City ventilation and Urban Warming

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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/m²), greater solar heat trapped, heat storage, reduced wind flow, urban heat and pollutant island.
Getting warmer and warmer

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

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

Reduced wind leads to
- urban warming (2-3°C),
- poor air quality,
- poor visibility,
- heat stress in summer,
- reduced productivity (May benefit cities in cold climate)

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

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

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

$y = 0.0004x - 0.2058$
$R^2 = 0.835$

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 60s in major cities in US (left) and Easten Asia (right)

(B) Phase change from 50s to 90s for major cities in US (left) and Eastern Asia (right)
Global, regional or local?

When local scale matters, when large scale matters?
A simple model?

\[ T_i(\omega t) = \tilde{T}_o + T_E + \sqrt{\frac{\lambda^2 + \omega^2 \tau^2}{\lambda^2 + \omega^2 \tau^2(1 + \lambda)^2}} \Delta \tilde{T}_o \sin(\omega t - \beta) \]
A ideal solution for urban air temperature

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

\[ T_B = \frac{E}{\rho C_p q} \]

\[ \tau = \frac{MC_M}{\rho C_p q} \]

\[ \lambda = \frac{h_M A_M}{\rho C_p q} \]

\[ \gamma \approx 1 + f_w \]

Mean temp  Amplitude  Phase shift

Temp rise  Thermal mass  Total heat transfer number

Time constant
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

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

Wind blow

Ground

No wind

5°C

20°C

Ground
Meso-scale

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

In Hong Kong, the buildings and hill are similarly high

Local scale

\[- \frac{\partial}{\partial z} \langle u'w' \rangle - \frac{\partial}{\partial z} \langle \tilde{u}\tilde{w} \rangle\]

Inertial sublayer

\[- \frac{\partial}{\partial z} \langle u'w' \rangle - \frac{\partial}{\partial z} \langle \tilde{u}\tilde{w} \rangle\]

Surface layer

Coherent structures

Roughness sublayer

small scale associated with surface shear

Urban canopy layer

Modified from Oke, 1997

\[- \frac{\partial}{\partial z} \langle u'w' \rangle - \frac{\partial}{\partial z} \langle \tilde{u}\tilde{w} \rangle + D\]

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


Wind over a hill


Slope flow


Slope flow merging

Sea breeze

Valley flow

Thermals, plumes and puffs
Large scale coherent structure is responsible for surface layer transport


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)
2 pm,
Ta = 20-22°C

2 am,
Ta = 16-18°C
Rotating water annulus
Wind dynamics in HK urban canopy layer is a multi-scale phenomenon.

Micro-scale (~10-100 m)

Local scale (~100-1000 m)

Regional meso-scale (~ 100-1000 km)

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

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