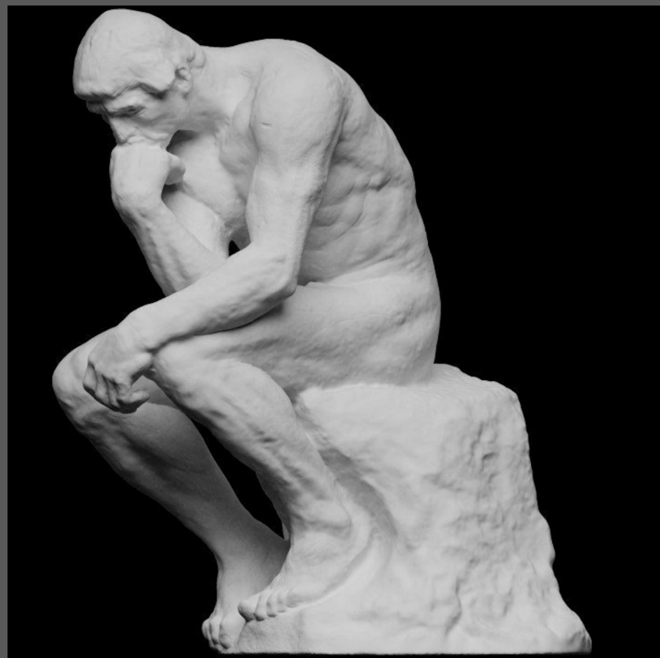
METEOROLOGY

COMBINING PHYSICAL REASONING WITH STATISTICAL PRACTICE IN UNCERTAINTY QUANTIFICATION ACROSS SCALES



Ted Shepherd, Grantham Chair of Climate Science

Department of Meteorology, University of Reading

also Jülich Supercomputing Centre, Forschungszentrum Jülich

A study in contrasts

- Black et al. (2004) explored in detail the various causal factors behind the 2003 European heatwave: persistent anticylone, SST anomalies, drying of land surface, surface fluxes....
  - "*It is not known at this time why the large-scale circulation had the character it did*."
- Stott et al. (2004) ignored all those factors and targeted a much weaker, coarse-grained ‘event’ of only 1.6 C above the mean, to avoid 'selection bias'
- Black et al. is certainly highly cited, but Stott et al. has become the dominant paradigm

Factors contributing to the summer 2003 European heatwave

Emily Black
Mike Blackburn
Giles Harrison
Brian Hoskins
John Methven

Department of Meteorology, University of Reading

mean daily temperatures! Averaging over each month the temperature anomalies were +4.2 degC in June, +3.8 degC in August and almost +2 degC in May and July. The temperature anomalies were most extreme in France and Switzerland although maximum temperature records were broken in many parts of Europe. For example, Schär *et al.* (2004) have shown that the June–July–August temperature averaged for four Swiss stations exceeded the

large-scale atmospheric flow and the regional heat budget from ECMWF analyses and measurements of the surface energy budget at the University of Reading. The influence of atmospheric flow anomalies on the surface of the land and ocean, and possible feedbacks are also discussed.

Atmospheric flow anomalies in the Northern Hemisphere

Weather (2004)

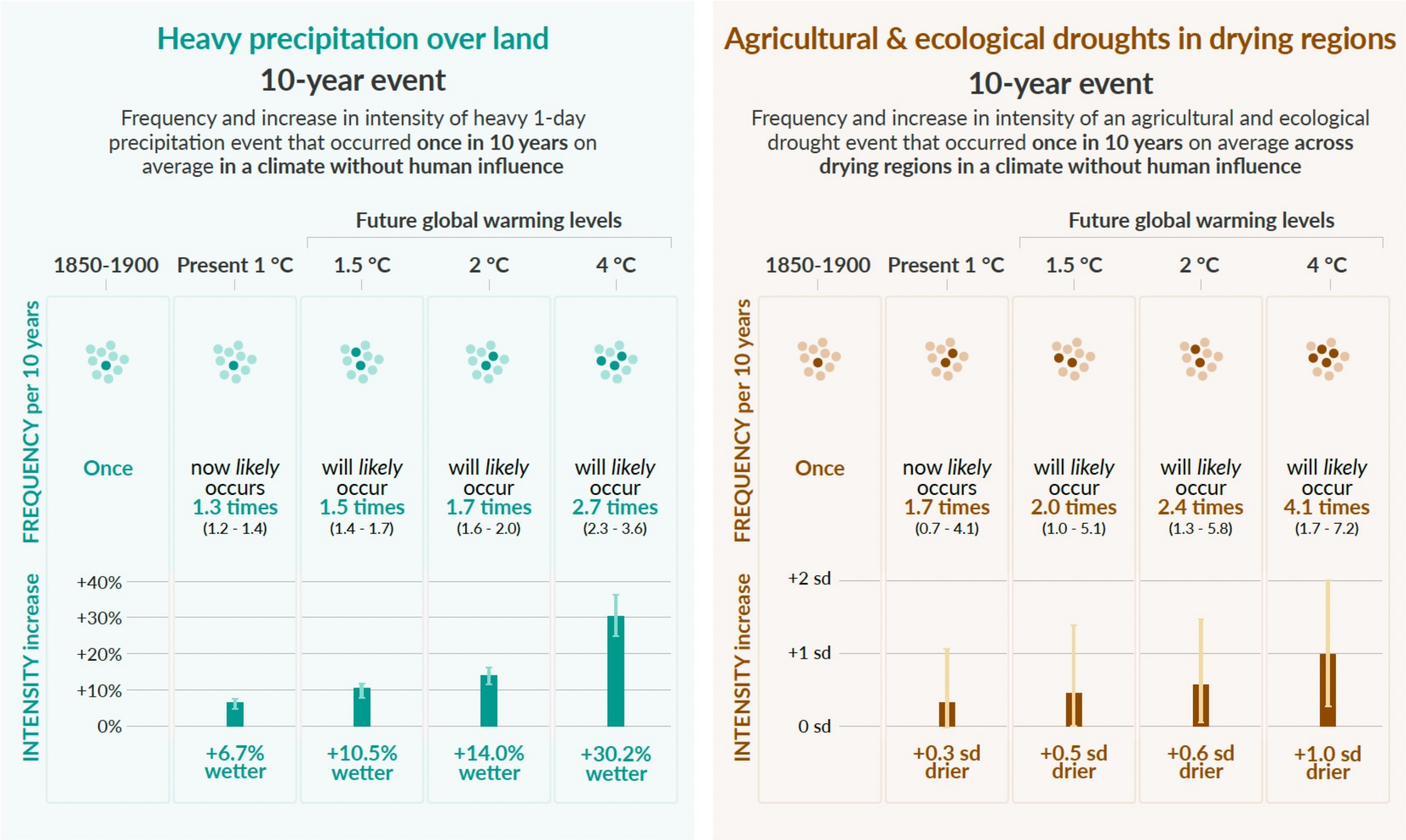
Human contribution to the European heatwave of 2003

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*
[3]*Department of Zoology, University of Oxford, Oxford OX1 3PS, UK*

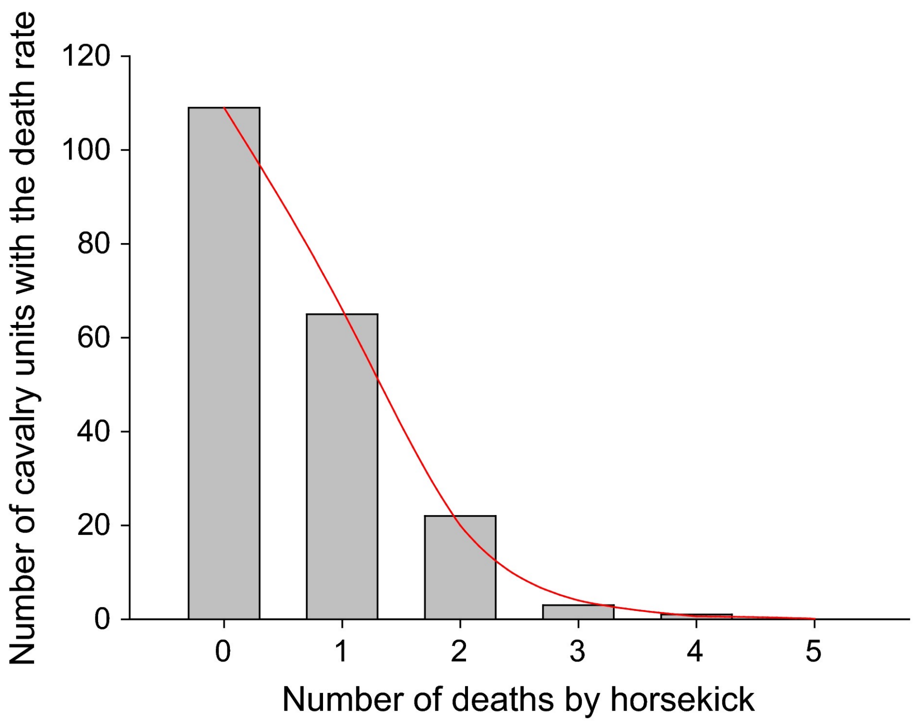
Nature (2004)

- Climate scientists tend to describe changes in extreme events **probabilistically**, which requires **aggregation**



SPM of AR6 WGI report (2021)

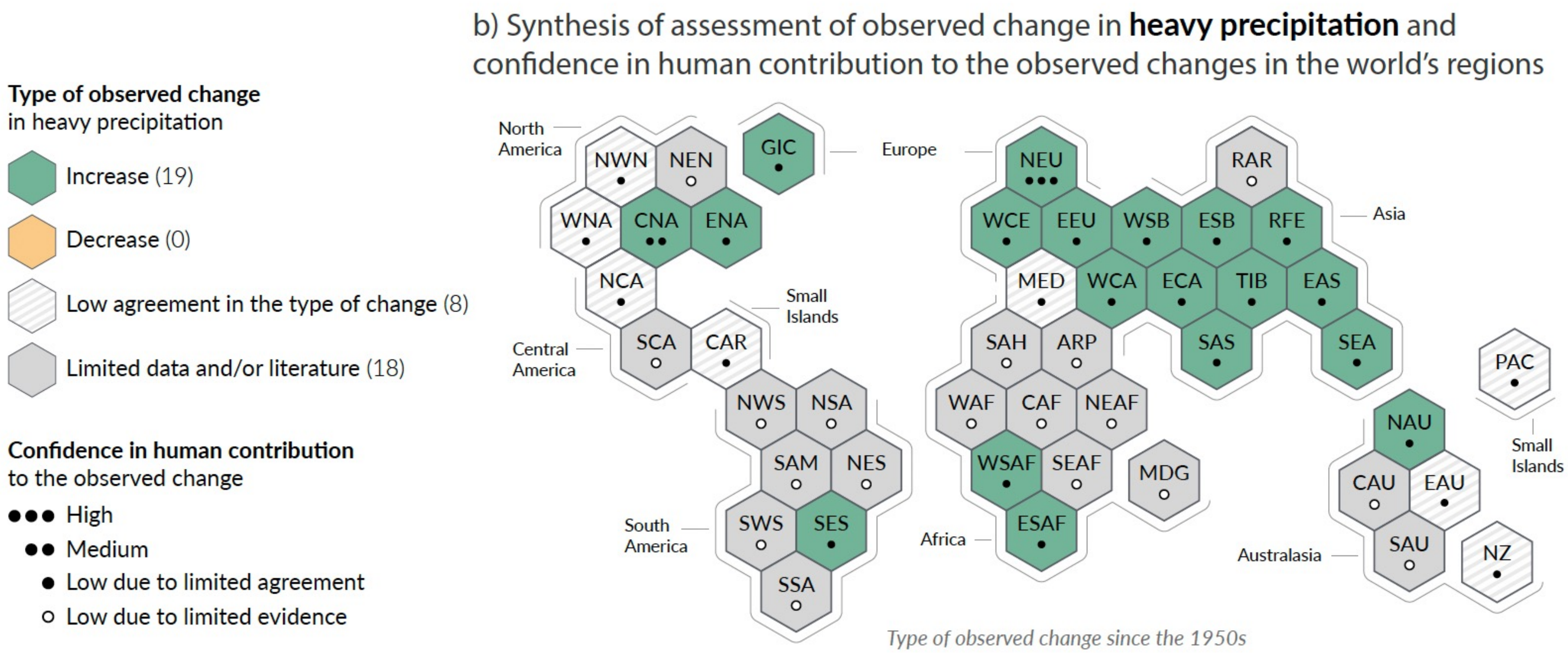
- Even when aggregation is reliable, **it is not informative about individual cases**
  - Events in the real world are not iid (independent and identically distributed)



Pandit (2016 Anaesthesia)

- A famous example (Bortkiewicz 1898): the number of Prussian cavalry units suffering a death of a soldier by horsekick in a given year (collected over a 20-year period)
  - Follows a Poisson distribution
- Shows that the deaths happened "by chance", even though **each one surely has a tragic story behind it**
- This sort of dialectic between aggregate and individual occurs across many disciplines
  - Public health vs clinical practice
  - Climate vs weather

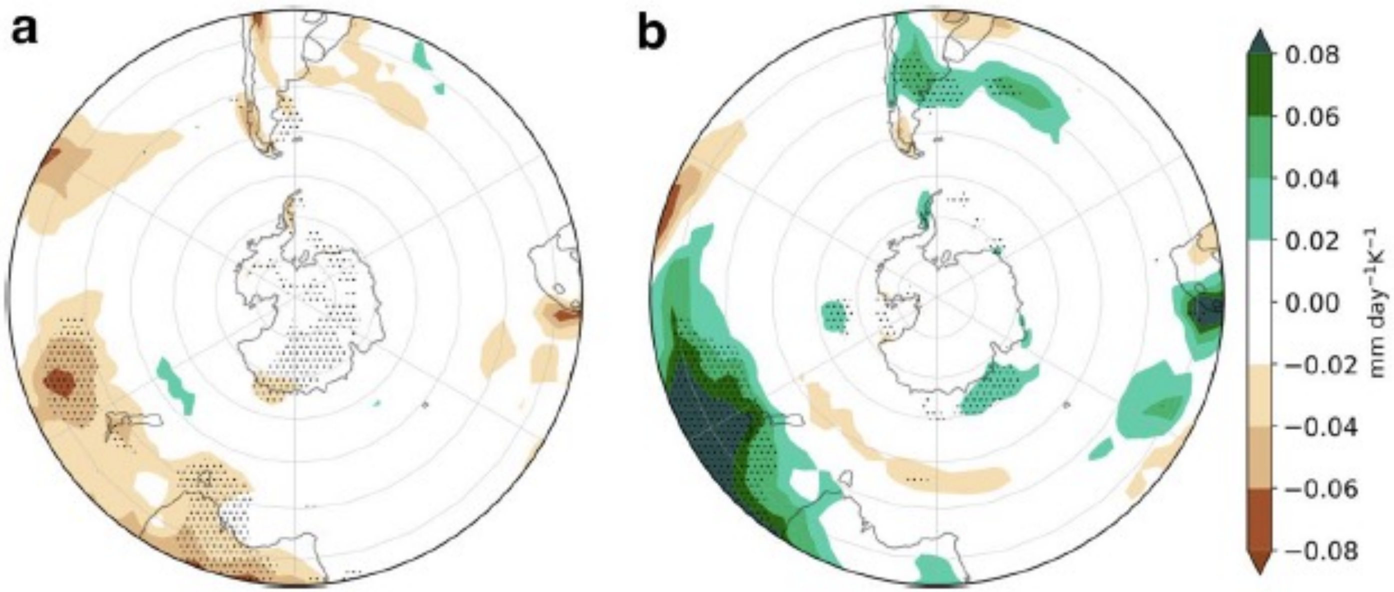
- At the regional scale, probabilistic attribution of changes in extremes is challenged not only by **uncertainties in model projections**, but also by a **lack of verifying data**
  - Represents a form of epistemic injustice (Shepherd & Sobel 2020 CSAAME)



SPM of AR6 WGI report (2021)

- In the IPCC, the uncertainty around dynamical aspects of climate change has typically been managed through **generalization**, e.g. a focus on zonally averaged quantities
- However, **generalization can be locally misleading**: precipitation changes in austral summer from a strengthening of the Southern Annular Mode (SAM) are completely different depending on whether the SAM change is induced by tropical warming (left) or by a delay in the breakdown of the stratospheric polar vortex (right)

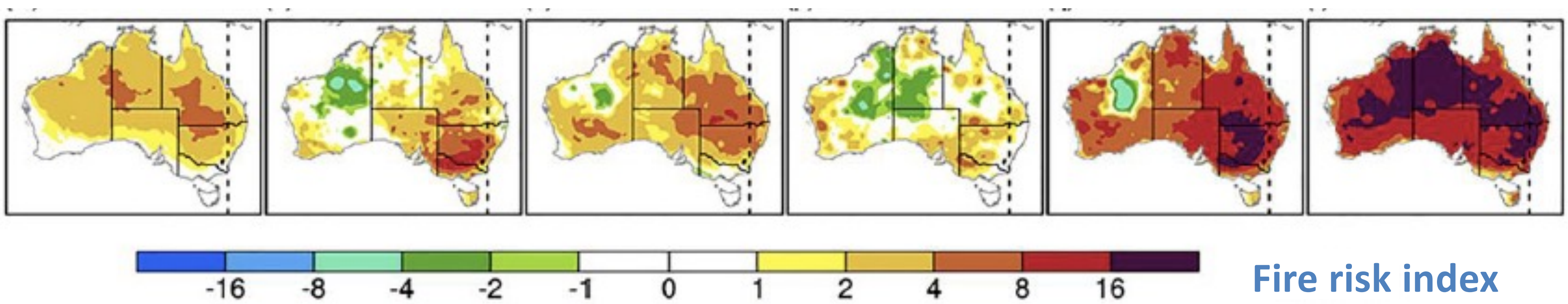
One corresponds to a strengthening of the westerlies, the other to a poleward shift



Mindlin et al. (2020 Clim. Dyn.)

- In most extreme events, the role of **unusual dynamical conditions** is generally a very important causal factor
  - **How those dynamical conditions could change** represents a major source of uncertainty in climate information for adaptation
- For the 2019 Australian wildfires, long-term warming (“Trend”) was actually only a minor contributor to increased fire risk, which mainly arose from **drying associated with unusual dynamical states (atmospheric circulation)**

Pacific SST | Indian SST | Vortex | Trend | Total | Observed

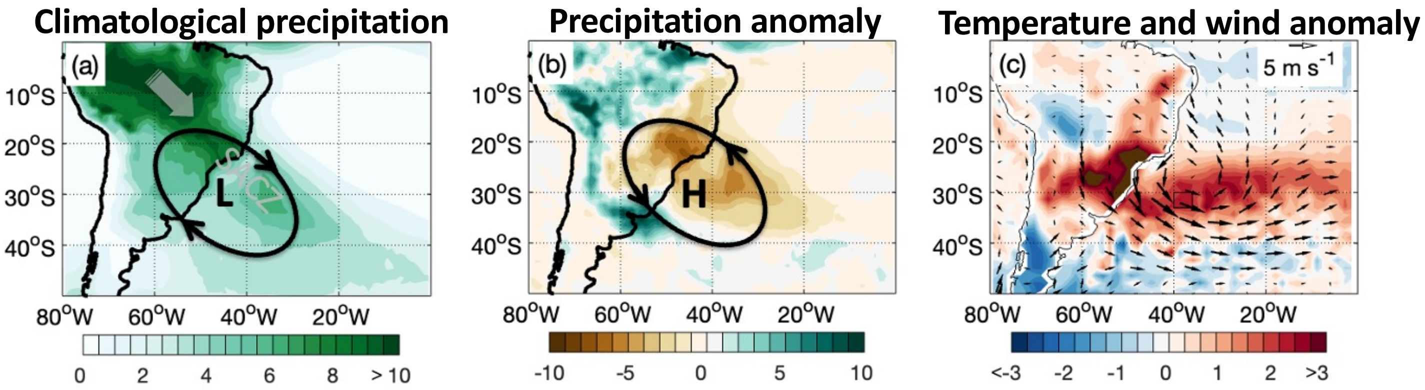


Fire risk index

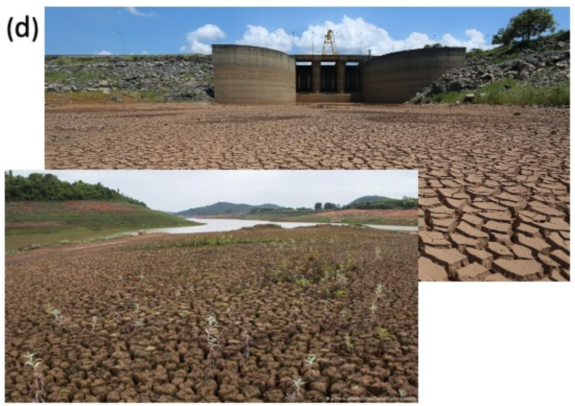
Lim et al. (2021 BAMS)

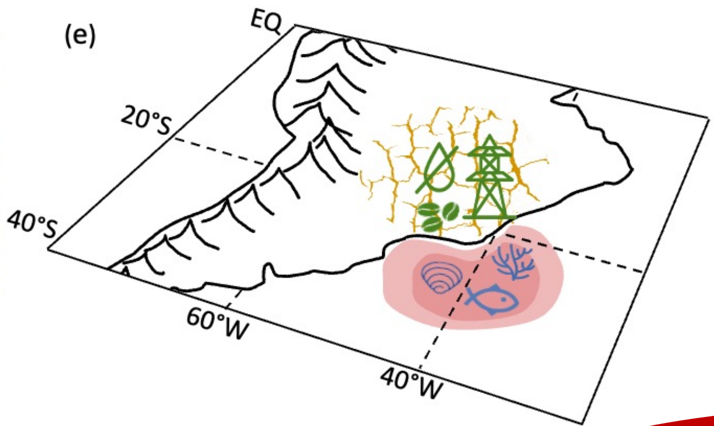
Example: a compound extreme event in southeast Brazil

- Anomalous anti-cyclonic circulation led to failure of 2013/14 South American monsoon
- Caused drought and heatwaves, affected food-water-energy nexus: correlated risk

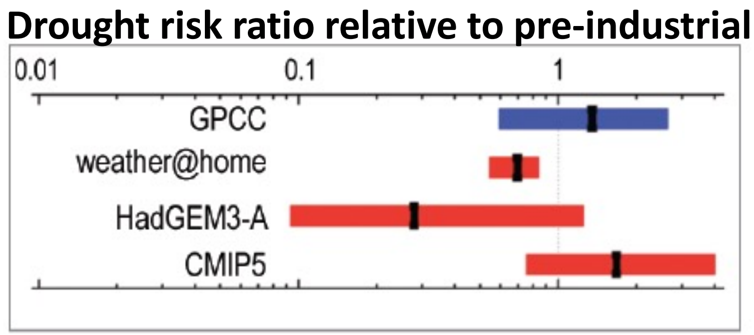


- A probabilistic attribution study of the event found "insufficient evidence" that climate change increased drought risk





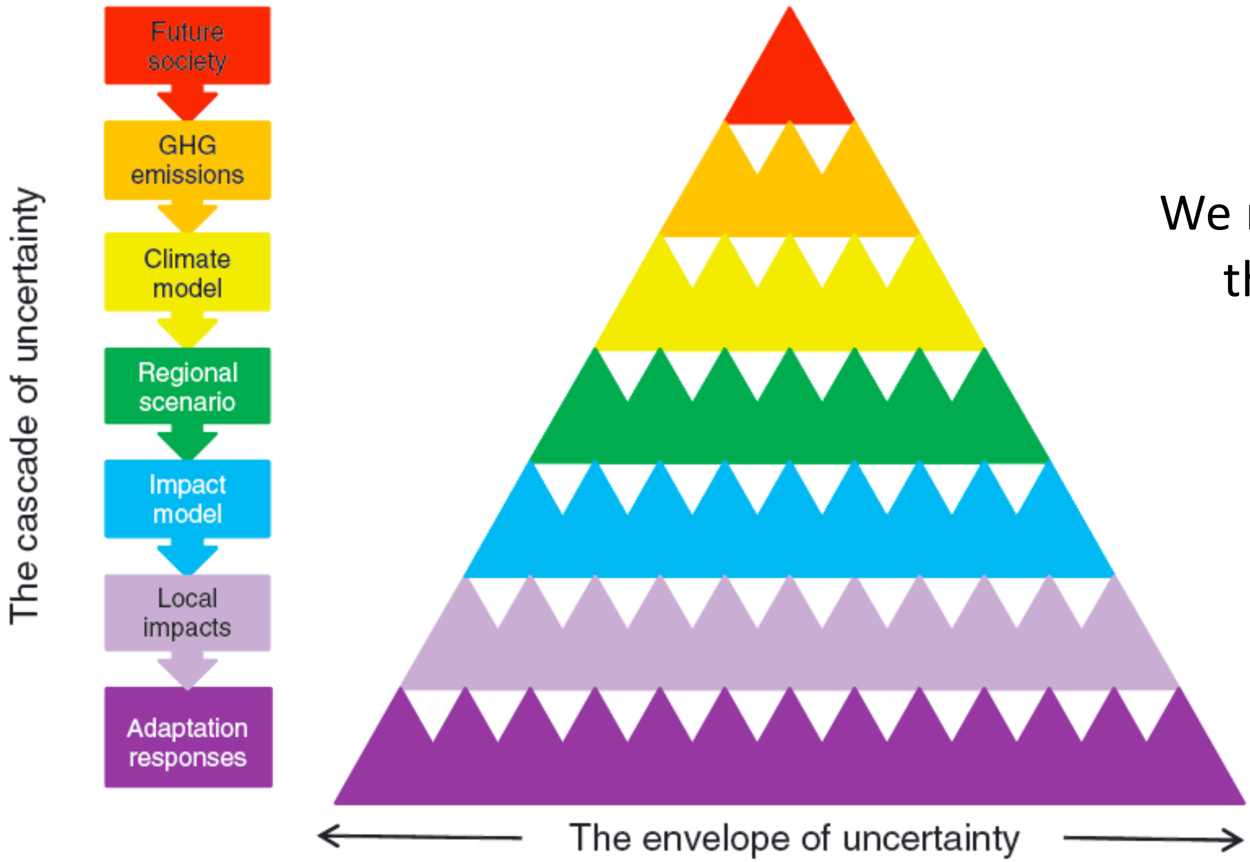
Rodrigues & Shepherd (2022 PNAS Nexus)



Martins et al. (2017 BAMS)

We can ask: **insufficient for whom?**

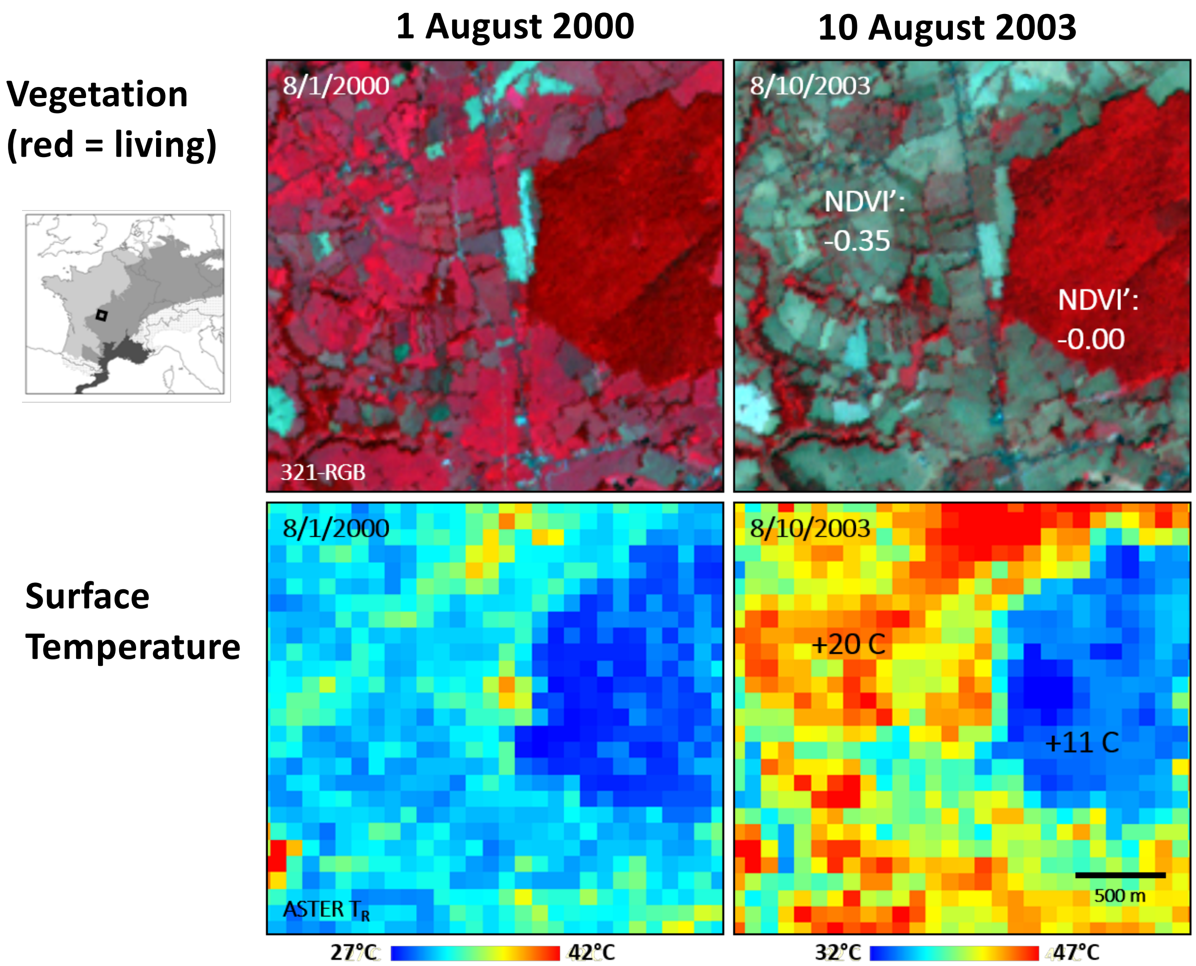
- Consideration of all the uncertainties in climate change in the traditional way leads to a “**cascade of uncertainty**” which obscures the climate information content



We need to navigate this somehow!

Wilby & Dessai (2010 Weather)

- **We actually have a huge amount of climate information, even at the local scale**, from both observations and modelling — it's just that the information is **conditional**

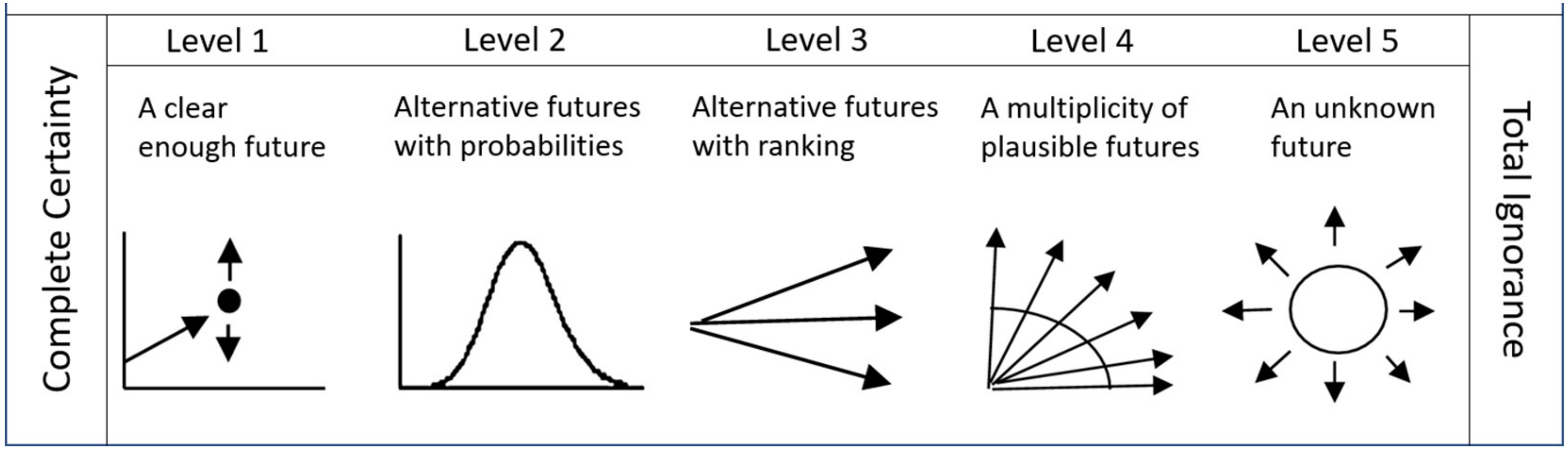


- The summer 2003 heat wave in central France
- Temperature difference between 2000 and 2003 was 11°C in forested areas, but 20°C where the vegetation died out
- We may not be able to predict the statistics of heat waves in the future, but we can predict their implications, and how to manage their impacts

Zaitchik et al. (2006 Int. J. Clim.)

- Scientists are pressured to issue **‘single, definitive’ statements** (Stirling 2010 Nature)
- In consensus mode, can lead to **reliable but rather uninformative** statements, e.g.
  “...there is low confidence in projected changes in the North Atlantic storm tracks” (IPCC AR6 WGI SPM 2021)
- We need a language for expressing a **‘plural, conditional’ state of knowledge**

Levels of uncertainty



Adapted from Marchau et al. (2019)

nature

EDITORIAL · 20 MARCH 2019

It's time to talk about ditching statistical significance

Looking beyond a much used and abused measure would make science harder, but better.

- Climate-change science is anchored in physical understanding, yet frequentist statistical practices and NHST absolutely dominate published climate-change science
- This creates a **disconnect between physical reasoning and statistical practice**
  - See Shepherd (2021 Climatic Change) for discussion and some examples
  - The **most basic error of all is intrepreting results dichotomously, as True/False**
    - The real world is much more complicated than that!

- **Hypothesis testing in a nutshell:** if H is the null hypothesis, then $P(D|H)$ is the p-value
- But we're actually interested in $P(H|D)$. **Bayes' theorem** tells us: $P(H|D) = \frac{P(D|H)}{P(D)} P(H)$
- $P(H)$ reflects the relevance of prior knowledge: "strong claims require strong evidence"
- $P(D)$ requires consideration of **all** plausible explanations for the data: if $\neg H$ is the negation (or complement) of H (possibly including several explanations),

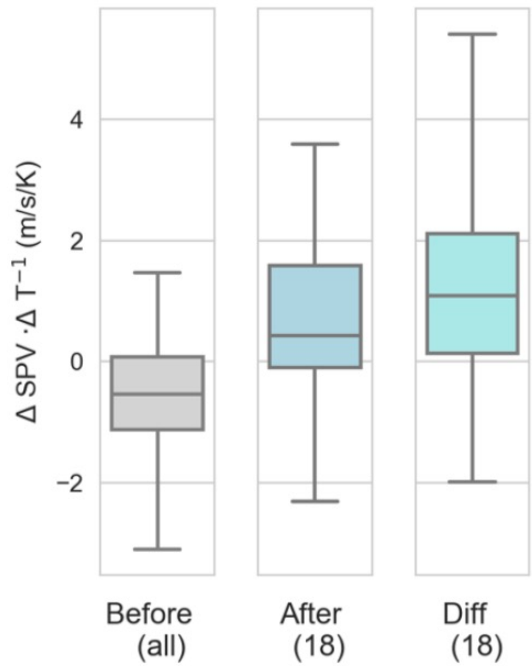
$$P(D) = P(D|H)P(H) + P(D|\neg H)P(\neg H)$$

- Yet **nowhere** in any climate science publication have I seen any explicit consideration of these two factors, which strongly affect the inference that can be obtained from a p-value!
  - With an implausible null hypothesis and only a loosely specified alternative hypothesis, a small p-value is pretty much worthless! (see also Nuzzo 2014 Nature)
- In practice, it is convenient to work with the '**odds**' form of Bayes' theorem

$$\frac{P(H|D)}{P(\neg H|D)} = \underbrace{\frac{P(D|H)}{P(D|\neg H)}}_{\text{Bayes factor}} \times \frac{P(H)}{P(\neg H)}$$

N.B. The Bayes factor is independent of the prior odds

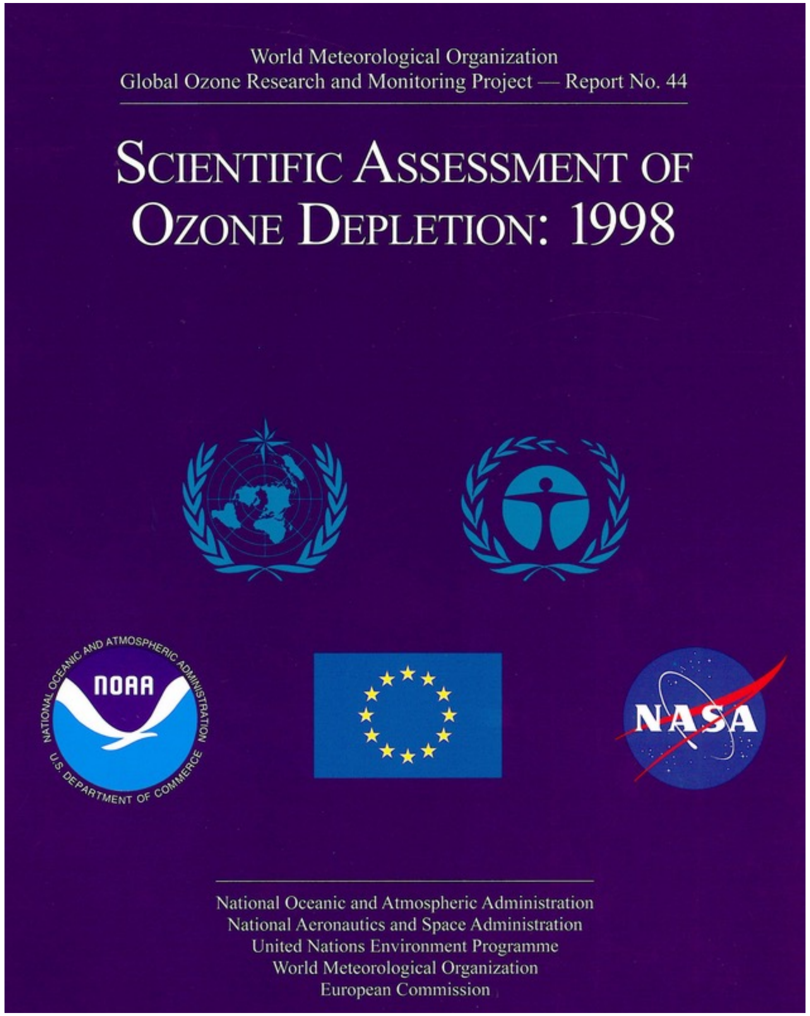
- **Example: response of the wintertime stratospheric polar vortex (SPV) to Barents-Kara (B-K) sea-ice loss**
  - Would have obvious implications for European extremes
- Nonlinearity in the SPV response to global warming plausibly explained by when B-K seas become ice-free in summer (right)
- But quantifying the causal linkage across CMIP5 is challenging
- Can test whether the SPV evolution is more linear after removing the causal effect of B-K sea-ice loss
  - Bayes factor is pretty close to unity!



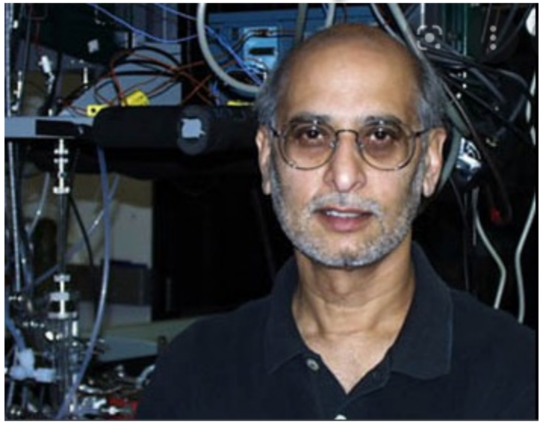
"There are cases where there is no positive evidence for a new parameter, but important consequences might follow if it was not zero, and we must remember that [a Bayes factor] > 1 does not prove that it is zero, but merely that it is more likely to be zero than not. Then it is worth while to examine the alternative [hypothesis] further and see what limits can be set to the new parameter, and thence to the consequences of introducing it." (Jeffreys 1961)

Kretschmer, Zappa & Shepherd (2020 WCD)

Chapter 7. Lower Stratospheric Processes (Lead Authors: A.R. Ravishankara and Theodore G. Shepherd)

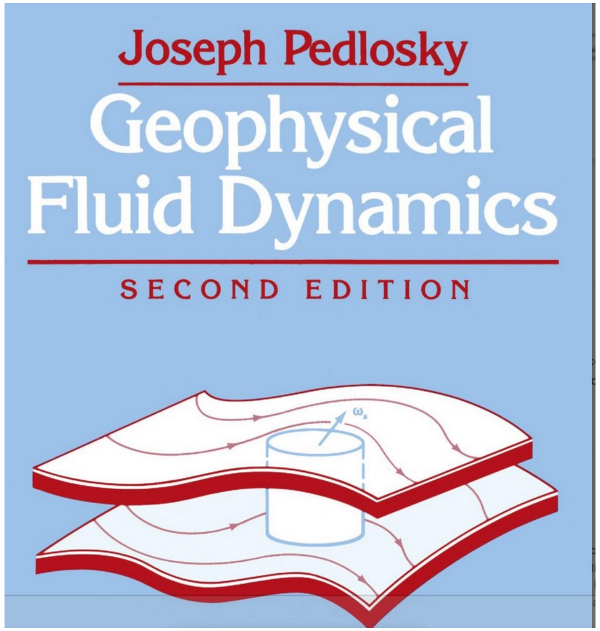


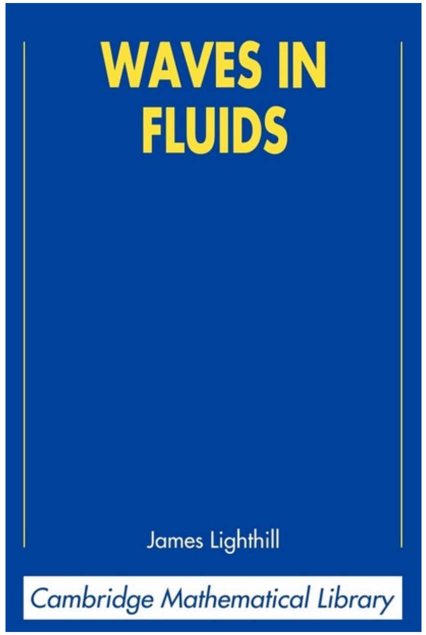
Ravi to Ted: "Why do you dynamicists never give a straight answer to a question?"



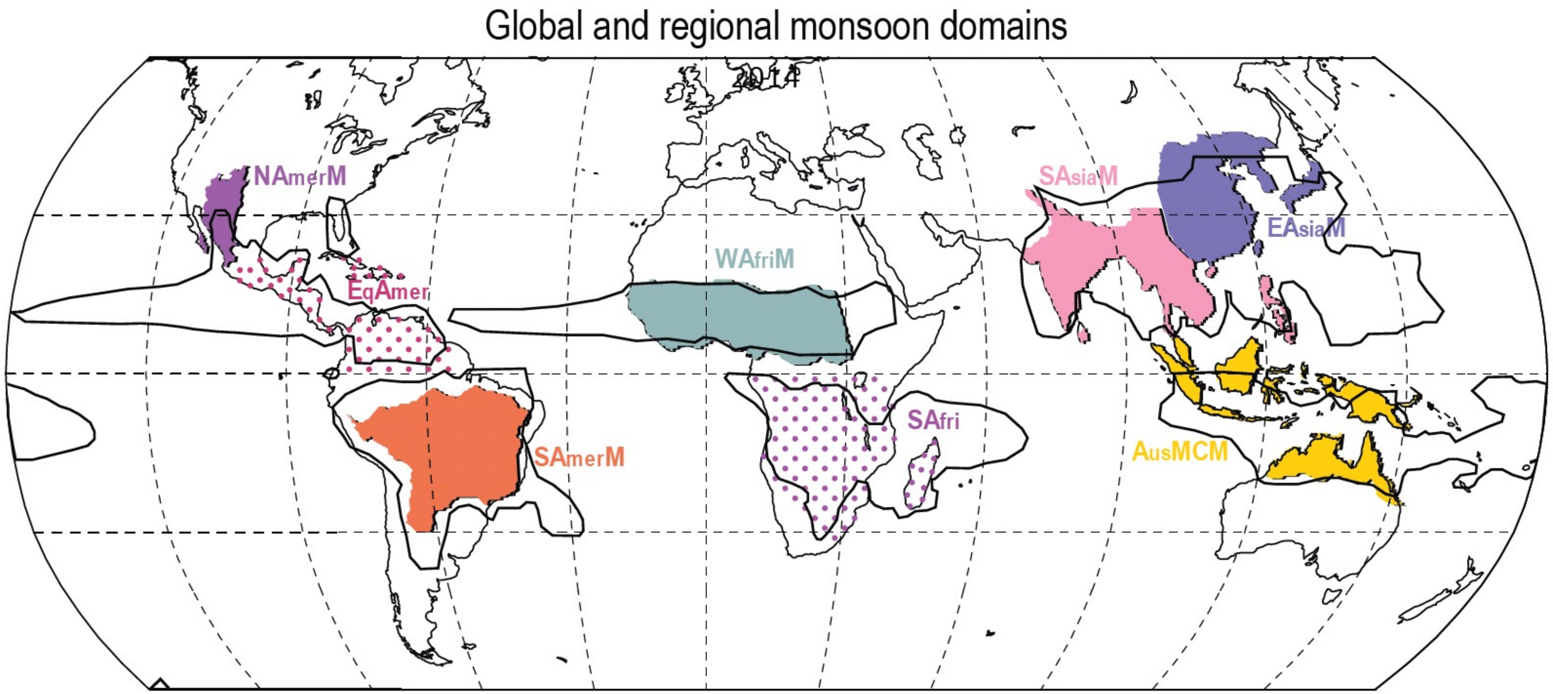
- Why *is* (fluid) dynamics such a fuzzy topic?
  - The systems we consider are generally **not spatially extensive**, so we cannot benefit from spatial aggregation (in contrast with, e.g., Earth's energy budget)
  - The phenomena of interest are **emergent**, without clear definitions, and do not follow in a straightforward way from the governing equations
  - In general, **many mechanisms are at play**, and they play out differently in different situations

A study in contrasts: two landmark textbooks in geophysical fluid dynamics for my generation





- Regional climate phenomena are **ambiguous and subjectively defined**
  - How the phenomena are predicted to evolve under climate change can sometimes depend quite sensitively on how the phenomena are defined



Monsoons are here defined as regions where the annual range (local summer minus local winter) exceeds 2.5 mm/day

Annex V of IPCC AR6 WGI report (2021)

Current Climate Change Reports (2019) 5:345–357
https://doi.org/10.1007/s40641-019-00145-8

MID-LATITUDE PROCESSES AND CLIMATE CHANGE (I SIMPSON, SECTION EDITOR)

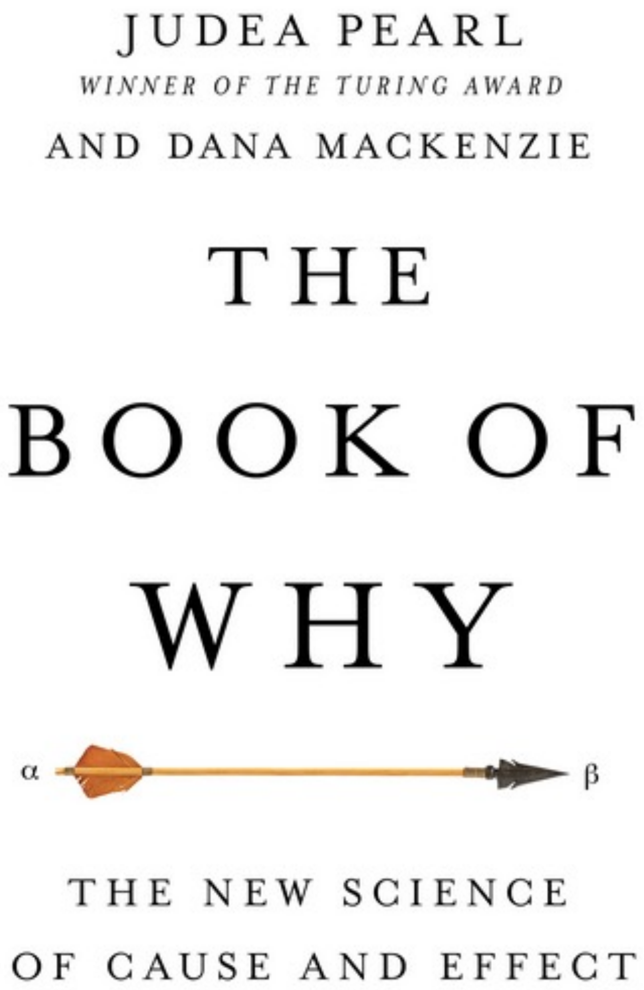
Mechanisms of Future Predicted Changes in the Zonal Mean Mid-Latitude Circulation

Tiffany A. Shaw[1]

"*There are 24 mechanisms and 8 thermodynamic starting points*"

Some things to note about this kind of work based on dynamical theory:

- Theories derived from the governing equations can provide central dynamical paradigms, but their match with observations is only qualitative
    - The analyst has to know what to look for, and what discrepancies to ignore
- Budgets reflecting steady-state balances are ambiguous regarding causality
    - Requires causal assumptions for their useable interpretation
    - N.B. Time lags are not a safe method in an autocorrelated system like the atmosphere (Runge et al. 2014 J. Clim.; Byrne et al. 2016 GRL)

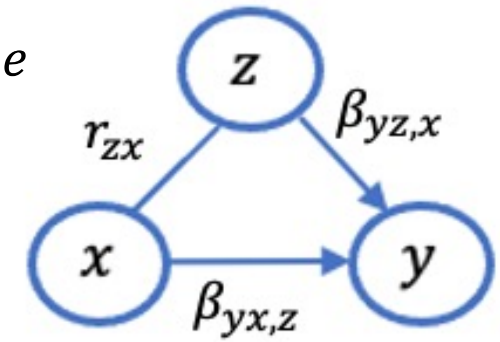


- **Causality** is not usually discussed in statistics textbooks
- However, understanding the causality involved in a particular situation is crucial for setting up the statistical analysis, and for interpreting the results
  - The mathematics is agnostic about causality, but the physical interpretation is not!
  - e.g. in an observed correlation between x and y, whether z is a **confounder** or a **mediator** depends on the direction of causation between x and z

$$y_i = \beta_{yx,z} x_i + \beta_{yz,x} z_i + noise$$

$$\Longrightarrow \quad r_{yx} = \underbrace{\beta_{yx,z}}_{\text{Direct}} + \underbrace{\beta_{yz,x} r_{zx}}_{\text{Indirect}}$$

(special case of the **path-tracing rule**)



Kretschmer et al. (2021 Bull. Amer. Meteor. Soc.)

- **Example:** Variability of Southern Hemisphere midlatitude jet in early austral summer (OND) is correlated with ENSO: $r_{JE} = -0.14$
- During this season the SH midlatitude jet is also known to be affected by interannual variability in the seasonal breakdown of the stratospheric polar vortex
  - Based on the NCEP reanalysis over 1949−2019, MLR gives

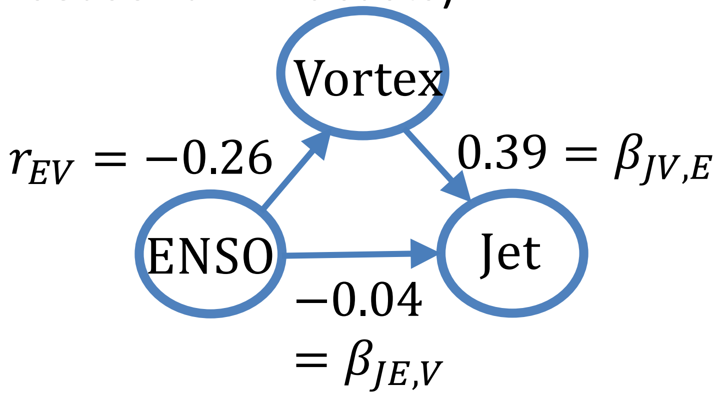
$$\text{Jet} = -0.04\ \text{ENSO} + 0.39\ \text{Vortex} + \text{noise}$$

- Most of the influence of ENSO on Jet is via the indirect stratospheric pathway (consistent with Byrne et al. 2019 JGR using ECMWF seasonal hindcasts)

$$r_{JE} = -0.14 \approx -0.04 + 0.39 \times (-0.26)$$

$$r_{yx} = \beta_{yx,z} + \beta_{yz,x} r_{zx}$$

- Generalizes naturally to conditional probabilities
- Causality needed to deal with non-stationarity
- Can be used to construct storylines



Kretschmer et al. (2021 BAMS)

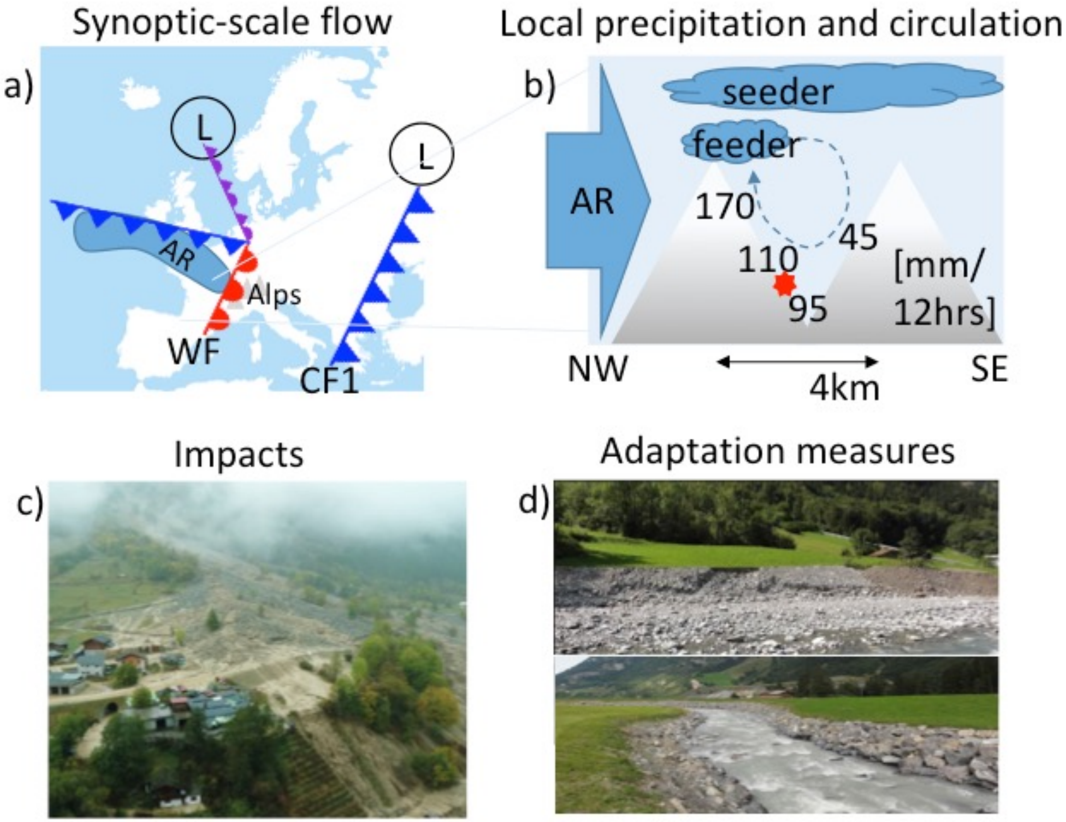
- **Storylines:** physically-based unfoldings of past climate or weather events, or of plausible future events or pathways (Shepherd et al. 2018 Climatic Change)
  - Definition now incorporated in IPCC Glossary (see also Box 10.2 of AR6 WGI report)
  - An **unforecasted rain-on-snow event in the Swiss Alps**: four typologies of use

Providing a physical basis for partitioning uncertainty

Exploring the boundaries of plausibility

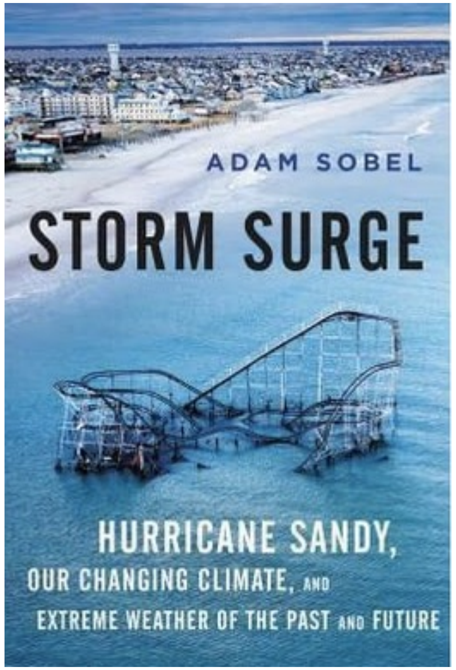
Improving risk awareness

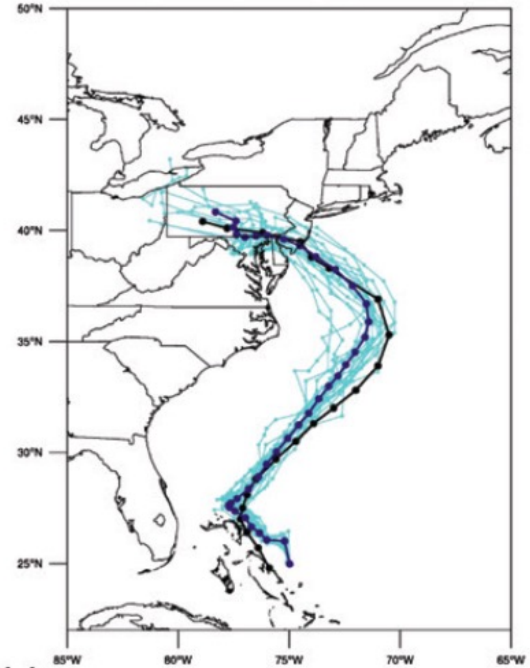
Strengthening decision-making



Shepherd et al. (2018 Climatic Change)

- Ultimately, **every extreme event is unique**, and this uniqueness matters for impacts



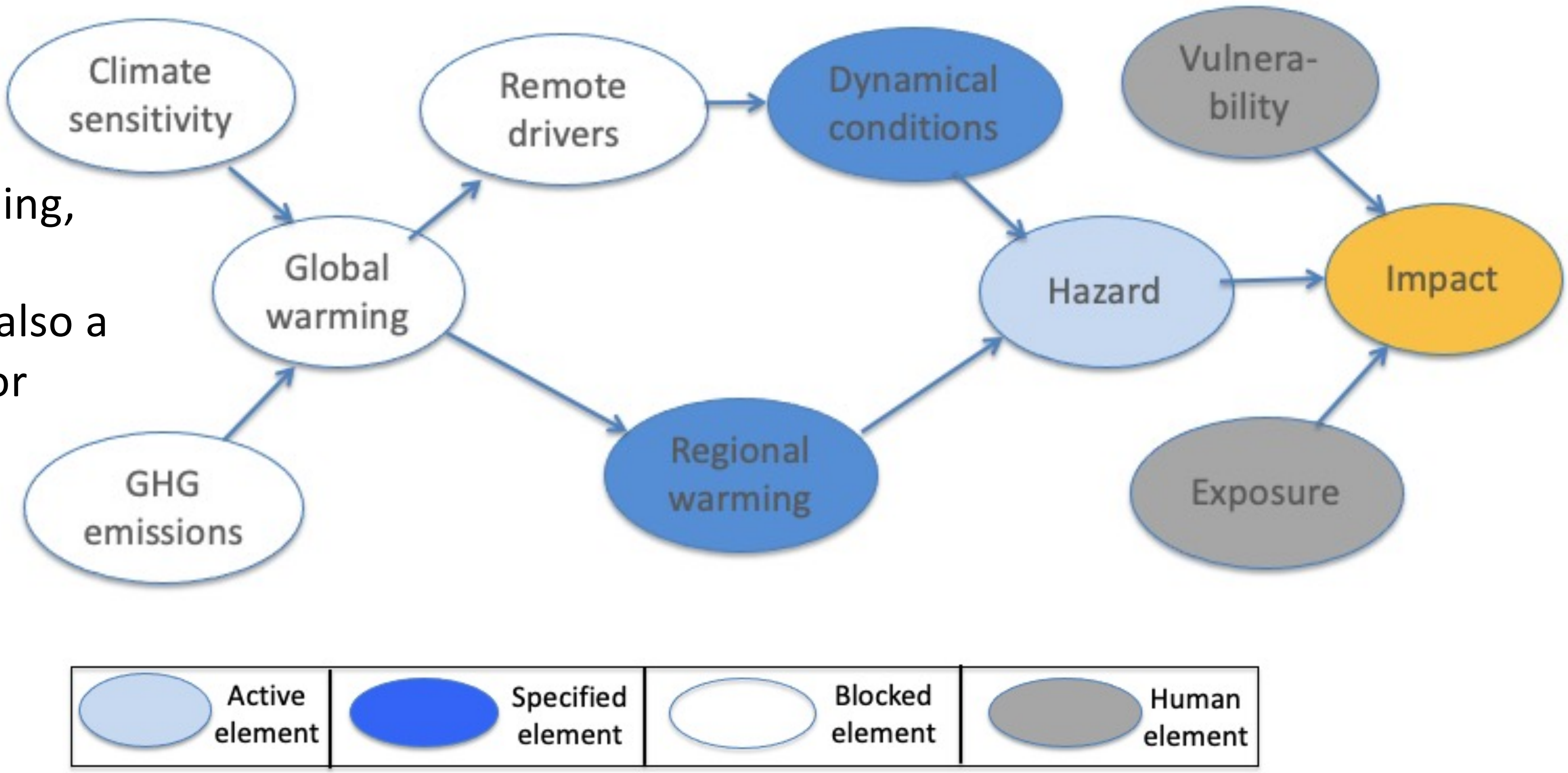


- **Hurricane Sandy** (2012) was unusual in its rapid westward steering and its merger with an extratropical storm, **both the result of a strongly deformed jet stream**
- US weather forecasters didn't even have a protocol for handling such an event
- It seems almost meaningless to ask if such a freak event would become more likely in the future

- But we do know that sea level will be higher, and storms will hold more moisture
- Thus we can legitimately ask (and plausibly answer) the counter-factual questions:
  - How much were the impacts of Sandy increased by climate change?
  - How much worse might they be in the future?

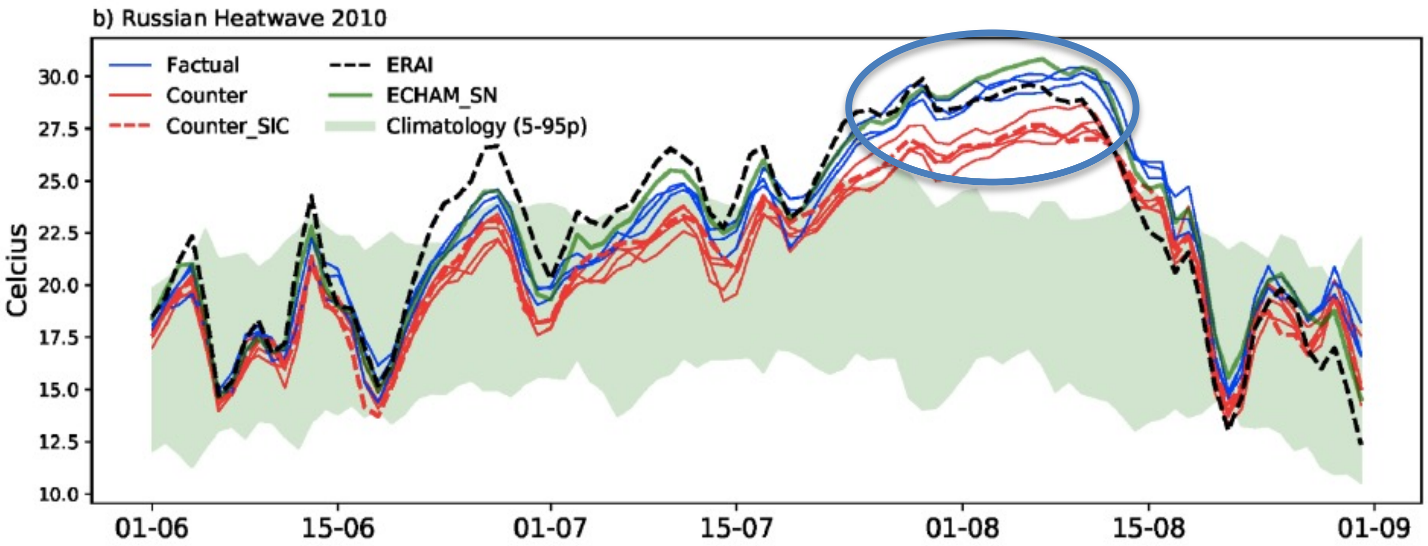
An event storyline

In this framing, the human element is also a causal factor (decision context)



After Shepherd (2019 Proc. Roy. Soc. A); in IPCC AR6 WGI Chapter 10, Box 10.2, Figure 1

- **A storyline of an observed event can be constructed in various ways**, e.g. by imposing the observed dynamical conditions in a climate model together with warmer ocean temperatures and increased greenhouse gas concentrations to fill in the ‘physics’
    - Called the ‘pseudo global warming method’ in regional climate modelling (Schär et al. 1996 GRL)
- Allows use of weather-resolving atmospheric models; physically self-consistent
    - Here the dynamical conditions are imposed through global spectral nudging

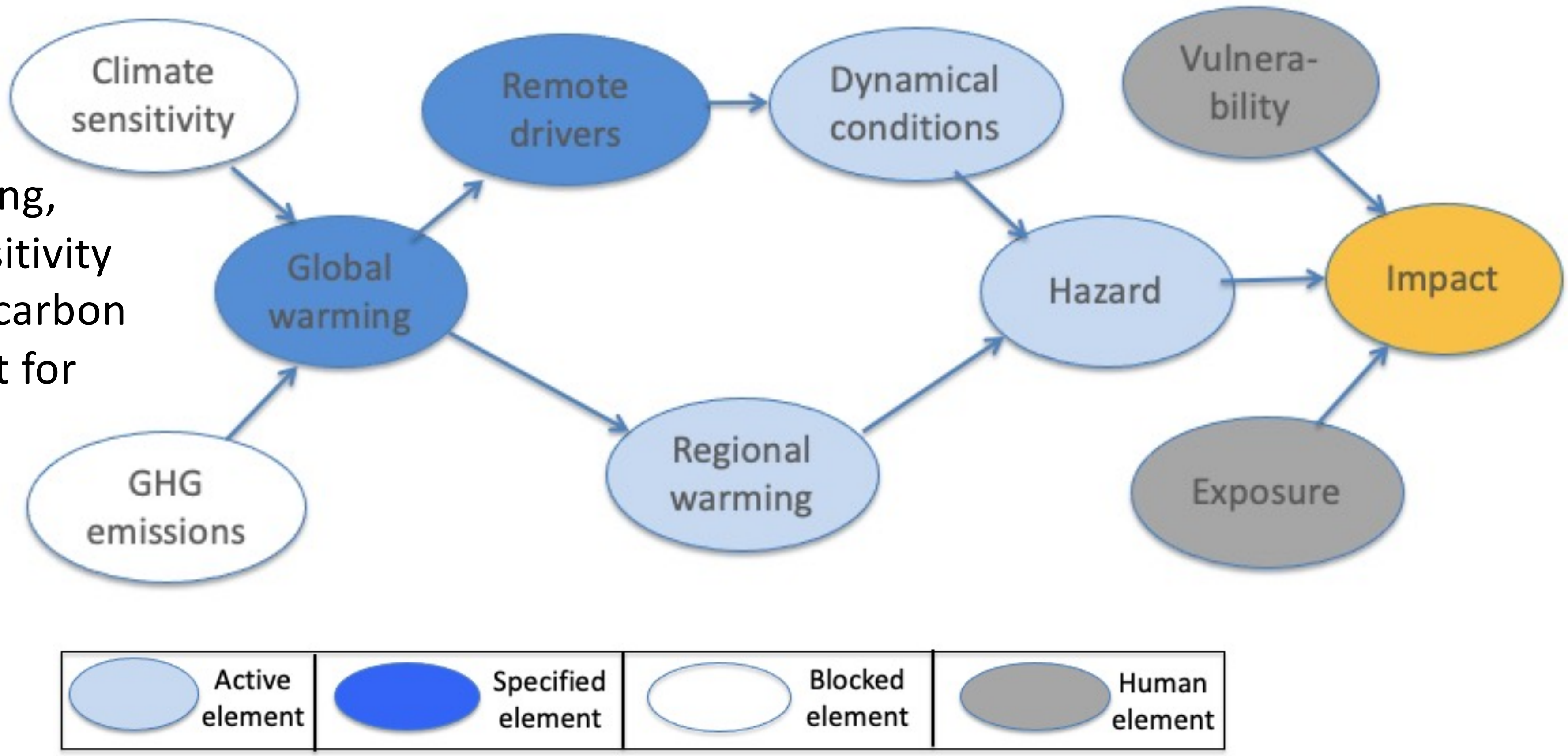


Very high signal-to-noise ratio achieved in both space and time

van Garderen, Feser & Shepherd (2021 NHESS)

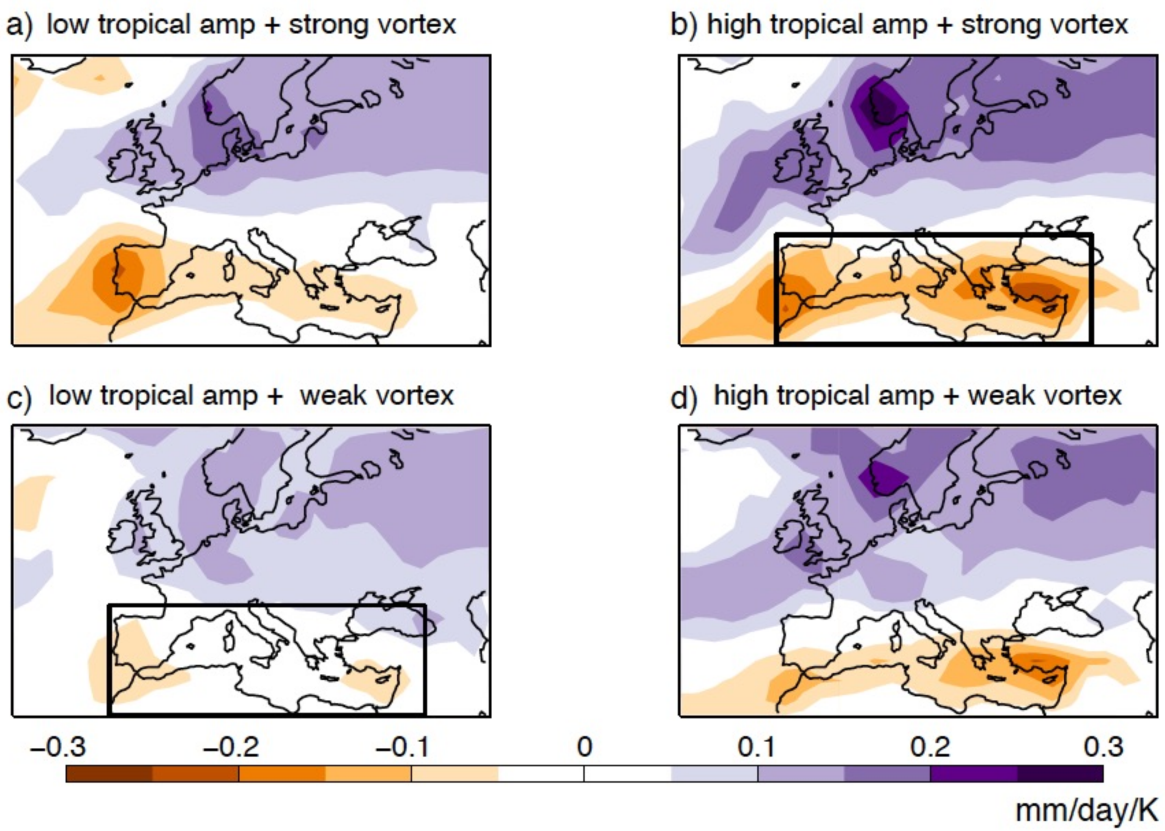
A dynamical (circulation drivers) storyline of regional climate change

In this framing, climate sensitivity matters for carbon budgets, not for impacts



After Shepherd (2019 Proc. Roy. Soc. A); in IPCC AR6 WGI Chapter 10, Box 10.2, Figure 1

- **Example of dynamical storylines:** four storylines of **future cold-season Mediterranean drying** (a major climate vulnerability for southern Europe)
  - So far as we know, any one of these could be true



These could each be used to interpret the observed changes, to articulate multiple causal hypotheses

Zappa & Shepherd (2017 J. Clim.)

Concluding Remarks

- To address adaptation challenges, we need to navigate the **'cascade of uncertainty'** in climate projections, and connect to the decision space
  - The **societally relevant question** is not "What will happen?" but rather "What is the impact of particular actions under an uncertain regional climate change?"
- We need to find a scientific language for describing the **'plural, conditional'** state of knowledge that exists at regional and local scales, and **resist aggregation**
  - The **storyline approach** to regional climate information does exactly this (see Shepherd 2019 Proc. Roy. Soc. A)
- Linking to historical events, in their proper context, brings a **salience to the risk**; well understood psychologically
  - Storylines also provide a **built-in (not contrived) narrative**, hence an emotional element, which is essential for decision-making (Damasio 1994; Davies 2018)
- We need to explore storylines of climate risk, combining the best information from all sources — **interpreted not as a prediction but as representing plausible futures**