The human influence on recent extreme storms.

Probabilistic Flood Hazard Assessment (PFHA) Research Workshop
US Nuclear Regulatory Commission
February 19, 2020

Michael F. Wehner
Lawrence Berkeley National Laboratory

Houston, Texas after Harvey

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Or
Did global warming flood my house?

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US DOE Policy 411.2A

SUBJECT: SCIENTIFIC INTEGRITY

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What is the “safe” amount of climate change?

- United Nations Framework Convention on Climate Change”
  - “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic [human] interference with the climate system.”
- 2009 Copenhagen Accord:
  - This level is such that the global average temperature should be stabilized at two degrees Celsius (3.6 degrees Fahrenheit) above its preindustrial level.
- 2015 Paris Agreement (COP21):
  - “Invites the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways”
- 2020: We are already over 1^{o}C above pre-industrial levels.
  - I will argue that this is not safe.
  - Dangerous climate change is here now.

Dangerous climate change is already here?!

What have we done to extreme weather?

- "How has the risk of a weather event changed because of climate change?"

Or

- "How did climate change affect the magnitude of that event?"

Extreme event attribution

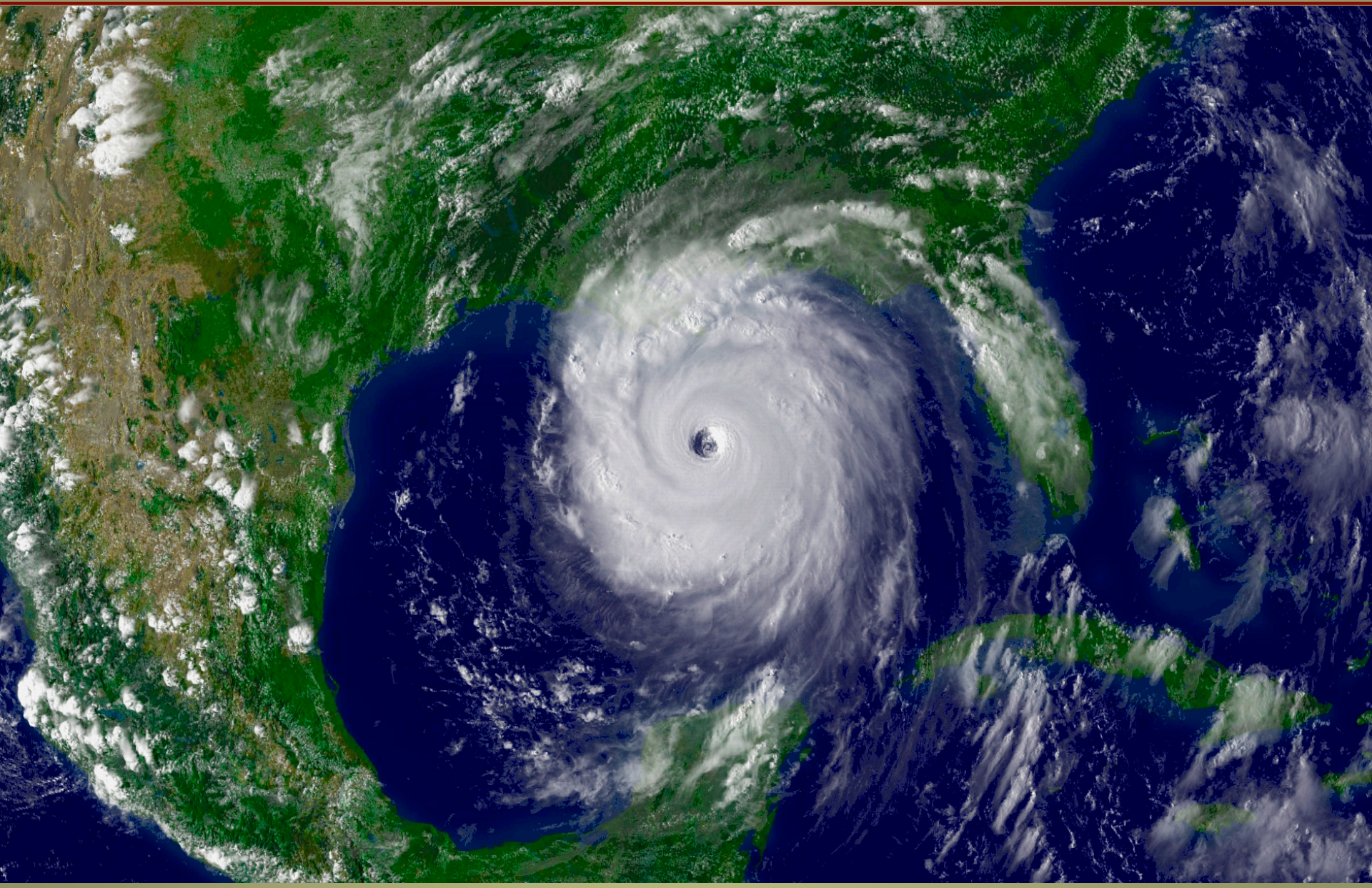
- This new science is called “Extreme Event Attribution”.
  - Invented in 2003 after the deadly European heatwave.
  - Quantifies the human influence, if any, on extreme weather events that have already occurred.
  - Borrows statistical methods from Epidemiology.
  - Fundamentally an exercise in Causal Inference.
  - A rapidly evolving science.
    - New technologies.
    - It is still getting warmer…

Extreme event attribution examples

- The chances of the 2003 European heat wave were found to be doubled.
  - Now, those chances have been increased by 10x.
- Global warming increased the chances of the 2015 hot and humid heat wave in Pakistan by a factor of at least 1000.

- Some seasonal flooding has been made more severe.
  - E.g. Spring 2013 Midwestern US
- As have some droughts.
  - E.g. 2011 East Africa

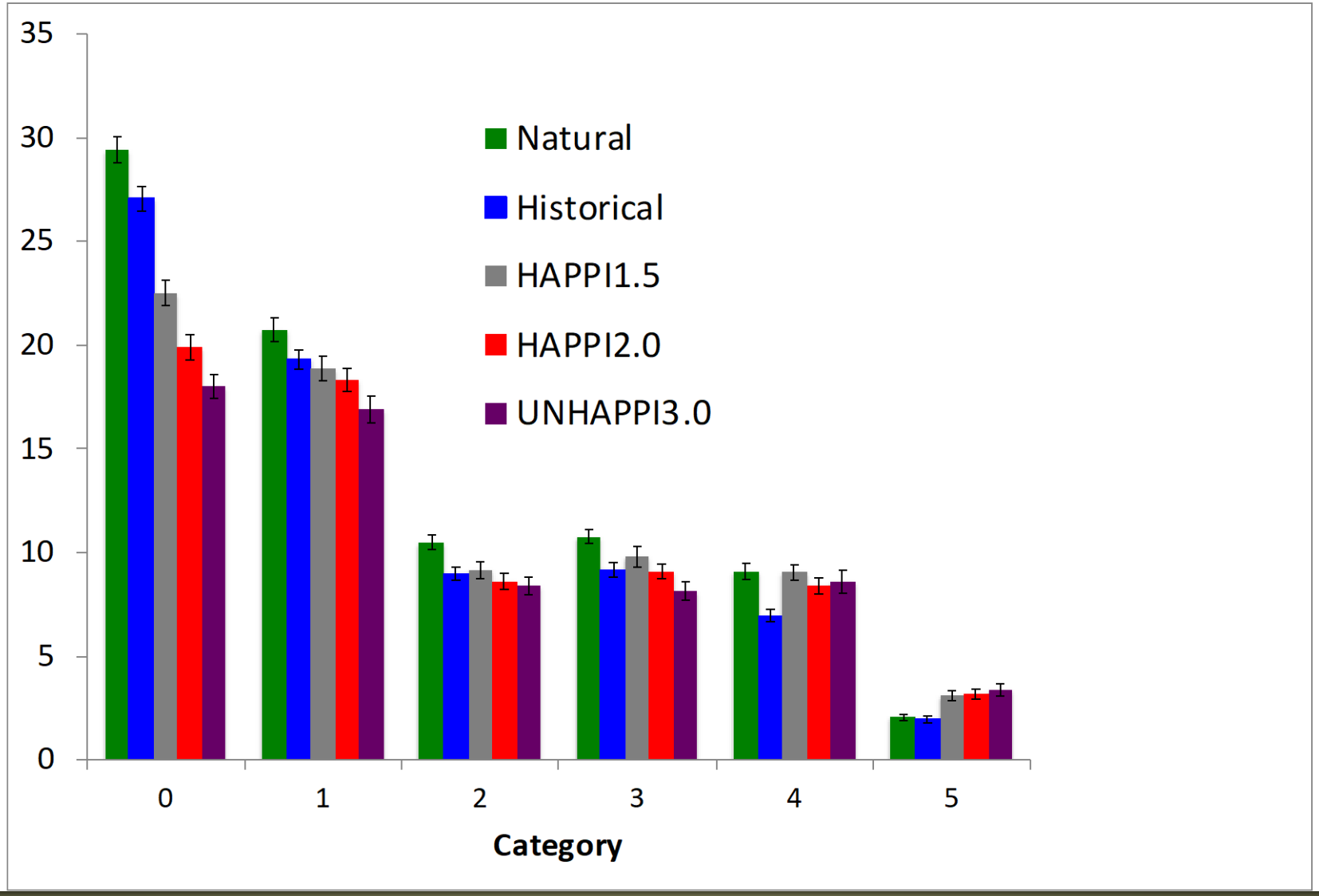
A significant human influence has been found in hundreds of similar large scale events.



Expectations about global warming and hurricanes.

- Tropical cyclones are the most intense storms on the planet.
  - They require warm ocean temperatures, high humidity and low wind shear to get really large.
  - Climate change increases temperature and humidity, but has only small effects on wind shear.
    - The general consensus is that global warming causes the most intense hurricanes to become more intense.
    - No real consensus on changes in the total TC number.
      - Either no change or a decrease.
    - Number of intense (cat 4 or 5) will either increase or decrease depending on the magnitude of this change.
    - Precipitation will increase. Available water increases according to Clausius-Clapeyron relationship
      - ΔQ = ~6% per ^{o}C warming

Global TC # (25km CAM5.1)



Extreme Event Attribution is causal inference.

Two complementary philosophies

1. Design ensembles of climate model simulations tailored to event attribution.
   - Actual world vs counterfactual world without human changes to the atmosphere. A direct interference.
   - Pearl causal inference.

Prof. Judea Pearl, UCLA

2. Analyze observed trends with a statistical model.
   - Postulate a plausible cause but beware of hidden covariates.
   - Granger causal inference.

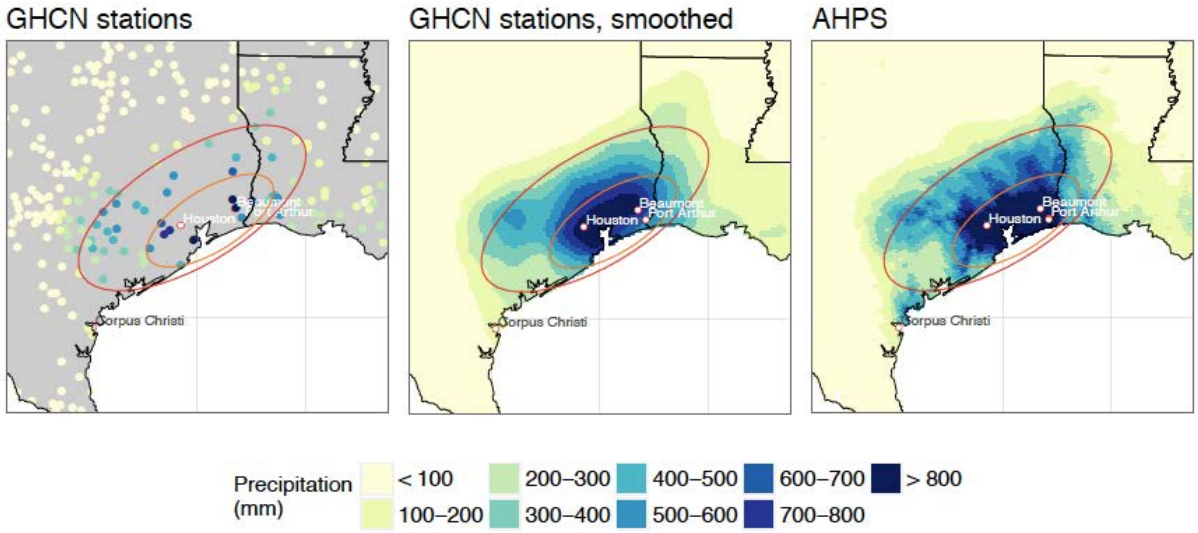
Sir Clive Granger (1934-2009)

Granger causality statement for Hurricane Harvey

- We constructed a non-stationary generalized extreme value statistical model of observed extreme precipitation (***Y***) in coastal Texas with two "covariates":

  X_1=Atmospheric carbon dioxide: The human influence

  X_2=El Nino index: The natural influence
- Two regions
- Three observational datasets
- No climate models.



Risser & Wehner (2017) Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation in the Houston, Texas region during Hurricane Harvey. *Geophysical Review Letters*. 44, 12,457–12,464. https://doi.org/10.1002/2017GL075888

Hurricane Harvey attribution statement (small region)

- Anthropogenic climate change *likely* increased Hurricane Harvey's total rain fall by at least 19% with a best estimate of 38%.
  - This is substantially larger than the 6-7% expected from thermodynamical arguments and C-C scaling.
- Anthropogenic climate change *likely* increased the chances of the observed rainfall by a factor of at least 3.5 with a best estimate of 9.6.

$$G_t(x) \equiv \mathbb{P}(Z_t \leq x) = \exp\left\{-\left[1+\xi_t\left(\frac{x-\mu_t}{\sigma_t}\right)\right]^{-1/\xi_t}\right\},$$

$\rightarrow$ defined for $\{x : 1+\xi_t(x-\mu_t)/\sigma_t > 0\}$

Attribution statements about Harvey total precipitation

Granger causality

- Risser & Wehner 2017 (small region)
  - Chances increased by 10X (*likely* lower bound of 3.5X)
  - Precipitation increased by 38% (*likely* lower bound of 19%)
- Risser & Wehner 2017 (large region)
  - Chances increased by 5x (*likely* lower bound of 1.4X)
  - Precipitation increased by 24% (*likely* lower bound of 7%)

Pearl causality:

- Van Oldenborgh, van der Wiel et al. 2017
  - Chances increased by 3x (range =1.5 to 5)
  - Precipitation increased by 15% (*very likely* range= 8-19%)
- Wang et al. 2018
  - Precipitation increased by 20% (interquartile range 13-37%)

The statements are all within each other stated uncertainties.

Pearl Causal modeling analyses

- As there is a hierarchy of climate modeling techniques, there is also a hierarchy of attribution methods.
- Every attribution study makes a number of assumptions that should be disclosed.

1. Long multidecadal simulations of the actual and counterfactual worlds
2. Short hindcast simulations of the actual event and a plausible counterfactual event.
   - Well suited for extreme storms, as attention is focused on the actual event.
   - But there is an additional condition that the large scale circulation is unaffected by climate change.
   - Attribution statements are conditional on this (and other assumptions) and are incomplete.
   - Hindcast attribution method AKA pseudo-global cooling.

Wehner, Zarzycki, Patricola (2018) Estimating the human influence on tropical cyclone intensity as the climate changes. Chapter 12 in *Hurricane Risk.* Jennifer Collins and Kevin Walsh, editors. Springer. ISBN 978-3-030-02402-4

Pearl Causality: Hurricanes

- Ensemble hindcast technique aka “Pseudo-global warming”
  - Factual: The storm that was.
  - Counterfactual: The storm that might have been.

The counterfactual storm is constructed by perturbing the initial and boundary conditions of the hindcast model.

- We used WRF as the hindcast model.
- We used the CAM5.1 ensemble of C20C+ simulations to construct the perturbation.
  - This removes the human influence.
- We also used the CESM1.0 RCP8.5 simulations to make a projection of the “storm that might be”.

3 km resolution regional climate model simulation of Hurricane Katrina (2005)

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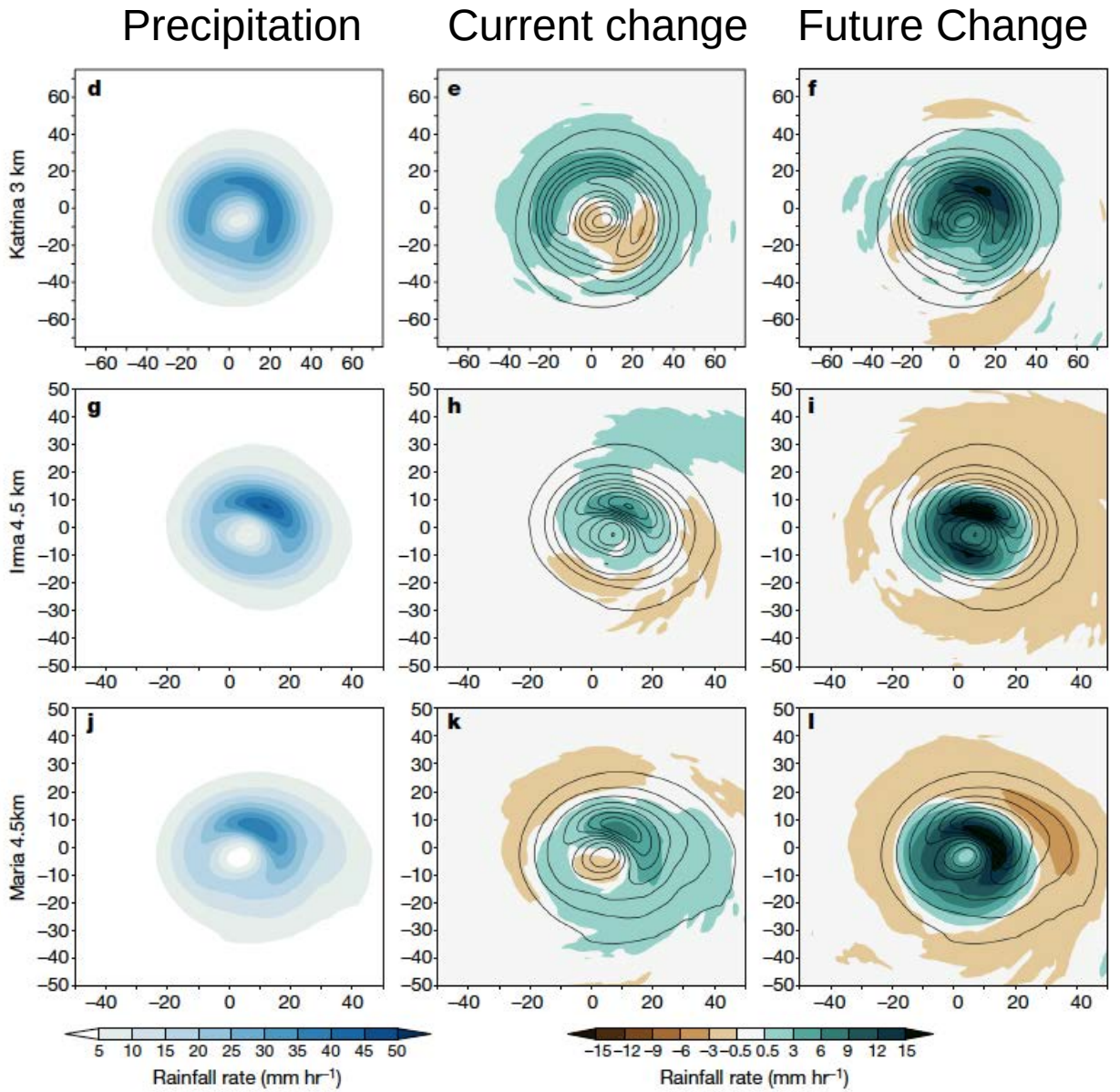
Pearl Causality statements for Katrina, Maria & Irma

Human induced increases in hurricane precipitation totals are already large and can exceed Clausius-Clapeyron scaling.

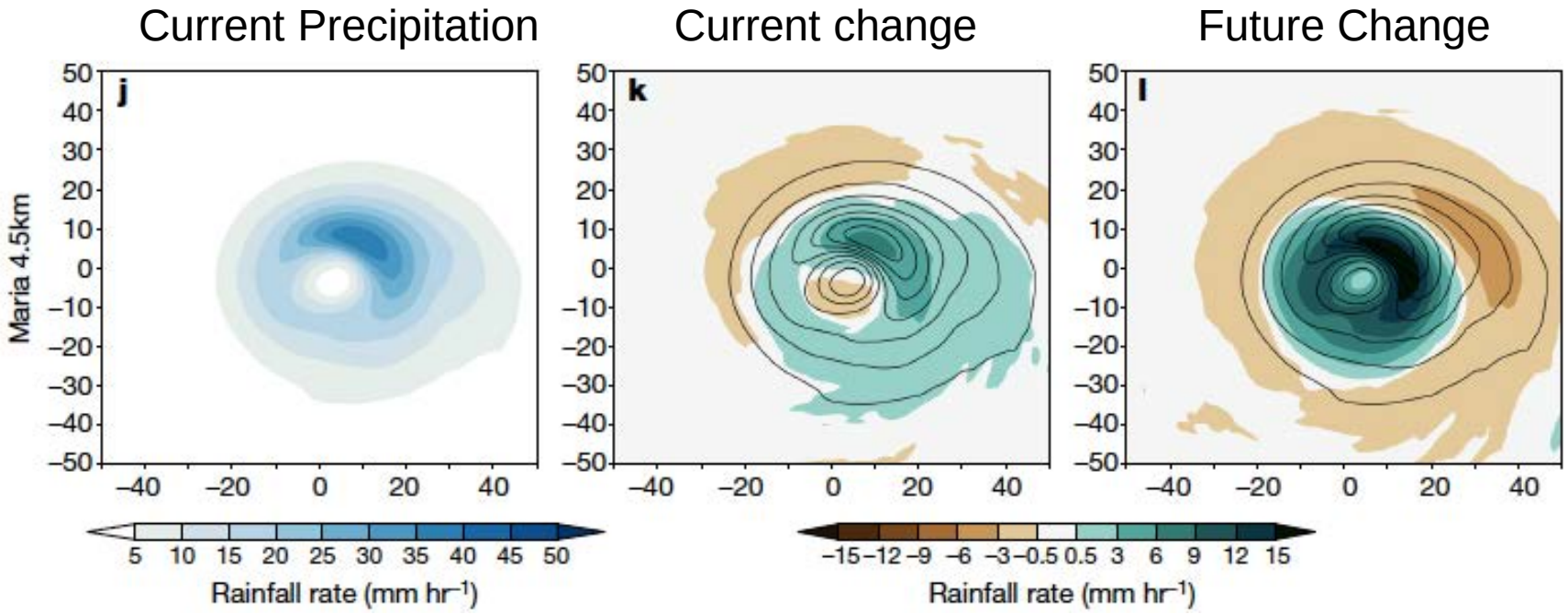
- Global warming induces a structural change in the storm

Storm composites →



Patricola & Wehner Nature 2018

C-C scaling case Study: A closer look at Maria



- Clausius-Clapeyron constraint on specific humidity= ~7%/^{o}C
- Actual is 0.6C warmer than counterfactual.
  - C-C scaling = ~4%
    - At peak = >6 mm/hour (20%)
- RCP8.5 is 2C warmer than actual.
  - C-C scaling = ~14%
    - At peak = = >12 mm/hour (40%)

Patricola & Wehner Nature 2018

Flooding of Houston

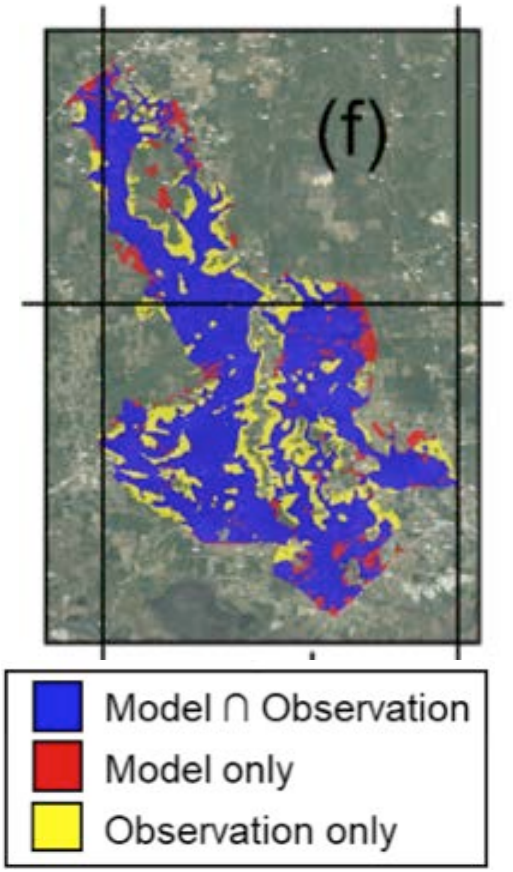
- How did this attributable increase in precipitation affect the Harvey flood?
- Design a storyline attribution analysis of the flood. (Pearl causality)
- Fathom-US, a continental-scale hydraulic model
  - 30 meter resolution
  - Demonstrated to be “fit for purpose”
    - “flood that was”
    - Most of the errors are at the periphery of the flood.

The “flood that was”.

- Driven by observed rainfall.

The “flood(s) that might have been”.

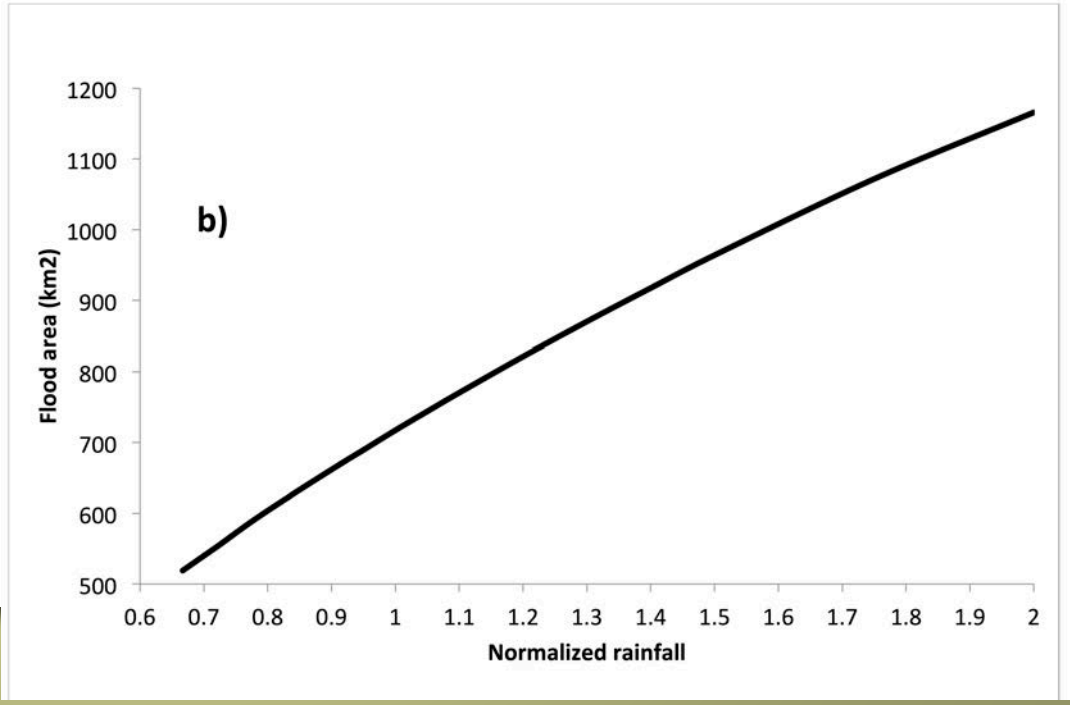
- Alter the rainfall uniformly by the published attribution statements.
- e.g. Risser & Wehner’s 24% statement
  - Decrease precipitation by 1/1.24=0.81



Wing, O. E. J., Sampson, C. C., Bates, P. D., Quinn, N., Smith, A. M., & Neal, J. C. (2019). A flood inundation forecast of Hurricane Harvey using a continental-scale 2D hydrodynamic model. *Journal of Hydrology X*, *4*, 100039. https://doi.org/https://doi.org/10.1016/j.hydroa.2019.100039

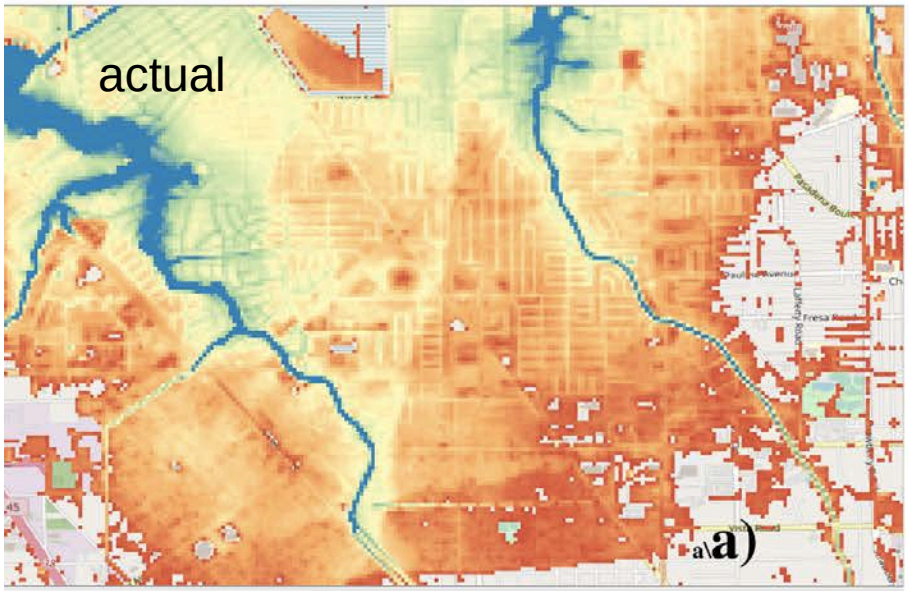
Greater Houston area

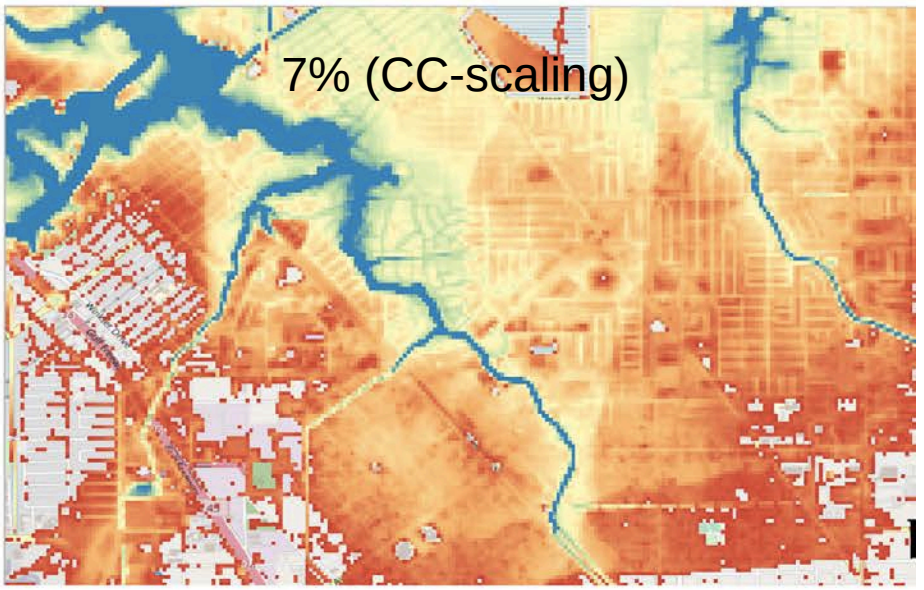
- Attributable flood water volume is essentially the same as the attributable precipitation.
  - Drainage to the Gulf is slow compared to rainfall rates
- Attributable flood water area is less than the attributable precipitation.
  - Weakly sublinear
  - But not small…
  - Highly non-uniform.

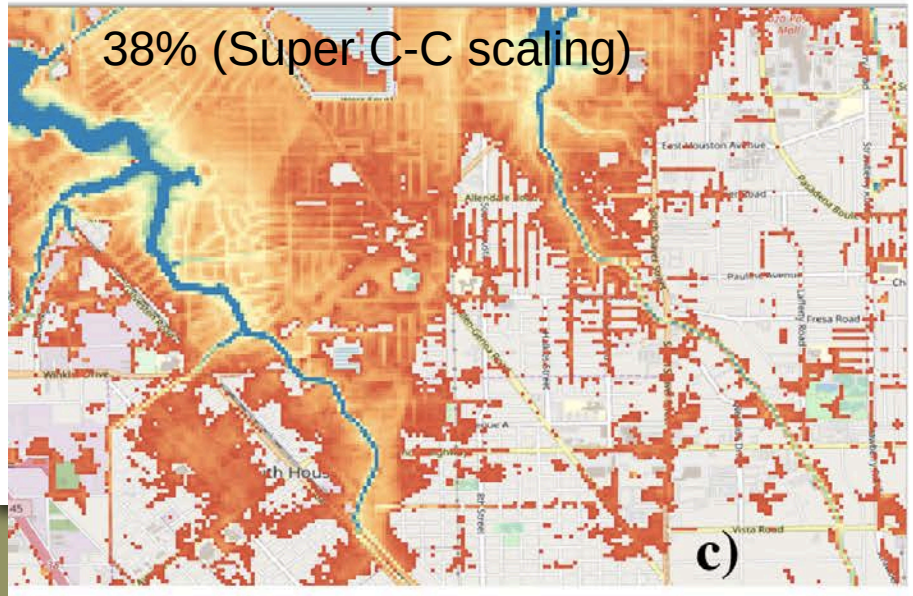


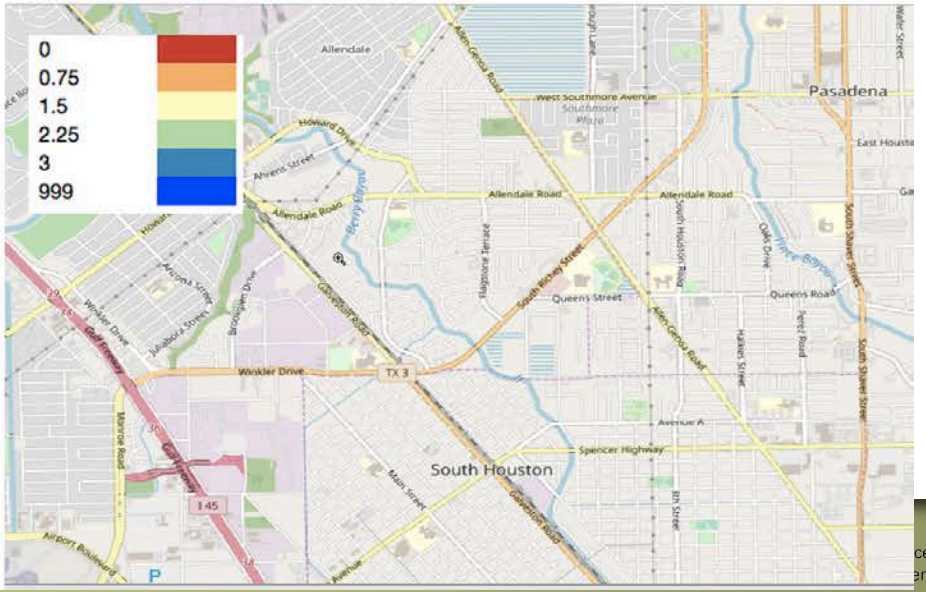
Wehner & Sampson, in preparation.

South Houston / Pasadena flooding after 5 days









Conclusions

- Super C-C scaling of tropical cyclone precipitation is a real thing.
- Changes in *local* dynamics are responsible.
- But we should not expect different extreme storms types to behave in the same way.
  - Tropical cyclones
  - Extra-tropical cyclones
  - Atmospheric Rivers
  - Mesoscale convective systems.
  - Frontal systems
- Multiple routes to super C-C.
  - But all are probably dynamical in nature.
  - What is the relative role of changes in local vs. large scale dynamics?

Did global warming flood my house?

- This question needs to be interpreted in the probabilistic sense of extreme event attribution.
- It depends a lot on which range of attribution statements you are willing to accept.
- It also depends a lot on where your house is.
  - Many homes would have been flooded even without the human increase in precipitation.
  - But some homes would not have been.

Data and software available at

https://portal.nersc.gov/cascade/Harvey/

BERKELEY LAB

Thank you!

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