Urban regional precipitation simulations - comparison of pseudo-global-warming with local forcing

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Local Measurements

Rainfall observations
(HK, Singapore)
  Heavy rainfall ↑
trend(urban) ≠ trend(rural)
  urban increase > rural increase

Lightning frequency London > countryside (Mossman, 1898)

Question: Why
METROMEX (Huff and Changnon, 1972 and 1973):
  Downstream effects in St. Louis ≈ 60km downstream

Hypothesis 1)
  Air pollution
  Aerosols and nucleation

Hypothesis 2)
  Human activity and buildings
  Dynamics and thermodynamics

Hypothesis 3)
  Climate Change

Holst et al., 2016

Wong et al., 2010
Concepts

Oke (1988):
- AH in Hong Kong >1k W/m²
- AH in Sydney ≈ 80 W/m²

Oke (1987):
- UBL downstream of city, “plume”

“The highest individual grid cell heat fluxes in urban areas were located in New York (577 Wm⁻²), Paris (261.5 Wm⁻²), Tokyo (178 Wm⁻²), San Francisco (173.6 Wm⁻²), Vancouver (119 Wm⁻²) and London (106.7 Wm⁻²).” from Allen et al., 2011
Experiments

“Hindcast” parametric studies of monsoon trough

Human Activities:
Anthropogenic heat (AH) (Holst et al., 2016)

Land surface changes:
Urban spatial extent (Holst et al., 2017)

Large scale forcing:
Moisture background state
Total rainfall on 24-May-2017 (based on raingauges and radar data)
## Model Setup

<table>
<thead>
<tr>
<th>Simulation</th>
<th>00 GMT July 5 2008</th>
<th>00 GMT July 9 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>WRF model version 3.5.1</td>
<td></td>
</tr>
<tr>
<td><strong>Domains</strong></td>
<td>25x25 km²</td>
<td>5x5 km²</td>
</tr>
<tr>
<td><strong>Grids</strong></td>
<td>310x200x51</td>
<td>151x91x51</td>
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<tr>
<td><strong>Cumulus</strong></td>
<td>New simplified Arakawa-Schubert scheme (NSAS)</td>
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<tr>
<td><strong>PBL</strong></td>
<td>Bougeault-Lacarerre (BouLac) [modified]</td>
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<tr>
<td><strong>Cloud microphysics</strong></td>
<td>WRF Single Moment 6 class scheme (WSM6)</td>
<td></td>
</tr>
<tr>
<td><strong>Radiative transfer</strong></td>
<td>Rapid Radiative Transfer Model for global simulations (RRTMG)</td>
<td></td>
</tr>
<tr>
<td><strong>Land surface</strong></td>
<td>Unified NOAH land surface model (unified NOAH LSM)</td>
<td></td>
</tr>
<tr>
<td><strong>Urban physics</strong></td>
<td>Single layer urban canopy model (UCM)</td>
<td></td>
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<tr>
<td><strong>Forcing data</strong></td>
<td>NCEP final reanalysis (FNL) (FDDA &gt; 1400x1200 km²)</td>
<td></td>
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</tbody>
</table>
Human activity effects

Surface sensible heat flux

\[ S = S_{LSM} + \psi(t) \times AH \]

Constant = 0, 50, 100, 250, 500, 1000 Wm\(^{-2}\)

True value probably:
250 Wm\(^{-2}\) < AH < 500 Wm\(^{-2}\)

Compared to LUCY simulations of PolyU#:
300 Wm\(^{-2}\) < AH < 450 Wm\(^{-2}\)

# Poster on display in HK Science Museum, 2014

Oke, 1988

Chose simplest available urban representation

Numerical Experiment
Drastic urbanisation effects

171 km²

9200 km²
Large scale forcing effects

Change moisture by ± 10%
Compare effect to AH effect:
“Climate change” against local forcing

Clausius Clapeyron ratio

\[
\frac{d e_s}{e_s} = \frac{L_v}{R_v T^2} \approx \frac{2.5 \times 10^6 \times 1}{461 \times 300^2} \approx 6\%
\]

± 10% Q ≈ ±1.66K
Snapshots
Human Activity

Heavier, urban rainfall is affected more than weaker rainfall

Effects noticeable for $AH > 100 \text{ Wm}^{-2}$

Due to convection behaviour

\[
\text{Rif} = \frac{\beta w'\theta'}{\frac{\partial u}{\partial z} w'u' + \frac{\partial v}{\partial z} w'v'}
\]

\[
\sigma_t(R_{f_{PBL}}(x,y,t))(x,y) = \sigma_t \left( \frac{1}{H} \int_0^H \text{Rif}(x,y,z,t)dz \right)
\]
Urbanisation

If urban area is small, the AH effect reverses (METROMEX)

Less energy release
Less buoyancy

Convection not triggered locally
Advection $\gg$ Convection

Holst et al., 2017
Urban spatial extent impact on stability
AH vs. global forcing

Cloud water mixing ratio and PR1 statistics show:
AH effect robust in different moisture regimes

In dryer simulation:
AH effect propagation out of the urban area (advection effect)
Refer to METROMEX

Holst and Chan, under preparation for Climate Dynamics
Atmospheric stability

Dry simulations more unstable near sfc and less unstable above 1500m
Regarding urban heat...

Near sfc:
- SH more important
- Dry simulation warmer
- Urban-rural difference larger

Above LCL:
- LH more important
- Wet simulation warmer
Effects on advection is intricate
Message to take away

Urban environments may affect their local and regional precipitation microclimate significantly, under certain conditions.

Factors:
- City size
- Human activity density
- Climatic background conditions
- Geographic setting
- More...

What we should* do:

Demonstrate the relationship between human activities and local micro-climate (attribution).

Design sufficiently simple experiments, that are conceptually accessible to non-experts and yet provide transferrable insights to scientists.

* (but nobody likes the implications)

“While small cities may not modify their precipitation microclimate significantly, megacities seem to do so; highlighting the importance of choosing the right neighborhood.” – C. C. Holst 2015

Black boxes:
- Droplet drag (downdrafts, micro interface-layers)
- Scaling behaviour/non-local scale interactions
- Coupling: particles (incl. sources) ⊗ precipitation
Thank you for paying attention.

References


APPENDIX 1) Bougeault and Lacarerre 1989: TKE

• Simplification

“1.5 order” closure
Therry and Lacarerre 1983

\[
\frac{\partial \bar{e}}{\partial t} + \frac{\partial}{\partial x_k} \left( \bar{u}_k \bar{e} + \bar{u}'_k \bar{e}' - \nu \frac{\partial \bar{e}}{\partial x_k} + \frac{1}{\rho} \bar{u}'_k \bar{p}' \right) = -\bar{u}_k' \bar{u}_i \frac{\partial \bar{u}_i}{\partial x_k} + \frac{g}{\theta} \bar{u}_i \bar{\theta}' - \nu \left( \frac{\partial \bar{u}_i}{\partial x_k} \right)
\]

\[
\frac{\partial e}{\partial t} = -U \frac{\partial e}{\partial X} - \frac{\partial e}{\partial \sigma} - \frac{1}{\rho} \frac{\partial}{\partial Z} \rho w'e'
\]

Meso-beta scale formulation
Bougeault and Lacarerre 1989

\[
\frac{\partial e}{\partial t} = -u'_w \frac{\partial U}{\partial Z} - v'_w \frac{\partial V}{\partial Z} + \beta w' \theta' - \epsilon,
\]

Derived from Navier-Stokes
(General form)

\[
\gamma_{ce} = \text{counter gradient correction (Deardorff 1972)}
\]

Einstein summation convention for \( u, i = 1, 2, 3 \)

• Parameterization

Choose a scheme that does take into account:
Buoyancy and shear generation, advection and dissipation of TKE

\[
\begin{align*}
\kappa_K &= \text{characteristic eddy length scale} \\
\ell &= \text{characteristic dispersion length scale} \\
\alpha_e &= \text{inverse Prandtl number}
\end{align*}
\]
APPENDIX 1a) Length Scales

Stratification: Buoyancy limits to atmospheric motion (upwards, downwards):

\[
\int_Z^{Z+l_{up}} \beta(\theta(Z) - \theta(Z'))dZ' = e(Z),
\]
\[
\int_Z^{Z-l_{down}} \beta(\theta(Z') - \theta(Z))dZ' = e(Z),
\]

Possible advection distance of parcel with layer-average TKE (Buoyant limit)

Length scales should be somewhat in the range of these lengths

Choose:

\[ l_K = \min(l_{up}, l_{down}) \]
\[ l_e = (l_{up}l_{down})^{1/2} \]

Eddies: near walls; smaller length scale limiting the motion

Dissipation: geometric mean (controversial)

Proportional to buoyancy length scale related to stratification

\[ l_B = e^{1/2}\left(\beta \frac{\partial \theta}{\partial Z}\right)^{-1/2} \]
APPENDIX 1b) Two stationary mountain wave simulations from Bougeault and Lacarrere 1989

Bougeault and Lacarrere’s scheme:
Produces reasonable topography wakes
(Related to Shear or Mechanical Production of TKE)
APPENDIX 2) Accumulated (simulation-mean) precipitation

- 0 Wm$^{-2}$: Transition: Urban convection
- 50 Wm$^{-2}$: Increase downstream/upstream
- 100 Wm$^{-2}$: Increase downstream/upstream
- 250 Wm$^{-2}$: Urban convection prominent
- 500 Wm$^{-2}$: Urban convection dominant
- 1 kWm$^{-2}$: Urban convection dominant
APPENDIX 2a) Snapshot comparison

0 Wm$^{-2}$

Intensification $66 \rightarrow 107$

Intensification $235 \rightarrow 324$

Relocation $116 \rightarrow 204$

rural $\rightarrow$ urban

500 Wm$^{-2}$
APPENDIX 3) Explanation slide

\[
\text{Rif} = \frac{\beta w' \theta'}{\frac{\partial \tilde{u} w' u'}{\partial z} + \frac{\partial \tilde{v} w' v'}{\partial z}}
\]

The (bulk) Richardson flux number

Ratio of TKE production terms
Buoyancy flux / shear flux

Transition between stable/unstable conditions in the atmosphere

Related to convection

Application: Take standard deviation \(\sigma\) in time of Rif (within the PBL)

Larger \(\sigma\)-values: More shifts between convective and non-convective states

Related to “activity” of convection
APPENDIX 3a) Convection

\[ \beta w' \theta' \]

\[ \frac{\partial \bar{u} w'u'}{\partial z} + \frac{\partial \bar{v} w'v'}{\partial z} \]

\[ \text{Rif} = \frac{\beta w' \theta'}{\frac{\partial \bar{u} w'u'}{\partial z} + \frac{\partial \bar{v} w'v'}{\partial z}} \]

No systematic difference buoyancy flux

No systematic difference shear flux

Urban fluctuation↑ for AH ↑

Plots of \( \frac{\hat{\alpha}}{\alpha} \) with

\[ \hat{\alpha} = \sigma_{t,x,y} \left( \alpha_{0 \text{Wm}^{-2}} \right)_{z<H} \]

\[ \tilde{\alpha} = \sigma_{t,x,y} \left( \alpha_{500 \text{Wm}^{-2}} \right)_{z<H} \]