Extreme events and Climate Change: a statistical perspective

Aurélien Ribes

27 June 2022, Kelowna (and Toulouse)

Motivation / This talk

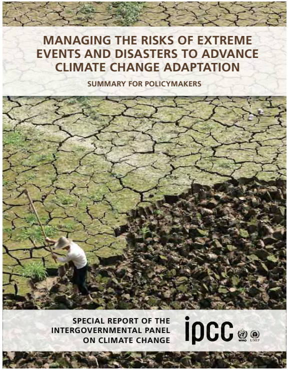
- Most impacts of climate change are expected to occur through extreme events.
  e.g., sea level rise,
- How extreme events are / will be affected by climate change?
  What events to expect in the future?
- Statistics play a central role.

This talk:

- A review of recent research and statistical challenges in investigating extreme events and climate change.
- I assume the audience is familiar with stats (e.g., GEV), but not familiar with climate data.

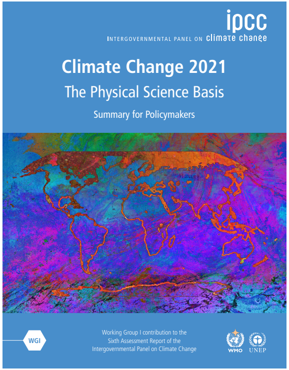
1. Extreme events in climate
2. Data
3. Questions to investigate
4. Some statistical challenges and personal work
5. Conclusion

IPCC assessments on extremes (last 10-yr)



SREX, 2012

AR5, 2014



AR6, 2021

Which events and the current knowledge

- **Temperature** (easy): warm ↗, cold ↘
- **Heavy precipitation** (quite easy): ↗ (most regions)
- **Droughts** (quite difficult): depends on def, region, period, length, . . .

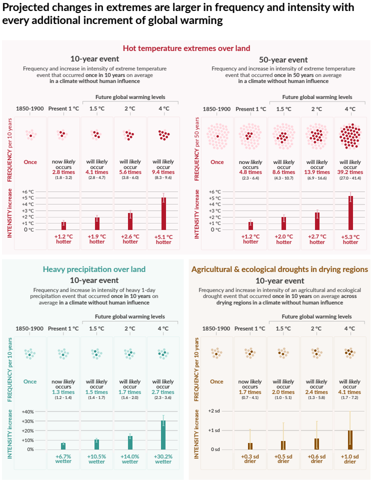


Figure SPM.6, IPCC WGI AR6.

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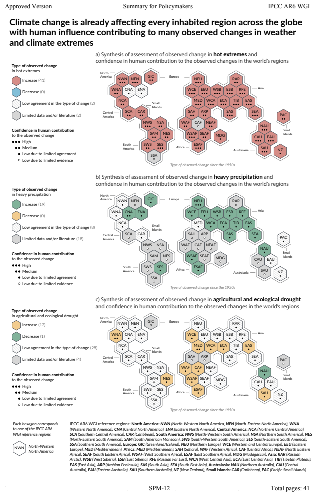

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- **Droughts** (quite difficult): depends on def, region, period, length, . . .
- **Floods**
- **Coastal floods / waves**
- **Storms**: tropical cyclones, extratropical storms
- **Convective storms**: thunderstorms, convective gusts, lightning, hail, etc
- **Compound events**: hot and dry, frost on active vegetation

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

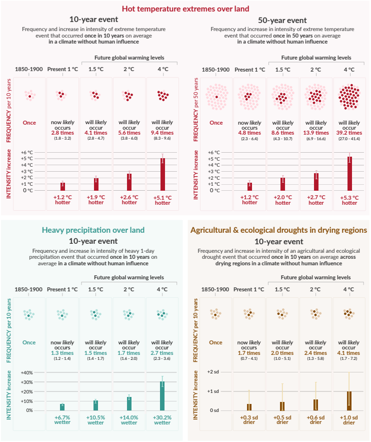
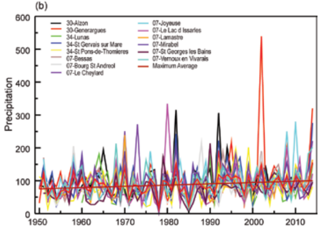


Figure SPM.6, IPCC WGI AR6.

Data

◇ **Observations**

Big bunch of literature to describe observed changes in extreme events



Seasonal max precip time-series
From Vautard et al. (2015)

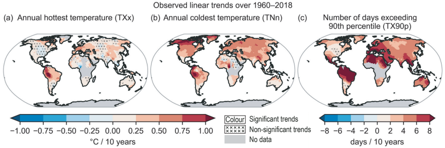


Figure 11.9, IPCC AR6 WG1 (2021)

Data

- **Observations**

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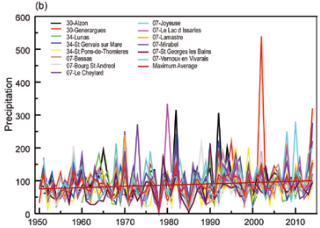
- **Models**



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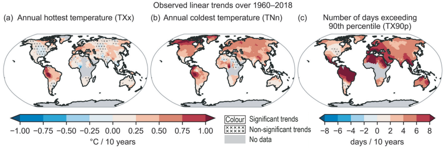
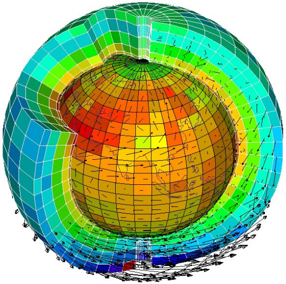


Figure 11.9, IPCC AR6 WG1 (2021)

Climate models: principle



Source : IPSL

Models are based on:

- physical equations (Navier-Stokes, thermodynamics, radiation, etc).
- numerical resolution of PDEs.

Resolution:

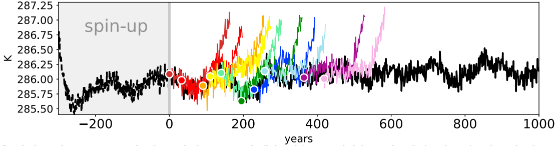
- spatial (H) $\sim$ 100 km,
- spatial (V) $\sim$ 500 m,
- temporal $\sim$ 15'.

Models simulate the climate system:

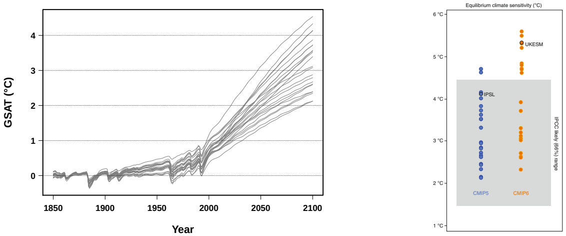
- atmosphere, ocean, land surfaces, biosphere, cryosphere, rivers, . . .
- IV and forcings.

Climate models: practical use

- Model development and use is a huge effort!!
- Numerical experiments: pi-control, historical, scenarios, theoretical experiments, . . .
- Coordinated simulations: CMIP ensemble ($\sim$40 models in CMIP6).
- Several types of models/resolution: global ($\sim$100km), regional ($\sim$10km), km-scale ($\sim$1km), . . .



Model spin-up, pre-industrial control (black), and historical (colors) simulations with the model CNRM-CM6. From Voldoire et al., 2019, JAMES.



Left: Response of CMIP6 models to SSP2-4.5 scenario
Right: Warming response to $2 \times CO_2$ in CMIP5/6 models

Questions

How extreme events are / will be affected by climate change?

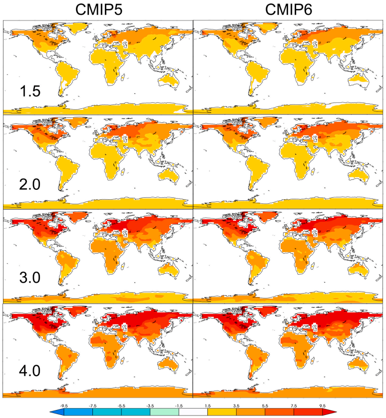
In IPCC AR6 WG1 Chapter 11:

- Mechanisms and Drivers
- Observed trends
- Model evaluation
- Detection and Attribution, Event attribution
- Projections

Projections

Describe how extreme events respond in (model) projections.

Examples:
Temp: Wehner et al. (2020, WACE);
Precip: Kharin et al. (2012, below); John et al. (2022).



Change in TNn 20-yr RV, at various Global Warming Levels (GWLs); from Wehner et al., 2020, WACE.

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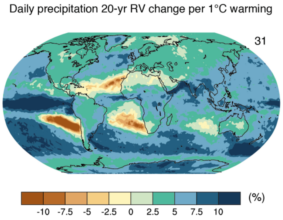
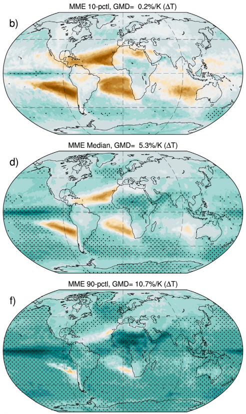




Confidence interval on daily precip 20-yr RV change; from John et al. (2022).

Detection / attribution

- **Detection:** are observations consistent with internal variability only?
- **Attribution:** assess the relative contribution of (various) external forcings.
  e.g., ANT / NAT, GHG / AER, etc.

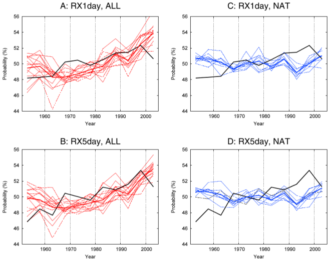
Example: Min et al (2011), Zhang et al (2013) looked at annual max 1d rainfall (RX1D) worldwide and report a statistically discernible human influence.

LETTER

doi:10.1038/nature09763

Human contribution to more-intense precipitation extremes

Seung-Ki Min[1], Xuebin Zhang[1], Francis W. Zwiers[1]† & Gabriele C. Hegerl[2]



From Zhang et al. (2013)

Event attribution

- Concept: consider a specific event that did happened
- Investigate / Describe human contribution to that event
  Assess human influence on probability / intensity of the event?
  What to expect in the future?
- Historical example: European 2003 HeatWave
  Stott et al., 2004, Nature

Key indices: $\text{PR} = \frac{p_1}{p_0}$, $\Delta I = I_1 - I_0$, $\text{FAR} = \frac{p_1 - p_0}{p_1}$.

FAR: Fraction of Attributable Risk.

Human contribution to the European heatwave of 2003

Peter A. Stott[1], D. A. Stone[2,3] & M. R. Allen[2]

[1]Met Office, Hadley Centre for Climate Prediction and Research (Reading Unit), Meteorology Building, University of Reading, Reading RG6 6BB, UK
[2]Department of Physics, University of Oxford, Oxford OX1 3PU, UK
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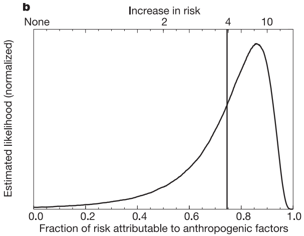
The summer of 2003 was probably the hottest in Europe since at latest AD 1500[1–4], and unusually large numbers of heat-related deaths were reported in France, Germany and Italy[5]. It is an ill-posed question whether the 2003 heatwave was caused, in a simple



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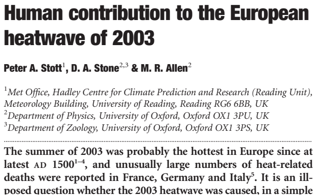

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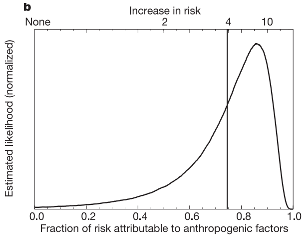

- Now: *rapid* attribution (eg, WWA).
- Potential interest: awareness-raising, legal aspects.

Causality

- The 2010 Russian heatwave (R10) example:

  Dole et al, 2011: R10 is “mainly natural in cause”,

  Rahmstorf and Coumou, 2010: R10 “*would not have occurred*” without climate change.

  Reconciling (Otto et al, 2012): most of the heat anomaly is natural; CC increased the risk significantly.

- Relationship between “(event) Attribution” and “Causal theory”,

  e.g., Hannart et al., 2016, BAMS; Hannart et al., 2018, JClim

  $\text{PN} = \max\left(1 - fracp_0 p_1, 0\right)$, $\text{PS} = \max\left(1 - \frac{1-p_1}{1-p_0}, 0\right)$, $\text{PNS} = \max(p_1 - p_0, 0)$.

- Usually, “*human influence*” is a necessary, but not sufficient cause.

Related to the extremes events

- Statistical model selection, e.g., non-stationary models

$$y_t \sim GEV(\mu_0 + \mu_1 x_t, \sigma_0 + \sigma_1 x_t, \xi).$$

  - Select appropriate covariate x_t,
  - Constant ξ?
  - GEV models may not fit annual max.
    Ben Alaya et al., 2020 (JClim), 2021 (WACE).

- Specific investigation of *Low Likelihood High Impact* scenarios / events,
  sse, e.g., Sutton, 2019, BAMS.

- If no data: statistical investigation of environmental conditions (incl. AI).
  e.g., Tropical cyclogenesis, Menkes et al., 2009, Clim Dyn; CAPE, Singh et al., 2017, PNAS.

Related to the data

- Observations
  - measurement uncertainty,
  - homogeneity,
  - missing data,
  - (spatial) representativity,
  - short records,
  - . . .

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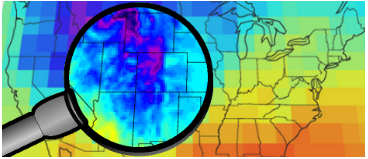

- Models
  - Systematic bias – need for bias correction (= stats),
  - Too coarse resolution – statistical downscaling,
  - Models do not necessarily agree,
  - Combining models: model uncertainty, non-independence, poor design.

    Knutti et al., 2010, Jclim; Knutti et al., 2013, GRL

Combining observations and models (1)

- Obs. now provide indication about warming strength
- Combination of model and obs to assess past and future changes
- GSAT warming in IPCC AR6...

  Tokarska et al., 2020, Sci Adv; Liang et al., 2020, GRL; Ribes et al., 2021, Sci Adv.

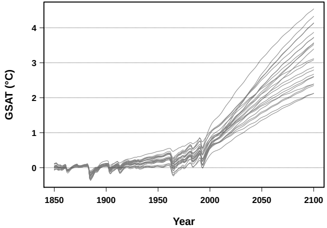

Illustration from Ribes et al. (2021)

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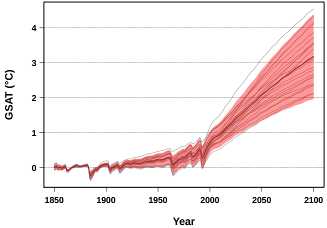

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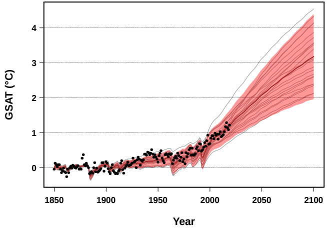

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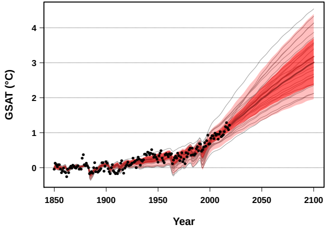

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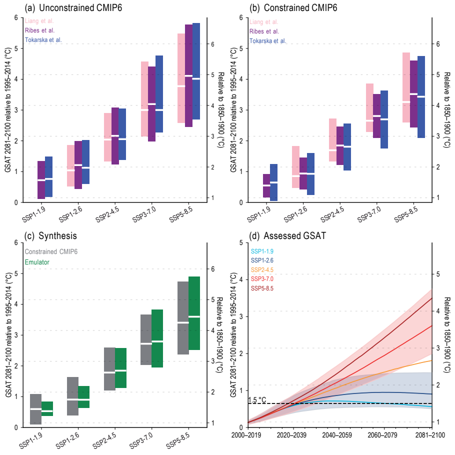

Fig 4.11 from IPCC AR6 (2021)

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  Tokarska et al., 2020, Sci Adv; Liang et al., 2020, GRL; Ribes et al., 2021, Sci Adv.
- ... now moving towards extremes.

  Thackeray et al., 2022, NCC

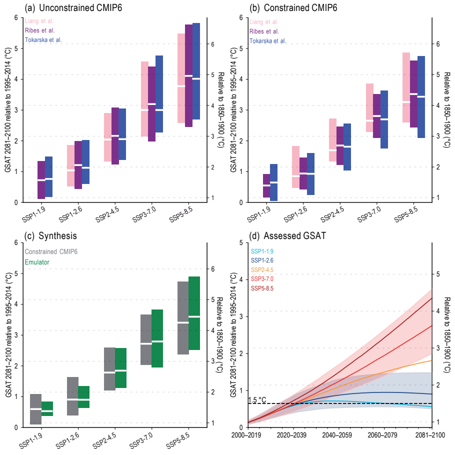


Fig 4.11 from IPCC AR6 (2021)

Combining observations and models (1)

- “*Best available information*” requires blending models + obs
- There might be interest in doing so.

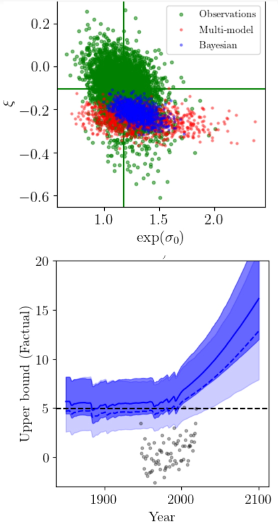
Illustration: $y_t \sim GEV(\mu_0 + \mu_1 x_t, \sigma_0 + \sigma_1 x_t, \xi)$.

- Parameters: $\theta = (\mu_0, \mu_1, \sigma_0, \sigma_1, \xi)$,
- ξ hard to estimate from obs (short record),
- μ_0, σ_0 often biased in models.

We use a Bayesian treatment:

- Models provide a prior $\pi(\theta) \sim N(\mu, \Sigma_{mod})$.
- We derive the posterior $p(\theta|y)$.

Ref: Robin & Ribes (2020), *ASCMO*



Conclusion

- A wide range of events – some are very poorly known.
- One central question: evaluating / quantifying the future hazard.
- Causal theory involved in relating extreme events to the human influence on climate, with potential societal implications.
- A number of statistical challenges that need continued statistical research, e.g., smart blending of model + observation data.