METEOROLOGY

University of Reading

THE STORYLINE APPROACH TO EXPLAINING EXTREME EVENTS AND ARTICULATING PLAUSIBLE FUTURES

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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
    - Requires the concept of causality, and counter-factuals
- 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

Can a narrative provide scientific evidence for decision-making?

- An apocryphal story of a conversation on 18 March 2020......

I'm going to see the Queen... That's what I do every Wednesday. Sod [coronavirus]. I'm going to go and see her.

You can't go and see the Queen. What if you go and give her coronavirus?

Yeah...I can't go

EDITORIAL · 20 MARCH 2019

nature

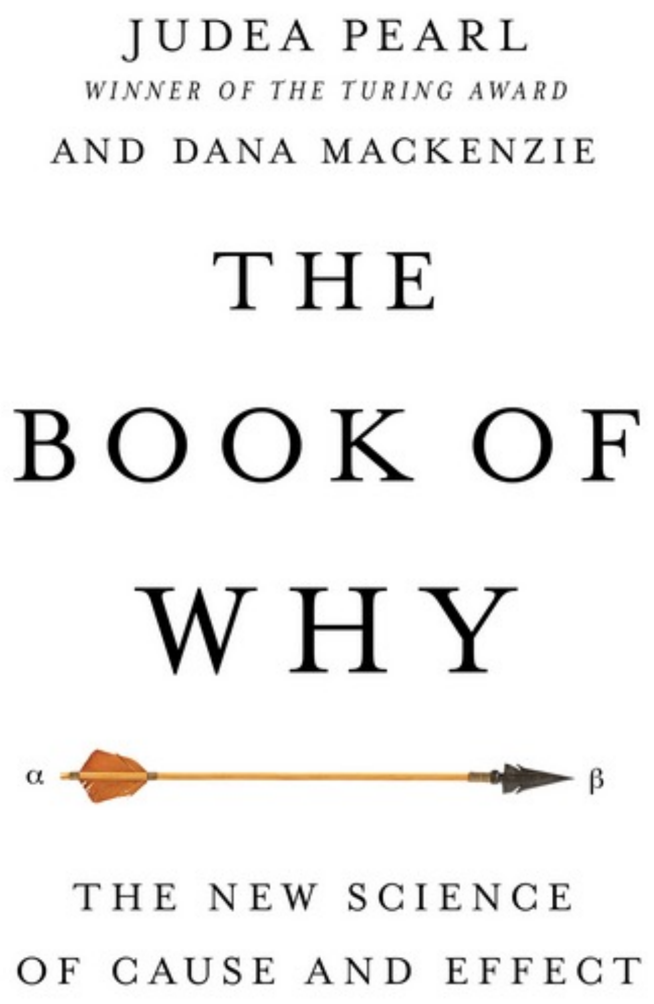
It’s time to talk about ditching statistical significance

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

- An obvious point is that $p < 0.05$ should not be interpreted dichotomously (as True/False), but the issue runs much deeper than this
- Climate-change science is anchored in physical understanding, yet frequentist statistical practices (rituals) 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

“La théorie des probabilités n’est que le bon sens reduit au calcul.”

(Pierre-Simon Laplace, 1819)

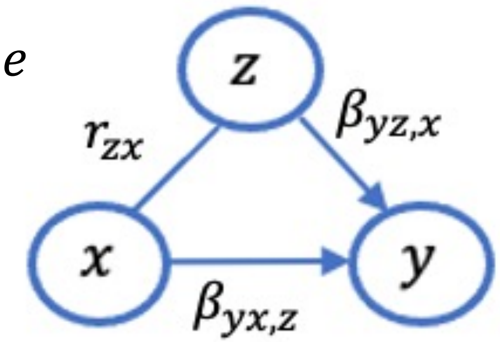


- **Causality** is not usually discussed in statistics textbooks
- However, understanding the causality involved in a particular situation is crucial for setting up the statistical analysis, and for interpreting the results
  - The mathematics is agnostic about causality, but the physical interpretation 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

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

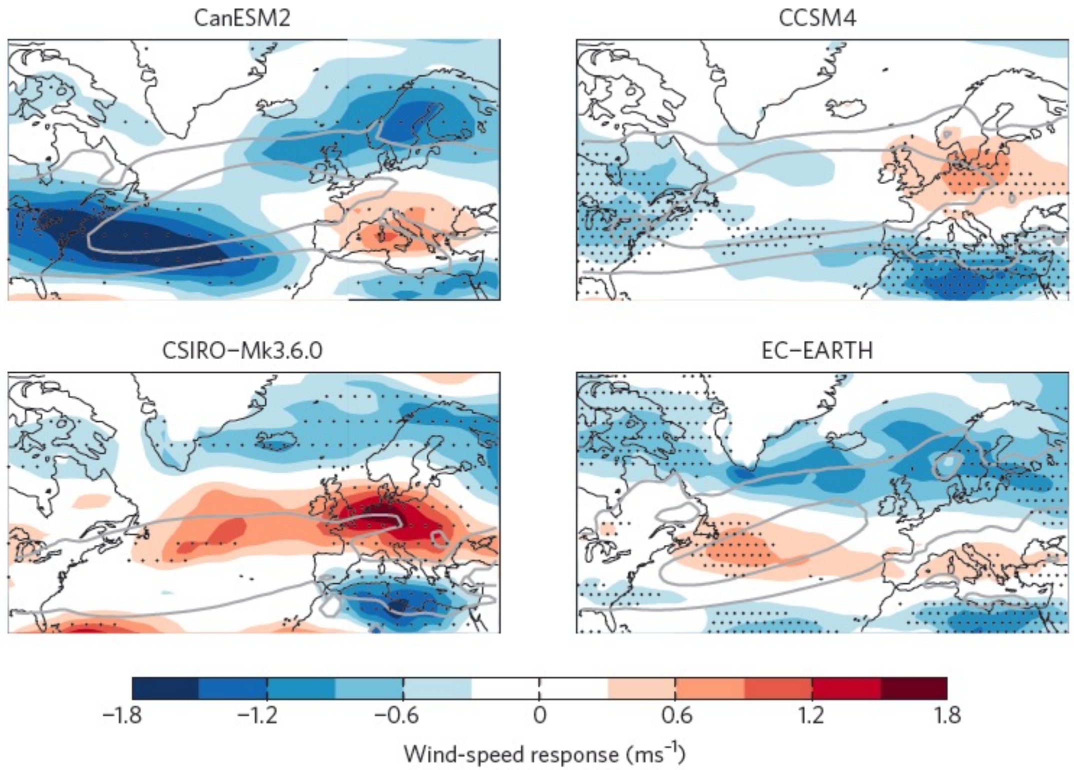
$$\Longrightarrow \quad r_{yx} = \underbrace{\beta_{yx,z}}_{\text{Direct}} + \underbrace{\beta_{yz,x} r_{zx}}_{\text{Indirect}}$$

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



Kretschmer et al. (2021 BAMS)

- *Why do we need physical climate storylines?* Climate models can **disagree on the nature of the atmospheric circulation response** to global warming
  - Has direct implications for precipitation and for weather-related extremes such as droughts and heat waves
  - The average of such different projections has no meaning!

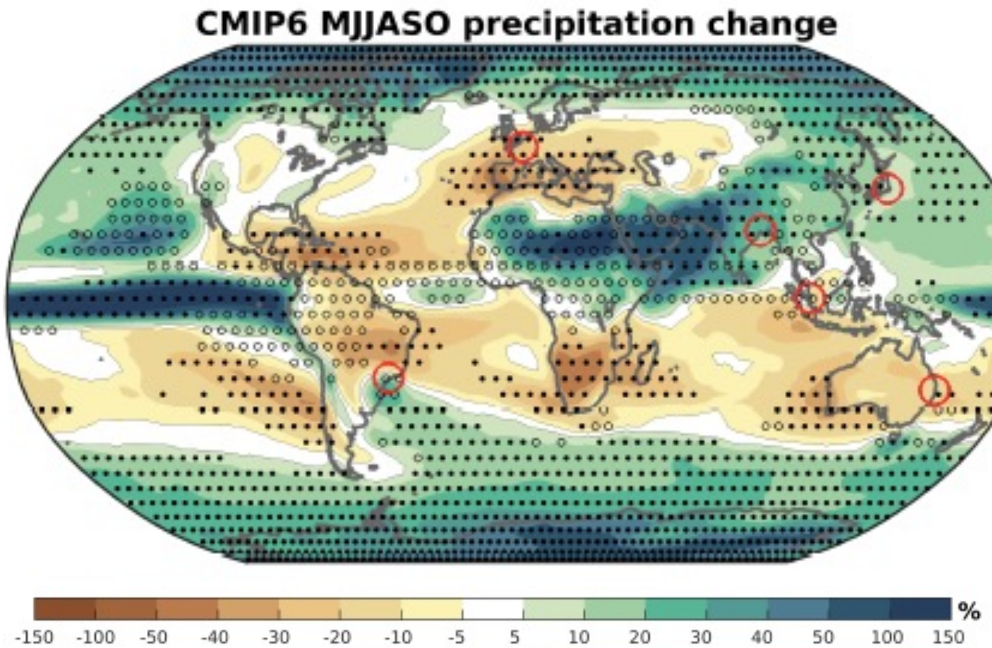


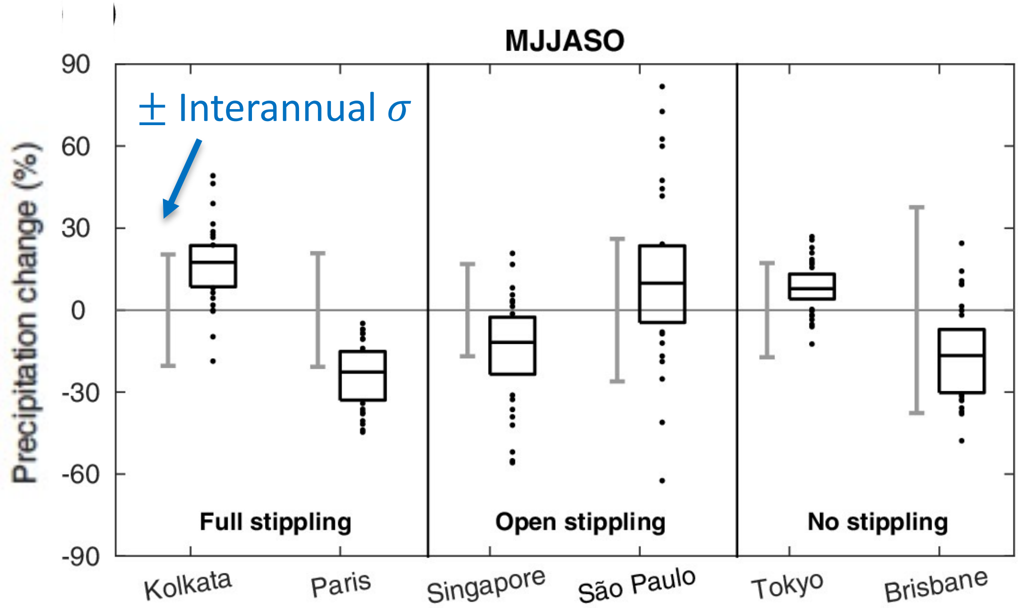
Wintertime lower tropospheric zonal wind speed climatology (contours) and end-of-century response to RCP 8.5 (shading)

Shepherd (2014 Nature Geosci.)

- 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

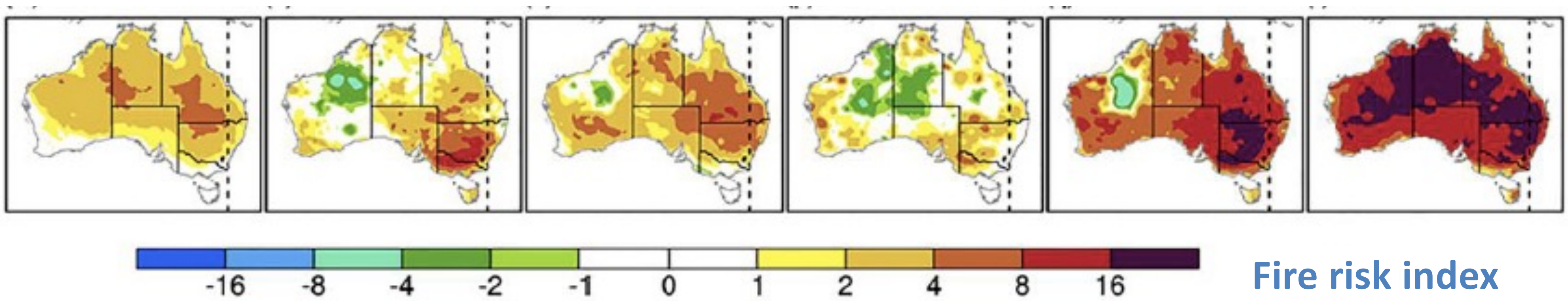




Zappa, Bevacqua & Shepherd (2021 Int. J. Clim.)

- 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)**

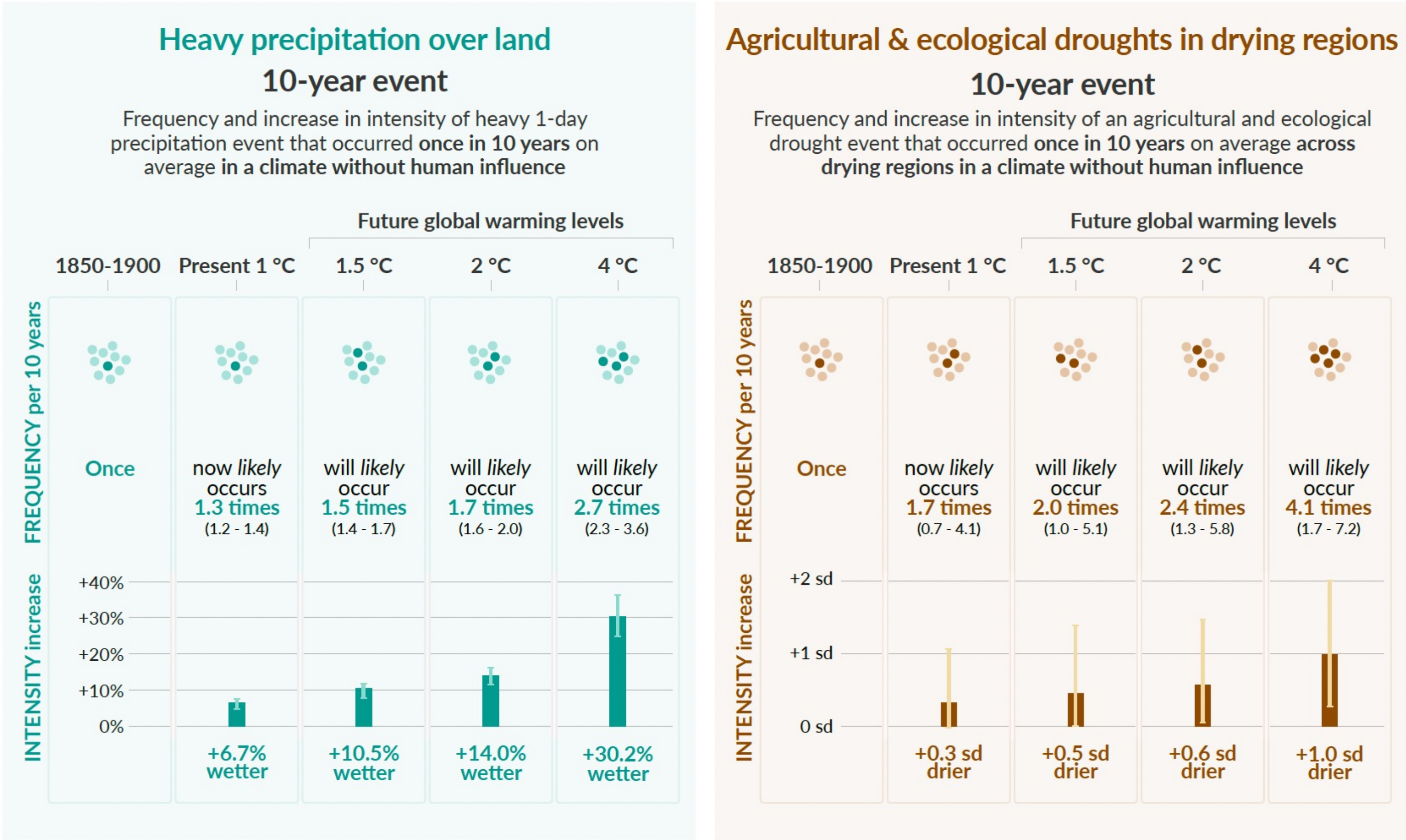
Pacific SST | Indian SST | Vortex | Trend | Total | Observed



Fire risk index

Lim et al. (2021 BAMS)

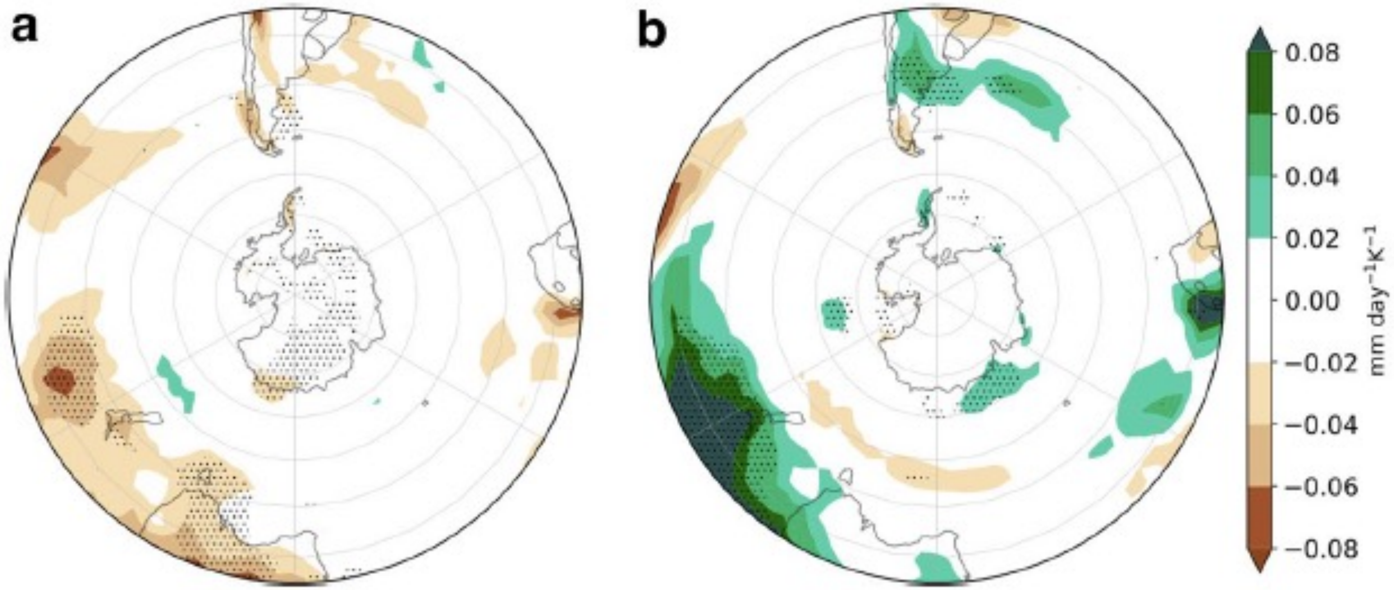
- Climate scientists tend to describe changes in extreme events **probabilistically**, which requires **aggregation**



IPCC AR6 WGI Summary for Policymakers (SPM), 2021

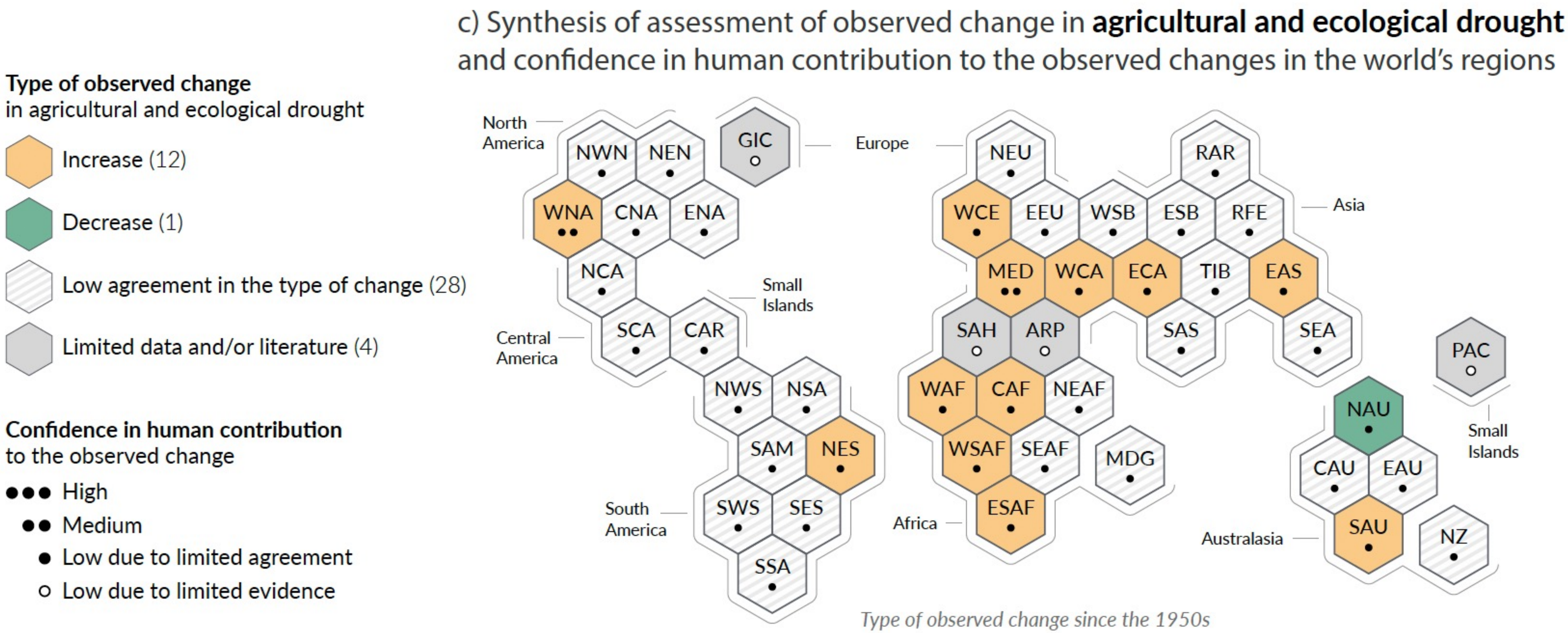
- In the IPCC, the uncertainty around dynamical aspects of climate change has typically been managed through **generalization**, e.g. a focus on zonally averaged quantities
- However, **generalization can be locally misleading**: precipitation changes in austral summer from a strengthening of the Southern 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.)

- At the regional scale, the traditional probabilistic attribution of changes in extremes is challenged by **uncertainties in model projections**, and by **lack of verifying data**



SPM of AR6 WGI report (2021)

nature climate change 2021 ARTICLES
https://doi.org/10.1038/s41558-021-01125-3

Climate services promise better decisions but mainly focus on better data

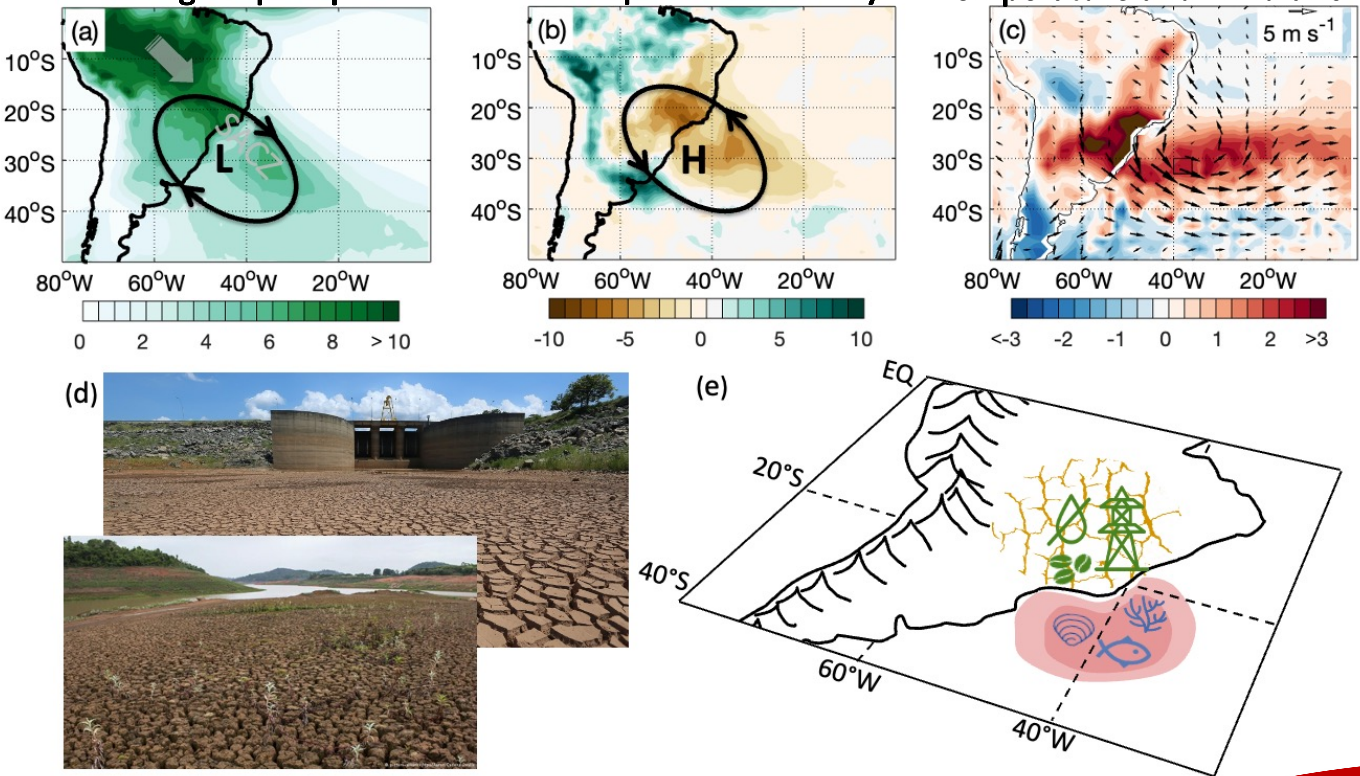
Kieran Findlater[1,2], Sophie Webber[3], Milind Kandlikar[1,2] and Simon Donner[4]

- "...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)
- We should derive a conceptual framework from reality, rather than deriving 'reality' from a conceptual framework (paraphrase from E.F. Schumacher's *Small is Beautiful,* 1973)
    - Requires **inverting the construction of climate information**

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

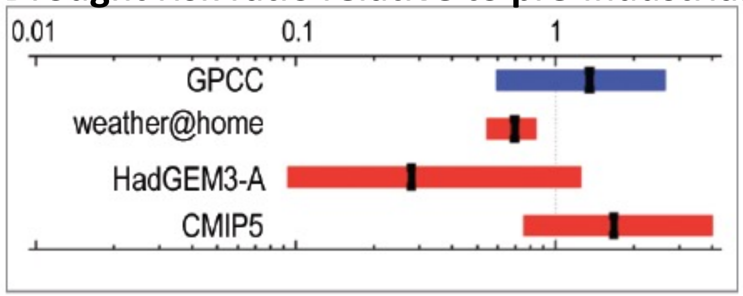
Climatological precipitation **Precipitation anomaly** **Temperature and wind anomaly**



Rodrigues & Shepherd (2022 PNAS Nexus)

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

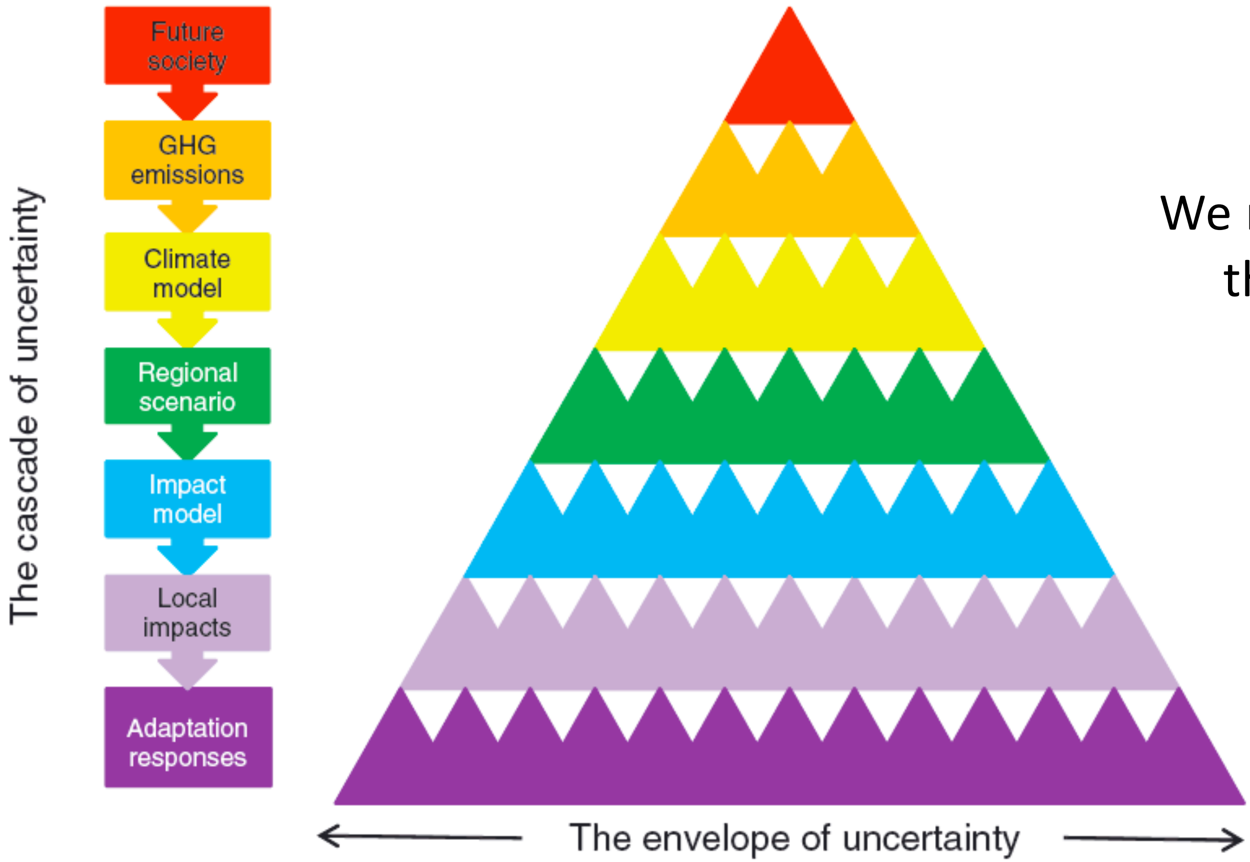
Drought risk ratio relative to pre-industrial



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)

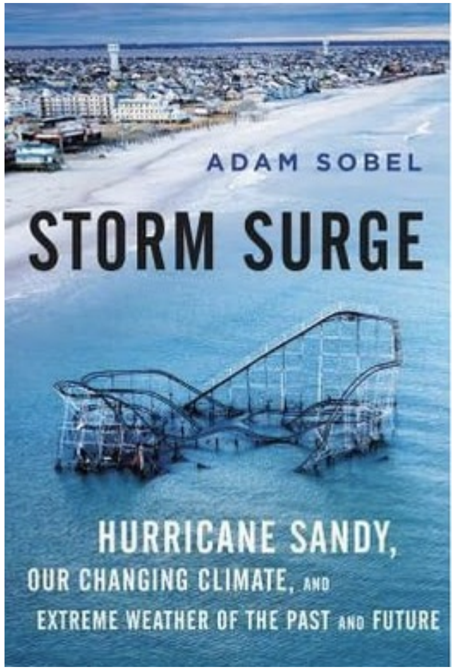
- Even when aggregation is reliable, **it is not informative about individual cases**
  - A famous example (Bortkiewicz 1898)

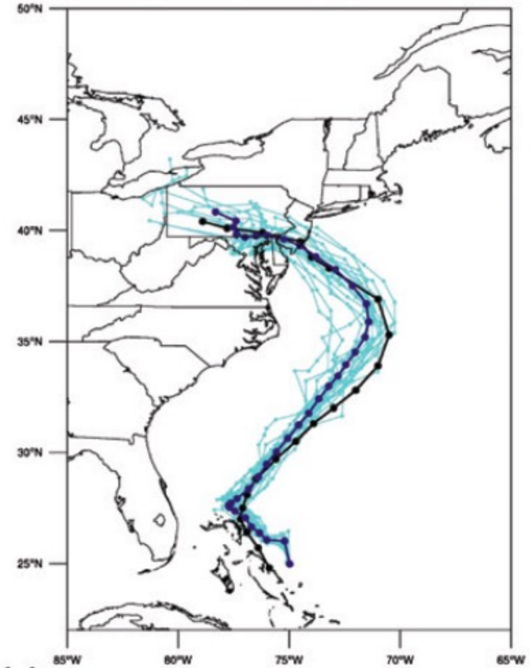
Pandit (2015 Anaesthesia)

- 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
  - Events in the real world are not iid

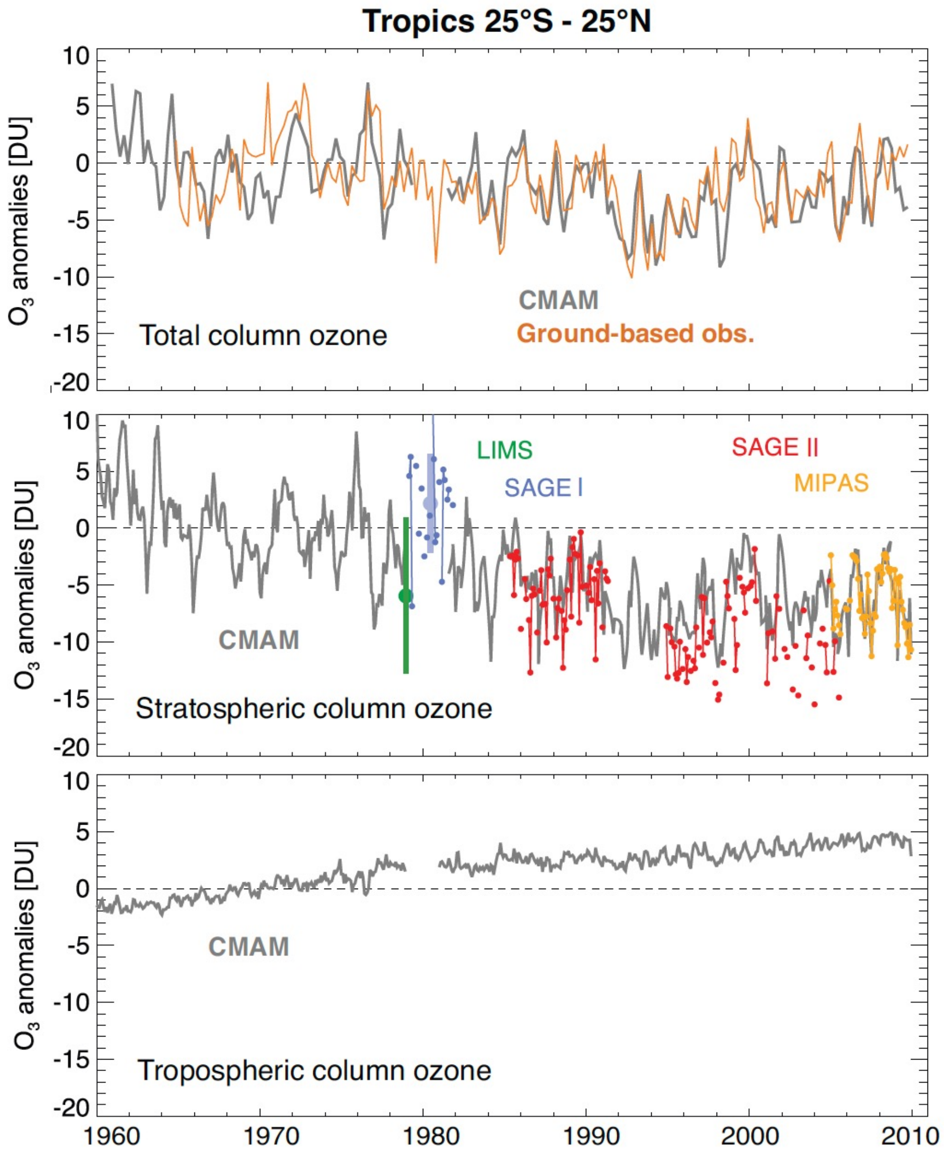
- Ultimately, **every extreme event is unique**, and this uniqueness matters for impacts





- **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

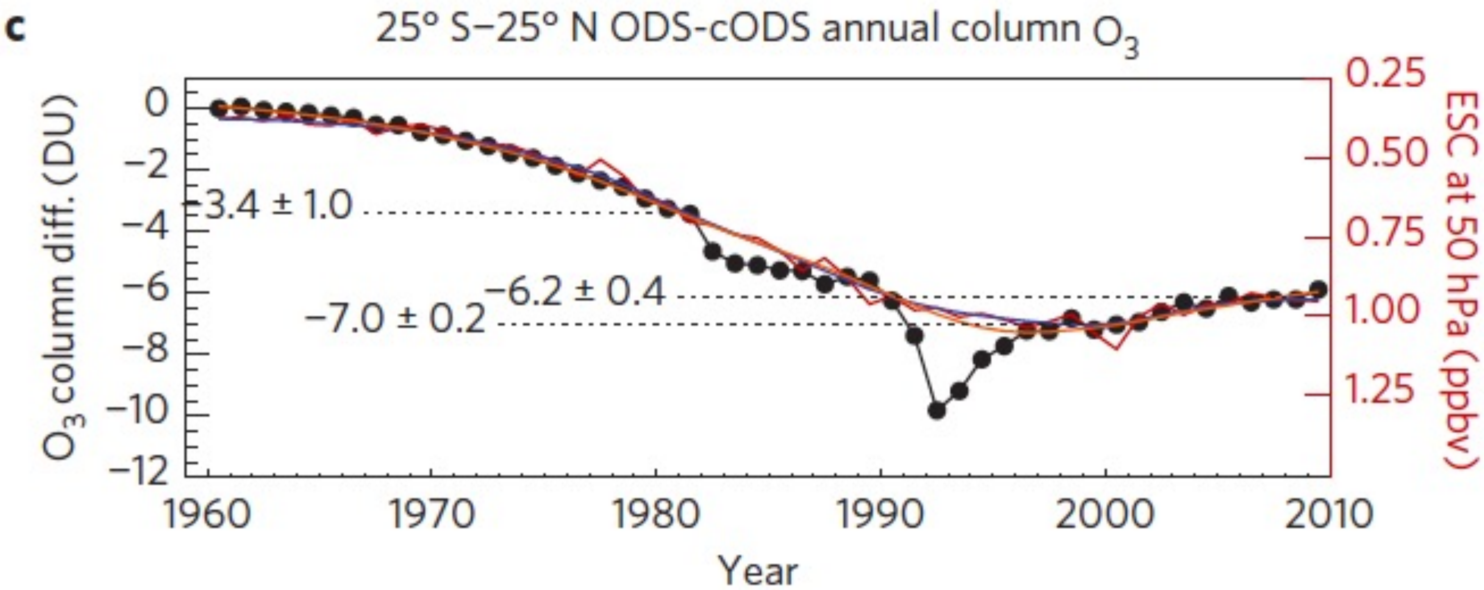
- But we do know that sea level will be higher, and storms will hold more moisture
- Thus we can legitimately ask (and plausibly answer) the counter-factual questions:
  - How much were the impacts of Sandy increased by climate change?
  - How much worse might they be in the future?



- **Counter-factual thinking is nothing new for atmospheric composition**, where often one considers the atmospheric conditions as given
- Nudging a chemistry-climate model towards reanalysis is a far more surgical approach for dealing with atmospheric variability than multiple linear regression
- This study resolved the longstanding discrepancy between the decline in tropical stratospheric ozone predicted by chemistry-climate models, and the lack of a clear decline in observed tropical column ozone

Figure 2.12 of WMO (2014), adapted from Shepherd et al. (2014 Nature Geosci.)

- In this case, the counter-factual question is how would ozone have evolved without the observed increases in ozone-depleting substances (ODS)
- **ODS-induced ozone loss** is evident in the tropics as well as elsewhere, and is just a weaker version of midlatitude ozone loss, with all the same features
  - Follows ESC very closely; enhanced by volcanic aerosol
  - At least 40% of the long-term non-volcanic ozone loss had occurred by 1980!



Shepherd et al. (2014 Nature Geosci.)

- 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.

- Recommendations work against any consideration of **the local** (Shepherd & Sobel 2020 Comp. Stud. South Asia, Africa & Middle East)
  - The process of abstraction and generalization in mainstream climate science "detaches knowledge from meaning" (Jasanoff 2010)

"We believe what we see, and not what we are told" (Dr Santosh Nepal, ICIMOD, 2021)

- Yet the most severe climate impacts are often exacerbated by the **human-modified environment**
  - Rather than being a ‘confounding effect’ for the effects of climate change, **the urban heat island effect is a threat multiplier for heat waves**

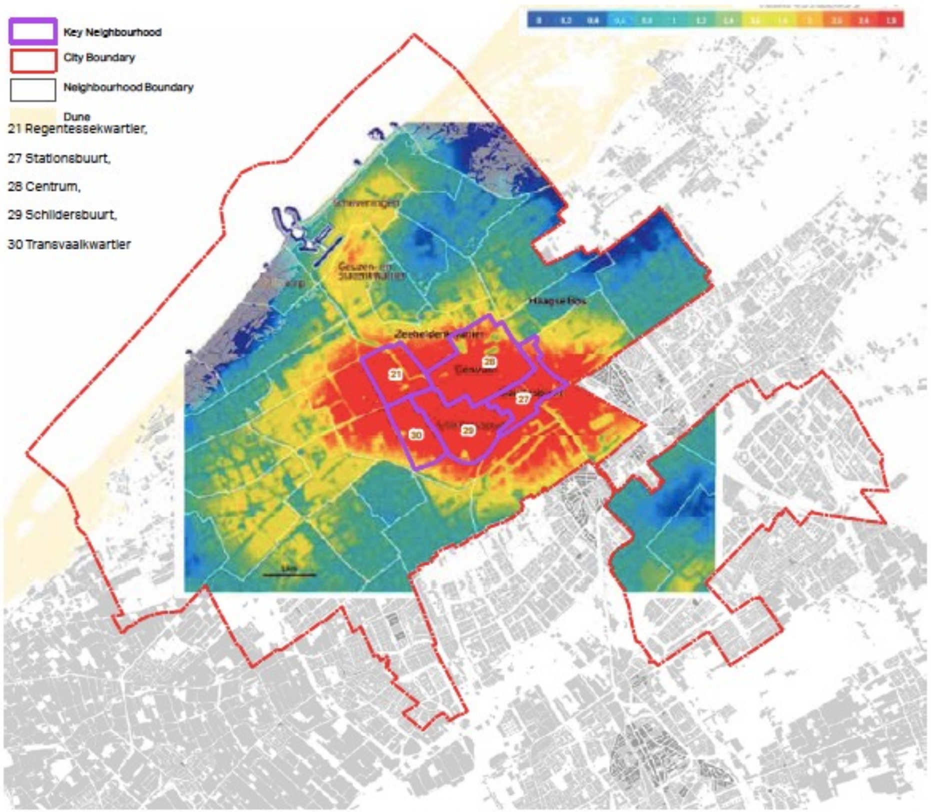


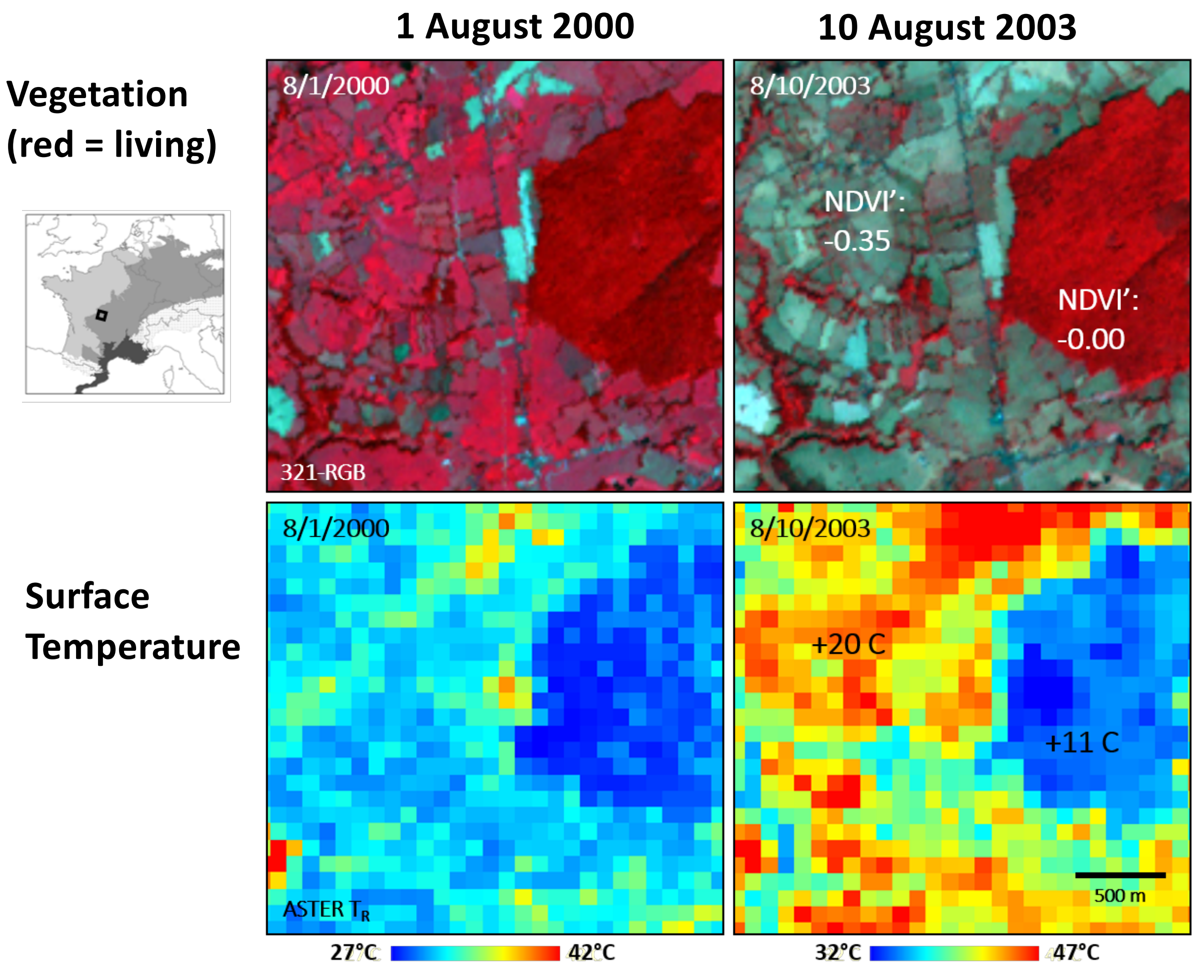
Figure 2-8: The urban heat island effect in The Hague – increased heat will affect more vulnerable neighbourhoods in The Hague

Urban heat island effect in The Hague, based on a recent heat wave

Not surprisingly, the poor neighbourhoods were disproportionately affected

From The Hague Resilience Assessment (January 2018)

- **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**

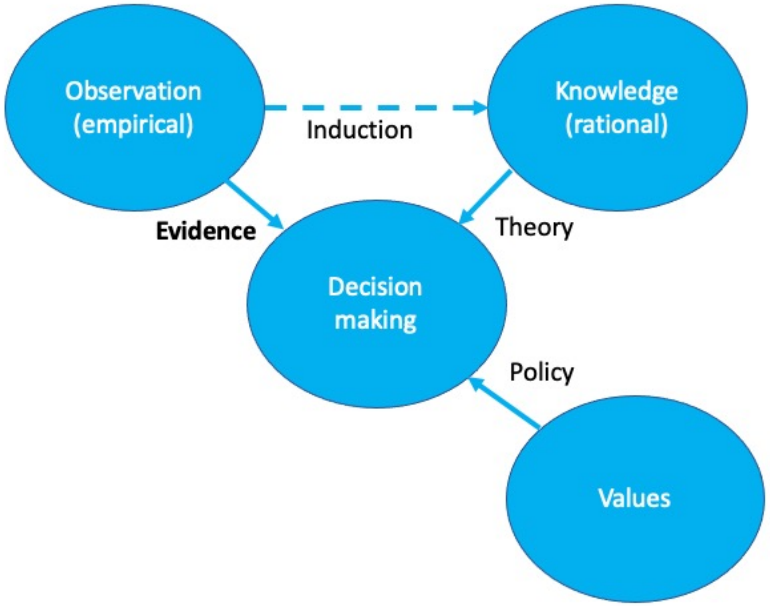


- The summer 2003 heat wave in central France
- Temperature difference between 2000 and 2003 was 11°C in forested areas, but 20°C where the vegetation died out
- We may not be able to predict the statistics of heat waves in the future, but we can predict their implications, and how to manage their impacts

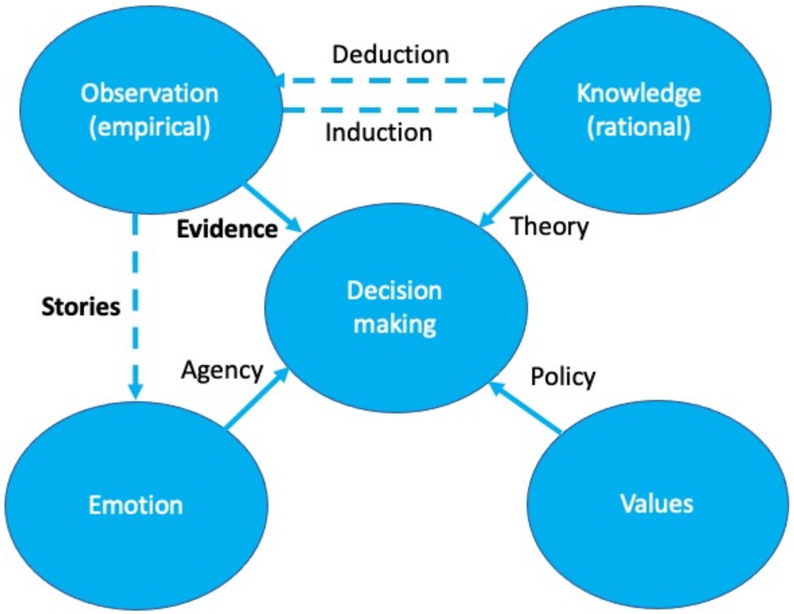
Zaitchik et al. (2006 Int. J. Clim.)

- Through the device of conditionality, **even single images can tell a powerful story**
  - It is well recognized that **emotion** is needed to trigger action (Damasio 1994)
- Permits a different way of constructing climate information for decision-making, where **observations can take on a stronger role**

Traditional approach



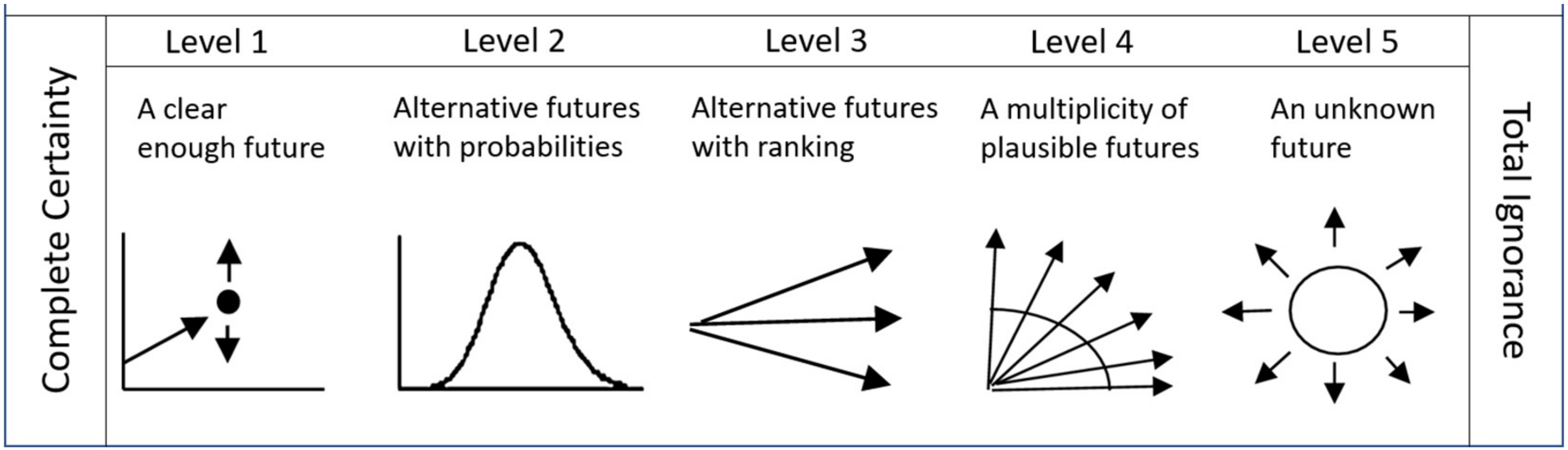
Proposed approach



Hegglin et al. (Front. Environ. Sci., in press)

- Scientists are pressured to issue ‘single, definitive’ statements (Stirling 2010 Nature)
- We need a language for expressing a **‘plural, conditional’ state of knowledge**
  - There are many decision-making methods that deal with deep uncertainty (Weaver et al. 2013 WIREs Clim Change; Rosner et al. 2014 Water Resources Res)

Levels of uncertainty



Adapted from Marchau et al. (2019)

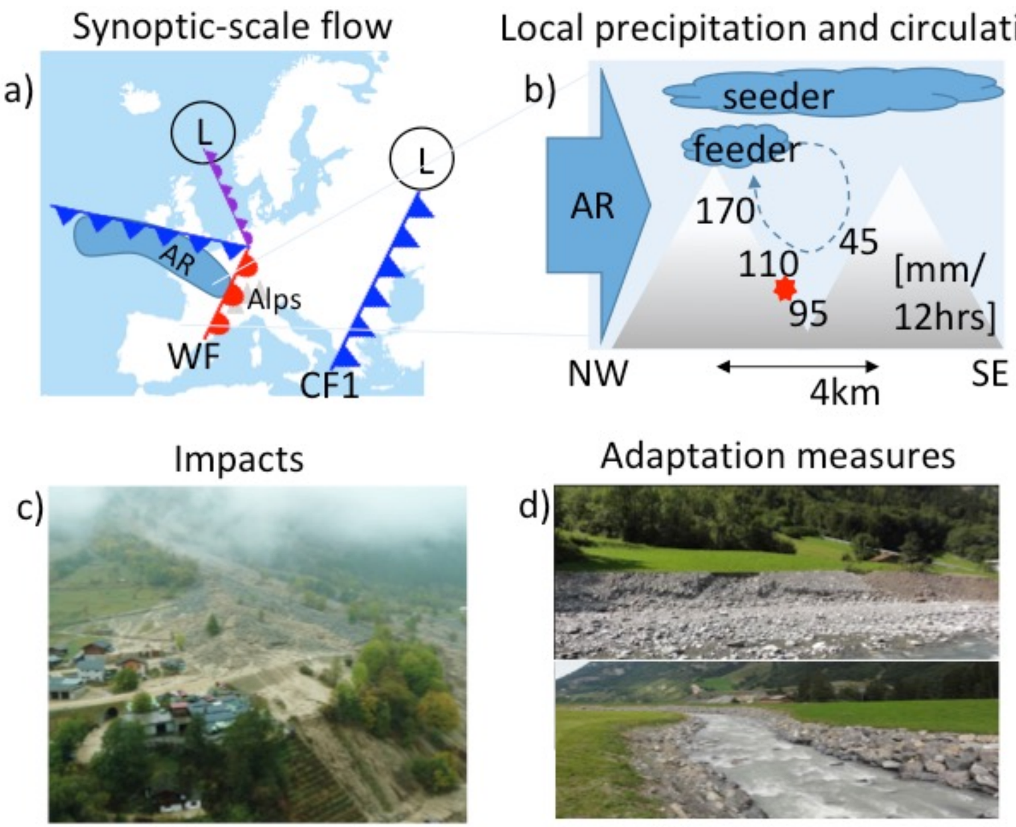
- **Storylines:** physically-based unfoldings of past climate or weather events, or of plausible future events or pathways (Shepherd et al. 2018 Climatic Change)
  - Definition now incorporated in IPCC Glossary (see also Box 10.2 of AR6 WGI report)
  - An **unforecasted rain-on-snow event in the Swiss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

Providing a physical basis for partitioning uncertainty

Exploring the boundaries of plausibility

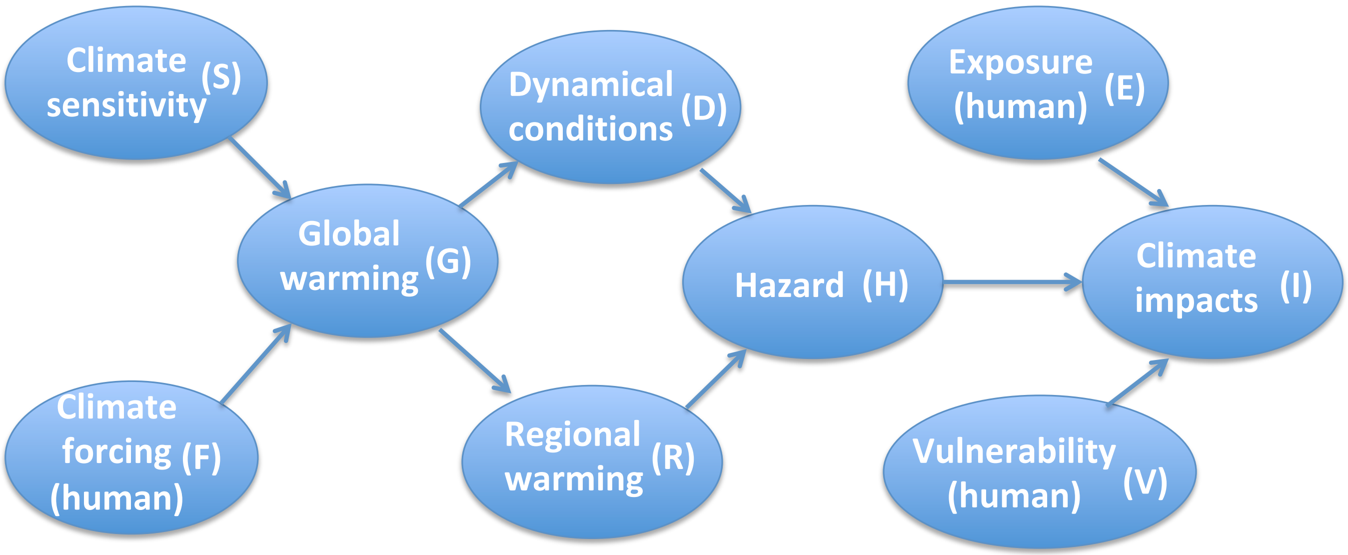
Improving risk awareness

Strengthening decision-making



Shepherd et al. (2018 Climatic Change)

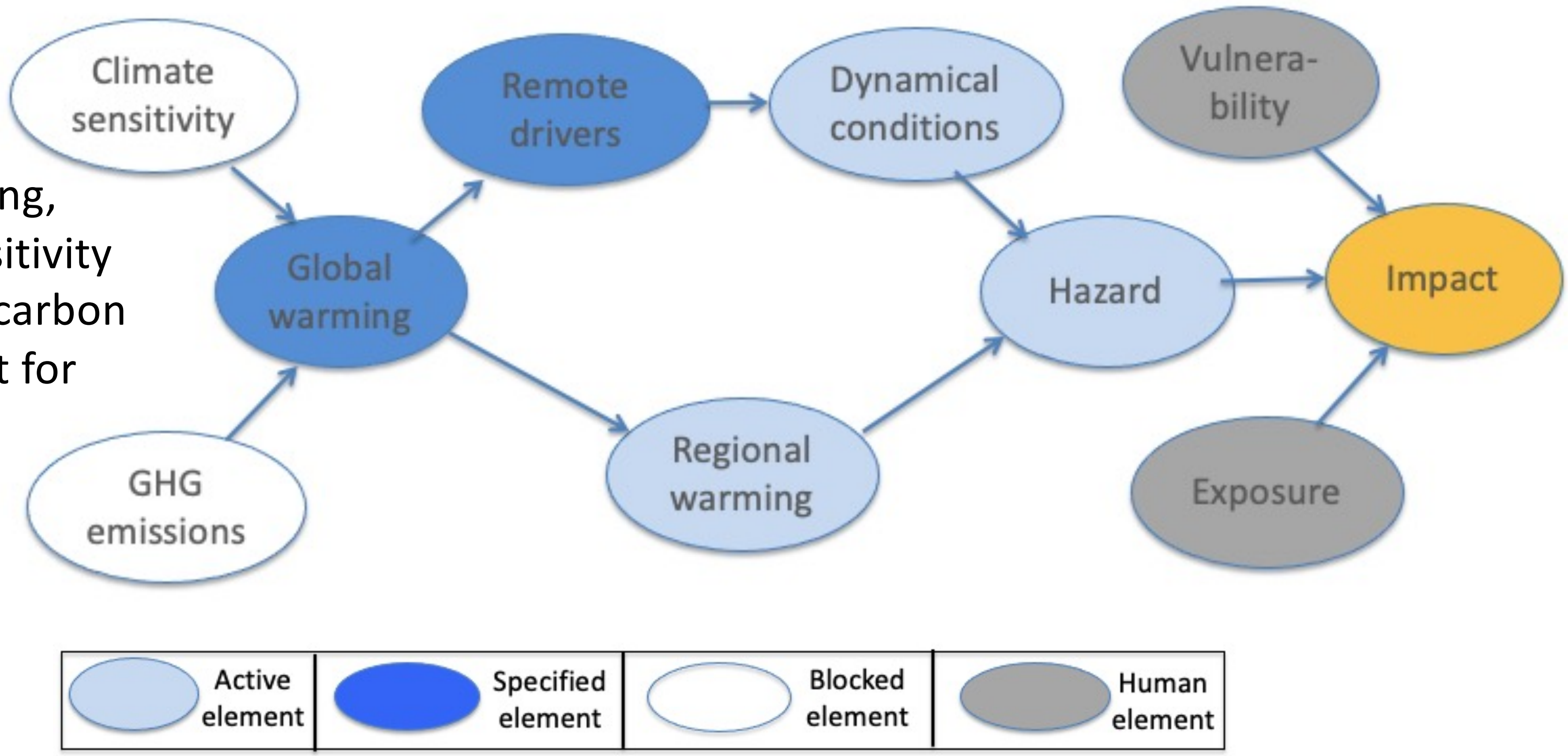
- **Storylines** are a way of navigating the cascade of uncertainty
  - **Causal networks** provide a means for representing **conditional** information
  - Storylines can be seen as **instantiations** of a causal network, by conditioning on one or more nodes: e.g. global warming levels and dynamical conditions
- The uncertainty space is thereby represented **discretely**, through a range of storylines
  - Builds in **self-consistency**, which is essential for consideration of correlated risk



Shepherd (2019 Proc. Roy. Soc. A)

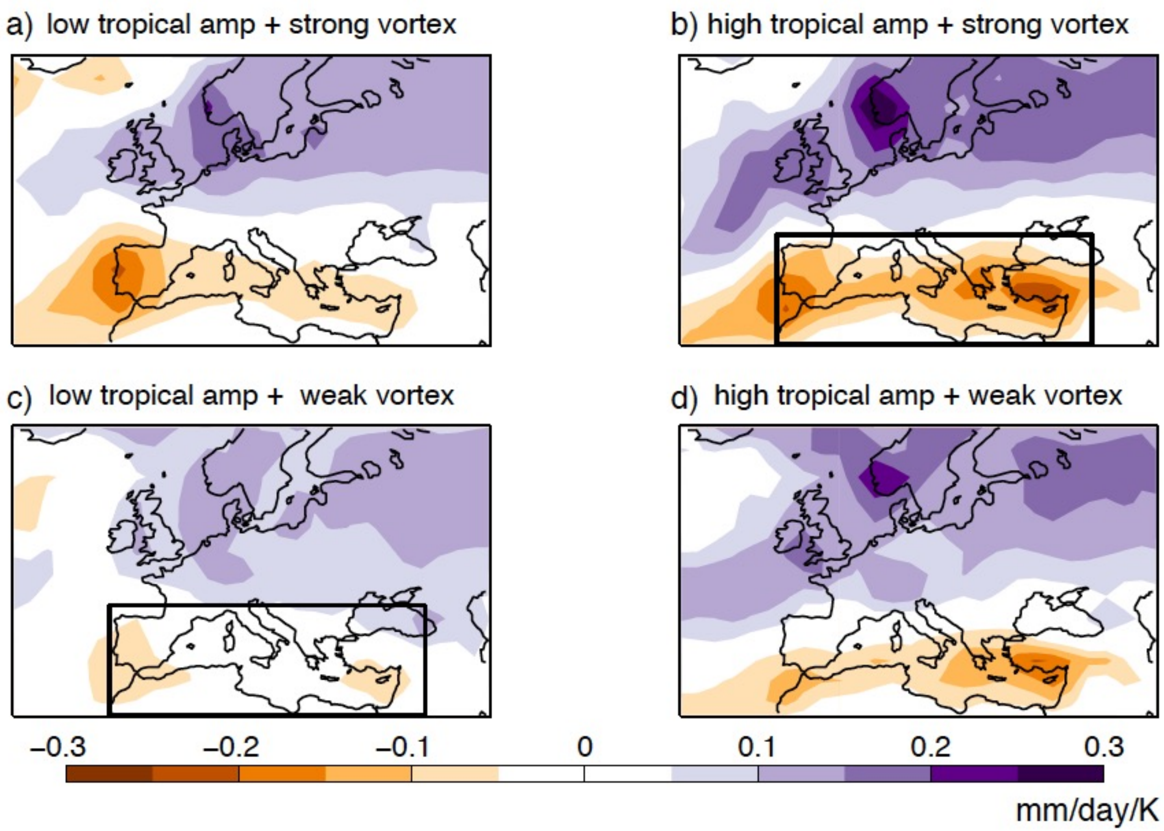
A dynamical (circulation drivers) storyline of regional climate change

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

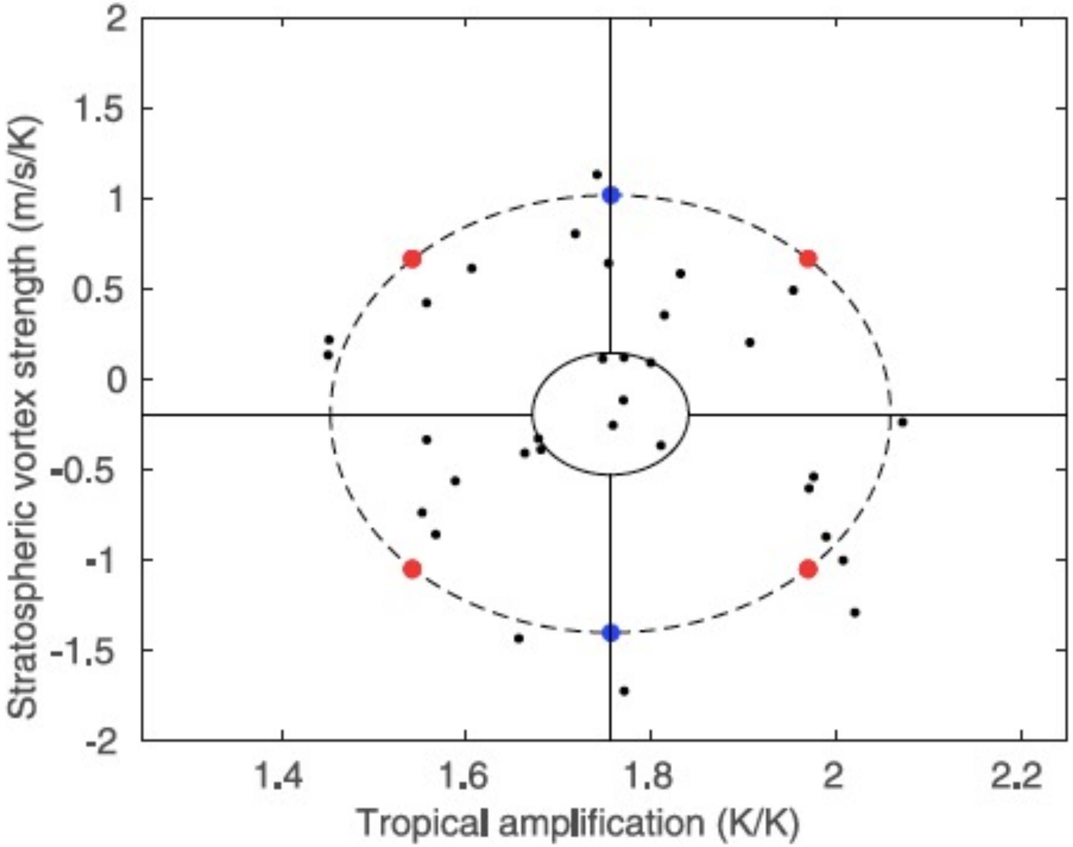
- **Example of dynamical storylines:** four storylines of **future cold-season Mediterranean drying** (a major climate vulnerability for southern Europe)
  - So far as we know, any one of these could be true



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

Zappa & Shepherd (2017 J. Clim.)

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.)

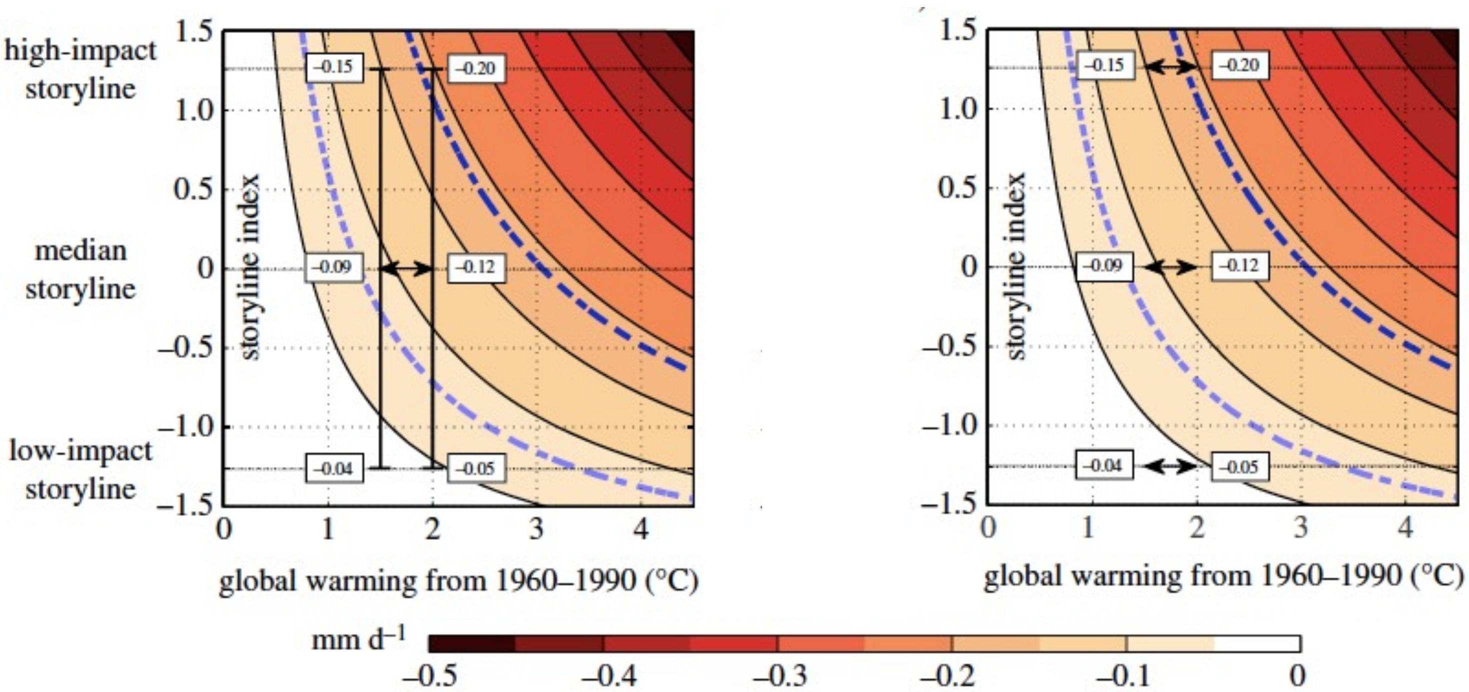
Sensitivity of cold-season Mediterranean drying to global warming level

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

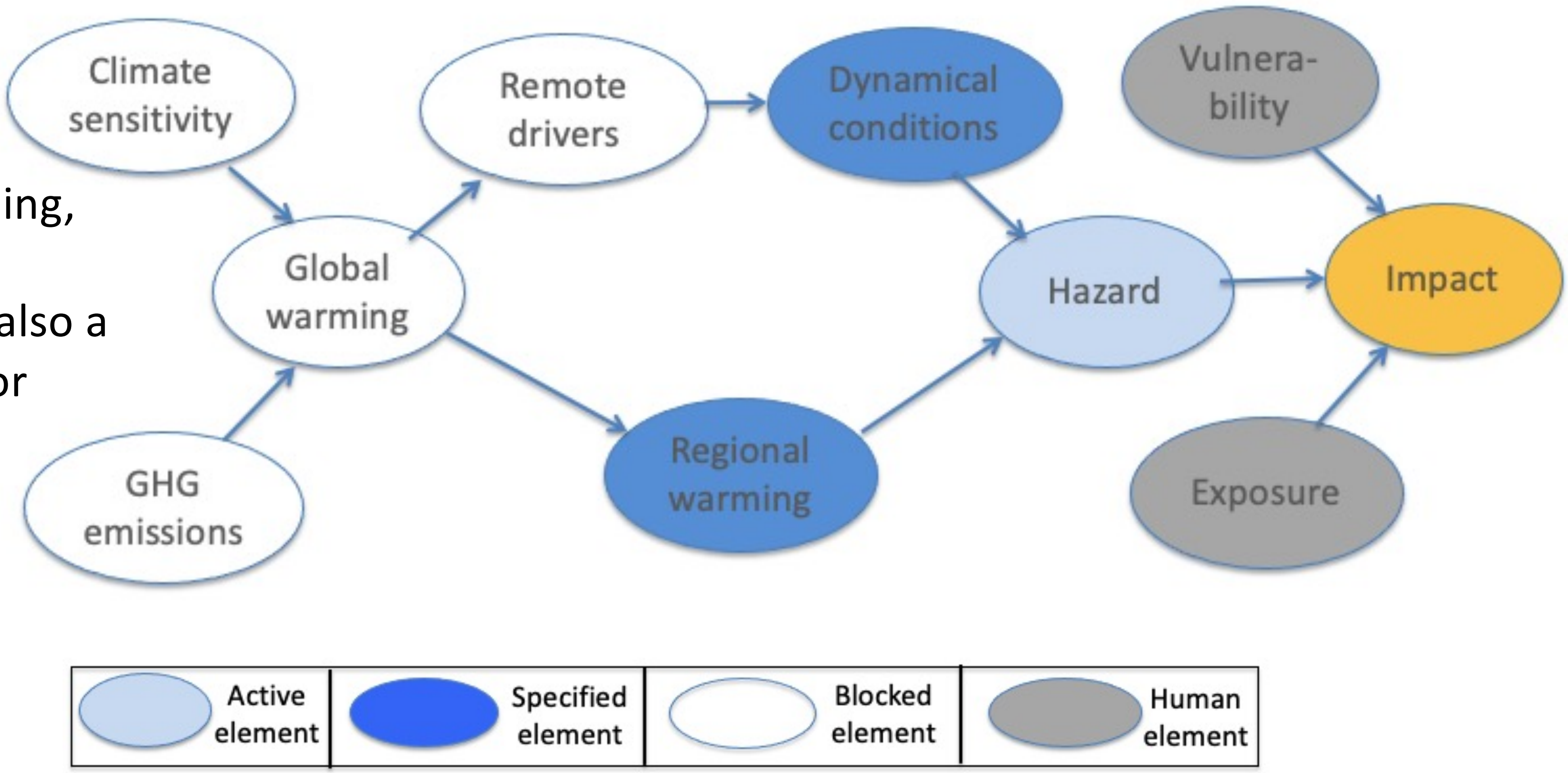


The key is the **conditionality** of the representation

Zappa & Shepherd (2017 J. Clim.)

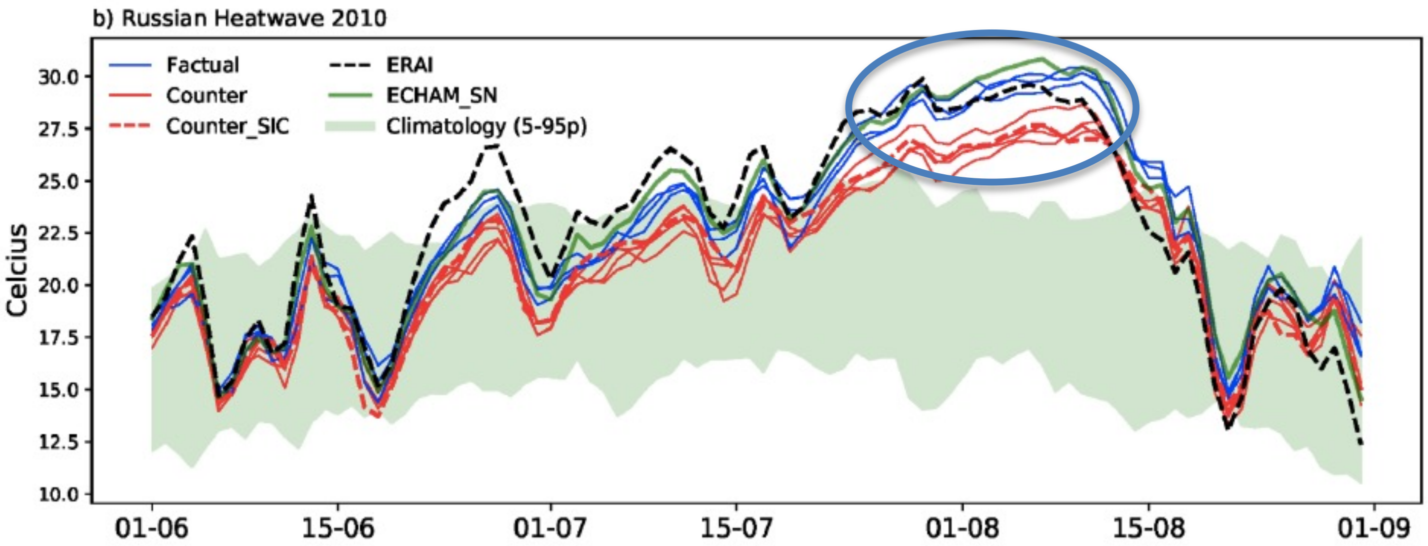
An event storyline

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); in this case, imposed through global spectral nudging
- Allows use of weather-resolving atmospheric models; physically self-consistent
- Removes the arbitrariness in event definition; users can define event as they wish

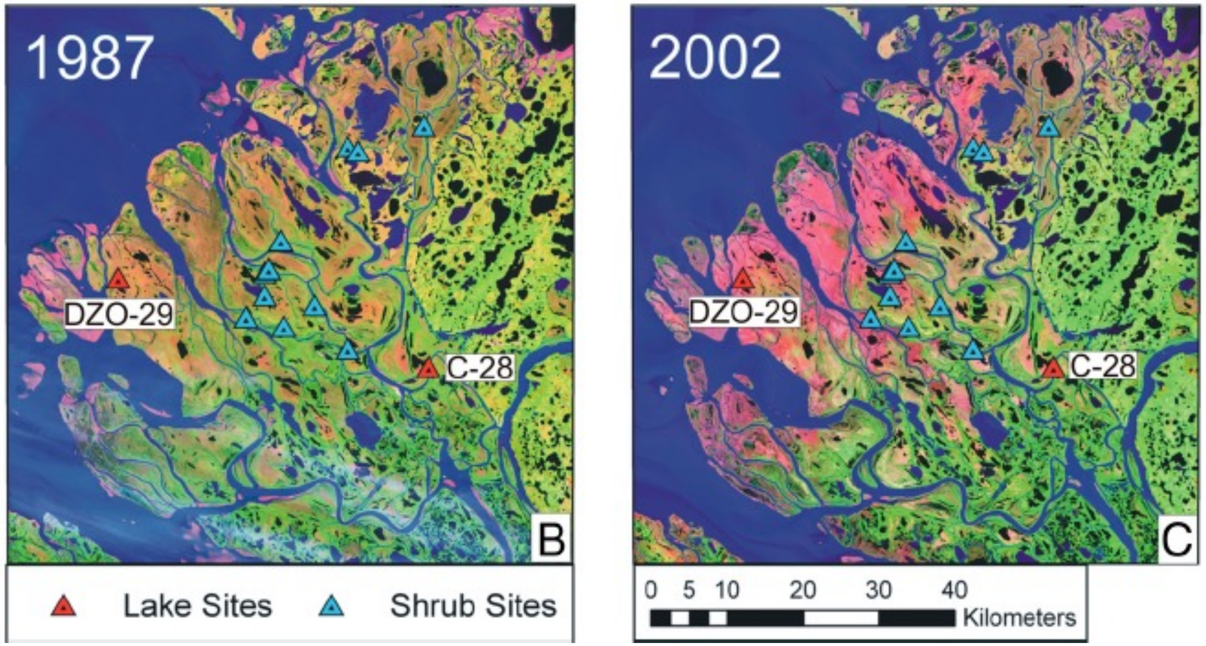


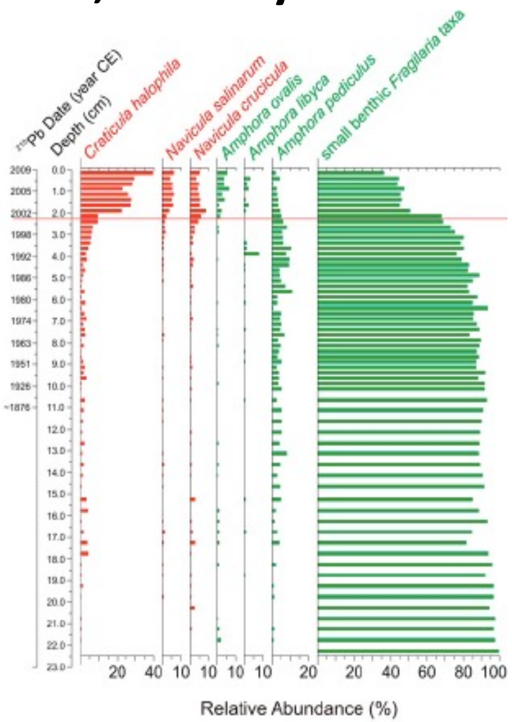
Very high signal-to-noise ratio achieved in both space and time

Could drive an impact model this way

van Garderen, Feser & Shepherd (2021 NHESS)

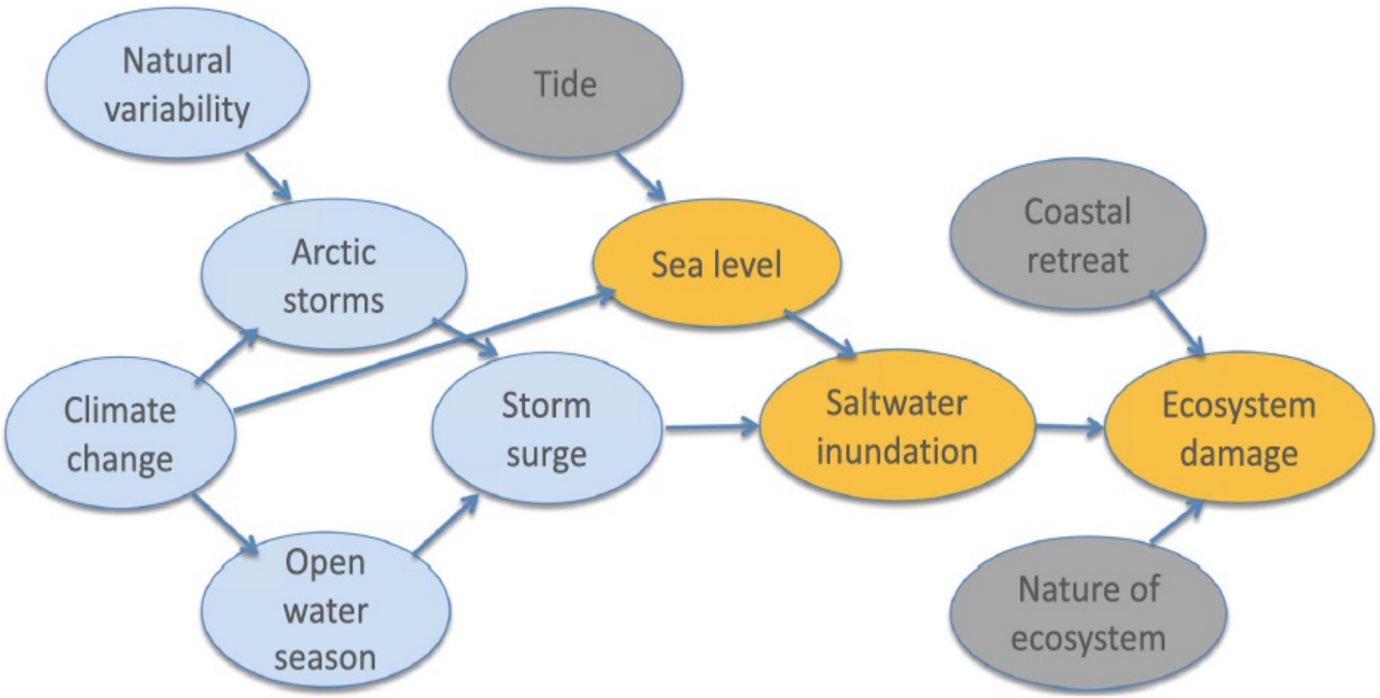
- **Example: Arctic ecosystem collapse**
  - A saltwater storm surge in the Mackenzie Delta (Canadian Arctic coast) in late September of 1999 led to irreversible changes from freshwater (green) to brackish (red) species, unmatched in over 1000 years (right)
  - Such a **singular event** is best described through a **narrative, or storyline**





Pisaric et al. (2011 Proc. Natl. Acad. Sci. USA)

- Pisaric et al. (2011) discuss all the factors below, and conclude that the only essential ones were the longer open-water season from climate change, and the Arctic storm
  - There is no assessment of “statistical significance”, or of likelihood



- The storyline approach aligns well with the forensic approach to attribution in the ecosystem literature
- It also aligns well with liability under tort law (Lloyd & Shepherd 2021 Climatic Change)

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

- How can we ensure that storylines are not **"just so stories"**?
- The answer lies in probability theory, and the logic of Bayesian reasoning

"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." (Harold Jeffreys, *Theory of Probability*, 3rd ed., 1961)

- See Shepherd (2021 Climatic Change) for more discussion on this point

(E.F. Schumacher 1973)

Small is Beautiful

- How would climate-change science look if it was structured "as if people mattered"? (Rodrigues & Shepherd 2022 PNAS Nexus) It would involve:
- **Grappling with complexity** of local situations....

  ....by expressing climate knowledge in a conditional form → *conditional probabilities*
- **The importance of simplicity** when dealing with deep uncertainty....

  ....through the use of *physical climate storylines*
- **Empowering local communities** to make sense of their own situation....

  ....by developing ''intermediate technologies'' that build trust and transparency → *causal networks*

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**