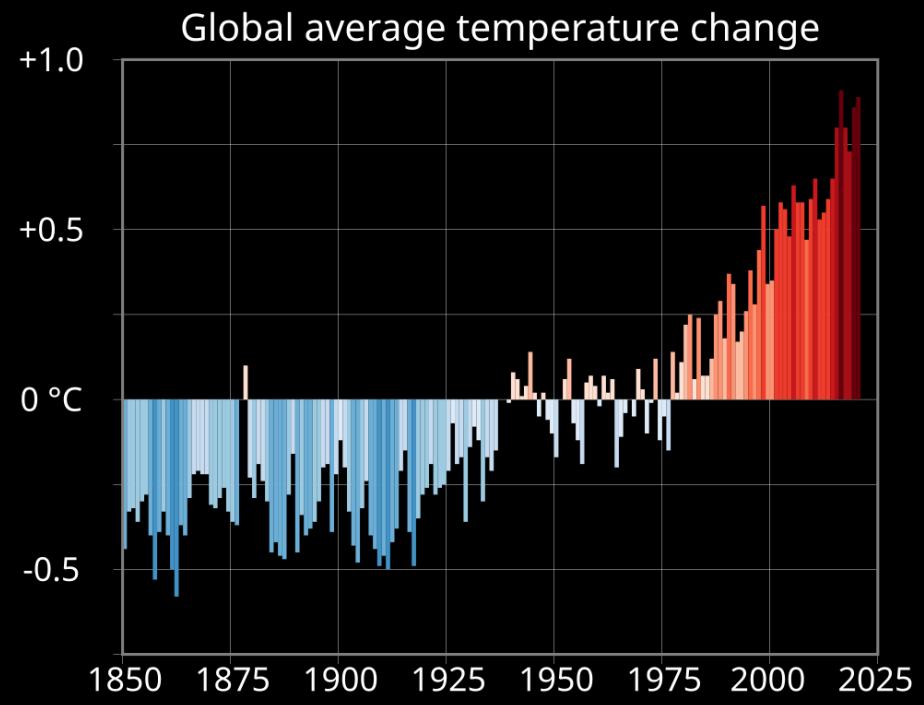
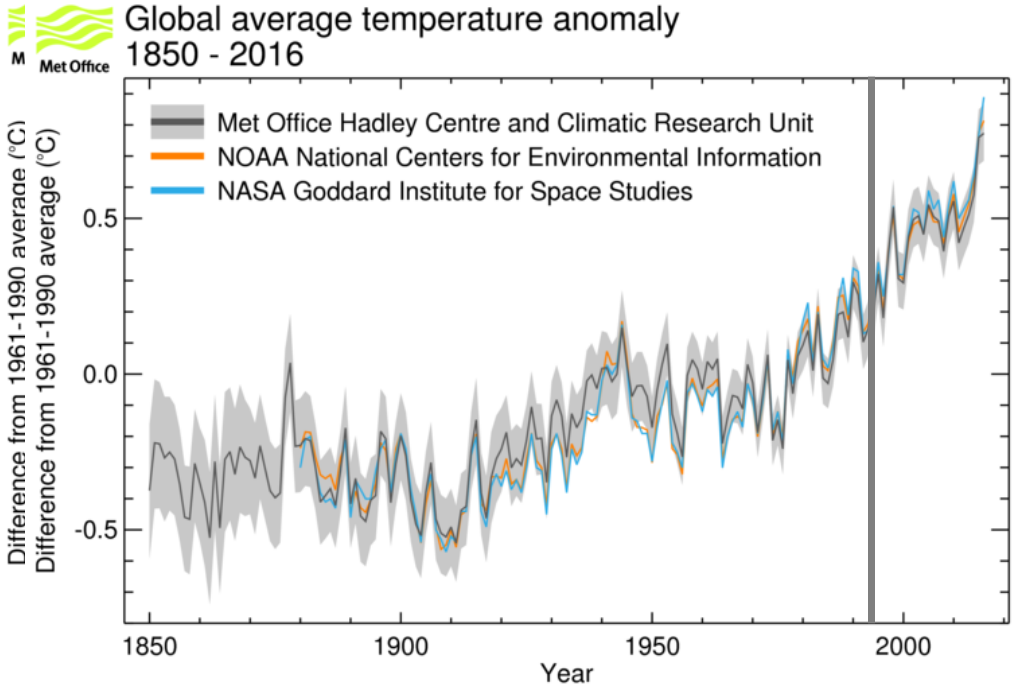


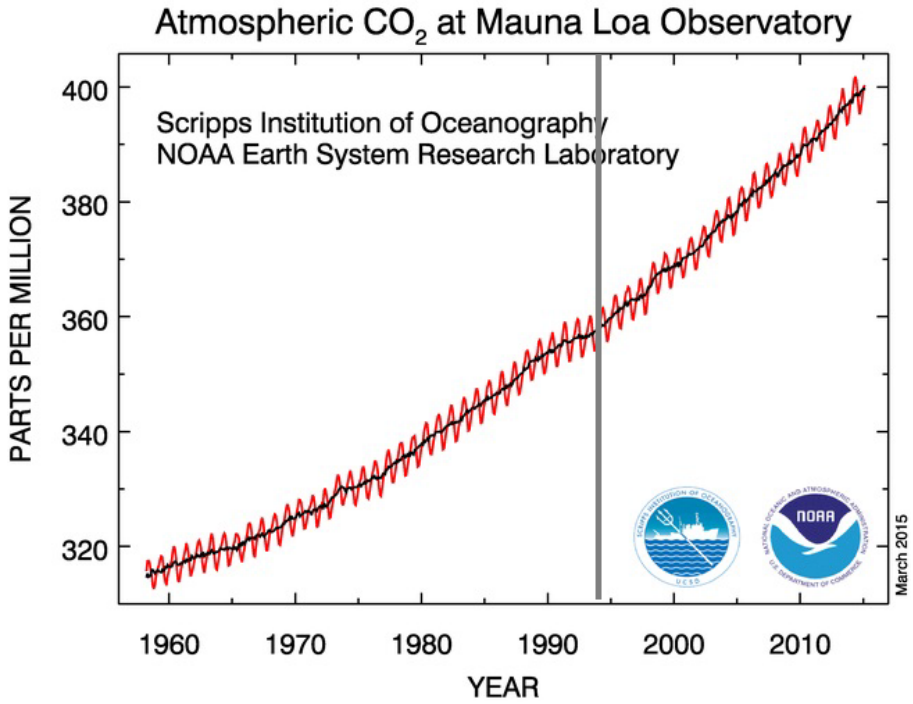
Fingerprints of climate change: From fingerprints in climate change to safe landing climates

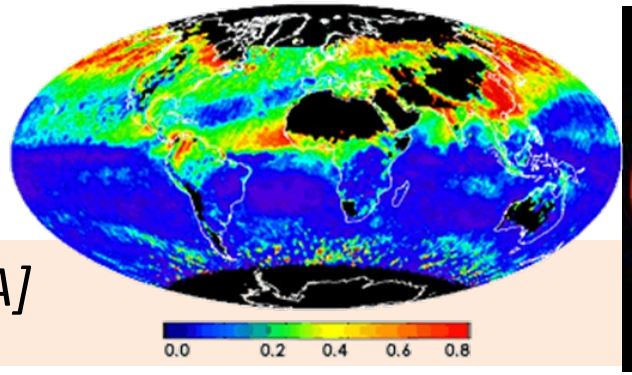
Gabriele Hegerl, University of Edinburgh

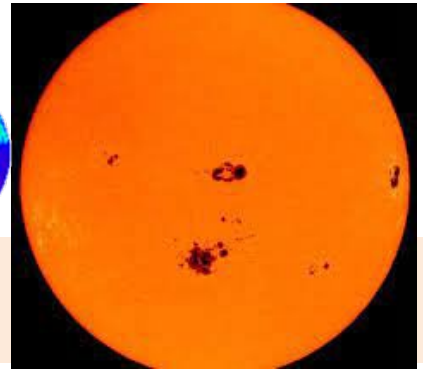
With thanks to: Andrew Schurer, Andrew Ballinger, Nico Freychet

Are increasing greenhouse gases warming the planet







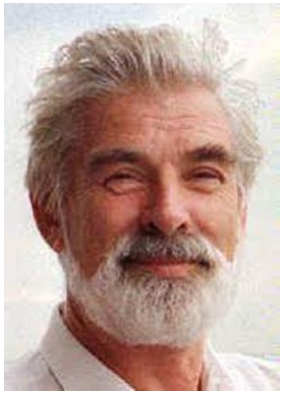


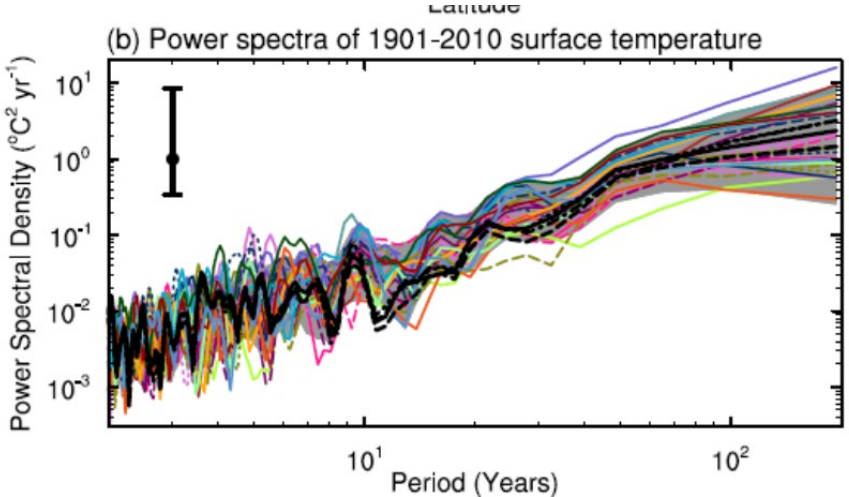
[*Figures: UK Met Office* and *US NOAA]*

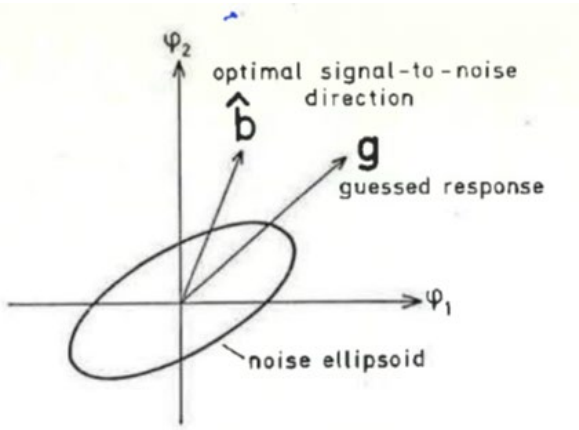
Detection of a signal in climate noise

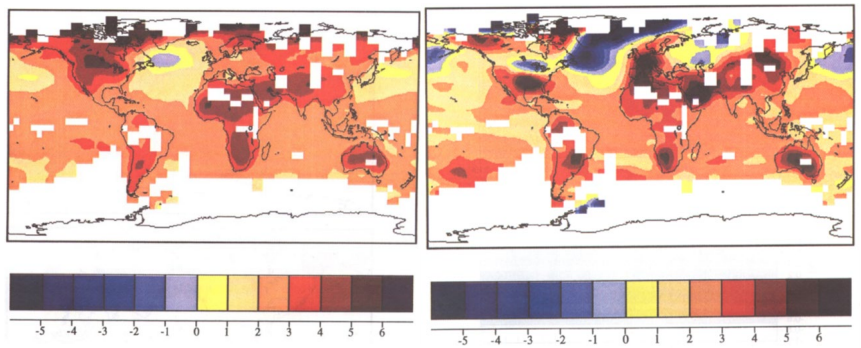
- Hasselmann 1976: Stochastic climate models (tellus 1976): Slow climate components integrate weather variability (red noise)

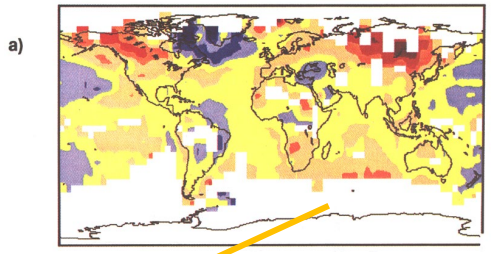
  Weather=> ocean=> ice sheets
- Response to greenhouse gas increases hidden in noise and needs a sophisticated detection technique (1979)
- Use shape of the expected change in time and space (eg from models)
- Estimate magnitude from data (this corrects if sensitivity of climate is incorrect)







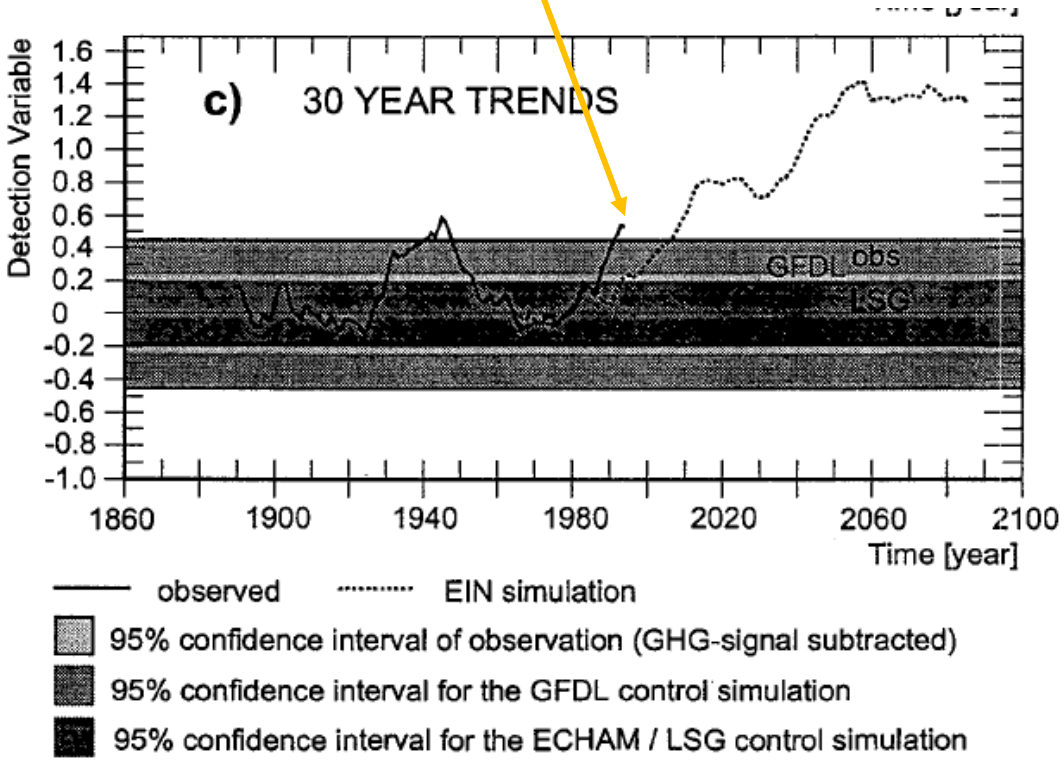




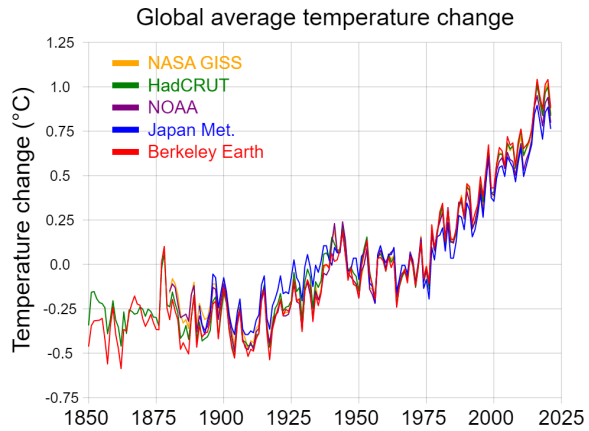
Early Examples

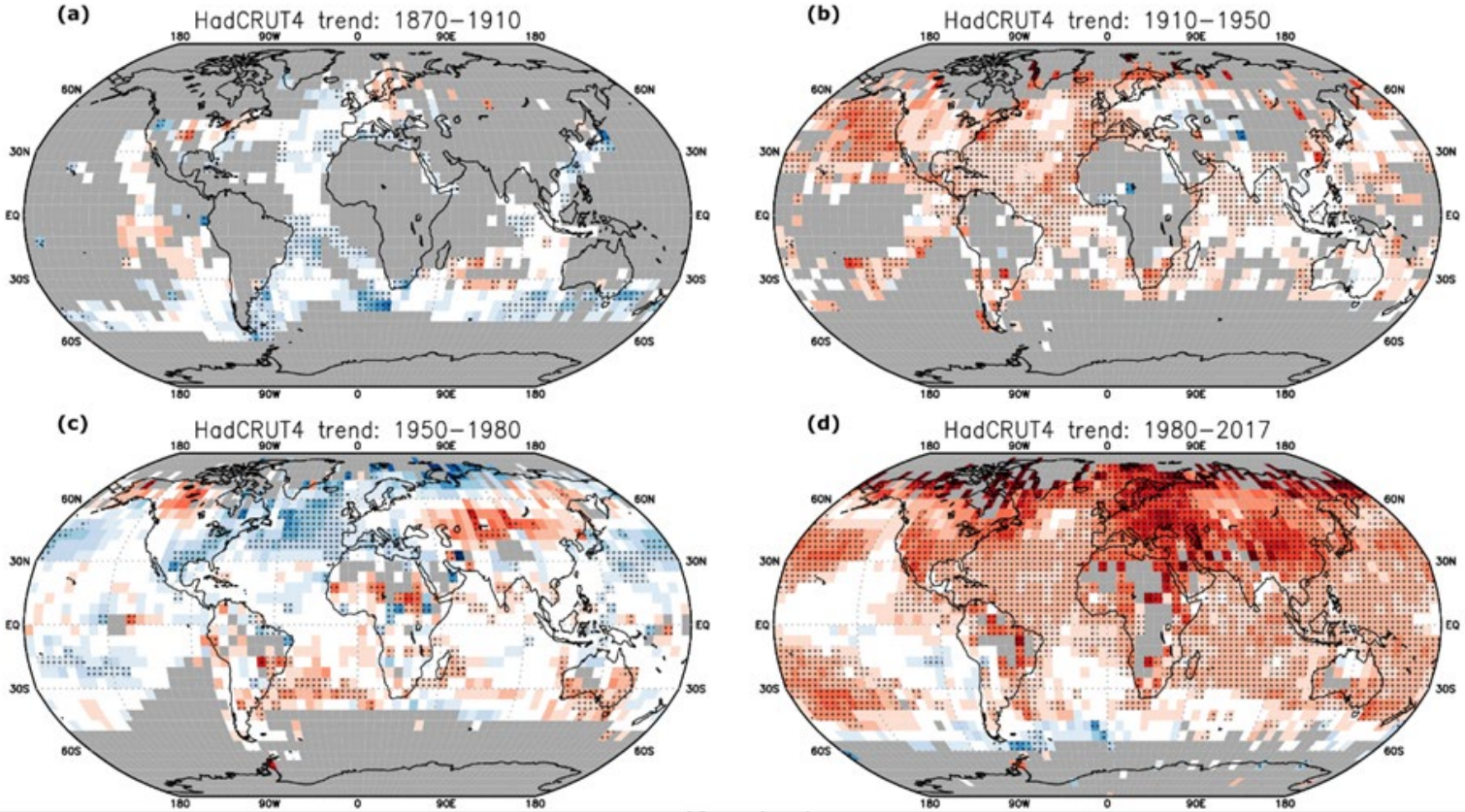
vectorproduct

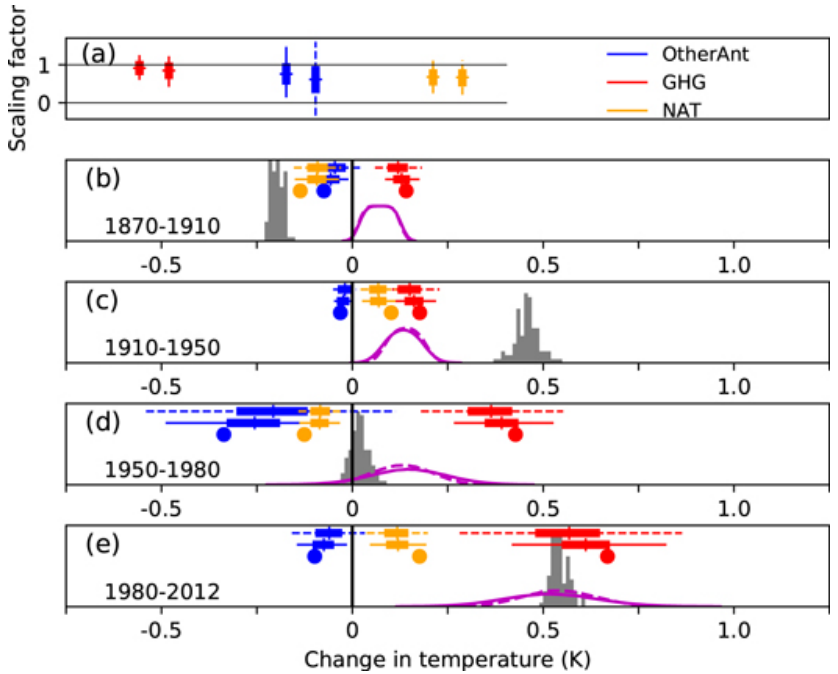
- pattern of observed warming emerges from 95% envelope of climate variability in trends 1965-94 (J Climate 1996)
- 2 years later: Pattern indicates that greenhouse gases and aerosols play a role in observed warming; solar variability cannot explain it



Causes of long-term climate change



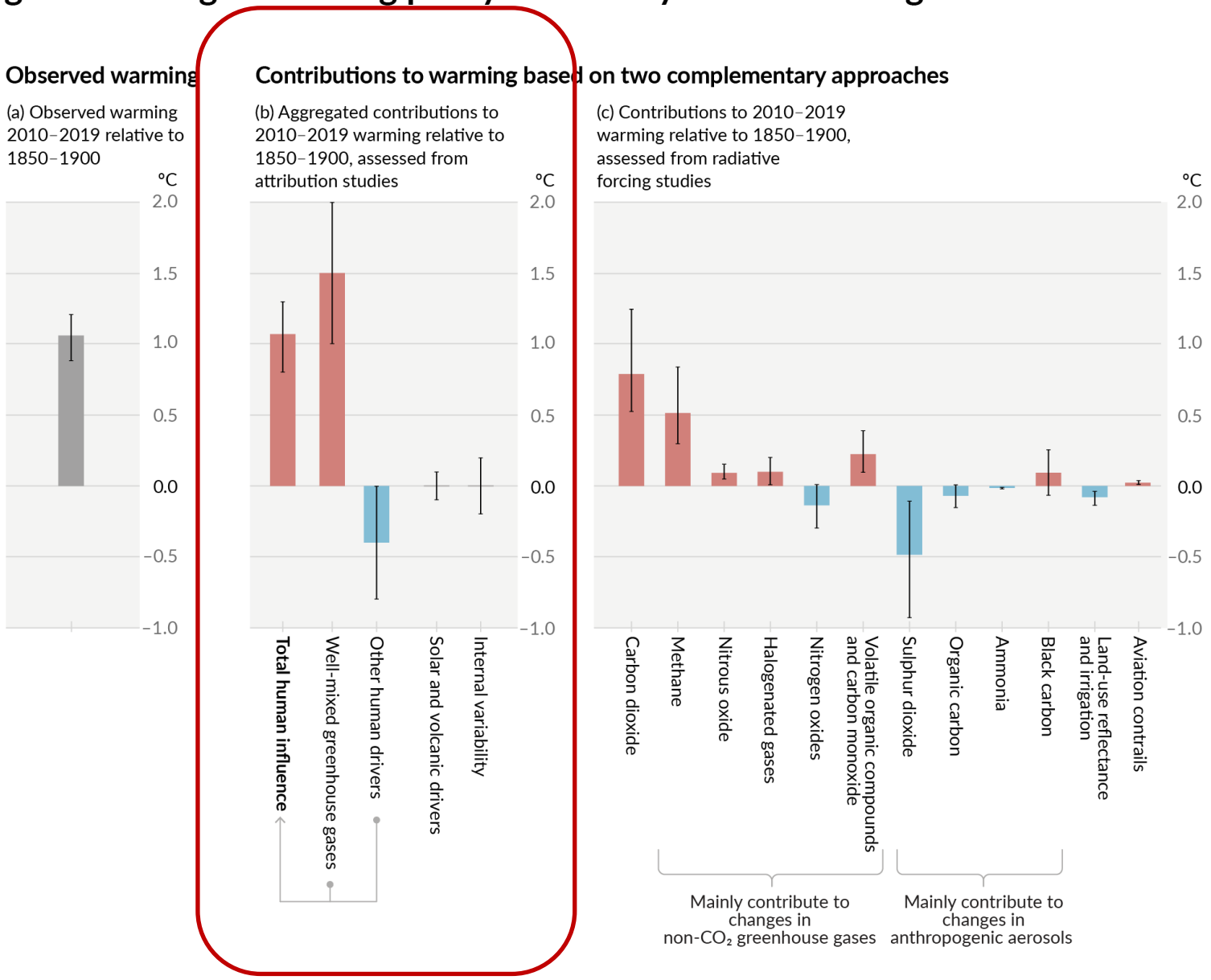




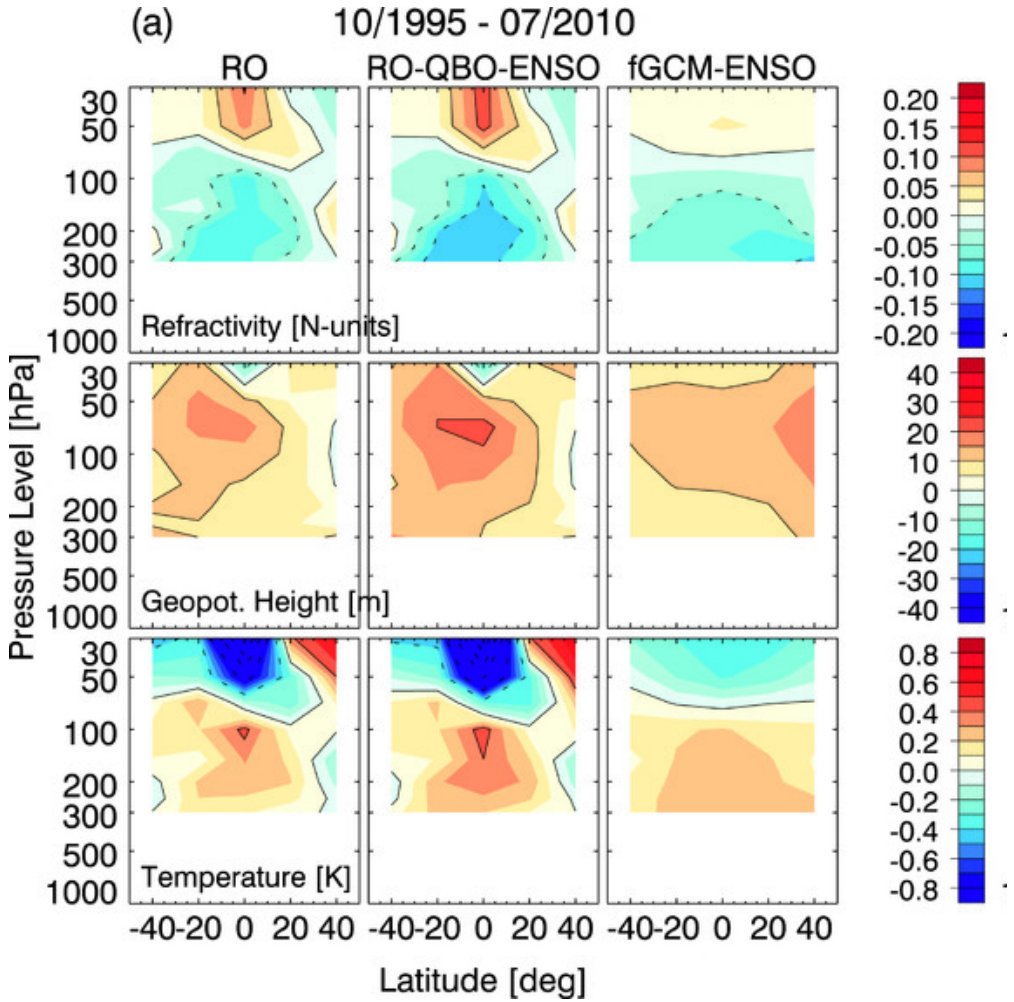
(Friedman; in Hegerl et al ERL 2019; WIRES 2018)

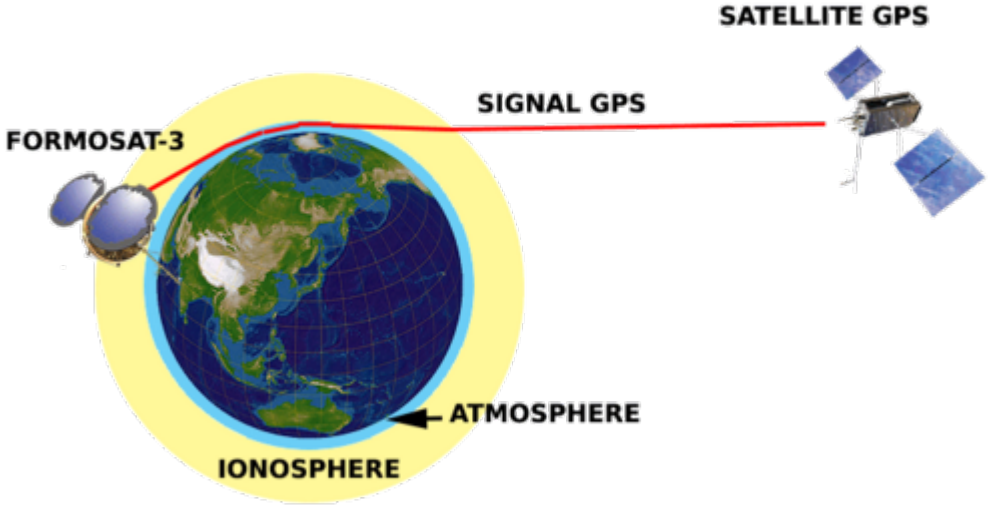
IPCC

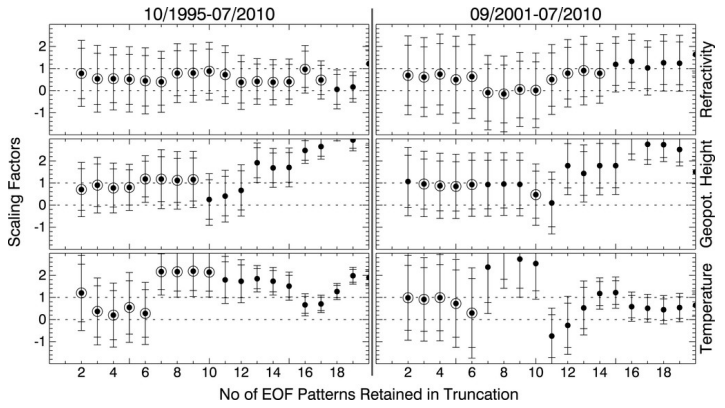
Assessment of attribution studies compared to process based estimates



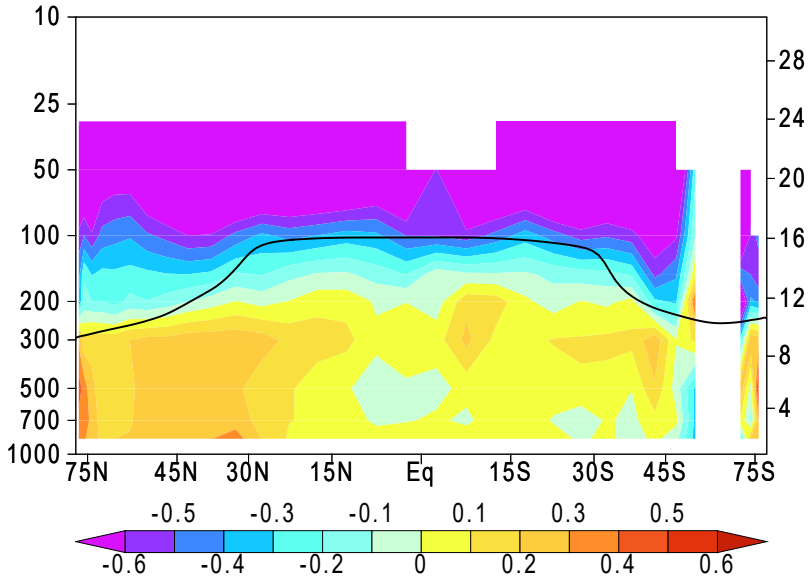
A detectable fingerprint in vertical temperature





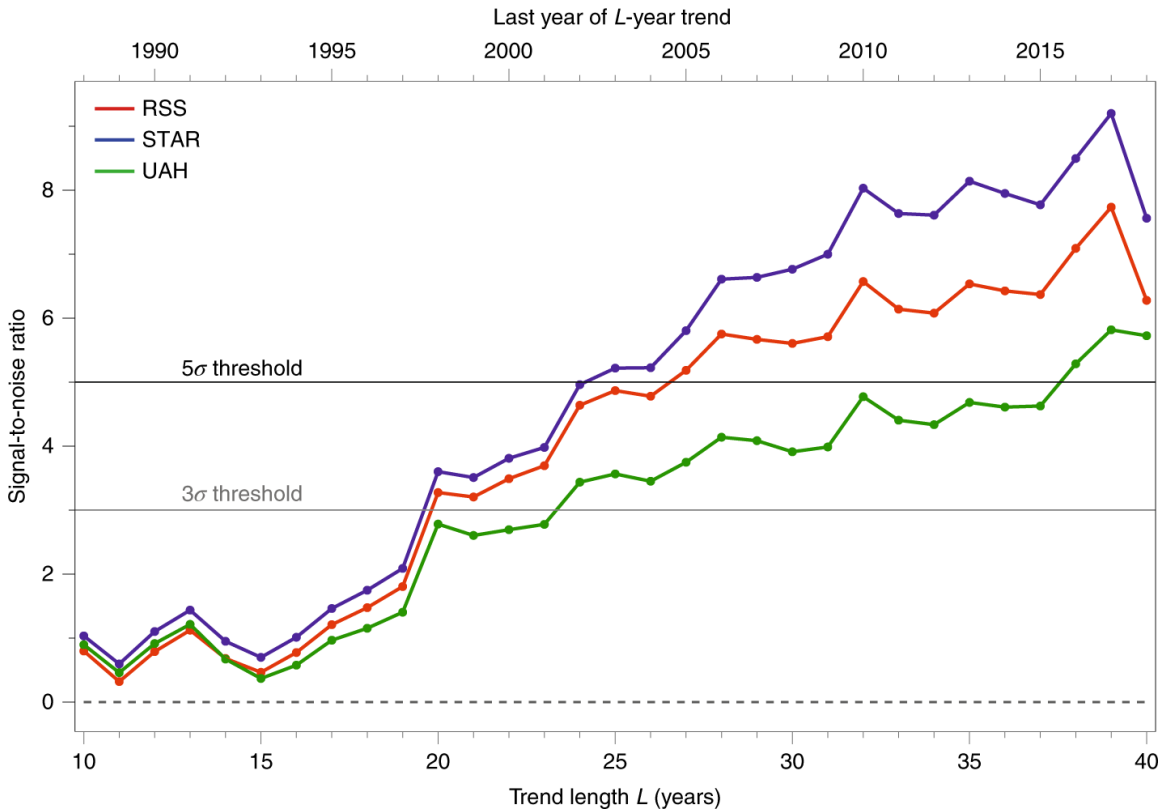


Lackner et al., 2011, J Climate



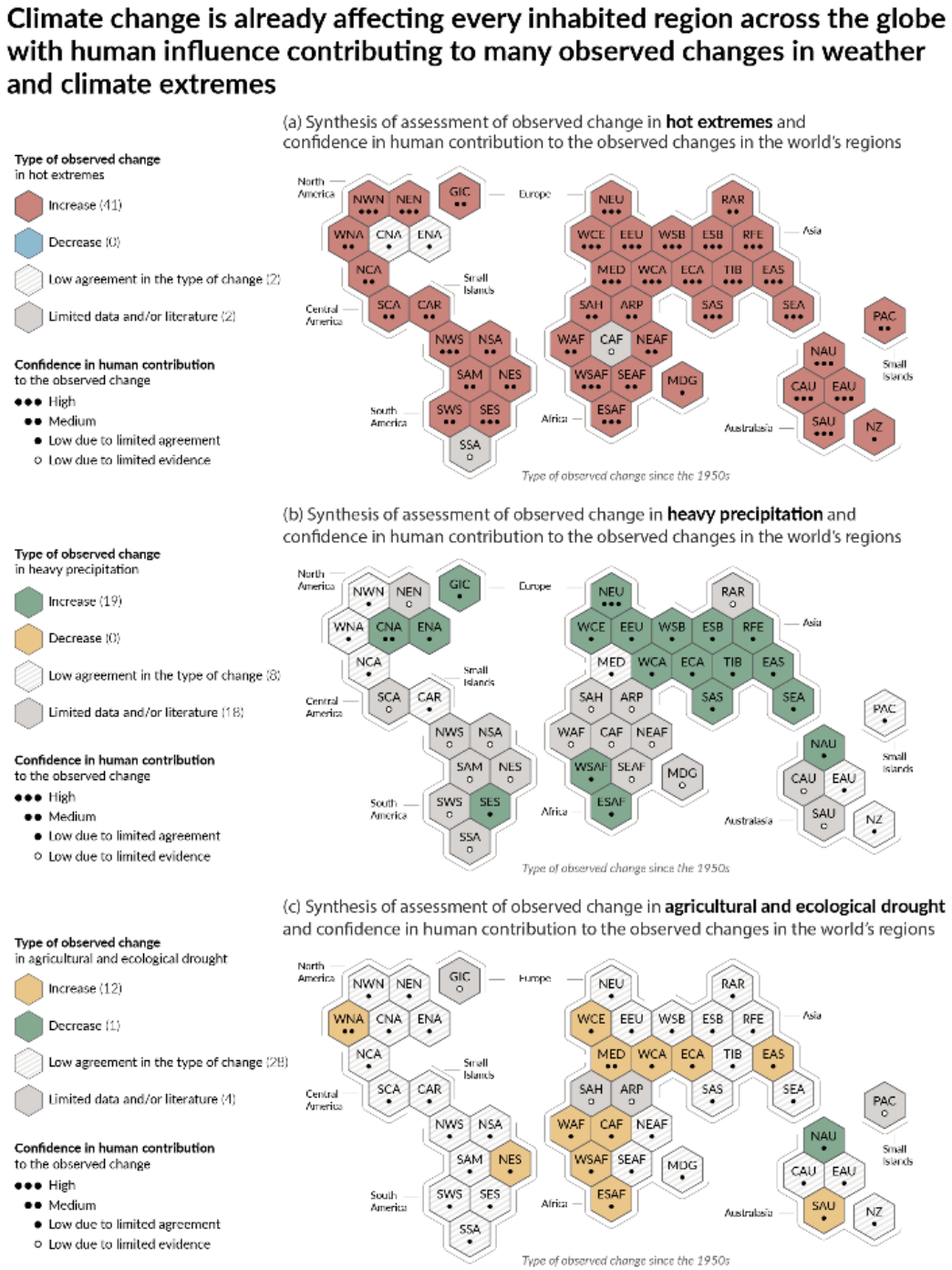
Observed trend, updated; from Santer, pers. com

Detection of fingerprint for tropospheric temperature



- Trend in measured tropospheric temperature/std dev of variability
- Multiple observed datasets to span uncertainty
- 5 sigma is higgs Boson detection standard
- Independent verification of trends and detection with RO data (e.g. Lackner et al 2011) – RO Data now long enough
- Santer er al., 2019

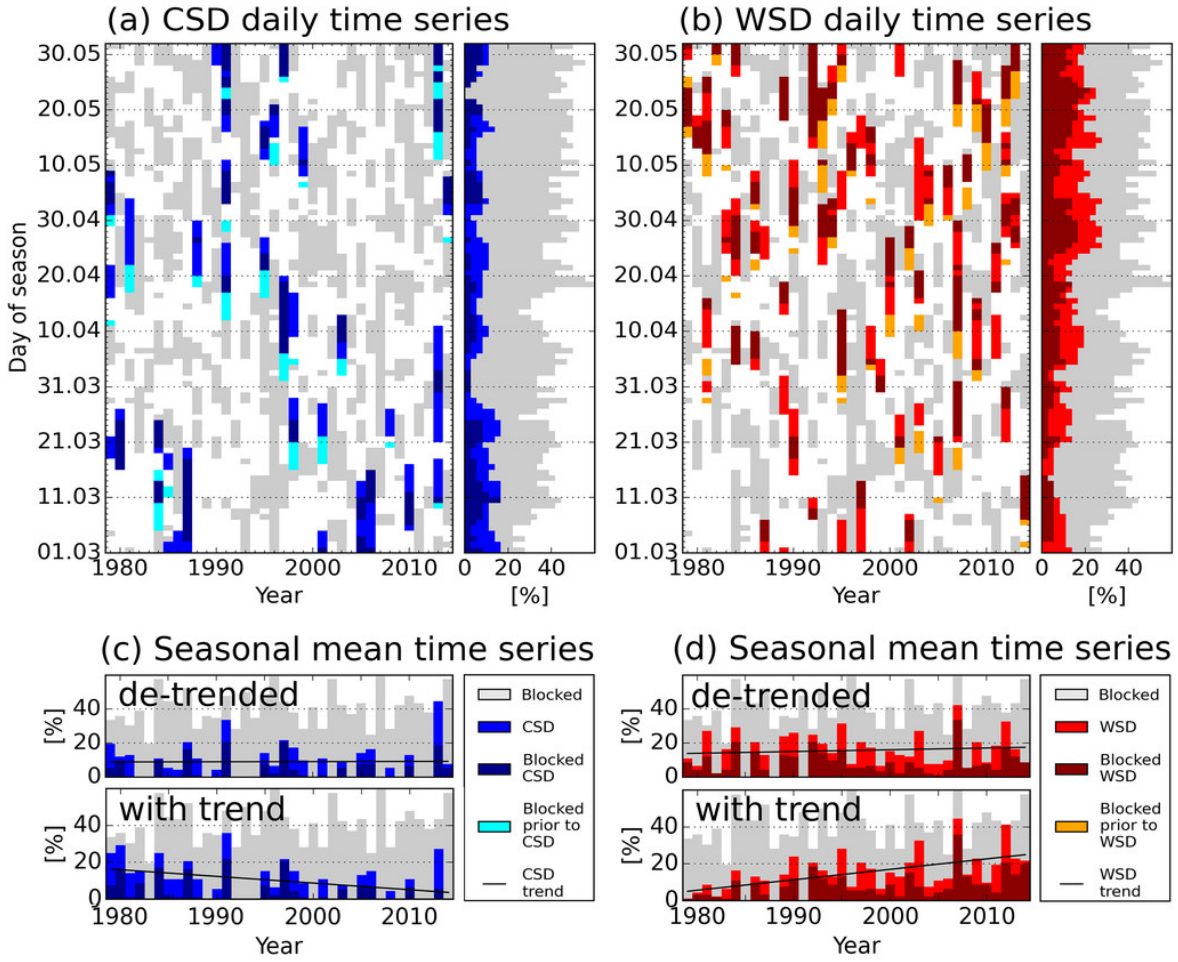
DW, Yale climate connections, WMO



Detectible and attributable change in extreme events – IPCC 2021

Gaps in data over Africa: Engdaw et al., 2023 filled extremes data over Africa with weather analyses

Do the reasons for warm and cold extremes change?



Extreme warm spells form all through spring when high pressure patterns are strong and stationary (blocking; dark red).

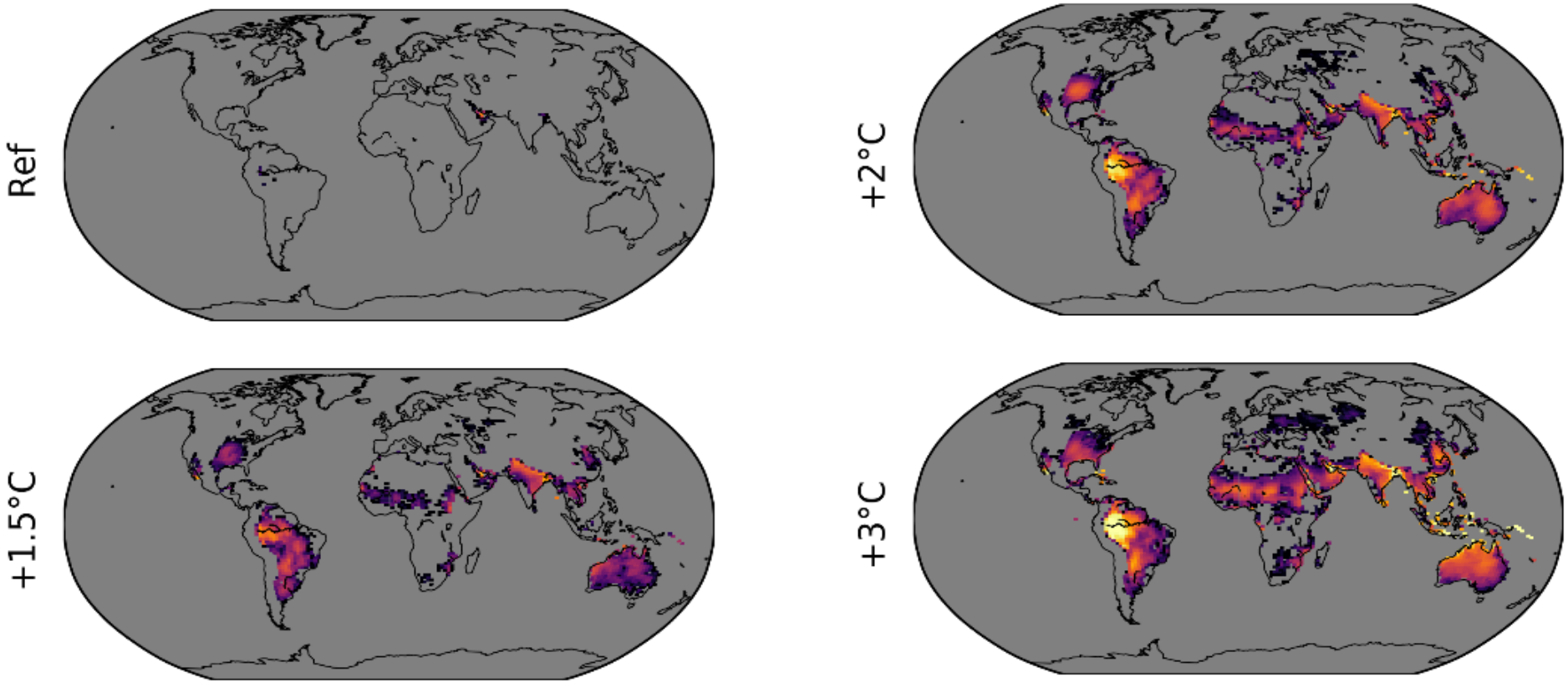
Blocking play a role in extremely cold days (dark blue) or preceed them them (light blue/orange)

Brunner shows that while there is no clear trend in spring blocking, warm spells associated with them get warmer

Brunner et al., J Climate, 2017

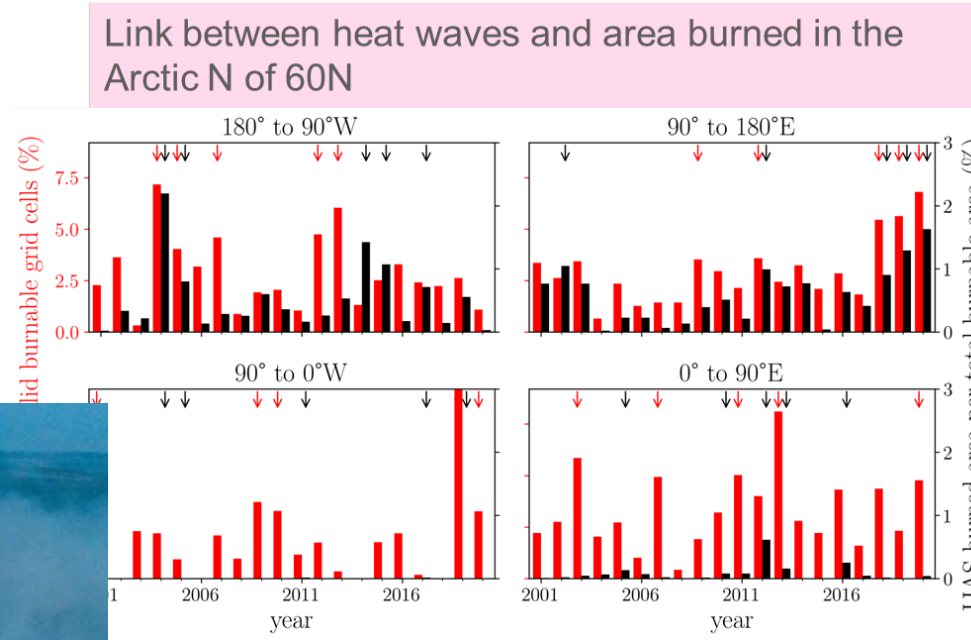
Extreme heat can be dangerous

- Here: Wetbulb temperature exceeding 31°C



Freychet et al., 2021

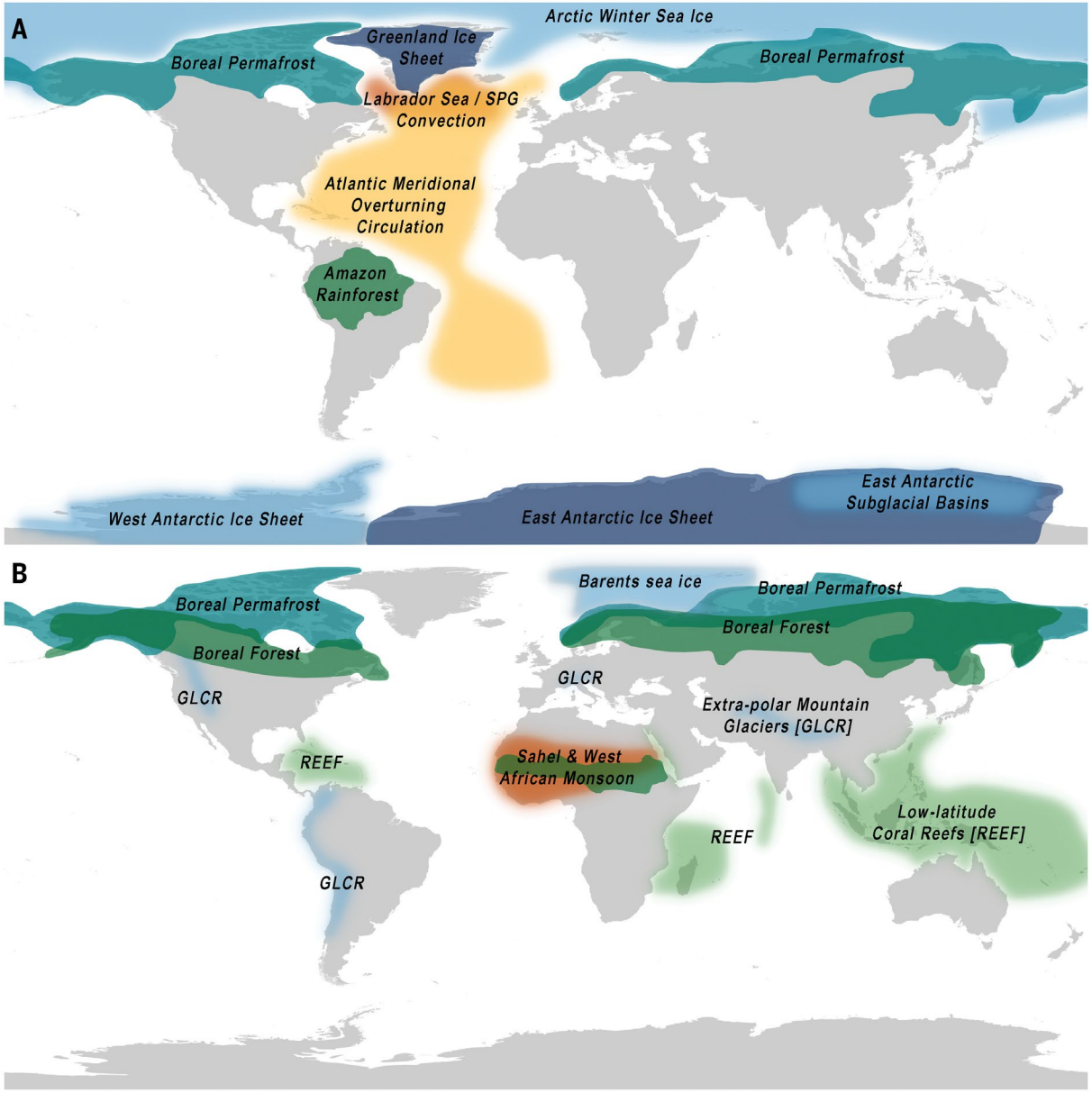
Extreme heat can cause fire – here in Arctic



- Spatial and temporal link
- On average fire follows ca week after peak heat, and also co-occur spatially

Hegedus et al., ERL, 2024

From barely detectable climate change to tipping points



Early on, climate change was a small quite linear signal in high variability.
Now the signal is large and nonlinear feedbacks are important

Tipping dynamics occurs when a system
- Changes rapidly and/or
- Changes self-amplify
- And are irreversible

(Kopp et al 2025; Winkelmann et al., 2025)

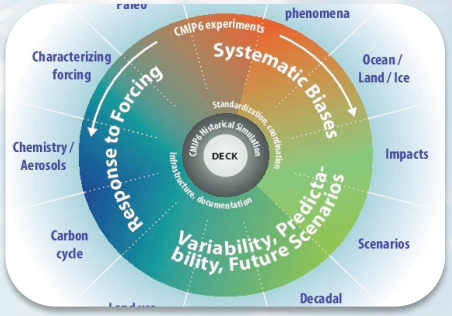
Processes uncertain but highlight risk

Armstrong McKay et al. 2022

WMO UNESCO INTERNATIONAL COUNCIL FOR SCIENCE WCRP World Climate Research Programme

Safe landing climates lighthouse

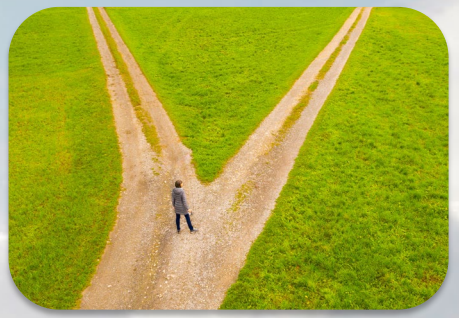
World Climate Research Programme activities



CMIP for climate risks

High-risk cascading shocks

Connecting across the IAM-GCM-impact hierarchy



Gaming and decision/scenario exploration

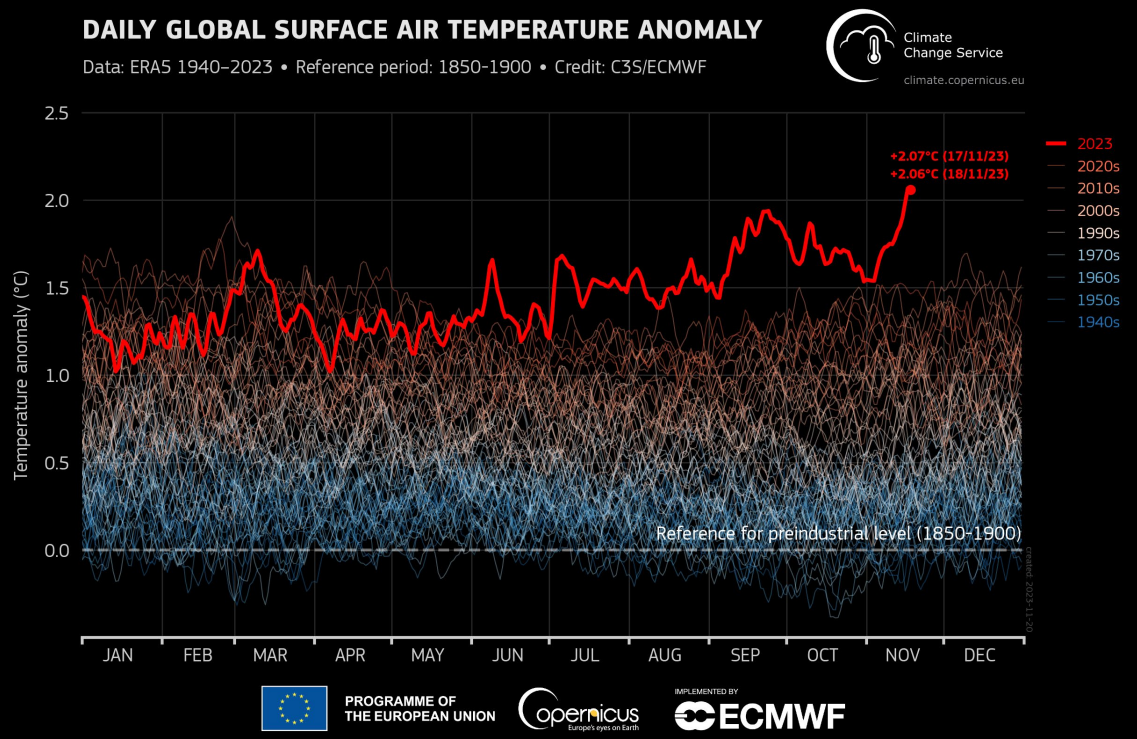
TCRE = Transient Climate Response to cumulative Emissions

TCRE assessment

Water variability impacts

Signposts for sea level rise

Conclusions



- IPCC: It is unequivocal that human influence has warmed the atmosphere, ocean and land.
- The large and continuing climate change can pose risks to the Earth system in ways that we still cannot fully predict.
- We need to find a safe trajectory to a mitigated climate – avoiding tipping points, or pathways to mitigation that create further risk
- The Wegener center has made important contributions and will continue to do so