D&A of changes in extremes

Photo: F. Zwiers

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Introduction

- Yesterday's talk
  - Detection and attribution of change in the mean state
  - Science using this technique has become the foundation for the series of attribution assessments that have been made by the IPCC
    - SAR – 1995 – "discernable evidence"
    - AR5 – 2013 – it is "extremely likely that most …"
- Today's talk
  - Detection and attribution of changes in extremes
  - Event attribution
- Key reference
  - WCRP summer school on extremes, ICTP, July, 2014

Outline

- Brief review
- Example of trend detection
- Event attribution
- Discussion

Definition of D & A

- *Detection* of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change.

- *Attribution* is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence.

- In WG1, casual factors usually refer to *external influences*, which may be *anthropogenic* (GHGs, aerosols, ozone precursors, land use) and/or *natural* (volcanic eruptions, solar cycle modulations).

IPCC Good Practice Guidance Paper on Detection and Attribution, 2010

Methods

- Involve simple statistical models
- Complex implementation due to data volumes (which are both small and large)

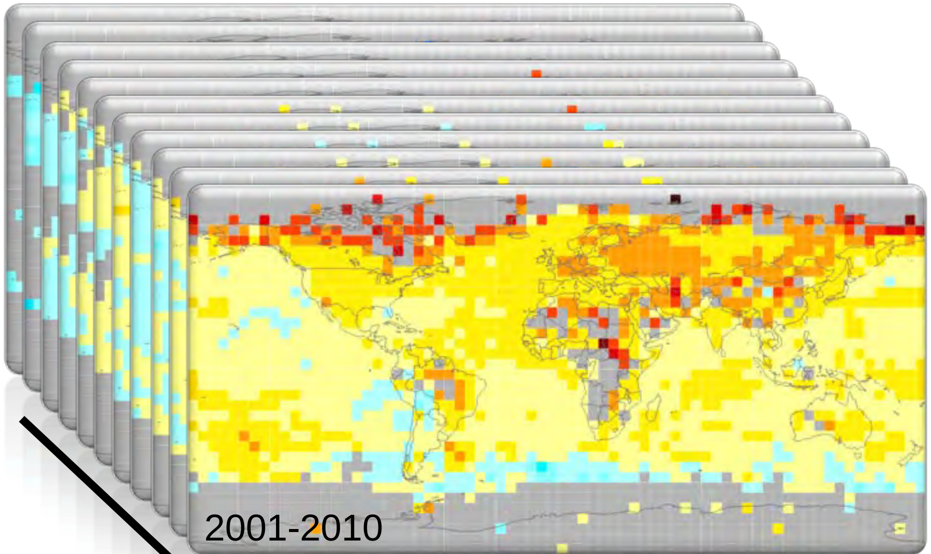
Usual assumptions

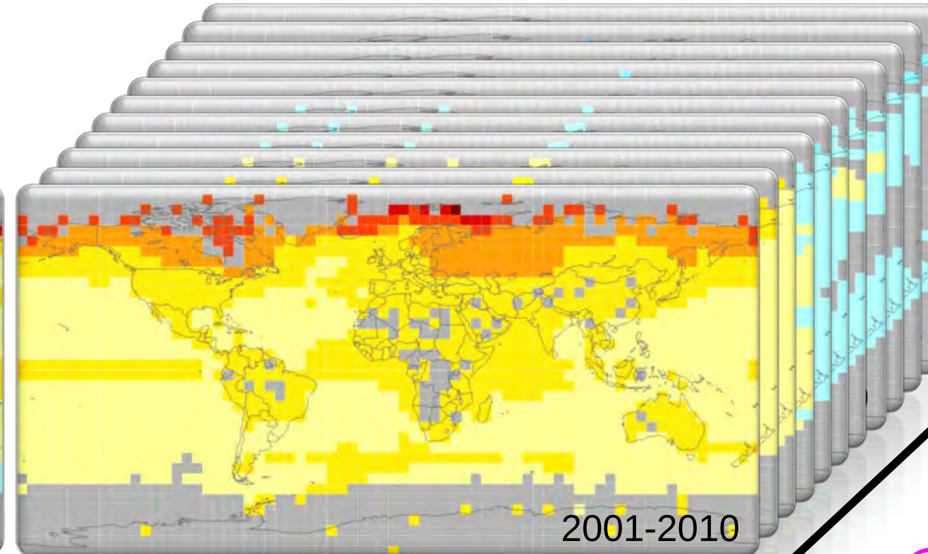
- Key forcings have been identified
- Signals and noise are additive
- The large-scale patterns of response are correctly simulated by climate models, but signal amplitude is uncertain

→ leads to a regression formulation

Observations (HadCRUT4)

Multi-model mean (ALL forcings)





11 decades (1901-1911 to 2001-2011)

$\mathbf{Y}$ $\mathbf{X}$

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

Evaluate scaling factors ← $\hat{\boldsymbol{\beta}}$

$\hat{\boldsymbol{\varepsilon}}$ → Evaluate residuals

After Weaver and Zwiers (2000)

A temperature extremes example

Photo: F. Zwiers (Lanzhou)

An approach to D&A on extremes using EV theory

- Several available indices are "block maxima"
  - Temperature: TNn, TXn, TNx, TXx
  - Precipitation: RX1day, RX5day
- Suggests using the "Generalized Extreme Value" (GEV) distribution, and incorporating the effects of forcing via its parameters
- An example is Zwiers et al, 2011

GEV distribution

- Based on limit theory which predicts that the distribution of block maxima will converge to a *Generalized Extreme Value* distribution as blocks become large
- Distribution function

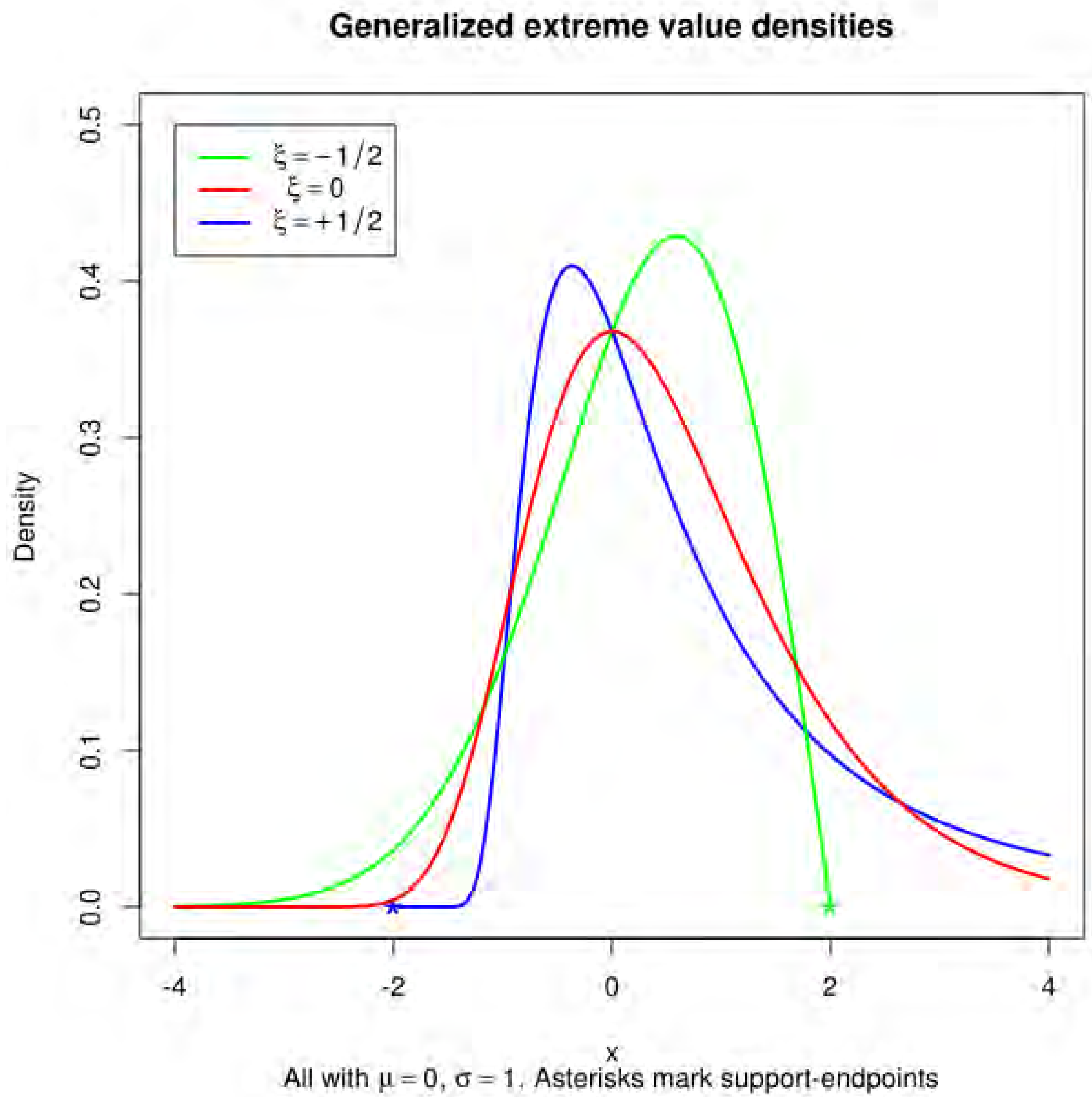
$$F(y|\mu,\sigma,\xi) = \begin{cases} \exp\left[-\,exp\left\{-\frac{y-\mu}{\sigma}\right\}\right], \ \xi = 0 \\ \exp\left[-\left\{1+\xi\frac{y-\mu}{\sigma}\right\}^{-1/\xi}\right], \ \xi \neq 0, 1+\xi\frac{y-\mu}{\sigma} > 0 \end{cases}$$

- m-block return value (blocks are often years)

$$y_m = \begin{cases} \mu - (\sigma/\xi)\left\{1-\left[-\ln\left(1-\frac{1}{m}\right)\right]^{-\xi}\right\} & \xi \neq 0 \\ \mu - \sigma\ln\left[-\ln\left(1-\frac{1}{m}\right)\right] & \xi = 0 \end{cases}$$

- Density function

$$f(y|\mu,\sigma,\xi) = \begin{cases} \frac{1}{\sigma}\exp\left[-\frac{y-\mu}{\sigma} - \exp\left(-\frac{y-\mu}{\sigma}\right)\right], \ \xi = 0 \\ \frac{1}{\sigma}\left(1+\xi\frac{y-\mu}{\sigma}\right)^{-1-1/\xi}\exp\left[-\left(1+\xi\frac{y-\mu}{\sigma}\right)^{-1/\xi}\right], \ \xi \neq 0, 1+\xi\frac{y-\mu}{\sigma} > 0 \end{cases}$$



Weibull $\xi<0$

Gumbel $\xi=0$

Fréchet $\xi>0$

Working assumption for D&A

- External forcing affects only the GEV location parameter μ

- Parallel to the regression approach
  - Estimates the conditional mean (“location parameter”) of the Gaussian distribution

How do we get the expected pattern of change in μ?

- For a given climate model and forcing, assume M runs
- 10M years of output for each decade

  → 10M block maxima x_{tlk} for decade t at grid box k

$t=1, \ldots, N$ decades

$l=1, \ldots, 10M$ simulated years for decade t

- Use these 10M block maxima to estimate GEV parameters for decade t at grid box k

→ estimate N+2 parameters μ_{tk}, σ_k and ξ_k at each grid box

- Do this via maximum likelihood

Estimation of μ_{tk}, σ_k and ξ_k

Maximize the joint likelihood

$$L(\mu_{1k}, \ldots, \mu_{Nk}, \sigma_{k,} \xi_k | x_{tlk}, t = 1, \ldots, N, l = 1, \ldots, 10M)$$
$$= \prod_{t=1}^{N} \prod_{l=1}^{10M} f(x_{tlk} | \mu_{tk}, \sigma_{k,} \xi_k)$$
$$= \prod_{t=1}^{N} \prod_{l=1}^{10M} \frac{1}{\sigma_k} \left[1 + \xi_k \left(\frac{x_{tlk} - \mu_{tk}}{\sigma_k}\right)\right]^{-1-1/\xi_k} \exp\left\{-\left[1 + \xi_k \left(\frac{x_{tlk} - \mu_{tk}}{\sigma_k}\right)\right]^{-\frac{1}{\xi_k}}\right\}$$

Equivalently, minimize the negative log-likelihood

$$-\ln(L) = \sum_{\substack{t=1,\ldots,N \\ l=1,\ldots,10M}} \left\{\ln(\sigma_k) + \left(1 + \frac{1}{\xi_k}\right) \ln\left[1 + \xi_k \left(\frac{x_{tlk} - \mu_{tk}}{\sigma_k}\right)\right] + \left[1 + \xi_k \left(\frac{x_{tlk} - \mu_{tk}}{\sigma_k}\right)\right]^{-\frac{1}{\xi_k}}\right\}$$

Do this at individual grid boxes k

How do we model the observed extremes?

- Use the GEV distribution
  - we have observed block maxima $y_{tk}, t = 1961, \ldots, 2000$
- Make the location parameter signal-dependent as follows

$$\mu_{tk}^{o} = \mu_{t_0 k}^{o} + \beta(\tilde{\mu}_{tk}^{m} - \tilde{\mu}_{t_0 k}^{m})$$

where $\begin{cases} t = t_0, \cdots, 2000, t_0 = 1961 \\ \mu' \text{s constant within decades} \end{cases}$

and $\tilde{\mu}_{tk}^{m}$ is the multi-model ensemble mean of the location parameter estimates for grid box k in decade t from the forced simulations

- Parameters to be estimated from obs are $\mu_{t_0 k}^{o}, \sigma_k^{o}, \xi_k^{o}, \beta$
- Note that β is the same at all locations k

Fit the GEV distribution to observations at all grid boxes simultaneously by minimizing

$$-\ln(L) = -\sum_{\boldsymbol{k}} \ln(L_k)$$

where

$$
\begin{aligned}
-\ln(L_k) \\
&= (T - t_0 + 1)\ln(\sigma_k^o) \\
&+ \left(1 + \frac{1}{\xi_k^o}\right) \sum_{t=t_0}^{T} \ln\left[1 + \xi_k^o \left(\frac{y_{tk} - \mu_{t_0 k}^o - \beta \Delta\tilde{\mu}_{tk}^m}{\sigma_k^o}\right)\right] \\
&+ \sum_{t=t_0}^{T} \left[1 + \xi_k^o \left(\frac{y_{tk} - \mu_{t_0 k}^o - \beta \Delta\tilde{\mu}_{tk}^m}{\sigma_k^o}\right)\right]^{-1/\xi_k^o}
\end{aligned}
$$

Do this using the profile likelihood technique

Parallels with standard D&A

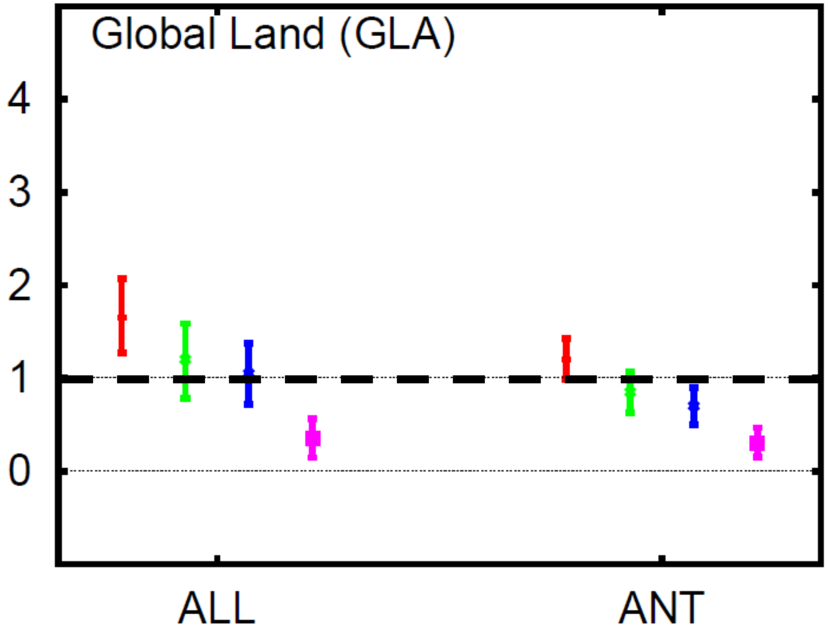
- Single scaling factor to modify the space-time pattern of change in model simulated location parameters
- Like OLS rather than TLS because we don’t take uncertainty in model derived location factors into account
- Non-optimized because the likelihood function does not represent dependence between extremes at different locations

Unlike standard D&A

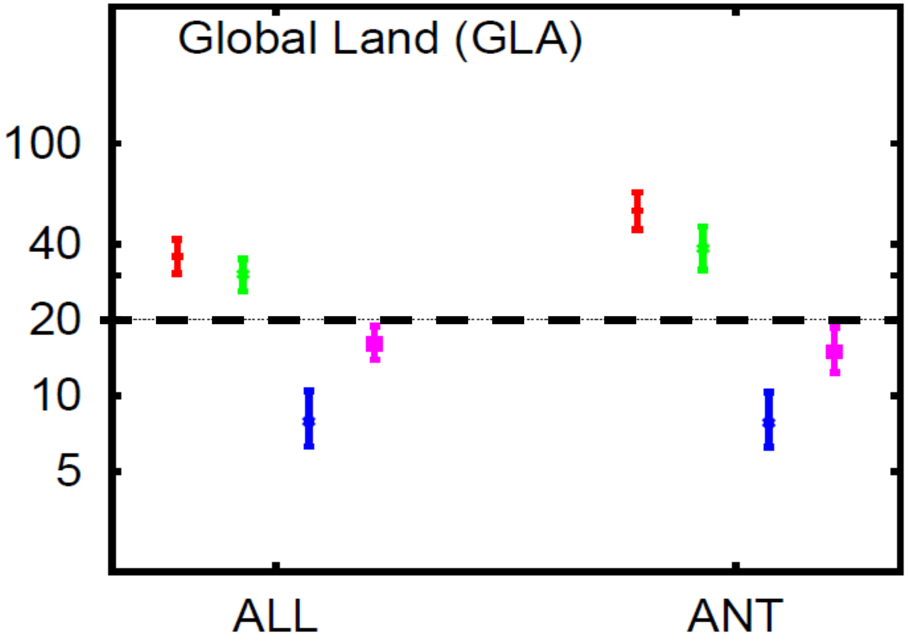
- Uncertainty analysis was not based on control variability because daily output was not available from CMIP3 control runs – used a block bootstrap approach instead

Global Results

Scaling factors and bootstrapped 5-95% uncertainty ranges



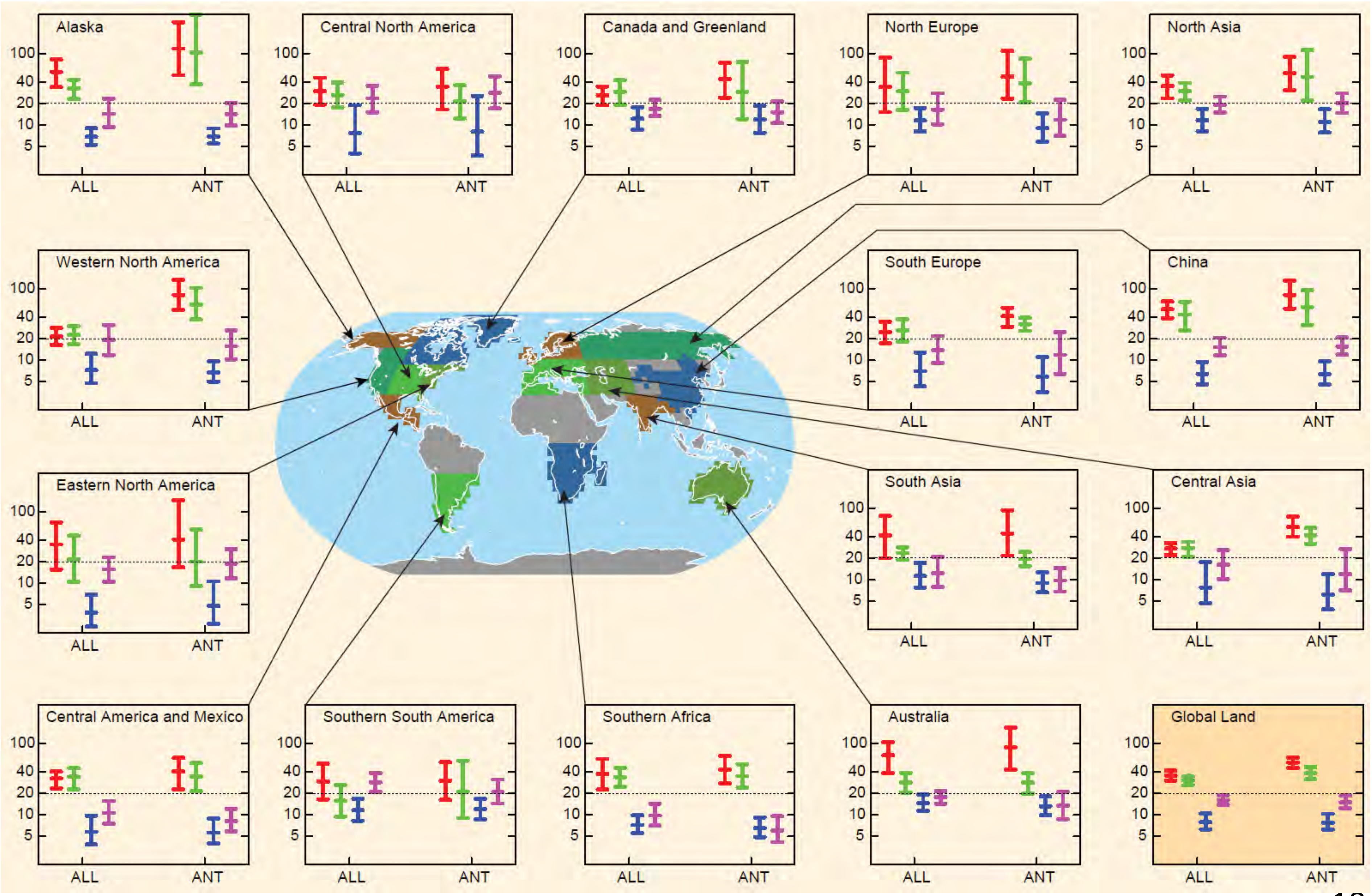
Implied change in waiting times for 20-year event (1990's vs 1960's)



Zwiers, et al., 2011, *J Climate*

TNn, TXn, TNx, TXx

Implied changes in waiting times (1990's vs 1960's)



Event attribution

The public asks:

Did human influence on the climate system cause the event?

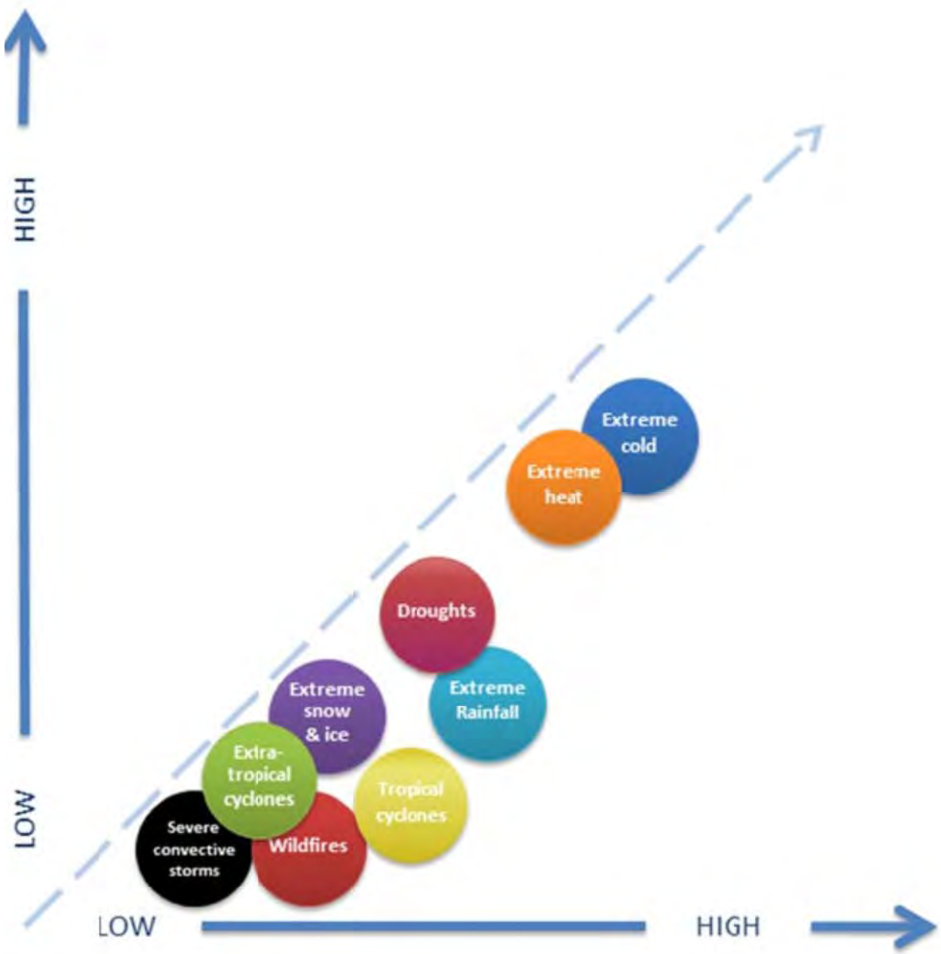
Photo: F. Zwiers (Jordan River, gathering storm)

Most studies

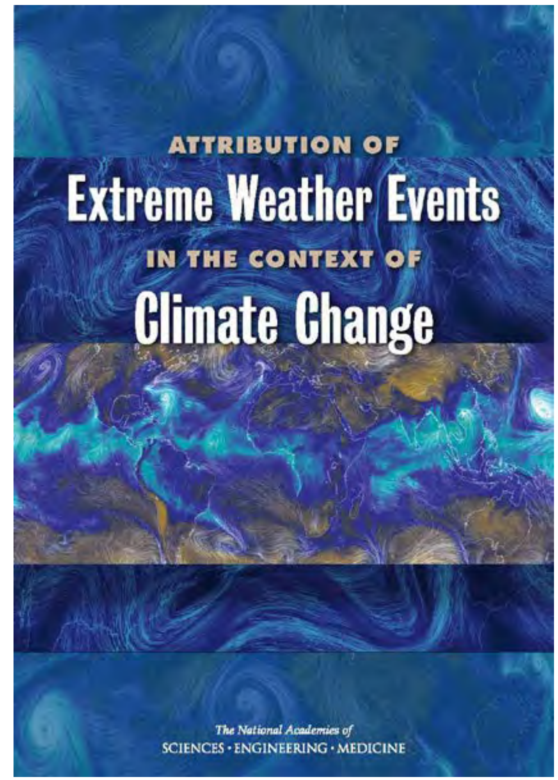
- Most studies ask: Did it …
  - Affect its odds? Alter its magnitude?
- Compare factual and “counterfactual” climates
  - Counterfactual → the world that might have been if we had not emitted the ~600GtC (and counting) that have been emitted since preindustrial
- These studies almost always
  - Define a class of events rather than a single event
  - Use a probabilistic approach
- Shepherd (2016) defines this as “risk based”
  - Contrasts it with a “storyline” based approach
  - i.e., analysis of the specific event that occurred

Status recently assessed by US NAS

Confidence in capability for event attribution



Understanding of effect of climate change on event type



Framing affects the answer

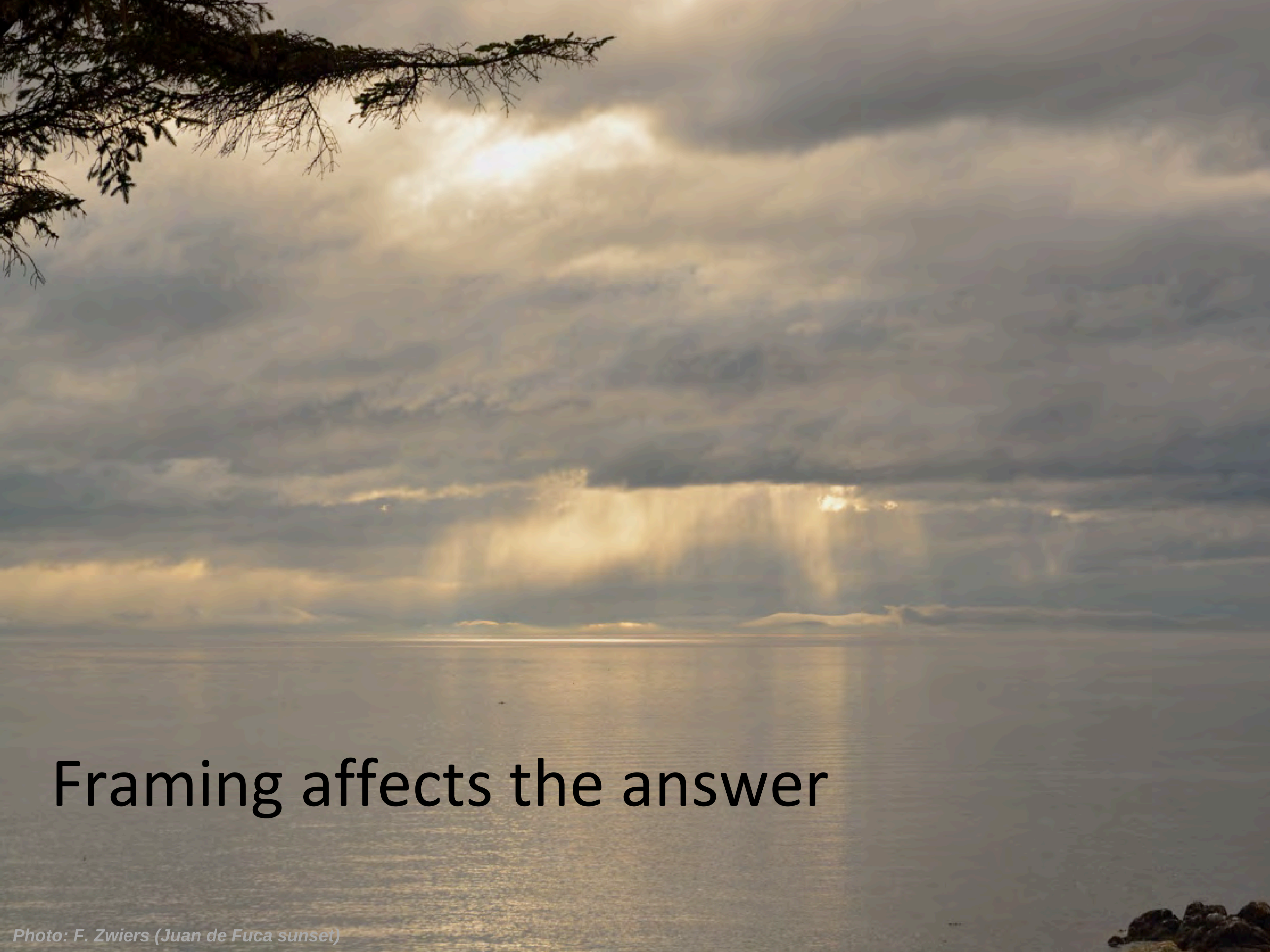


Photo: F. Zwiers (Juan de Fuca sunset)

Fort Mac Fire – May through July 2016

- 590,000 ha burnt
- 88,000 people displaced
- 2 fatalities (indirect)
- 2400 homes and 665 work camp units destroyed
- $3.6 B CDN insured losses


Mandatory evacuation. Photo, Jason Franson/CP


Avian escape. Photo, Mark Blinch/Reuters

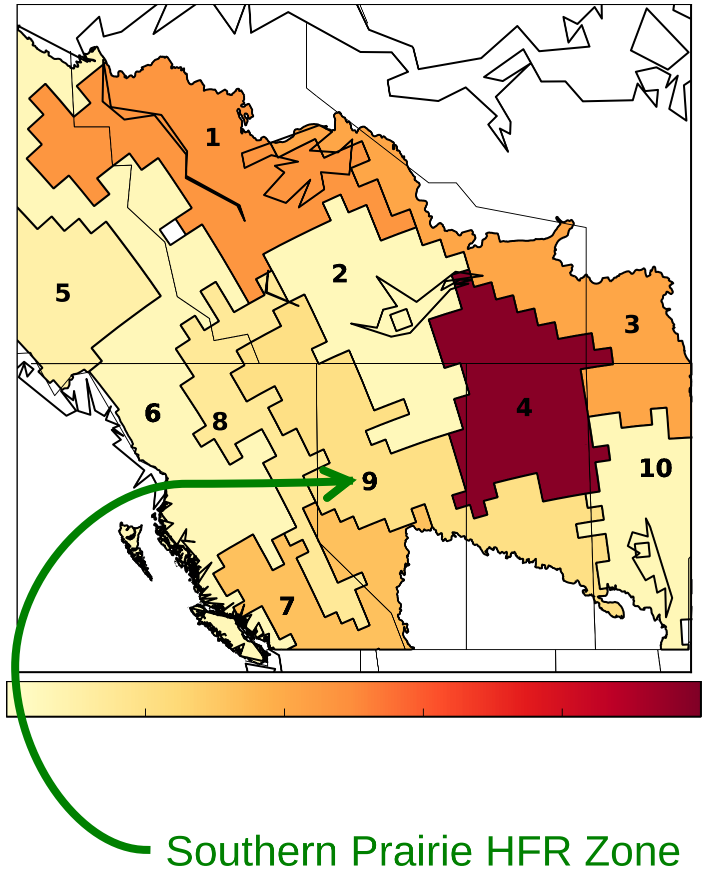

Edmonton Expo Centre at Northlands. Photo, Chris Bolin


Timberlea. Photo, Chris Bolin

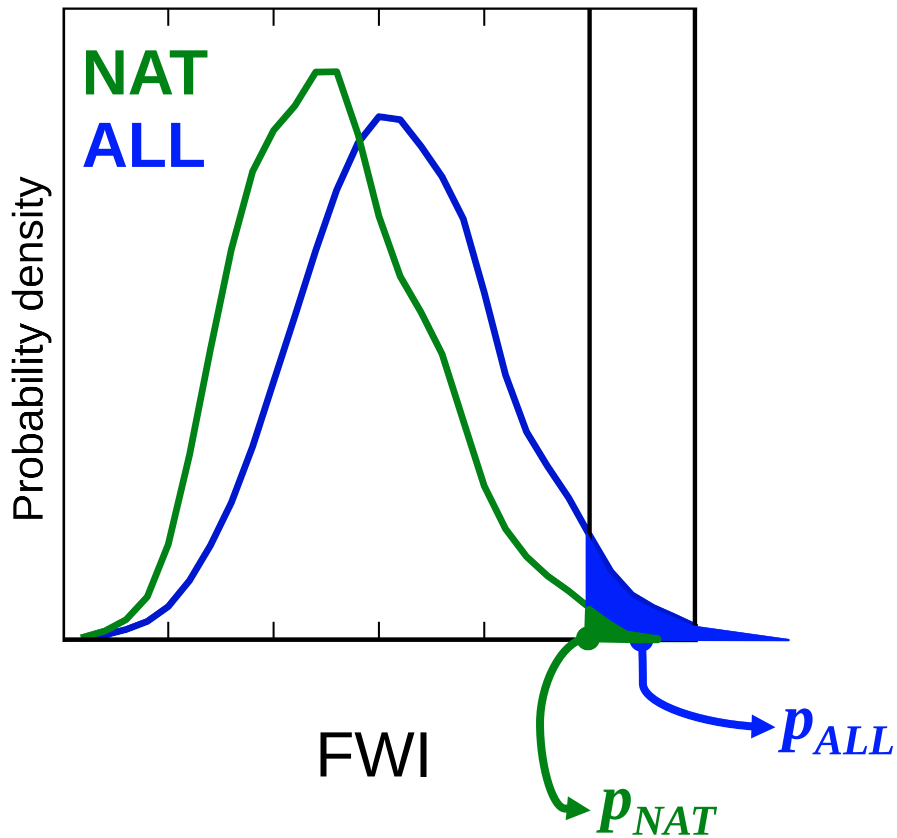
Fire risk (Kirchmeier-Young et al, 2017)

- We ask whether human induced climate change has affected fire risk in the"Southern Prairie" Homogeneous Fire Regime zone
- Measure fire risk using "CWFIS" system indicators
  - Fire Weather Index
  - Fine Fuels Moisture Code
  - Duff Moisture Code
  - Drought Code
  - Etc
- These indices depend on temperature, relative humidity, wind speed, and precipitation

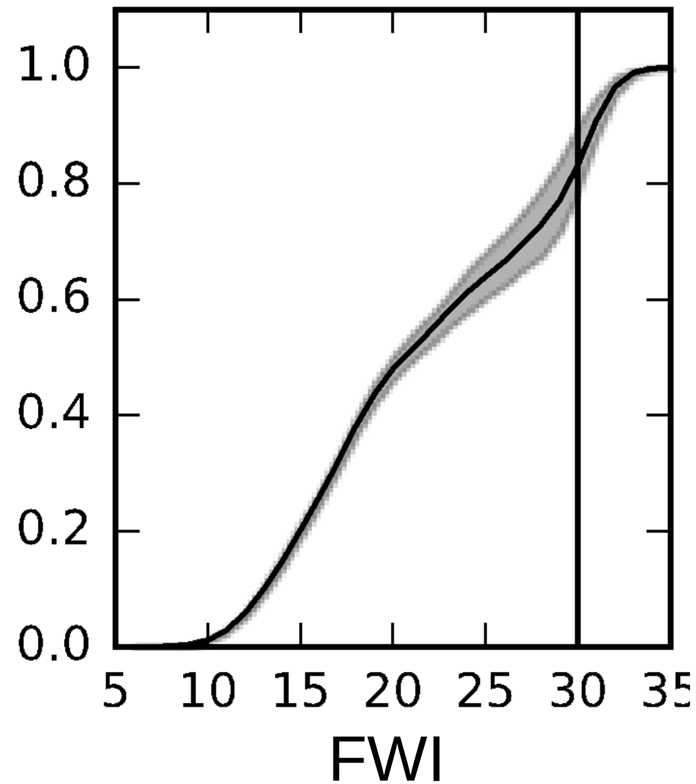
Annual area burned 1981-2010
Canadian National Fire Database



Fire Weather Index for Southern Prairies HFR for the current decade (2011-2020)



$$FAR = \frac{p_{ALL} - p_{NAT}}{p_{ALL}}$$



CWFIS "Extreme" FWI level = 30

Observed FWI level in Fort Mac area ≈ 40

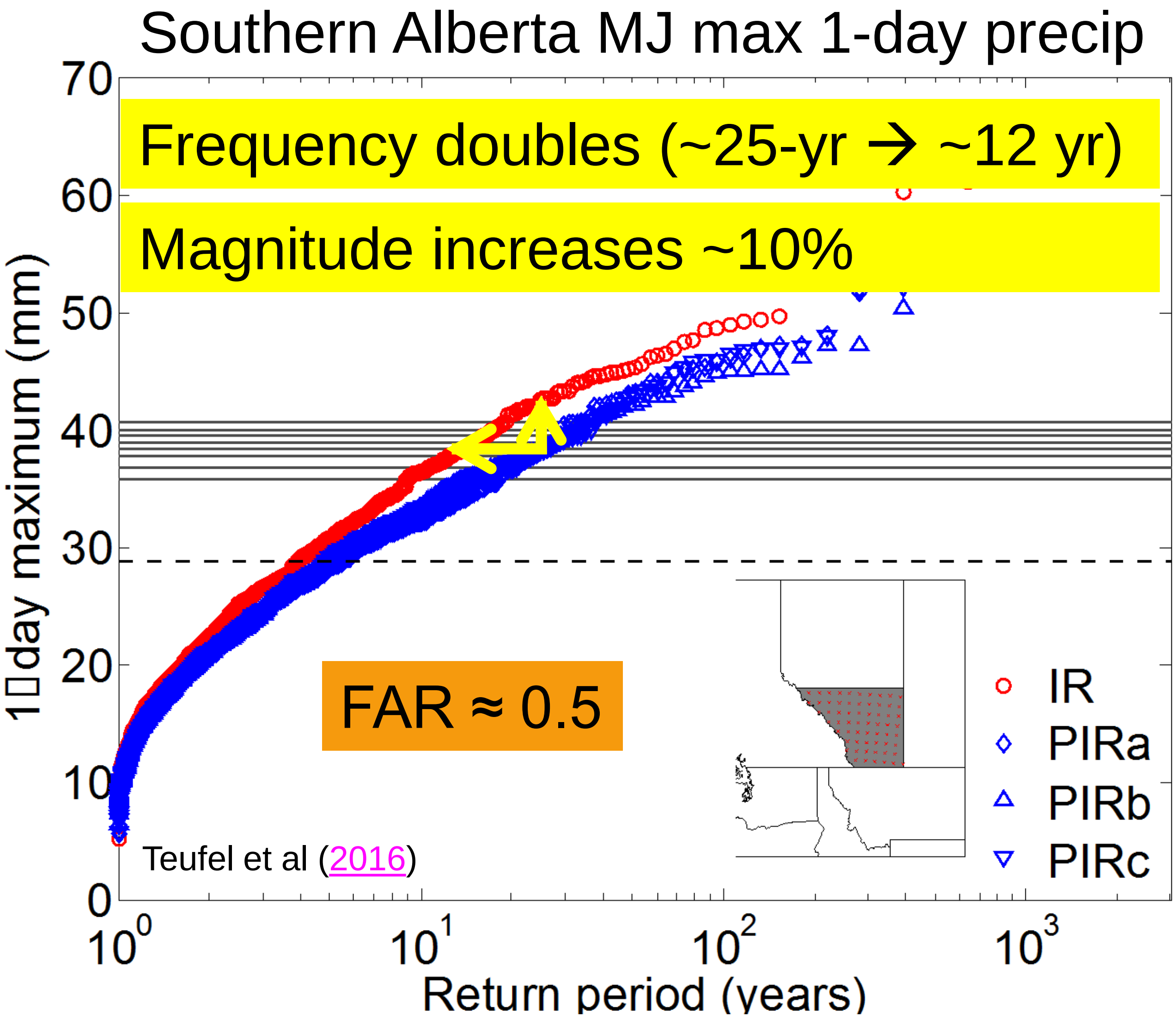
Calgary flood, 2013

- 100,000 displaced, 5 deaths
- Costliest (?) disaster event in Canadian history
- Estimated $5.7B USD loss ($1.65B USD insured)

Calgary East Village (June 25, 2013), courtesy Ryan L.C. Quan

Calgary floods

Distribution of annual May-June maximum 1-day southern-Alberta precipitation in CRCM5 under factual and counter-factual conditions (conditional on the prevailing global pattern of SST anomalies)

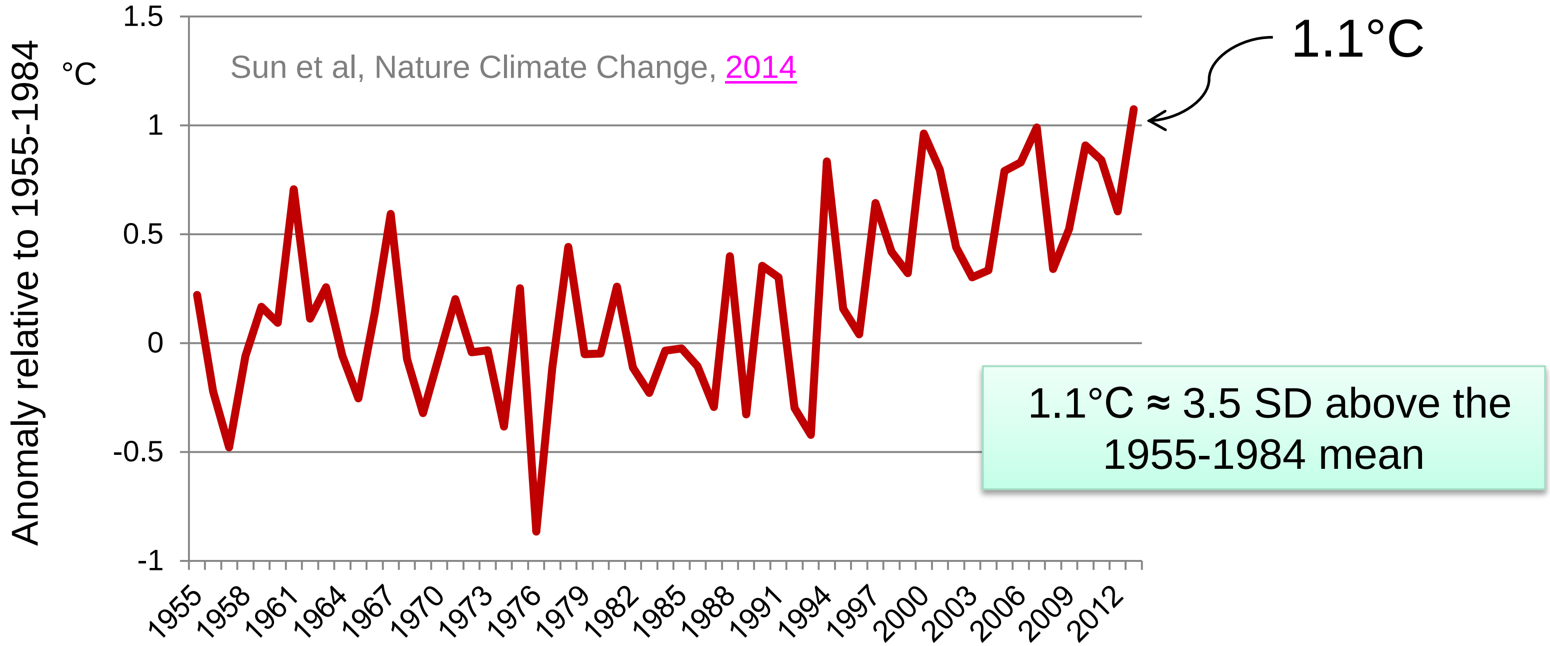


China’s Hot Summer of 2013

- Impacts included estimated $10B USD agricultural yield loss

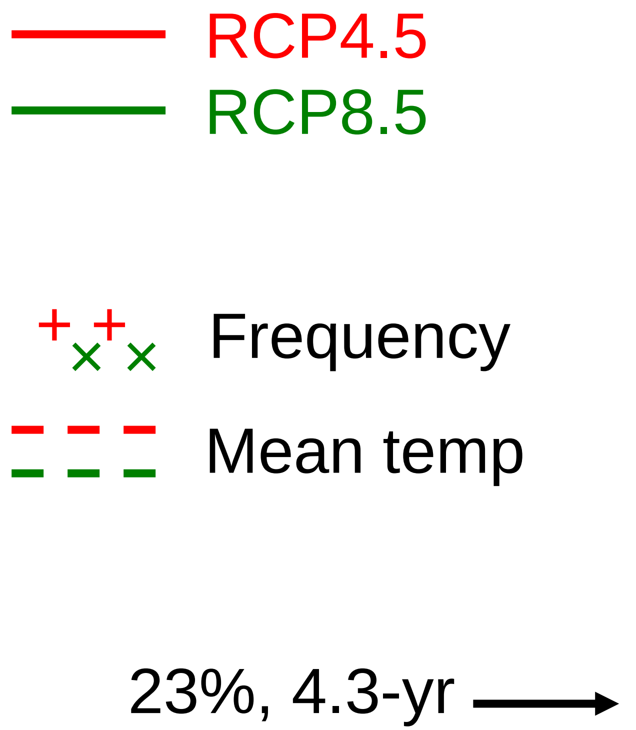
Photo: F. Zwiers **(Yangtze River)**

How rare was JJA of 2013?



- Estimated event frequency
  - once in 270-years in control simulations
  - once in 29-years in “reconstructed” observations
  - once in 4.3 years relative to the climate of 2013
- Fraction of Attributable Risk in 2013: $(p_1 – p_0)/p_1 \approx 0.984$
- Prob of “sufficient causation”: $PS=1-((1-p_1)/(1-p_0)) \approx 0.23$

Projected event frequency



Conclusions

Photo: F. Zwiers (Ucluelet)

Conclusions

- Understanding of the impact of anthropogenic forcing on observed extremes remains limited
  - Relatively high confidence for temperature extremes
  - Some confidence in precipitation extremes
  - Can say relatively little about storms, droughts, floods
- Often very limited by data (models and methods can be improved; historical data is much harder)
- Need further methodological development and improved process understanding
- Event attribution is increasingly undertaken
  - Still much work to do to develop methods and capabilities, understand implications of framing choices, and develop objective evaluation techniques


Questions?
https://www.pacificclimate.org/
Photo: F. Zwiers