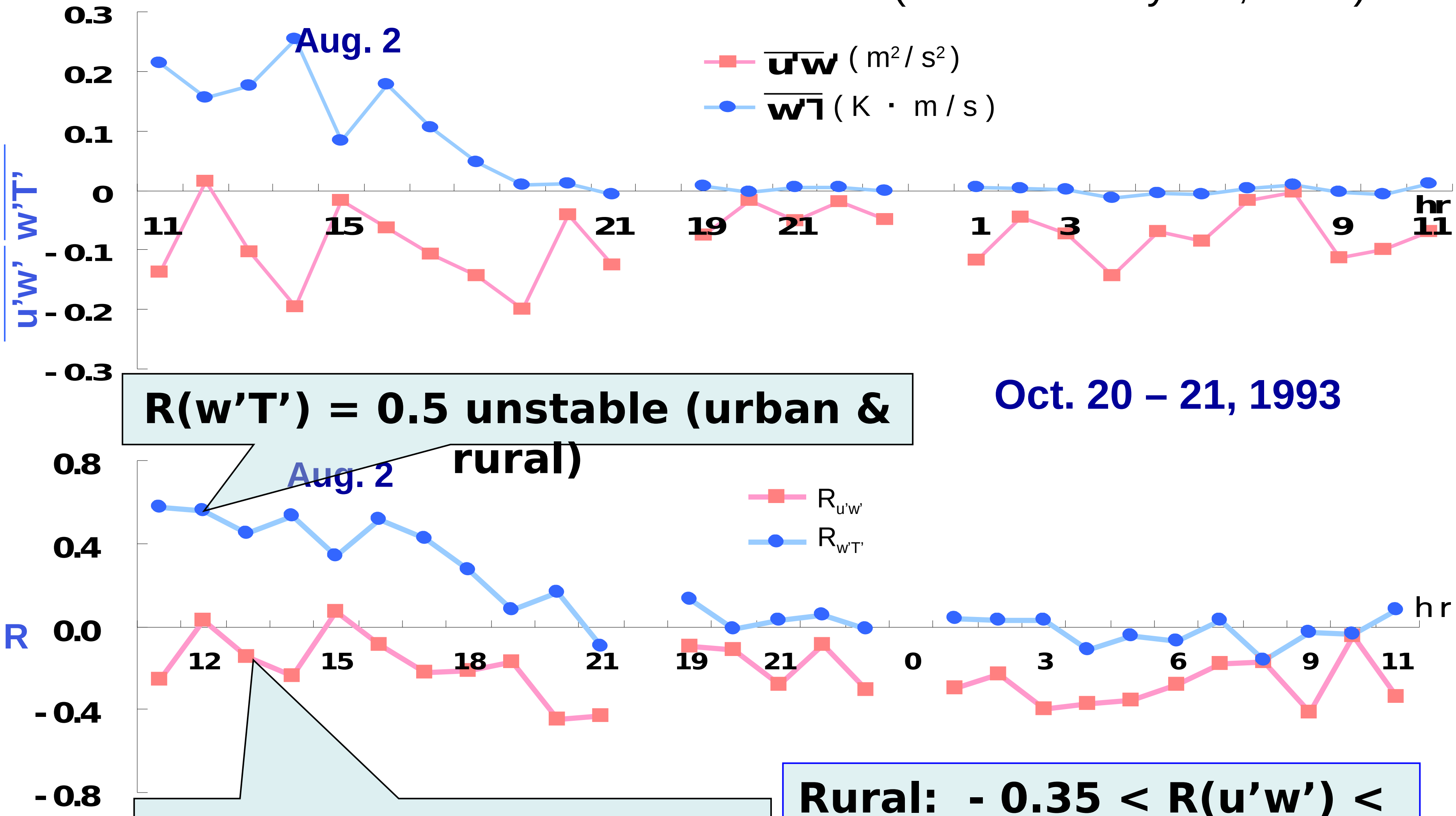
Aug. 2, 12 :00 – 12:20



Strong upward convection

Momentum flux, temperature flux, correlation between u' and w' and correlation between w' and T' measured at the tower (z=54m)

(Kono and Koyabu, 2005)



R(w'T') = 0.5 unstable (urban & rural)

$-$ 0.3 < R(u'w') < 0
unstable

Rural: - 0.35 < R(u'w') < -0.2 (Kaimal and Finnigan, 1994)

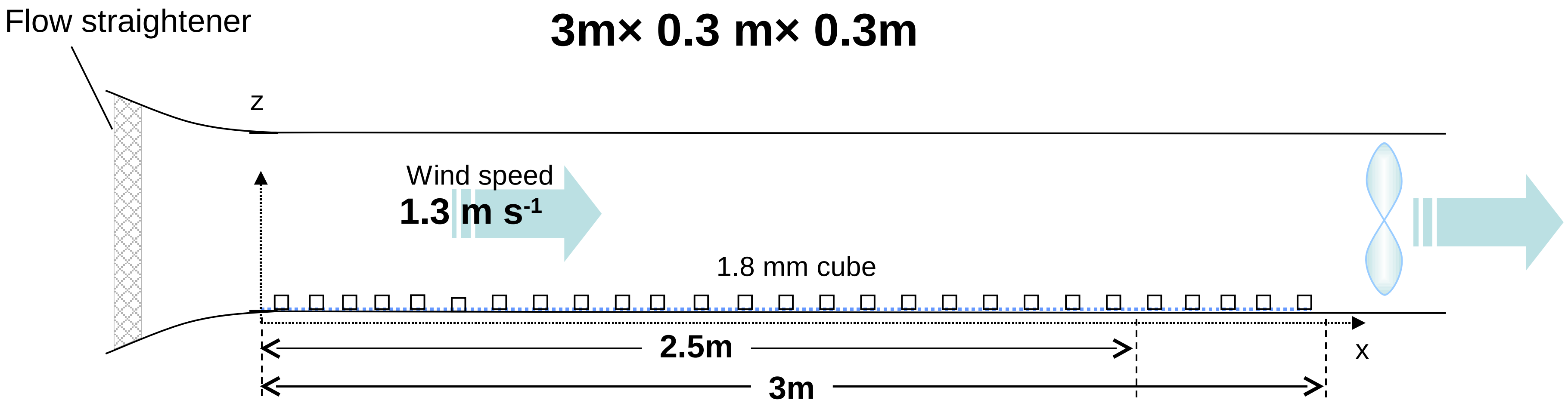
Urban: − 0.3 < R(u'w') < 0 unstable
Rural: - 0.35 < R(u'w') < -0.2
(Kaimal and Finnigan, 1994)

R(w'T') = 0.5 unstable (urban & rural)

In urban areas, convective turbulence transports heat but transports momentum less effectively in unstable conditions.

Under unstable conditions, the eddy diffusivity at the lower part of urban boundary layer, is different from that calculated from the empirical formula at smooth sites using the Monin-Obukhov similarity theory.

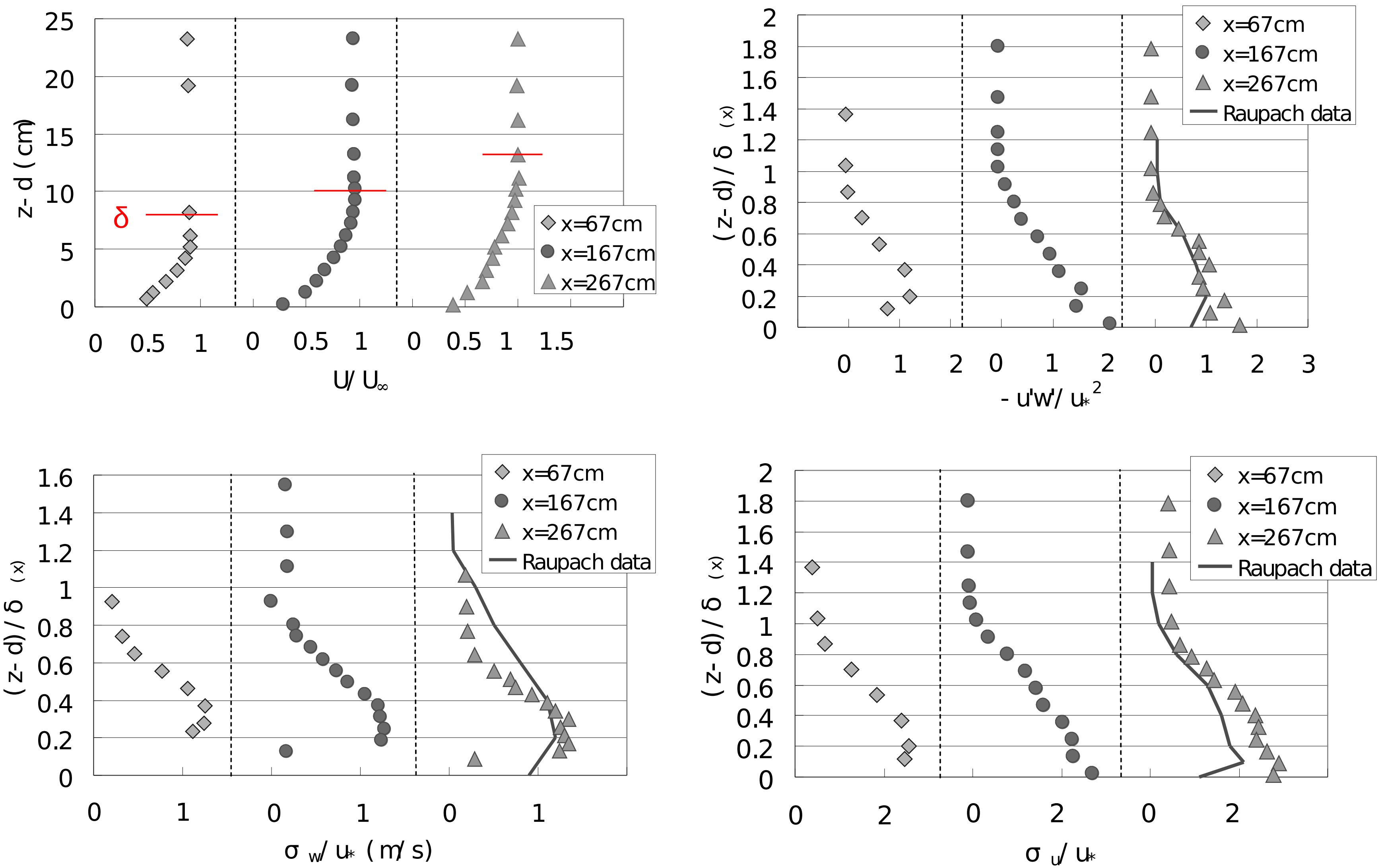
Test section of the wind tunnel.



18 mm cubes, in diamond arrays with 36 mm nearest-neighbour separation

Re = 67,000

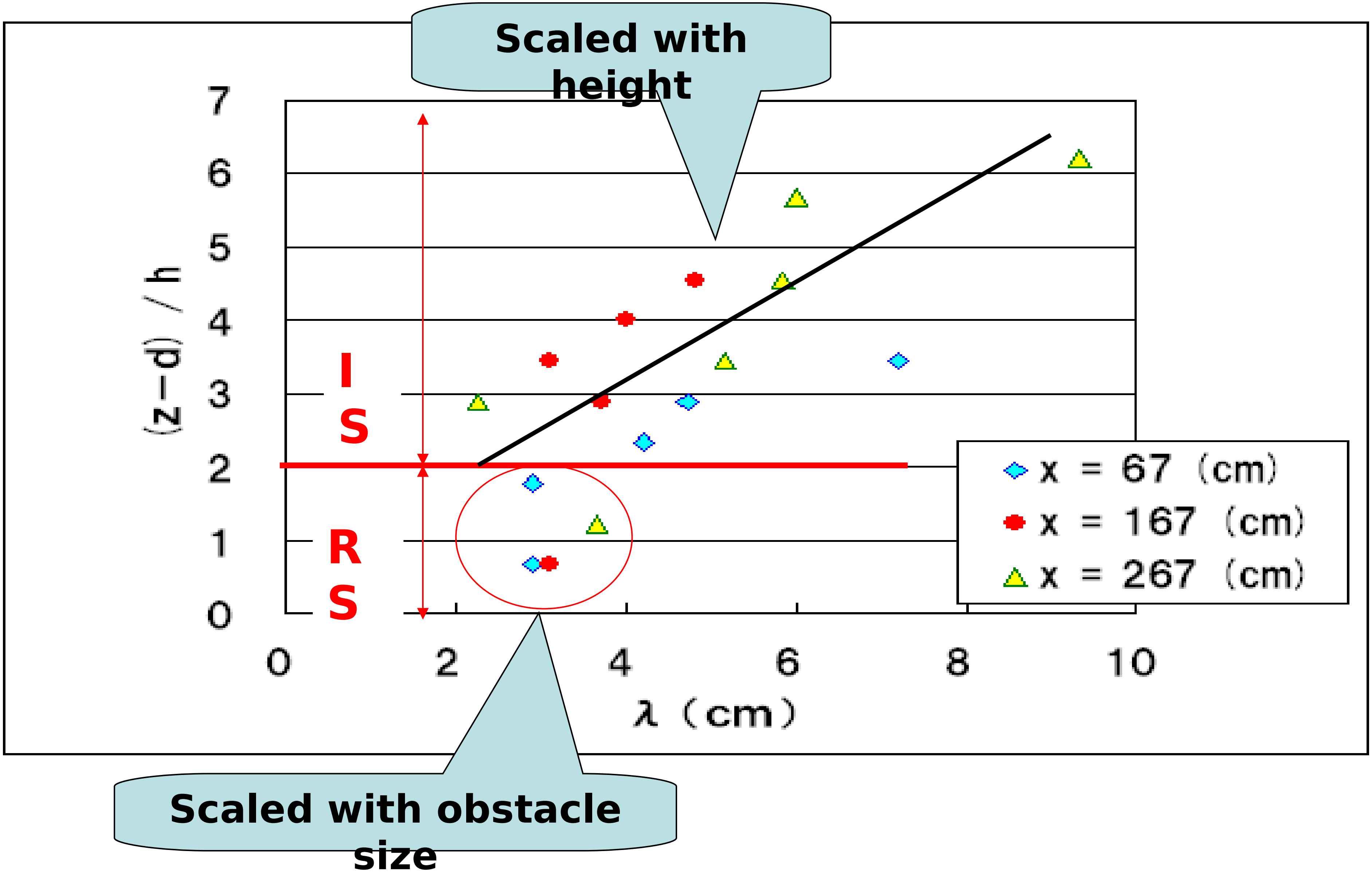
U, $-u'w'$, σ_w, σ_u in the wind tunnel



Raupach, M. R. (1981) Conditional statistics of Reynolds stress in rough-wall and smooth-wall turbulent boundary layers

Eddy size λ which has maximum energy in the wind tunnel

$\lambda = U / 2n$, $d = h = 1.8$ cm



LES was used to predict turbulent flow

in the **roughness sublayer**.

- **Adaptive research - CFD 2000**

- **Computational domain**:

(100 times as large as those in the wind tunnel)

streamwise 150 m, span wise 22 m, normal direction 12 m

grid spacing 0.33 m.

450×66×26 cells.

- **Boundary conditions**:

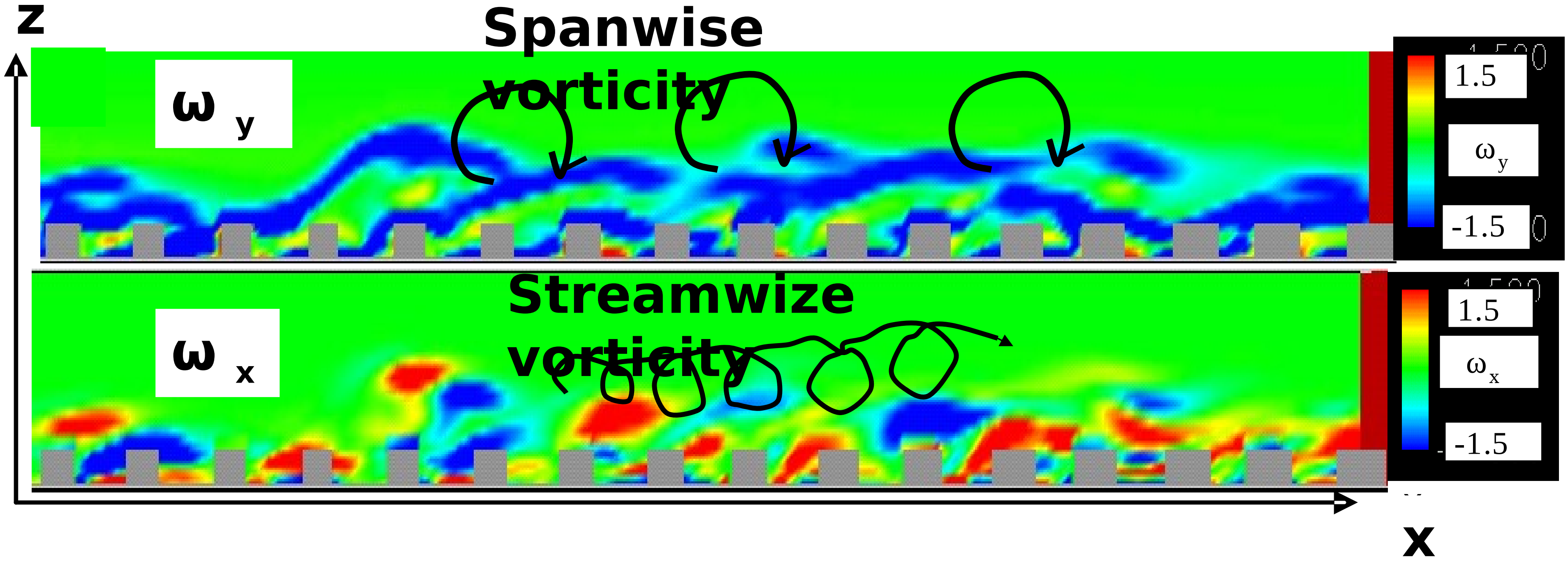
The lower boundary: The 1.8 m cubes were placed in diamond arrays.

The lower boundary and the surface of cubes : the logarithmic wind profile wall function for a smooth surface

The upper and the both side boundary : free slip

The inlet wind speed: 5 m s^{-1} (uniform)

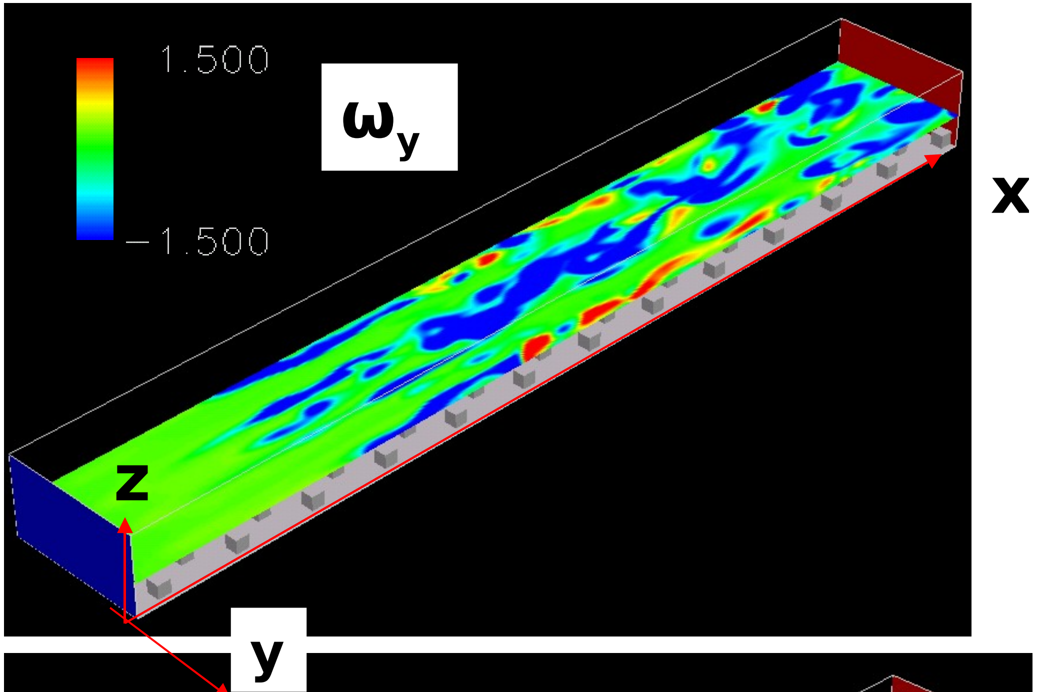
Side view of calculated vorticity (ω_x, ω_y)

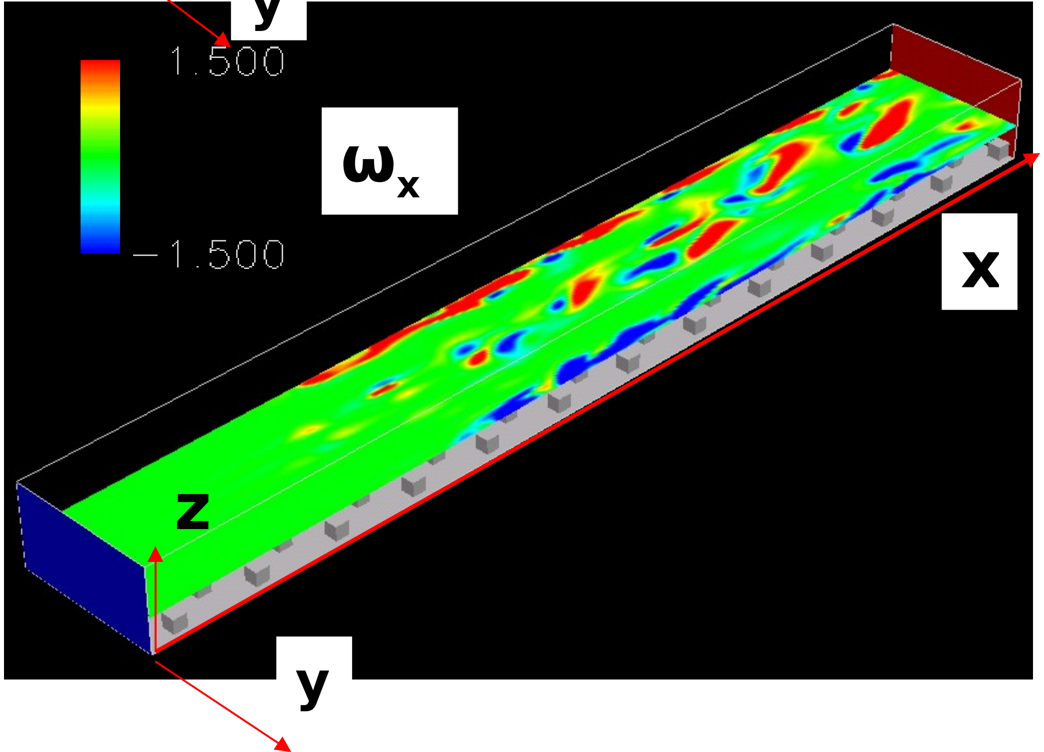


At y = 11 m (center)

View from the top
ω_y, ω_x

At z / h = 2.5





CONCLUSION

In the upper RS, u_* / u under unstable conditions, were close to that under neutral conditions.

These values showed large deviations from the empirical formula presented by Businger et al.(1971) which fitted observations at rural smooth sites.

Therefore, under unstable conditions, turbulence transports momentum less effectively in urban areas than in rural areas.

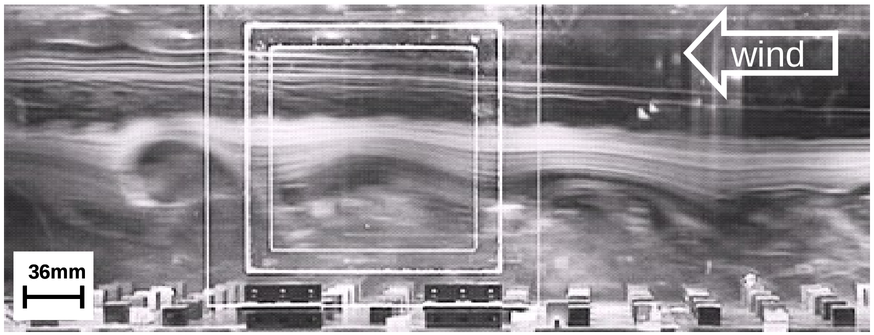
I n the RS, the size of eddies having maximum kinetic energy is scaled with the obstacle size, in the IS, it is proportional to the height. They were shown in the wind tunnel.

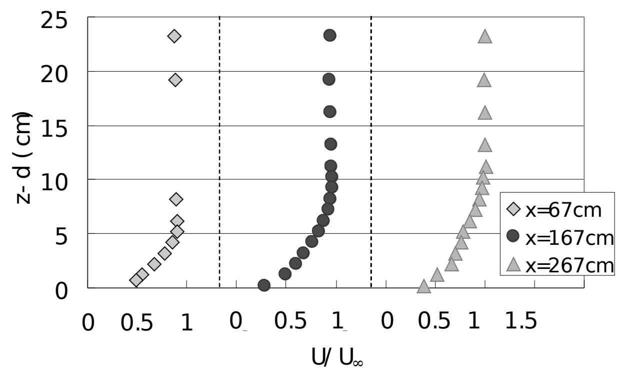
LES showed that eddies in the RS were directly generated by cubes like wakes and they were transported downwind.

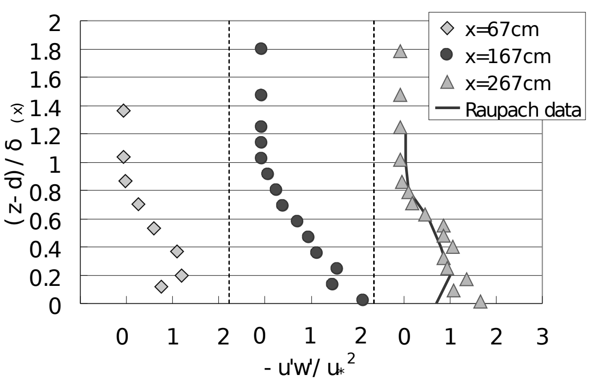
The eddy structure in the RS is expected to be different from that in the IS.

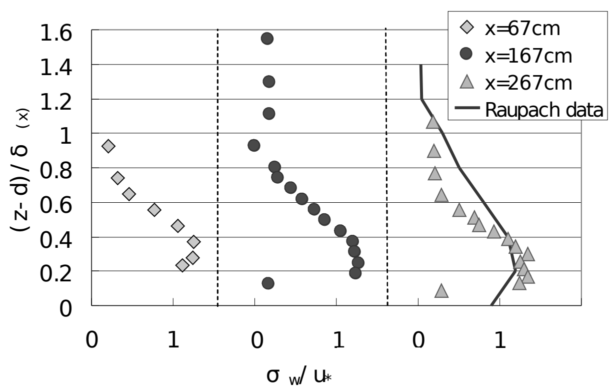
Thank you for your attention!

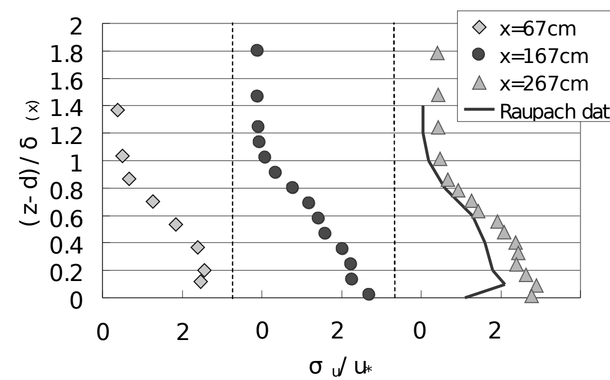
A visualization of the urban boundary layer and U, $-u'w'/u_*^2$, σ_w/u_*, σ_u/u_* in the wind tunnel.





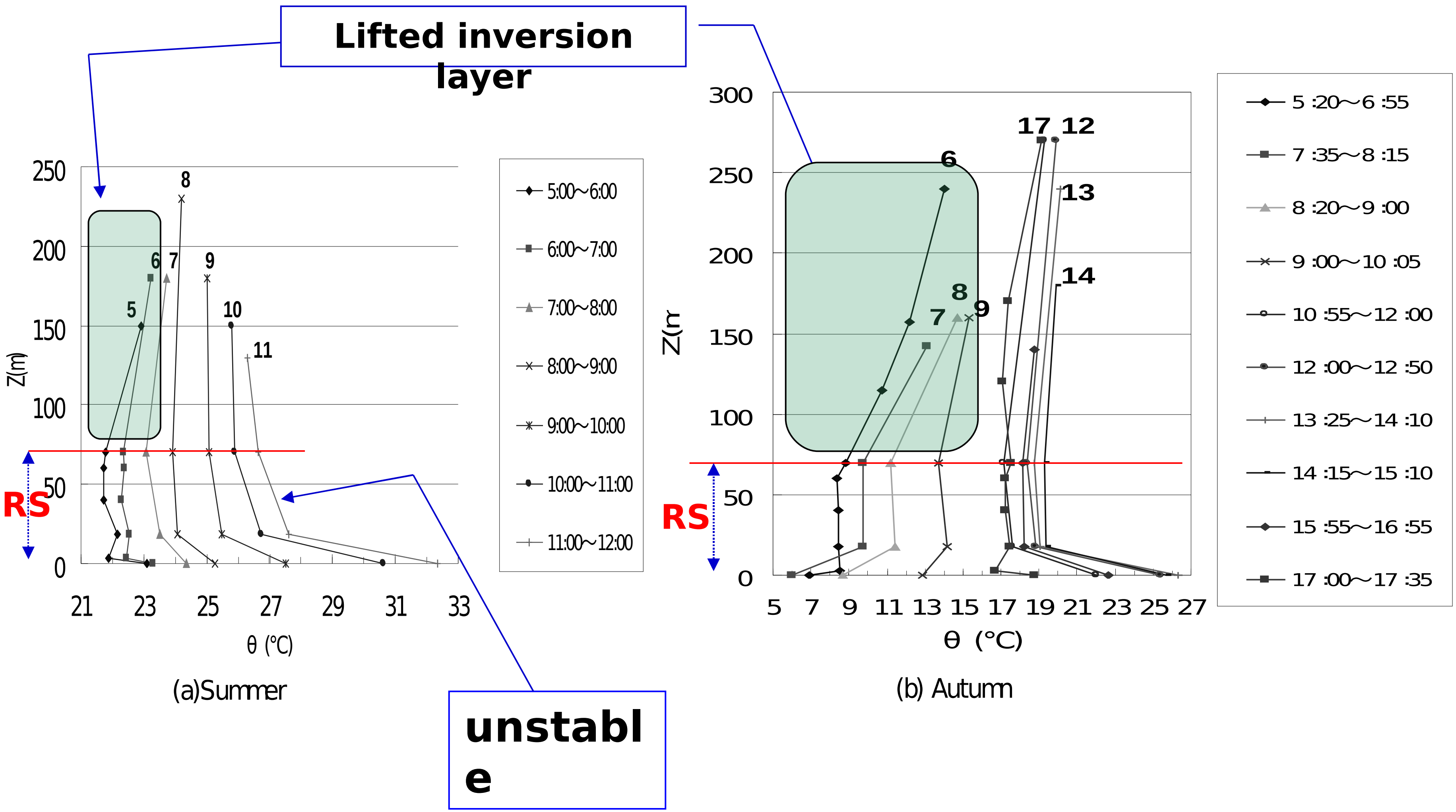






Vertical profile of potential temperature and surface temperature in summer (19 July, 2007) and autumn

(8 November, 2007) in an Urban area of Himeji City



Instruments

- Sonic anemometer: KAIJO SAT – 550, 10Hz, 60 min
- Temperature: at height 4 m, 18 m, 40 m, 60 m, 70 m
- **for one year**
- thermistor thermometer (Espec RT-30S)
- **Surface temperature**: infrared thermometer Eko Instruments Co. **MR-40**
- Doppler Sodar: KAIJO KPA200: sampling interval 3 s