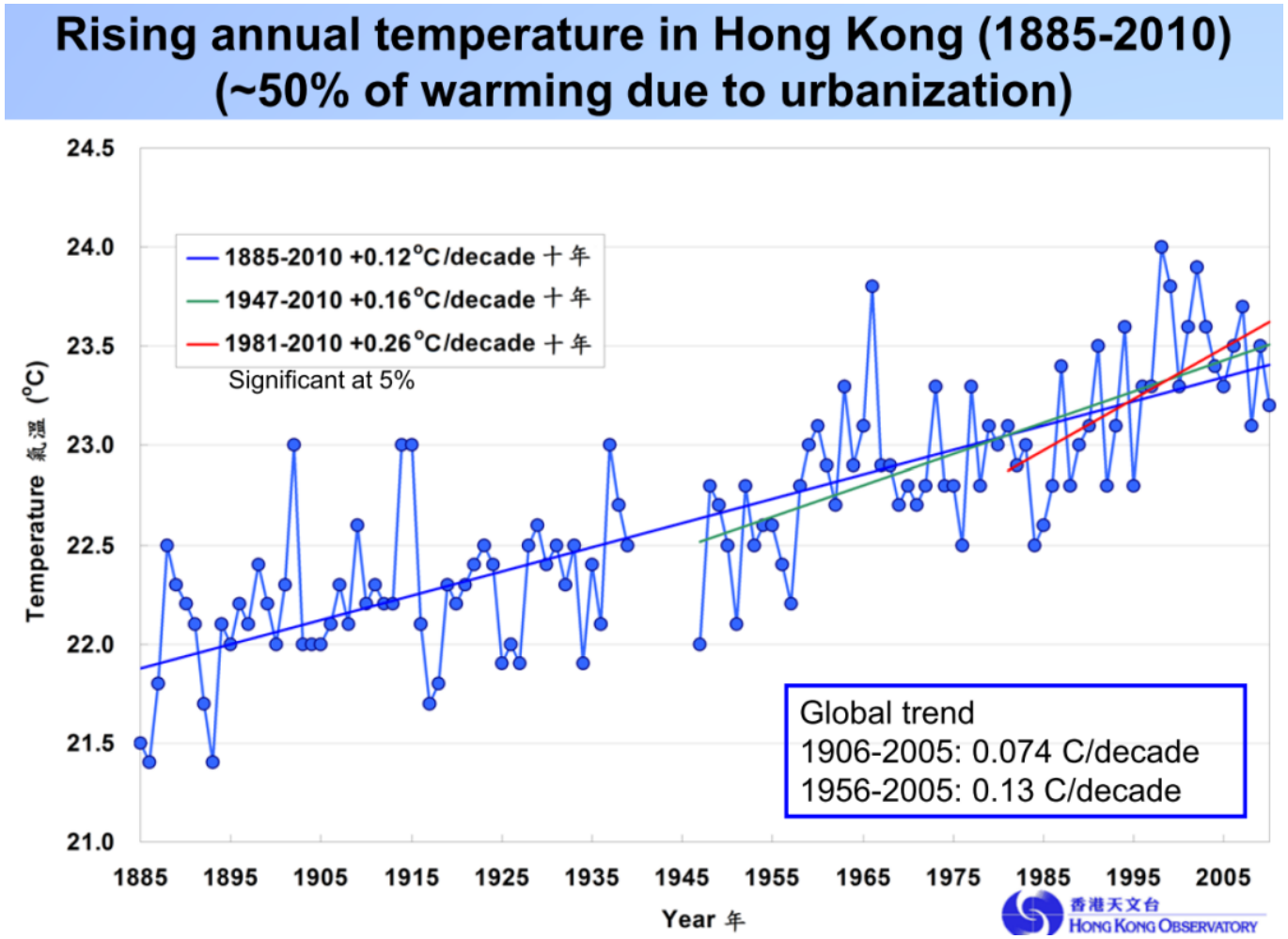
City ventilation and Urban Warming

Yuguo Li 李玉國
Department of Mechanical Engineering
The University of Hong Kong
Hong Kong SAR, China

Importance of cities

- 70% of world's energy is consumed in cities.
- >50% of world population lives in cities.
- Urban population will reach 1 billion by 2030 in China.
- 20,000 to 50,000 new skyscrapers in the next 20 years.
- A high-rise compact city means high building density, population density, human activity, anthropogenic heat (1000W/m^2), greater solar heat trapped, heat storage, reduced wind flow, urban heat and pollutant island.

Getting warmer and warmer



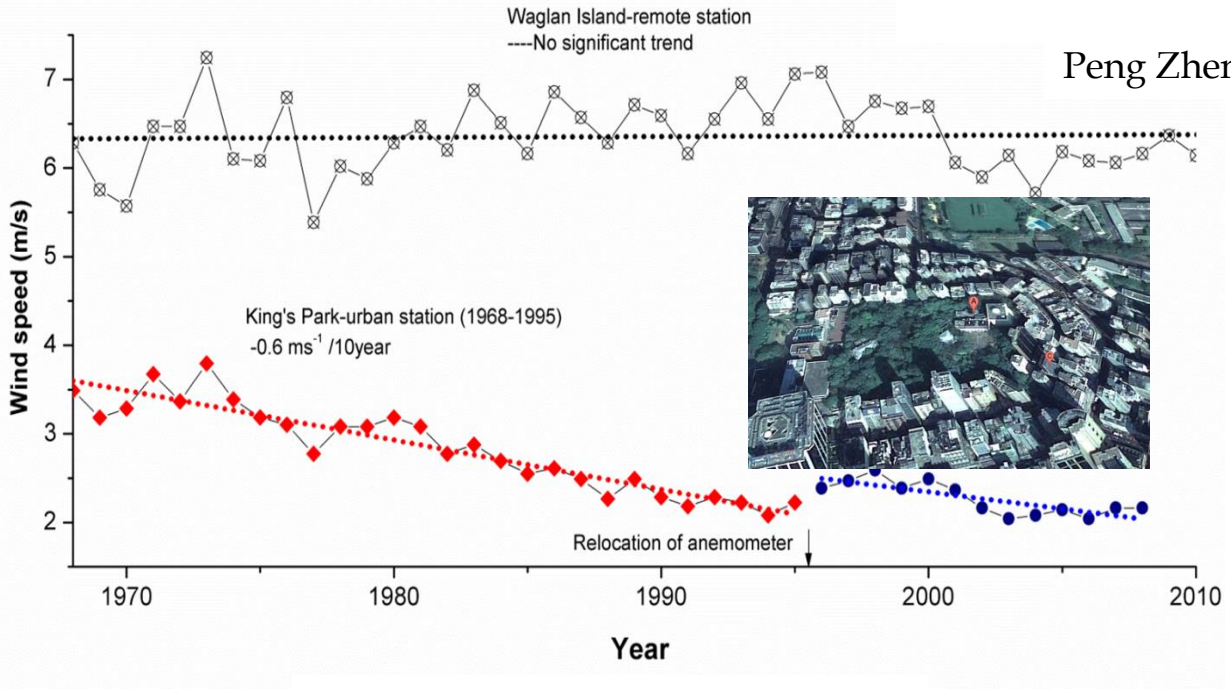
HKO

Urban air warmer by >2°C. 1°C increase in daily mean temp >28.2°C increases 1.8% in mortality (Chan et al 2010) . 1°C increase increases 4.5% in electricity use (Fung et al. 2006)

London in fog

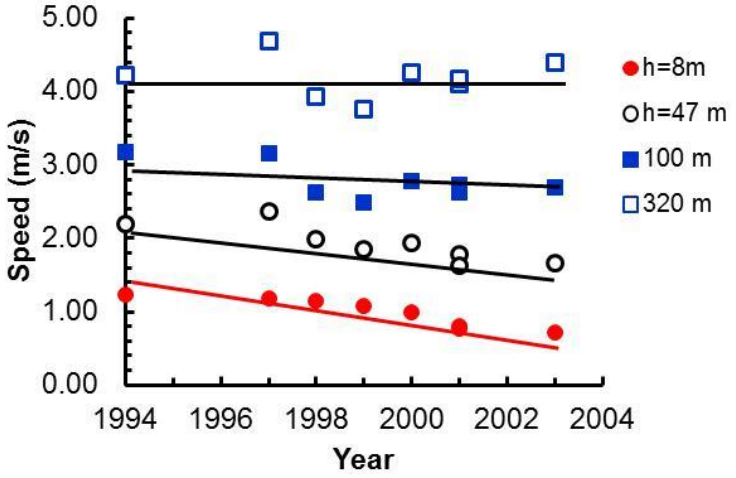
Less and less wind in some megacities – why and how to stop it?

Reducing mean wind at **Hong Kong** King's Park and no change at Waglan Island.



Ginn et al., *HKO* (2009) @ new data

Reducing wind at 8 m above along the North-west **Beijing** 325 m met tower (close to Tsinghua University)

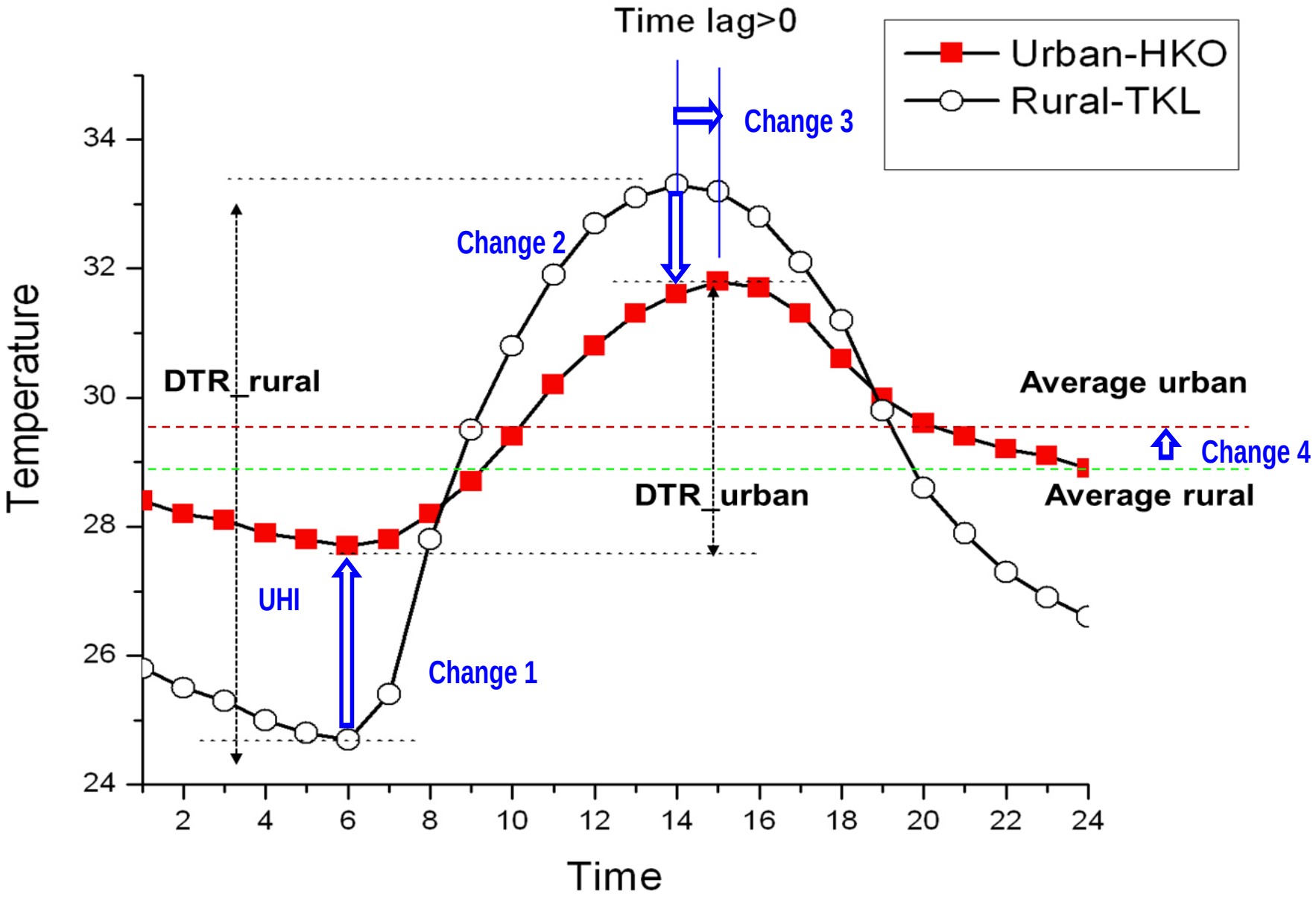


Peng Zhen, *MPhil thesis, CAS*(2004)

Reduced wind leads to

- urban warming (2-3^{o}C),
- poor air quality,
- poor visibility,
- heat stress in summer,
- reduced productivity

(May benefit cities in cold climate)


Time lag>0
Urban-HKO
Rural-TKL
Change 3
Change 2
DTR_rural
Average urban
Change 4
DTR_urban
Average rural
UHI
Change 1
Temperature
Time
34
32
30
28
26
24
2
4
6
8
10
12
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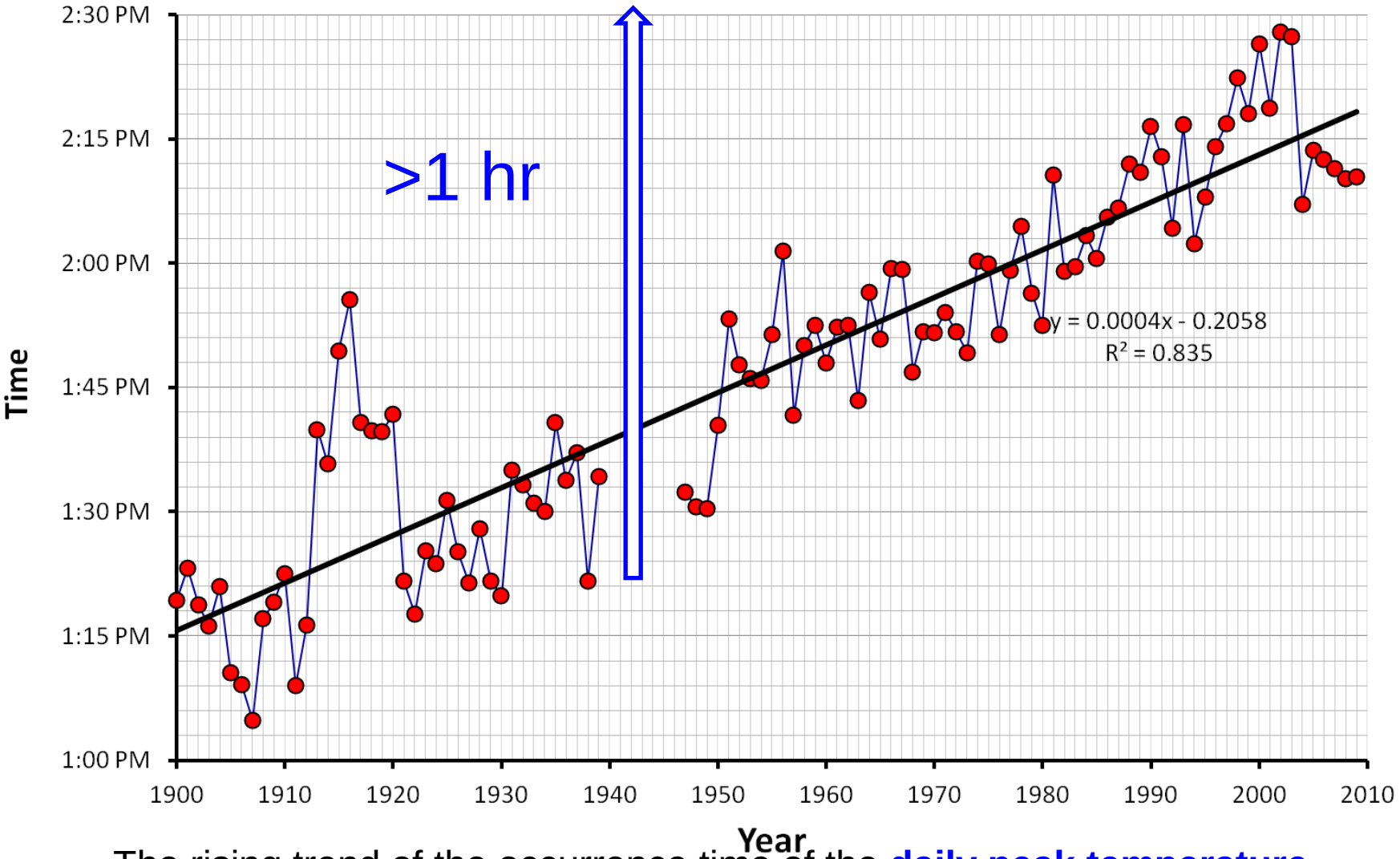
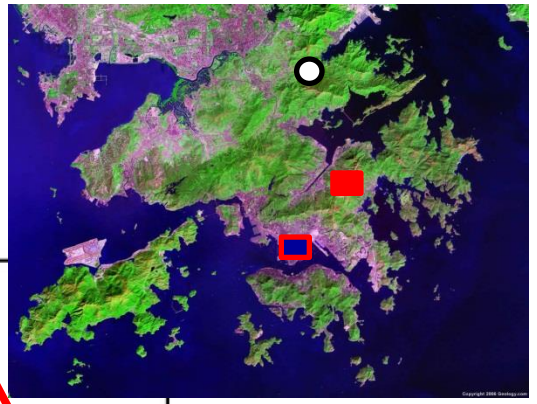
16
18
20
22
24

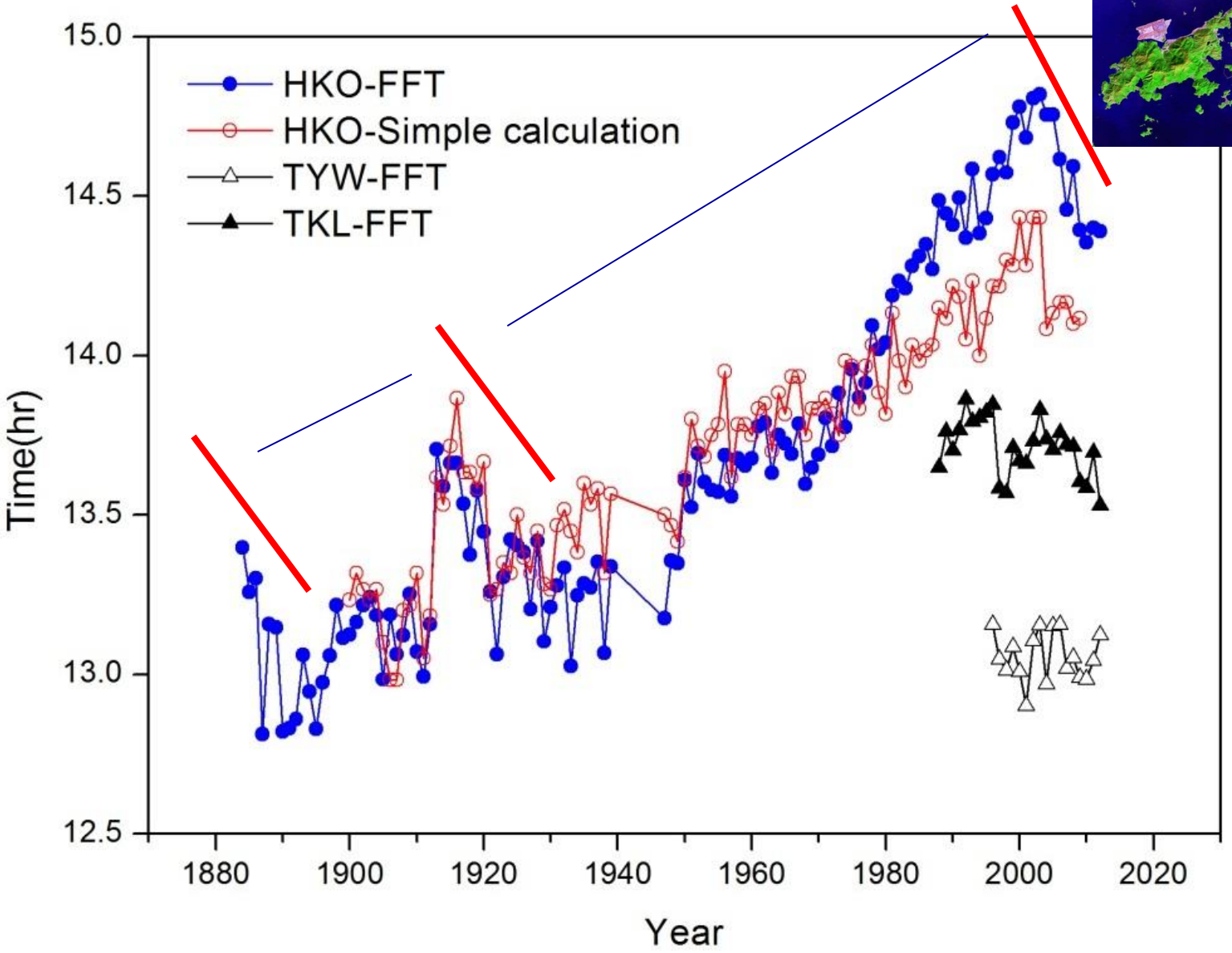
Why daily timing of max temp has shifted later
为什么日最高温时间后移？

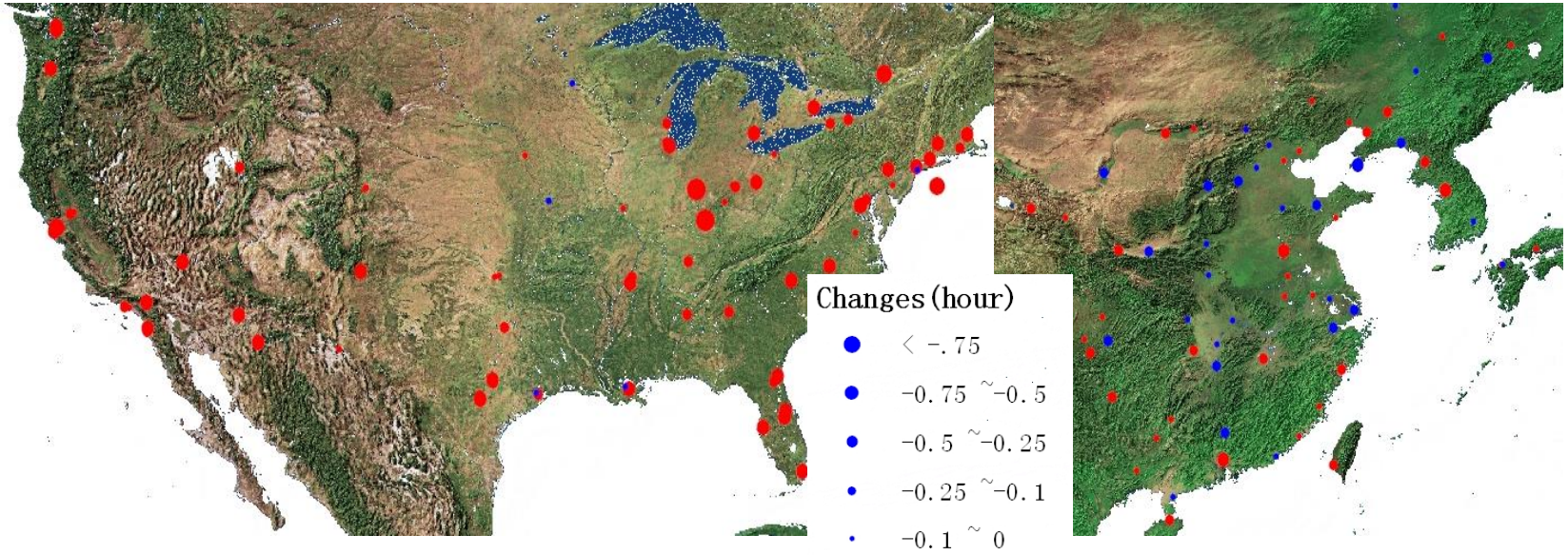


The rising trend of the occurrence time of the **daily peak temperature** from 1900 to 2010, Hong Kong

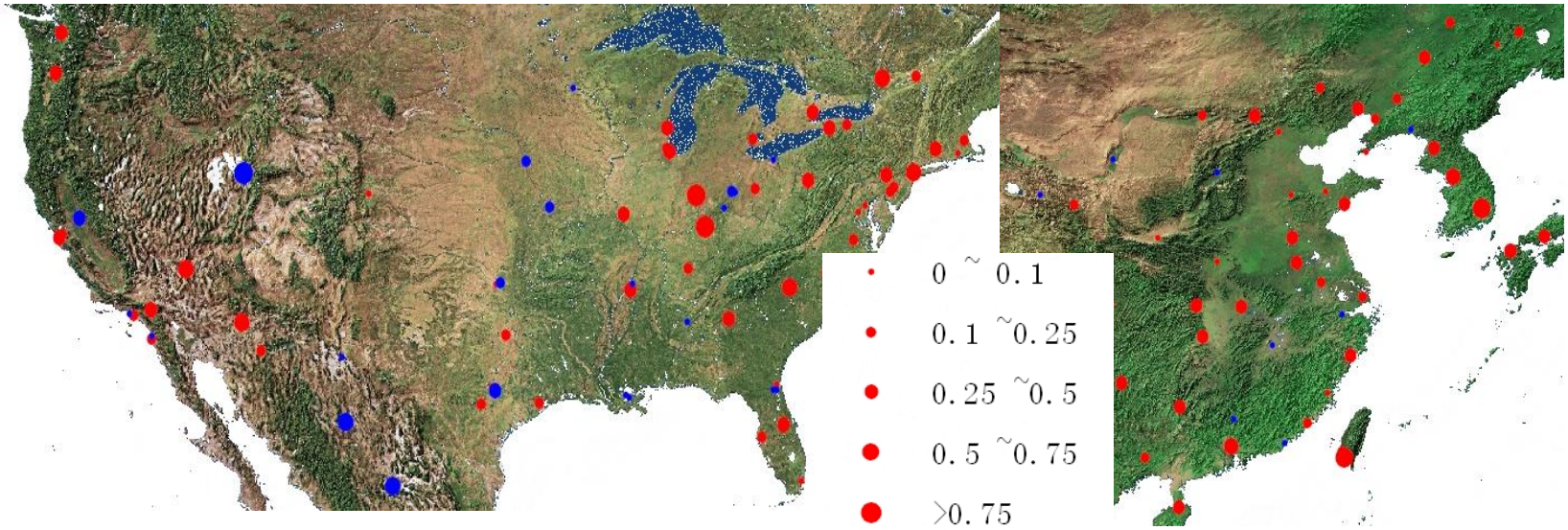
Why 2 rises and 3 down
为什么二升三降？







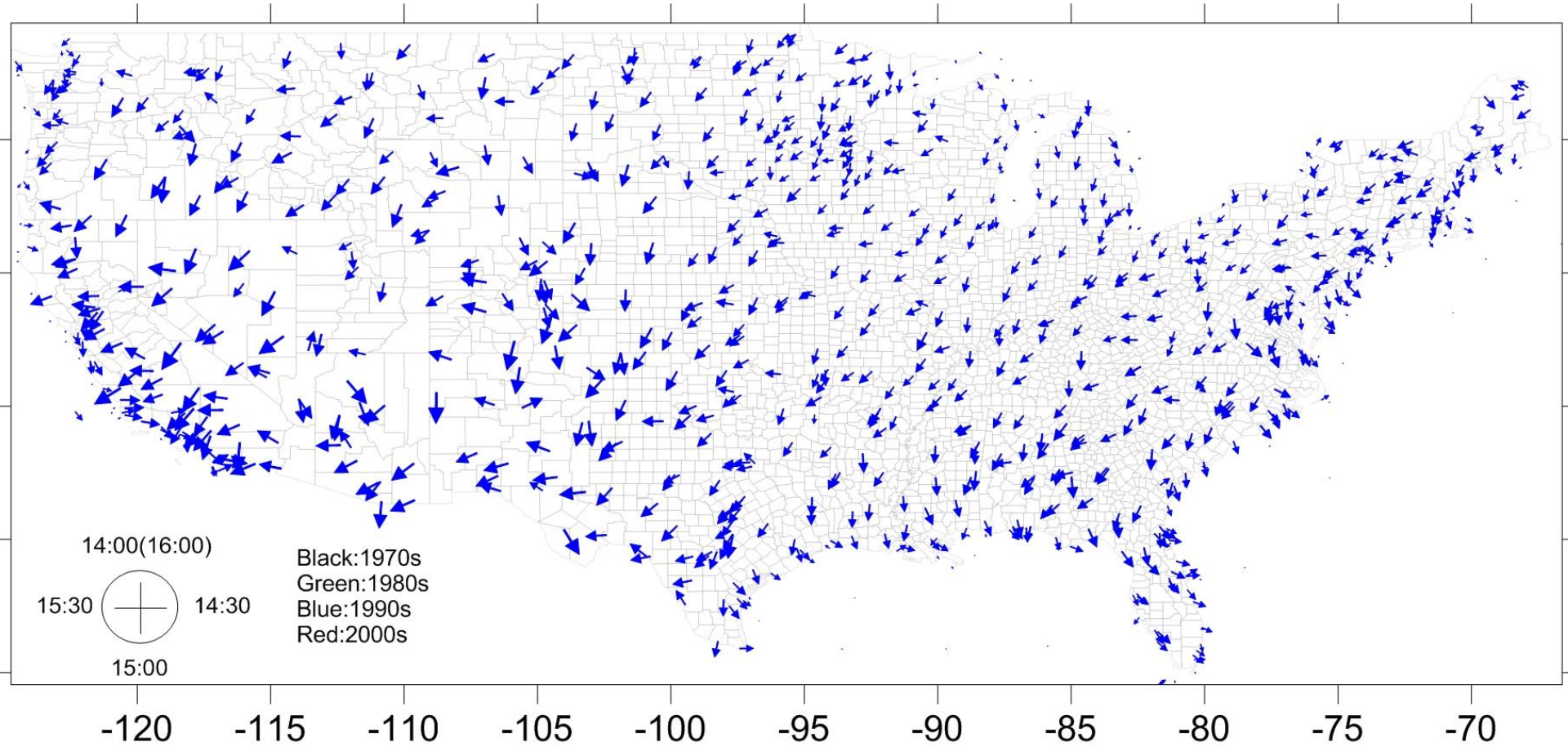
(A) Phase change from 50s to 60 s in major cities in US (left) and Easten Asia (right)



(B) Phase change from 50s to 90 s for major cities in US (left) and Eastern Asia (right)

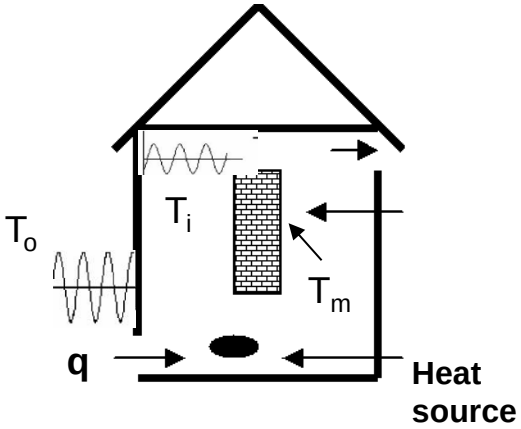
Global, regional or local?

美国 **1990-1999**

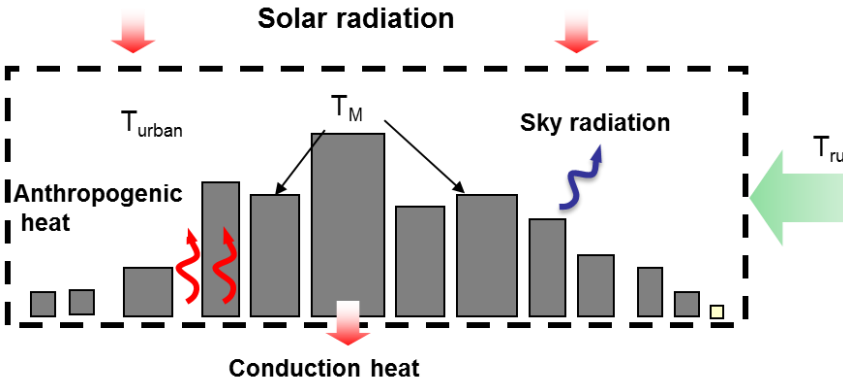


When local scale matters, when large scale matters?

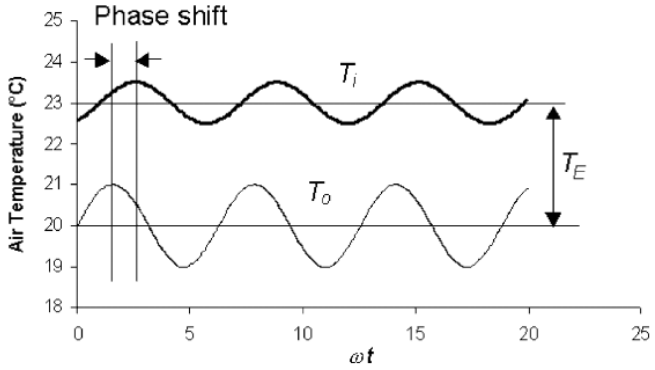
A simple model ?



In an analog



$$T_i(\omega t) = \tilde{T}_o + T_E + \sqrt{\frac{\lambda^2 + \omega^2\tau^2}{\lambda^2 + \omega^2\tau^2(1+\lambda)^2}}\,\Delta\tilde{T}_o \sin(\omega t - \beta)$$



A ideal solution for urban air temperature ???

Mean temp **Amplitude** **Phase shift**

$$T_i(t) = \tilde{T}_i + A\Delta\tilde{T}_o \times \sin(\omega t - \beta)$$

$$T_E = \frac{E}{\rho C_p q}$$

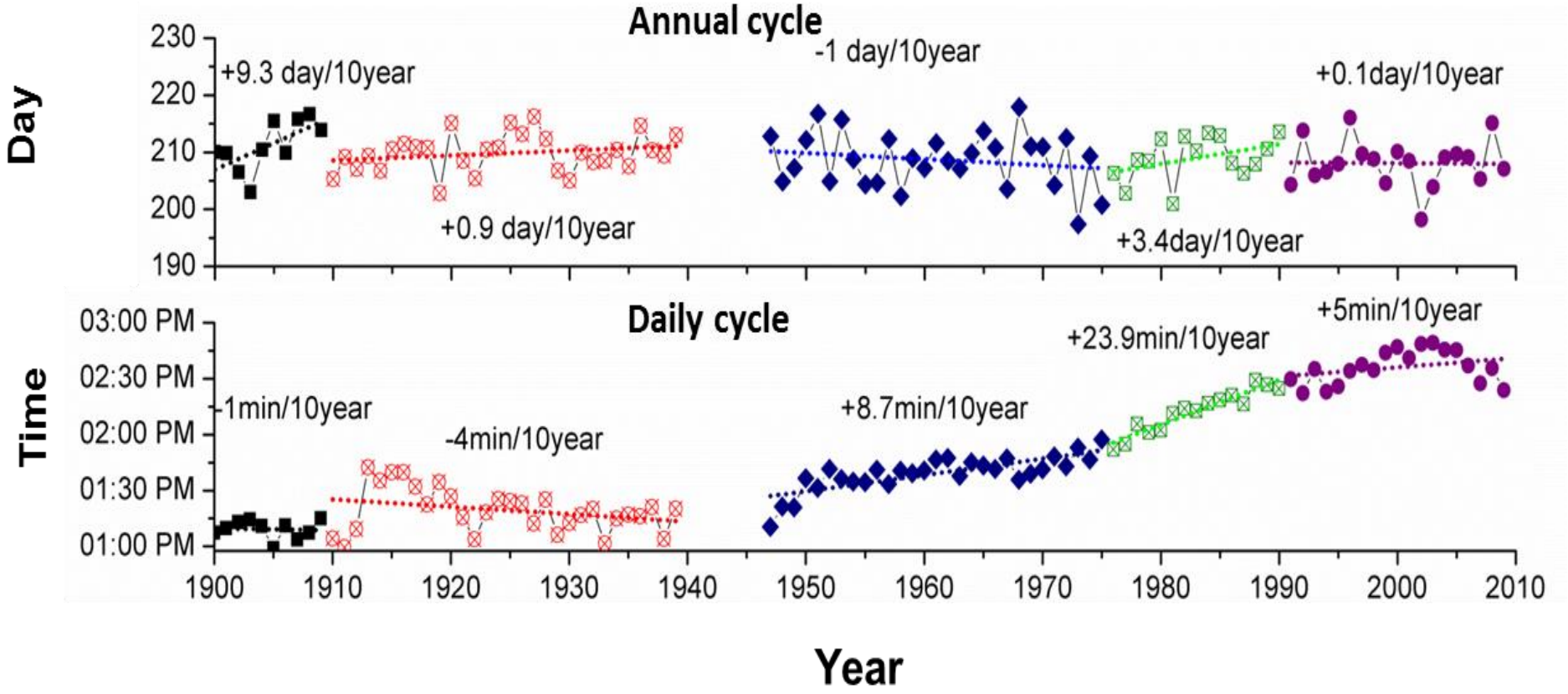
$$\tau = \frac{MC_M}{\rho C_p q} \qquad \lambda = \frac{h_M A_M}{\rho C_p q} \qquad \gamma \approx 1 + f_w$$

Convection number

Temp rise

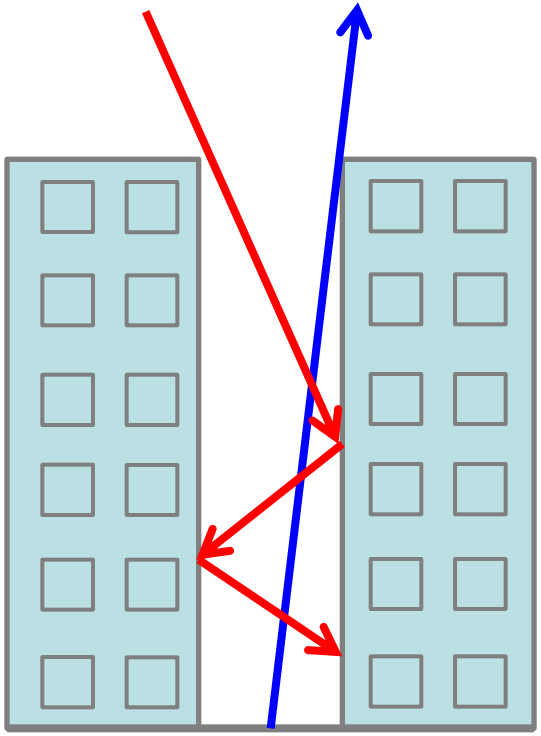
Thermal mass
Time constant

Total heat
transfer number



Why small changes in annual cycle, but large in daily cycle?
为什么年循环变化小，日循环变化大？

Man-made surfaces/structures – the cause of urban warming?

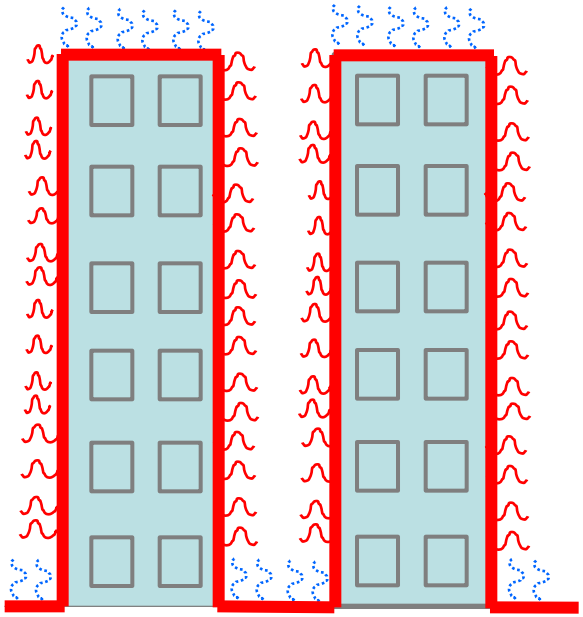


Solar heat trapped

Surface radiation trapped

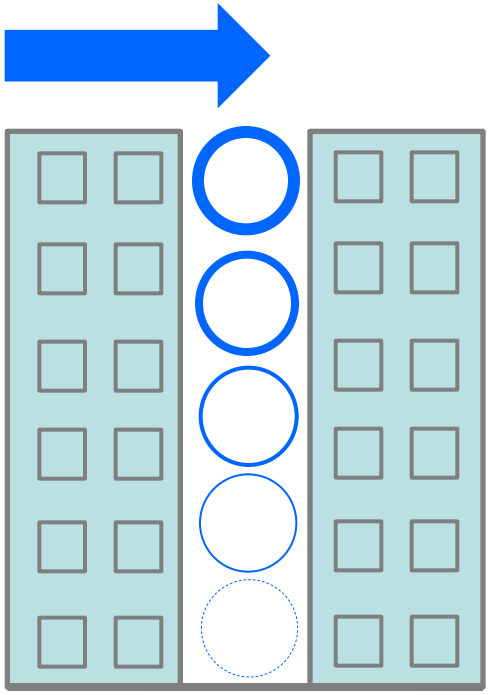
More heat generated

Daily cycle penetrates 0.5 m only into surface



More surfaces for heat storage

Lack of evaporation



Lack of wind

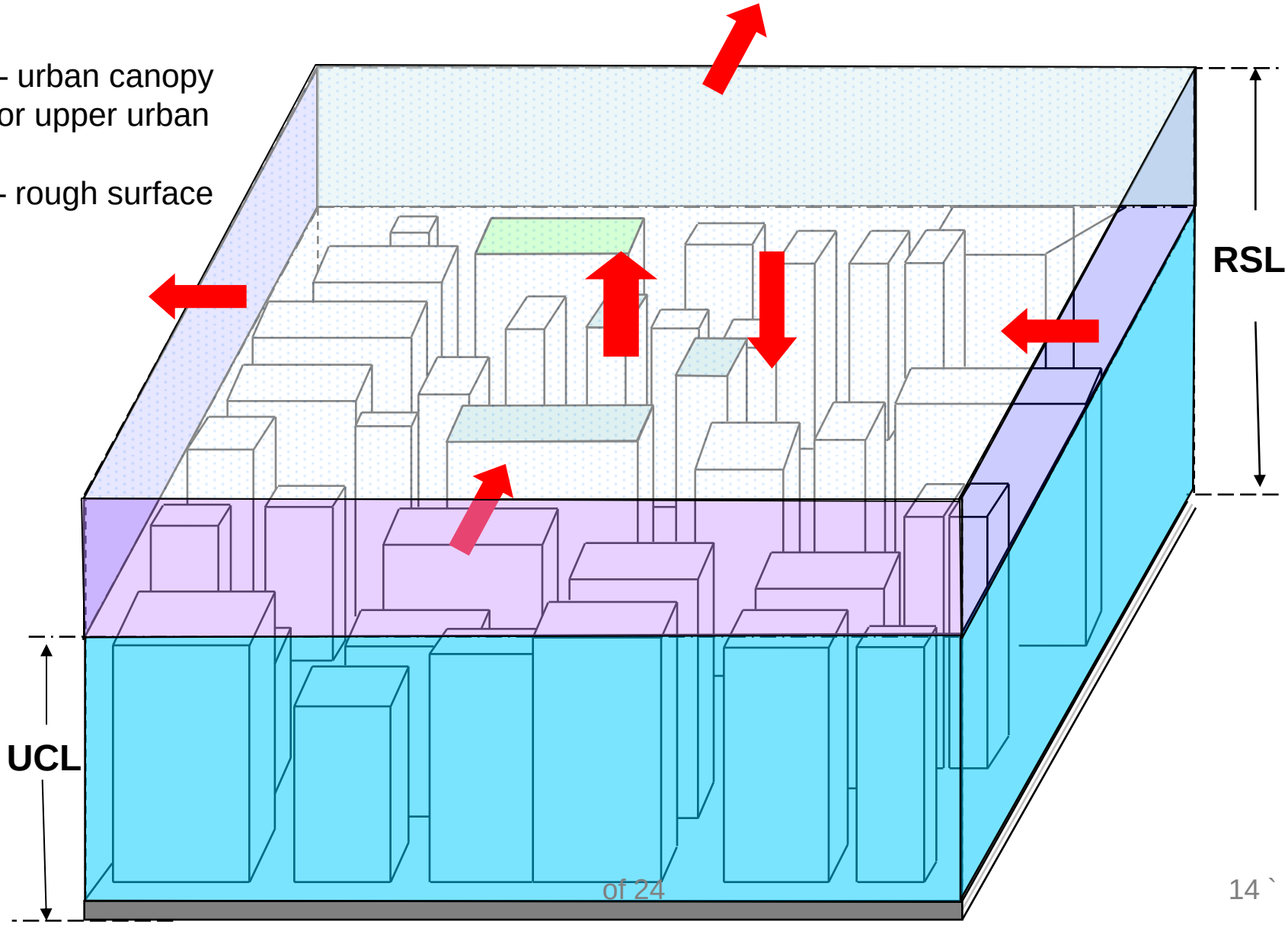
More residence time

Lack of heat removal

Central HK: 100 m high, 60% built area, surface increase by 10 folds, albedo reduces by 50%, less vegetated area… the worst - the heat sources cannot be easily controlled as source control in air pollution control.

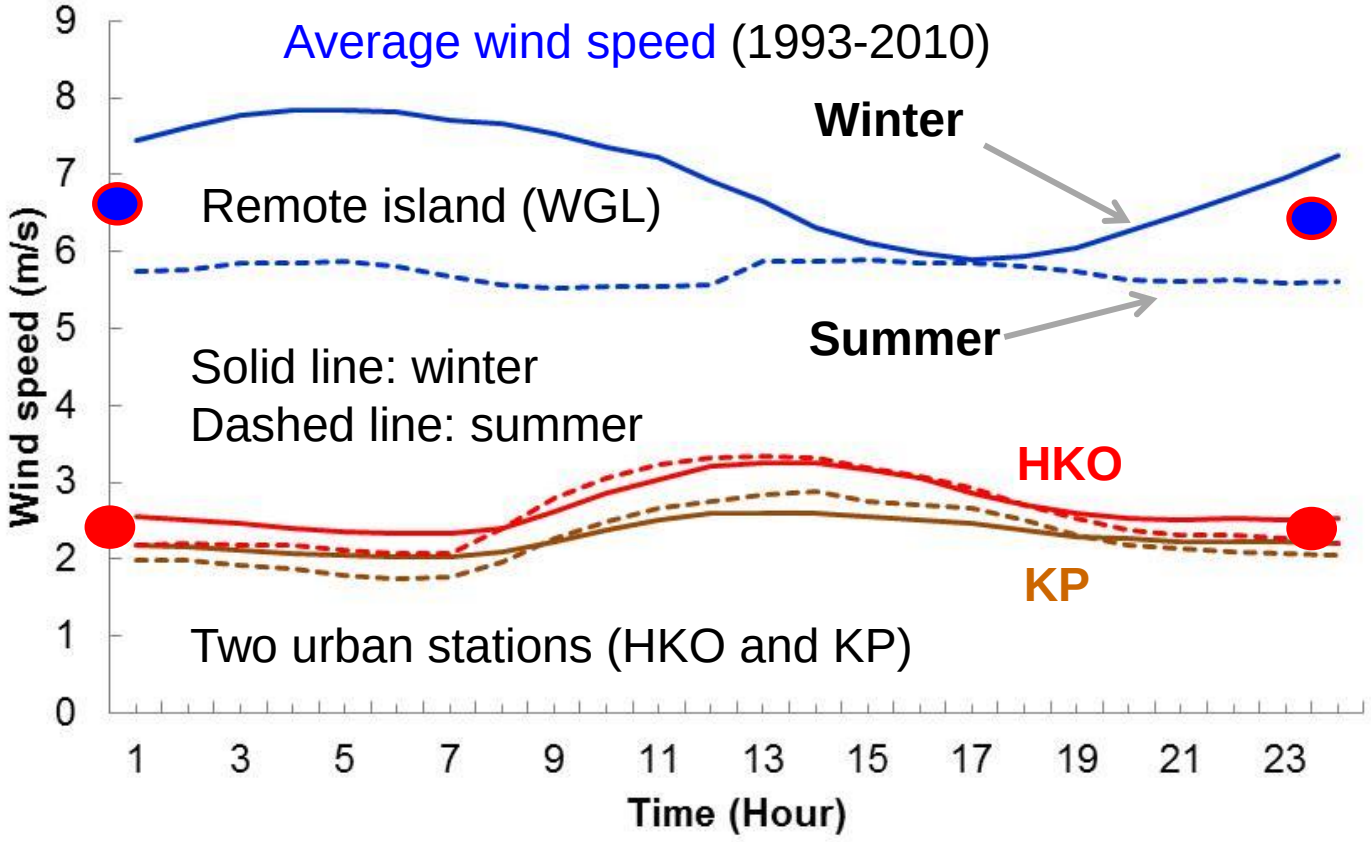
Not easy - our key concept – where does heat go in a district or city volume?

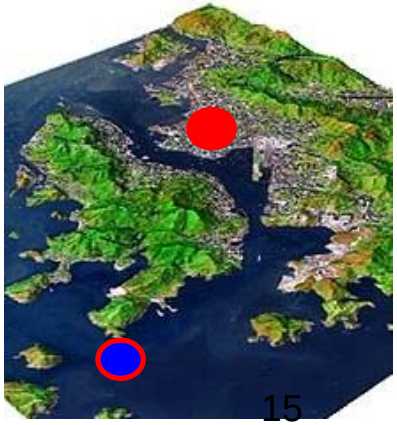
UCL – urban canopy layer or upper urban layer
RSL – rough surface layer



Diurnal wind change

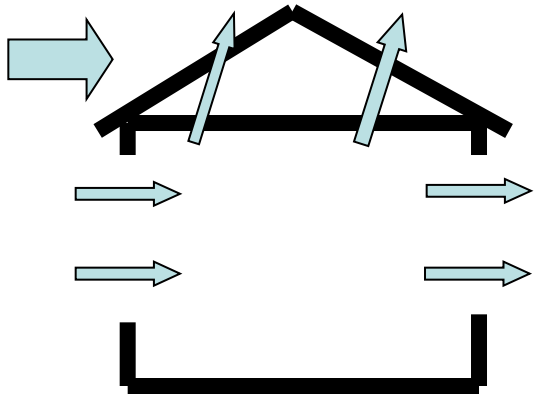
- Different trends in rural/urban wind speeds.
- Stronger urban wind @ 11 am – 2 pm.
- Stronger urban wind in summer @ 11 am – 2 pm.

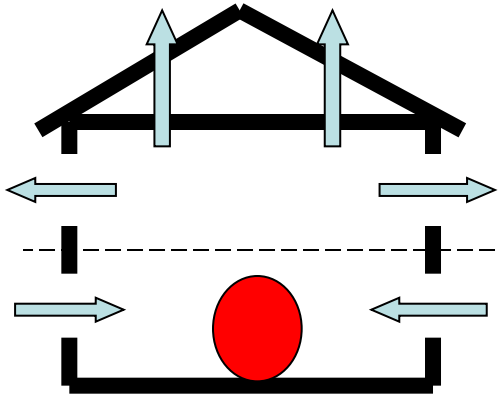


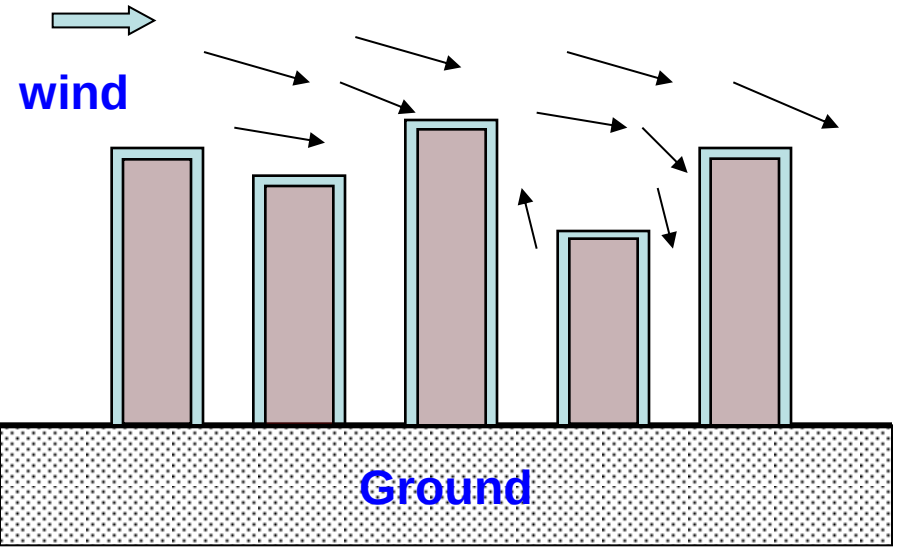


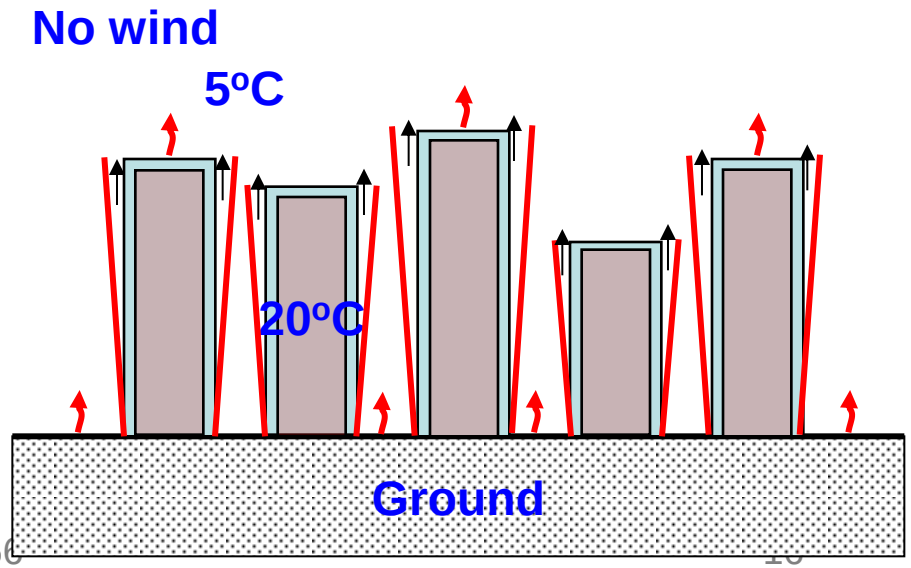
Wang and Li, *unpublished*

Building ventilation and city ventilation
比较建筑自然通风和城市自然通风



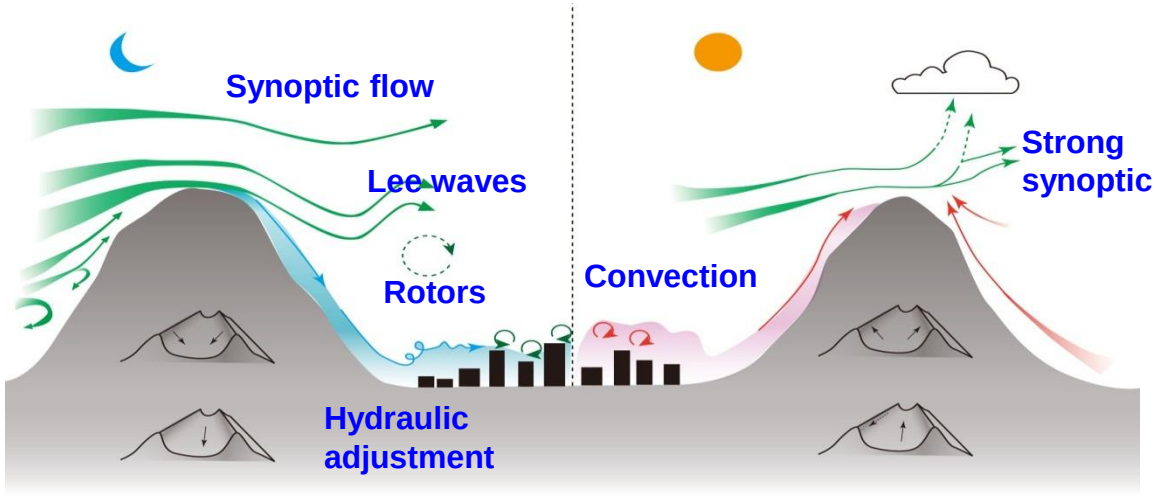




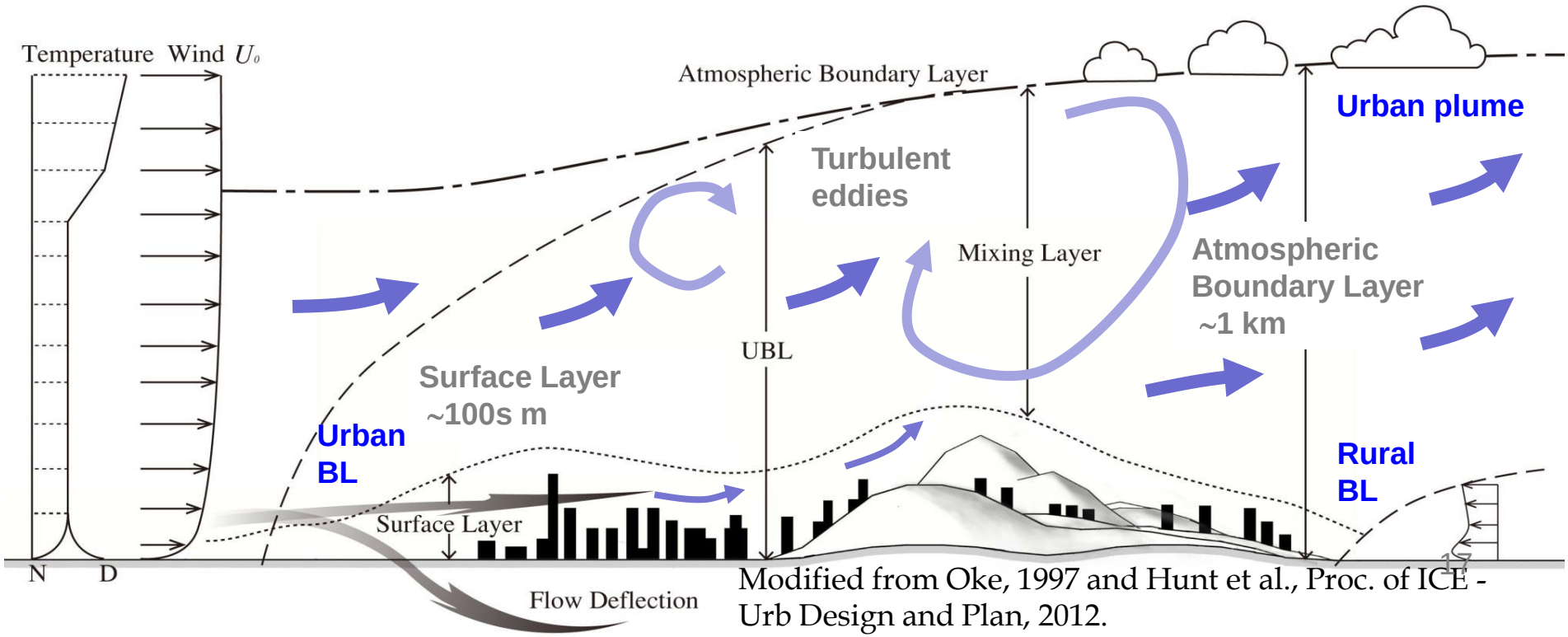


Meso-scale

Development and structure of urban boundary layer in a high-rise compact city



Modified from Fernando. *Ann Rev Fluid Mech* 42:365-389 (2010)
In Hong Kong, the buildings and hill are similarly high

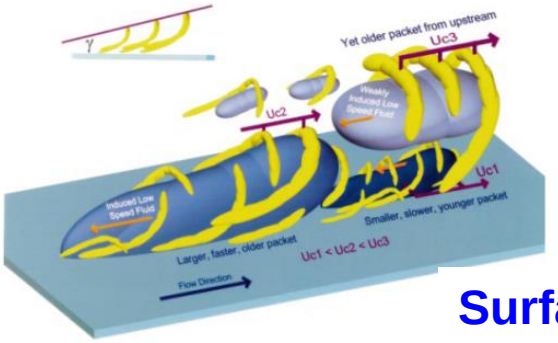


Modified from Oke, 1997 and Hunt et al., Proc. of ICE - Urb Design and Plan, 2012.

Local scale

$$-\frac{\partial}{\partial z}\langle\overline{u'w'}\rangle$$

Inertial sublayer



Tomkins and Adrian,
J Fluid Mech 490:37-74 (2003)

$$-\frac{\partial}{\partial z}\langle\overline{u'w'}\rangle-\frac{\partial}{\partial z}\langle\tilde{u}\tilde{w}\rangle$$

Surface layer

Coherent structures

small scale associated with surface shear

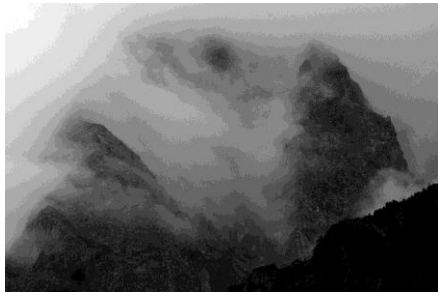
Roughness sublayer

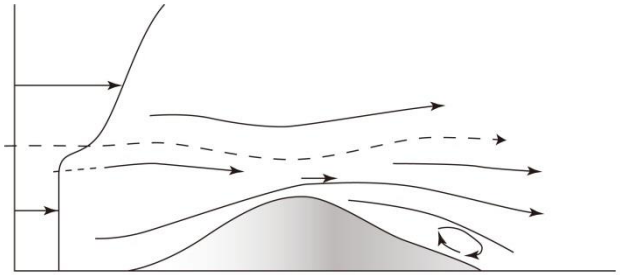
Urban canopy layer

Modified from Oke, 1997

$$-\frac{\partial}{\partial z}\langle\overline{u'w'}\rangle-\frac{\partial}{\partial z}\langle\tilde{u}\tilde{w}\rangle+D$$

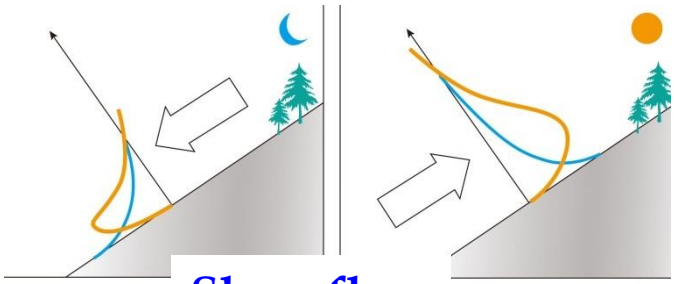
Individual flow mechanism is better known, but their interaction with a city is mostly unknown





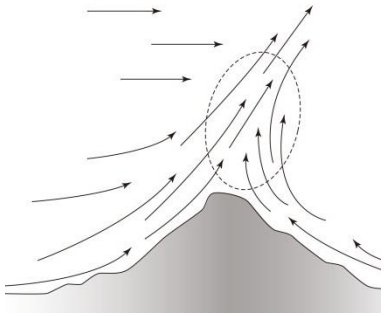
Hunt and Snyder *J Fluid Mech* 96:671-704 (1980)

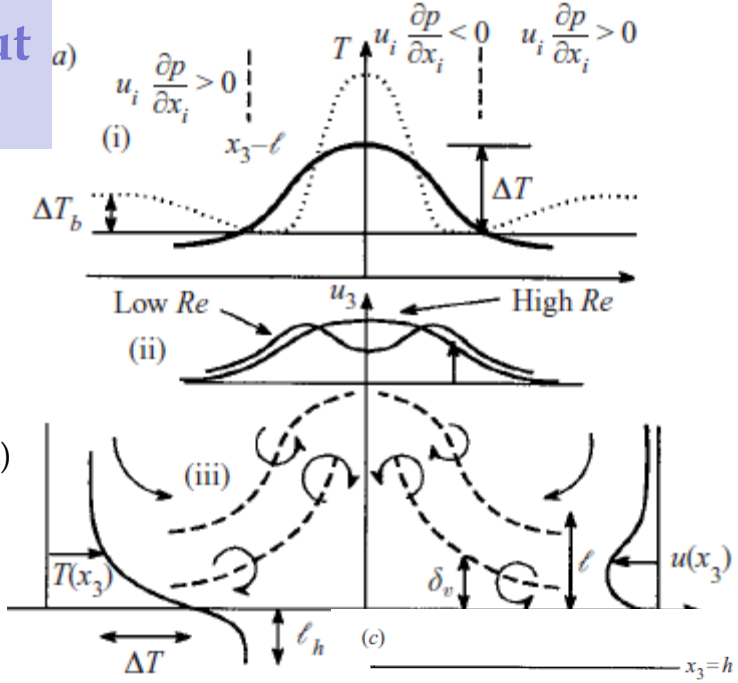
Wind over a hill



Slope flow

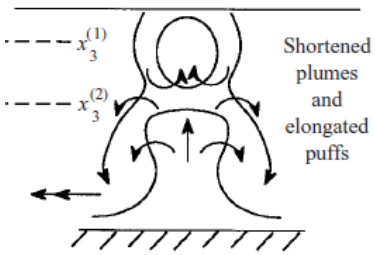
Luo & Li, *Atmos Environ* 45:5946-5956 (2011)

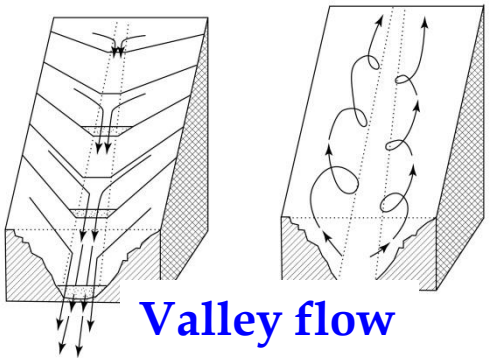




Hunt et al. *J Fluid Mech* 491:183-205 (2003)

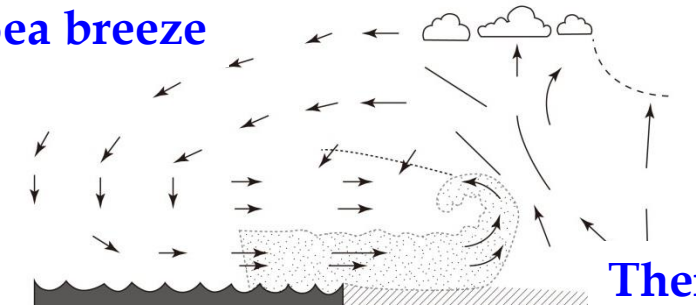
Slope flow merging

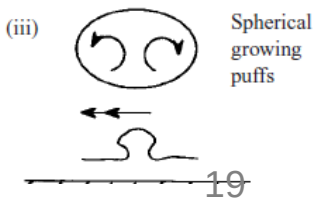




Valley flow

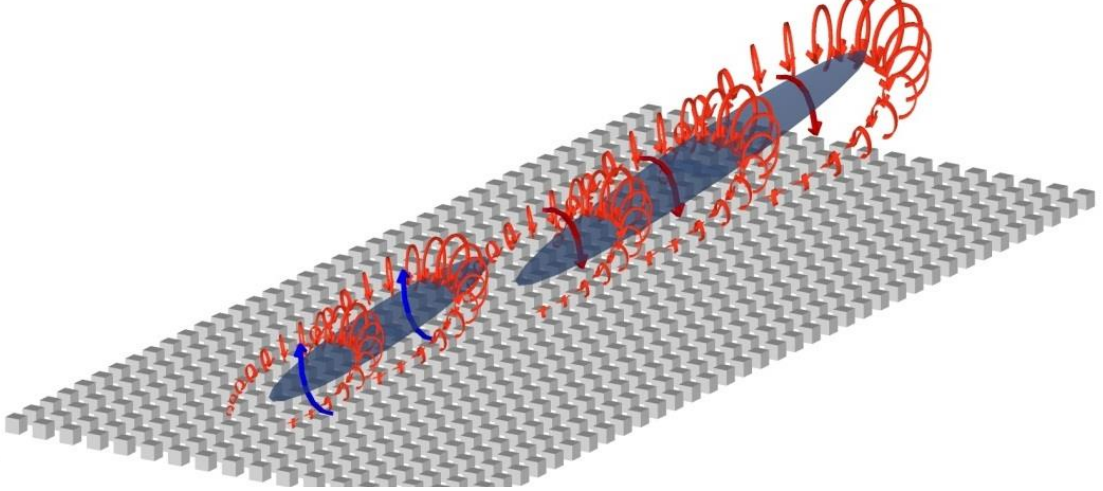
Sea breeze



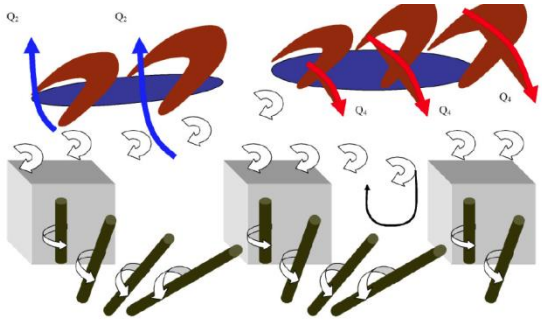


Thermals, plumes and puffs

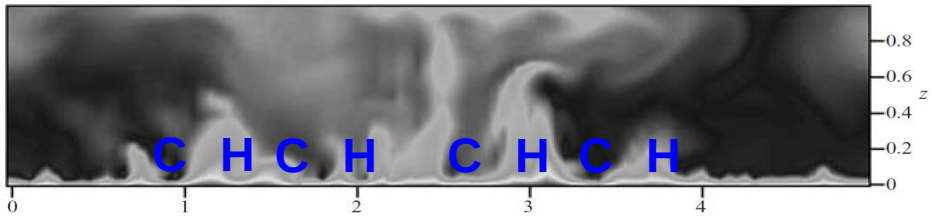
Large scale coherent structure is responsible for surface layer transport



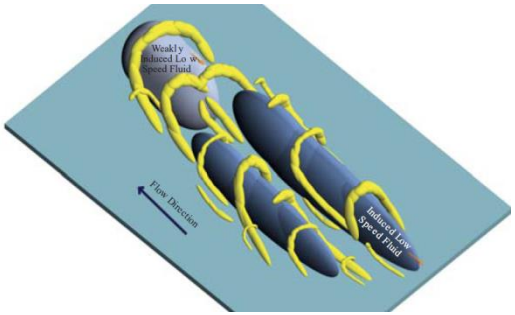
Drawn based on Coceal et al, *Int J Climatol* 27: 1943–1953 (2007) and Tomkins and Adrian, *J Fluid Mech* 490:37-74 (2003)



Coceal et al, *Int J Climatol* 27: 1943–1953 (2007)



Hunt et al *J Fluid Mech* 491 (2003)



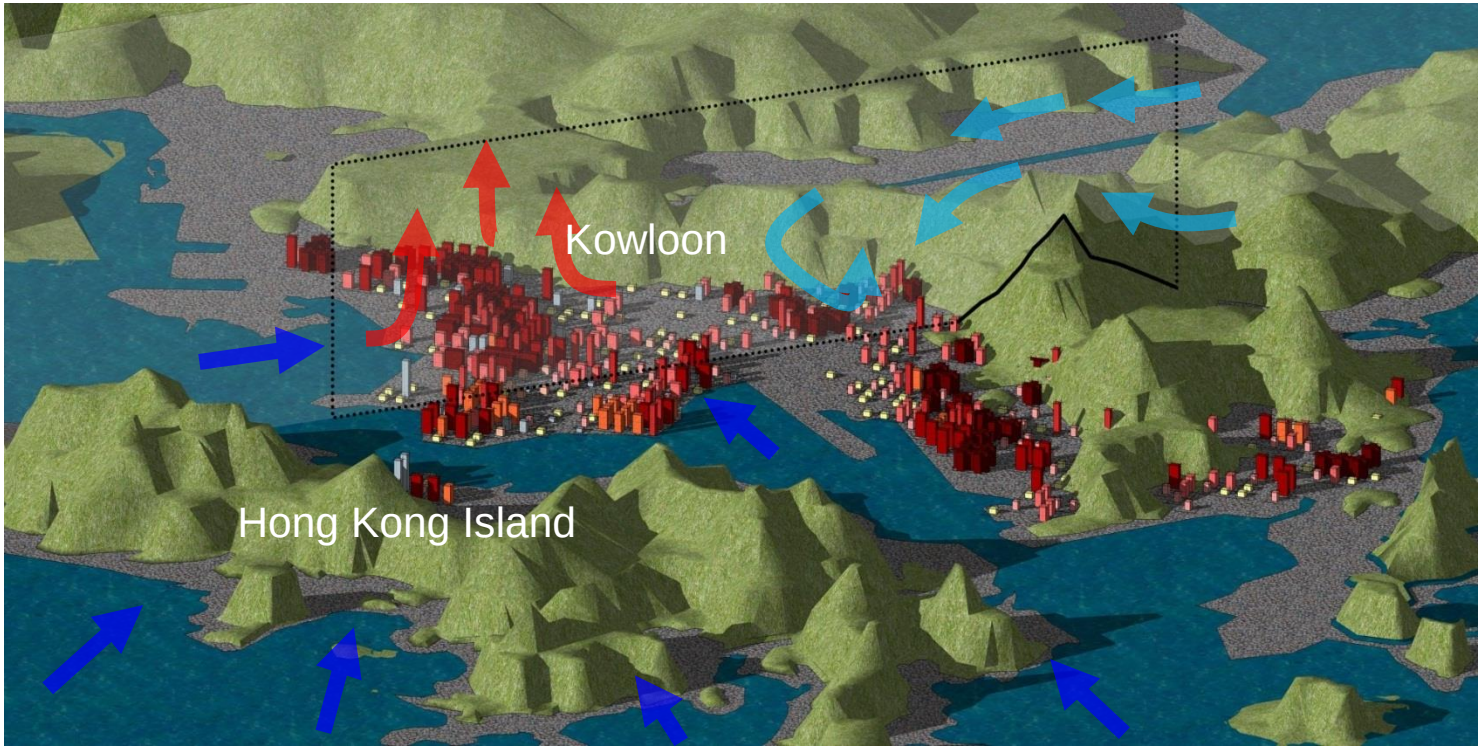
Scale growth model by vortex merging

Tomkins and Adrian, *J Fluid Mech* 490:37-74 (2003)

Zilitinkevich, Hunt et al *Q J R Meterorol Soc* 132 (2006)

Extreme horizontal and vertical spatial variability in Hong Kong

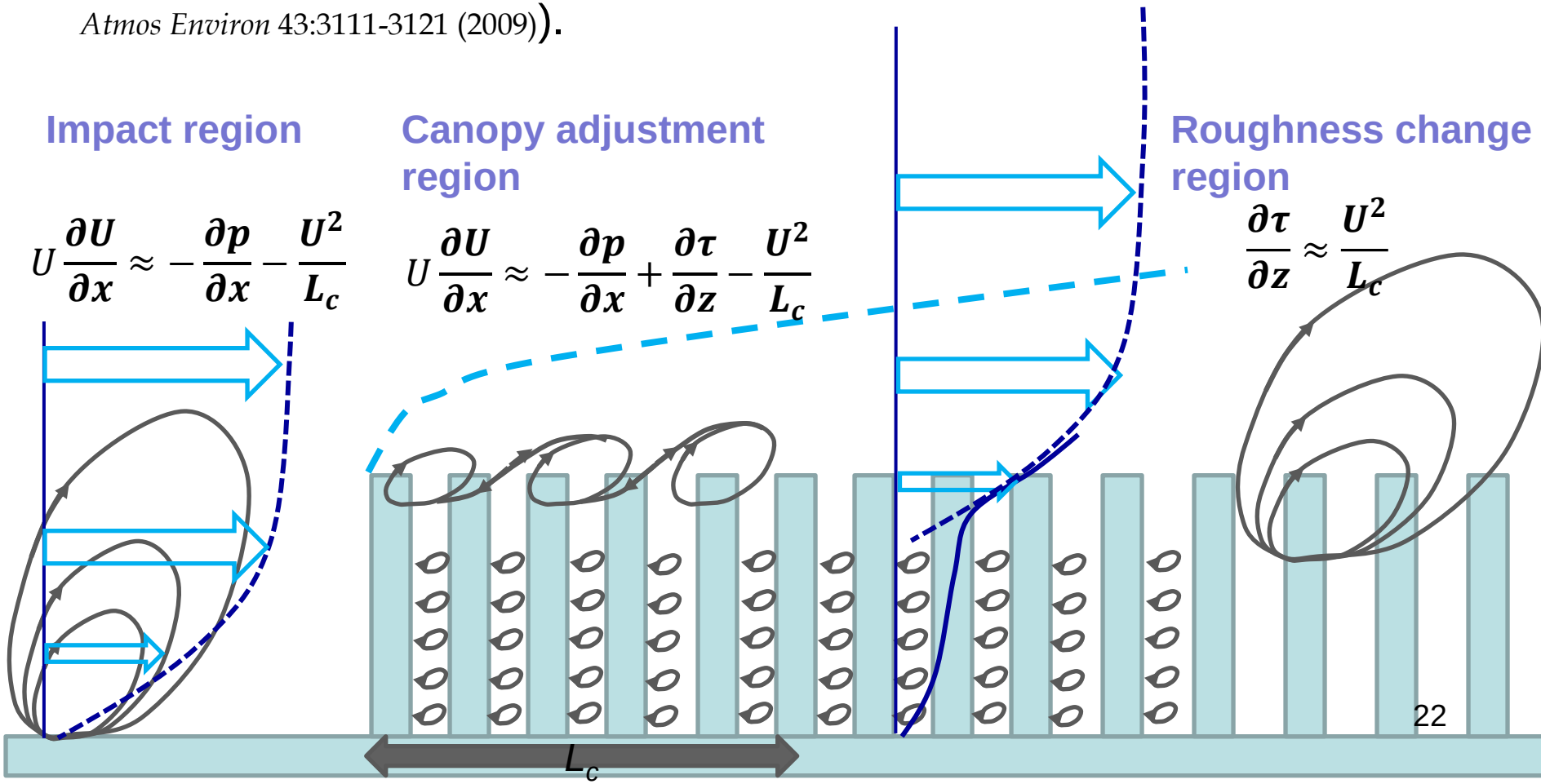
Viewed from Kowloon



Viewed from Hong Kong Island

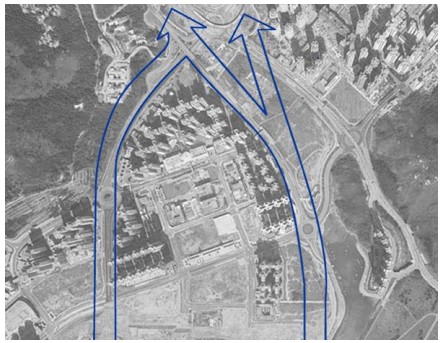
Two characteristics in high-rise compact cities

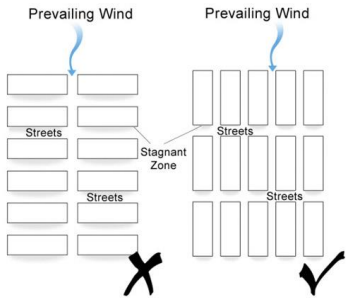
- Wind cannot penetrate into a high-rise compact city due to the large canopy drag (Belcher, Jerram and Hunt, *J Fluid Mech* 488:369-398 (2003)).
- The buoyancy driven flows along building walls (wall slope flows) become dominant due to building heights and large wall areas (Yang & Li, *Atmos Environ* 43:3111-3121 (2009)).

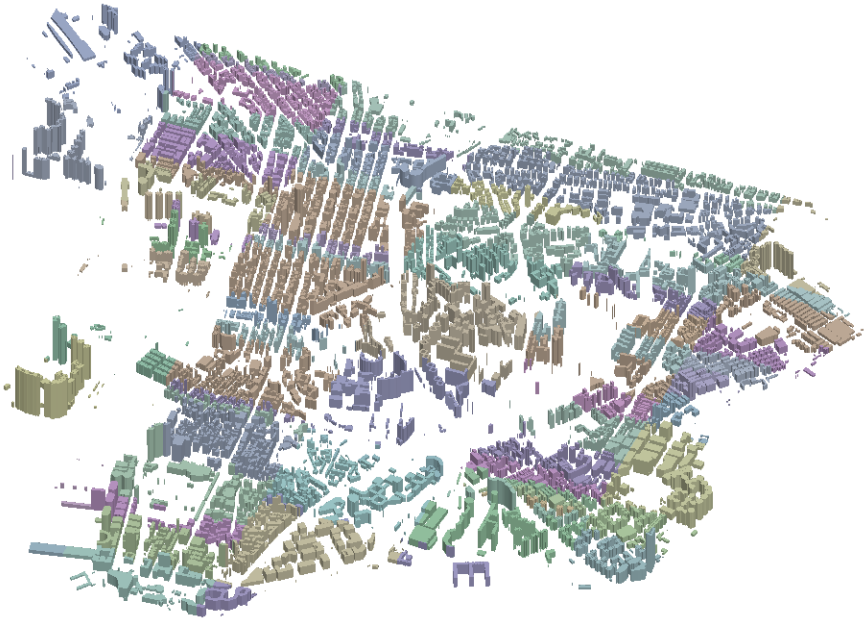


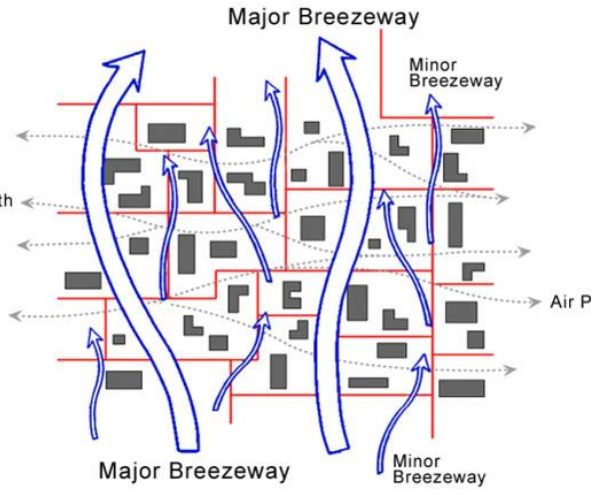
Do ventilation corridors work?

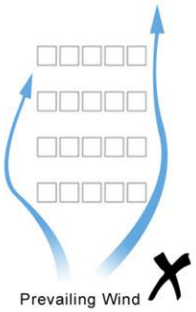
Figure 35 : Major Breezeways

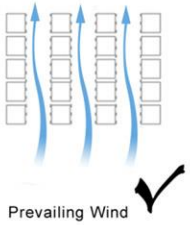


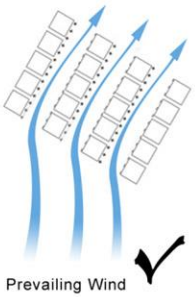






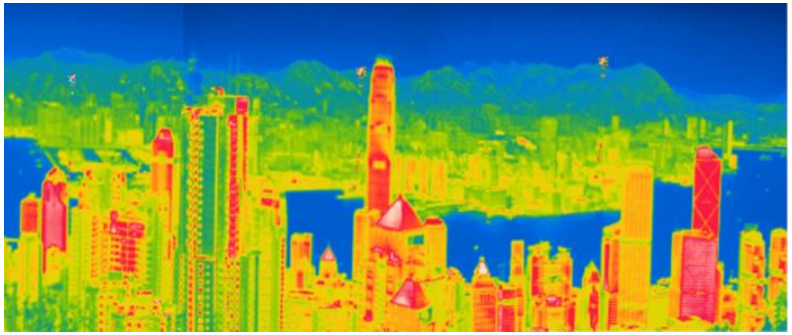




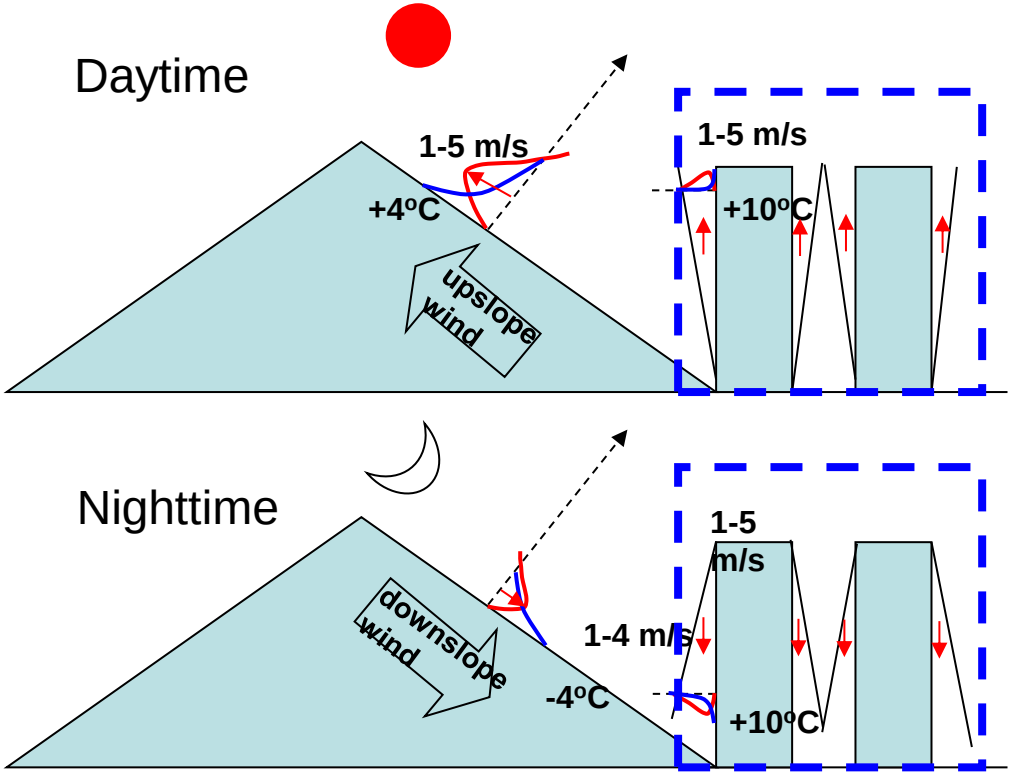


HK Urban design guidelines

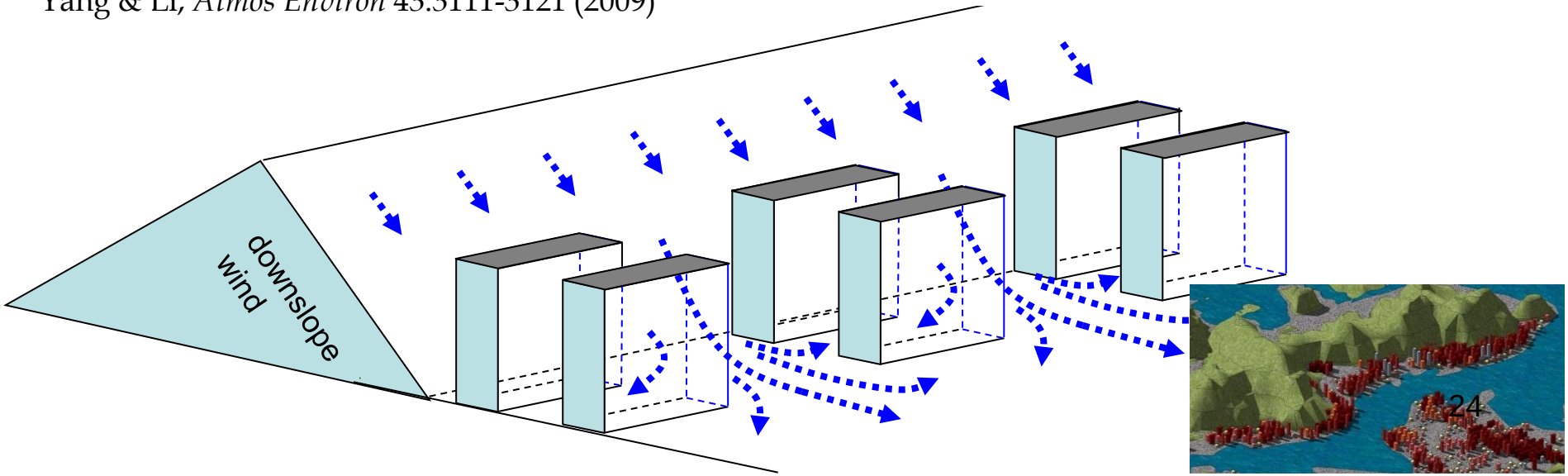
Slope winds along northern shore of Hong Kong Island

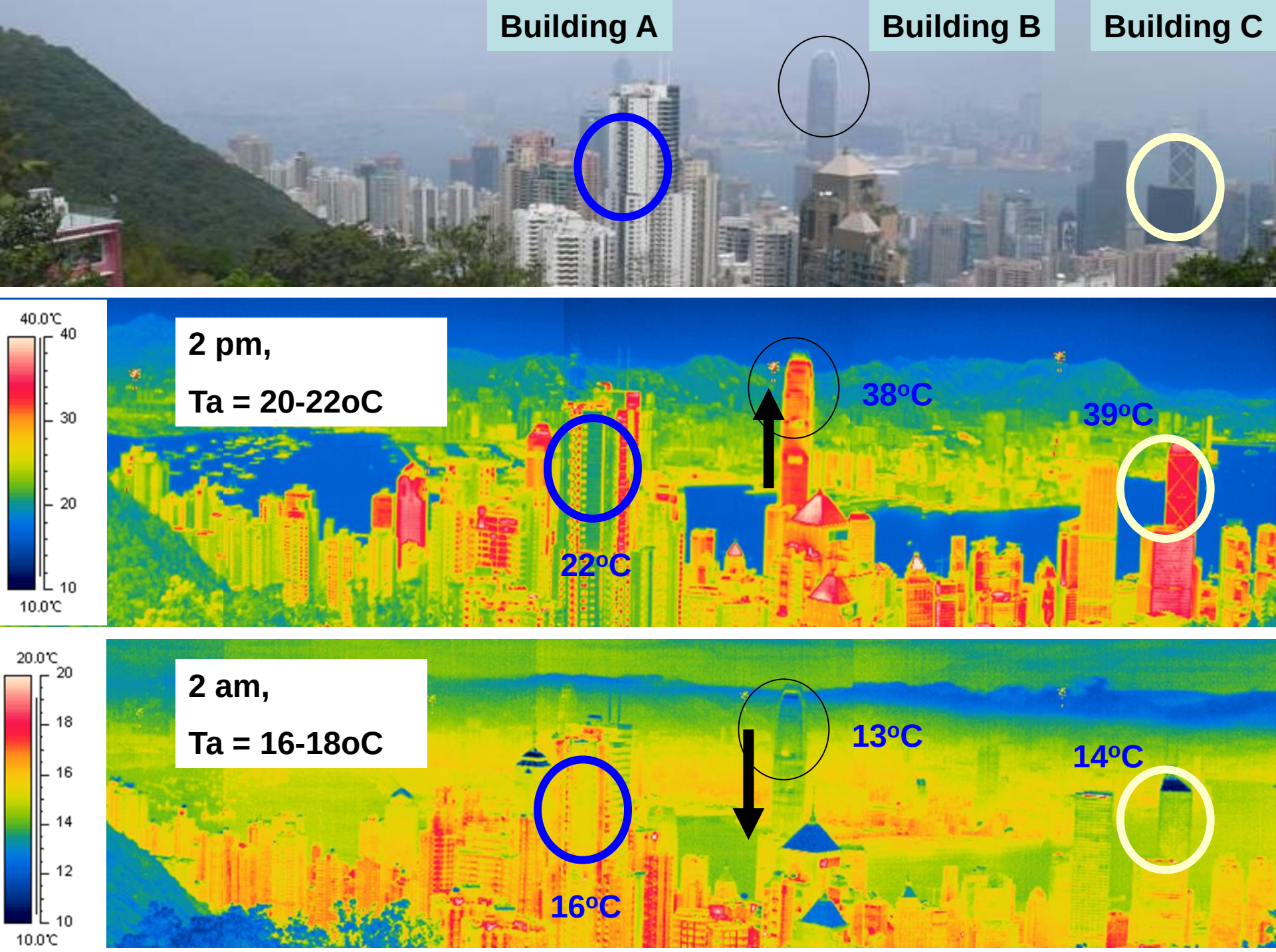


Yang & Li, *Atmos Environ* 43:3111-3121 (2009)

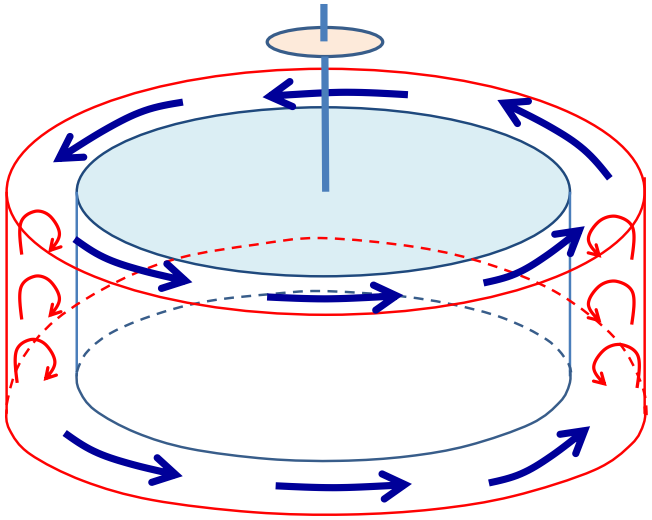


Luo & Li, *Atmos Environ* 45:5946-5956 (2011)

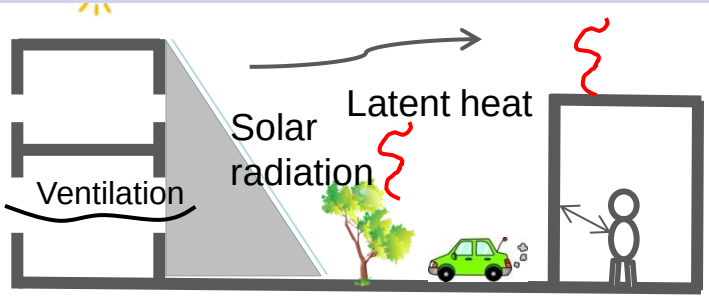



Building A
Building B
Building C
40.0℃
40
30
20
10
10.0℃
2 pm,
Ta = 20-22oC
38ºC
39ºC
22ºC
20.0℃
20
18
16
14
12
10
10.0℃
2 am,
Ta = 16-18oC
13ºC
14ºC
16ºC

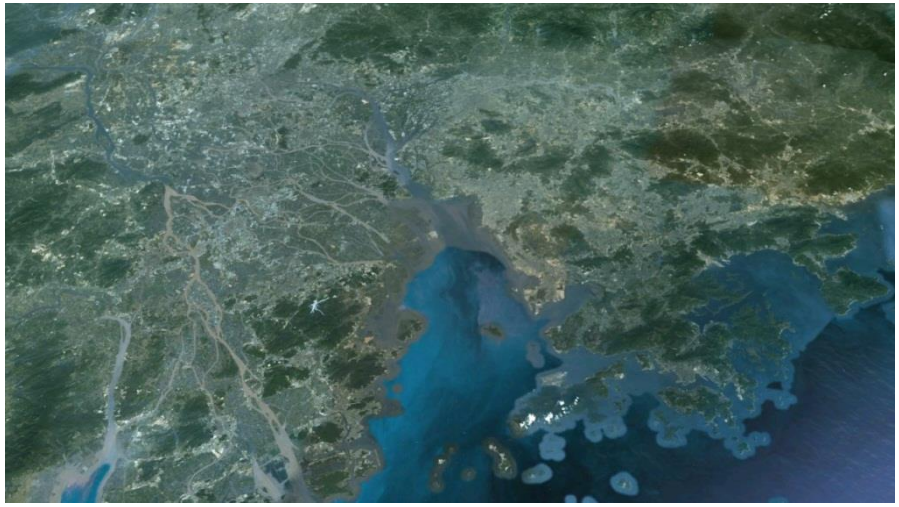
Rotating water annulus



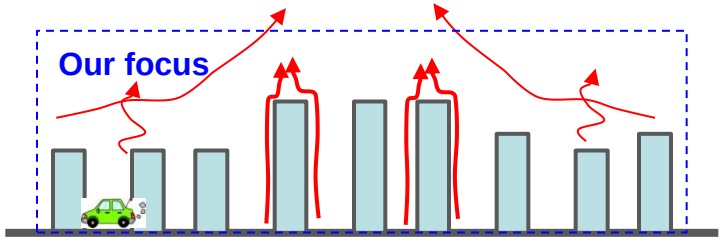
Wind dynamics in HK urban canopy layer is a multi-scale phenomenon.



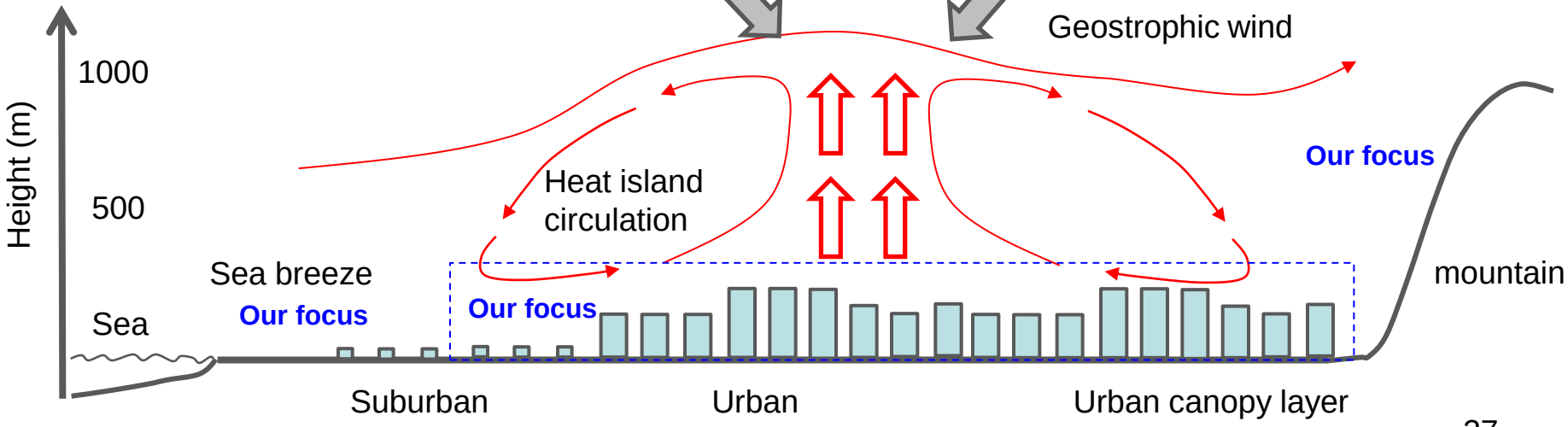
Micro-scale (~10-100 m)



Regional meso-scale (~ 100-1000 km)



Local scale (~100-1000 m)



City meso-scale (~50-100 km)

Concluding remarks

- Man-made structures impact more on daily urban air temperature cycles than the annual cycles
- Thermal storage affects the amplitude and phase shift, but less the mean temperatures
- City ventilation affects the entire daily temperature cycles, but systematic studies are rare
- Understanding the daily cycle change is the key to understanding urban warming
- Further work is needed – despair on a number of issues

HKU Urban Climate Team

Our team

Dr Hang Jian, PhD 2005-09, post-doc, 2009-2012
Dr Lina Yang, PhD 2005-09, post-doc, 2009-2010
Dr Yang Shuai, post-doc, 2010-2012
Dr Xie Min, post-doc, 2010-2012
Luo Zhiwen, PhD 2006-2010, post-doc 2010-
Yang Xinyan, PhD, 2009-
Edward Tsui, Mphil, 2005-09, PhD 2009-
Xiaoxue Wang, PhD, 2010-
Wang Kai, PhD, 2012-
Yin Shi, PhD, 2011-

Our collaborators

Mats Sandberg, Sweden
Julian Hunt, HKU DVSS Professor
Bill Nazaroff, US Berkeley
Janet Nichol, PolyU Geography
TW NG, Hong Kong Planning Department
PW Chan, Hong Kong Observatory

Funding

RGC 2007 Cityvent, HK$1m
HKU UDF 2008, HK$2m (21m)
HKU UDF 2009, HK$1m (10m)
RGC CRF 2013, HK$5m