Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey and tropical storm Allison

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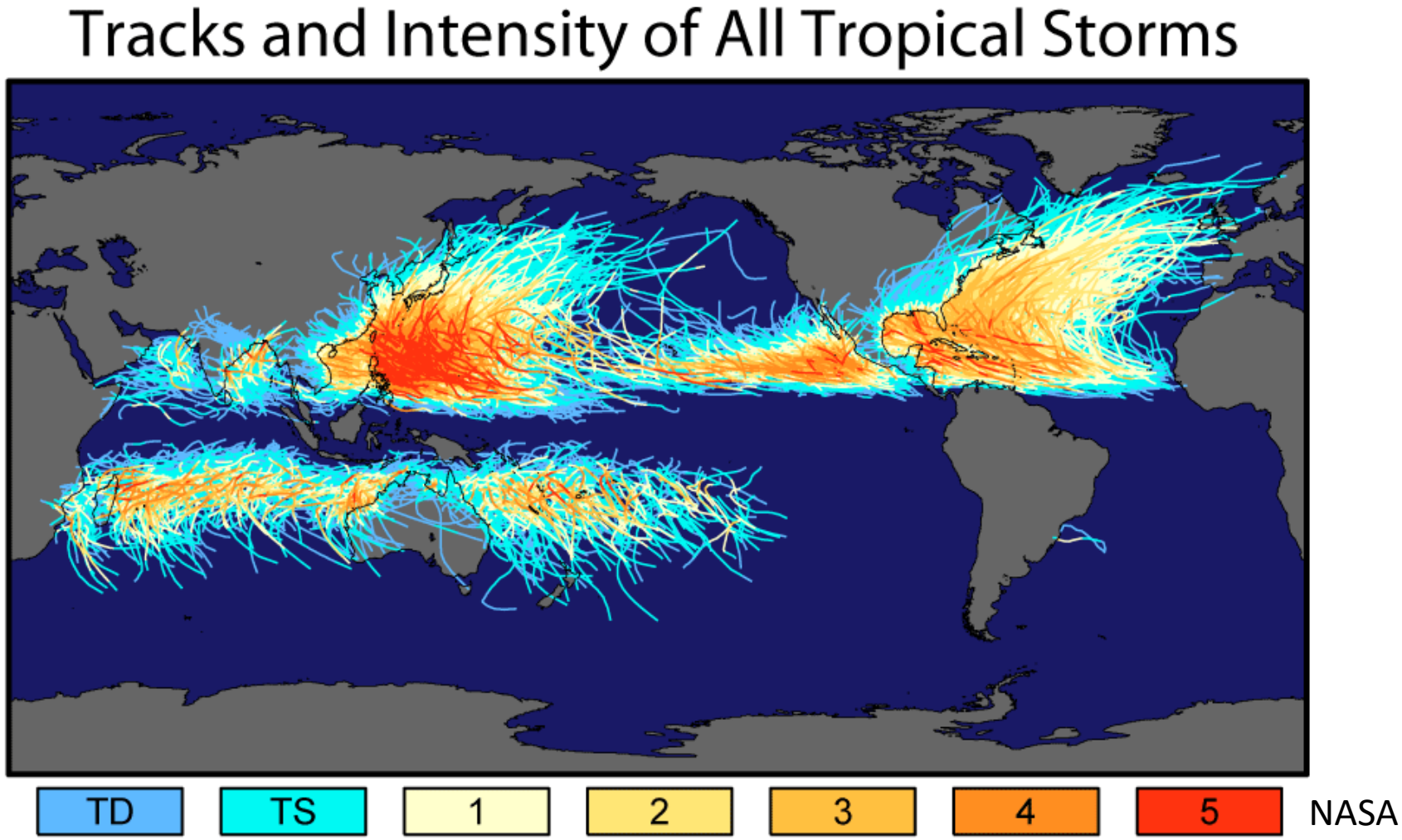
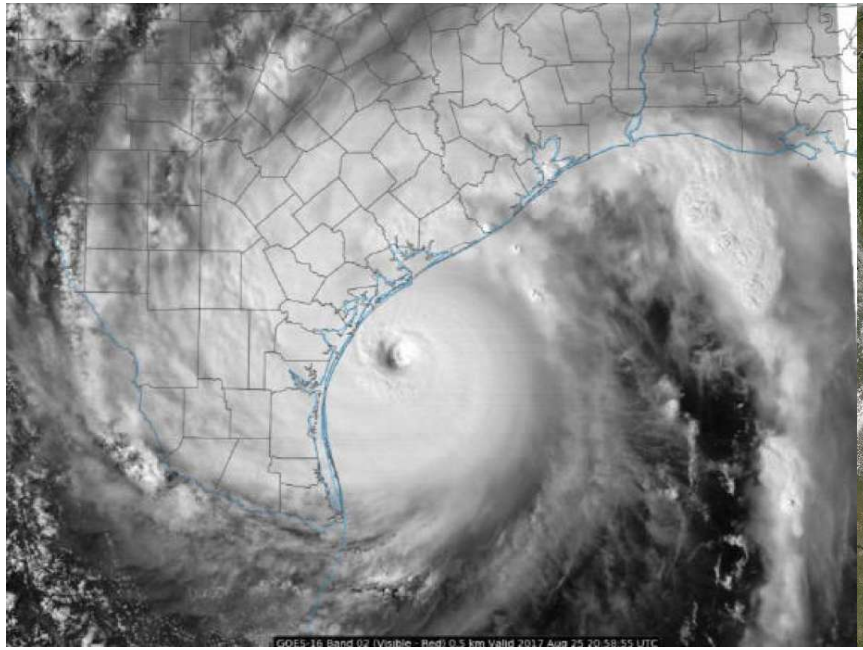
Hurricanes are formed in the warm ocean and make landfall over coastal regions occasionally.



NASA

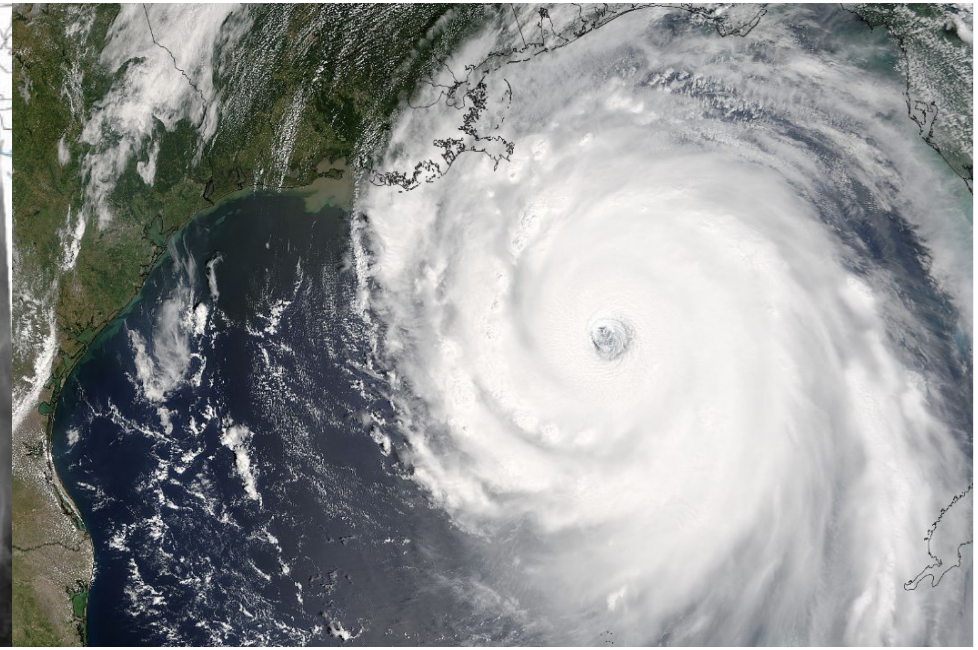
Hurricanes are warm-core low-pressure systems with destructive winds and torrential rainfall.

Harvey in 2017



100+ casualties
$125+ billion in damage

Katrina in 2005

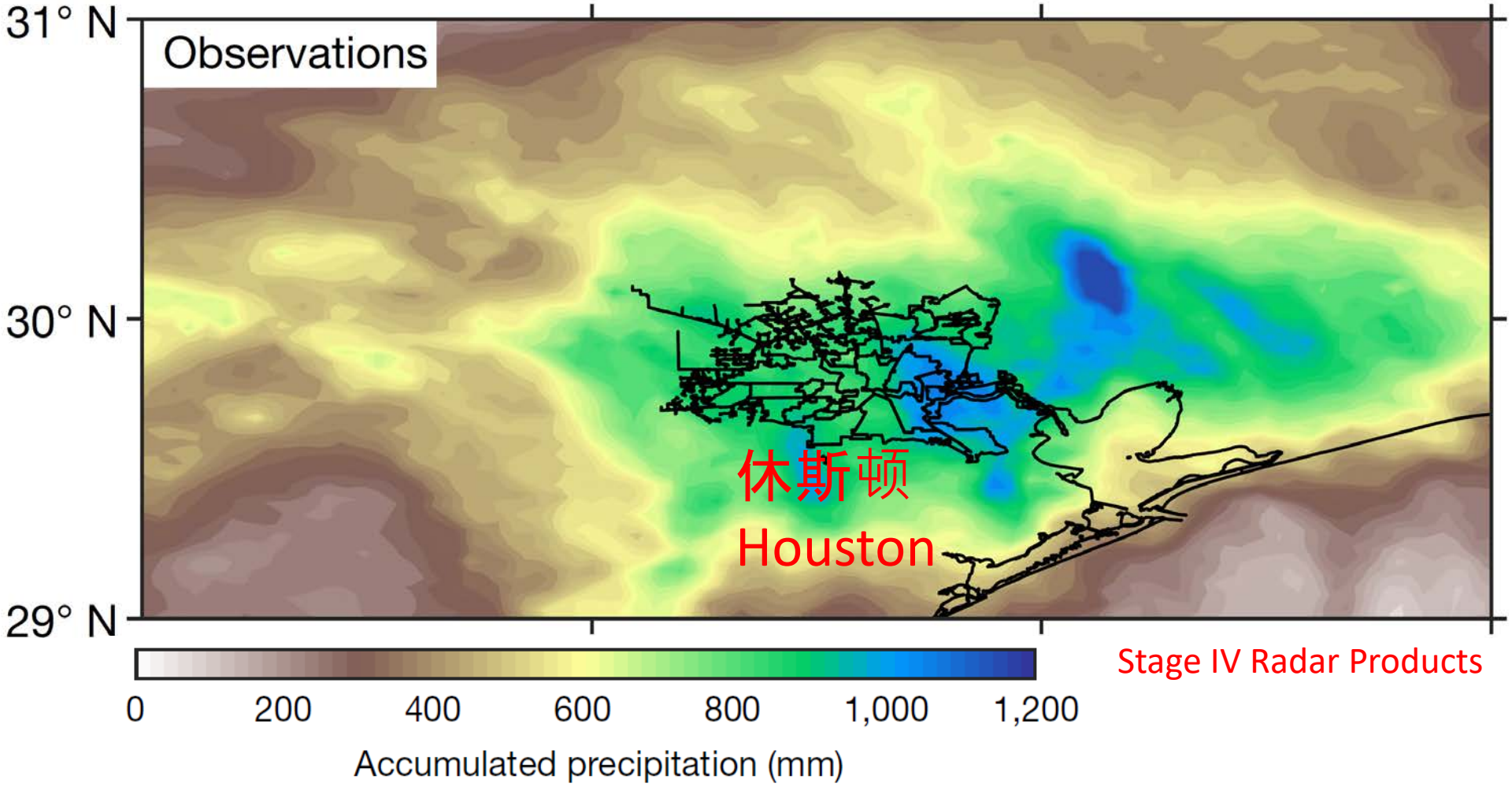


1,800+ casualties
$160+ billion in damage

National Weather Service

Harvey stayed in Texas for several days. The reason for its stalling movement is still under investigation.

Record-breaking hurricane Harvey poured more than 1 meter rainfall over some parts of Houston.



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

Associated Press

CNN

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)

Climate change increased the probability of Harvey rainfall events.

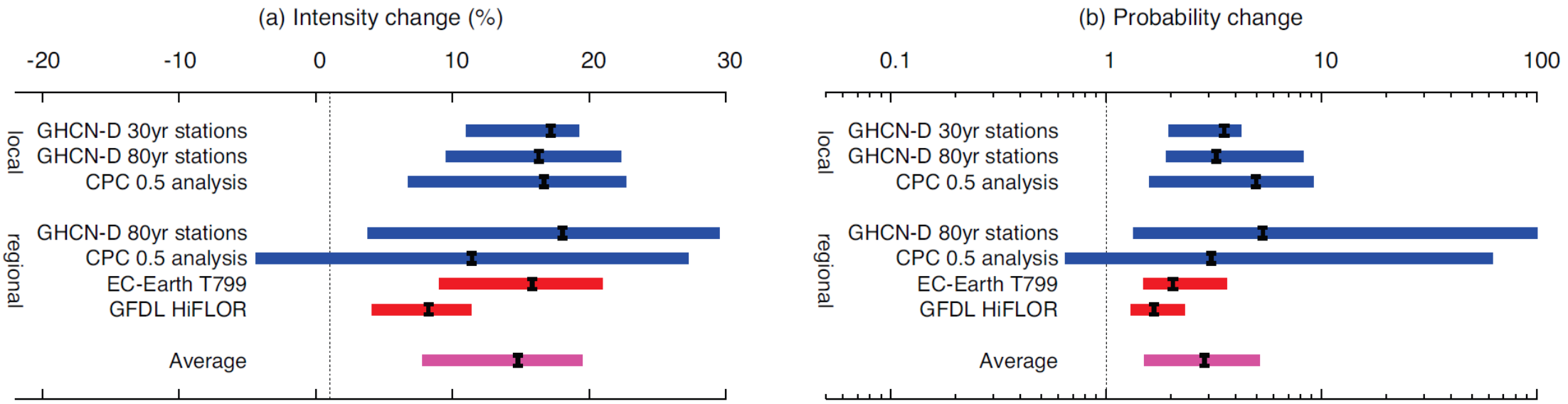
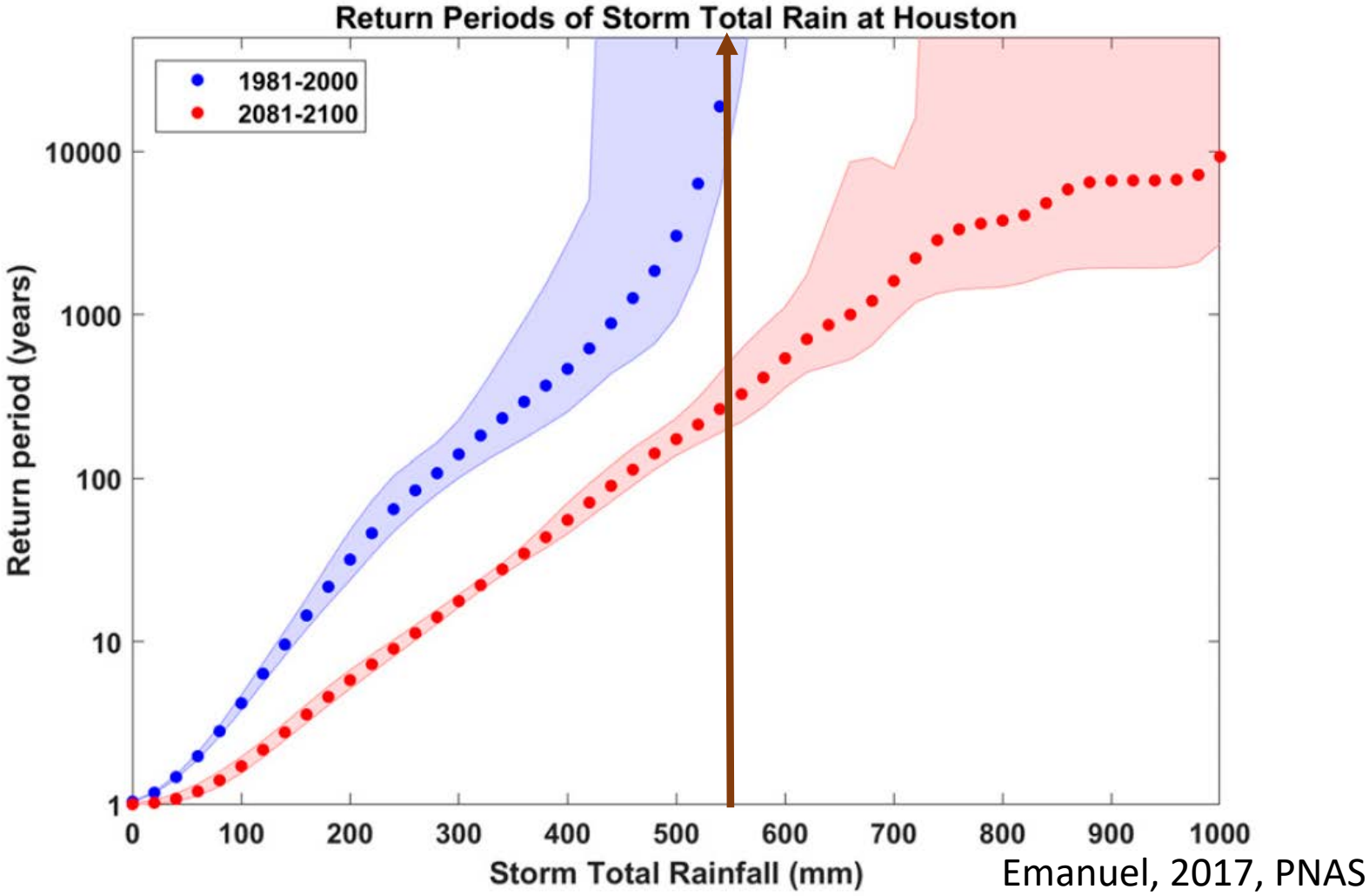


Figure 7. Synthesis of the results. (*a*) Intensity changes 1880–2017 for local and regional extreme three-day precipitation events along the US Gulf Coast (%). Observations are shown in blue, models in red. The magenta line is the average of the three estimates from local observations (with smaller uncertainties) and the two regional model analyses (that can only reproduce these more extreme events reliably). (*b*) Same for the RRs (changes in probability).

(Van Oldenborgh et al. 2018)

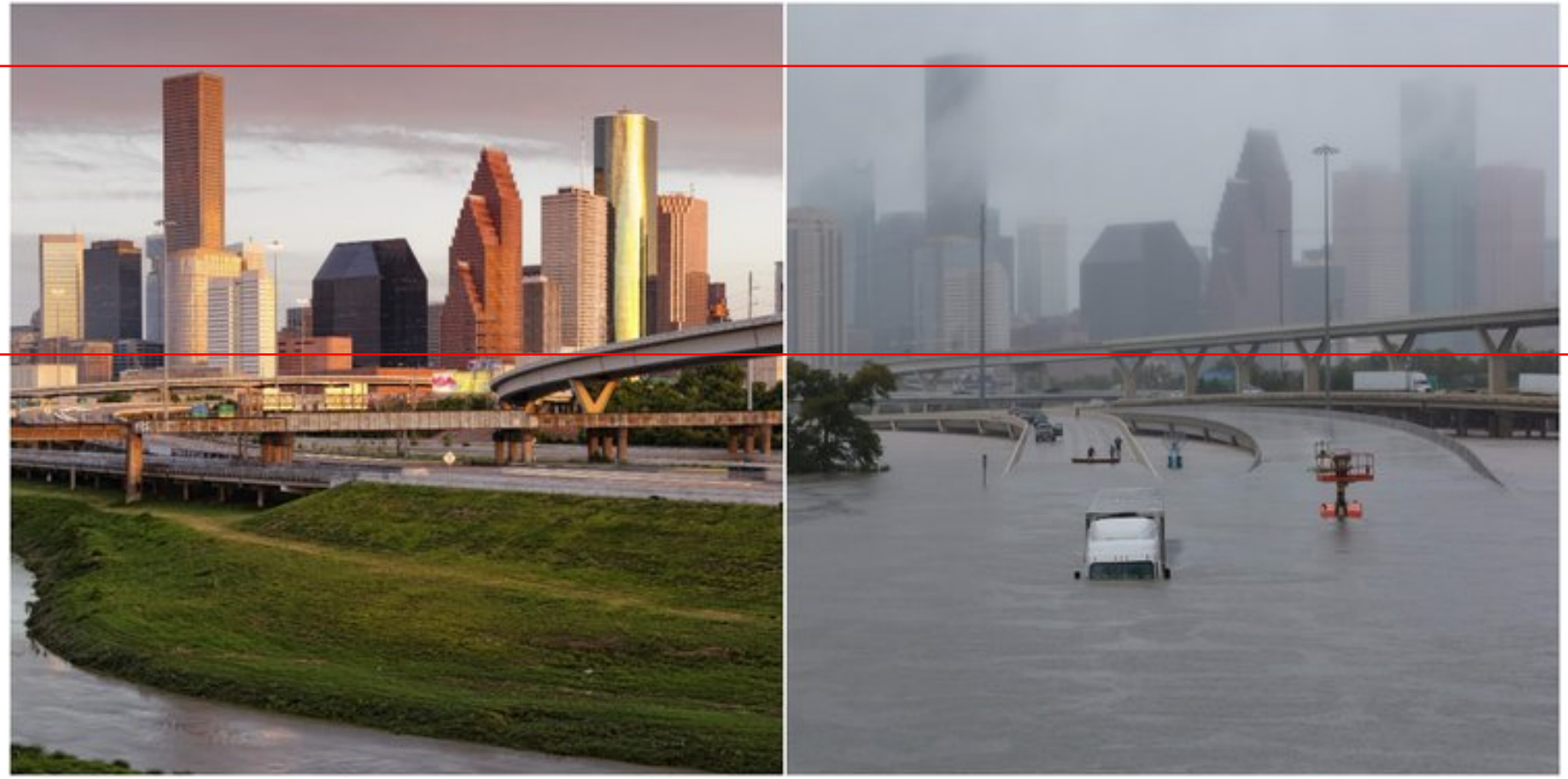
Again, climate change increased the probability of Harvey rainfall events.



Emanuel, 2017, PNAS

But, I examined Harvey rainfall from a different perspective …

What was the role played by buildings in Houston in changing the rainfall associated with hurricane Harvey?



Before Hurricane Harvey

After Hurricane Harvey

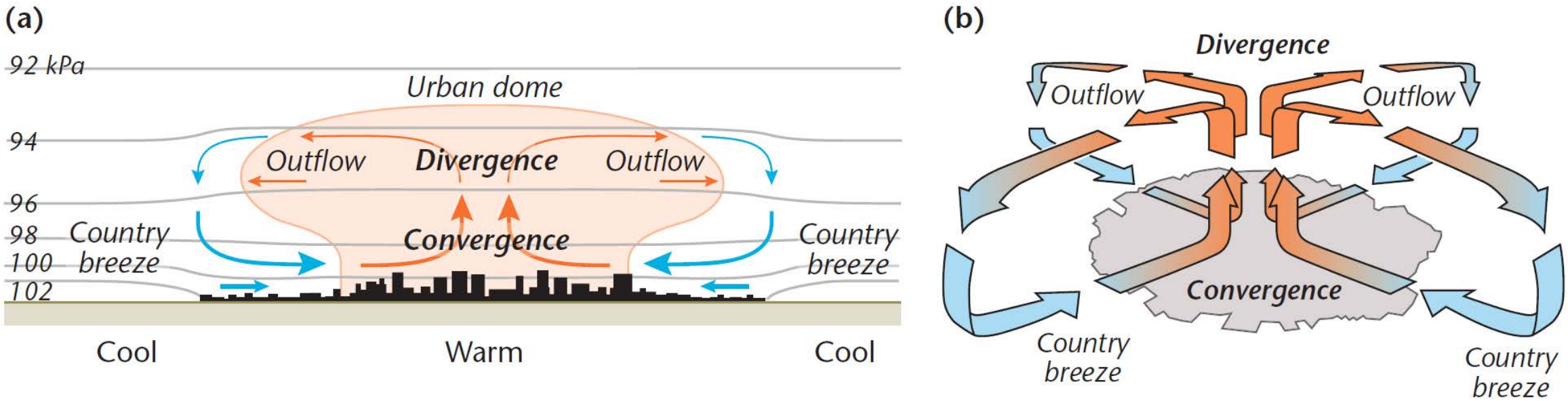


Figure 4.31 Schematic of the urban heat island circulation (UHIC). **(a)** Idealized 2D air pressure distribution (thin horizontal arrows represent horizontal pressure gradient forces), and dotted lines are isobars (lines of equal atmospheric pressure in kPa). The thick lines are the resulting circulation. **(b)** Highly simplified view of the 3D circulation pattern (neglecting the Coriolis force).

Oke et al. 2018, Urban Climates

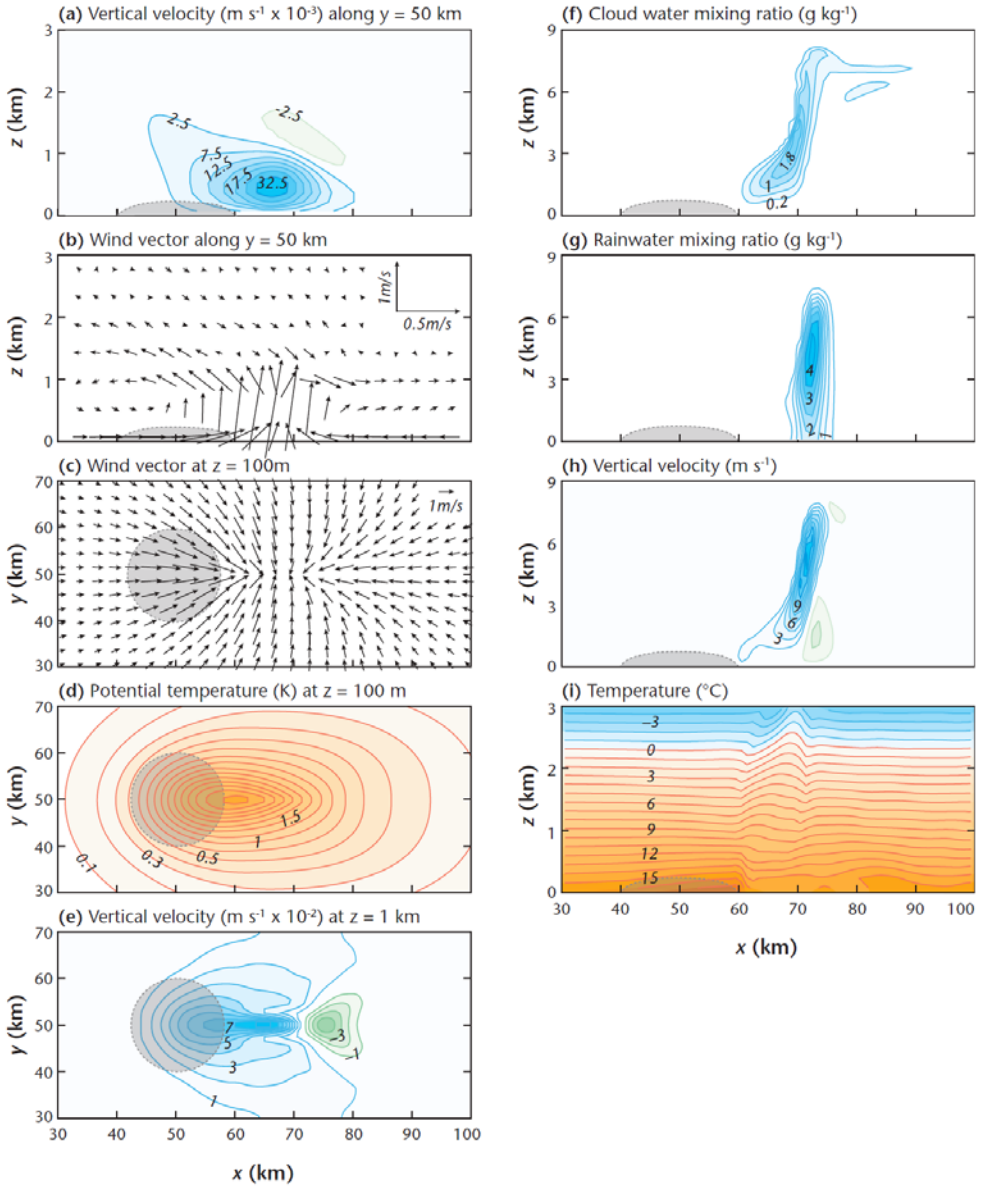
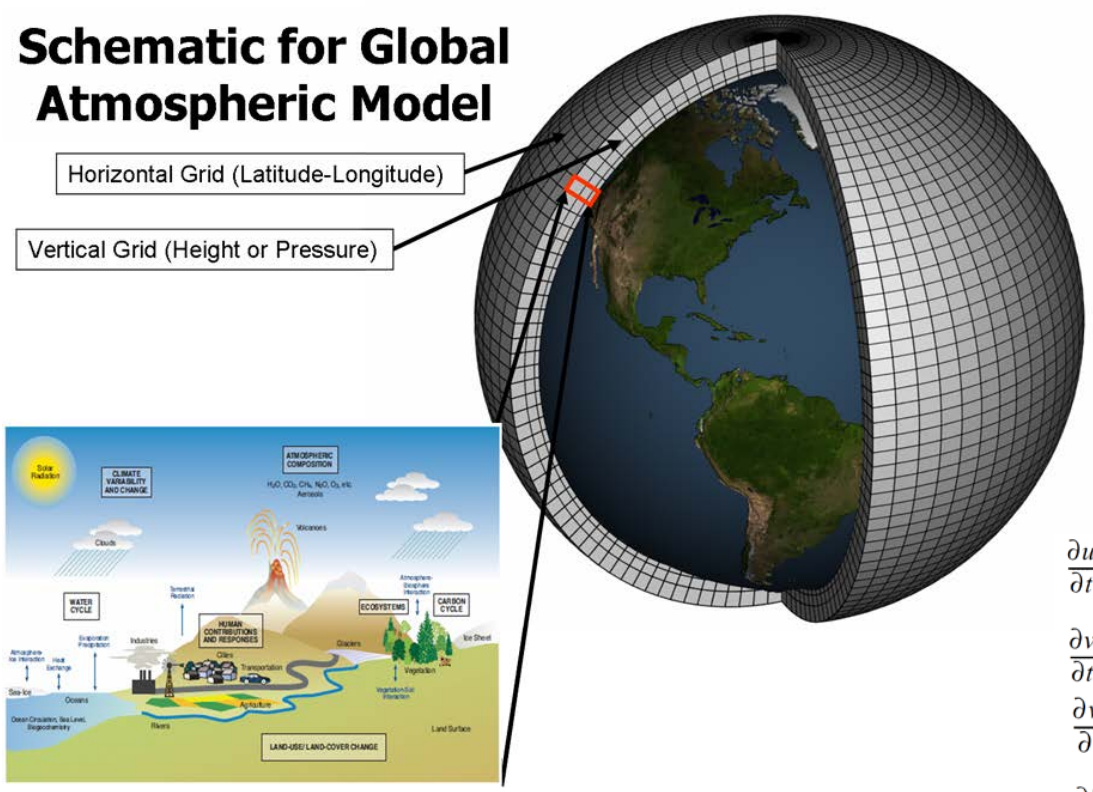


Figure 10.10 Numerical simulations of the impacts of urban heating (circular dotted region between 40–60 km on the *x* axis) in a dry (left panels) and moist (right panels) atmosphere. Left panels: **(a)** vertical velocity (m s^{-1}), **(b)** perturbation wind vector through and downwind of the urban 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.

How can we quantify the role of urbanization in shaping rainfall caused by hurricanes?

Numerical models are computer programs to simulate the Earth's climate system.



Source:
Geophysical Fluid Dynamics Laboratory

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} + \frac{uv\tan\phi}{a} - \frac{uw}{a} - \frac{1}{\rho}\frac{\partial p}{\partial x} - 2\Omega(w\cos\phi - v\sin\phi) + Fr_x$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \frac{u^2\tan\phi}{a} - \frac{uw}{a} - \frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega u\sin\phi + Fr_y$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \frac{u^2+v^2}{a} - \frac{1}{\rho}\frac{\partial p}{\partial z} + 2$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} + (\gamma - \gamma_d)w + \frac{1}{c_p}\frac{dH}{dt}$$

$$\frac{\partial \rho}{\partial t} = -u\frac{\partial \rho}{\partial x} - v\frac{\partial \rho}{\partial y} - w\frac{\partial \rho}{\partial z} - \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial q_v}{\partial t} = -u\frac{\partial q_v}{\partial x} - v\frac{\partial q_v}{\partial y} - w\frac{\partial q_v}{\partial z} + Q_v$$

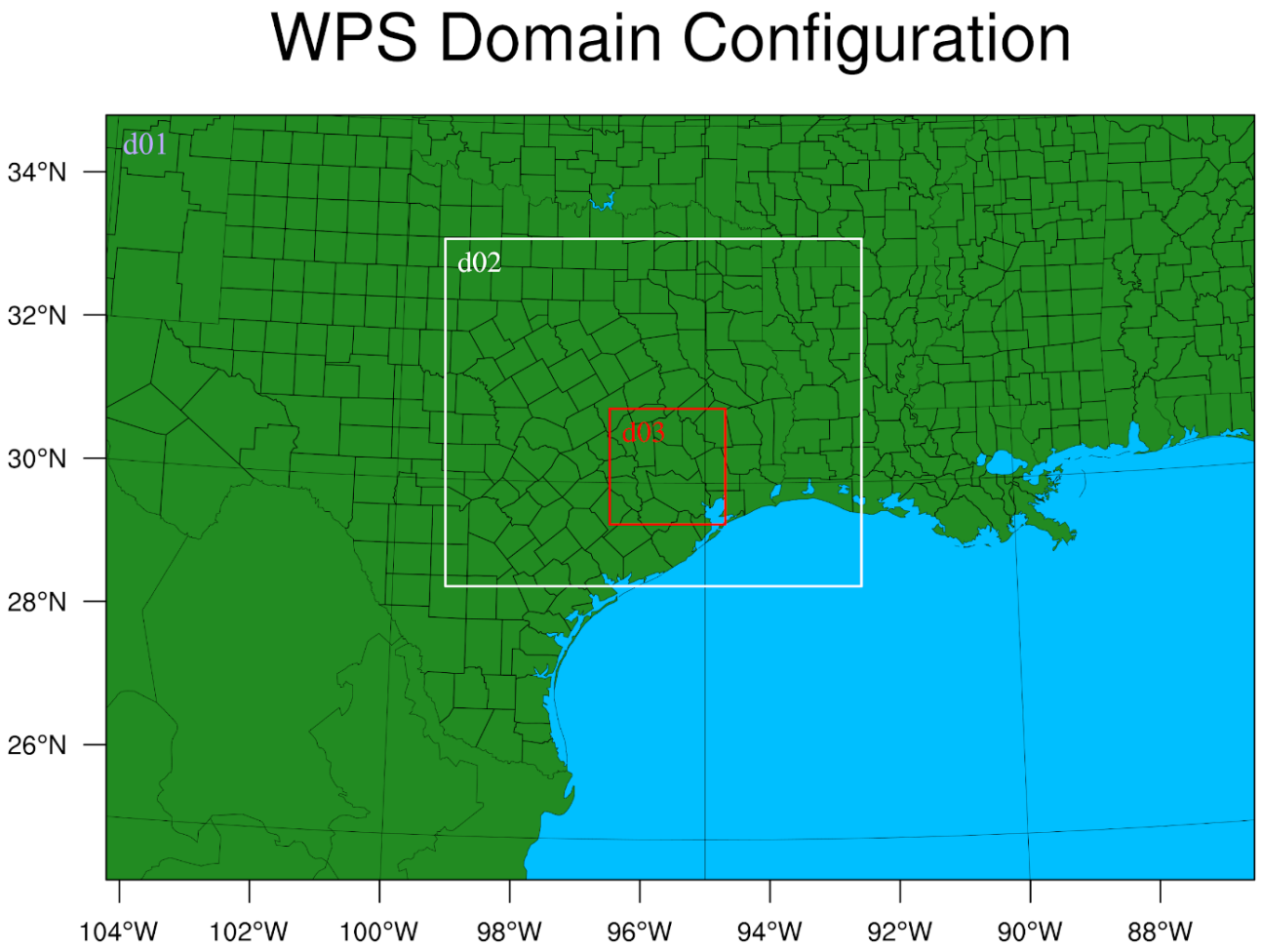
$$P = \rho RT$$

The “Urban” and “NoUrban” experiments allow us to quantify the role of the urban environment during Harvey.

With Urban

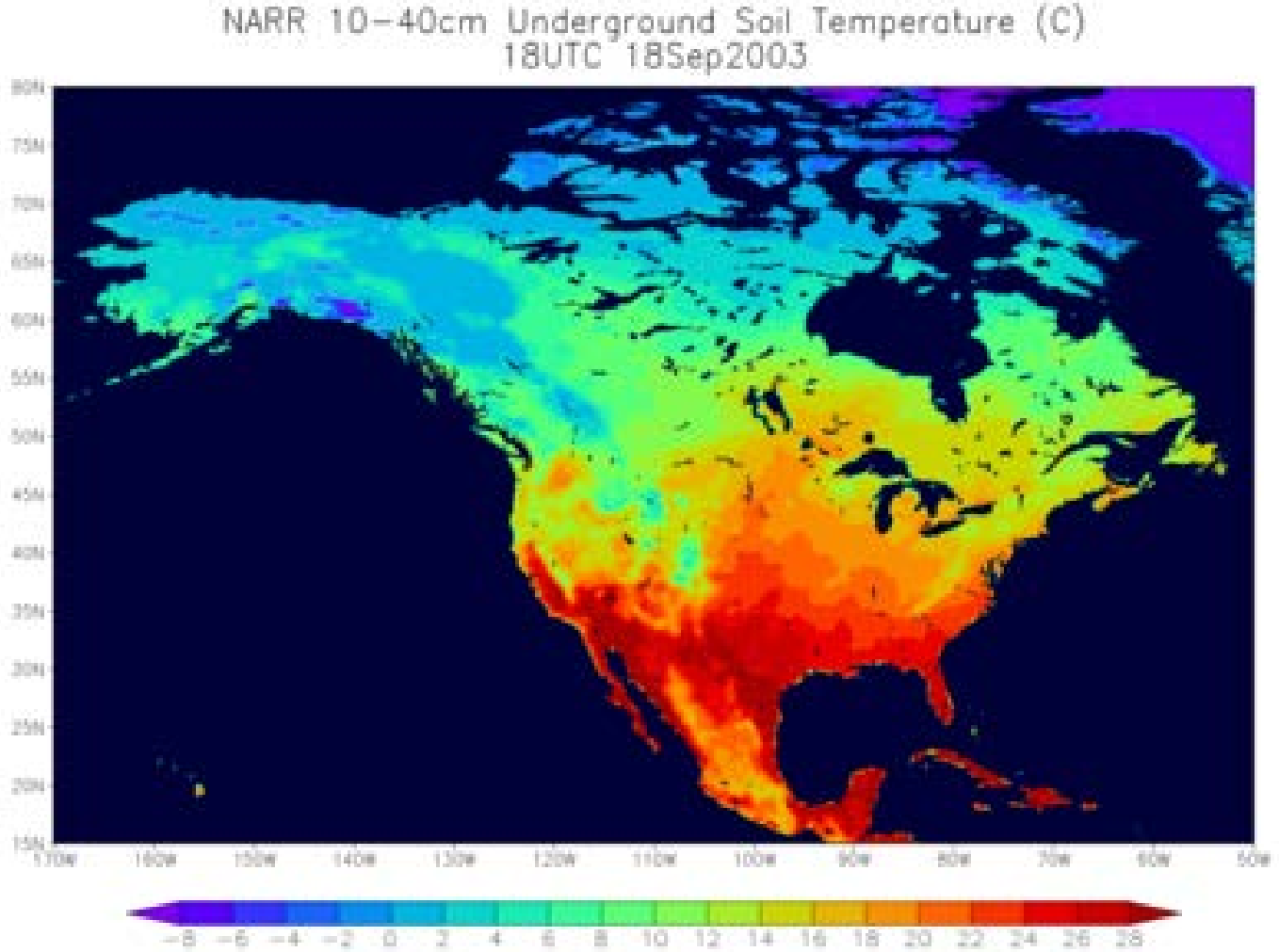
Without Urban

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



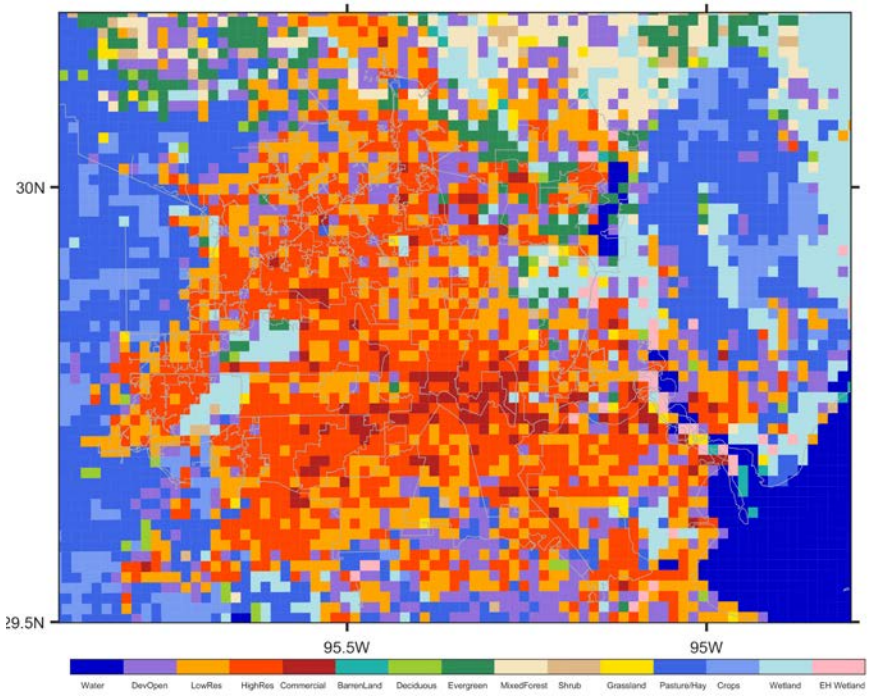
Physics	Options
Microphysics	WSM 6-class graupel scheme
Surface layer	Monin-Obukhov scheme
Land surface	unified Noah land-surface model
Boundary layer scheme	Mellor-Yamada-Janjic TKE scheme
Cumulus parameterization	None for d02 and d03, and the Betts-Miller-Janjic scheme for d01
Longwave radiation	Rapid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

The North American Regional Reanalysis (NARR) is a regional reanalysis of North America containing temperatures, winds, moisture, soil data at 3-hourly temporal resolution and 32-km spatial resolution.

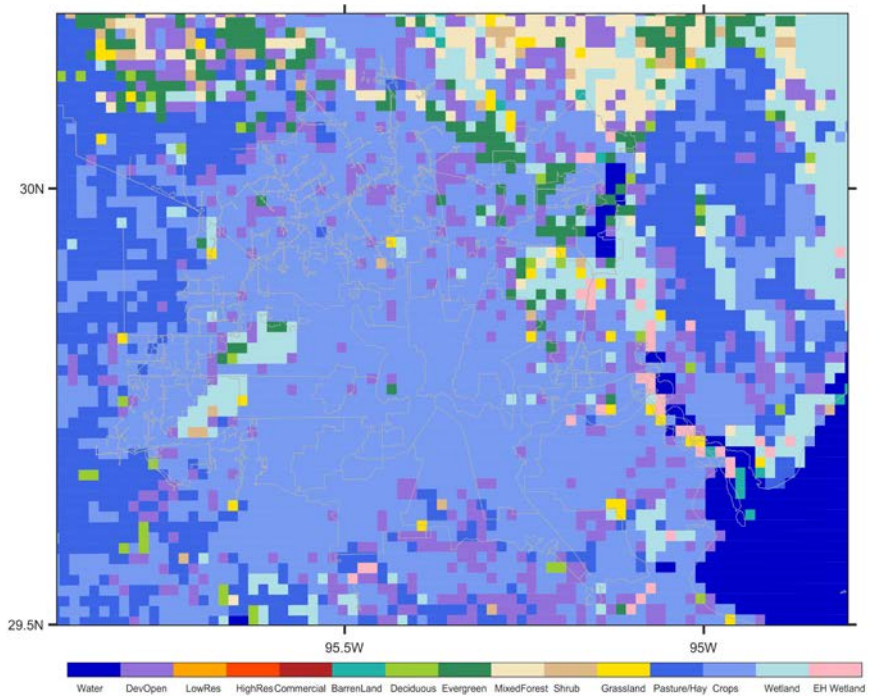


National Centers for Environmental Prediction (NCEP)

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



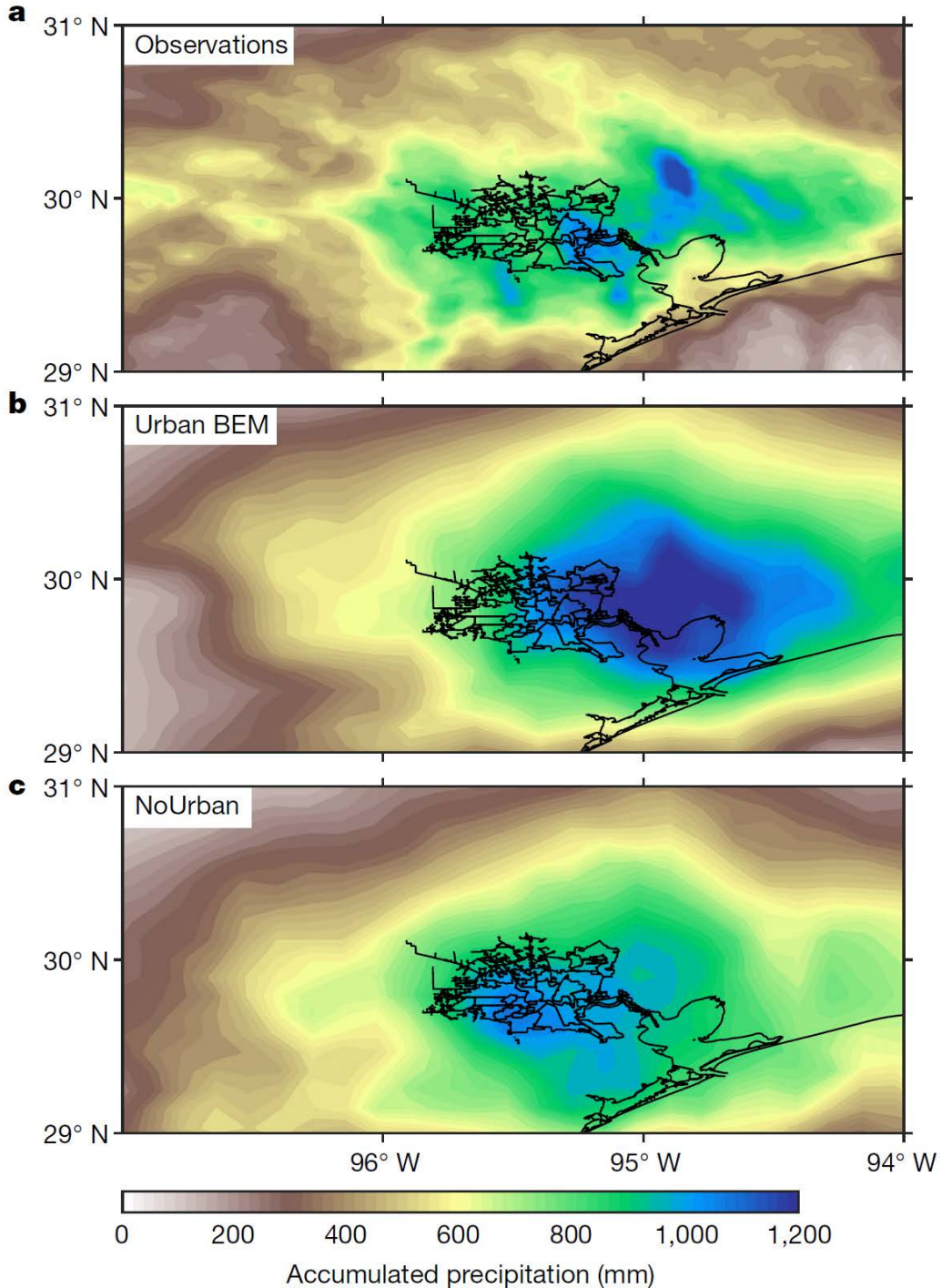
Urban



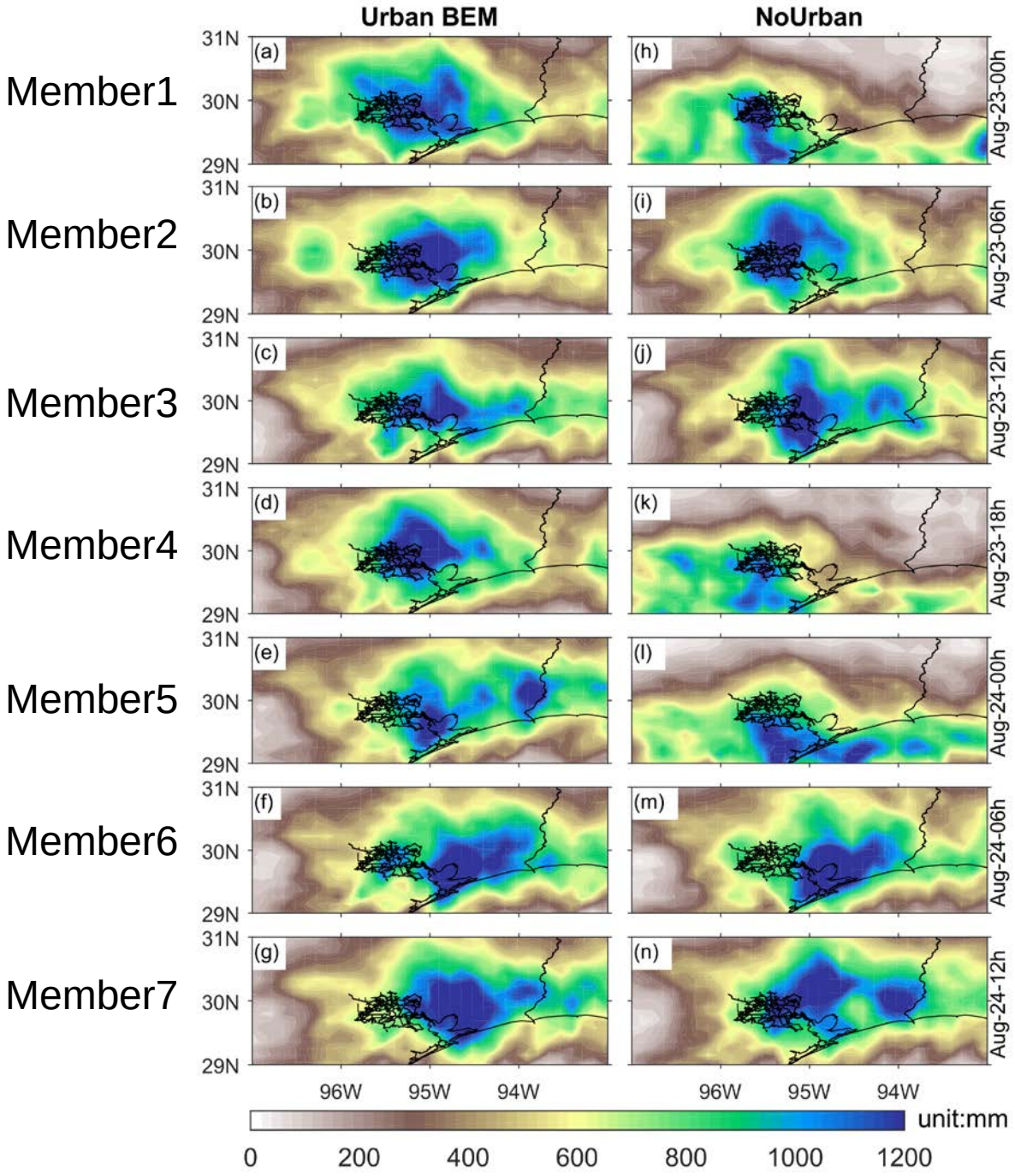
NoUrban

Urban minus NoUrban = Impacts of Urban

National Land Cover Database (NLCD) 2011



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

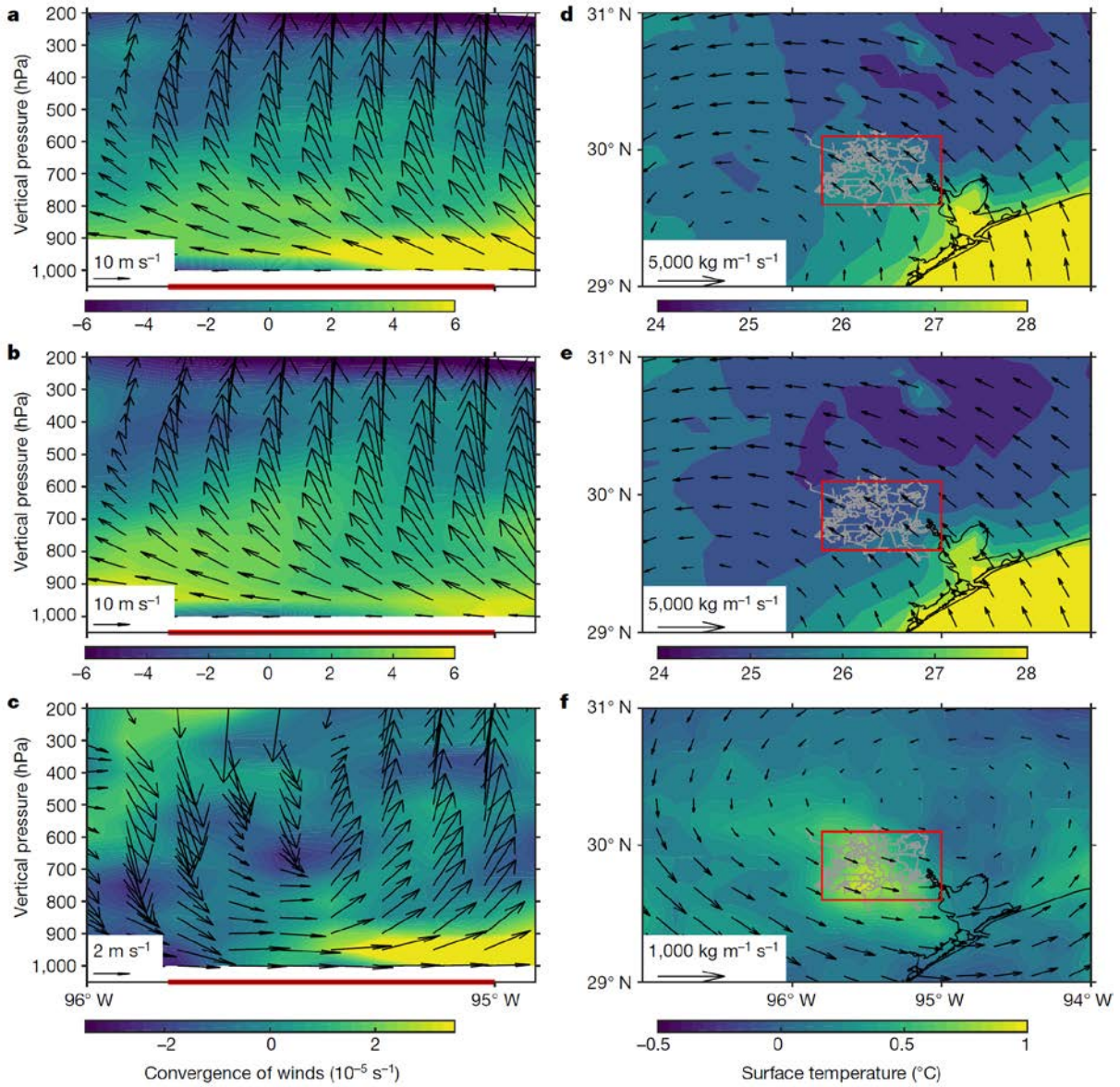

Urban BEM
NoUrban
Member1
Member2
Member3
Member4
Member5
Member6
Member7
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
31N
30N
29N
96W
95W
94W
Aug-23-00h
Aug-23-06h
Aug-23-12h
Aug-23-18h
Aug-24-00h
Aug-24-06h
Aug-24-12h
unit:mm
0
200
400
600
800
1000
1200

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

Urban

NoUrban

Urban minus NoUrban

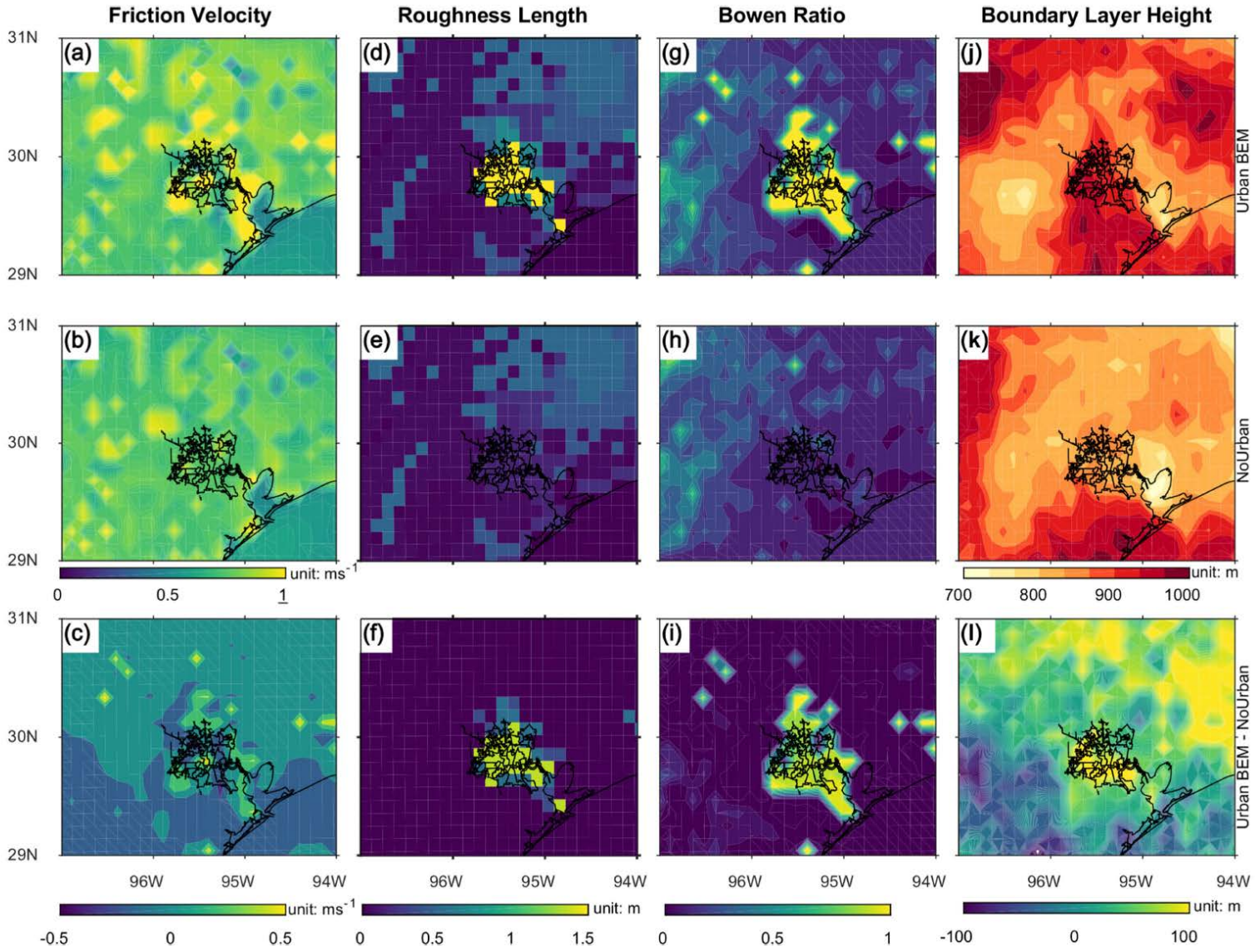


The city led to an increase in roughness length, leading to an increase in friction velocity and drag over the city.

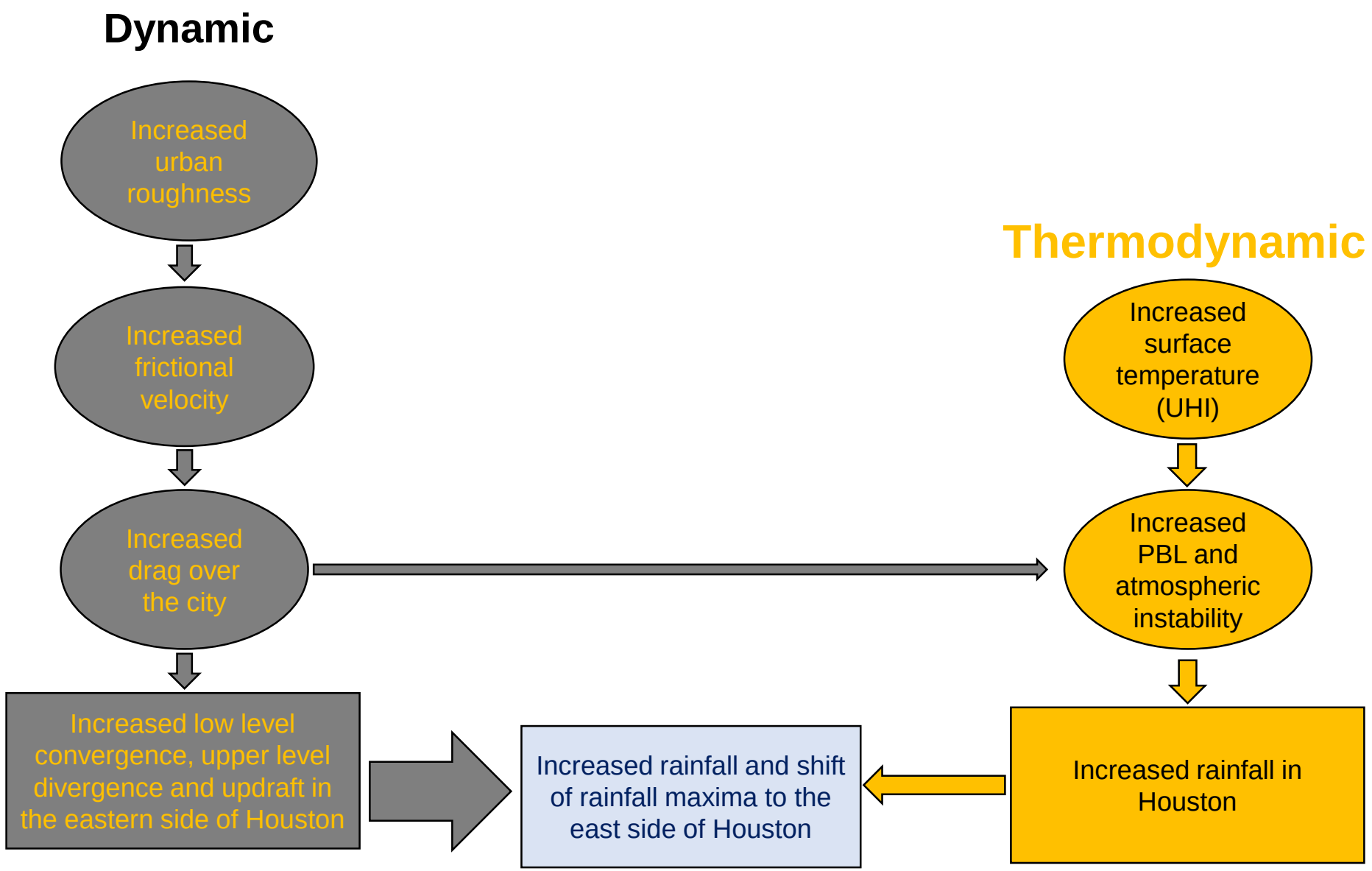
Urban

NoUrban

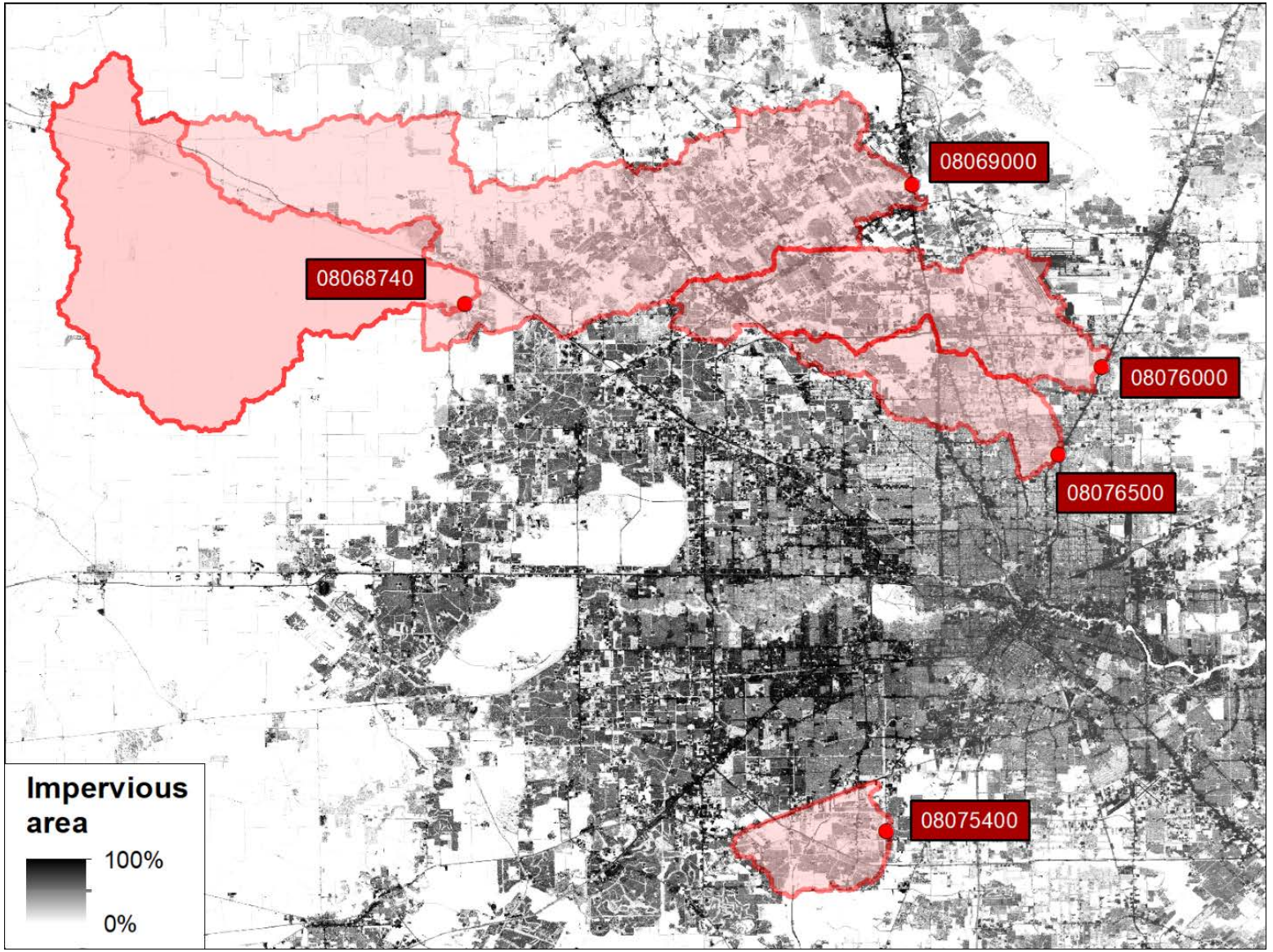
Urban minus NoUrban

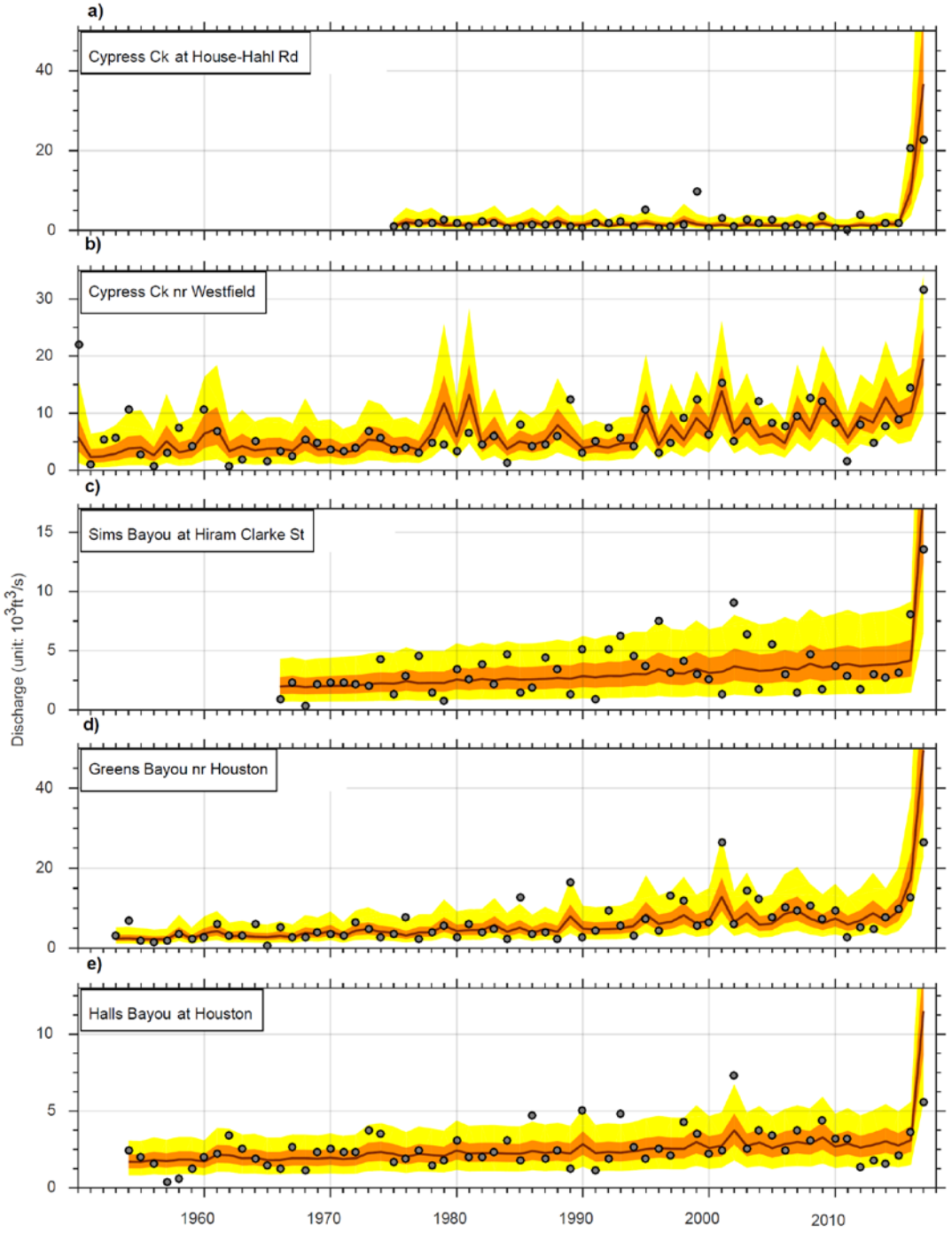


Urban Impacts on Rainfall Caused by Harvey

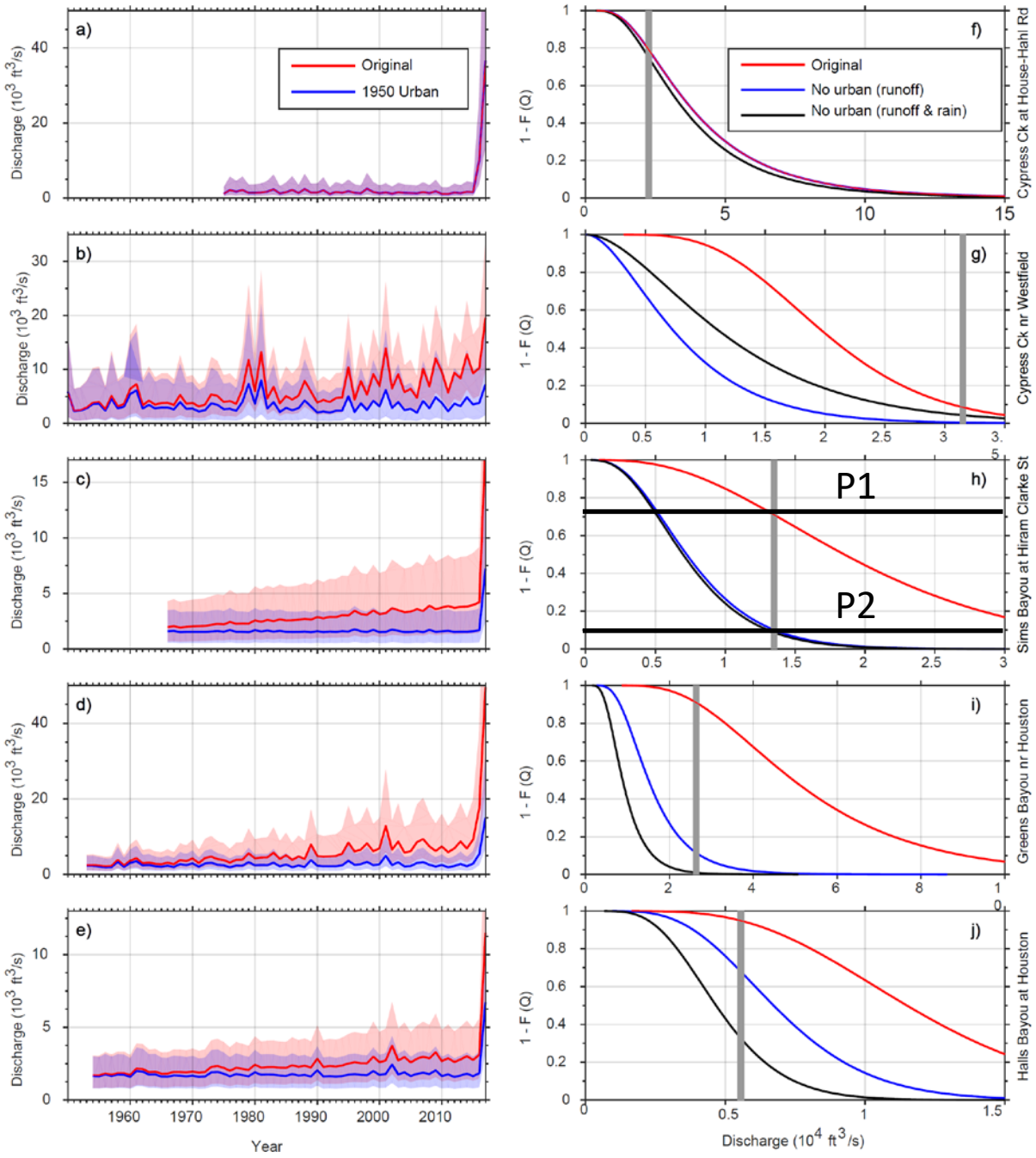


Basin boundaries of the five watersheds considered in this study, together with their United States Geological Survey (USGS) station ID numbers.





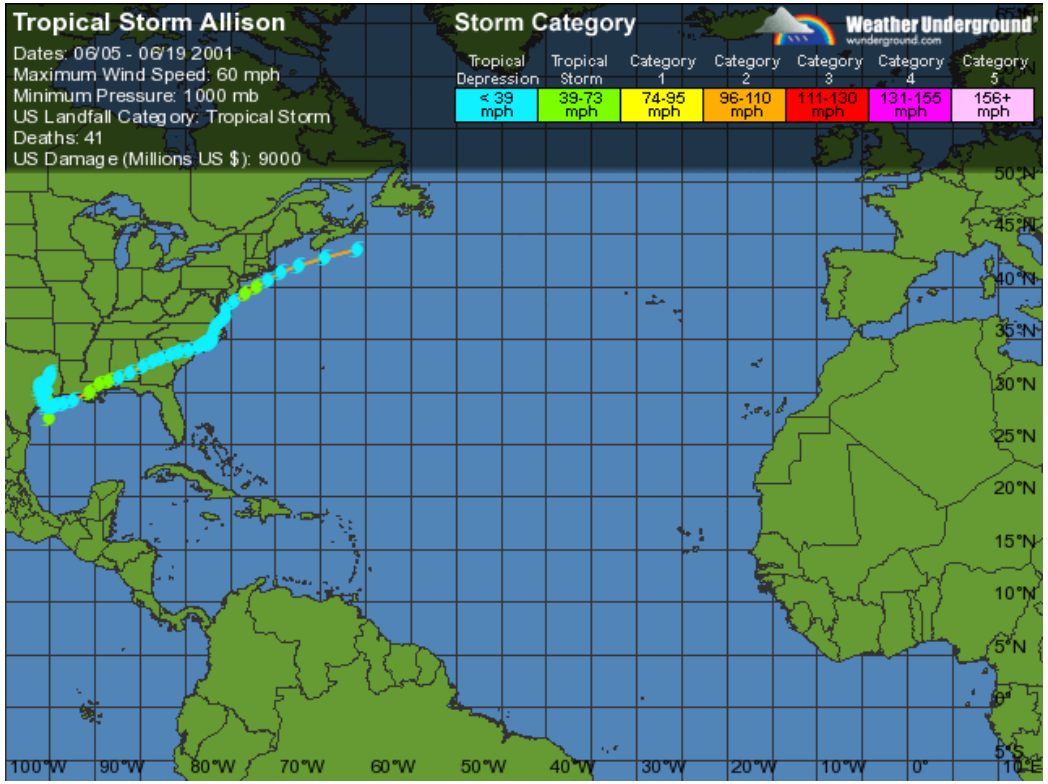
The annual maximum of daily discharge can be well represented by population, which is used as a proxy of urbanization.



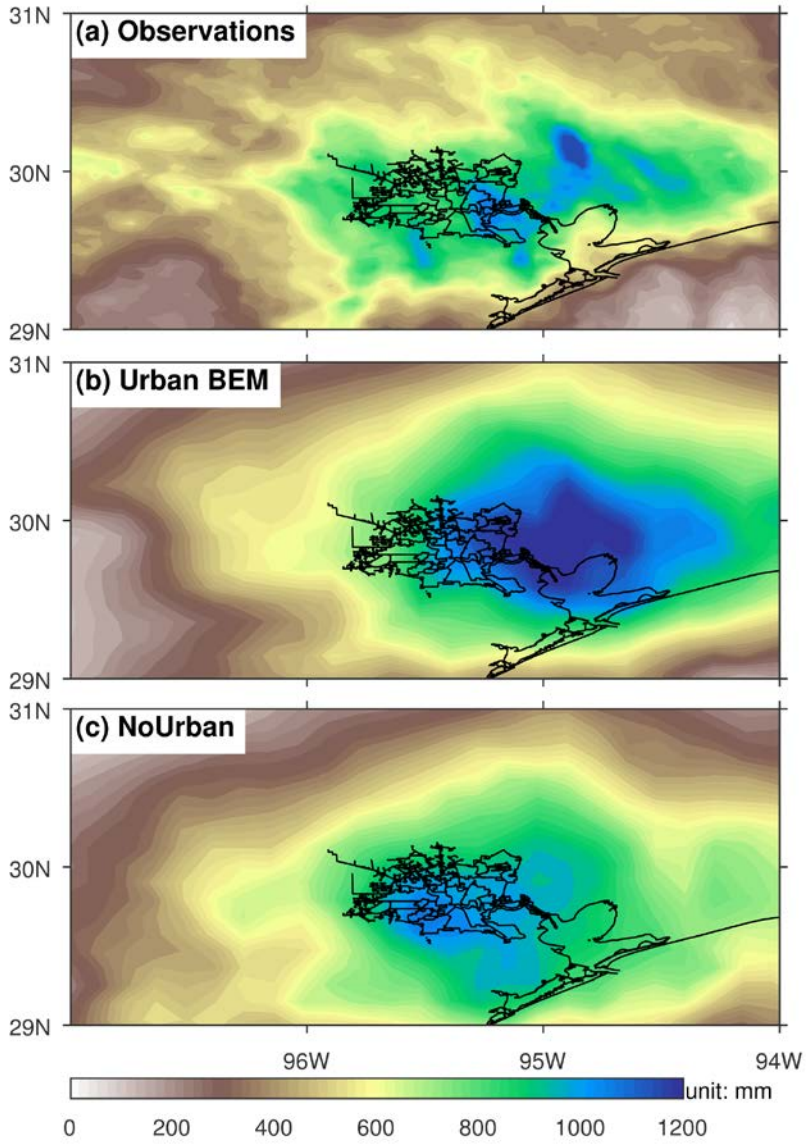
Risk ratio = P1/P2

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

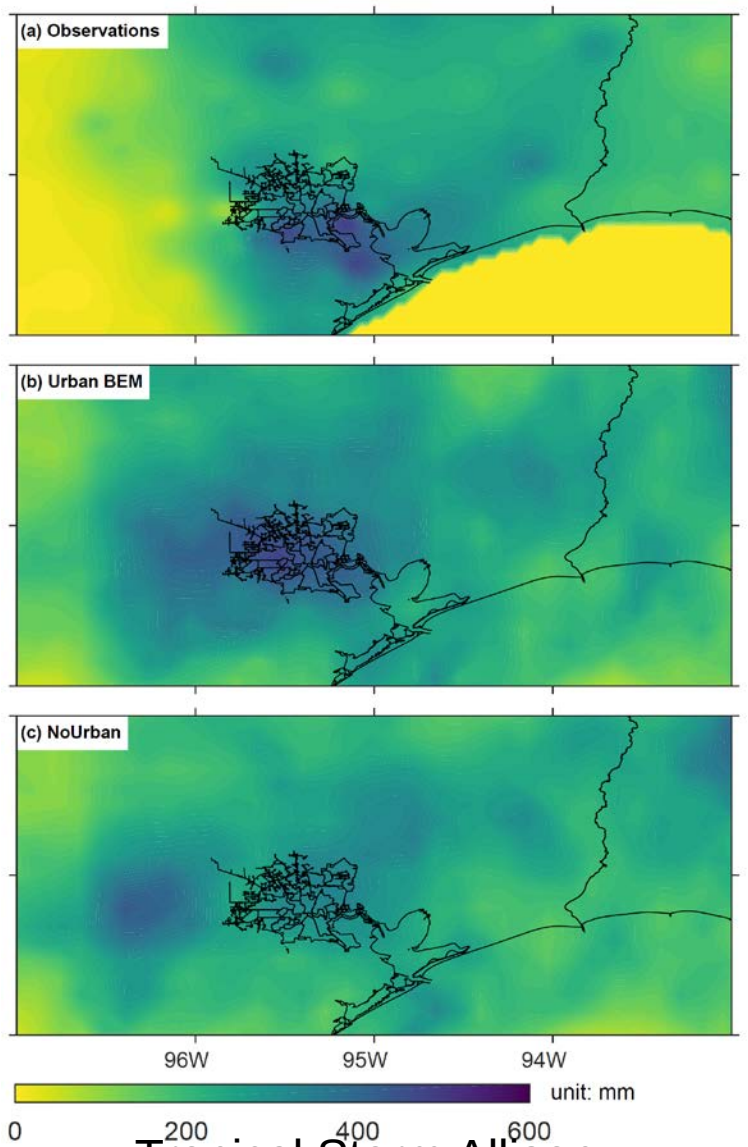
Tropical storm Allison also led to flooding in Houston in 2001.



Both storms exhibit a westward shift in precipitation in “NoUrban” experiments.

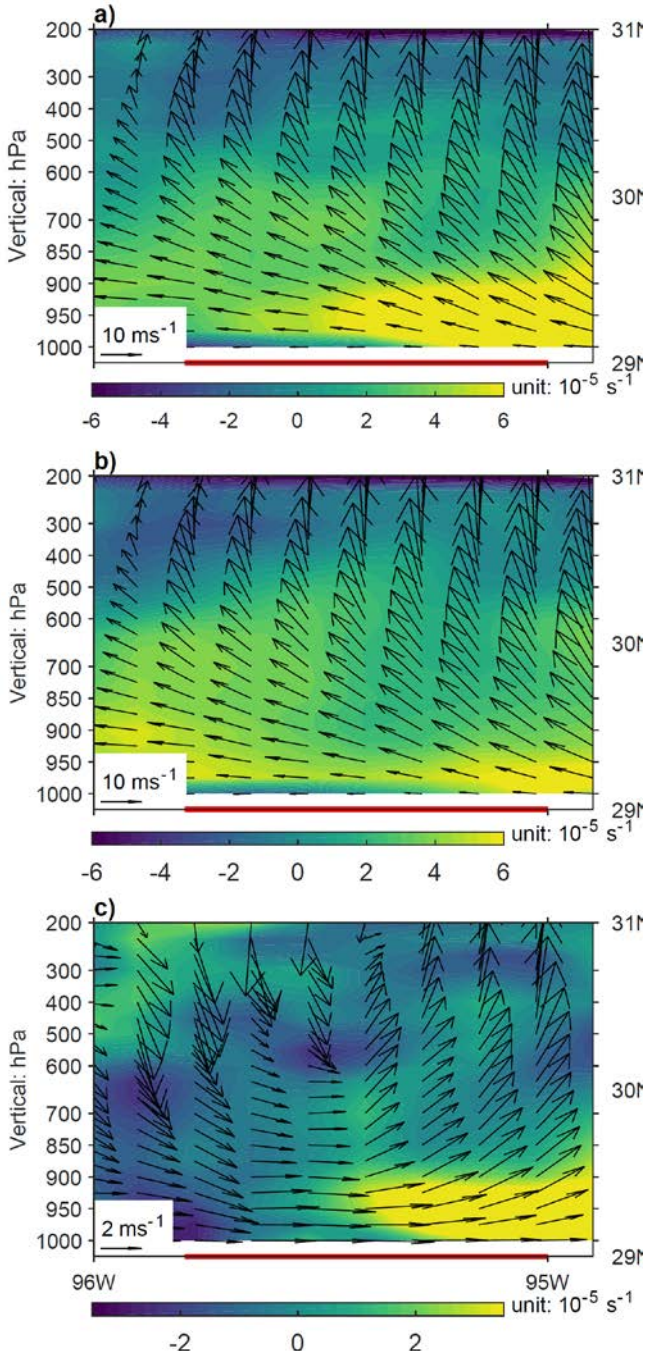


Hurricane Harvey

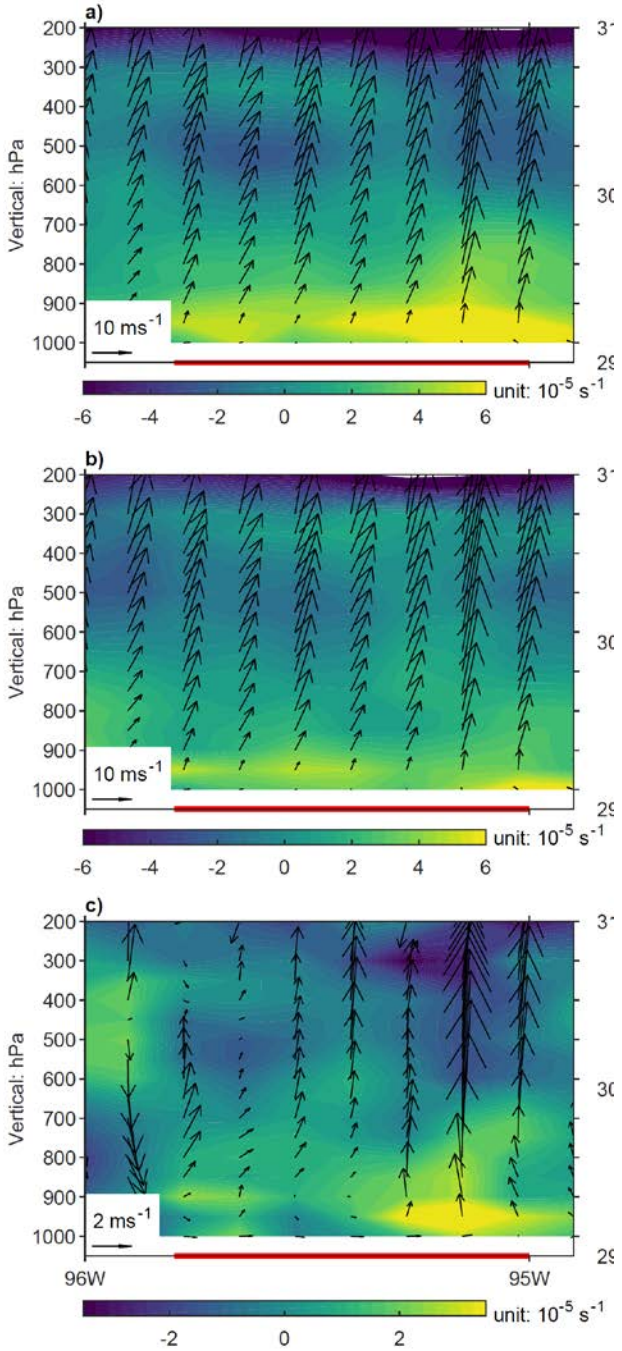


Tropical Storm Allison

Hurricane Harvey

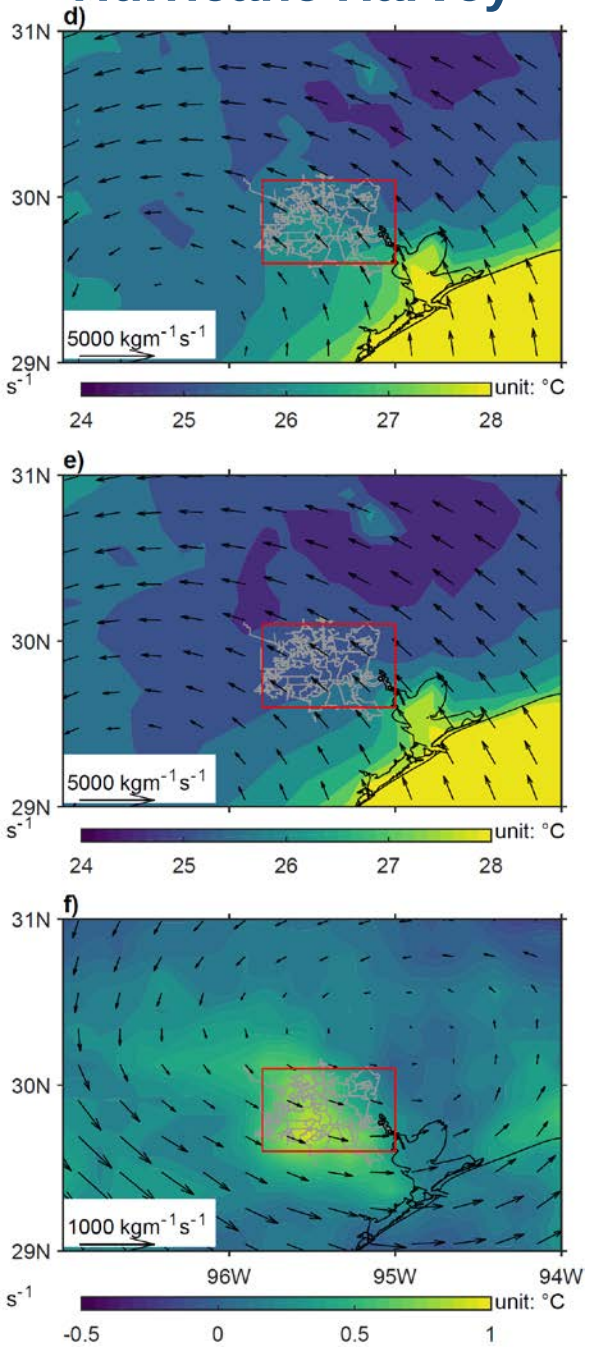


Tropical Storm Allison

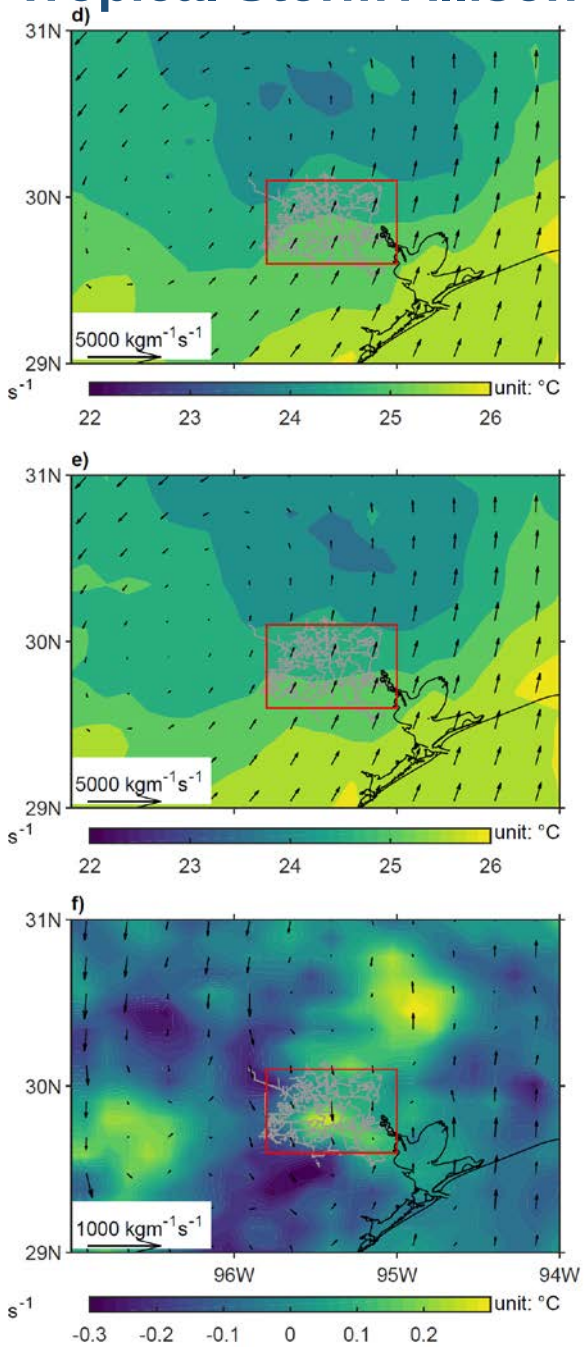


Upward drafts appear in the eastern side of Houston for Harvey and the entire Houston for Allison.

Hurricane Harvey



Tropical Storm Allison



Urban heat island effects in Houston for both storms

Summary

- Urbanization strongly exacerbated the impact that this storm has had in terms of both precipitation and flood response.
- The probability of such extreme flood events across the studied basins increased on average by about 21 times in the period 25–30 August 2017 because of urbanization.

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.

- **PhD Student Opportunity (Impacts of Urbanization on Flooding from Tropical Cyclones)**

IIHR – Hydroscience & Engineering and the Department of Civil and Environmental Engineering at the University of Iowa seek a highly motivated PhD student. The research is part of a project funded by the National Science Foundation entitled "Quantification of the Impacts of Urban Areas on Heavy Rainfall and Flooding from North Atlantic Tropical Cyclones."

Qualifications: Candidates must have a degree in an engineering field, atmospheric or climate-related science. A background in hydrologic is preferred. Individuals with experience running WRF or a comparable model, good knowledge of computer programming (in particular R and Python), and comfort in Linux environment are strongly encouraged to apply. Please include the following material:

1) Cover letter discussing research interests and relevant experience/background
2) Resume
3) Unofficial transcripts and/or GRE scores (TOEFL scores where applicable)

Thanks!
Q & A