Impacts of Urbanization on Hurricane Rainfall using WRF coupled with NoahMP

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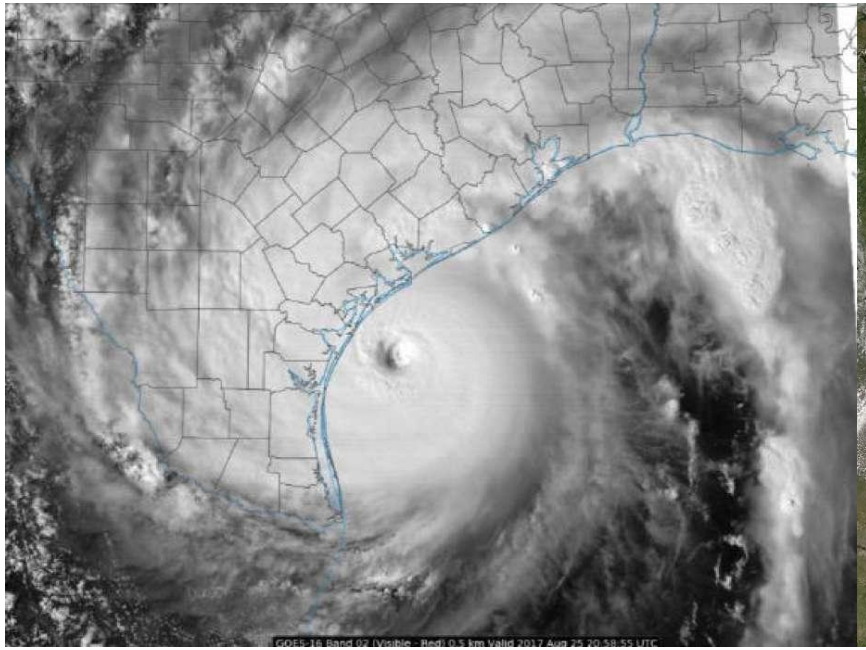
Hurricanes are warm-core low-pressure systems with destructive winds and torrential rainfall.

Harvey in 2017



100+ casualties
$125+ billion in damage

Katrina in 2005

1,800+ casualties
$160+ billion in damage

National Weather Service

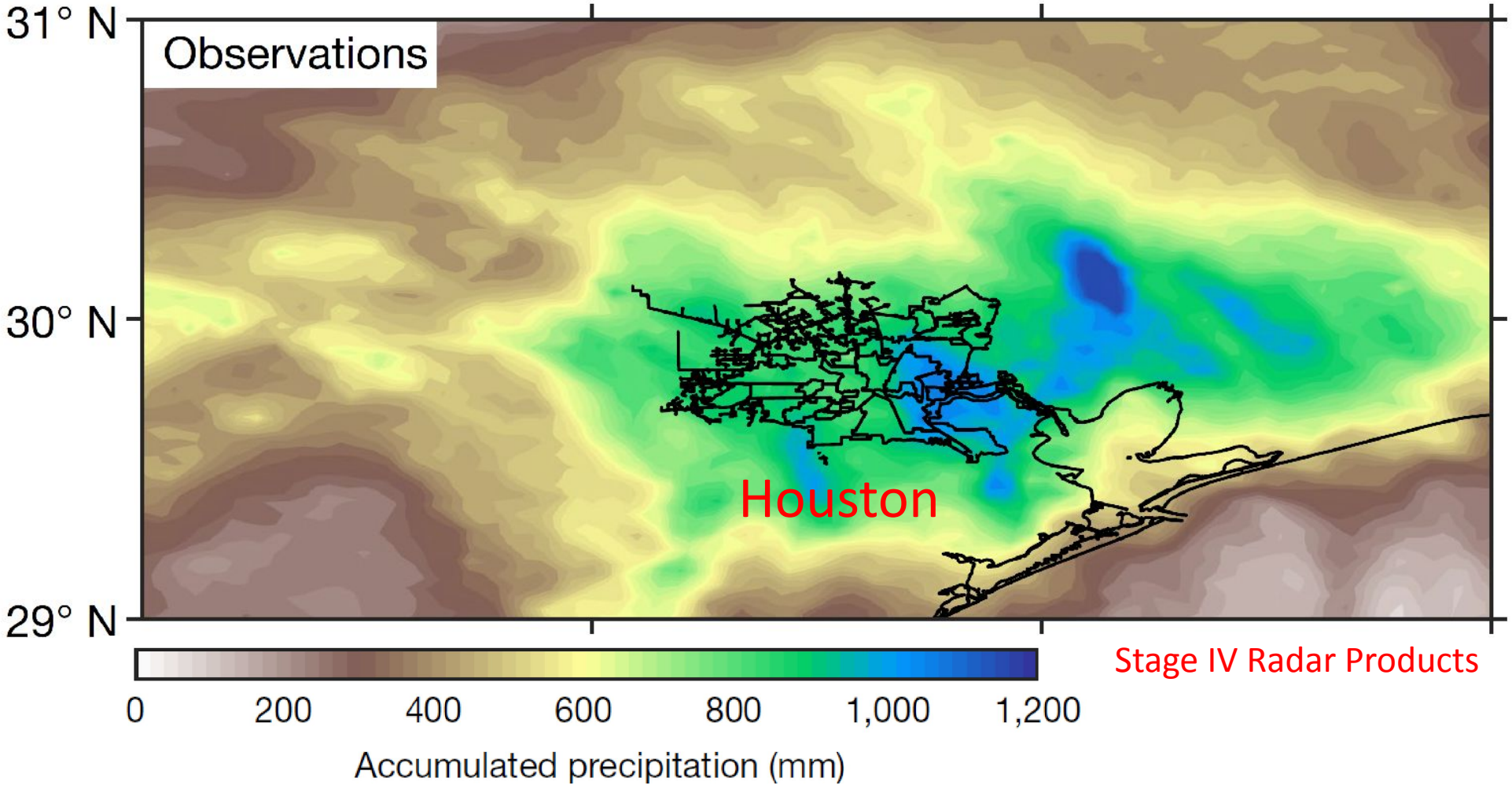
Hurricane Harvey stalled in Texas for several days in 2017.

Extreme precipitation and flash flooding caused by hurricane Harvey have led to major damages to Houston and surrounding areas.

Associated Press

CNN

Record-breaking hurricane Harvey poured more than 1 meter rainfall over some parts of Houston during 25–30 August 2017.



Research on Harvey Rainfall (Impacts of anthropogenic forcing)

- Assessing the present and future probability of Hurricane Harvey's rainfall (Emanuel 2018)
- Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas (Wang et al. 2018)
- Attribution of extreme rainfall from Hurricane Harvey, August 2017 (Van Oldenborgh et al. 2018)
- Hurricane Harvey links to ocean heat content and climate change adaptation (Trenberth et al. 2018)

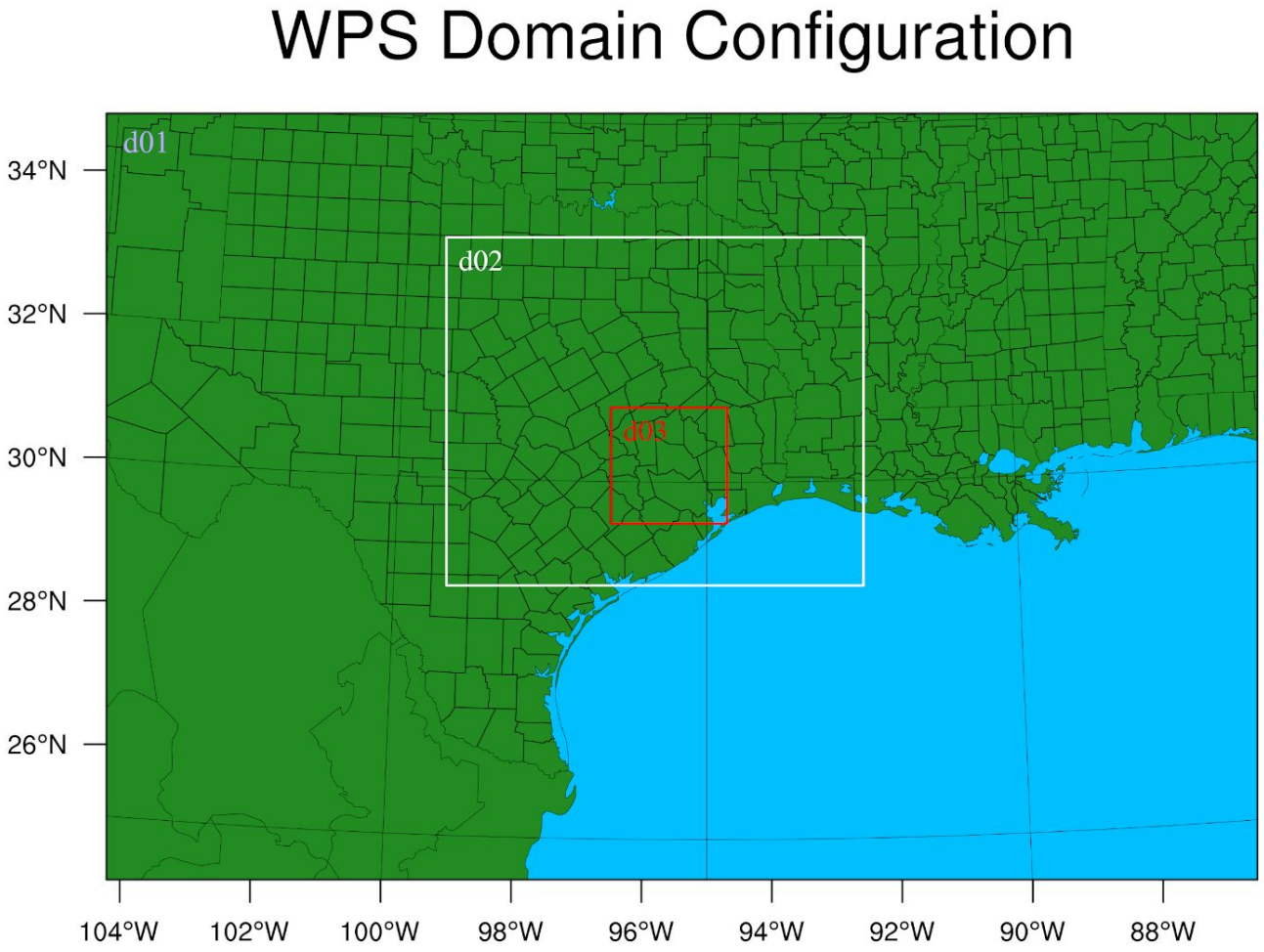
What was the role played by urbanization in modulating the rainfall associated with hurricane Harvey?

Before Hurricane Harvey

After Hurricane Harvey

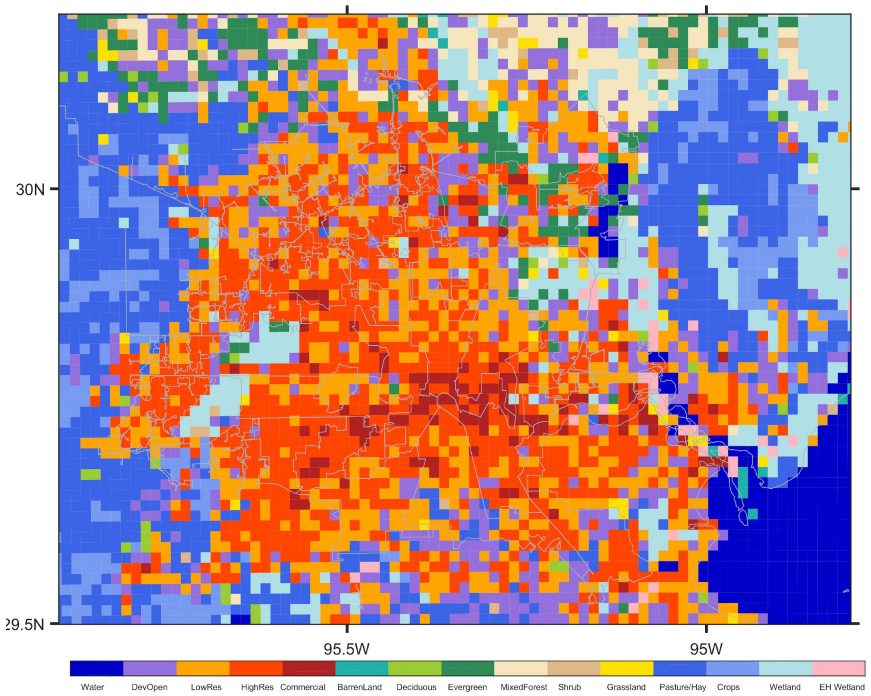
1. How can we quantify the role of urbanization in shaping rainfall caused by hurricane Harvey?

Three spatial domains d01, d02 and d03 in the WRF simulations with 12km, 4km and 1.33 km spatial resolution respectively.

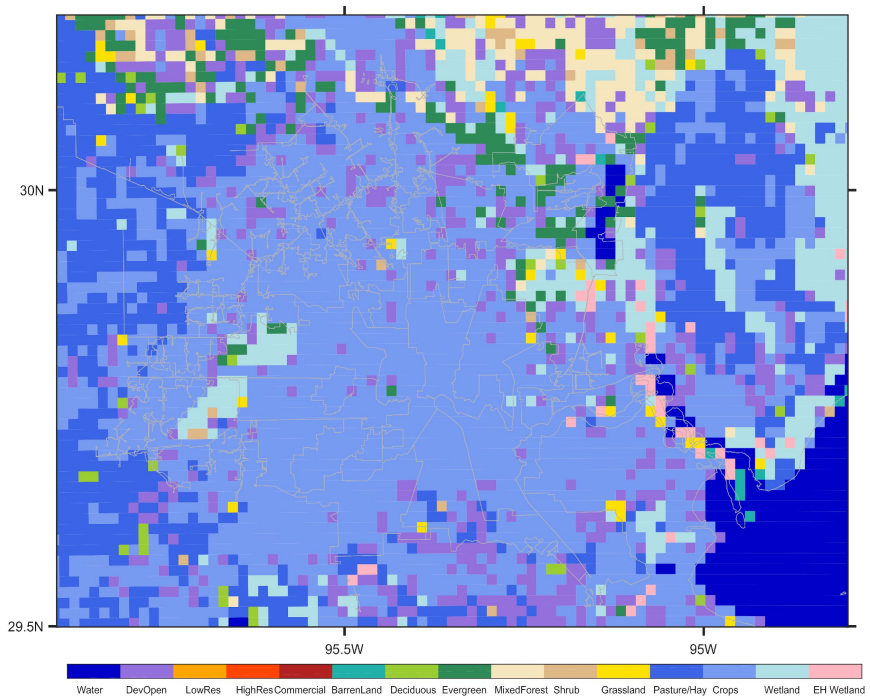


Physics	Options
Microphysics	WSM 6-class graupel scheme
Surface layer	Monin-Obukhov scheme
Boundary layer scheme	Mellor-Yamada-Janjic TKE scheme
Cumulus parameterization	None for d02 and d03, and the Betts-Miller-Janjic scheme for d01
Longwave radiation	Rapid Radiative Transfer Model
Shortwave radiation	Dudhia scheme
Land use	NLCD2011 (40 categories)

The urban land-use categories are replaced by “croplands” in the “NoUrban” experiments.



Urban



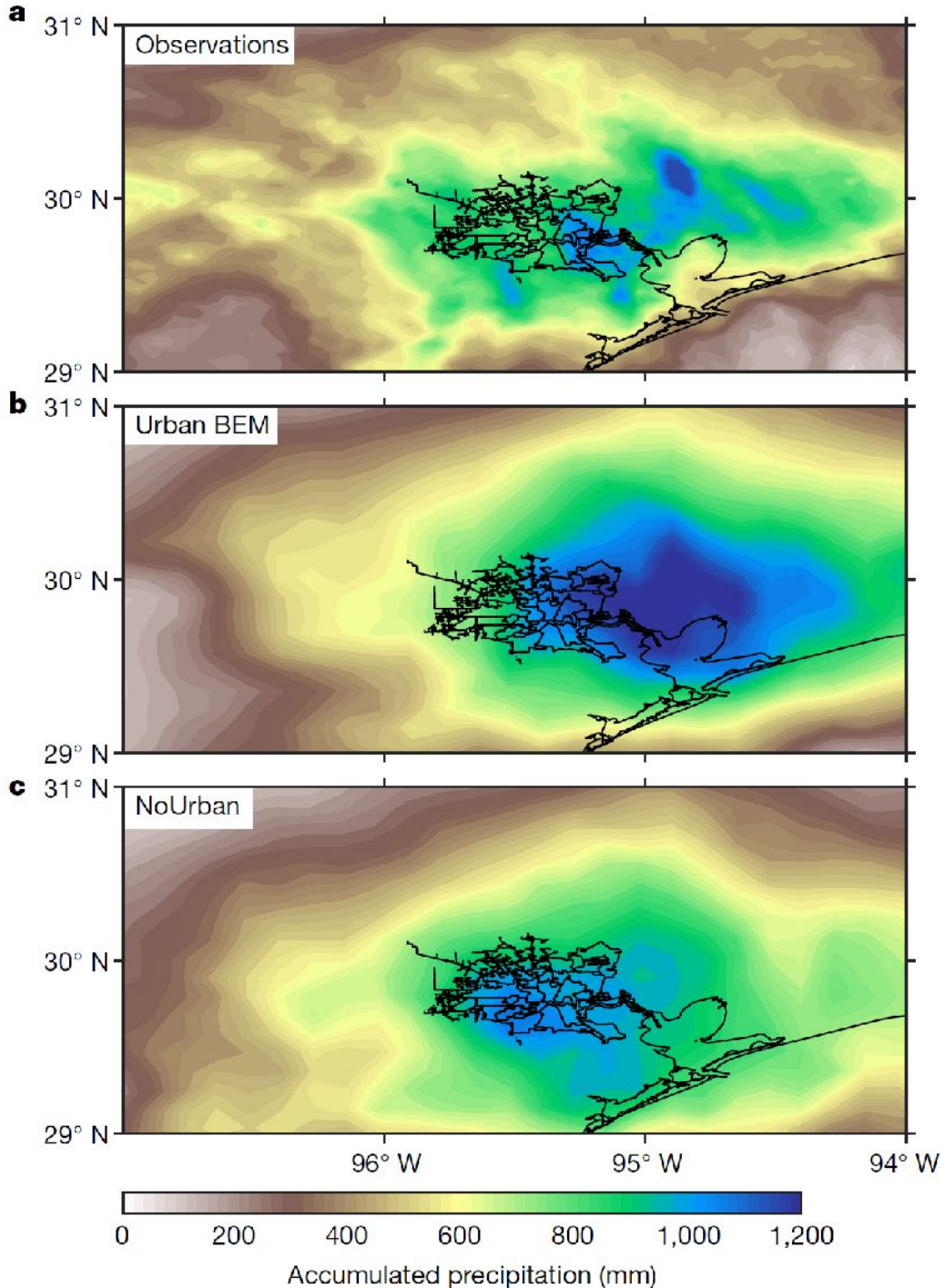
NoUrban

Urban minus NoUrban = Impacts of Urban

Urban experiments: Switch on Building Energy Model (BEM)

Initial and boundary forcing: North American Regional Reanalysis (NARR)

Landuse Landcover data: National Land Cover Database (NLCD) 2011



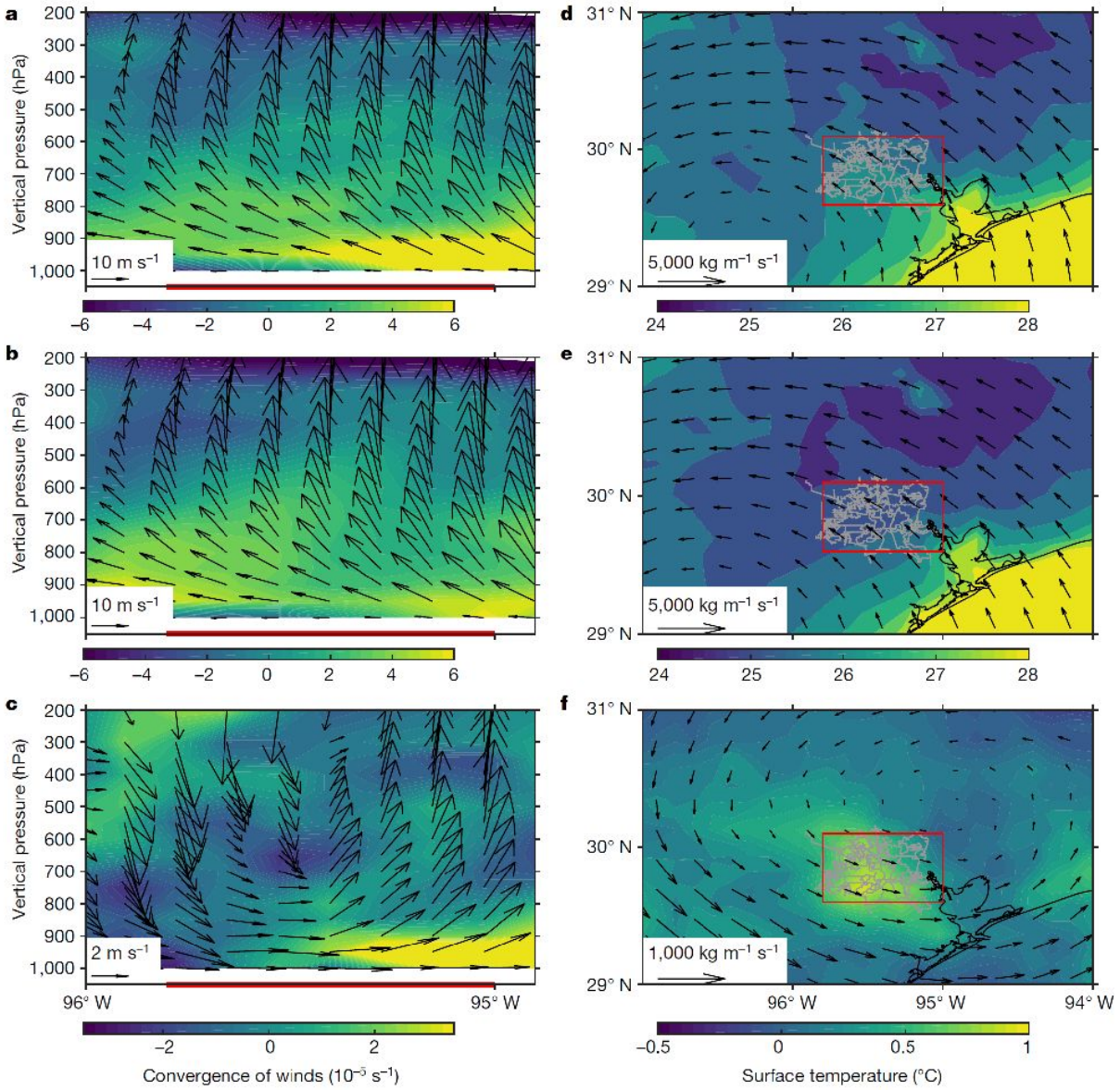
After replacing “urban” with “croplands”, the rainfall associated with Harvey is much weaker and shifted slightly westward.

The urbanization led to an increase in low-level convergence, upper-level divergence and enhanced vertical velocities.

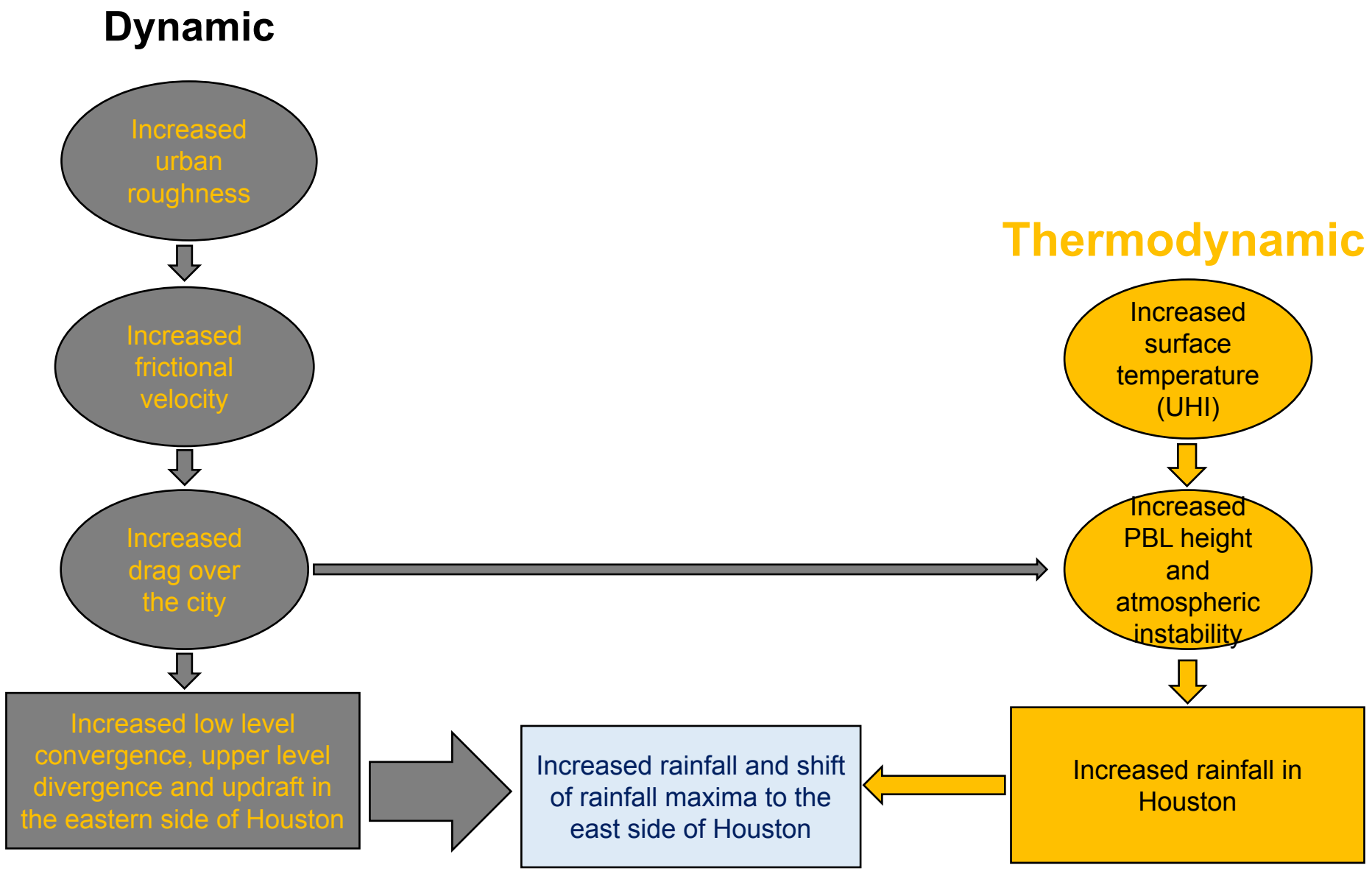
Urban

NoUrban

Urban minus NoUrban

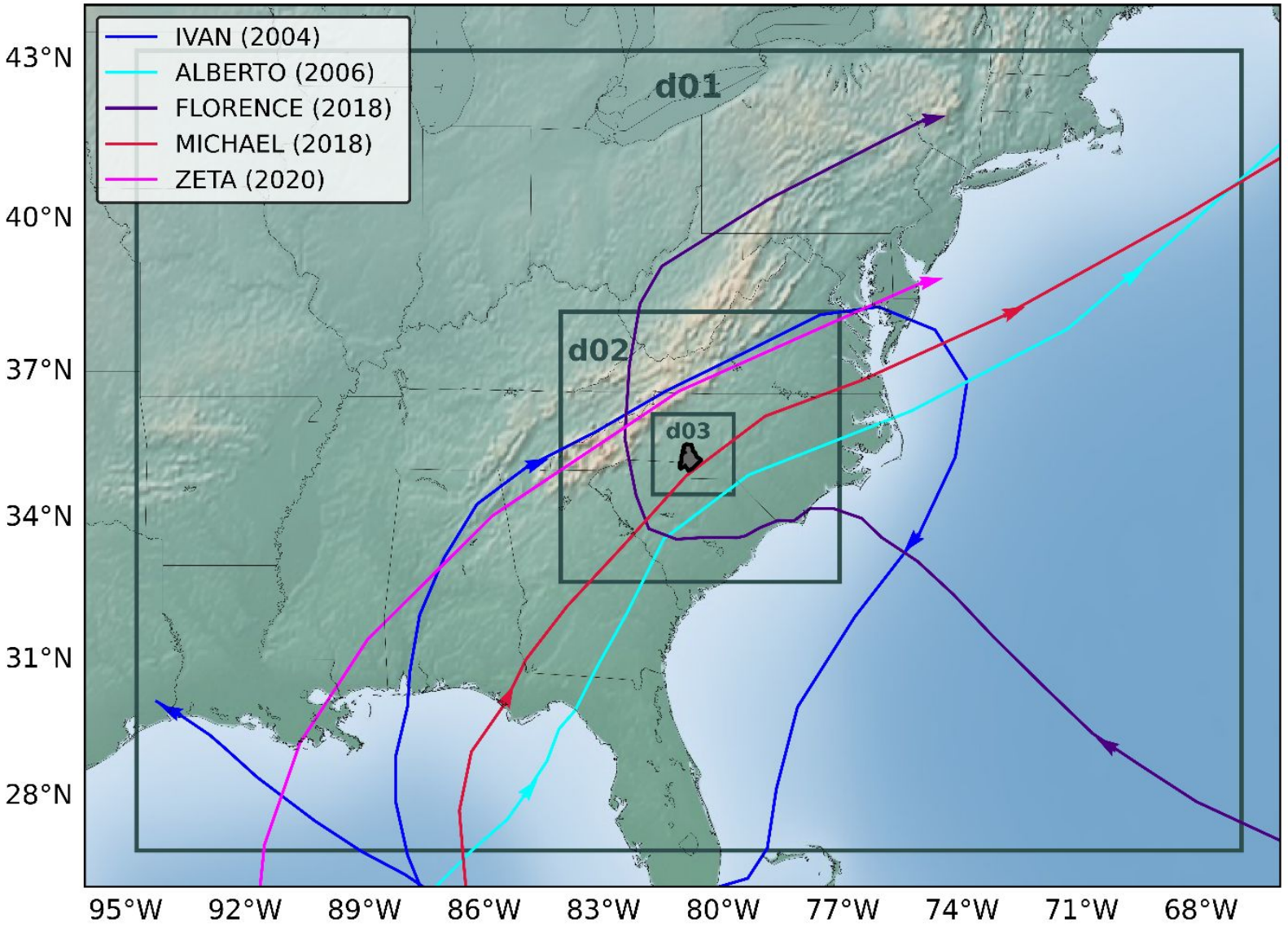


Urban Impacts on Rainfall Caused by Hurricane Harvey

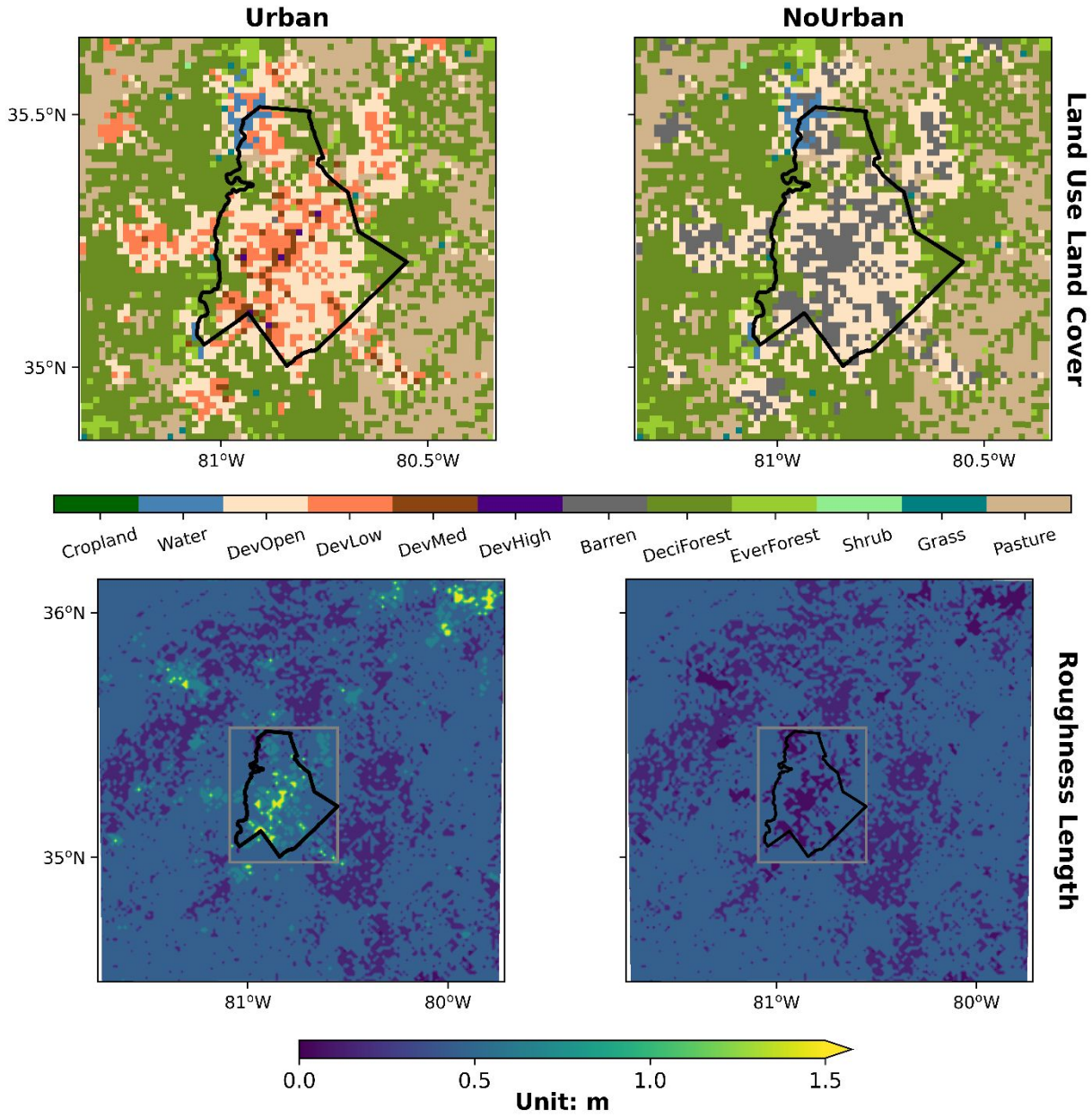


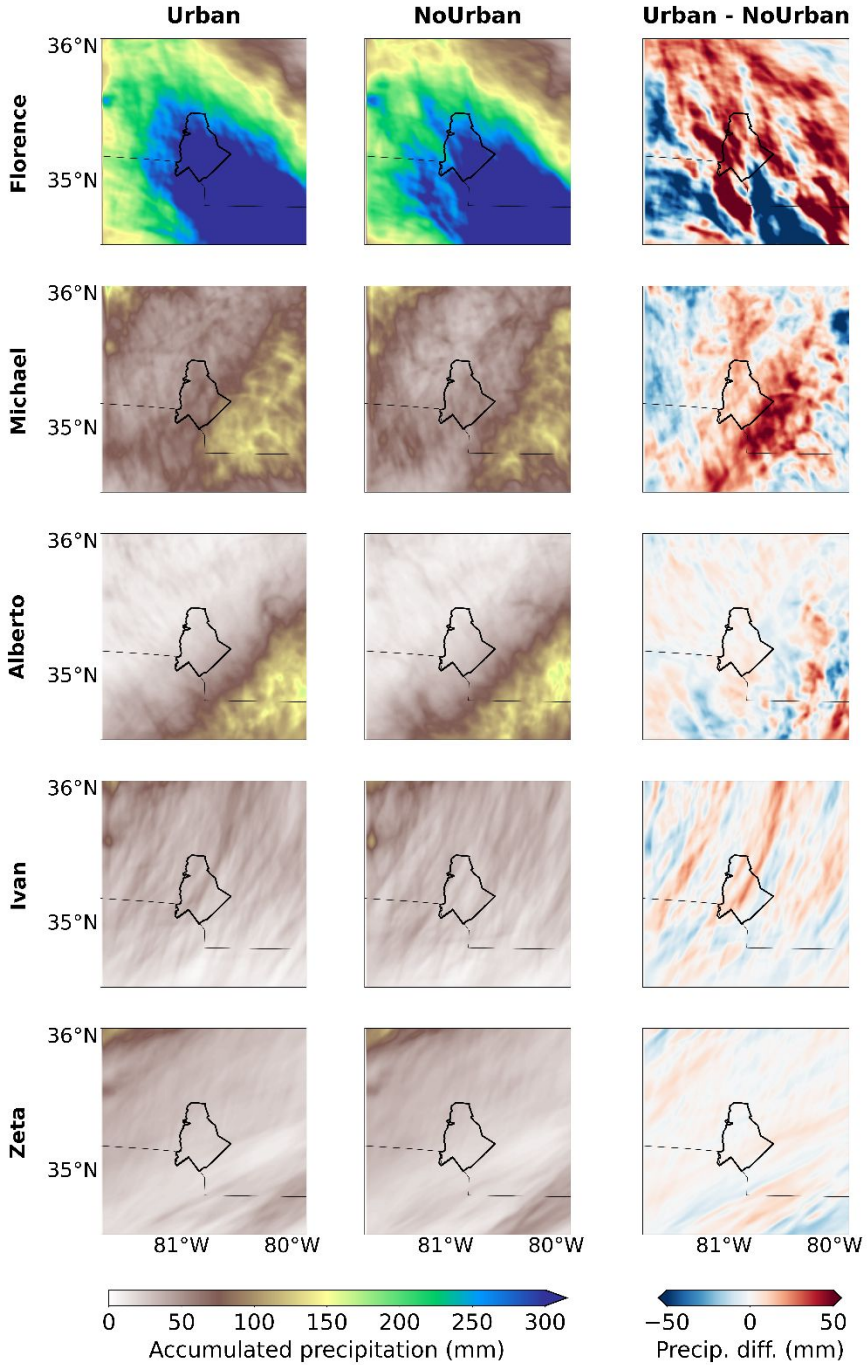
2. Do the research findings hold for other cities and hurricanes?

We tested another five hurricanes that influenced Charlotte, NC.



We performed similar WRF-urban experiments in Charlotte, North Carolina.





Overall, urbanization enhances hurricane precipitation in Charlotte.

Summary

- Urbanization strongly exacerbated the impacts that the storms have had in terms of rainfall.
- Overall, the results hold for storms that made landfall over Houston and Charlotte.
- More experiments are being performed to test the robustness of our findings.

Zhang W, Villarini G, Vecchi GA, Smith JA (2018) Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. Nature 563:384-388.
Isla, S., Villarini G, Zhang W, (2023) Quantification of the Role of Urbanization in Changing the Rainfall Associated with Tropical Cyclones affecting Charlotte, North Carolina, Urban Climate, under revision.

Thanks!

Q & A

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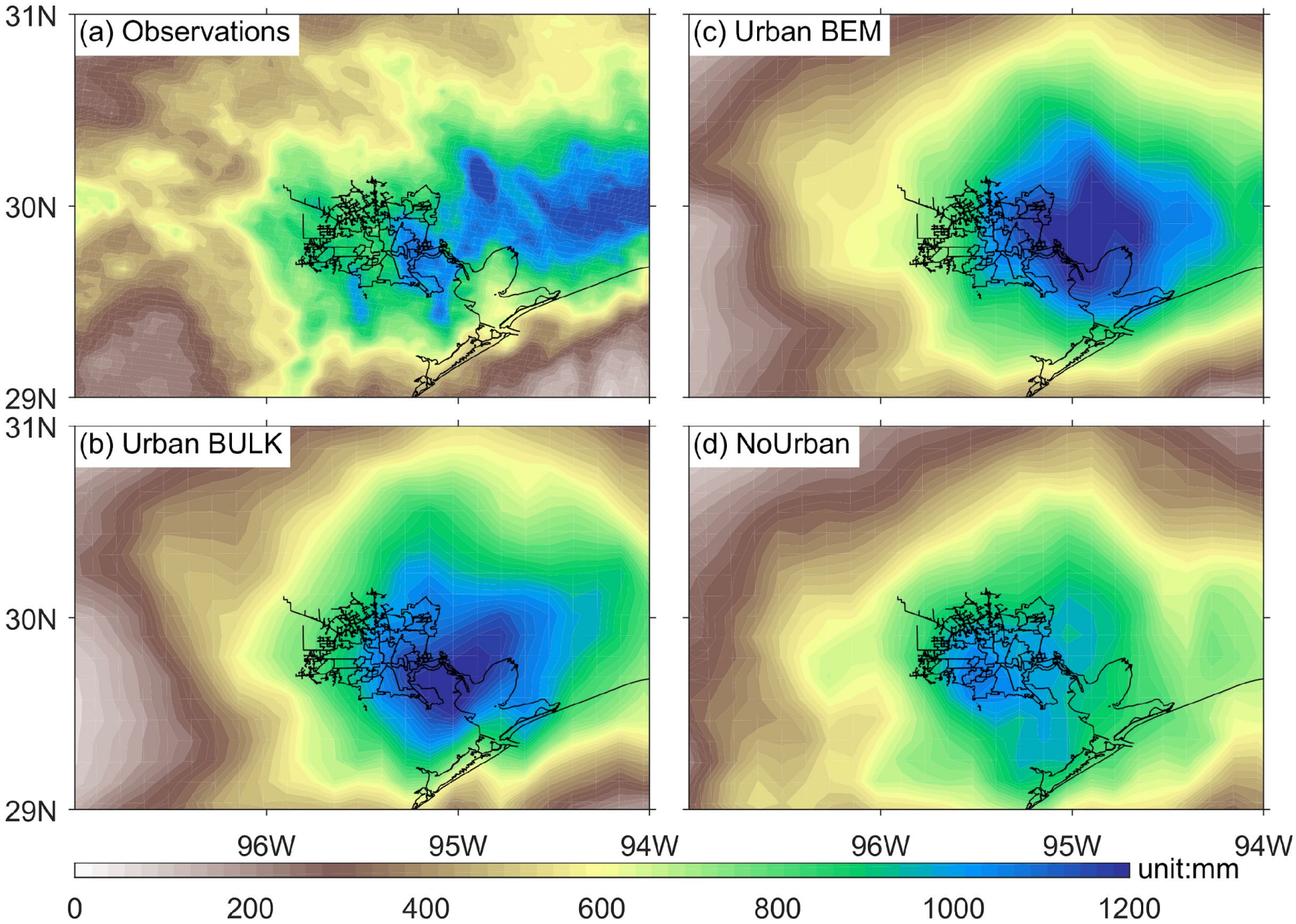

(a) Observations
(c) Urban BEM
(b) Urban BULK
(d) NoUrban
31N
30N
29N
96W
95W
94W
unit:mm
0
200
400
600
800
1000
1200

Why does urbanization matter?

```
NLCD40
40,1, 'SHDFAC NROOT  RS      RGL     HS     SNUP  MAXALB    LAIMIN  LAIMAX  EMISSMIN EMISSMAX ALBEDOMIN ALBEDOMAX  Z0MIN    Z0MAX    ZTOPV    ZBOTV'
1,     .70,   4,    125.,    30.,   47.35,  0.08,   52.,     5.00,   6.40,   .950,    .950,     .12,       .12,      .50,     .50,    17.00,    8.50,          'Evergreen Needleleaf Forest'
2,     .95,   4,    150.,    30.,   41.69,  0.08,   35.,     3.08,   6.48,   .950,    .950,     .12,       .12,      .50,     .50,    35.00,    1.00,          'Evergreen Broadleaf Forest'
3,     .70,   4,    150.,    30.,   47.35,  0.08,   54.,     1.00,   5.16,   .930,    .940,     .14,       .15,      .50,     .50,    14.00,    7.00,          'Deciduous Needleleaf Forest'
4,     .80,   4,    100.,    30.,   54.53,  0.08,   58.,     1.85,   3.31,   .930,    .930,     .16,       .17,      .50,     .50,    20.00,   11.50,          'Deciduous Broadleaf Forest'
5,     .80,   4,    125.,    30.,   51.93,  0.08,   53.,     2.80,   5.50,   .930,    .970,     .17,       .25,      .20,     .50,    18.00,   10.00,          'Mixed Forest'
6,     .70,   3,    300.,   100.,   42.00,  0.03,   60.,     0.50,   3.66,   .930,    .930,     .25,       .30,      .01,     .05,     0.50,    0.10,          'Closed Shrubland'
7,     .70,   3,    170.,   100.,   39.18,  0.035,  65.,     0.60,   2.60,   .930,    .950,     .22,       .30,      .01,     .06,     0.50,    0.10,          'Open Shrubland'
8,     .50,   3,     70.,    65.,   54.53,  0.04,   50.,     0.50,   3.66,   .930,    .930,     .25,       .30,      .01,     .05,     0.00,    0.00,          'Woody Savanna'
9,     .50,   3,     70.,    65.,   54.53,  0.04,   50.,     0.50,   3.66,   .920,    .920,     .20,       .20,      .15,     .15,     0.50,    0.10,          'Savanna'
10,    .80,   3,     40.,   100.,   36.35,  0.04,   70.,     0.52,   2.90,   .920,    .960,     .19,       .23,      .10,     .12,     0.50,    0.10,          'Grassland'
11,    .60,   2,    100.,    30.,   51.93,  0.02,   50.,     1.75,   5.72,   .950,    .950,     .14,       .14,      .30,     .30,     0.50,    0.10,          'Permanent Wetland'
12,    .80,   3,     40.,   100.,   36.25,  0.04,   66.,     1.50,   5.68,   .920,    .985,     .15,       .23,      .05,     .15,     0.50,    0.10,          'Cropland'
13,    .10,   1,    200.,   999.,   999.0,  0.04,   46.,     1.00,   1.00,   .880,    .880,     .15,       .15,      .50,     .50,     0.00,    0.00,          'Urban and Built-Up'
14,    .80,   3,     40.,   100.,   36.25,  0.04,   66.,     2.29,   4.29,   .920,    .980,     .18,       .23,      .05,     .14,     0.50,    0.10,          'Cropland / Natural Veg. Mosaic'
15,    .00,   1,    999.,   999.,   999.0,  0.02,   82.,     0.01,   0.01,   .950,    .950,     .55,       .70,     0.001,   0.001,   0.00,    0.00,          'Permanent Snow'
16,    .01,   1,    999.,   999.,   999.0,  0.02,   75.,     0.10,   0.75,   .900,    .900,     .38,       .38,      .01,     .01,     0.02,    0.01,          'Barren / Sparsely Vegetated'
17,    .00,   0,    100.,    30.,   51.75,  0.01,   70.,     0.01,   0.01,   .980,    .980,     .08,       .08,     0.0001,  0.0001,  0.00,    0.00,          'IGBP Water'
18,    .00,   0,    999.,   999.,   999.0,  999.,   999.,    999.0,  999.0,  999.,    999.0,    999.0,     999.0,    999.0,   999.0,   0.00,    0.00,          'Unclassified'
19,    .00,   0,    999.,   999.,   999.0,  999.,   999.,    999.0,  999.0,  999.,    999.0,    999.0,     999.0,    999.0,   999.0,   0.00,    0.00,          'Fill Value'
20,    .00,   0,    999.,   999.,   999.0,  999.,   999.,    999.0,  999.0,  999.,    999.0,    999.0,     999.0,    999.0,   999.0,   0.00,    0.00,          'Unclassified'
21,    .00,   0,    100.,    30.,   51.75,  0.01,   70.,     0.01,   0.01,   .980,    .980,     .08,       .08,     0.0001,  0.0001,  0.00,    0.00,          'Open Water'
22,    .00,   1,    999.,   999.,   999.0,  0.02,   82.,     0.01,   0.01,   .950,    .950,     .55,       .70,     0.001,   0.001,   0.00,    0.00,          'Perennial Ice/Snow'
23,    .30,   1,    200.,   999.,   999.0,  0.04,   46.,     1.00,   1.00,   .880,    .880,     .20,       .20,      .50,     .50,     0.00,    0.00,          'Developed Open Space'
24,    .27,   1,    200.,   999.,   999.0,  0.04,   46.,     1.00,   1.00,   .880,    .880,     .20,       .20,      .70,     .70,     0.00,    0.00,          'Developed Low Intensity'
25,    .02,   1,    200.,   999.,   999.0,  0.04,   46.,     1.00,   1.00,   .880,    .880,     .20,       .20,     1.5,     1.5,     0.00,    0.00,          'Developed Medium Intensity'
26,    .11,   1,    200.,   999.,   999.0,  0.04,   46.,     1.00,   1.00,   .880,    .880,     .20,       .20,     2.0,     2.0,     0.00,    0.00,          'Developed High Intensity'
27,    .01,   1,    999.,   999.,   999.0,  0.02,   75.,     0.10,   0.75,   .900,    .900,     .38,       .38,      .01,     .01,     0.02,    0.01,          'Barren Land'
28,    .80,   4,    125.,    30.,   54.70,  0.08,   56.,     1.00,   5.16,   .930,    .940,     .14,       .17,      .50,     .50,    20.00,   11.50,          'Deciduous Forest'
29,    .95,   4,    140.,    30.,   44.00,  0.08,   42.,     3.08,   6.48,   .950,    .950,     .12,       .12,      .50,     .50,    17.00,    8.50,          'Evergreen Forest'
30,    .80,   4,    125.,    30.,   51.93,  0.08,   53.,     2.80,   5.50,   .930,    .970,     .17,       .25,      .20,     .50,    18.00,   10.00,          'Mixed Forest'
31,    .70,   3,    170.,   100.,   39.18,  0.035,  65.,     1.00,   4.00,   .930,    .950,     .16,       .30,      .01,     .04,     0.50,    0.10,          'Dwarf Scrub'
32,    .70,   3,    300.,   100.,   42.00,  0.03,   60.,     0.50,   3.66,   .930,    .930,     .22,       .30,      .01,     .05,     0.50,    0.10,          'Shrub/Scrub'
33,    .80,   3,     40.,   100.,   36.35,  0.04,   70.,     0.52,   2.90,   .920,    .960,     .19,       .23,      .10,     .12,     0.50,    0.10,          'Grassland/Herbaceous'
34,    .60,   2,     40.,   100.,   60.00,  0.01,   68.,     1.50,   5.65,   .950,    .950,     .14,       .14,      .20,     .20,     0.50,    0.10,          'Sedge/Herbaceous'
35,    .60,   2,     40.,   100.,   60.00,  0.01,   68.,     1.00,   2.00,   .950,    .950,     .31,       .31,      .01,     .01,     0.00,    0.00,          'Lichens'
36,    .60,   2,     40.,   100.,   60.00,  0.01,   68.,     1.00,   2.00,   .950,    .950,     .24,       .24,      .01,     .01,     0.00,    0.00,          'Moss'
37,    .80,   3,     40.,   100.,   36.25,  0.04,   66.,     1.56,   5.68,   .920,    .985,     .17,       .23,      .05,     .15,     0.50,    0.10,          'Pasture/Hay'
38,    .80,   3,     40.,   100.,   36.25,  0.04,   66.,     1.56,   5.68,   .930,    .985,     .20,       .25,      .02,     .10,     0.50,    0.10,          'Cultivated Crops'
39,    .60,   2,    100.,    30.,   51.93,  0.02,   50.,     0.70,   3.50,   .950,    .950,     .14,       .14,      .40,     .40,    20.00,   11.50,          'Woody Wetland'
40,    .60,   2,     40.,   100.,   60.00,  0.01,   68.,     0.70,   3.50,   .950,    .950,     .12,       .12,      .20,     .20,     0.50,    0.10,          'Emergent Herbaceous Wetland'
```

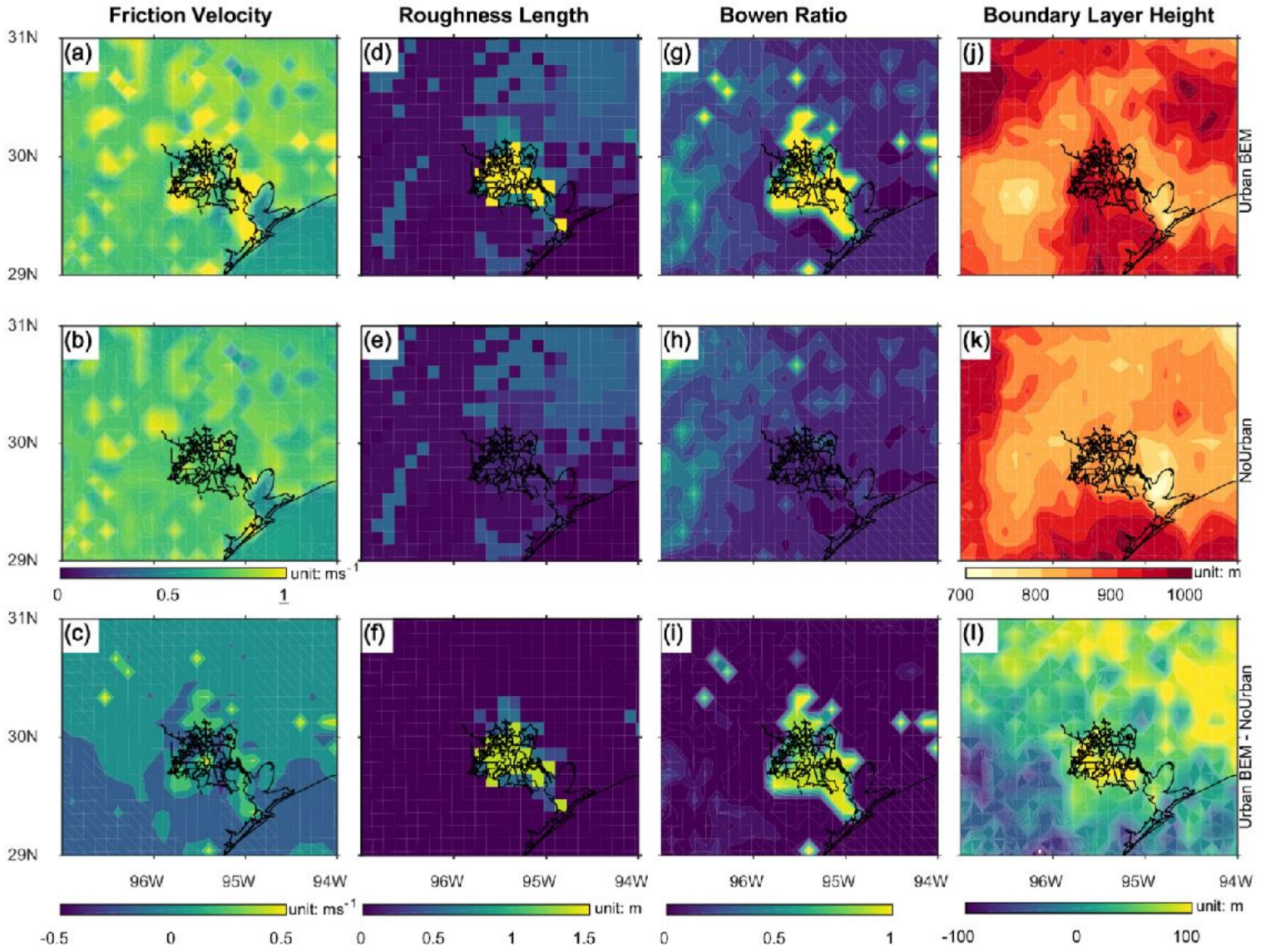
```
# The parameters in this table may vary greatly from city to city.
# The default values are probably not appropriate for any given city.
# Users should adapt these values based on the city they are working
# with.

# Urban Parameters depending on Urban type
# USGS

Number of urban categories: 3

#
#  Where there are multiple columns of values, the values refer, in
#  order, to: 1) Low density residential, 2) High density residential,
#  and 3) Commercial:  I.e.:
#
#  Index:     1           2              3
#  Type:  Low-dens Res, Hi-dens Res, Commercial
#


#
# ZR:  Roof level (building height)  [ m ]
#      (sf_urban_physics=1)

ZR: 5.0,  7.5,  10.0

#
# SIGMA_ZED:  Standard Deviation of roof height  [ m ]
#      (sf_urban_physics=1)

SIGMA_ZED: 1.0,  3.0,  4.0

#
# ROOF_WIDTH:  Roof (i.e., building) width  [ m ]
#      (sf_urban_physics=1)

ROOF_WIDTH: 8.3, 9.4, 10.0

#
# ROAD_WIDTH:  road width  [ m ]
#      (sf_urban_physics=1)
#

ROAD_WIDTH: 8.3, 9.4, 10.0

#
# AH:  Anthropogenic heat [ W m{-2} ]
#      (sf_urban_physics=1)
#

AH:  20.0, 50.0, 90.0


#
# ALH:  Anthropogenic latent heat [ W m{-2} ]
#      (sf_urban_physics=1)
#

ALH:  20.0, 25.0, 40.0

#
#  AKANDA URBAN:  Coefficient modifying the Kanda approach to computing

DDZR:  0.05, 0.05, 0.05, 0.05

#
# DDZB:  Thickness of each building wall layer [ m ]
#        This is currently NOT a function urban type, but a function
#        of the number of layers.  Number of layers must be 4, for now.
#      (sf_urban_physics=1)
#

DDZB: 0.05, 0.05, 0.05, 0.05

#
# DDZG:  Thickness of each ground (road) layer [ m ]
#        This is currently NOT a function urban type, but a function
#        of the number of layers.  Number of layers must be 4, for now.
#      (sf_urban_physics=1)
#

DDZG: 0.05, 0.25, 0.50, 0.75

#
# BOUNDR:  Lower boundary condition for roof layer temperature [ 1: Zero-Flux,  2: T = Constant ]
#      (sf_urban_physics=1)
#

BOUNDR: 1

#
# BOUNDB:  Lower boundary condition for wall layer temperature [ 1: Zero-Flux,  2: T = Constant ]
#      (sf_urban_physics=1)
#

BOUNDB: 1

#
# BOUNDG:  Lower boundary condition for ground (road) layer temperature [ 1: Zero-Flux,  2: T = Constant ]
#      (sf_urban_physics=1)
#

BOUNDG: 1

#
# Ch of Wall and Road [ 1: M-O Similarity Theory, 2: Empirical Form of Narita et al., 1997 (recommended) ]
#      (sf_urban_physics=1)
#

CH_SCHEME: 2

#
# Surface and Layer Temperatures [ 1: 4-layer model,  2: Force-Restore method ]
#      (sf_urban_physics=1)
#

TS_SCHEME: 1

#
# AHOPTION [ 0: No anthropogenic heating,  1: Anthropogenic heating will be added to sensible heat flux term ]
#      (sf_urban_physics=1)
#
```

The city led to an increase in roughness length, leading to an increase in friction velocity and drag over the city.

Urban

NoUrban

Urban minus NoUrban



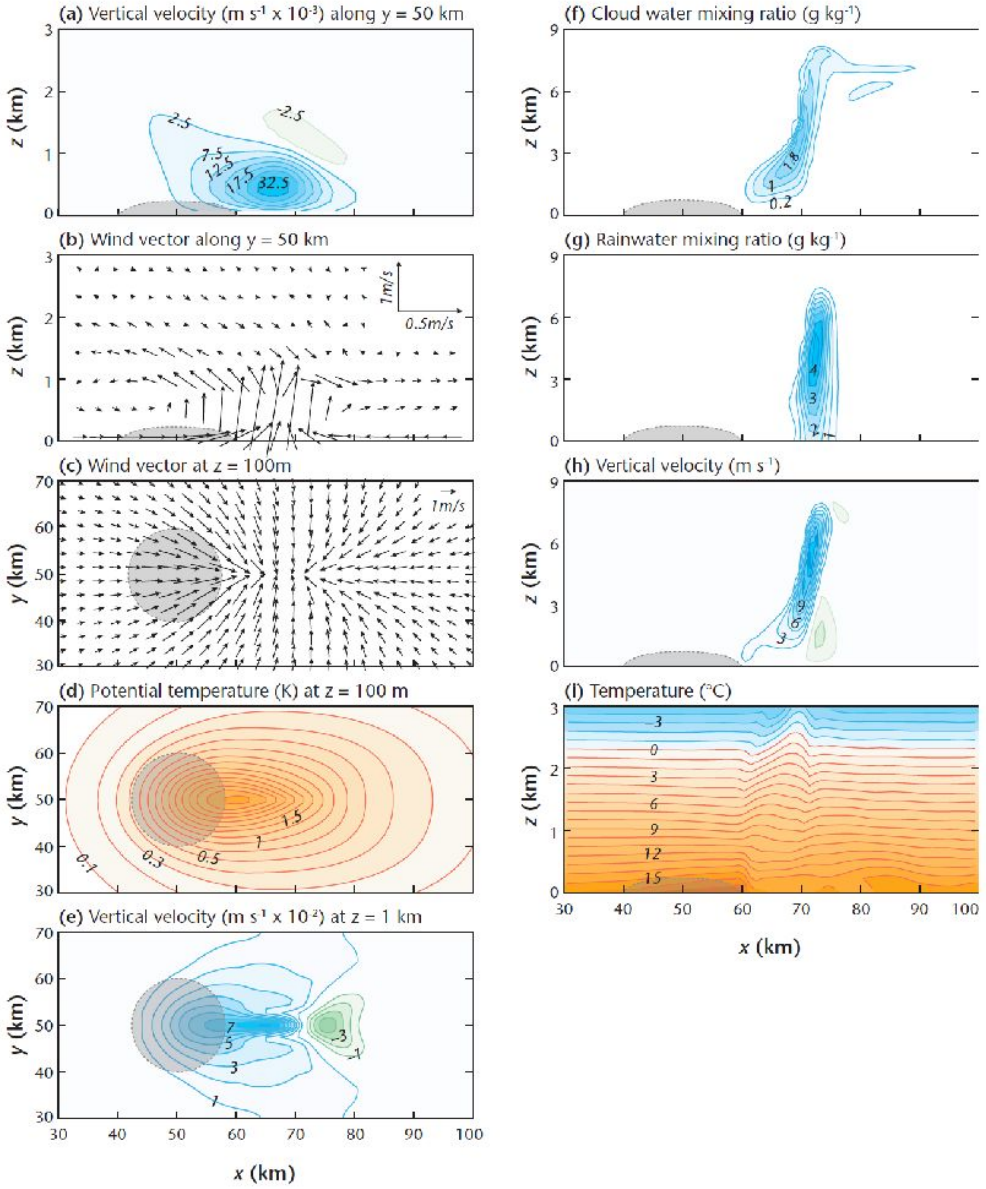
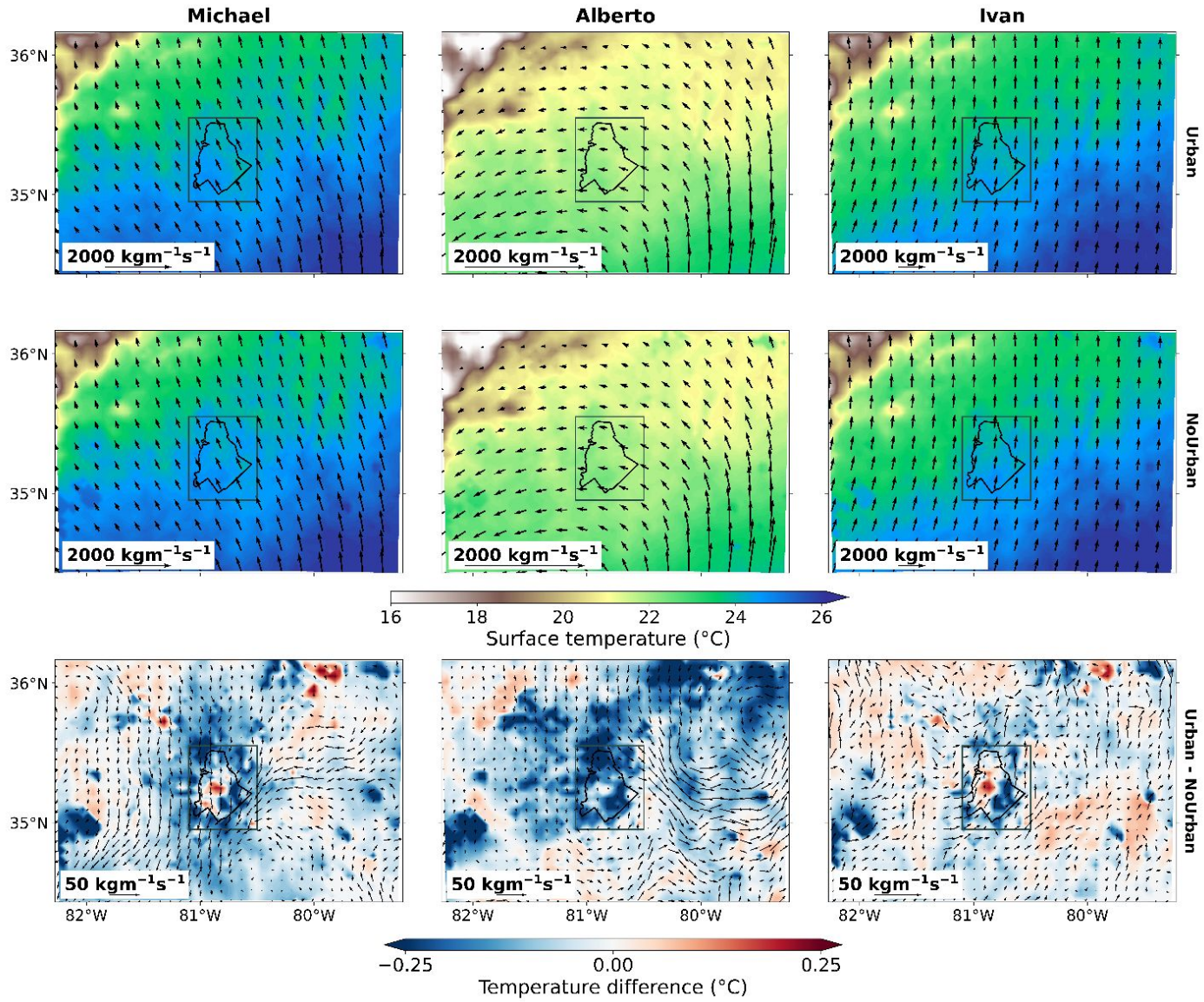
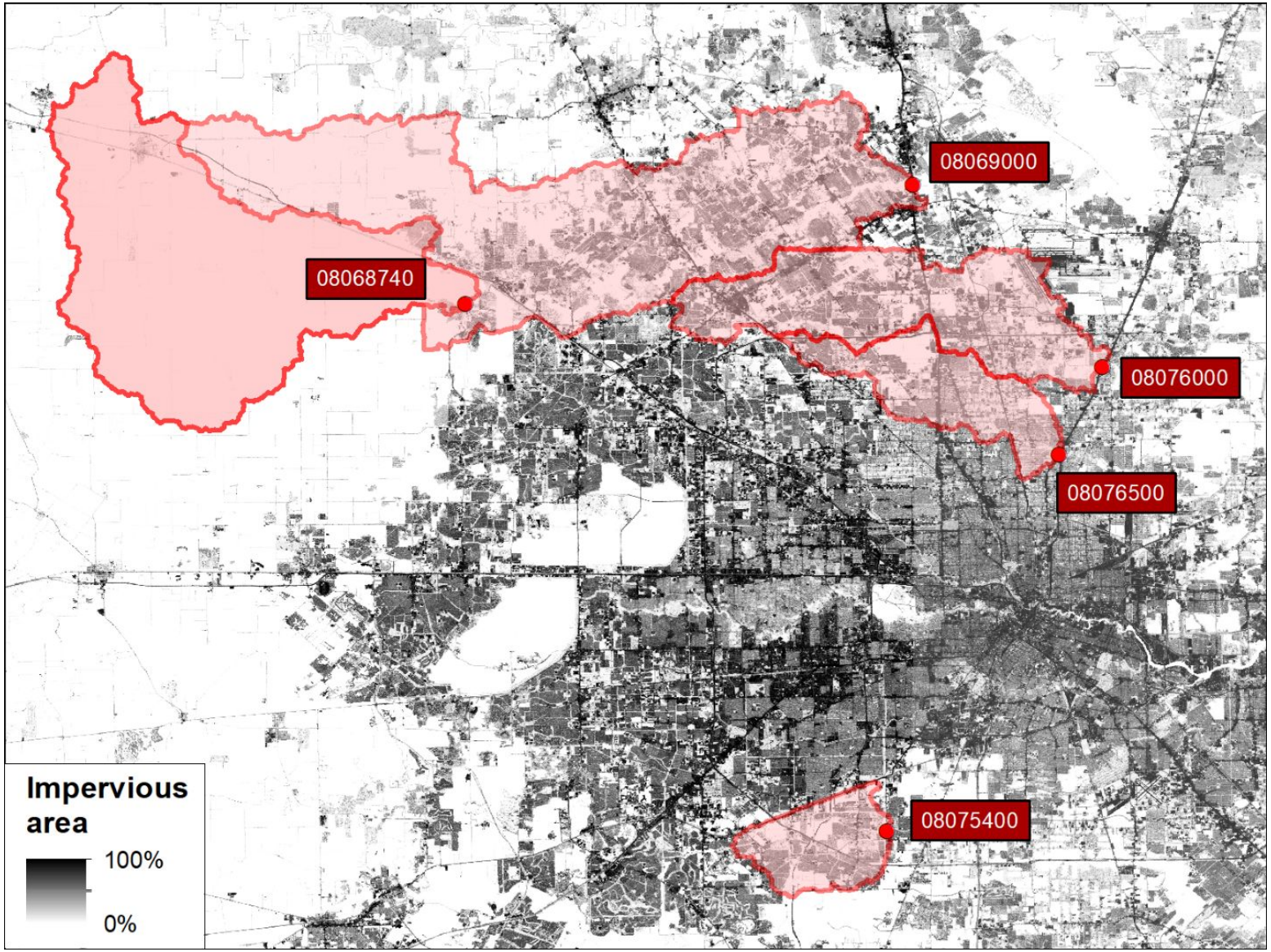


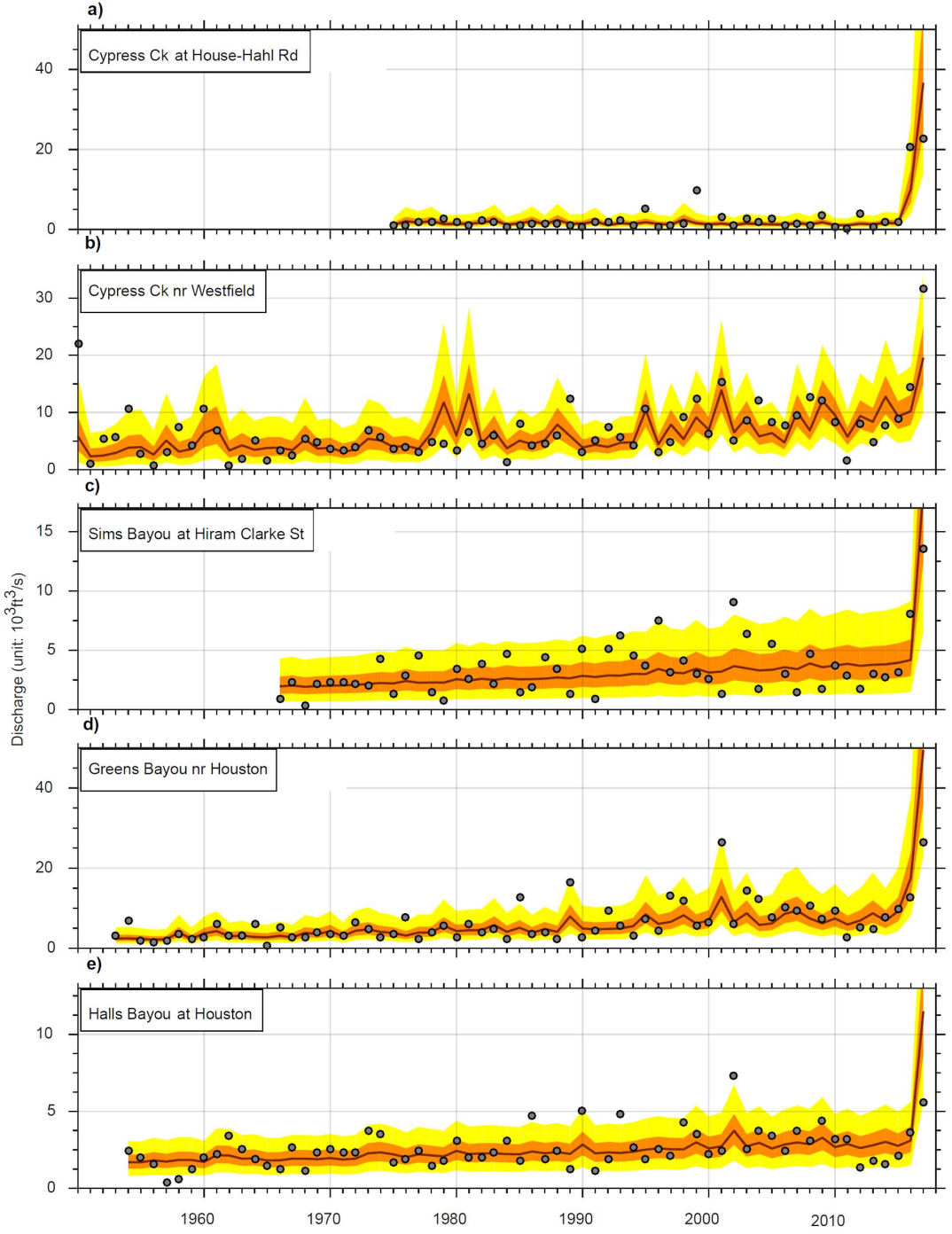
Figure 10.10 Numerical simulations of the impacts of urban heating (circular dotted region between 40–60 km on the *x* axis) in a dry (left panels) and moist (right panels) atmosphere. Left panels: **(a)** vertical velocity (m s^{-1}), **(b)** perturbation wind vector through and downwind of the urban area along the centreline of the domain, **(c)** plan view of the wind vector perturbation, **(d)** plan view of potential temperature perturbation, **(e)** vertical velocity field at a height of 1 km. Right panels: **(f)** cloud water mixing ratio (g kg^{-1}), **(g)** rainwater mixing ratio (g kg^{-1}), **(h)** vertical velocity (m s^{-1}) and **(i)** temperature fields along the simulation centre line 3 hours into a moist simulation. Mean horizontal wind speed is 4 m s^{-1} and considered to be constant with height for all cases (Source: Han and Baik, 2008; © American Meteorological Society, used with permission).

Enhanced updrafts and clouds are found in the downwind of the urban area.

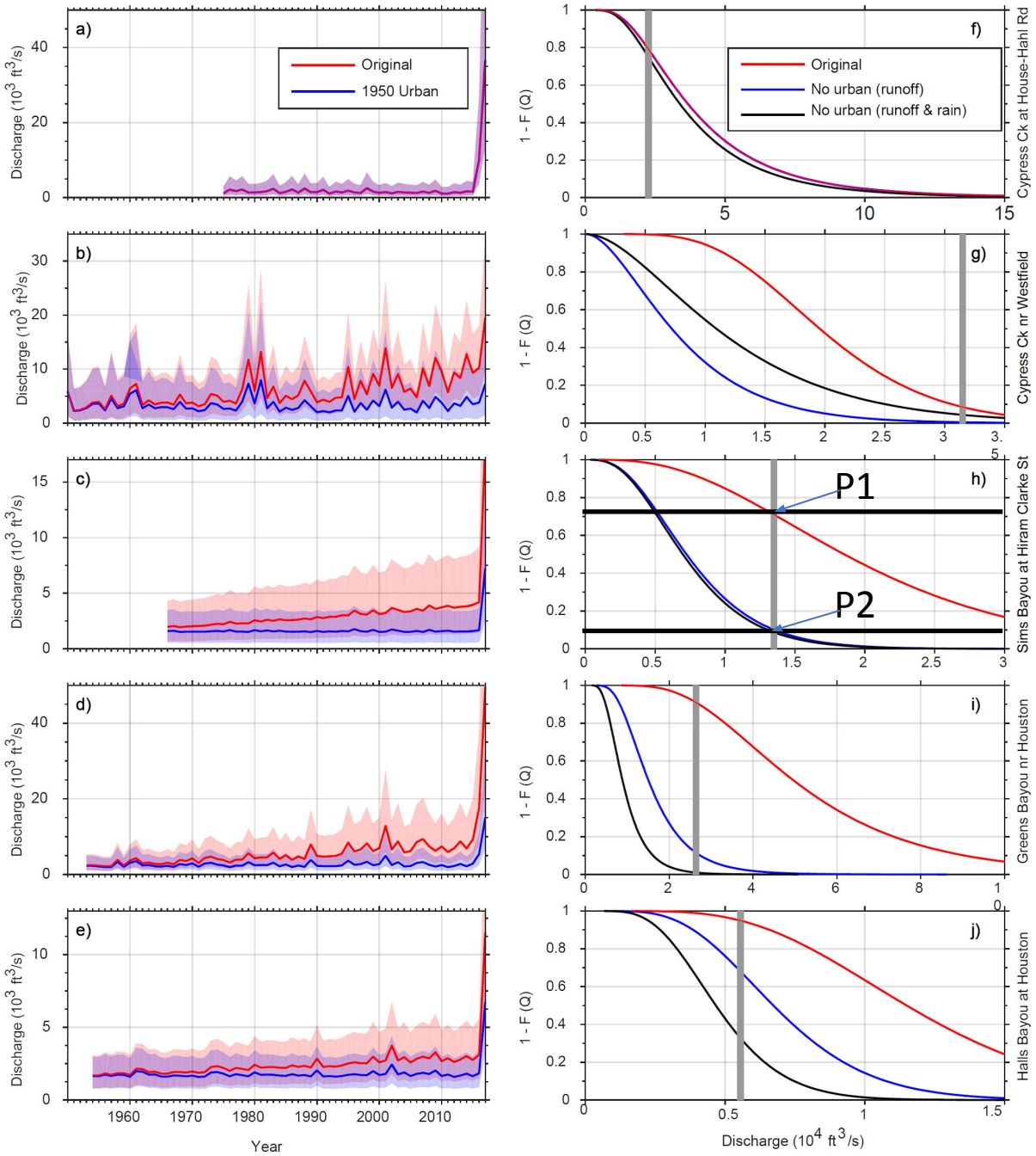

Michael
Alberto
Ivan
Urban
NoUrban
Urban - NoUrban
36°N
35°N
82°W
81°W
80°W
2000 kgm⁻¹s⁻¹
50 kgm⁻¹s⁻¹
16
18
20
22
24
26
Surface temperature (°C)
−0.25
0.00
0.25
Temperature difference (°C)

Basin boundaries of the five watersheds considered in this study, together with their United States Geological Survey (USGS) station ID numbers.





The annual maximum of daily discharge can be well represented by population, which is used as a proxy of urbanization.



Risk ratio = P1/P2

Urbanization greatly increase the probability of extreme discharge at almost all the basins.