METEOROLOGY

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RELIABILITY VS INFORMATIVENESS: THE STORYLINE APPROACH TO REPRESENTING UNCERTAINTY AND RISK IN CLIMATE CHANGE

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Storyline approach to the construction of regional climate change information

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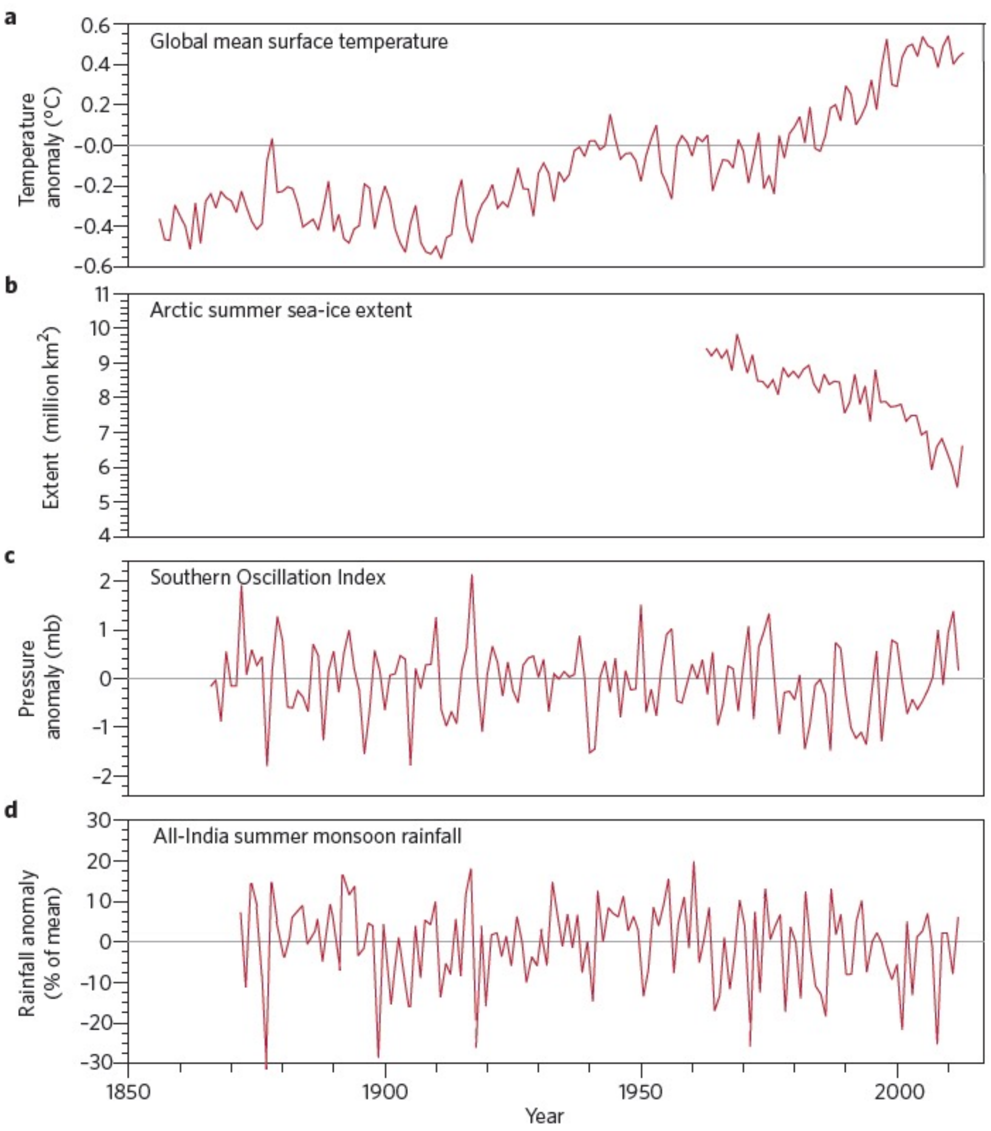
"If we can learn to substitute evolution-from-what-we-know for evolution-toward-what-we-wish-to-know, a number of vexing problems may vanish in the process."

Thomas Kuhn, *The Structure of Scientific Revolutions* (1962)

The heart of the matter

- Climate risk involves three aspects:
  - Internal variability (extreme weather and climate events)
  - Changes in the possible weather and climate states (climate change)
  - Human-managed aspects of vulnerability and exposure
- Only the first of these is subject to a (frequentist, or aleatoric) probabilistic treatment, and even that may be highly uncertain for the most extreme events
  - The second is subject to epistemic uncertainty (even for a given climate forcing)
  - The third is also uncertain, and needs to be cast in the decision space
- Ultimately, probability is degree of belief (and proclivity to action), hence is **subjective**
  - Our challenge is to develop a scientific language for meaningfully representing and communicating this complex web of uncertainty
  - Needs to combine multiple lines of evidence, and extend into the decision space



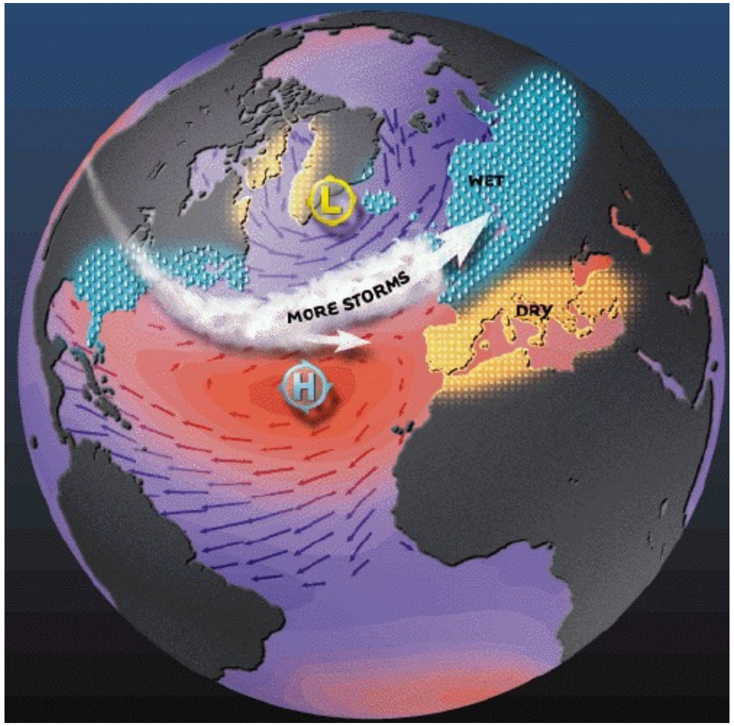
- Clear changes are evident in long-term observed records of temperature-related climate indices (high S/N ratio) ➔ Detection & Attribution

- Indices related to atmospheric circulation generally do not show clear long-term changes
- Climate models can give very different predictions
- There is no *accepted* theory of any such changes

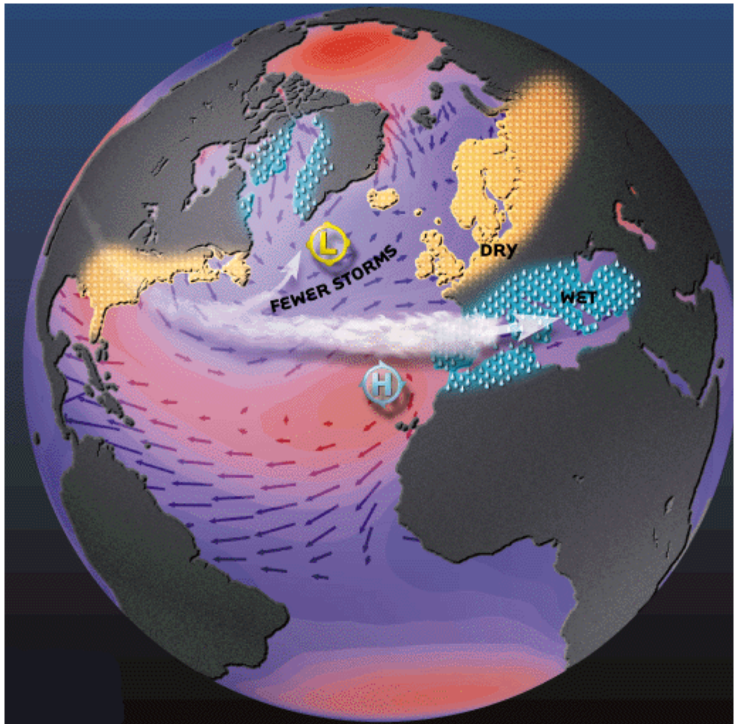
Shepherd (2014 Nature Geosci.)

- **Yet atmospheric circulation patterns** exert a very strong control on climate and climate variability at the regional scale
  - For example, the "North Atlantic Oscillation" (NAO) affects weather and climate extremes over Europe through **shifts in the jet stream**

NAO positive phase

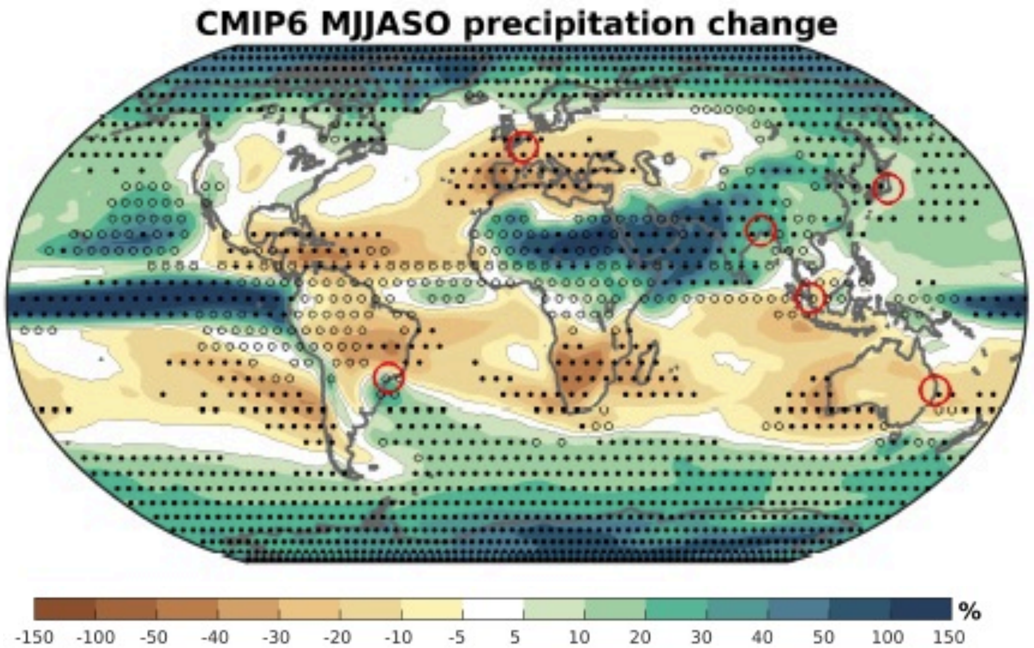


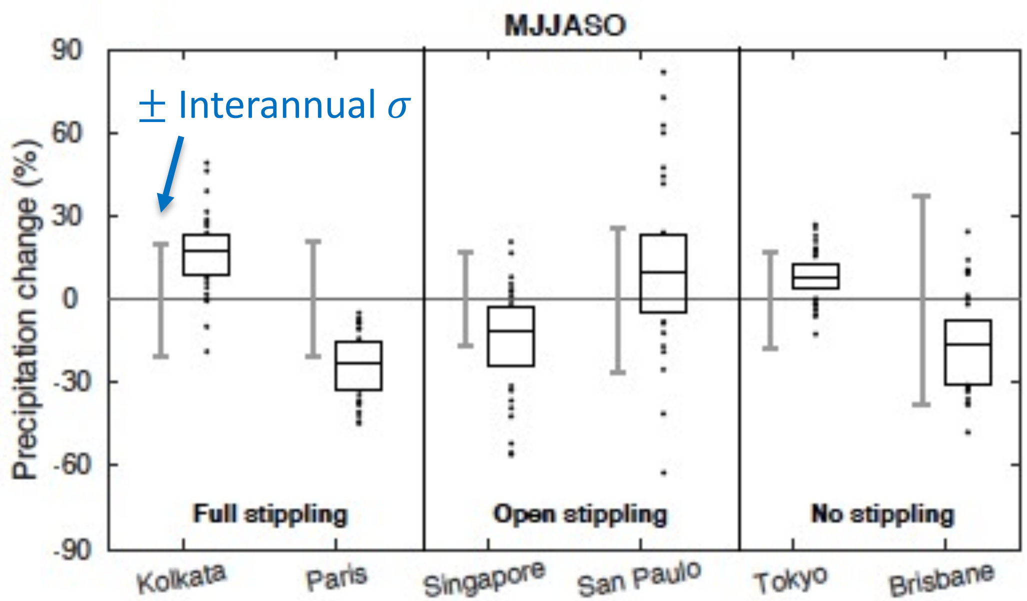
NAO negative phase



- Because of such dynamical uncertainty, the **uncertainty of the nature of precipitation changes over many regions** stands in contrast to the certainty of regional warming
- In this figure, full stippling indicates robustness in sign (as in the IPCC stippling), whilst open stippling indicates the potential for large, but non-robustly projected, changes
  - The latter includes many tropical regions

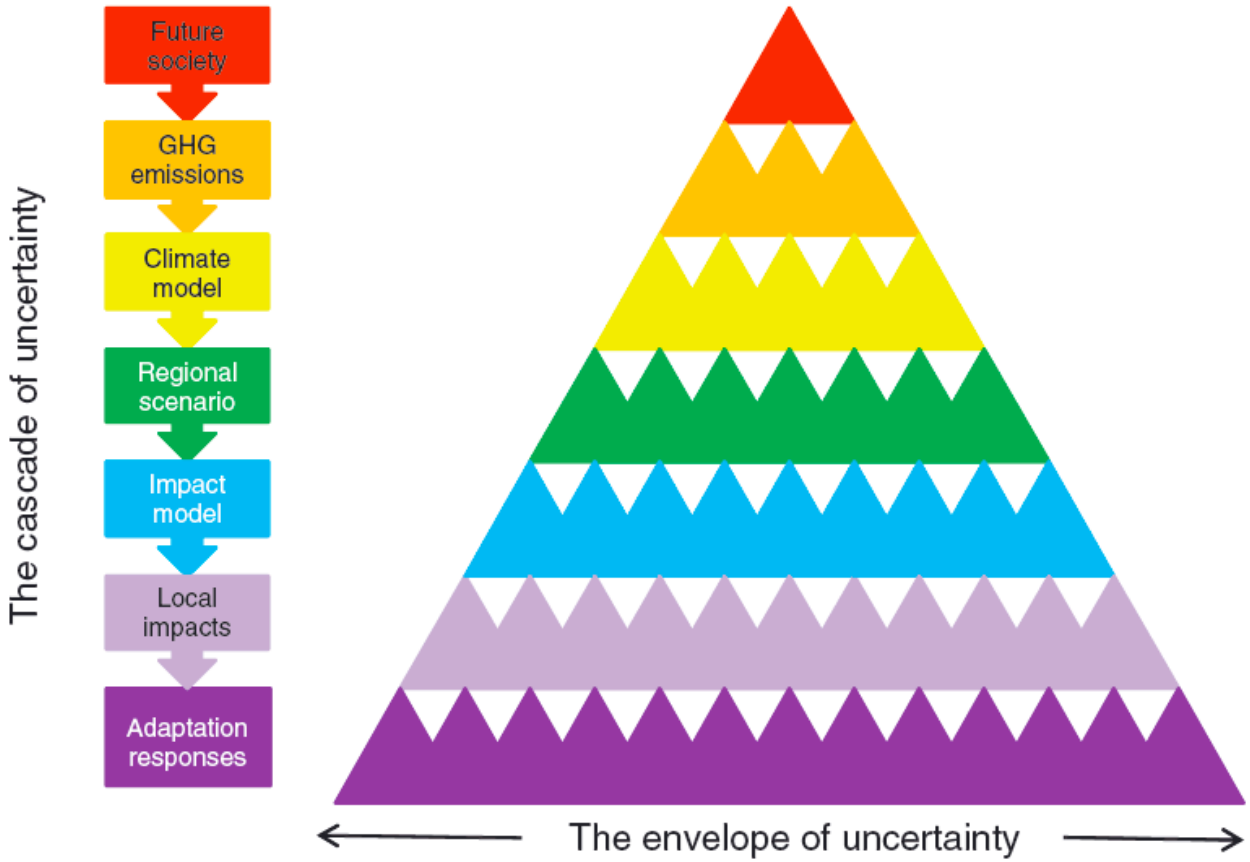
Changes over 21st century under RCP8.5





Zappa, Bevacqua & Shepherd (2021 Int. J. Clim.)

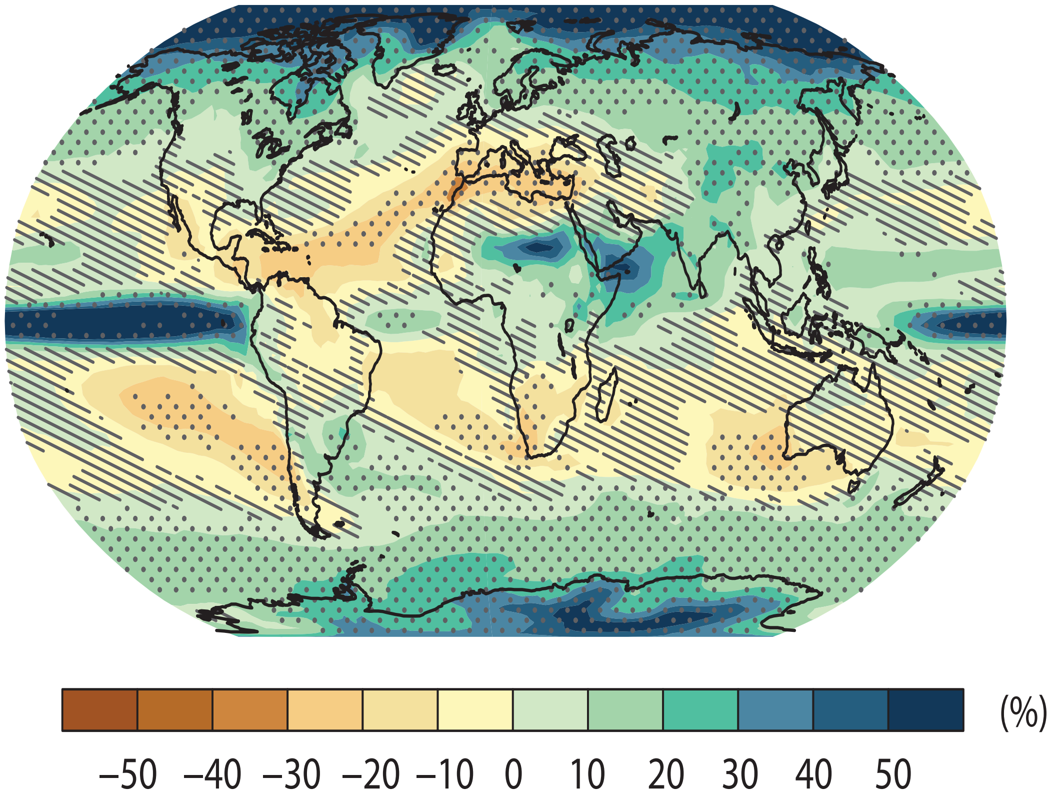
- Consideration of all the uncertainties in climate change in the traditional way leads to a "**cascade of uncertainty**" which obscures the climate information content



Wilby & Dessai (2010 Weather)

The IPCC AR5 narrative on the water cycle

Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions (see Figure SPM.8).



IPCC AR5 WGI (2013)

- The statement achieves its reliability in the tropics by including the (very extensive) oceanic regions, but it is precipitation over land that matters
- The final caveat also increases reliability
- Together they make the statement completely **uninformative** for any particular region over land!

Reliability is achieved at the price of informativeness

See also Løhre et al. (2019 Wea. Clim. Soc.)

- The climate science community’s consensus view on the North Atlantic **storm track response to climate change** (IPCC WGI AR5 Technical Summary):
  - The AR5 SPM was completely silent on circulation changes!

> *“Substantial uncertainty and thus low confidence remains in projecting changes in NH storm tracks, especially for the North Atlantic basin.”*
>
> *“…it is unlikely that the response of the North Atlantic storm track is a simple poleward shift”*

- Note that in IPCC WGI, the word “unlikely” is generally used to *dismiss* possibilities
  - Tends to de-emphasize risk (Juanchich, Shepherd & Sirota 2020 Clim. Change)

Term*	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

The IPCC calibrated uncertainty language does not seem to correspond to common usage!

- From the *Good Practice Guidance Paper on Detection and Attribution Related to Anthropogenic Climate Change* (IPCC 2010)

> To avoid *selection bias* in studies, it is vital that the data are not preselected based on observed responses, but instead chosen to represent regions / phenomena / timelines in which responses are expected, based on process-understanding.

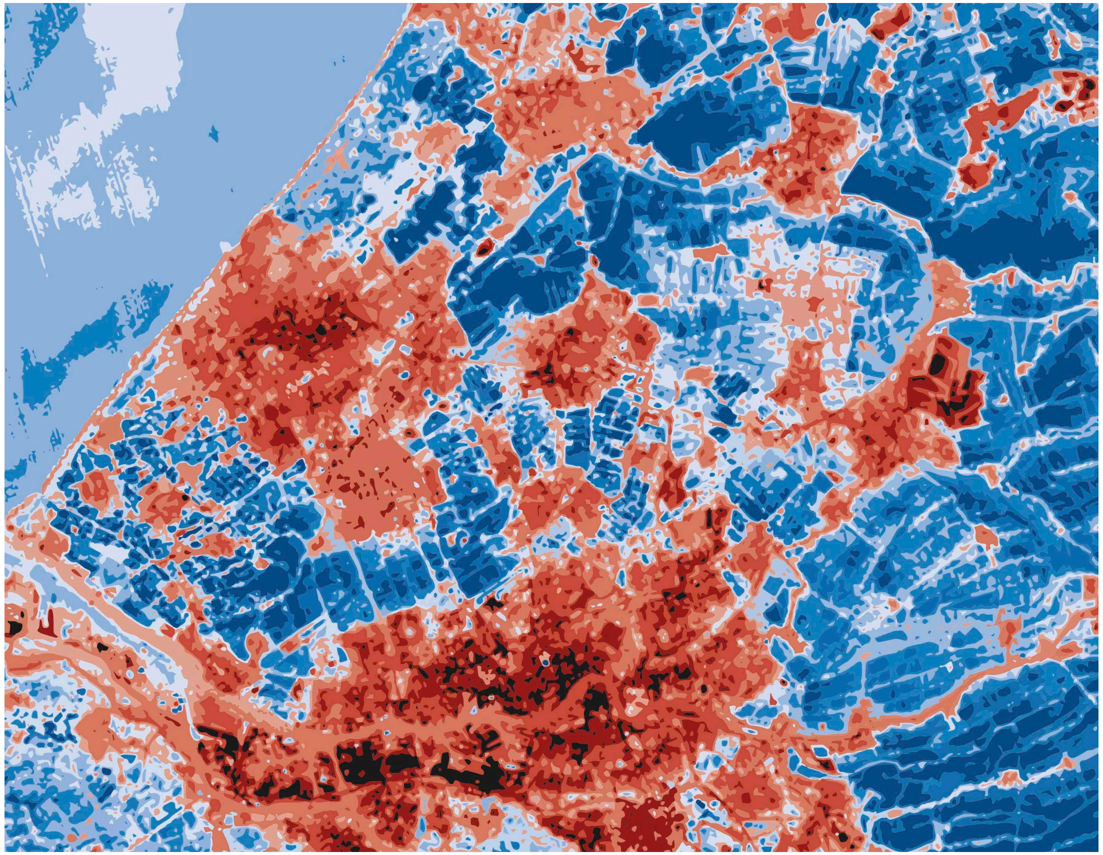
> Confounding factors (or influences) should be explicitly identified and evaluated where possible.

"(Unlike WGII), IPCC WGI deals with the facts"

A famous climate scientist, to Ted

- Recommendations work against any consideration of **the local** (Shepherd & Sobel 2020 Comp. Stud. South Asia, Africa & Middle East)
  - "Detaches knowledge from meaning" (Jasanoff 2010)
  - Represents a form of "hermeneutical injustice" (Fricker 2007)
- Interestingly, IPCC WGII defines climate change as *any* observed change, without requiring attribution to anthropogenic forcing!

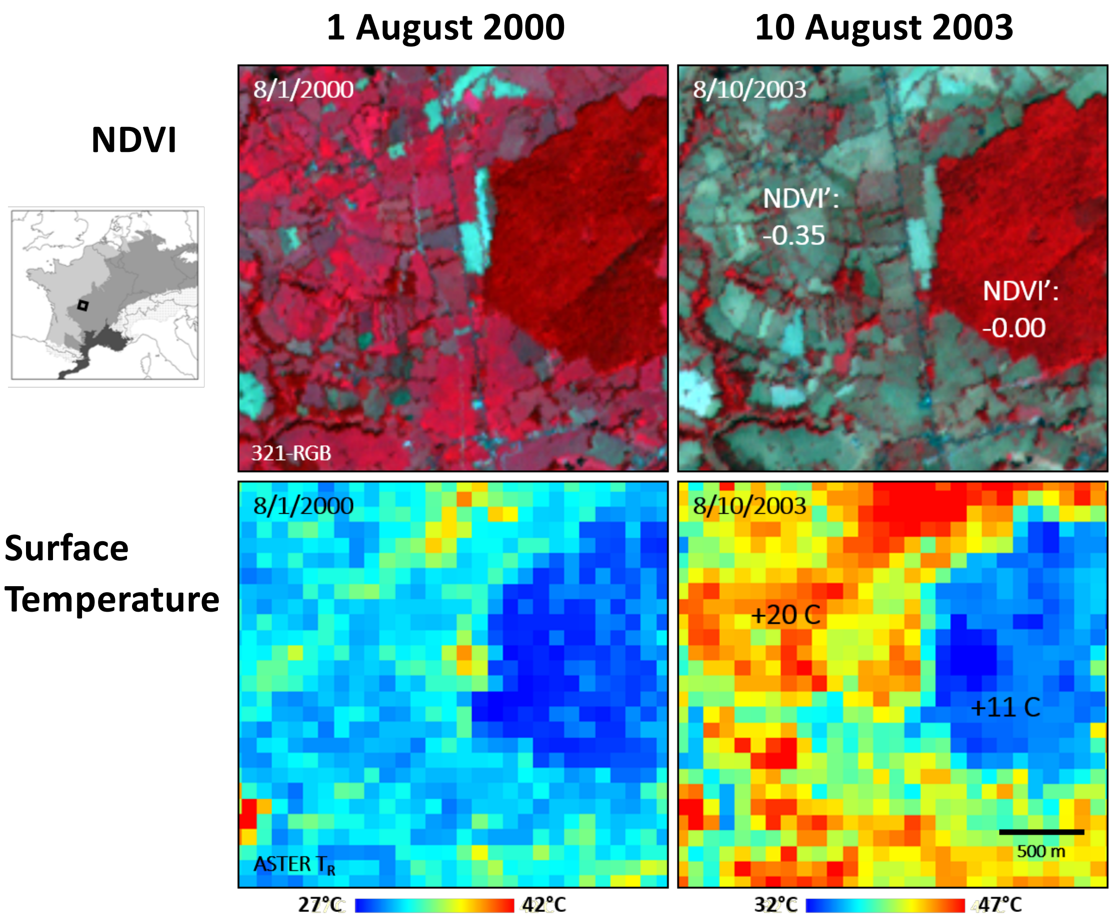
- Yet the most severe climate impacts are generally exacerbated by the **human-modified environment**
  - Nighttime summertime temperature differences across Southern Holland, based on three nights of data



- To treat the urban heat island effect as a confounding factor seems perverse

van der Hoeven & Wandl (2017)

- We actually have a wealth of information relevant to climate change, even (and sometimes more so) on the local scale (e.g. Hall 2014 Science)
    - Example from the summer 2003 heat wave in central France



- There is information here, it's just that it is **conditional**

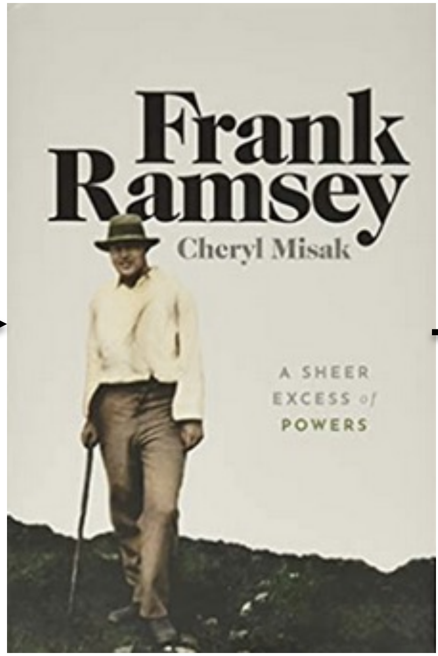
- We may not be able to predict the statistics of heat waves in the future, but we can predict their implications, and how to manage their impacts

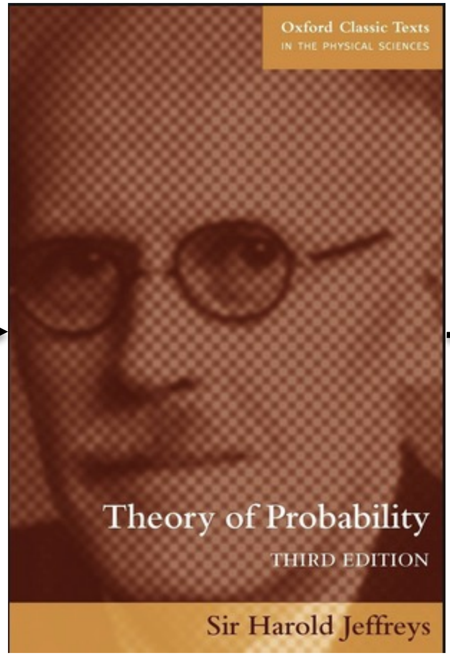
Zaitchik et al. (2006 Int. J. Clim.)

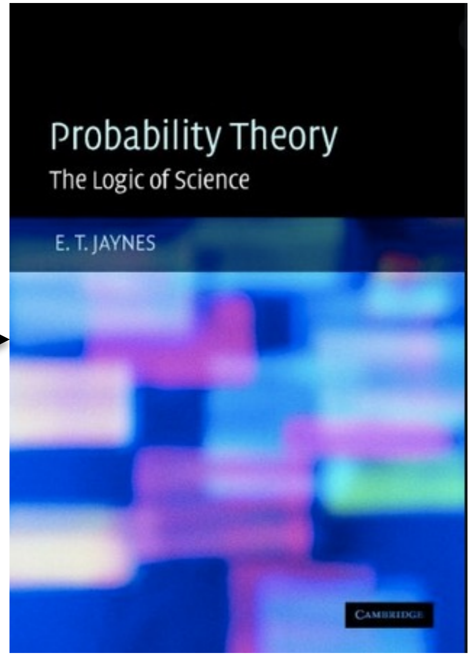
- **“A paradigm can…insulate the [scientific] community from those socially important problems that …cannot be stated in terms of the conceptual and instrumental tools the paradigm supplies”** (Thomas Kuhn, *The Structure of Scientific Revolutions*, first published 1962)
- The societally relevant question is not “What will happen?” but “What is the impact of particular actions under an uncertain regional climate change?” (Shepherd 2019 Proc. R. Soc. A) → cf. quote from Kuhn on my second slide
- Epistemic uncertainties are different from aleatoric (random) uncertainties, and cannot be treated in the same way
  - Epistemic uncertainties are intrinsically **subjective**
  - Raises issue of **trust** and **intelligibility** (cf. Onora O’Neill)
- **Singular causation** is a perfectly sensible philosophical concept; aggregation (as in randomized control trials) has its own problems (Nancy Cartwright, Univ Durham Working Paper, 2017)
  - Our samples are *never* independent and identically distributed (iid)!

- In climate change we are dealing with **uncertainty**, not with true/false statements
- We need to extend classical logic to deal with probabilities that lie between 0 and 1
  - Probabilities about the real world are inherently **subjective**; this brings in **values**
- Yet the way climate science is done, this is hardly appreciated
  - There is a mismatch between statistical practice and reasoning under uncertainty

C.S. Peirce

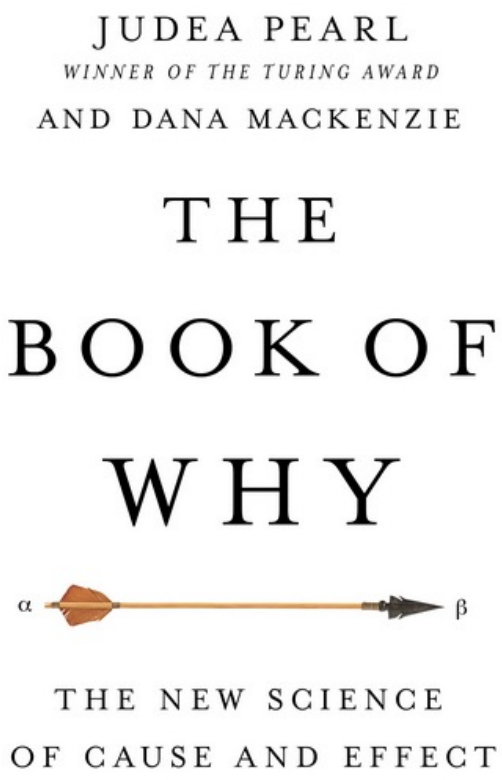






Misak (145): "Peirce argued that a belief is in part a habit which cashes out in behaviour."

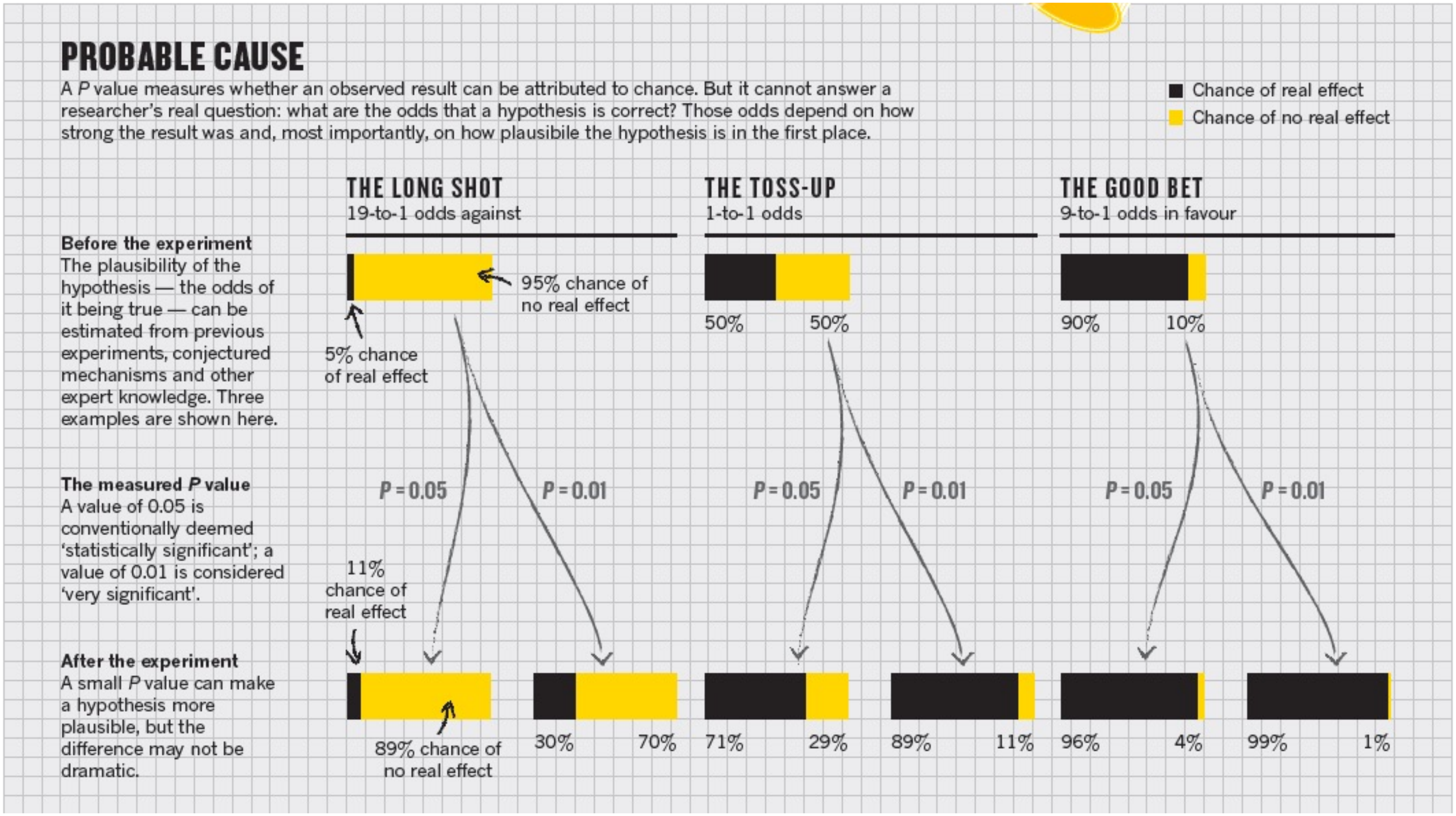
Pearl's "Ladder of Causation"

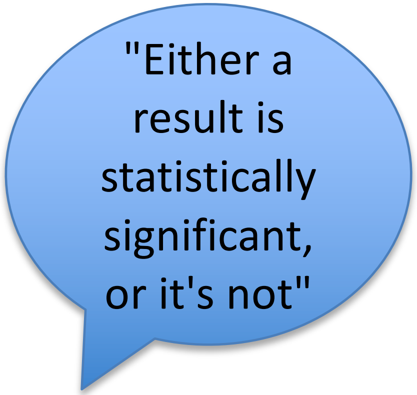


- *Association (correlation)*:
  - Climate system is non-stationary, and sampling is incomplete
  - Aggregation and conditioning always involves assumptions
- *Intervention*:
  - Generally not possible, although there are natural experiments (e.g. volcanic eruptions)
- *Counterfactuals*:
  - Requires imagination; by definition, not "real" (and cannot be created)
  - Where theory and models come in; need to build *evidence*
- Conclusion: **primacy of causal reasoning**
  - But it's very hard to *prove* anything!

"Mindless statistics" (Gigerenzer 2004)

- Point 1: failure to reject the null hypothesis does not confirm the null hypothesis
- Point 2: focusing on statistical significance rather misses the point
- Point 3: applied statistics requires physics, through the priors





Another famous climate scientist, to Ted

Nuzzo (2014 Nature)

- Jeffreys (1961):

  "We get no evidence for a hypothesis by merely working out its consequences and showing that they agree with some observations, because it may happen that a wide range of other hypotheses would agree with those observations equally well. To get evidence for it we must also examine its various contradictories and show that they do not fit the observations."

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)} = \frac{P(D|H)P(H)}{P(D|H)P(H) + P(D|\bar{H})P(\bar{H})} = \left\{1 + \frac{P(D|\bar{H})}{P(D|H)}\left[\frac{1}{P(H)} - 1\right]\right\}^{-1}$$

Bayes Factor: $\frac{P(D|\bar{H})}{P(D|H)}$

Prior: $P(H)$

- P(D|H) [which is a frequency calculation] is part of Bayesian reasoning
- But P(D|H) ≠ P(H|D); "inversion of the conditional" (or the "prosecutor's fallacy")
- *"It is sometimes considered a paradox that the answer depends not only on the observations but on the question; it should be a platitude"* (Jeffreys 1961)

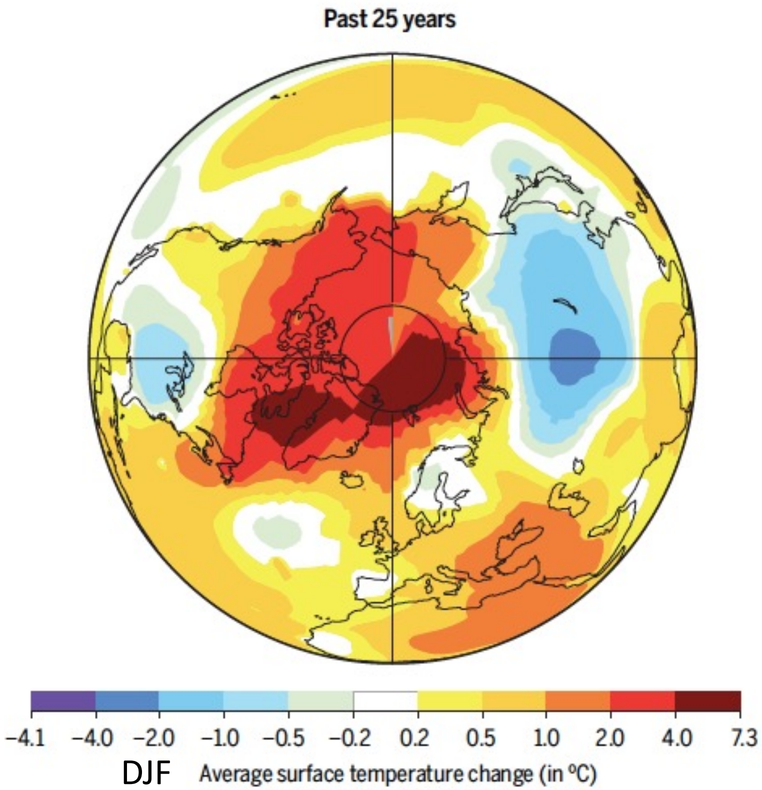
Example of illogical reasoning: environmental skepticism

- It is sometimes argued that environmental issues (e.g. acid rain, UV increase from ozone depletion) were exaggerated because the predicted catastrophes did not come to pass
  - This ignores the fact that actions were taken to avoid them!
- In the event, nothing serious happened (D). Was it all a hoax (H)?
- Bayes' theorem: $P(H|D) = \frac{P(D|H)}{P(D)} P(H)$
- $P(D|H) = 1$. In order for D to provide evidence in favour of the hoax hypothesis, we need $P(D) \ll 1$, hence $P(\neg D) \lesssim 1$
- Thus we need to assume that something catastrophic would have happened if it hadn't been a hoax; i.e. that the mitigation actions would have been ineffective (and the scientists incompetent, not merely opportunistic)
  - Otherwise, **posterior belief determined by the prior belief**

Adapted from the Y2K example in Dennis Lindley, *Understanding Uncertainty* (2014)

Example: Arctic-to-midlatitude connections

- Highly controversial topic, with many papers having quite unconditional titles
  - Yet absence of evidence is not evidence of absence! (inversion of the conditional)



Shepherd (2016 Science)

Insignificant effect of Arctic amplification on the amplitude of midlatitude atmospheric waves

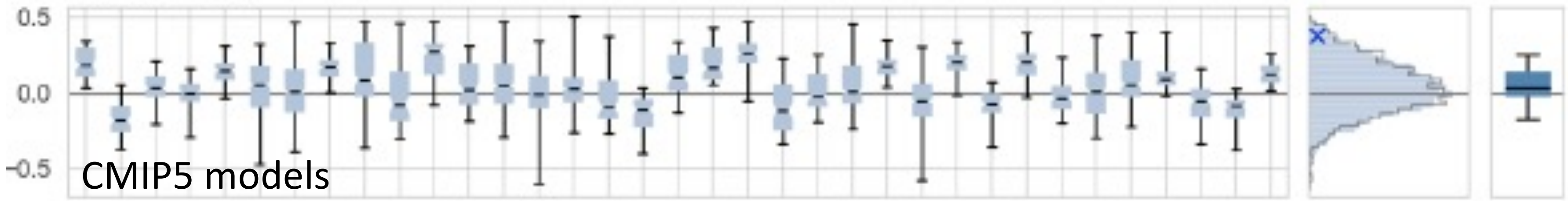
Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes

Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss

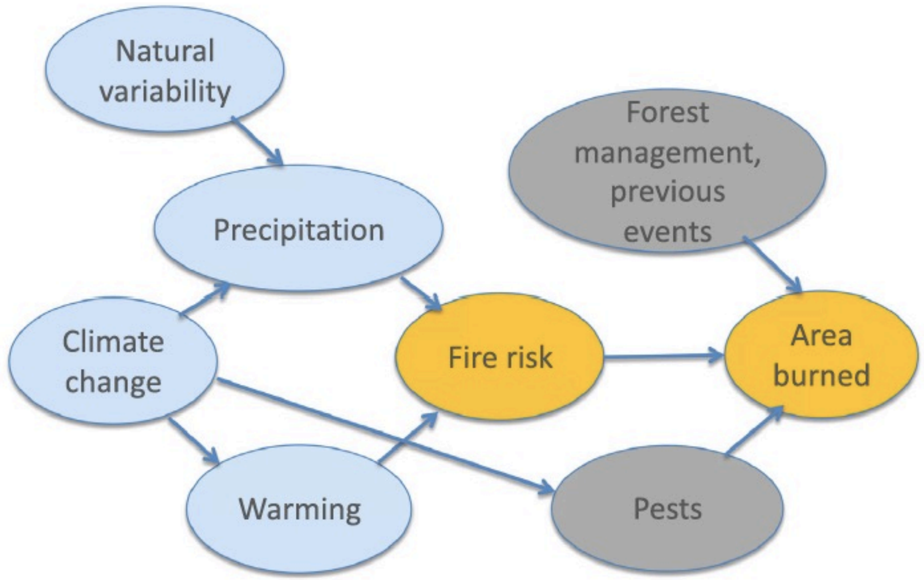
Midlatitudes unaffected by sea ice loss

- Challenges (see Shepherd 2016 Science)
  - Background knowledge in this area is not very strong
  - Climate models have acknowledged deficiencies
  - The observational record is short
  - Causality is difficult to disentangle, since midlatitudes certainly affect the Arctic
- Essentially, **the Bayes Factor is close to unity**, meaning that 'believers' can publish papers in favour of the connection, and 'skeptics' can publish papers against it
- It is important to be explicit about the 'belief' (in the form of a scientific hypothesis)
  - See Kretschmer, Zappa & Shepherd (2020 Wea. Clim. Dyn.) for an explicit example

Standardized coupling from Barents-Kara sea-ice extent to stratospheric polar vortex



- **Storylines:** physically-based unfoldings of past climate or weather events, or of plausible future events or pathways (Shepherd et al. 2018 Climatic Change)
    - Is readily aligned with the forensic methods employed in ecosystem studies
    - Asks what were the relevant causal factors in an event, and how they might change in the future
- Representable in a **causal network**
    - Distinguishes between P(A), and P(B|A), for the pathway A → B
    - P *is not a prediction*, but is a plausible assumption; specifies the **storyline**
- Provides a way to represent complex environments and adaptation options, bringing meaning to the climate information
- Connects naturally to decision frameworks



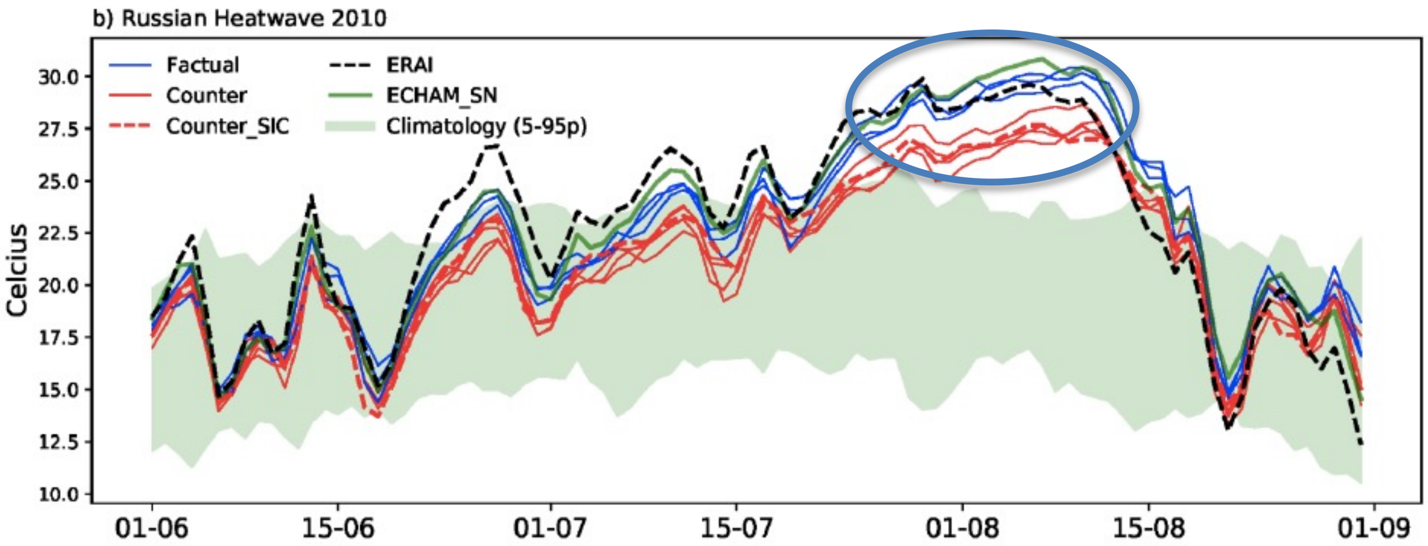
Lloyd & Shepherd (2020 Ann. NY Acad. Sci.)

- **Storylines provide a physical basis for partitioning uncertainty**

$$\frac{p_1(E,C)}{p_0(E,C)} = \frac{p_1(E|C)}{p_0(E|C)} \times \frac{p_1(C)}{p_0(C)}$$ (US NAS 2016)

  - p_1 is future, p_0 is present-day (for example)
  - E is the event of interest, C is the circulation regime conducive to that event
- The ratio of conditional probabilities represents the effects of climate change *for a given circulation regime*
  - **Builds in what we know with confidence about climate change**
  - Sometimes called the 'thermodynamic' component of change; can be defined in various ways (is not a precise distinction, but is very useful)
- The second ratio, representing the 'dynamical' component of change, **should be treated separately**, e.g. via storylines (Shepherd 2016 CCCR; 2019 PRSA)
  - The uncertainty space is thereby represented **discretely**
  - Builds in **self-consistency**, which is essential for consideration of correlated risk

- **Such conditional probabilities can be computed 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

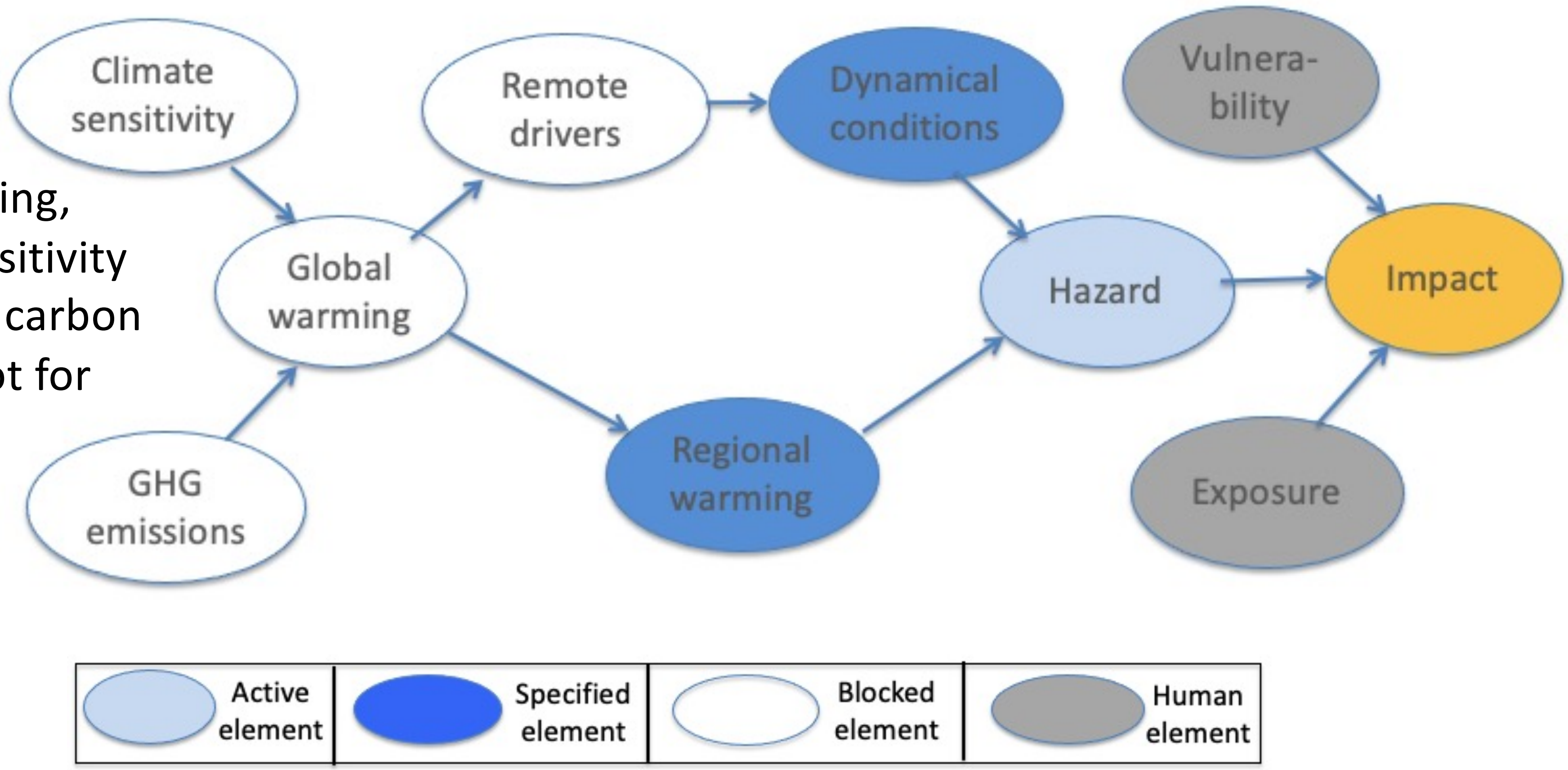


Very high signal-to-noise ratio achieved in both space and time

van Garderen, Feser & Shepherd (2021 NHESS)

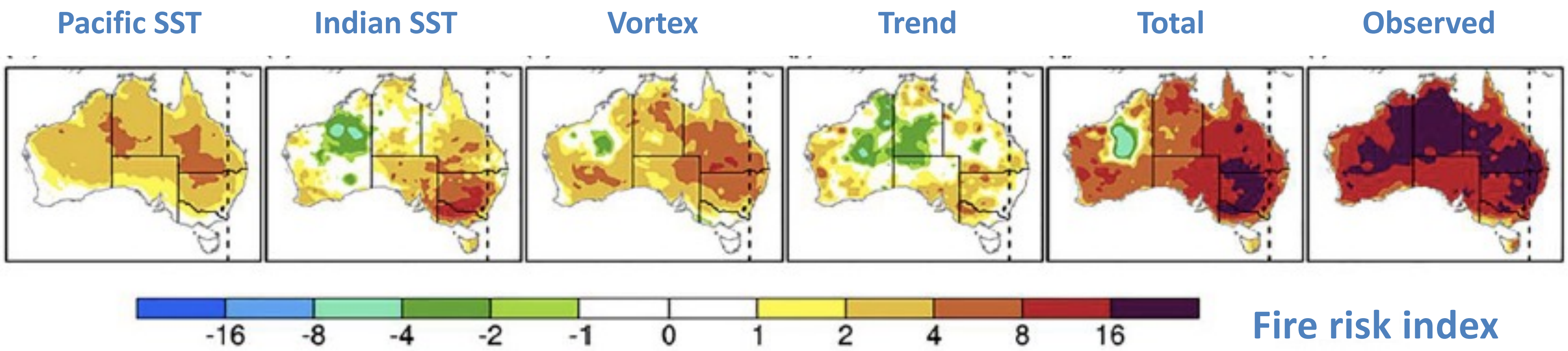
A pseudo global warming storyline (or an event storyline)

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



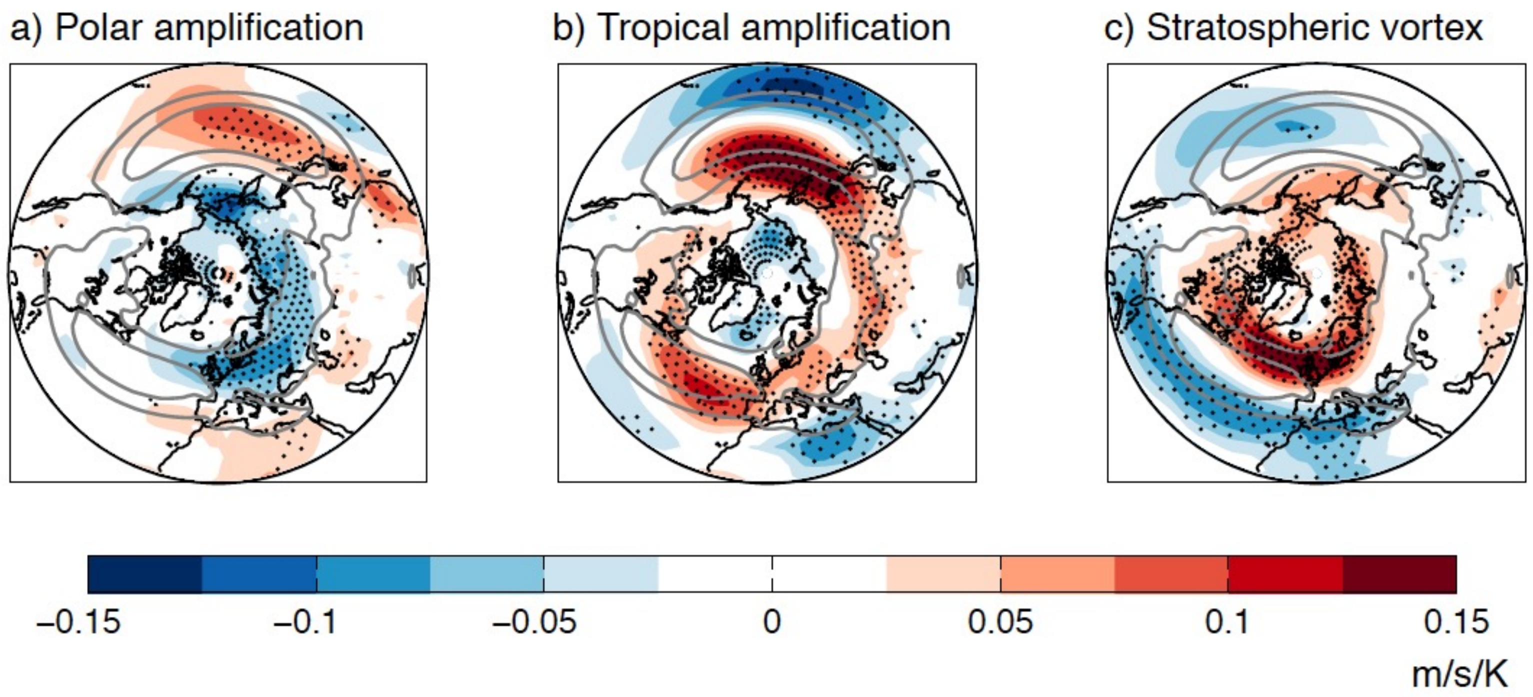
After Shepherd (2019 Proc. Roy. Soc. A)

- However, the **dynamical conditions certainly could change**, and this 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)**



Lim et al. (2021 BAMS)

- The regional circulation response to global warming can be usefully characterized in terms of **storylines based on uncertainties in the response of remote drivers**
- The patterns (here for NH cold-season lower tropospheric zonal wind, U850) are similar to those expected from single-forcing experiments
  - Also from seasonal prediction!

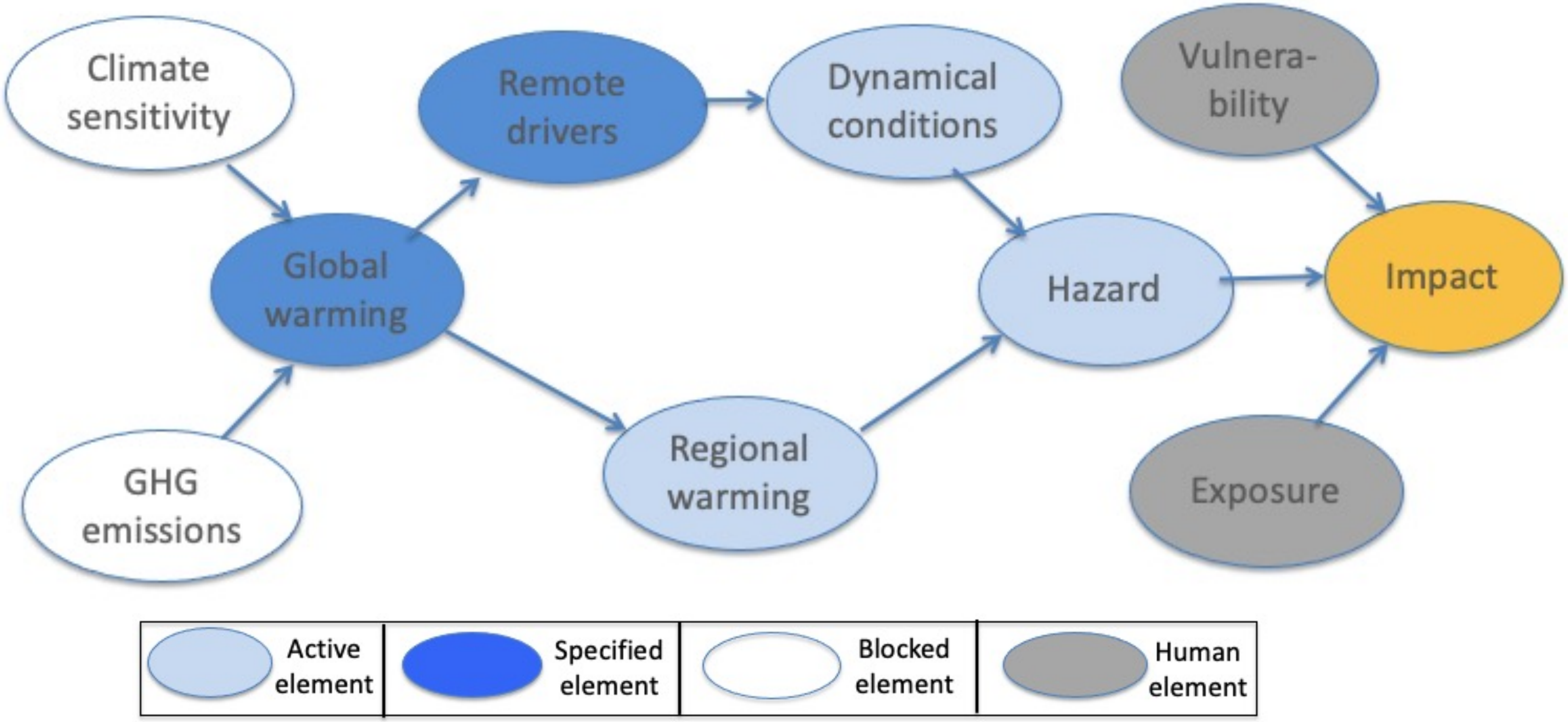


Colour shading denotes changes

Contours show climatology

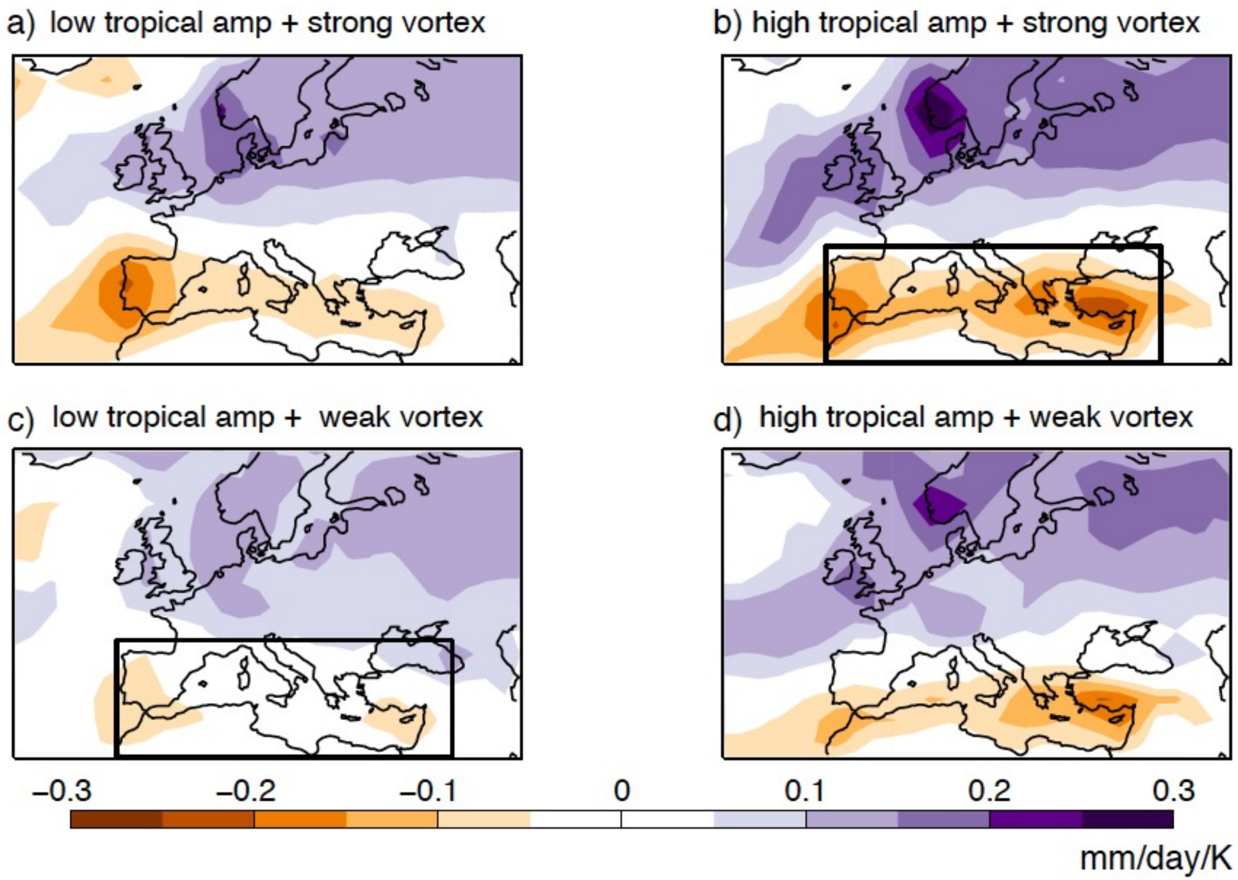
Zappa & Shepherd (2017 J. Clim.)

A circulation drivers storyline of regional climate change



After Shepherd (2019 Proc. Roy. Soc. A)

- Four **storylines of future cold-season Mediterranean drying**
  - So far as we know, any one of these could be true



Zappa & Shepherd (2017 J. Clim.)

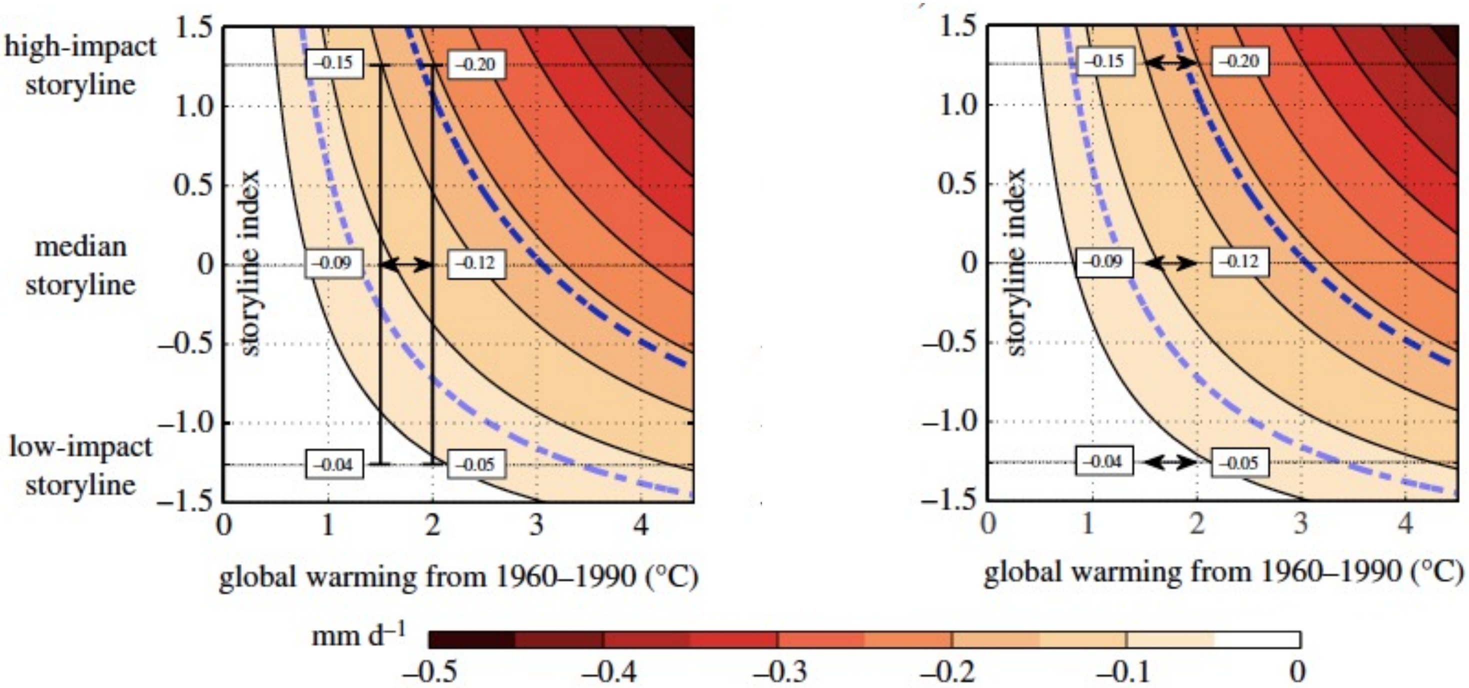
Sensitivity of cold-season Mediterranean drying to global warming level

Traditional view of 1.5 C vs 2.0 C:

- 0.03 to 0.15 mm/day at 1.5 C
- 0.05 to 0.20 mm/day at 2.0 C
- Indistinguishable within uncertainties

Storyline view of 1.5 C vs 2.0 C:

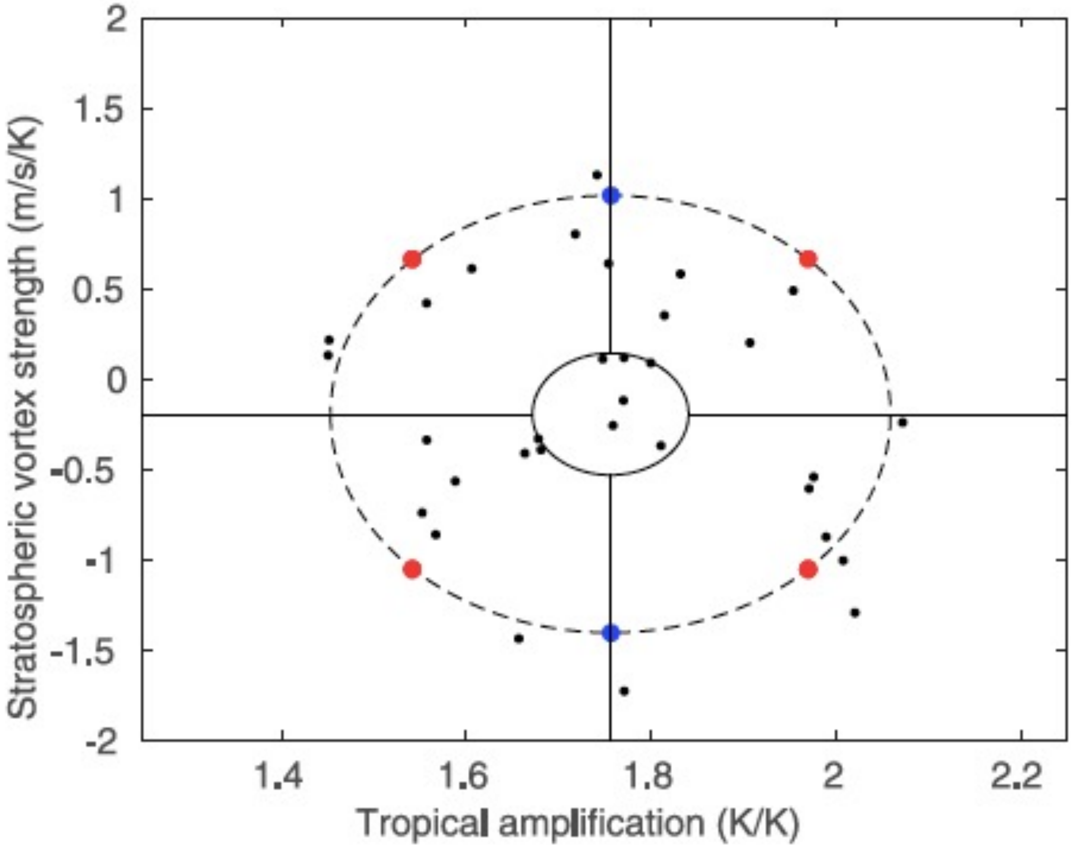
- 0.15 vs 0.20 mm/day for high-impact storyline
- 0.03 vs 0.05 mm/day for low-impact storyline
- Distinguishable for any storyline



The key is the **conditionality** of the representation

Zappa & Shepherd (2017 J. Clim.)

Remote driver responses across the CMIP5 ensemble



- The storylines **can be given a probabilistic interpretation**, if you are comfortable with that
- Can be refined in the future, based on new knowledge (e.g. elimination of one of the storylines as implausible)

Zappa & Shepherd (2017 J. Clim.)

First published 1973

Inverting the power structure

“the traditional domination of ‘hard facts’ over ‘soft values’ [is] inverted… traditional scientific inputs… become ‘soft’ in the context of the ‘hard’ value commitments that will determine the success of policies for mitigating the effects of [climate change]” (Funtowicz & Ravetz 1993 Futures)

From E.F. Schumacher's "Intermediate technologies":
Production methods should be

- used in workplaces where people live
- cheap
- relatively simple
- using local materials and mainly for local use

Rather than formulating our science questions in a way that requires use of fancy (and expensive) tools, perhaps we should use simpler tools in order to democratize the creation of climate information

Yet the climate science enterprise is big business

Concluding Remarks

- The storyline approach respects the **singular nature of climate risk** (both from singular events, and from climate change itself which is necessarily singular)
  - Linking to historical events, in their proper context, brings a **salience to the risk**; well understood psychologically (also in terms of episodic vs semantic memory)
- Storylines also provide a **built-in (not contrived) narrative**, hence an emotional element, which is essential for decision-making (Damasio 1994; Davies 2018)
- **Climate models** are essential sources of information, to confront the issues of statistical non-stationarity and unprecedented events
  - Yet the current (CMIP) approach to climate modelling is highly non-optimal
- **Statistical practice** should be embedded within structured logical reasoning (e.g. in the form of causal networks), which will help avoid the errors of inference that can easily arise when the statistical analysis is treated as an end in itself
- Need to explore storylines of climate risk, combining the best information from all sources — **interpreted not as a prediction but as representing plausible futures**