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K O R E A

Physical Climate Storylines as a Way of Bridging between Attribution and Prediction

Ted Shepherd, Grantham Professor of Climate Science

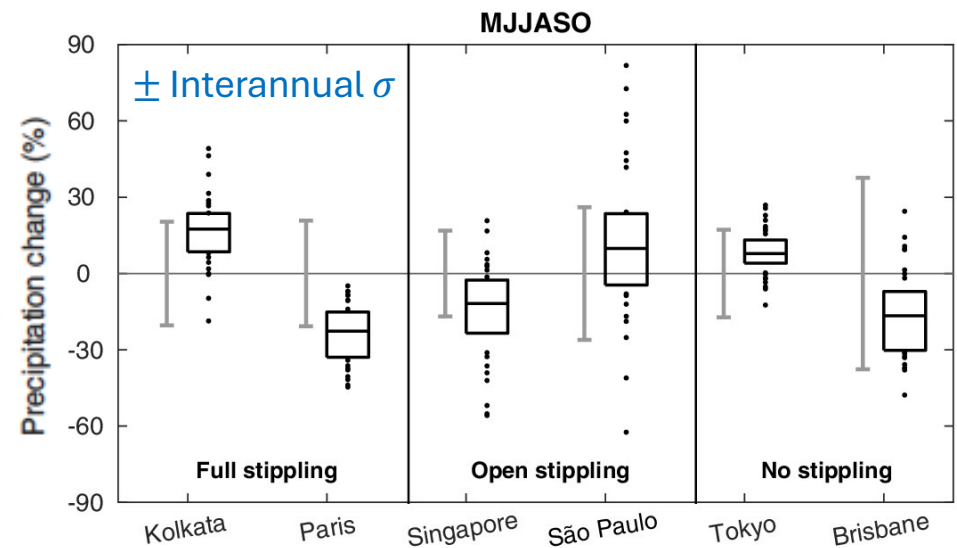
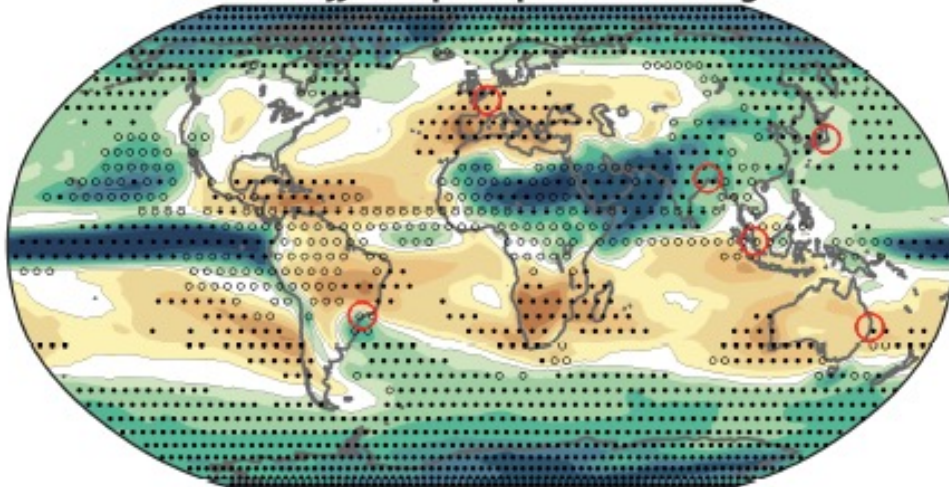
Department of Meteorology, University of Reading, UK

Uncertainty in projected regional precipitation changes

- **The uncertainty stands in contrast to the certainty of regional warming**
- In this figure, full stippling indicates robustness in sign, 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

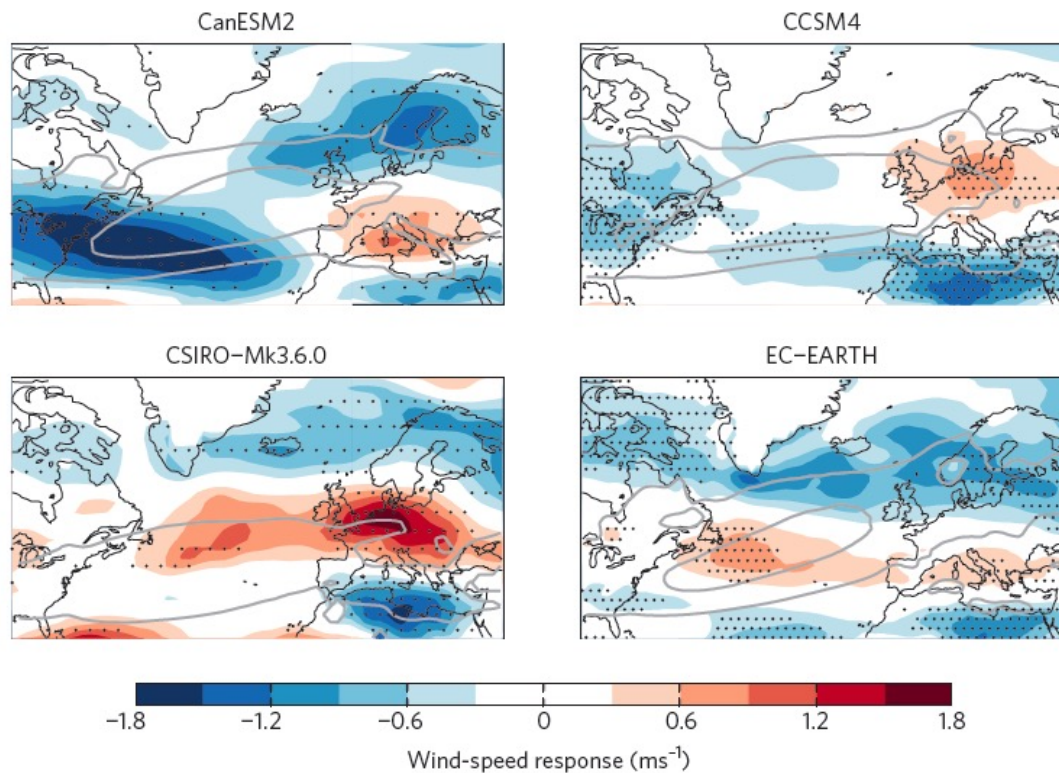
CMIP6 MJJASO precipitation change



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

Divergence in model projections of circulation changes

- Climate models **can differ substantially** in their prediction of how **atmospheric circulation will respond to greenhouse gas forcing**



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

- The average of such different predictions has no physical meaning!

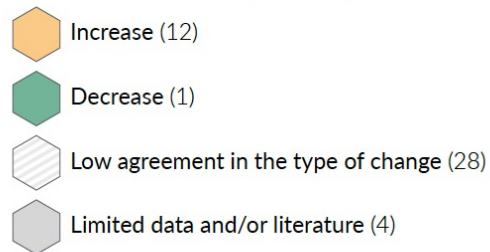
Shepherd (2014 Nature Geosci.)

The limitations of traditional, unconditional attribution

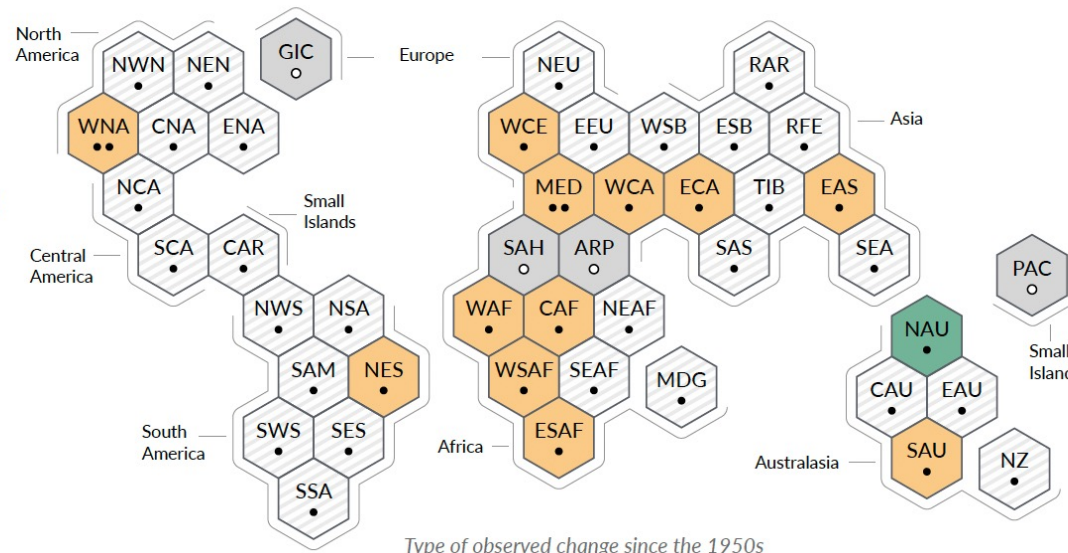
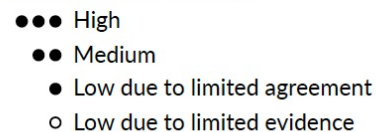
- At the regional scale, the traditional approach to attribution of long-term changes is challenged by **uncertainties in model projections**, and by **lack of verifying data**
 - Yet there can be a **wealth of climate information** when it is expressed in **conditional form** (see Chapter 10 of the IPCC AR6 WGI report)

c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change in agricultural and ecological drought

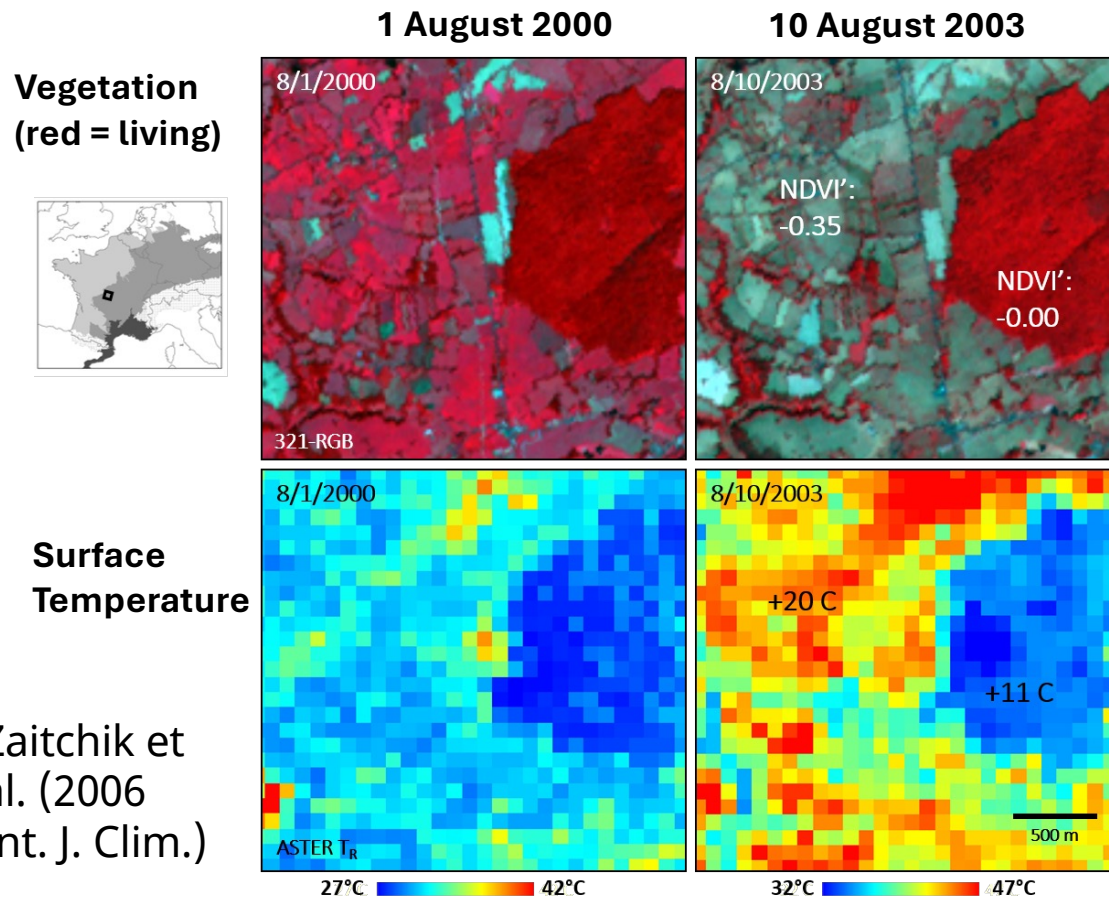


Confidence in human contribution to the observed change



SPM of
IPCC AR6
WGI report
(2021)

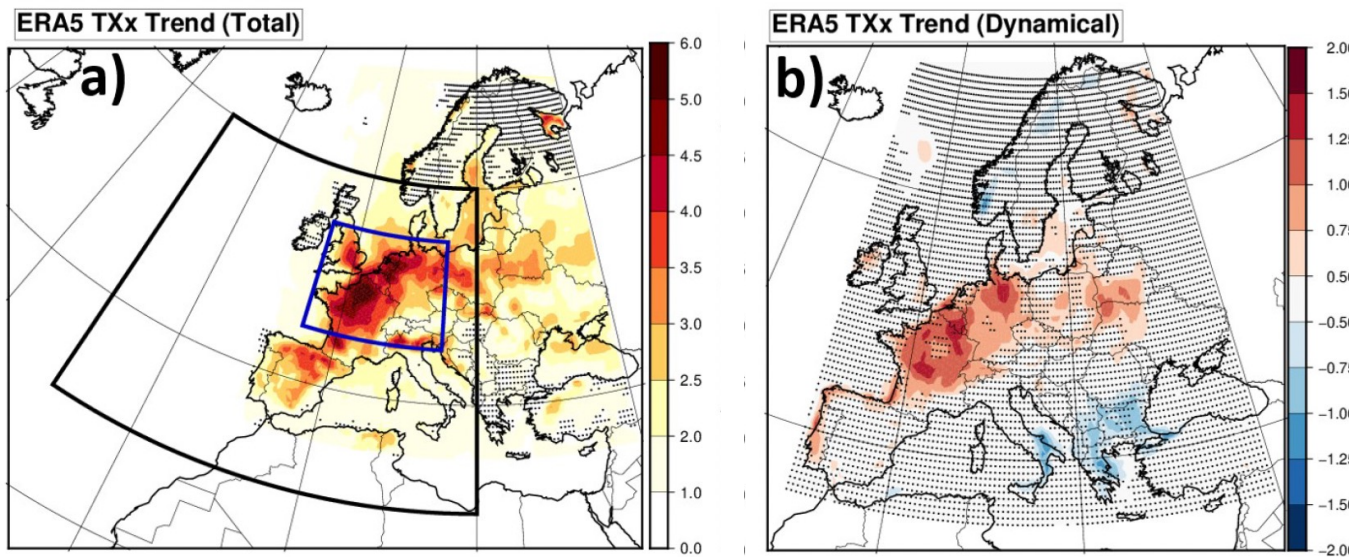
Conditional information



- 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 have a huge amount of such conditional information at the local scale, from both measurements and modelling**
- 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 (see discussion in Shepherd 2019 Proc. Roy. Soc. A)

Observed trends lying outside what models project

- In France, the summer maximum of daily maximum temperature has been increasing since 1950 **up to five times faster than the global mean temperature**
 - About 1/3 of this is due to **dynamical trends which are not present in any model**



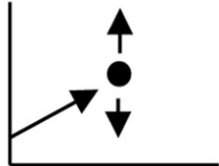

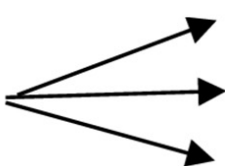

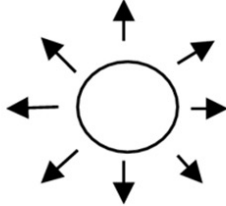
Units: °C per °C of global mean warming

Vautard et al. (2023 Nature Comm.)

- Maybe the models underestimate variability and the observed dynamical trend will reverse
- Or maybe the dynamical trend is forced and the models are missing it
- **Both represent plausible causal explanations**

Levels of uncertainty

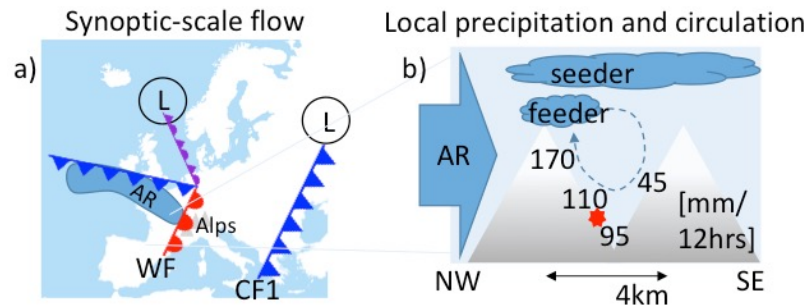
- Scientists are pressured to issue **'single, definitive' statements** (Stirling 2010 Nature)
- Works well for thermodynamic aspects of climate change, but for dynamical aspects this can lead to reliable but rather uninformative statements, e.g.
 - “...there is low confidence in projected changes in the North Atlantic storm tracks” (IPCC AR6 WGI SPM 2021)
- We need a language for expressing a **'plural, conditional' state of knowledge**

	Level 1	Level 2	Level 3	Level 4	Level 5	
Complete Certainty	A clear enough future	Alternative futures with probabilities	Alternative futures with ranking	A multiplicity of plausible futures	An unknown future	Total Ignorance
						

Adapted from Marchau et al. (2019)

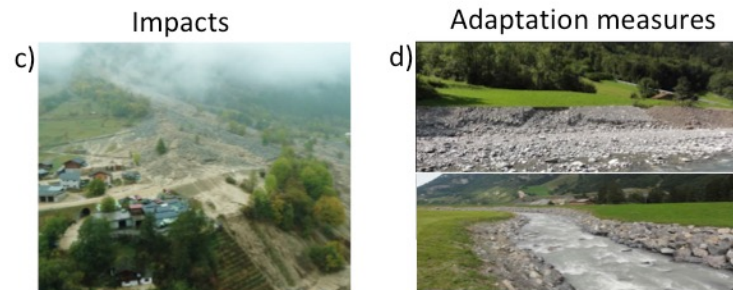
- **Storylines:** physically-based unfoldings of past climate or weather events, or of plausible future events or pathways (Shepherd et al. 2018 Climatic Change)
 - Definition now incorporated in IPCC Glossary (see also Box 10.2 of AR6 WGI report)
 - An **unforecasted rain-on-snow event in the Swiss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

Providing a physical basis for partitioning uncertainty



Exploring the boundaries of plausibility

Improving risk awareness



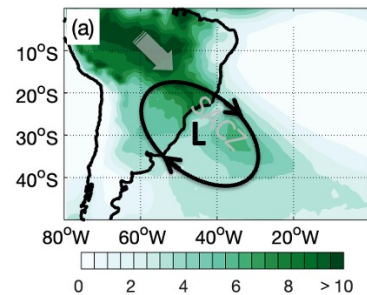
Strengthening decision-making

Shepherd et al. (2018 Climatic Change)

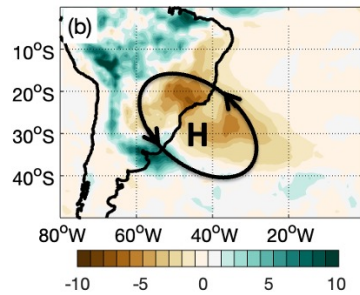
Example: a compound extreme event in southeast Brazil

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

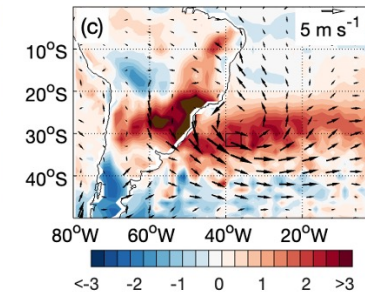
Climatological precipitation



Precipitation anomaly

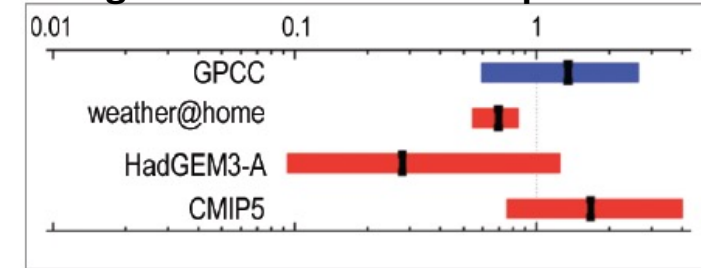


Temperature and wind anomaly

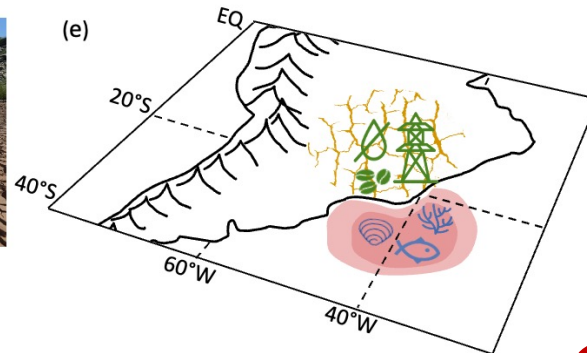


- A probabilistic attribution study of the event found “insufficient evidence” that climate change increased drought risk

Drought risk ratio relative to pre-industrial



Martins et al. (2017 BAMS)

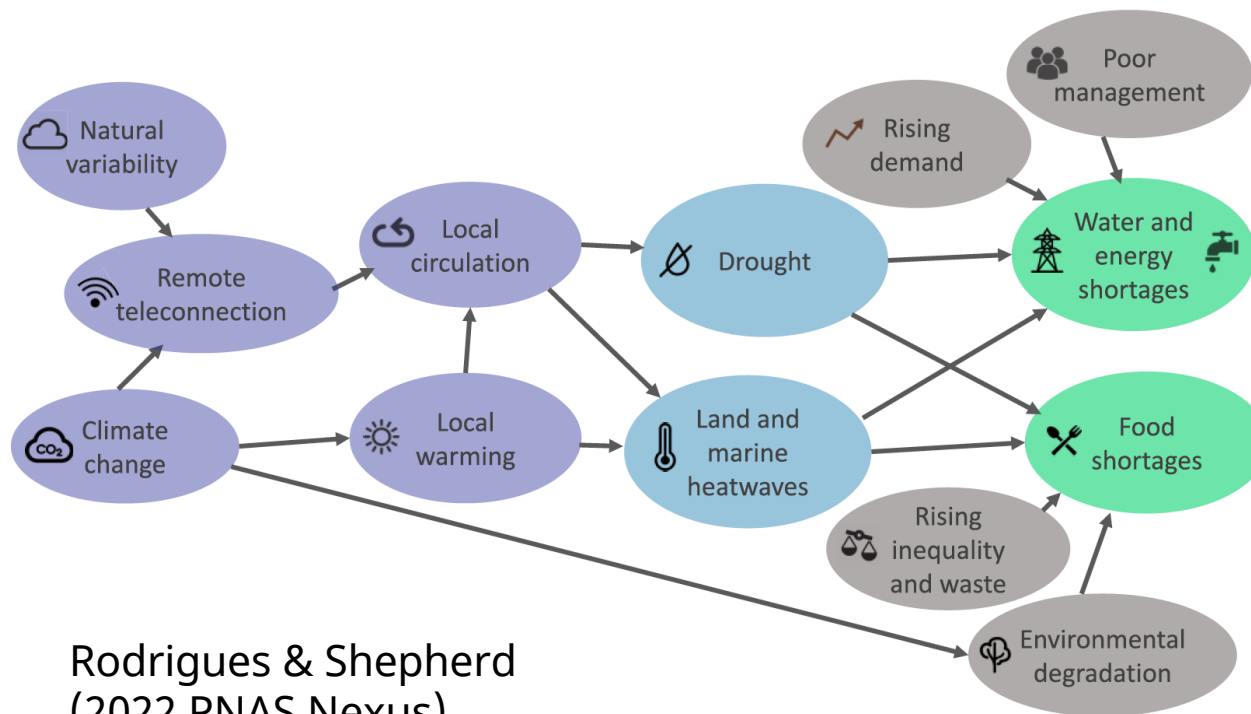


Rodrigues & Shepherd (2022 PNAS Nexus)

We can ask: insufficient for whom?

Storylines and causal networks

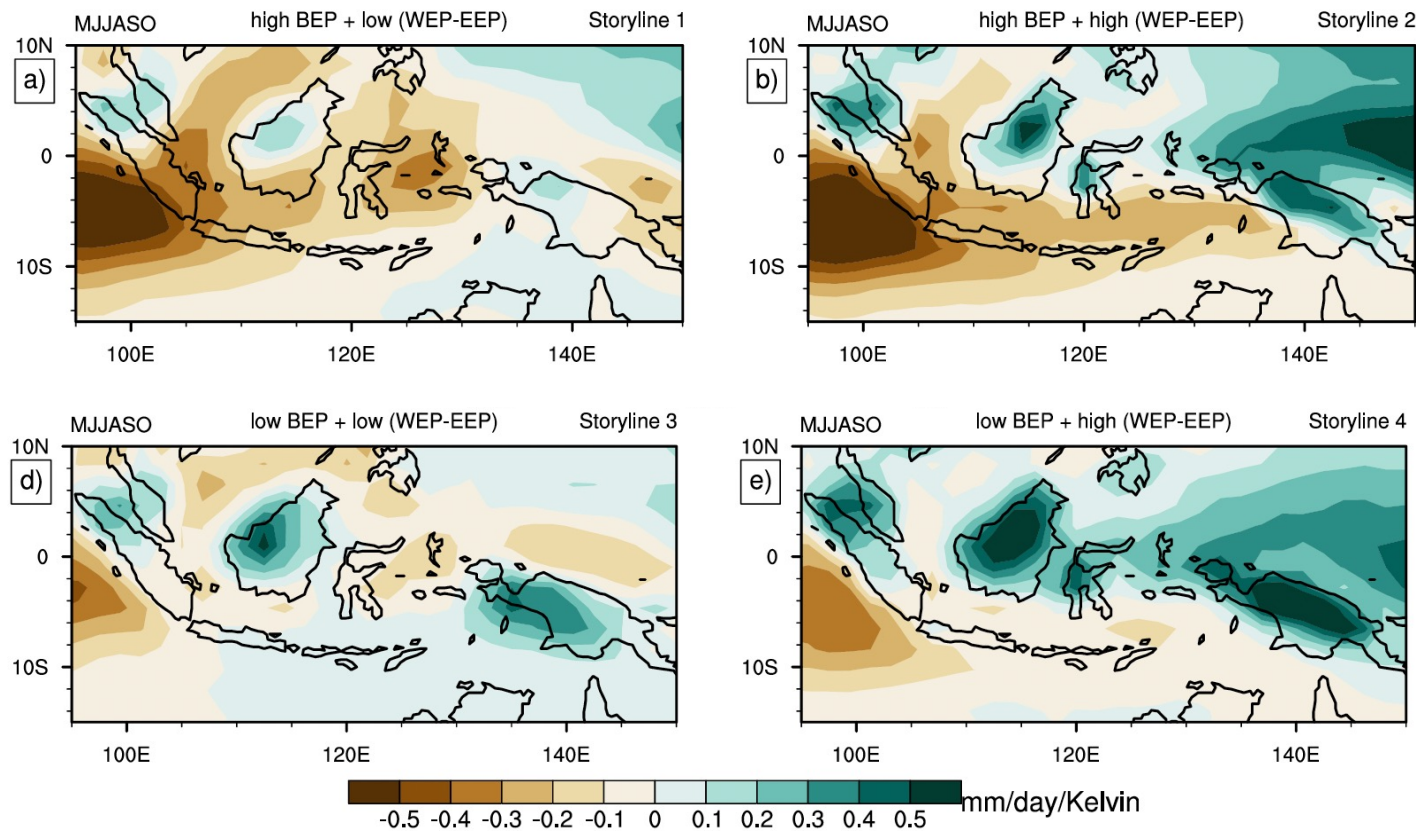
- Storylines represent the uncertainty space **discretely**, and can represent **correlated aspects of climate risk**



Rodrigues & Shepherd
(2022 PNAS Nexus)

- A key uncertainty is whether **observed trends in remote drivers of regional change** are forced or represent low-frequency variability
- The causal networks can be readily extended into the **human domain** where they can represent **intervention/decision points**, which are important for adaptation

Example: CMIP6 storylines of Maritime Continent precipitation changes (per degree of global warming)



So far as we know, any one of these could be true

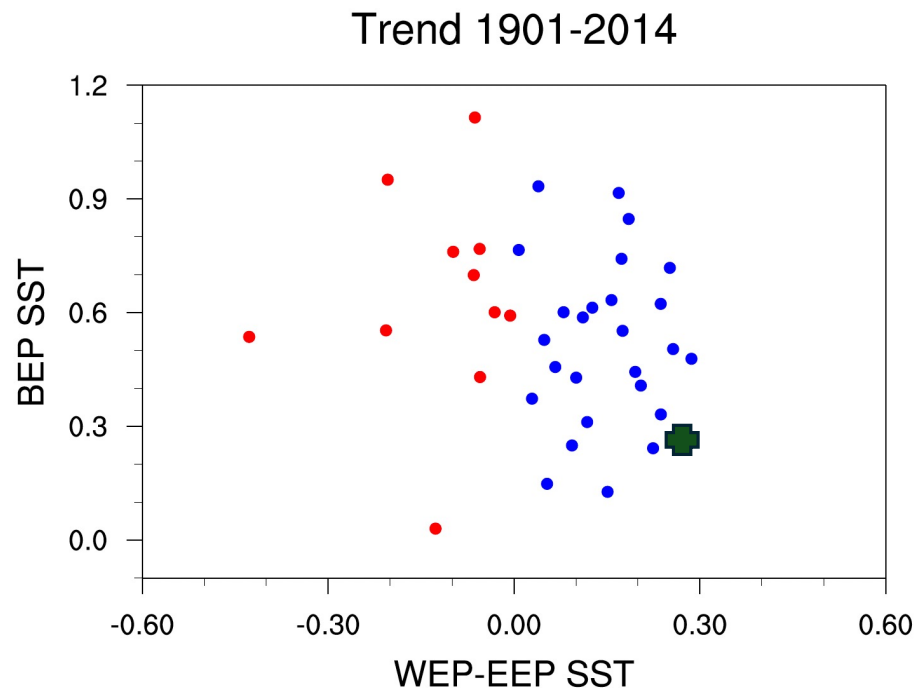
BEP = basin-wide equatorial Pacific SST
WEP-EEP = west minus east equatorial Pacific SST

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

Ghosh & Shepherd (2023 Env. Res. Lett.)

Observed trends in drivers of regional change

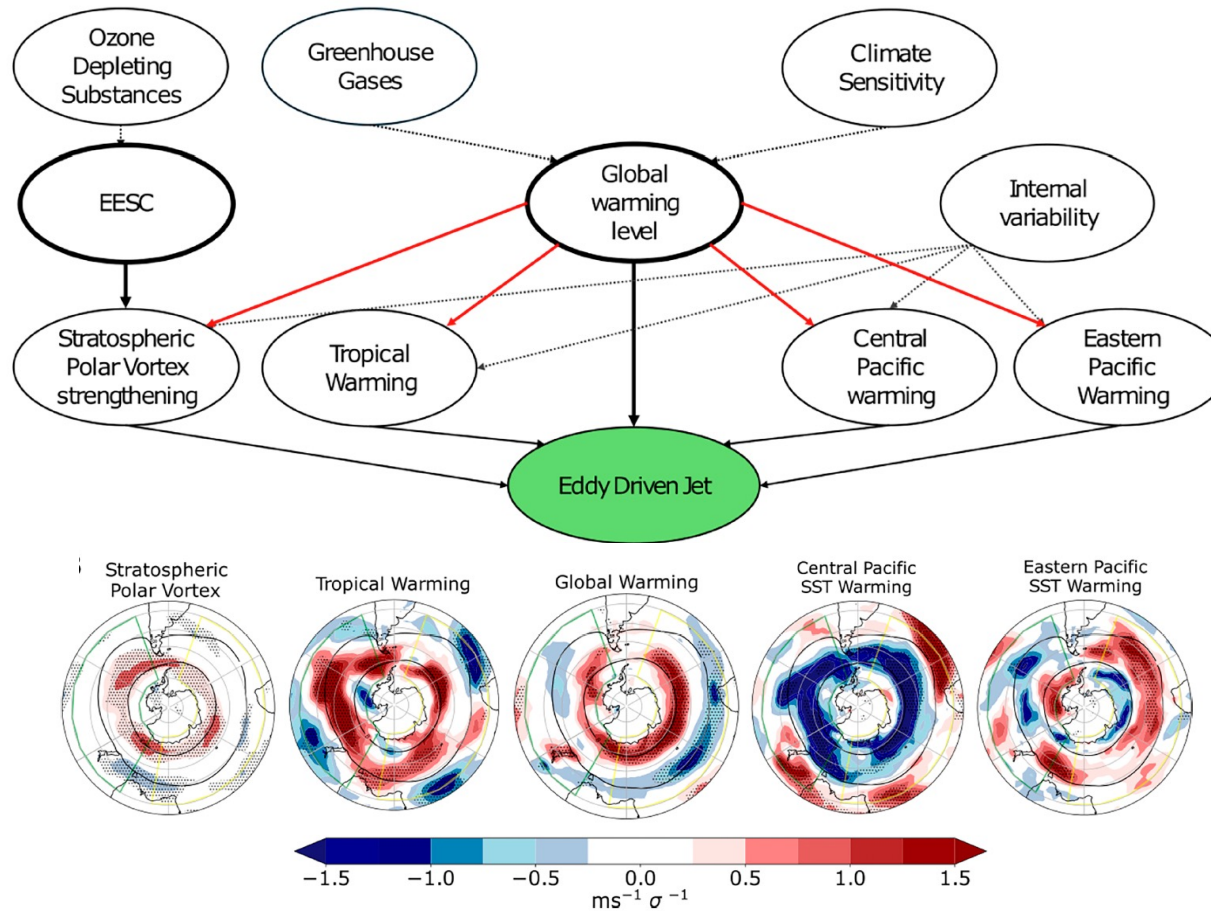
- The observed trend in the WEP-EEP SST driver lies right on the edge of the CMIP6 ensemble
 - What to do?



Ghosh & Shepherd (2023 Env. Res. Lett.)

- **There are many other such cases around the world** (see Shaw et al. 2024 Frontiers Clim.)
- We surely have to give some guidance in how to handle such cases

Observationally-based conditional attribution

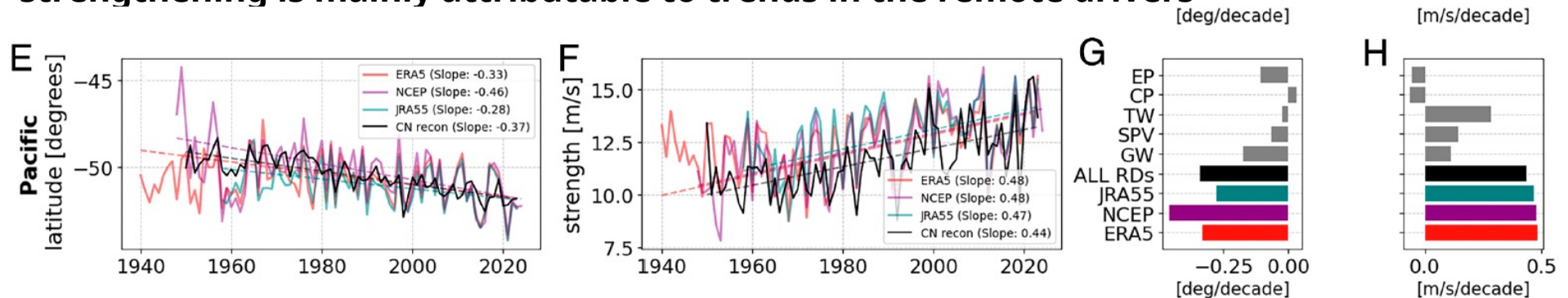


- One can construct dynamical storylines **from the observed variability**
- Here for the **variability and trends in the SH summertime eddy-driven (midlatitude) jet**
- Long-term trends in the EDJ can be attributed to forcings (EESC and GW) as well as to trends in the remote drivers, **whose own forced response is left open** (conditional attribution)
- The jet response patterns are quite distinct (lower panels)

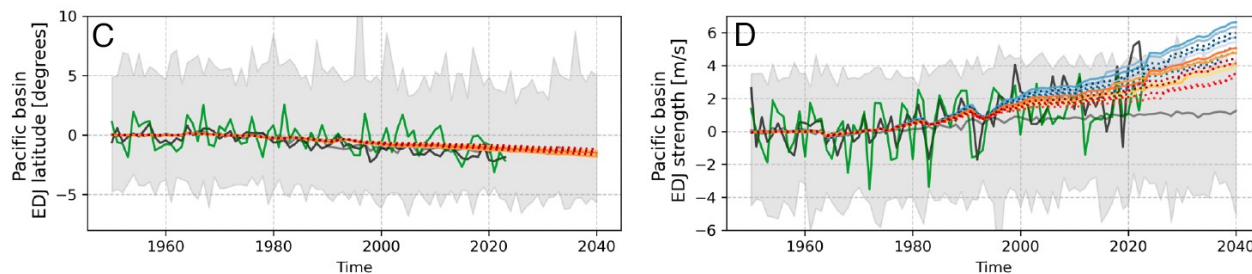
Mindlin et al. (2025 PNAS)

From attribution to prediction (case of Pacific jet)

- The variability and long-term trends are well explained by this simple causal model
- The poleward jet shift is mostly directly attributable to global warming, but **the jet strengthening is mainly attributable to trends in the remote drivers**



- For the near term, we can construct storylines based on a continuation of the remote driver trends, which yields **predictions outside of what the CMIP6 models project**

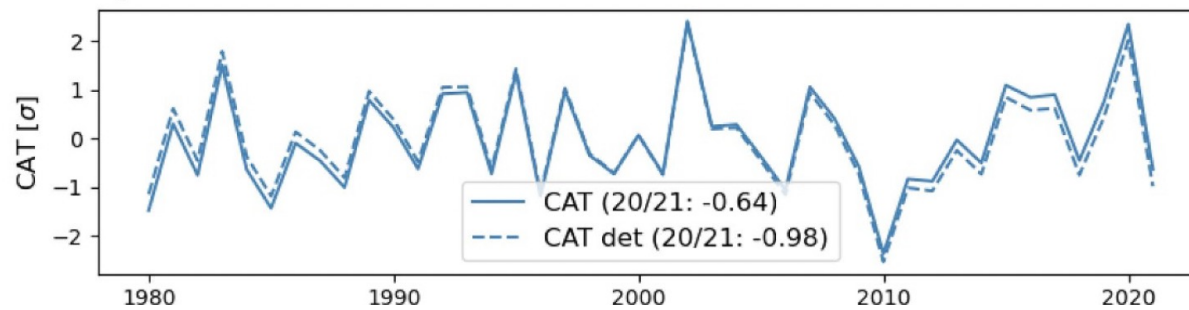


Mindlin et al. (2025 PNAS)

Example: Arctic sea-ice loss and Eurasian cold extremes

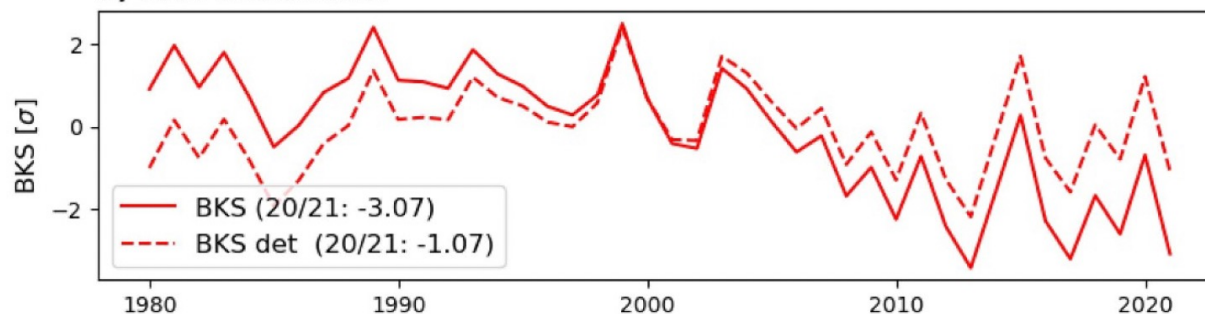
- Here, an observationally-based causal network is used to attribute Central Asia wintertime temperature (CAT) variability and trends to autumn Barents-Kara sea-ice extent (BKS)

e) CAT Timeseries



(The σ is computed from the detrended data; for CAT it is 2°C)

a) BKS Timeseries



Cosford et al. (2025 Env. Res. Lett.)

- The -3.1σ BKS anomaly implies a -0.8σ CAT anomaly, which can fully explain the observed CAT anomaly
 - But is this the right question?
- An alternative formulation: **BKS decline has more than halved the expected warming from climate change**
- Rather than debating a wintertime cooling trend in CAT, we suggest focus should shift to how Arctic Amplification impacts expected warming trends

Concluding remarks



- To address adaptation challenges, we need to navigate the '**cascade of uncertainty**' in climate predictions and 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 a situation of uncertainty?"
- 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**
 - By distinguishing between the thermodynamic and dynamic aspects of climate change, the **storyline approach** to regional climate information does exactly this
- Different framings of the attribution question (specifically, whether or not internal properties of the climate system — 'external drivers', in IPCC lingo — are included) lead to **very different possible and responsive answers** (Lloyd & Shepherd 2023 ERCL)
- 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**
 - This may mean **starting from observations rather than from CMIP models!**