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

Christopher C. Holst

Johnny C. L. Chan

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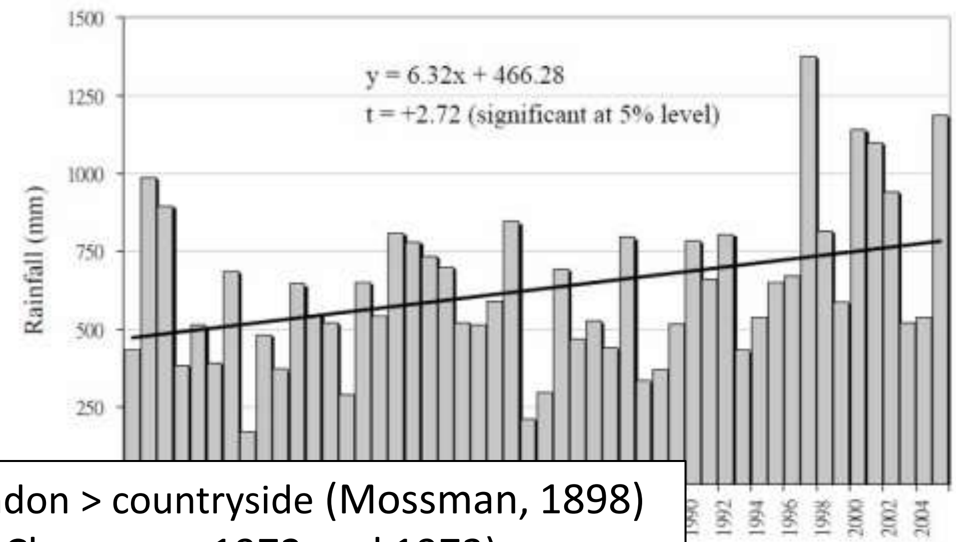
Guy Carpenter Asia-Pacific Climate Impact Centre

City University of Hong Kong

Local Measurements



Vong et al., 2010

Rainfall observations

(HK, Singapore)

- Heavy rainfall ↑
- trend(urban) ≠ trend(rural)
- urban increase > rural increase

Lightning frequency London > countryside (Mossman, 1898)
METROMEX (Huff and Changnon, 1972 and 1973):
Downstream effects in St. Louis ≈ 60km downstream

Question: Why

Hypothesis 1)

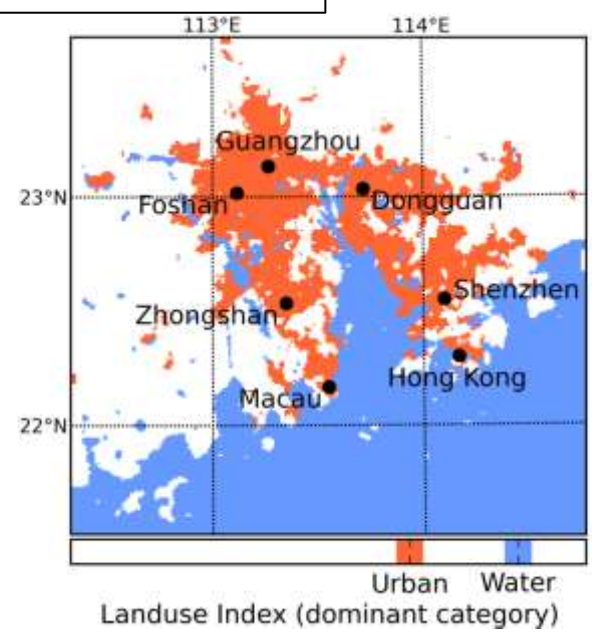
- Air pollution
- Aerosols and nucleation

Hypothesis 2)

- Human activity and buildings
- Dynamics and thermodynamics

Hypothesis 3)

- Climate Change

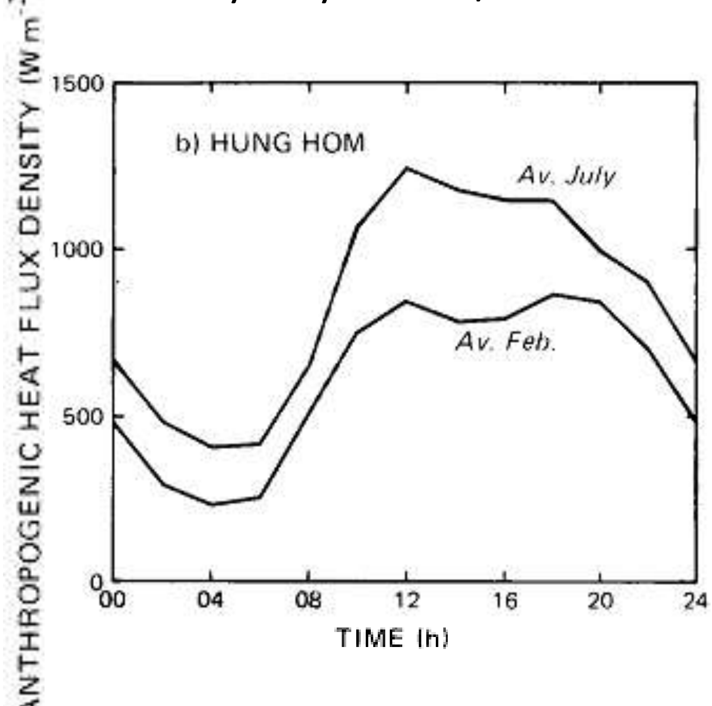


Holst et al., 2016

Concepts

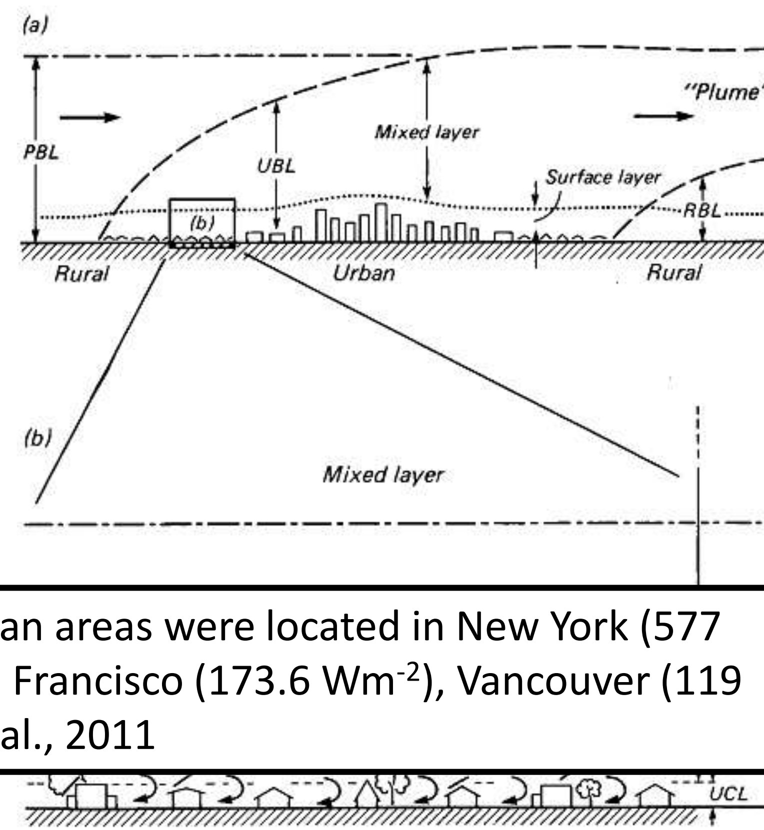
Oke (1988):

- AH in Hong Kong >1k W/m^2
- AH in Sydney ≈ 80 W/m^2



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)

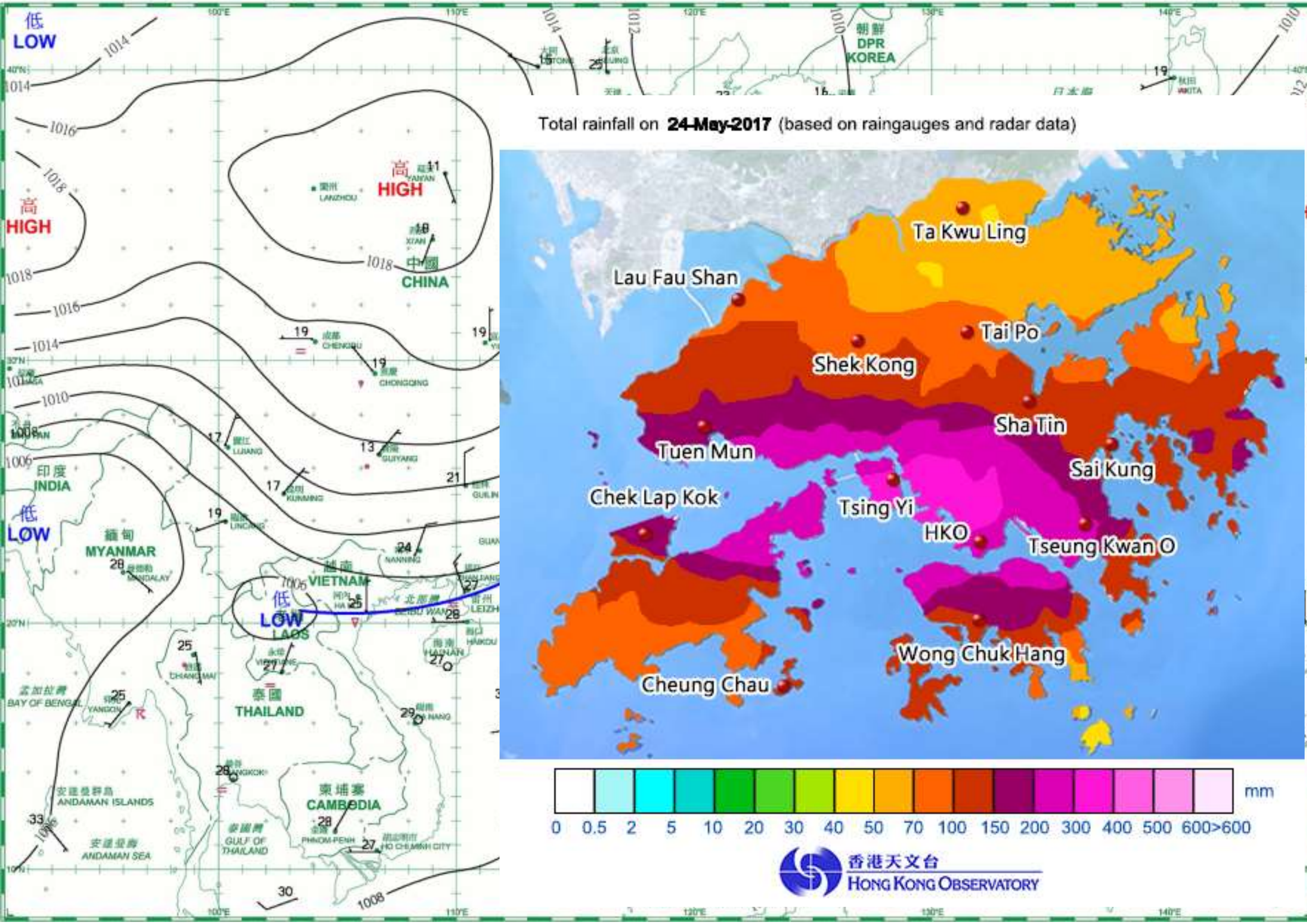
Land surface changes:

Urban spatial extent (Holst et al., 2017)

Large scale forcing:

Moisture background state

日期/Date: 24.05.2017 香港時間/HK Time: 08:00 香港天文台 Hong Kong Observatory

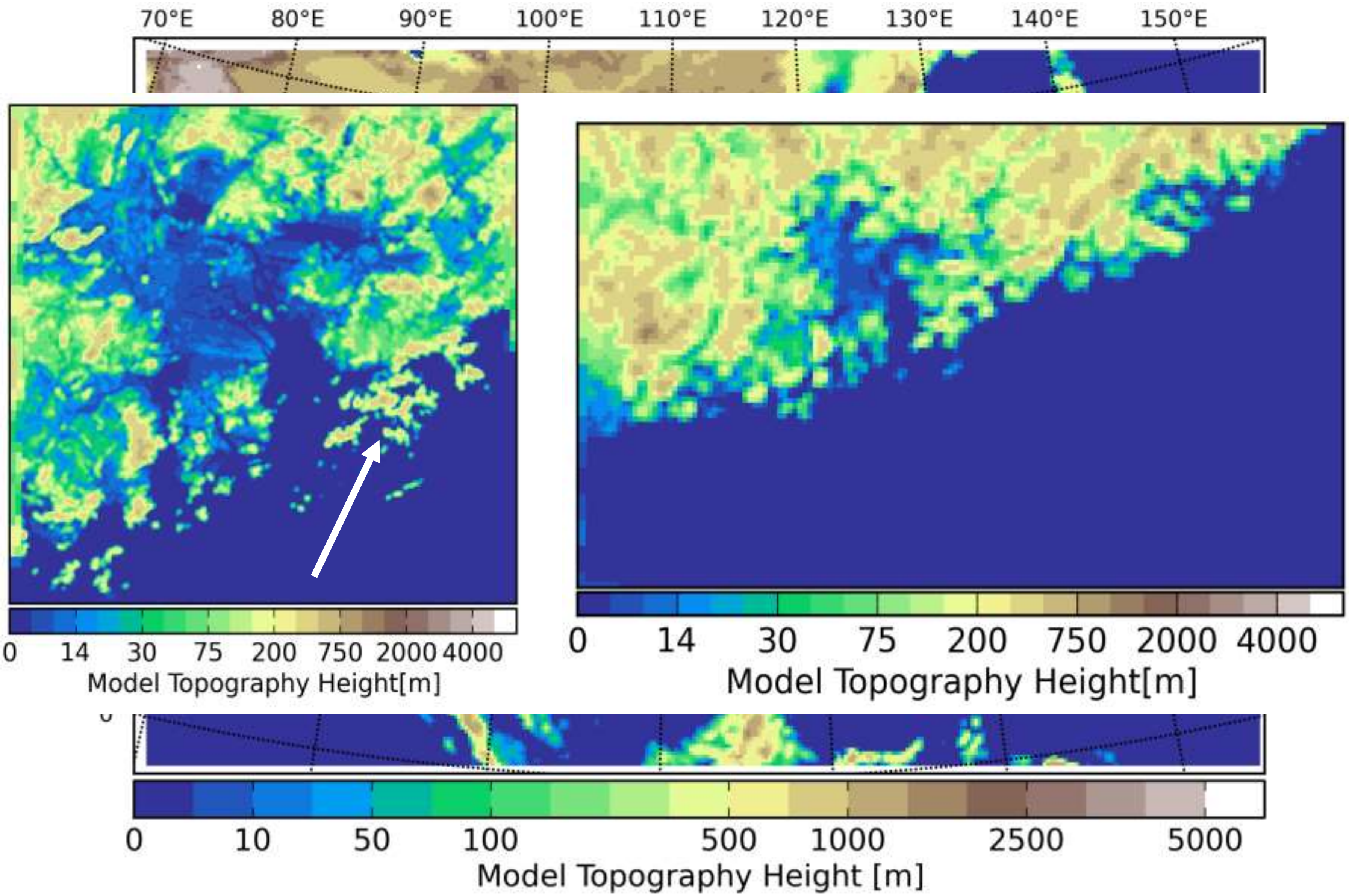


Model Setup

+/- 6h Ensemble

Simulation	00 GMT July 5 2008	00 GMT July 9 2008	
Model	WRF model version 3.5.1		
Domains	25x25 km^2	5x5 km^2	1x1 km^2
Grids	310x200x51	151x91x51	241x231x51
Cumulus	New simplified Arakawa-Schubert scheme (NSAS)		
PBL	Bougeault-Lacarerre (BouLac) [modified]		
Cloud microphysics	WRF Single Moment 6 class scheme (WSM6)		
Radiative transfer	Rapid Radiative Transfer Model for global simulations (RRTMG)		
Land surface	Unified NOAH land surface model (unified NOAH LSM)		
Urban physics		Single layer urban canopy model (UCM)	
Forcing data	NCEP final reanalysis (FNL) (FDDA > 1400×1200 km^2)		

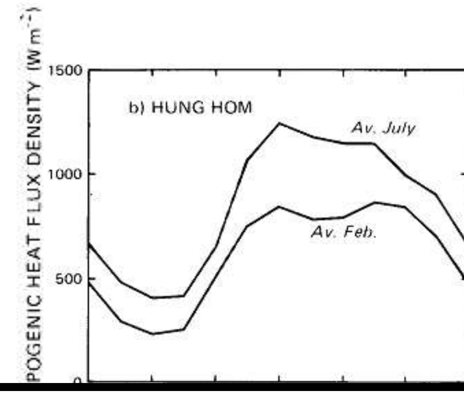
Domain


70°E
80°E
90°E
100°E
110°E
120°E
130°E
140°E
150°E
0
14
30
75
200
750
2000
4000
Model Topography Height[m]
0
14
30
75
200
750
2000
4000
Model Topography Height[m]
0
10
50
100
500
1000
2500
5000
Model Topography Height [m]

Human activity effects

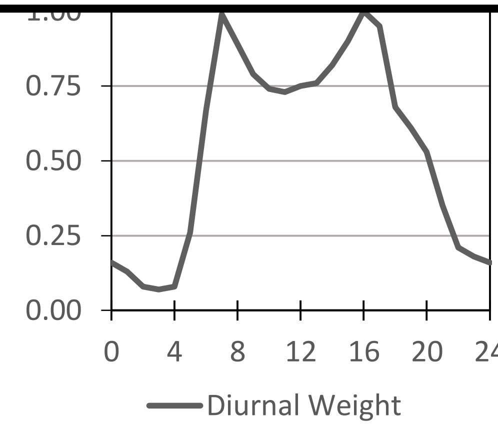
Surface sensible heat flux

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



Oke, 1988

Chose simplest available urban representation



Numerical Experiment

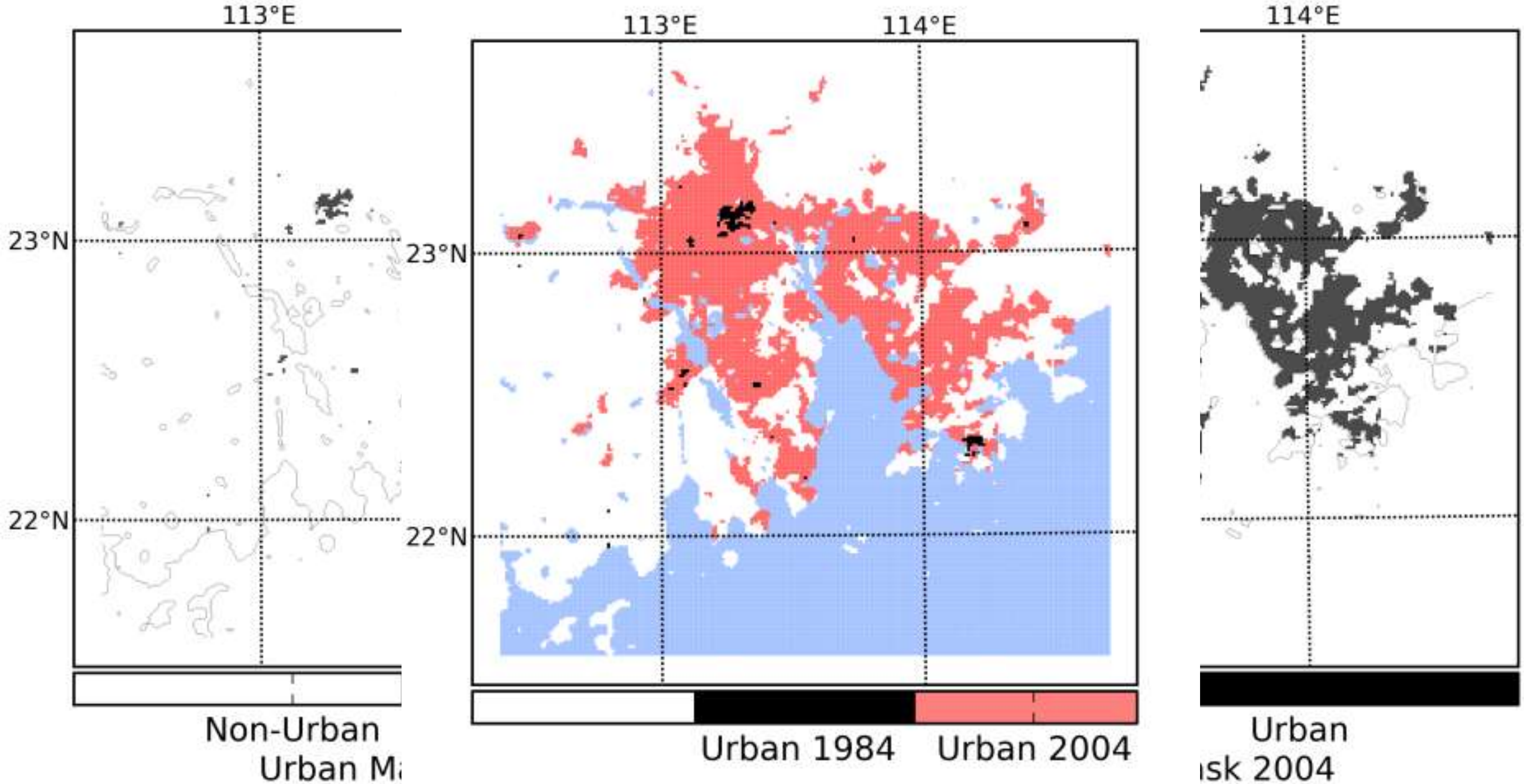
Constant = 0, 50, 100, 250, 500, 1000 Wm^{-2}

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

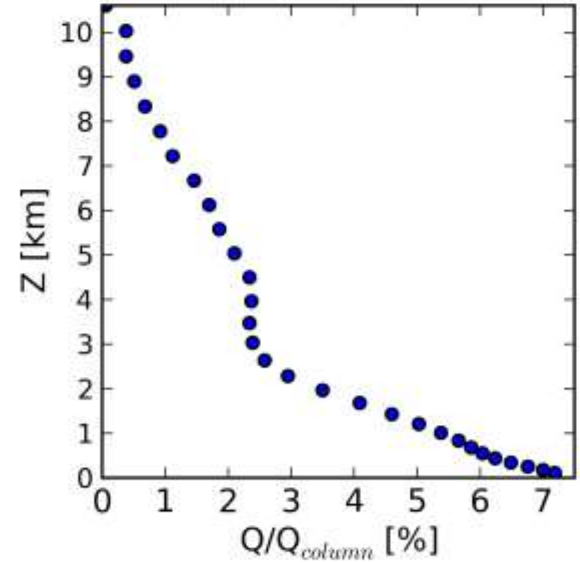
Drastic urbanisation effects



171 km²

9200 km²

Large scale forcing effects



Change moisture by ± 10%

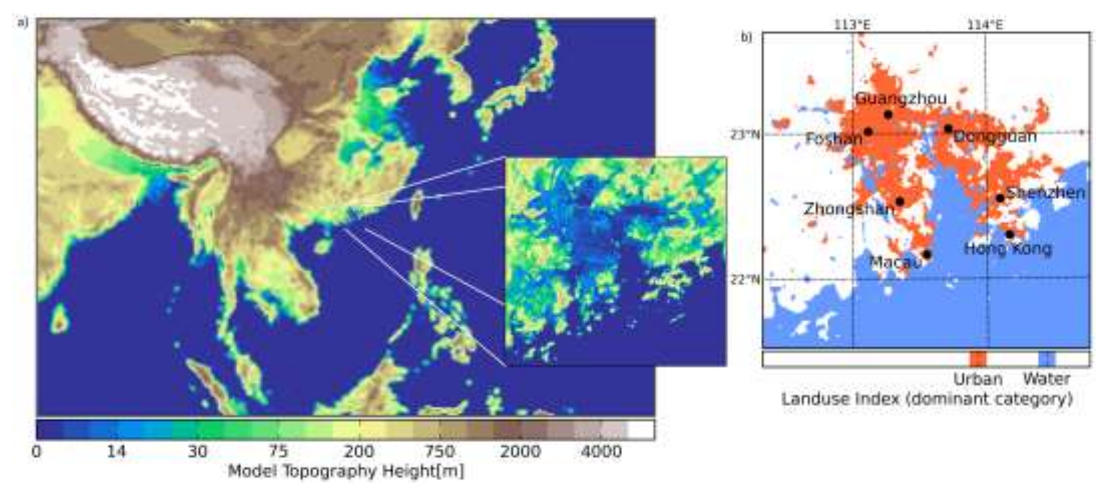
Compare effect to AH effect:

“Climate change” against local forcing

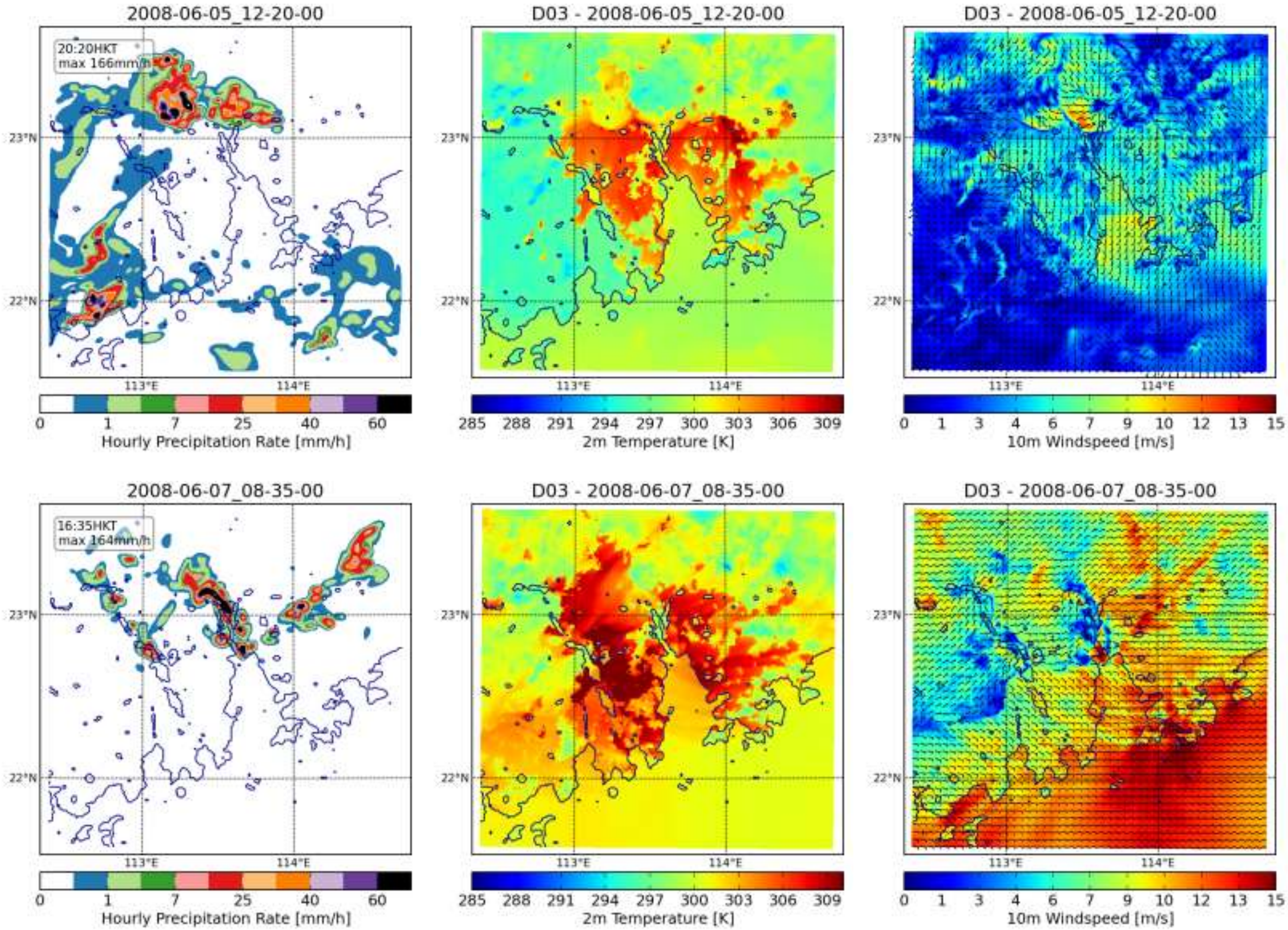
Clausius Clapeyron ratio

$$\frac{de_s}{e_s} = \frac{L_v}{R_v}\frac{dT}{T^2} \approx \frac{2.5 \times 10^6 \times 1}{461 \times 300^2} \approx 6\,\%$$

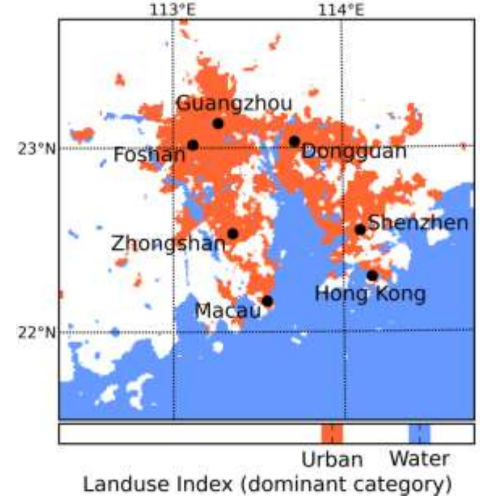
± 10% Q ≈ ±1.66K



Snapshots


2008-06-05_12-20-00
20:20HKT
max 166mm/h
D03 - 2008-06-05_12-20-00
D03 - 2008-06-05_12-20-00
23°N
22°N
113°E
114°E
0 1 7 25 40 60
Hourly Precipitation Rate [mm/h]
285 288 291 294 297 300 303 306 309
2m Temperature [K]
0 1 3 4 6 7 9 10 12 13 15
10m Windspeed [m/s]
2008-06-07_08-35-00
16:35HKT
max 164mm/h
D03 - 2008-06-07_08-35-00
D03 - 2008-06-07_08-35-00

Human Activity



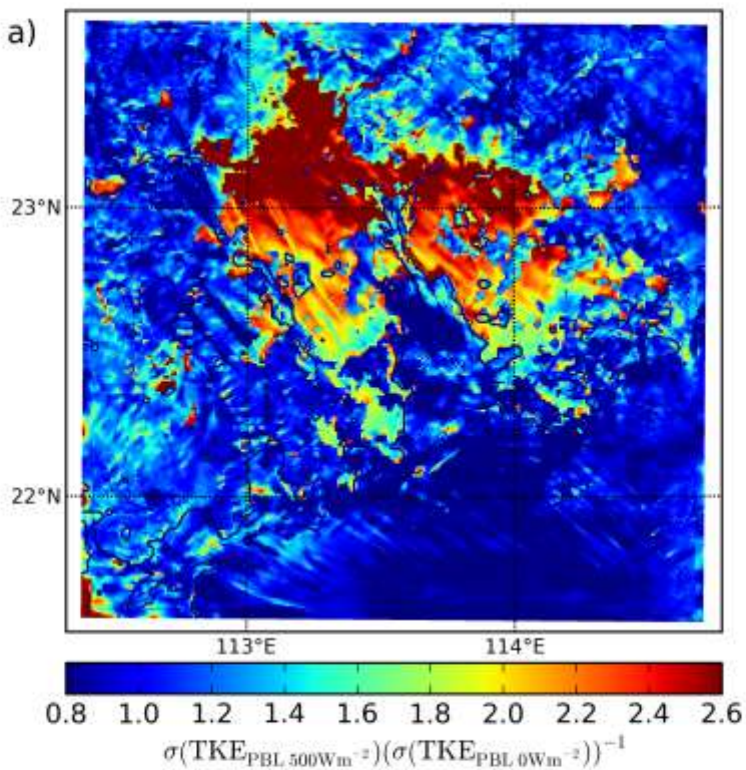
Heavier, urban rainfall is affected more than weaker rainfall

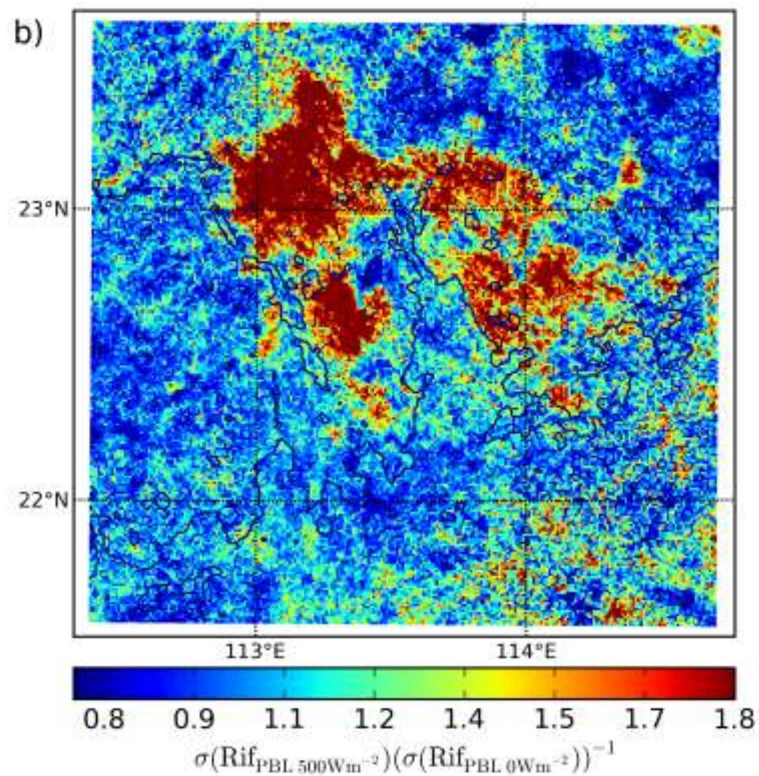
Effects noticeable for AH > 100 Wm^{-2}

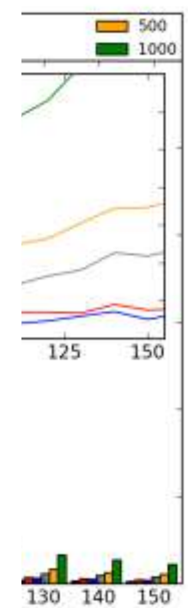
Due to convection behaviour

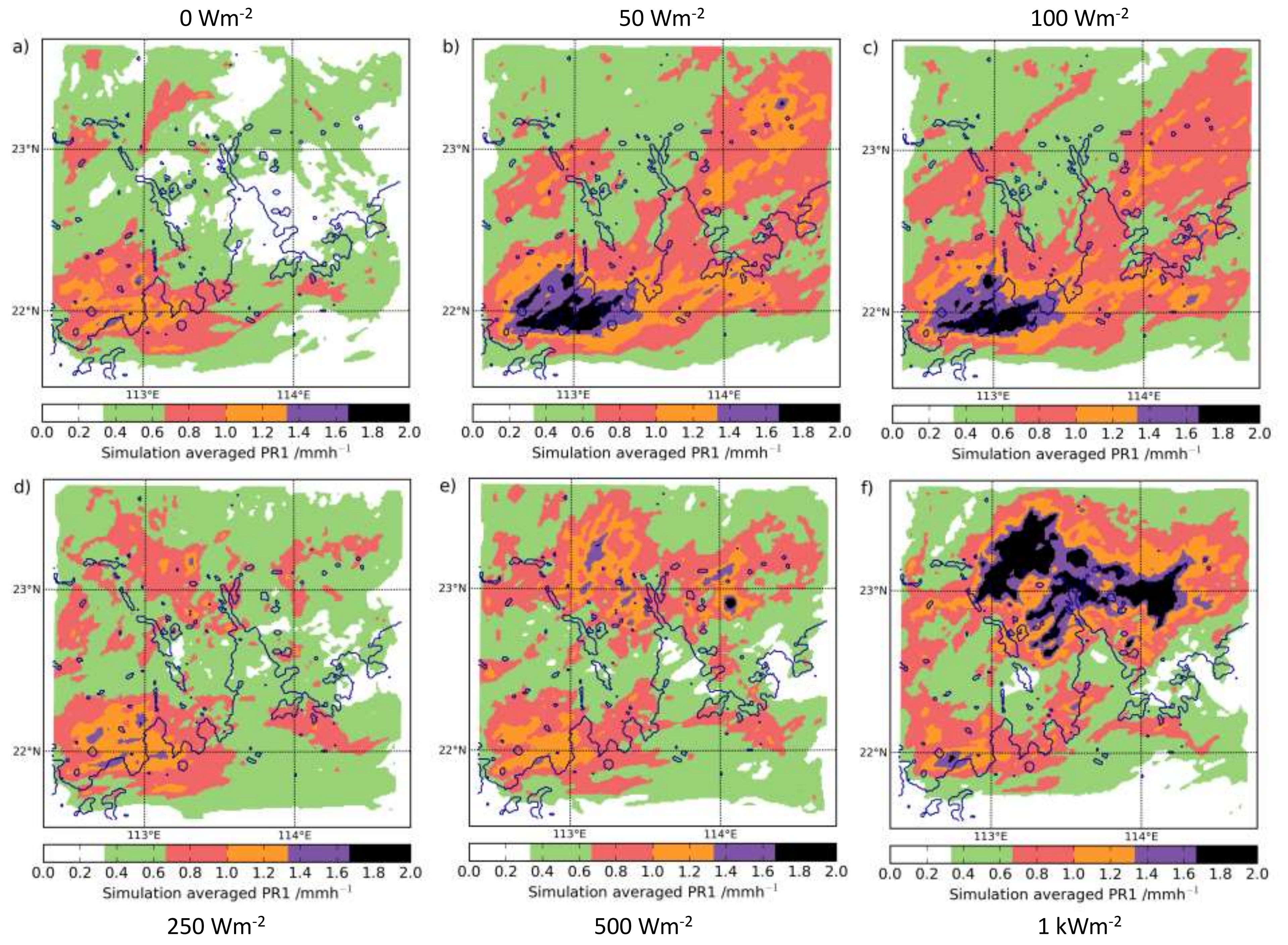
$$\mathrm{Rif} = \frac{\beta \overline{w'\theta'}}{\frac{\partial \overline{u}}{\partial z}\overline{w'u'} + \frac{\partial \overline{v}}{\partial z}\overline{w'v'}}$$

$$\sigma_t(Rif_{PBL}(x,y,t))(x,y) = \sigma_t\left(\frac{1}{H}\int_0^H Rif(x,y,z,t)dz\right)$$







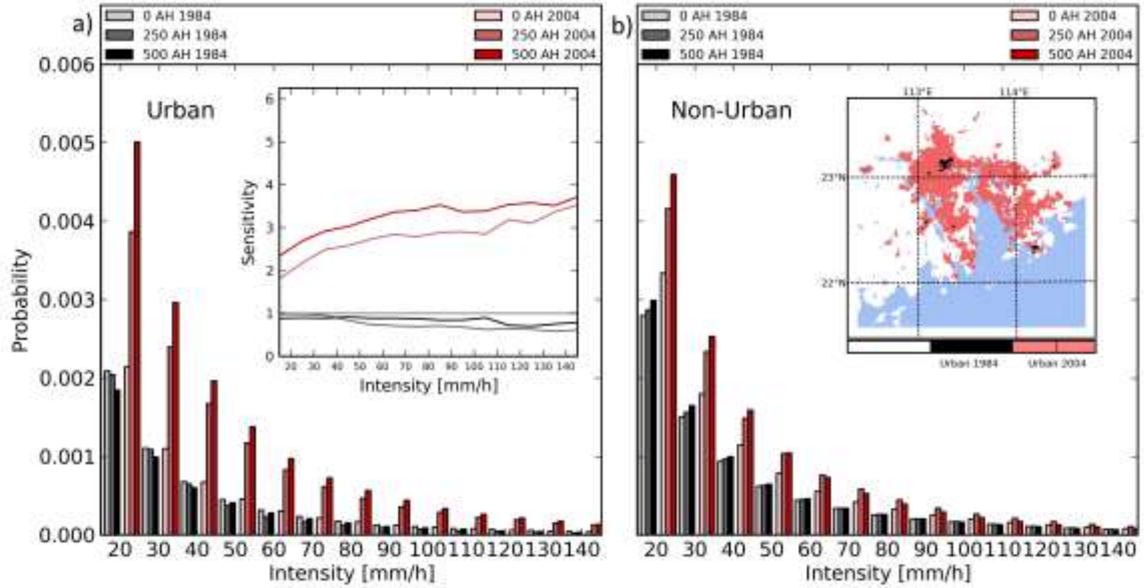


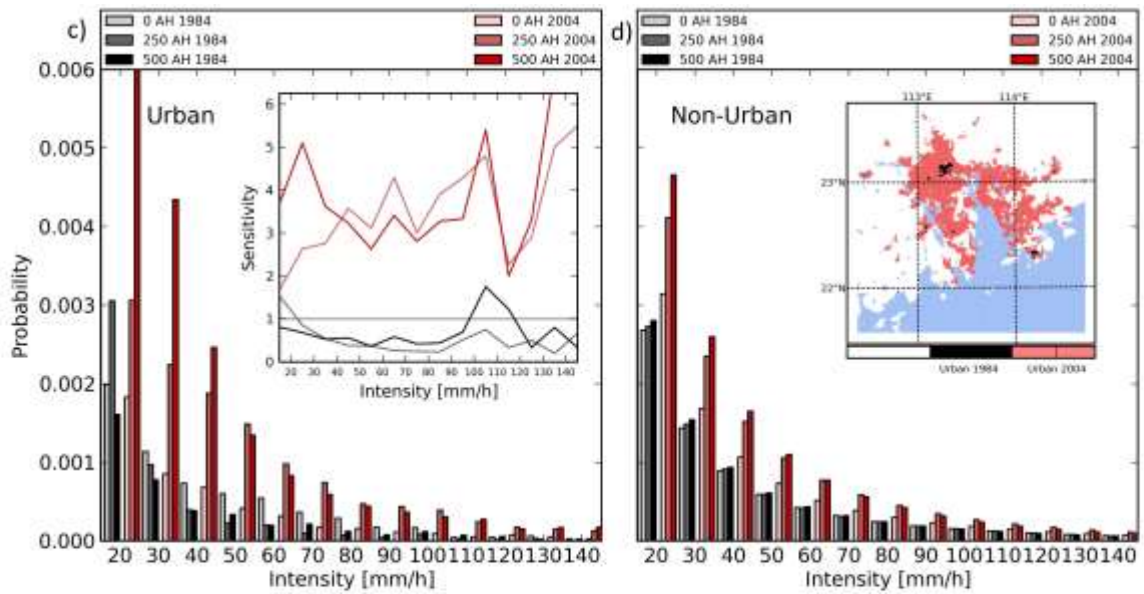
0 Wm-2
50 Wm-2
100 Wm-2
a)
b)
c)
d)
e)
f)
23°N
22°N
113°E
114°E
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Simulation averaged PR1 /mmh-1
250 Wm-2
500 Wm-2
1 kWm-2

Urbanisation

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

Less energy release
Less buoyancy



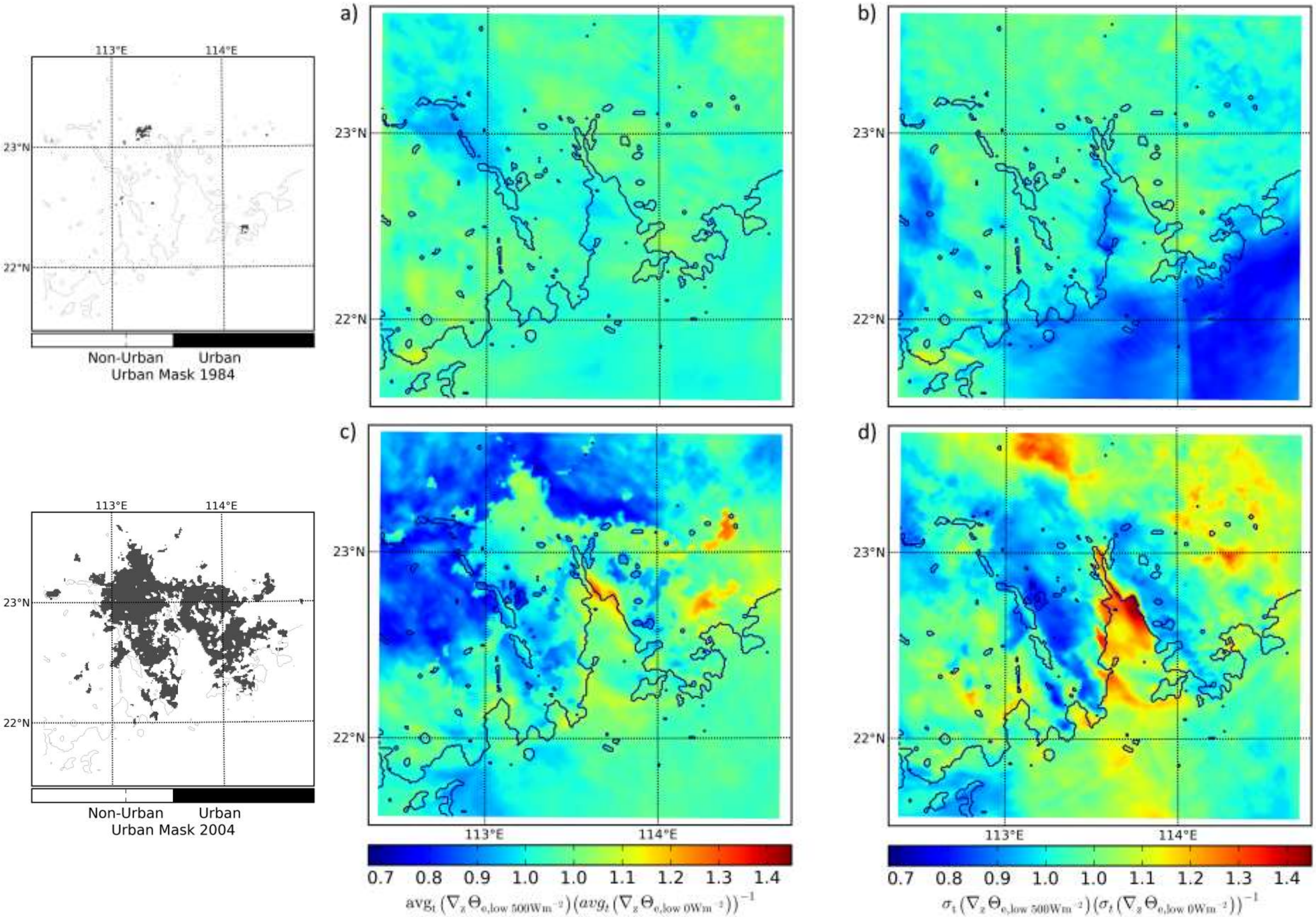


Holst et al., 2017

Convection not triggered locally

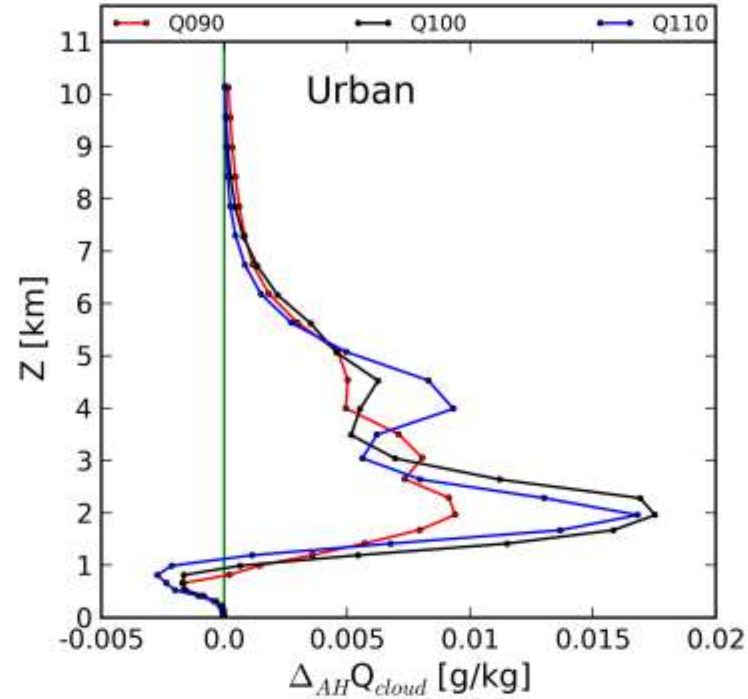
Advection >> Convection

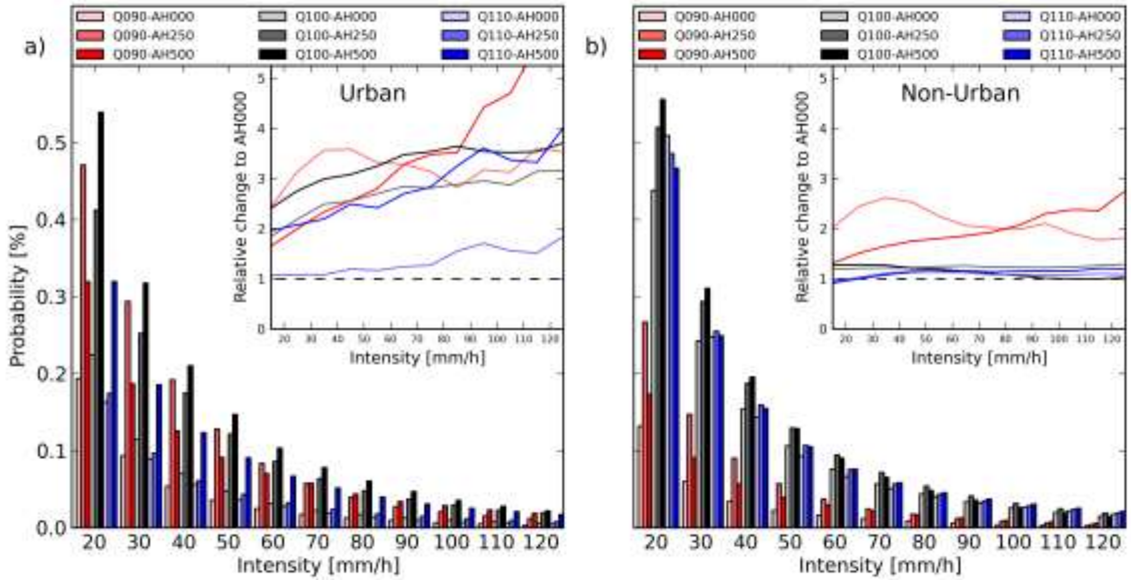
Urban spatial extent impact on stability



AH vs. global forcing

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





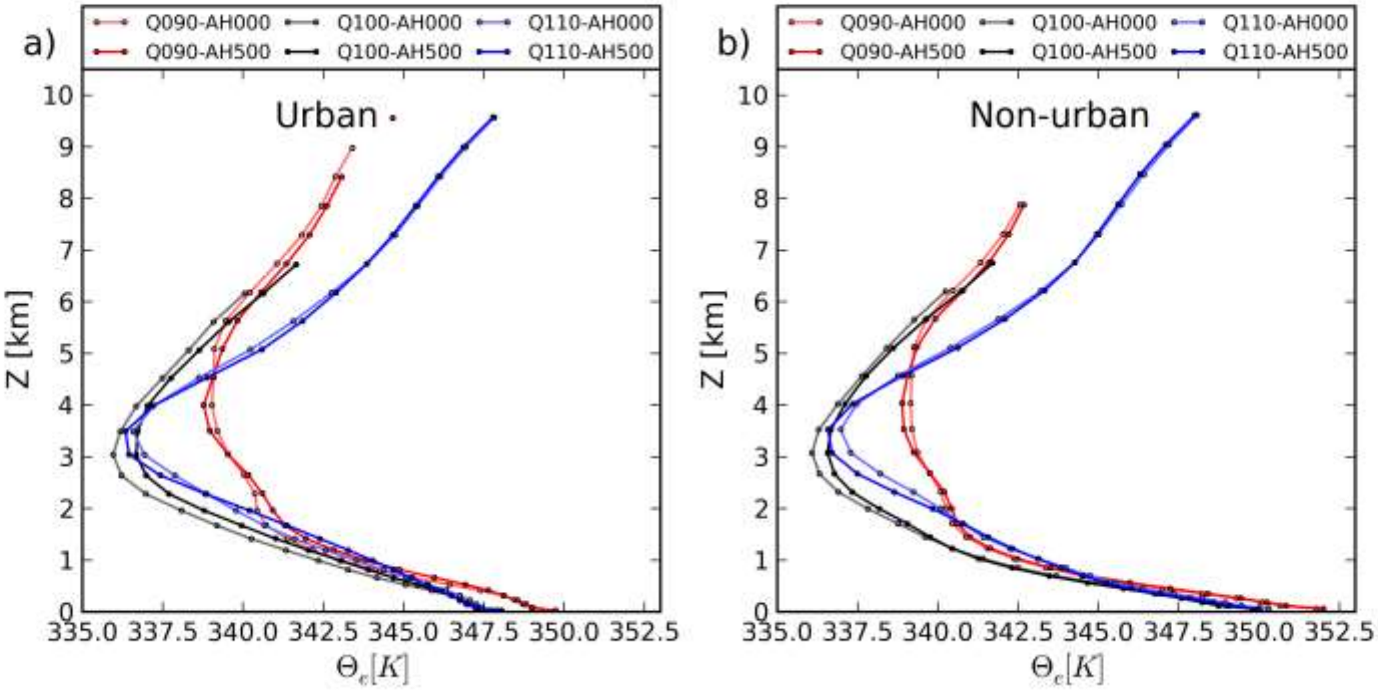
In dryer simulation:

- 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

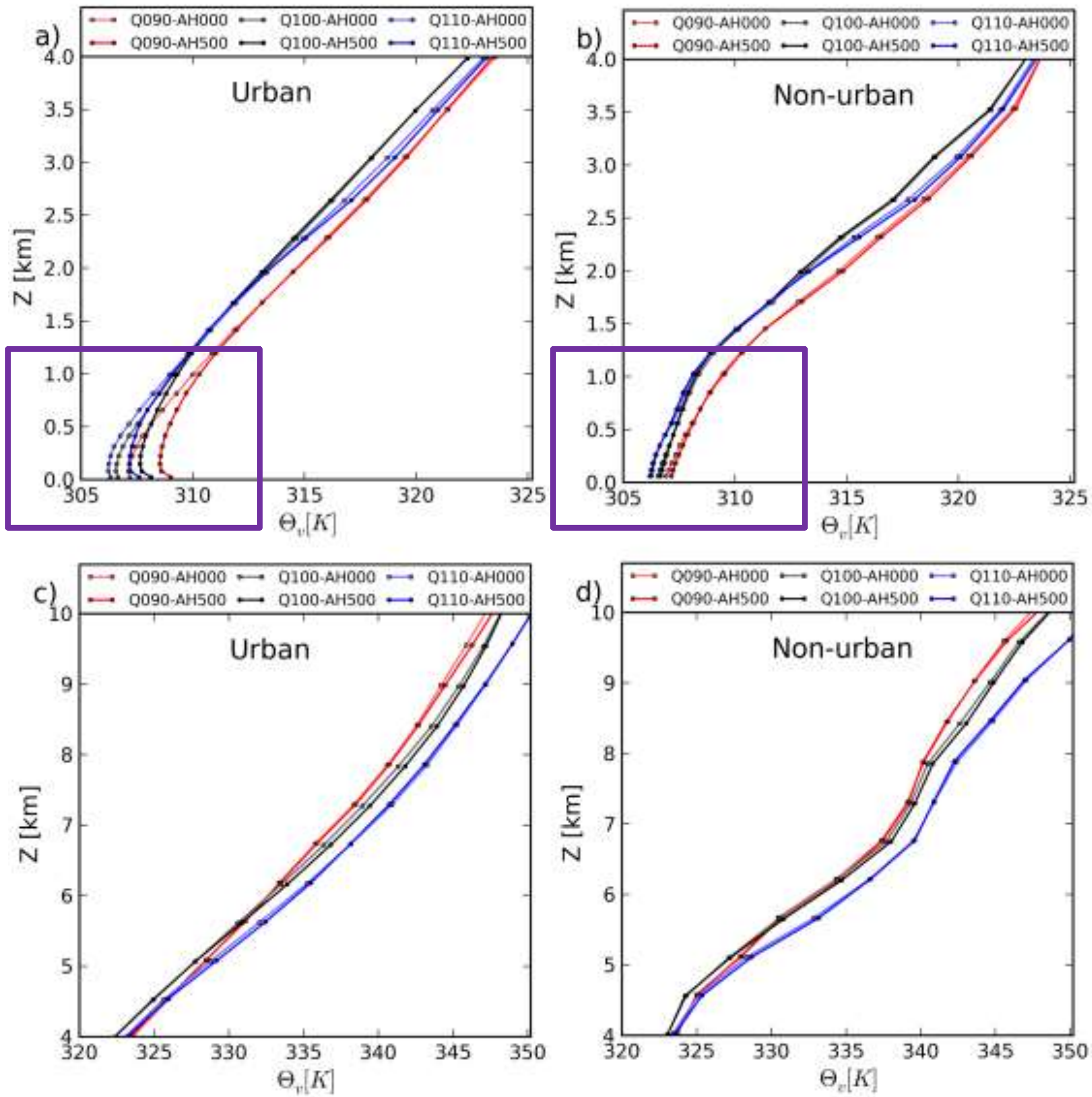


Holst and Chan, under preparation

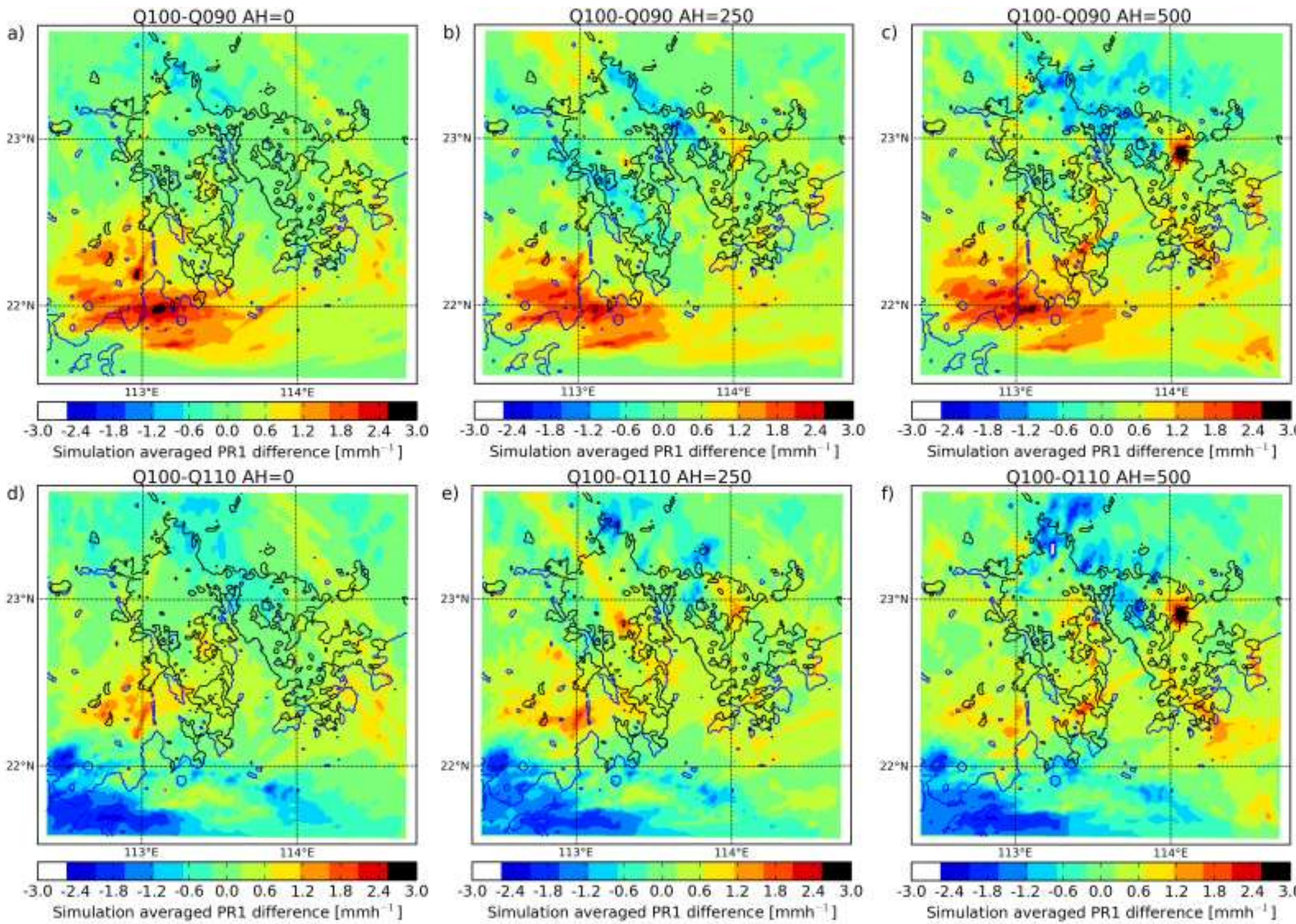
Regarding urban heat…

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

Above LCL:
LH more important
Wet simulation warmer



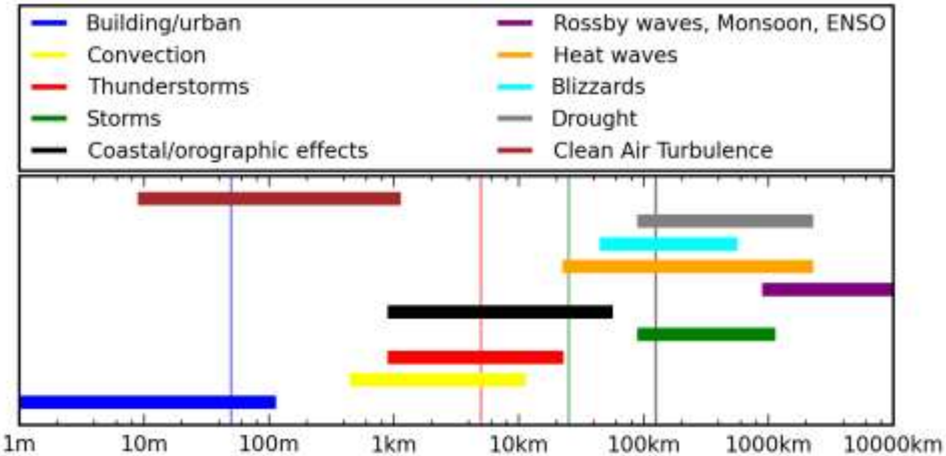
Effects on advection is intricate



Message to take away

"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

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…

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

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)

Thank you for paying attention.

References

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APPENDIX 1) Bougeault and Lacarerre 1989: TKE

- Simplification

"1.5 order" closure
Therry and Lacarerre 1983

$$\frac{\partial e}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial Z}\rho\overline{w'e'} - \overline{u'w'}\frac{\partial U}{\partial Z} - \overline{v'w'}\frac{\partial V}{\partial Z} + \beta\overline{w'\theta'} - \epsilon,$$

V = 0
In Bougeault's simulation

Meso-beta scale formulation
Bougeault and Lacarerre 1989

$$\frac{\partial e}{\partial t} = -U\frac{\partial e}{\partial X} - \dot{\sigma}\frac{\partial e}{\partial \sigma} - \frac{1}{\rho}\frac{\partial}{\partial Z}\rho\overline{w'e'} - \overline{u'w'}\frac{\partial U}{\partial Z} - \overline{v'w'}\frac{\partial V}{\partial Z} + \beta\overline{w'\theta'} - \epsilon.$$

$$\frac{\partial \bar{e}}{\partial t} + \frac{\partial}{\partial x_k}\left(\bar{u_k}\bar{e} + \overline{u_k' e} - \nu\frac{\partial \bar{e}}{\partial x_k} + \frac{1}{\bar{\rho}}\overline{u_k' p'}\right) = -\overline{u_k' u_i'}\frac{\partial \bar{u}_i}{\partial x_k} + \frac{g}{\bar{\theta}}\overline{u_3'\theta'} - \nu\overline{\left(\frac{\partial u_i'}{\partial x_k}\right)}$$

Derived from Navier-Stokes
(General form)

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

$$\overline{w'\theta'} = \begin{cases} -K_h\left(\frac{\partial \theta}{\partial Z} - \gamma_{cg}\right), & \text{in the convective PBL} \\ -K_h\frac{\partial \theta}{\partial Z}, & \text{elsewhere.} \end{cases}$$

l_K = characteristic eddy length scale
l_ε = characteristic dispersion length scale
$\alpha_e = \alpha_T = 1$ = inverse Prandtl number
γ_{cg} = counter gradient correction (Deardorff 1972)

APPENDIX 1a) Length Scales

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

$$\int_{Z}^{Z+l_{up}} \beta(\theta(Z) - \theta(Z'))dZ' = e(Z),$$

$$\int_{Z-l_{down}}^{Z} \beta(\theta(Z') - \theta(Z))dZ' = e(Z),$$

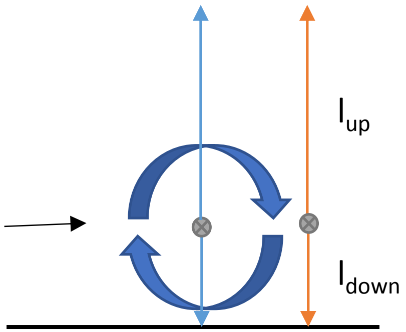
Possible advection distance of parcel with layer-average TKE (Buoyant limit)

Length scales should be somewhat in the range of these lengths

Choose:

$l_K = \min(l_{up}, l_{down})$ Eddies: near walls; smaller length scale limiting the motion

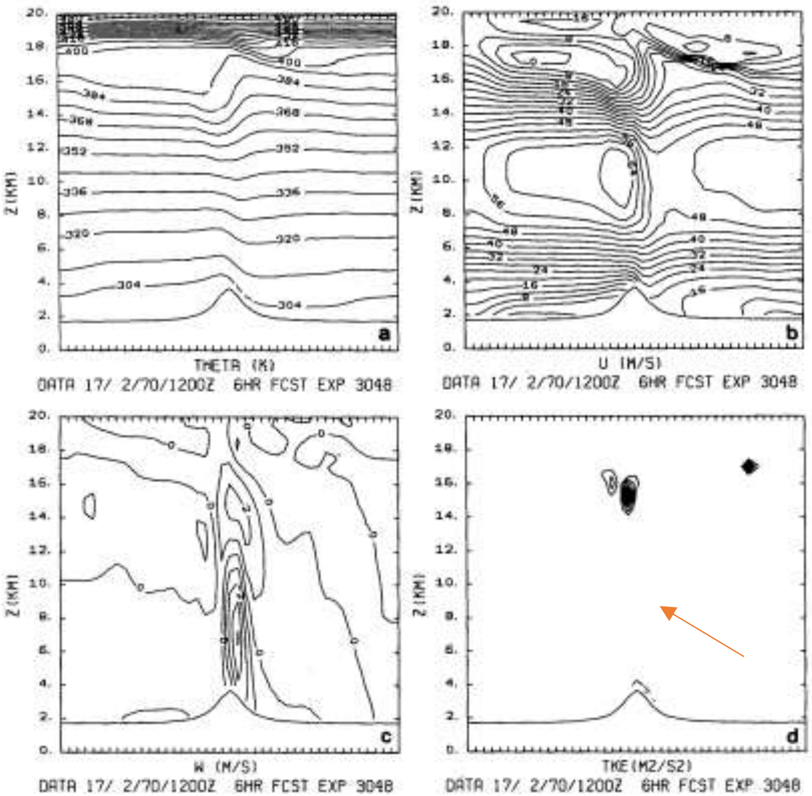
$l_\epsilon = (l_{up} l_{down})^{1/2}$ Dissipation: geometric mean (controversial)

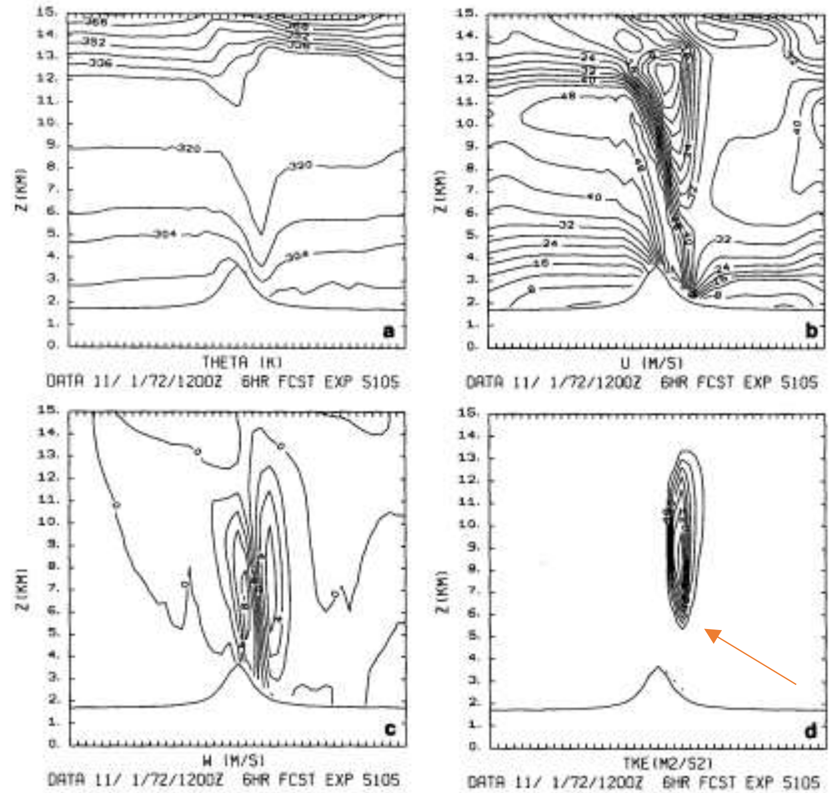


Proportional to buoyancy length scale related to stratification

$$l_B = e^{1/2}\left(\beta \frac{\partial\bar{\theta}}{\partial Z}\right)^{-1/2}$$

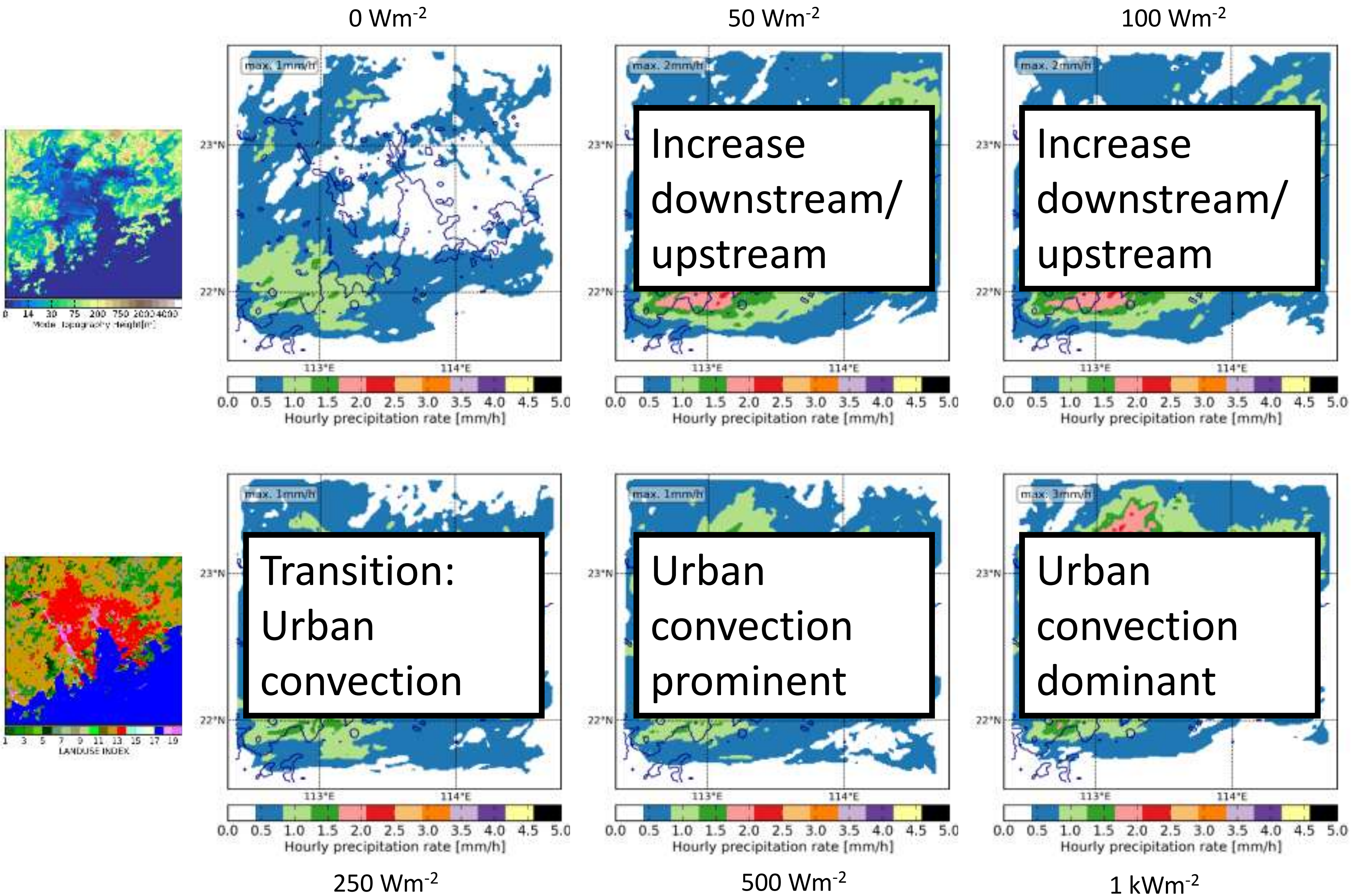
APPENDIX 1b) Two stationary mountain wave simulations from Bougeault and Lacarrere 1989



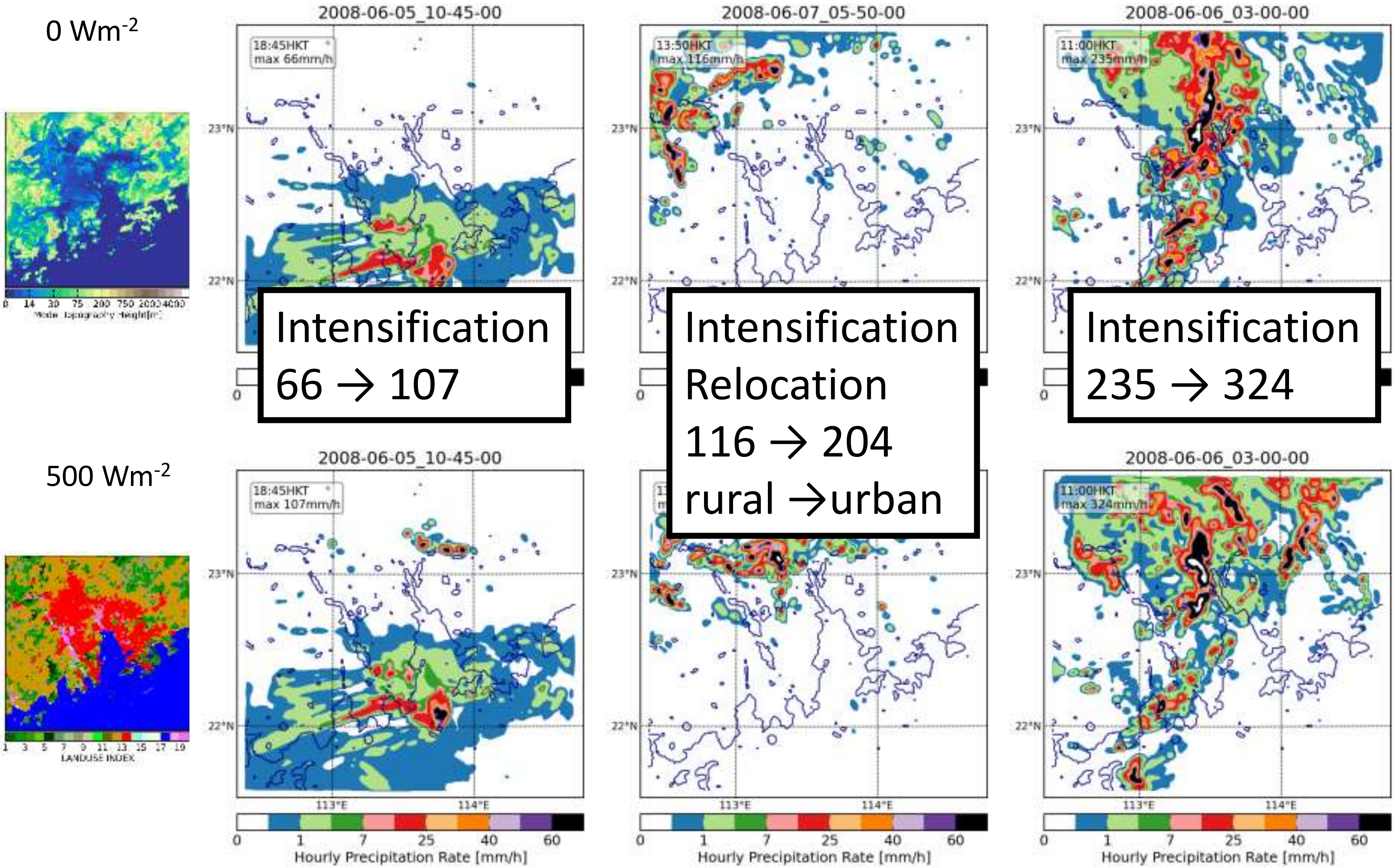


Bougeault and Lacarrere's scheme:
Produces reasonable topography wakes
(Related to Shear or Mechanical Production of TKE)

APPENDIX 2) Accumulated (simulation-mean) precipitation



APPENDIX 2a) Snapshot comparison



#1 #2 #3

APPENDIX 3) Explanation slide

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

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

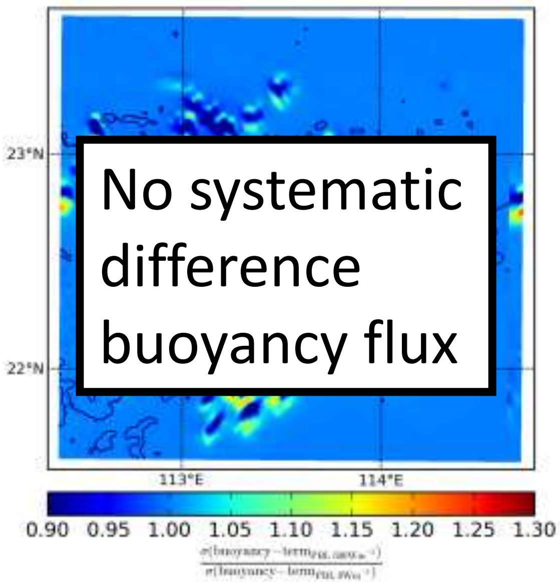
Application: Take standard deviation σ in time of Rif (within the PBL)

Larger σ-values: More shifts between convective and non-convective states

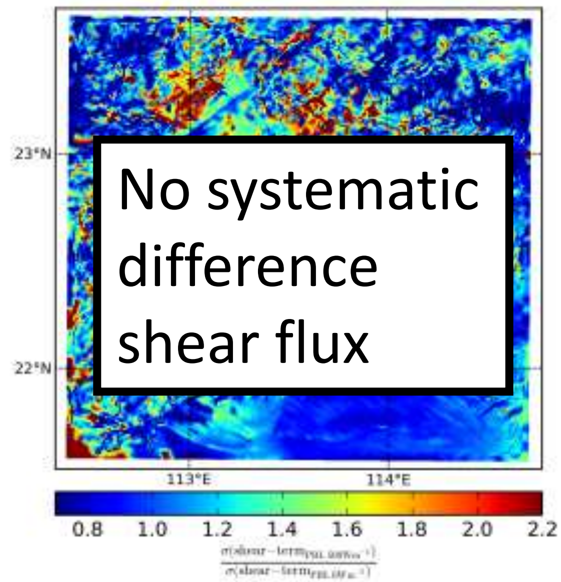
Related to “activity” of convection

APPENDIX 3a) Convection

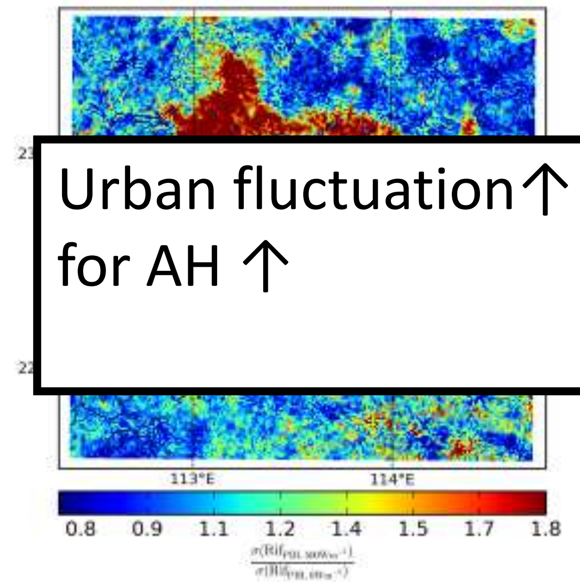
$\beta\overline{w'\theta'}$

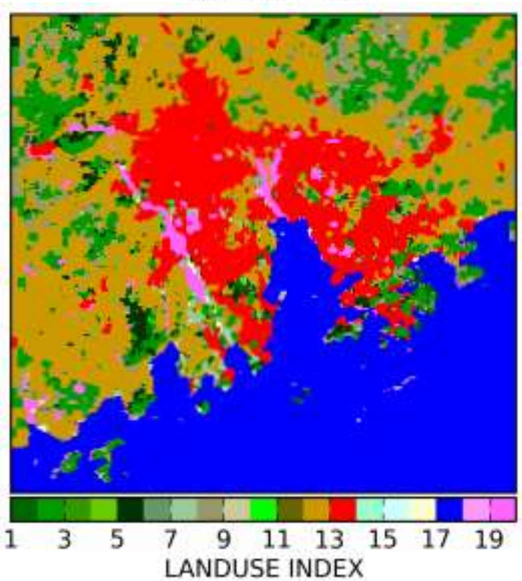


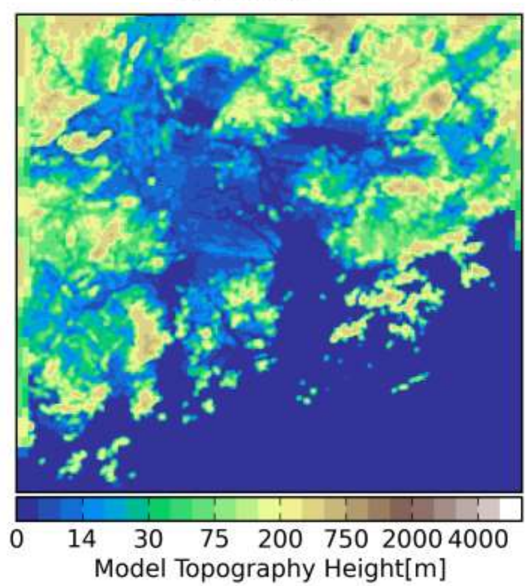
$\frac{\partial\bar{u}}{\partial z}\overline{w'u'} + \frac{\partial\bar{v}}{\partial z}\overline{w'v'}$



$$\mathrm{Rif} = \frac{\beta\overline{w'\theta'}}{\frac{\partial\bar{u}}{\partial z}\overline{w'u'} + \frac{\partial\bar{v}}{\partial z}\overline{w'v'}}$$







Plots of $\frac{\hat{\alpha}}{\tilde{\alpha}}$ with

$$\begin{cases} \hat{\alpha} = \sigma_{t,x,y}\left(\overline{[\alpha_{0Wm^{-2}}]_{z<H}}\right) \\ \tilde{\alpha} = \sigma_{t,x,y}\left(\overline{[\alpha_{500Wm^{-2}}]_{z<H}}\right) \end{cases}$$