CLIMATE CHANGE, EXTREMES AND RISK

Richard L. Smith

ASA-Risk Analysis Section Webinar

September 29, 2021

http://rls.sites.oasis.unc.edu/faculty/rs/talks/talks.html

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Outline of Talk

- Over the past several years but 2021 in particular, there have been many extreme weather events
  - Extreme heat in the north-west of US and Canada
  - Flooding in Europe
  - Wildfires throughout the US west
  - Many others throughout the world
- To what extent can we say that these events are "caused by" climate change?
- I will draw particular attention to a group calling themselves *World Weather Attribution* (WWA) and their contributions to the methodology of extreme event attribution
- In particular, I want to draw attention to the uses this group have made of extreme value theory, and suggest some alternative ways forward

The New York Times

What Cutting-Edge Science Can Tell Us About Extreme Weather

Aug. 17, 2021

Jungho Kim for The New York Times

By Katharine Hayhoe and Friederike Otto
Dr. Hayhoe, an atmospheric scientist, is the chief scientist at the Nature Conservancy. Dr. Otto is the associate director of the Environmental Change Institute at the University of Oxford and a co-investigator for World Weather Attribution, which assesses the human influence on extreme weather.

Hotter, faster, stronger: That isn't a tagline for the next blockbuster superhero movie. This is what climate change is doing to many

Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021.

Contributors

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WEATHER ATTRIBUTION

Pathways and pitfalls in extreme event attribution

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Abstract

The last few years have seen an explosion of interest in extreme event attribution, the science of estimating the influence of human activities or other factors on the probability and other characteristics of an observed extreme weather or climate event. This is driven by

Discussion paper of concepts, May 2021

Adv. Stat. Clim. Meteorol. Oceanogr., 6, 177–203, 2020
https://doi.org/10.5194/ascmo-6-177-2020

ASCMO
Open Access

A protocol for probabilistic extreme event attribution analyses

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Abstract. Over the last few years, methods have been developed to answer questions on the effect of global warming on recent extreme events. Many "event attribution" studies have now been performed, a sizeable frac-

Background on methodology, November 2020

Eight Steps to Attribution (van Oldenborgh et al., 2021)

1. Analysis trigger;
2. Event definition;
3. Observational trend analysis;
4. Climate model evaluation;
5. Climate model analysis;
6. Hazard Synthesis;
7. Trends in vulnerability and exposure;
8. Communication.

Analysis Trigger

- How do we decide when an event justifies an analysis?
  - Criteria based on economic impacts would lead to undue emphasis on rich countries
  - Instead, used criteria based on number of deaths or size of population affected
  - Still numerous sources of selection bias, e.g. events of decreasing frequency are unlikely to be analyzed (example: flooding due to snowmelt in England, last occurred in 1947)

Event Definition

- How do we define the spatial and temporal scale of the event
  - Different (conflicting) goals, e.g. maximizing anthropogenic contribution, maximizing return period, finding an index that emphasizes impacts on humans and ecology
  - Fixed boundary conditions? (e.g. high El Niño)
  - Events may be defined by a combination of factors, e.g. impact of a flood may be greater if there was previous heavy rainfall or snowmelt
  - Different meteorological variables (e.g. wet bulb temperature to emphasize effect of heatwave on human health)
  - Sources of data (e.g. remote sensing versus station data)
  - The most extreme event over a large region will have different statistics from an extreme event at a specific location (example of Hurricane Harvey)

Observational Trend Analysis

- Analyzing data for a trend in extreme values
  - Fit Generalized Extreme Value (GEV) distribution to annual maxima or Generalized Pareto distribution (GPD) to exceedances over a threshold
  - Account for trends by conditioning on global mean surface temperature (GMST)
  - Sometimes this analysis shows events that have effectively zero probability without a trend (example of temperature trends in De Bilt, Netherlands)

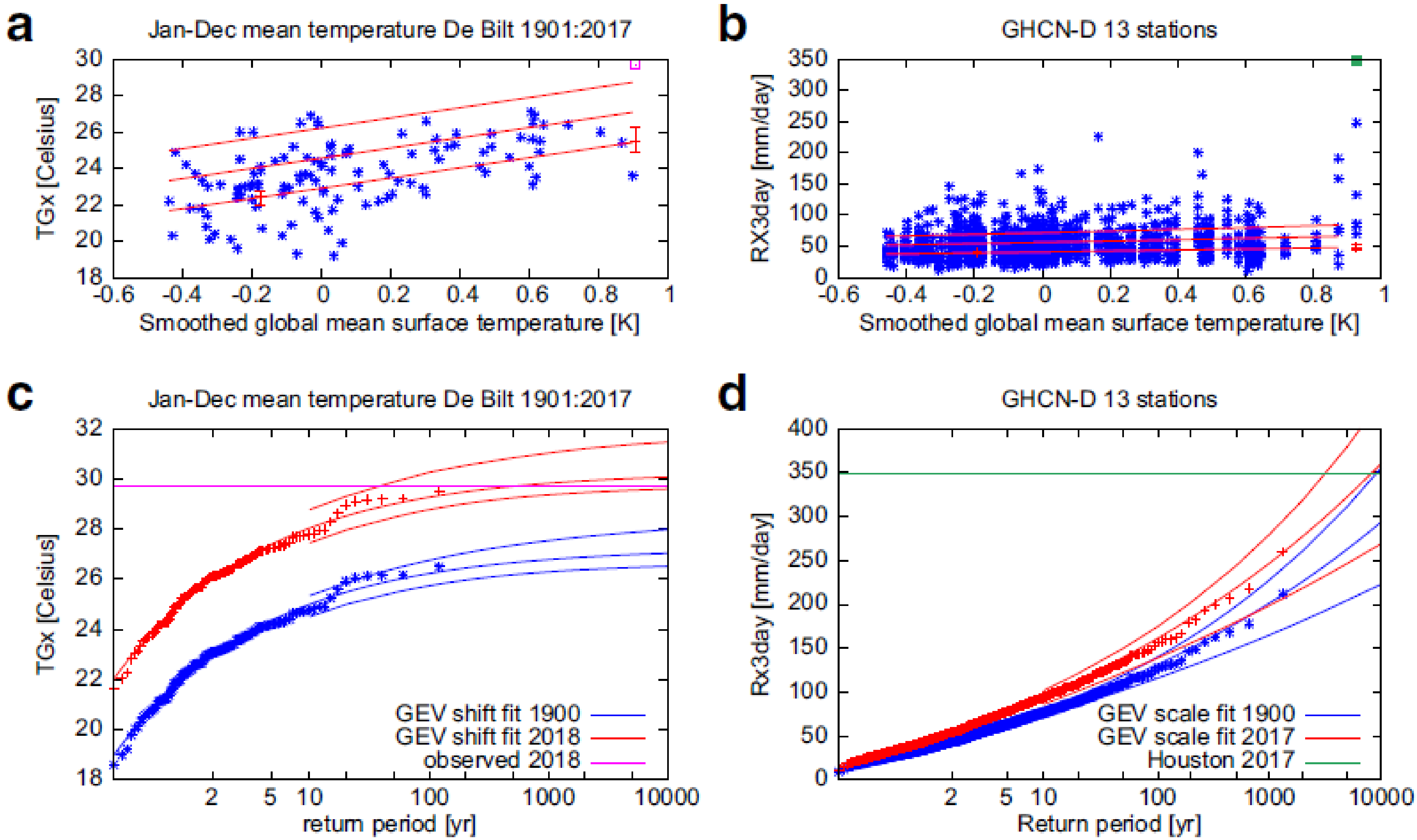


Fig. 2 **a,c** Highest daily mean temperature of the year at De Bilt, the Netherlands (homogenised), fitted to a GEV that shifts with the 4-year smoothed GMST. **a** As a function of GMST and **c** in the climates of 1900 and 2018. **b,d** The same for the highest 3-day averaged precipitation along the US Gulf Coast fitted to a GEV that scales with 4-year smoothed GMST. From climexp.knmi.nl, (**b,d**) also from van Oldenborgh et al. (2017)

From van Oldenborgh et al. (2021)

Climate Model Evaluation

- The intention is to select a climate model that can represent trends in the defined extreme event
  - Is the model capable in principle of representing the extreme events of interest?
  - Extreme value analysis with model data should give results comparable to results with observational data

Climate Model Analysis

- Basic idea is to run the model twice, once under anthropogenic forcings and a second time under natural forcings
- Alternative: use transient climate experiments and analyze same way as observational data
- Framing of the problem may still affect the results (e.g. whether to impose boundary conditions)

Hazard Synthesis

- Combining results from observational data and model experiments into a single attribution statement
- Sometimes model and observation results are in conflict!

Analysis of Trends in Vulnerability and Exposure

- Exposure: maybe more people are exposed to a climate hazard than before
- Vulnerability: maybe a population or a community is more susceptible to the damaging effects of a meteorological event than previously
- Example: an analysis of the 2014-15 drought in Saõ Paulo suggested that the water scarcity was due to population increase not climate change

Communication

- Different types of communication for different users, e.g. general public, policymakers, scientific community

Methods of Extreme Value Trend Analysis

- Good background references: Coles (2001), Gilleland and Katz (2016) for software
- Generalized Extreme Value distribution (GEV): $\Pr\{Y \leq y\} = \exp\left\{-\left(1+\xi\frac{y-\mu}{\sigma}\right)_+^{-1/\xi}\right\}$ where μ, σ, ξ are location, scale and shape parameters and Y is typically an annual maximum
- Generalized Pareto distribution (GPD): $\Pr\{Y \leq y\} = 1 - \left(1+\xi\frac{y}{\psi}\right)_+^{-1/\xi}$ where ψ, ξ are scale and shape parameters and Y is typically an exceedance over a high threshold
- Any of μ, σ, ψ, ξ may also depend on covariates (e.g. the GMST)
- Fitting typically by maximum likelihood though alternative methods have also been considered at different times (e.g. L-moments method, Bayesian analyses)

WWA Analysis of the Pacific Northwest Heatwave

Main findings

- Based on observations and modeling, the occurrence of a heatwave with maximum daily temperatures (TXx) as observed in the area 45–52 ºN, 119–123 ºW, was virtually impossible without human-caused climate change.
- The observed temperatures were so extreme that they lie far outside the range of historically observed temperatures. This makes it hard to quantify with confidence how rare the event was. In the most realistic statistical analysis the event is estimated to be about a 1 in 1000 year event in today's climate.

- There are two possible sources of this extreme jump in peak temperatures. The first is that this is a very low probability event, even in the current climate which already includes about 1.2°C of global warming -- the statistical equivalent of really bad luck, albeit aggravated by climate change. The second option is that nonlinear interactions in the climate have substantially increased the probability of such extreme heat, much beyond the gradual increase in heat extremes that has been observed up to now. We need to investigate the second possibility further, although we note the climate models do not show it. All numbers below assume that the heatwave was a very low probability event that was not caused by new nonlinearities.
- With this assumption and combining the results from the analysis of climate models and weather observations, an event, defined as daily maximum temperatures (TXx) in the heatwave region, as rare as 1 in a 1000 years would have been at least 150 times rarer without human-induced climate change.
- Also, this heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).
- Looking into the future, in a world with 2°C of global warming (0.8°C warmer than today which at current emission levels would be reached as early as the 2040s), this event would have been another degree hotter. An event like this -- currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.

Smmary of Their Method

- Data on TXx (annual max daily temperature) over 45–52$^{\text{O}}$N, 119–123$^{\text{O}}$W
- Model extremes as a function of GMST (GEV distribution)
- $\mu_t = \beta_0 + \beta_1 \text{GMST}_t,\ \sigma_t = \sigma,\ \xi_t = \xi$
- Compare 2021 with late nineteenth century (GMST 1.2$^{\text{O}}$C lower than 2021) or projected future events (GMST 0.8$^{\text{O}}$C higher than 2021)

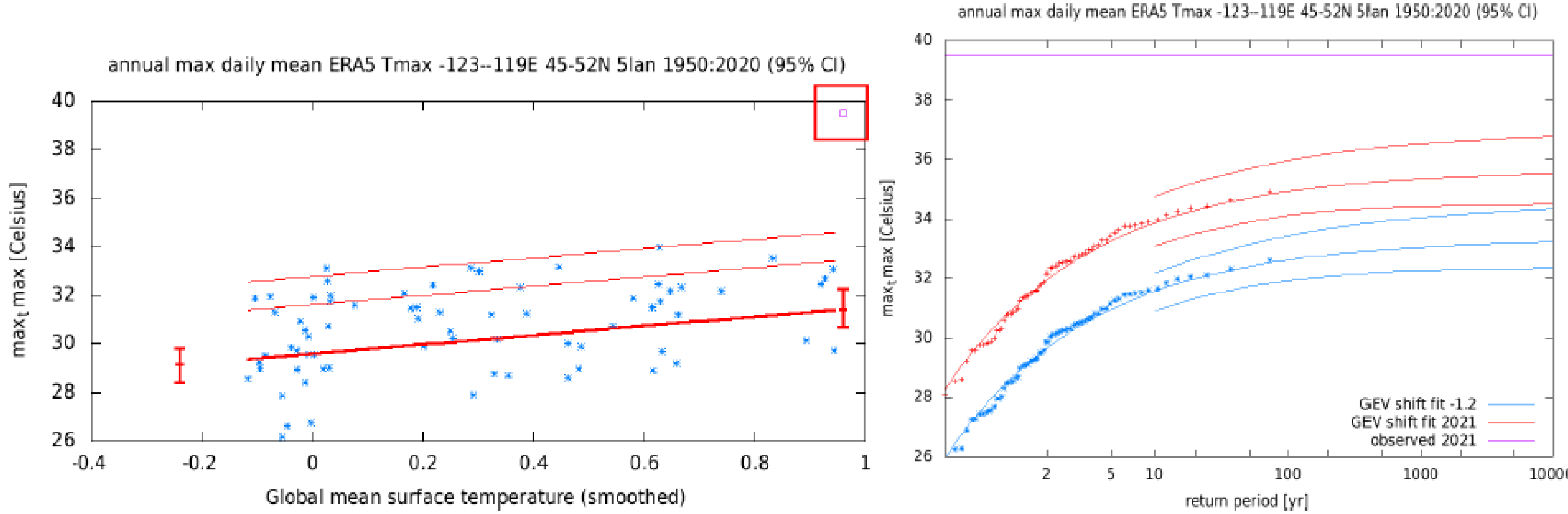


Figure 6. GEV fit with constant scale and shape parameters, and location parameter shifting proportional to GMST of the index series. No information from 2021 is included in the fit. Left: the observed TXx as a function of the smoothed GMST. The thick red line denotes the location parameter, the thin red lines the 6 and 40-yr return times. The June 2021 observation is highlighted with the red box and is not included in this fit. Right: Return time plots for the climate of 2021 (red) and a climate with GMST 1.2 ºC cooler (blue). The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. Based on ERA5 extended with operational ECMWF analyses for June 2021.

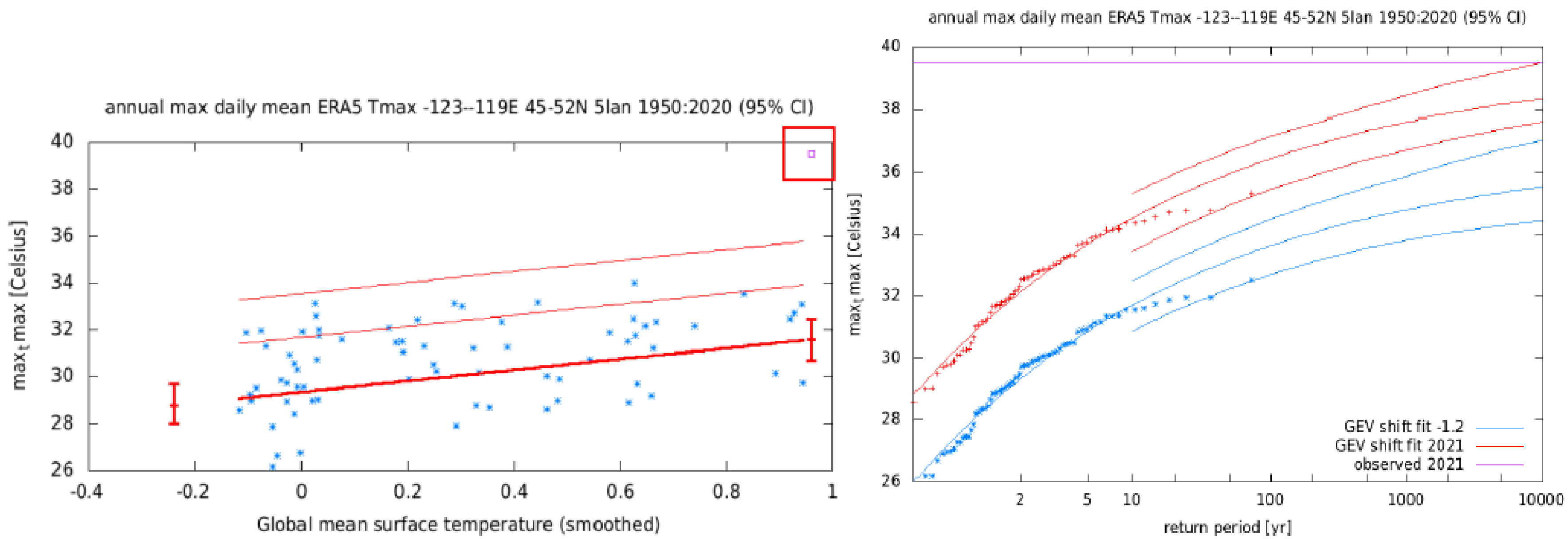


Figure 7. As Figure 6 but demanding the 2021 event is possible in the fitted GEV function, i.e., the upper bound is higher than the value observed in 2021.

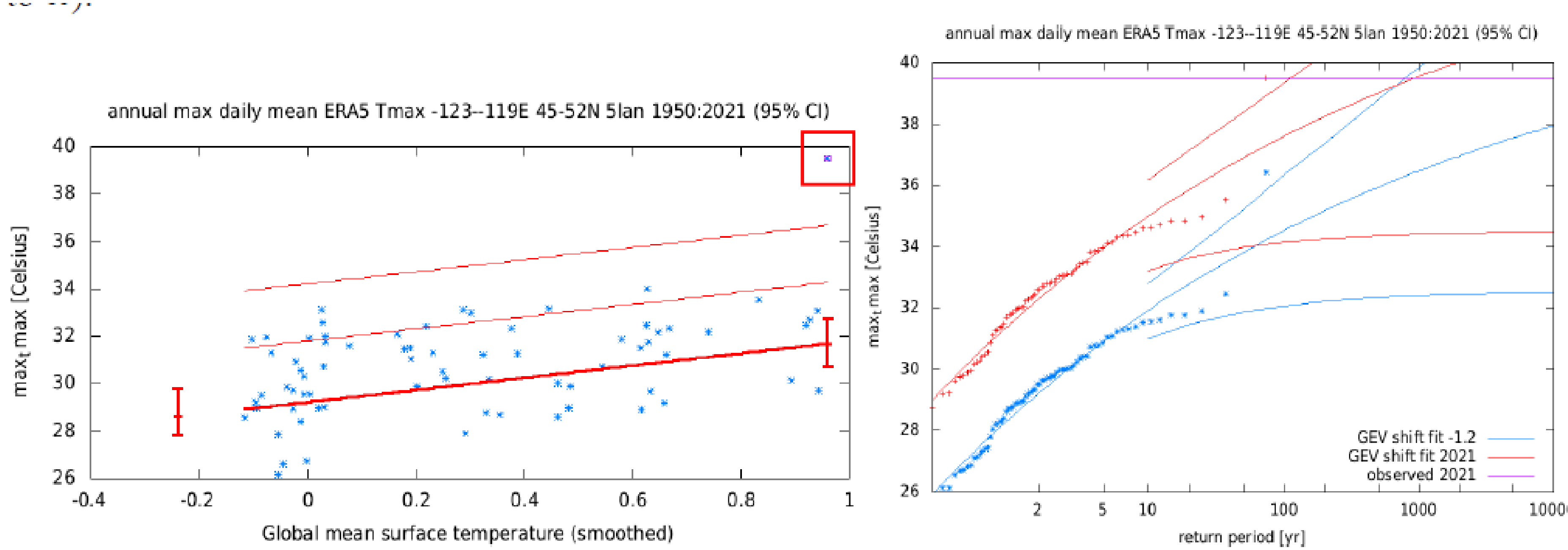


Figure 8. As for Figure 6 but including data from the 2021 heatwave into the fit.

How Extreme was Hurricane Harvey?

- Hurricane Harvey hit the Houston area at the end of August 2017

- Very excessive precipitations led to major flooding

- Meteorologically, associated with a stalling of the storm system just off the Gulf coast, but recent work by Kossin and others has suggested such events are becoming more common overall

- Statistically, questions about (a) just how extreme an event this was, (b) whether such events will become more common in the future

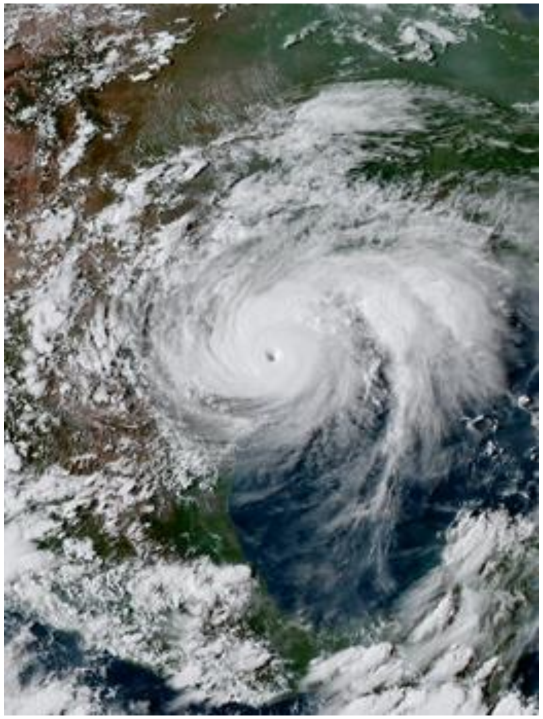


Photo Credits: NASA, CNN, Wikipedia, National Geographic

Scientific questions

1. How extreme was this event?
   - May be characterized as a once in N years event — but what is N?
   - What is the uncertainty of such a statement?

2. To what extent can the event be "attributed" to human influence?

3. What are the projected probabilities of a similar event in the future?

Other references on Hurricane Harvey:

- Van Oldenborgh et al, *Environmental Research Letters*, 2017
  - GEV applied to precipitation data from both observations and models, used global temperatures as a covariate
- Risser and Wehner, *GRL*, 2017
  - GEV applied to annual max 7-day precipitations, used Nino 3.4 and global CO_2 as covariates, no climate models
- Emanuel, *PNAS*, 2017
  - Not a statistical approach, used atmospheric model simulations under present-day and projected future conditions
- and others...

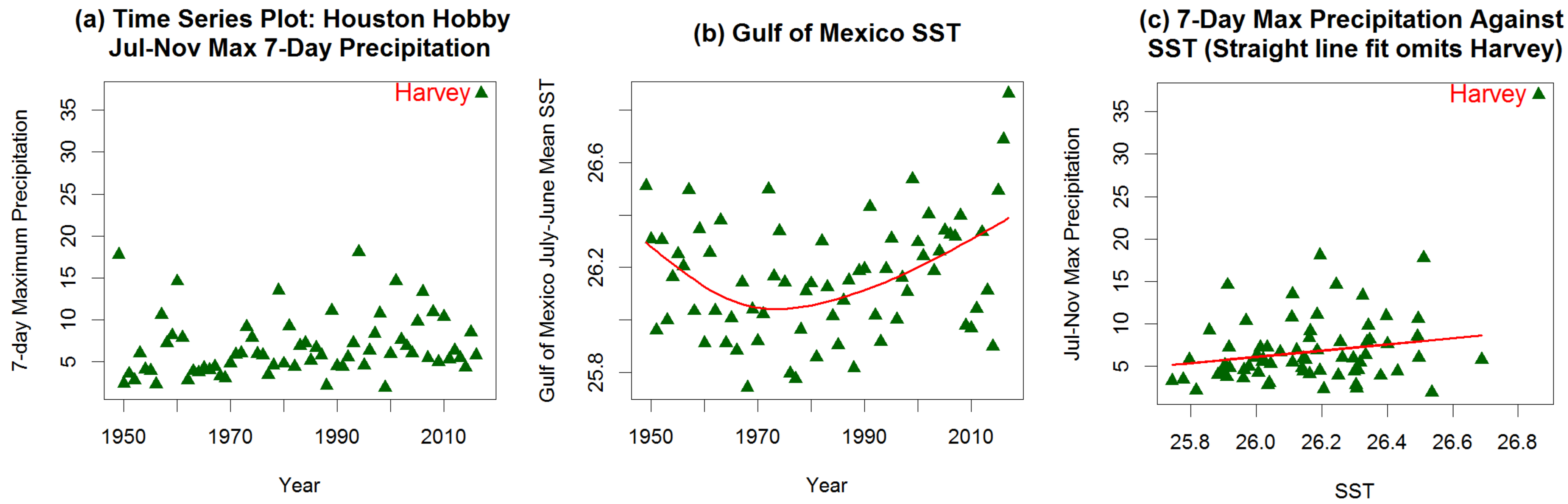
Analysis from a Single Station (Hammerling *et al.*, 2019)

- Precipitation data from Houston Hobby airport
- For each year, calculate max 7-day precipitation from June–November
- Also, mean Gulf of Mexico SST for year ending June 30
- Plotting the data suggests

  (a) Steady increase in max precips. over $\sim$70 years, but Harvey a particular outlier

  (b) SSTs have also risen slowly with 2016-7 largest in history

  (c) Even excluding Harvey, there appears to be a positive relationship between the two



(a) Annual max 7-day precipitation in Houston, 1949–2016

(b) Annual mean Gulf of Mexico SST

(c) Plotting the annual 7-day max precipitation against the annual mean Gulf of Mexico SST

Statistical Methodology

- Annual maxima follow GEV:

$$\Pr\{Y_t \le y\} = \exp\left[-\left\{1+\xi\left(\frac{y-\eta_t}{\tau_t}\right)\right\}_+^{-1/\xi}\right].$$

- Assume η_t and $\log \tau_t$ are linear functions of SST_t (Gulf of Mexico annual mean SST in year t) and $CO2_t$ (global mean CO_2 in year t).

- AIC chooses model:

$$\begin{aligned}\eta_t &= \theta_1 + \theta_4 SST_t + \theta_5 CO2_t,\\ \log \tau_t &= \theta_2 + \theta_6 SST_t,\\ \xi &= \theta_3.\end{aligned}$$

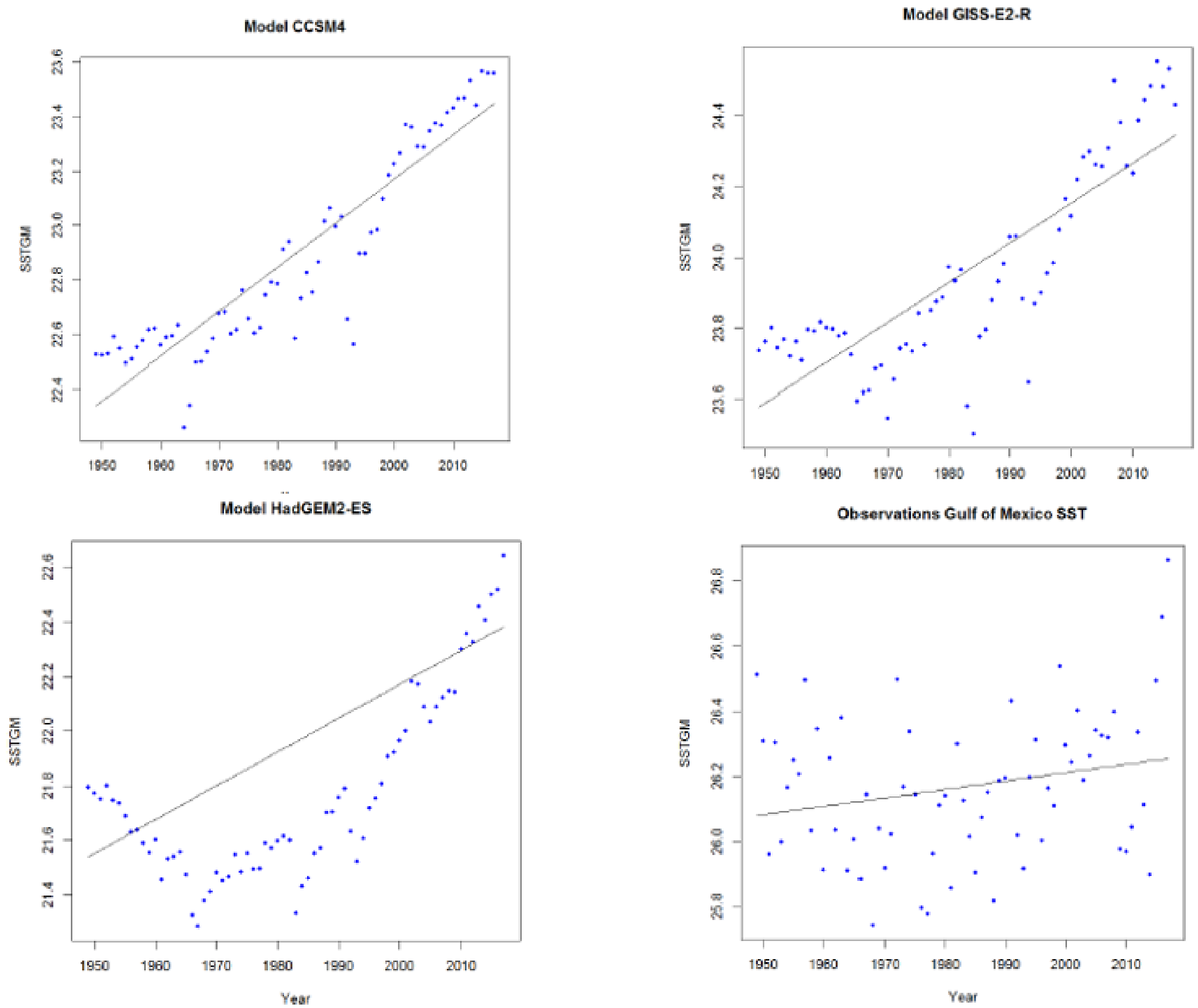
Parameter Estimates

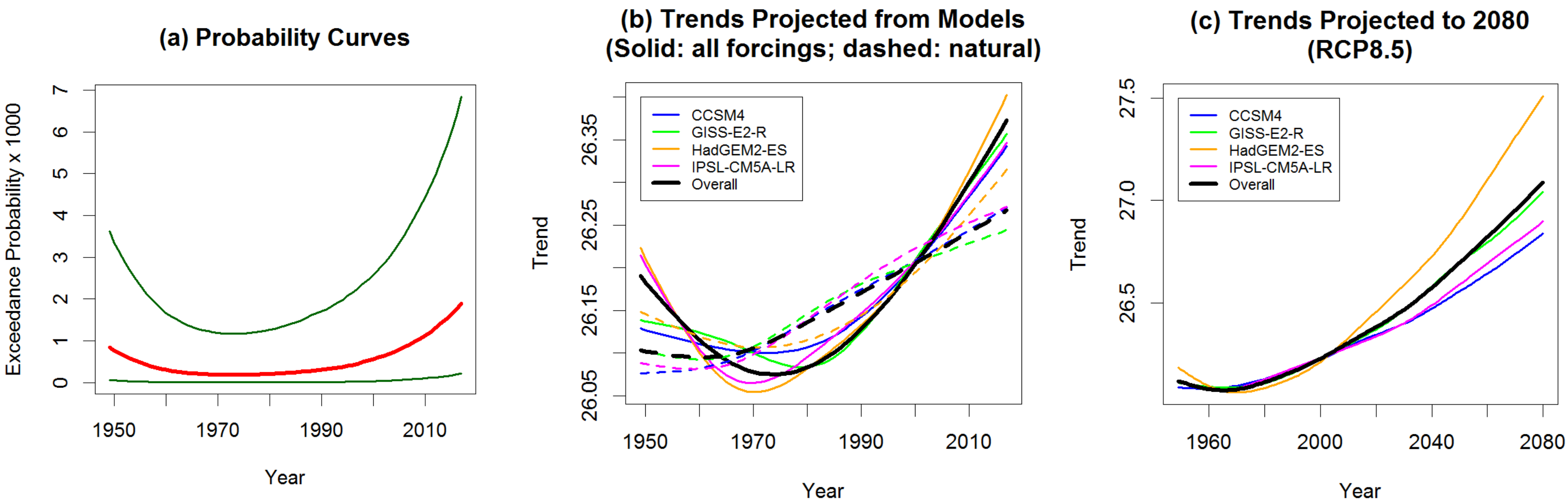
Parameter	Estimate	Standard error	t-statistic	p-value
θ_1	4.70	0.29	16.22	0.00
θ_2	0.56	0.13	4.25	0.00
θ_3	0.15	0.09	1.64	0.10
θ_4	3.06	1.49	2.06	0.04
θ_5	1.95	0.82	2.36	0.018
θ_6	1.24	0.50	2.48	0.013

Climate Model Projections

- Downloaded climate data from four climate models (part of CMIP5 archive)
- Computed GoM SSTs from three scenarios:
  - Historical data, all-forcings model
  - Historical data, natural forcings only
  - Future data (RCP8.5 scenario)
- Unfortunately, the historical data did not look much like the observational data
- To correct for this, a secondary detection and attribution analysis was performed on the SST data alone (regress observed SSTs on model values — either historical or natural)
- Hence, future projections...

GoM SST observations and models





(a) Estimated probability of a Harvey-sized event, as a function of SST, using EVT (66% confidence bands in green)

(b) Trends in SST from 4 climate models, under natural and natural+anthropogenic forcing

(c) Projected trends in SST through 2080, under "business as usual" emissions scenario

Relative Risks

Model	Present			Future		
	Lower	Mid	Upper	Lower	Mid	Upper
CCSM4	1.5	2.0	3.2	9.0	26.2	133
GISS-E2-R	1.8	2.5	4.8	13.5	43.5	244
HadGEM2-ES	1.6	2.1	3.5	23.6	73.3	415
IPSL-CM5A-LR	1.5	2.0	3.3	10.8	33.8	186
Combined	1.7	2.4	4.4	14.3	46.0	254

Relative risks. The columns labelled "Present" refer to relative risks for the 2017 event under an all-forcings scenario versus a natural-forcings scenario, computed under four climate models and with all four models combined. Lower, mid and upper bounds correspond to the 17th, 50th and 83rd percentiles of the posterior distribution. The columns labelled "Future" are relative risks for such an event in 2080 against 2017; same conventions regarding climate models and percentiles.

How Can We Extend This to a Spatial Field?

- Full "detection and attribution" not so far attempted, but this follows Russell *et al.* (*Environmetrics*, 2020)

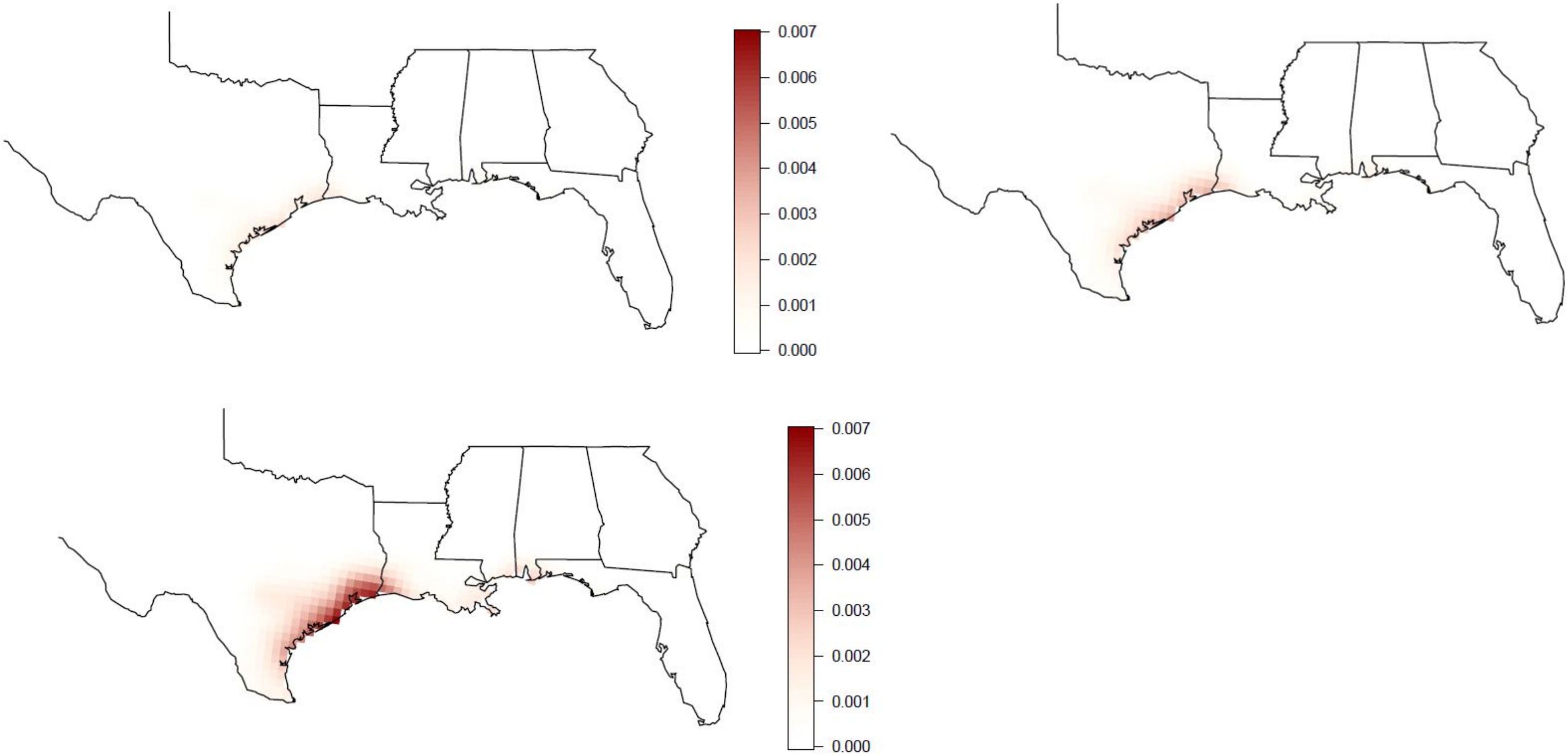
- Precipitation data, 326 stations in 6 states bordering Gulf

- Model $\eta_t(\mathbf{s})$, $\tau_t(\mathbf{s})$, $\xi_t(\mathbf{s})$ in year t at station $\mathbf{s}$:

$$
\begin{aligned}
\eta_t(\mathbf{s}) &= \theta_1(\mathbf{s}) + \theta_2(\mathbf{s}) SST_t, \\
\log \tau_t(\mathbf{s}) &= \theta_3(\mathbf{s}) + \theta_4(\mathbf{s}) SST_t, \\
\xi_t(\mathbf{s}) &= \theta_5(\mathbf{s}),
\end{aligned}
$$

- $\boldsymbol{\theta}(\mathbf{s}) = \left(\theta_1(\mathbf{s}) \;\; \ldots \;\; \theta_5(\mathbf{s}) \right)^T$ modeled as a 5-dim spatial process based on *co-regionalization* (Wackernagel and many others)

- Two-stage estimation procedure allows also for spatial correlation among individual measurements



Estimated probability that the annual maximum seven-day rainfall event exceeds 70 cm. under three scenarios: low SST (top left); high SST (top right); 2017 SST (bottom). From Russell *et al.* (2020)

Summary

- There is much evidence on the role of climate change in increasing the probability and/or the severity of extreme events

- Many issues related to selection of events to analyze, definitions of a meteorological variable, consistency between observations and climate models, and interpretation of the results

- Many new possibilities for statistics — recent advances in extreme value theory include asymptotic dependence/independence models for multivariate events, spatial extremes and many others

- CMIP6 is projected to generate about 20 PB of data

- Many possibilities for ambitious data science!!

Future Event

IMSI workshop on Climate and Weather Extremes, October 3-7, 2022

https://www.imsi.institute/

Organizers are Bo Li, Tiffany Shaw and Richard Smith

References

1. Coles, S. (2001), *An Introduction to Statistical Modeling of Extreme Values*. Springer, London.

2. Gilleland, E. and Katz, R.W. (2016), extRemes 2.0: An Extreme Value Analysis Package in R. *Journal of Statistical Software* **72:8**, doi: 10.18637/jss.v072.i08

3. Hammerling, D., Katzfuss, M and Smith, R.L. (2019), *Climate Change Detection and Attribution*, in *Handbook of Environmental and Ecological Statistics*, edited by A. Gelfand, M. Fuentes, J. Hoeting and R.L. Smith, Chapman and Hall/CRC Handbooks of Modern Statistical Methods.

4. Russell, B., Risser, M., Smith, R.L. and Kunkel, K.E. (2020), Investigating the association between late spring Gulf of Mexico sea surface temperatures and US Gulf Coast precipitation extremes with focus on Hurricane Harvey. Environmetrics, Vol. 31, issue 2, March 2020, paper e2595.

5. Van Oldenborgh, G.J., van der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., King, A., Lott, F., Arrighi, J., Singh, R and van Aalst, M. (2021), Pathways and pitfalls in extreme event attribution. *Climatic Change* **166:13**, https://doi.org/10.1007/s10584-021-03071-7.

6. Philip, S., Kew, S., van Oldenborgh, G.J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R van Aalst, M. (2020), A protocol for probabilistic extreme event attribution analysis. *Adv. Stat. Clim. Meteorol. Oceanogr.* **6**, 177–203, https://doi.org/10.5194/ascmo-6-177-2020.

7. Philip, S. and 26 others, Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. https://www.ecodebate.com.br/wp-content/uploads/2021/07/20210707-rapid-attribution-analysis-of-the-extraordinary-heatwave-on-the-pacific-coast-of-the-us-and-canada-june-2021.pdf (online July 2021).