Decadal climate variability, attribution and prediction

Rowan Sutton

Director of Climate Research

National Centre for Atmospheric Science

Department of Meteorology

University of Reading

The link between attribution and prediction

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

- The evolution of climate on timescales of years-to-decades is determined by:
  1. Natural internal variability
  2. Responses to changing natural (e.g. volcanic, solar) and anthropogenic (e.g. greenhouse gases, aerosols, land use) forcing factors

- **Decadal prediction** aims to capture the combination of internal variability and forced response that is relevant to the decade ahead.

- **Attribution** aims to determine the combination of internal variability and forced response that accounts for specific past events
  - This includes the extent to which such events were in principle predictable.

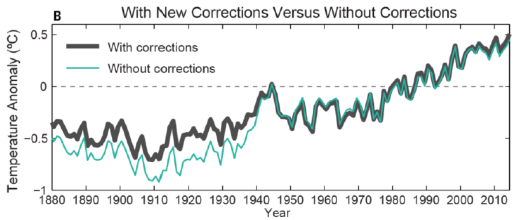
- **To have (any) confidence in decadal predictions we must demonstrate a capability to attribute past events to specific causes *robustly, at a process level*** (within the constraints of observational uncertainties).

University of Reading

Walker INSTITUTE

Attribution questions

- What processes were responsible for specific observed events?
  - proximal causes (e.g. storm track shifts, SST changes etc)
- To what extent do these processes and events reflect:
  1. Internal variability
  2. A response to changing forcings
  3. A linear or non-linear combination of 1 & 2
  4. Other factors (e.g. problems in instrumental record)



Karl et al, 2015

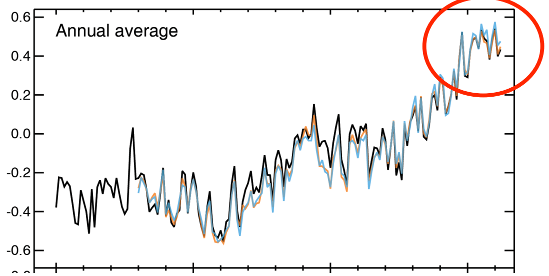
- To what extent were the events predictable?

  – Invites a focus on forecasting case studies.

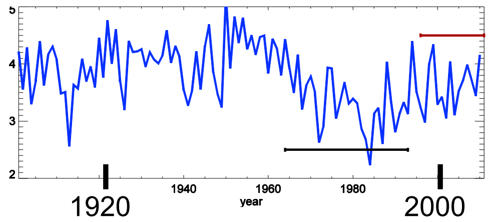
Some problems in decadal attribution and prediction

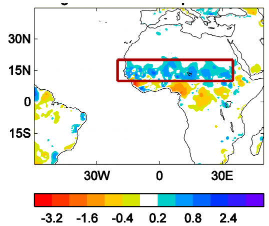
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Observed globally averaged combined land and ocean surface temperature anomaly1850–2012

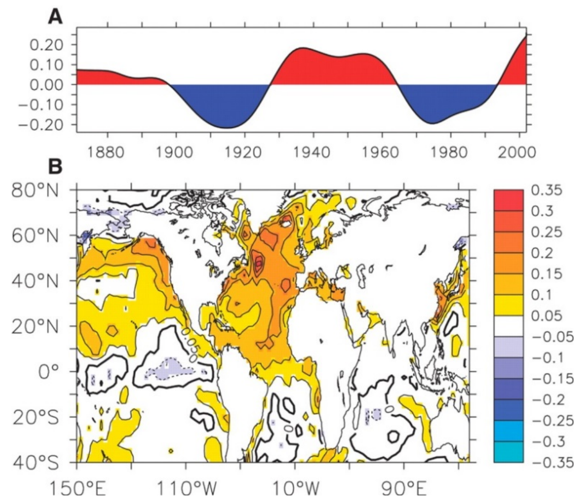


Sahel summer rainfall





AMV



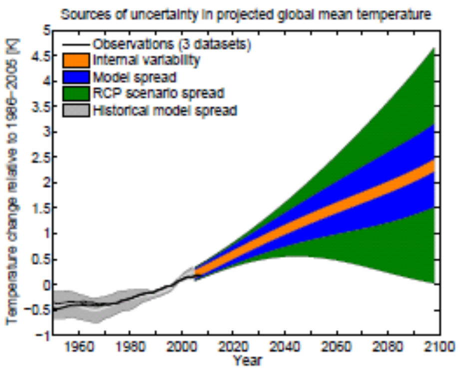
University of Reading

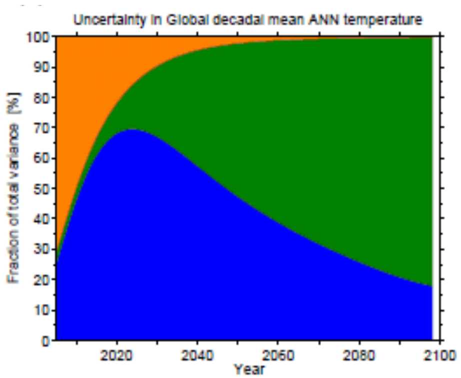
Walker INSTITUTE

Challenges for attribution and prediction

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

- Ignorance of internal variability
- Ignorance of forcing factors (aerosol & volcanoes important for decadal)
- Ignorance of the responses to forcings





Hawkins & Sutton, 2009; 2011 + AR5

1. Forcing
2. Response
3. Internal variability

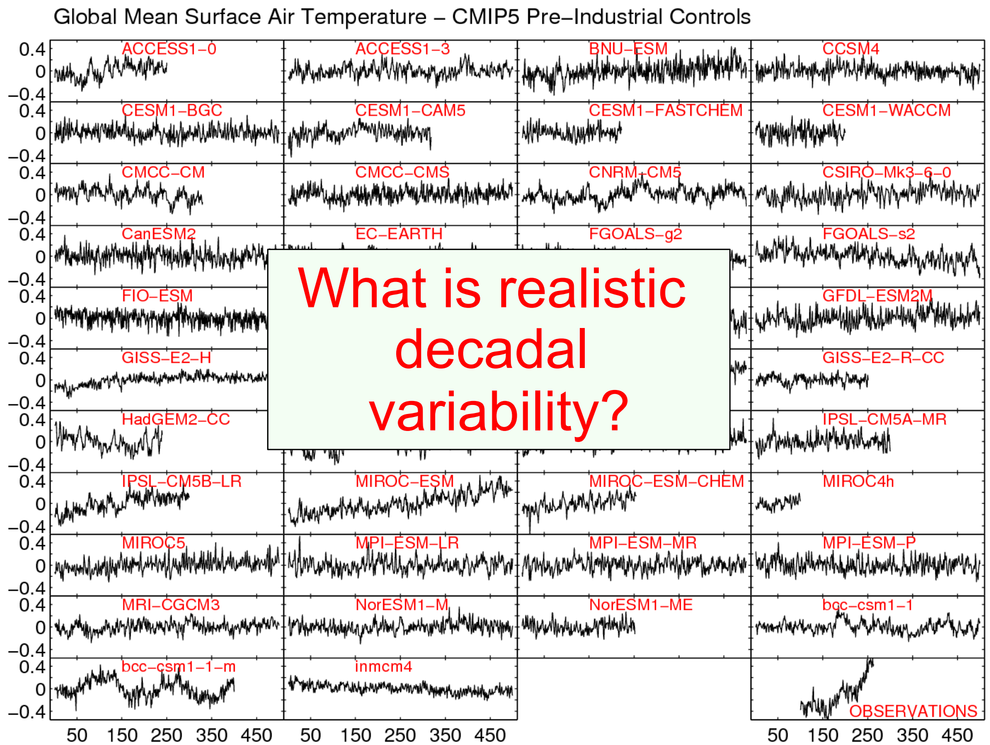
Internal variability increasingly important on smaller space and time scales

University of Reading

Walker INSTITUTE

Internal variability is not only large, it is also uncertain

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL



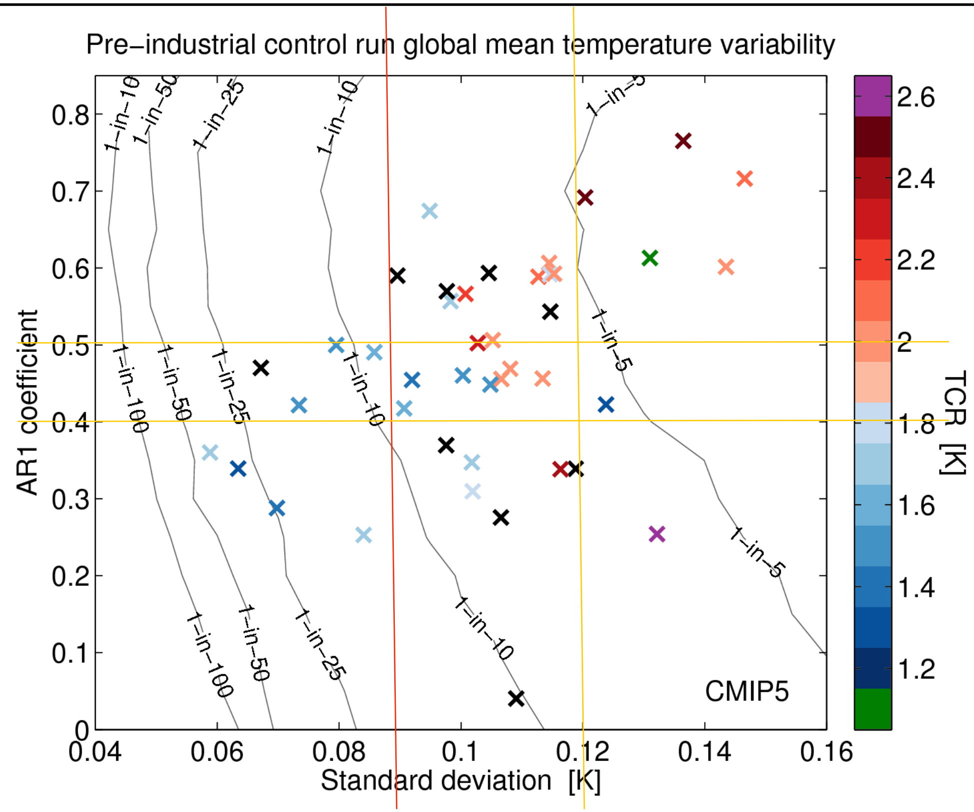
University of Reading

Fig from Ed Hawkins (in Sutton et al, *Phil Trans Roy Soc A*, 2015)

Walker Institute

Internal variability is not only large, it is also uncertain

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL



High TCR models generally but not always more variable

Constraints estimated from observations after removing linear or higher order trends

Ed Hawkins

(Contours show probability of decadal decline assuming long term warming of 0.16K/decade + AR(1) noise)

University of Reading

Walker INSTITUTE

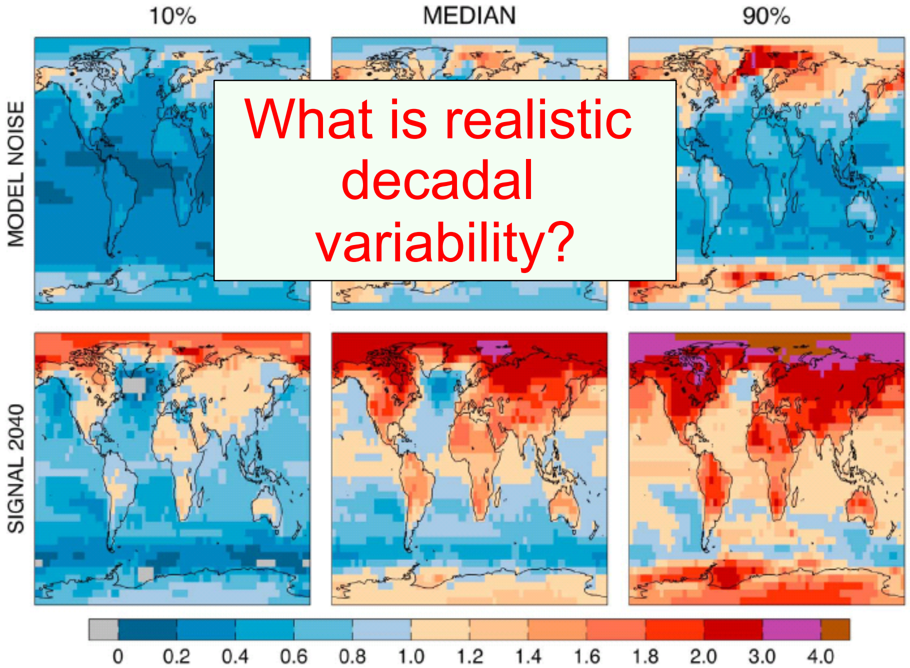
Internal variability is not only large, it is also uncertain.

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Internal variability

(std. dev. of annual mean SAT)

Response uncertainty



10-90% range spans a factor of 3 in some regions

University of Reading

Hawkins & Sutton, Time of Emergence of Climate Signals, GRL, 2012

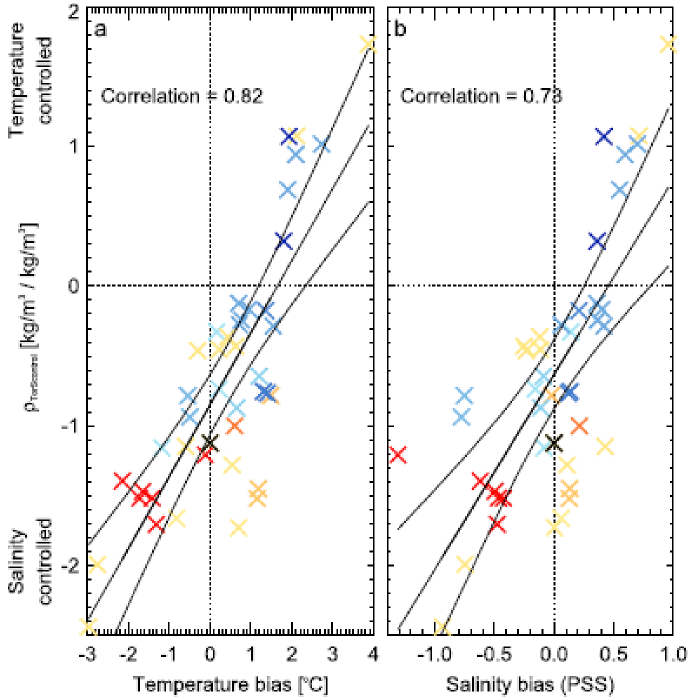
Walker INSTITUTE

Towards understanding the diversity of N. Atlantic decadal variability

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Menary et al, GRL, 2015 demonstrate a relationship amongst CMIP5 models between mean T and S biases in the Labrador Sea and important aspects of simulated decadal variability

=> need to reduce or eliminate mean biases to simulate variability reliably.

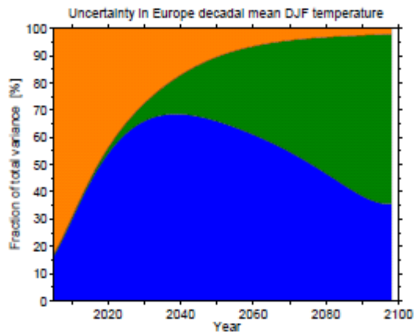


University of Reading

Walker INSTITUTE

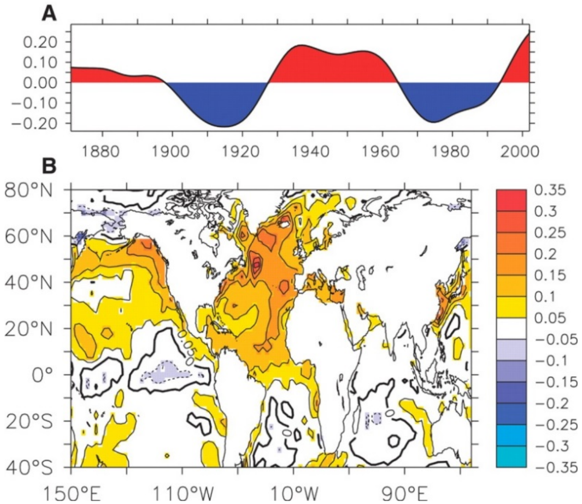
Response uncertainty

- For global mean temperature transient climate response (TCR) is the most important metric.
- For regional climate many other metrics matter, notably **circulation change** in atmosphere & ocean (e.g Shepherd, Nat. Geosci, 2014)



- Model spread provides only a very crude of response uncertainty (lower bound?)
- **Model adequacy** e.g. due to missing processes / errors common to all models is a major issue (as it isfor internal variability).
  - Hard to quantify impact but must not be ignored

Example: Atlantic Multidecadal Variability



Sutton & Hodson, 2005

- What are the respective roles of internal variability and forcings?
- What are the roles of different forcings?
  - Aerosols
  - Greenhouse gases
  - Volcanoes
  - Solar variations
- What is the role of the MOC?
- *No current consensus*

University of Reading

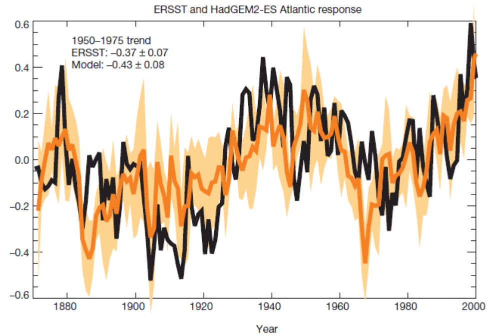
Walker INSTITUTE

Is *observed AMV* explained by an ocean mixed-layer response to varying surface fluxes?

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability

Booth et al, *Nature*, 2012: “Here we … show that aerosol emissions and periods of volcanic activity explain 76% of the simulated multidecadal variance [in detrended AMV]”



The Atlantic Multidecadal Oscillation without a role for ocean circulation

Clement et al, Science, 2015: “Here we show that ***the main features of the observed AMO*** are reproduced in models where the ocean circulation is prescribed and thus cannot be the driver”.

Issues:

- ***Are the models adequate*** in their representations of internal variability, forcings and responses?
- How are models compared to the real world?

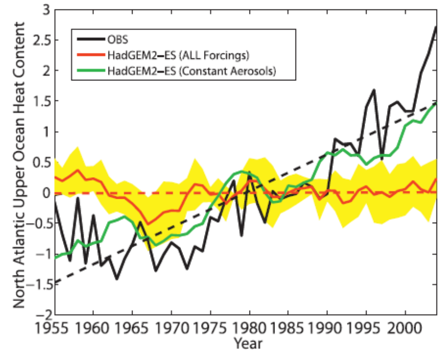
University of Reading

Walker INSTITUTE

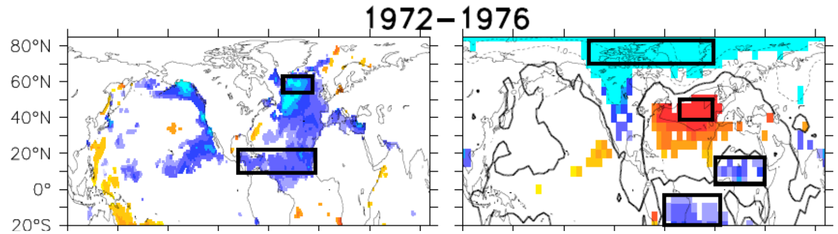
Essential to examine multiple metrics, not just SST

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Zhang et al, JAS, 2013 point out "major discrepancies between the HadGEM2-ES simulations and observations in the North Atlantic upper-ocean heat content, in the spatial pattern of multidecadal SST changes within and outside the North Atlantic, and in the subpolar North Atlantic sea surface salinity."



Hodson et al, J. Clim, 2014 point out "strong evidence that changes in atmospheric circulation, linked to a southward shift of the Atlantic ITCZ, played an important role in the [N. Atlantic cooling] event, particularly in the period 1972–76."



University of Reading

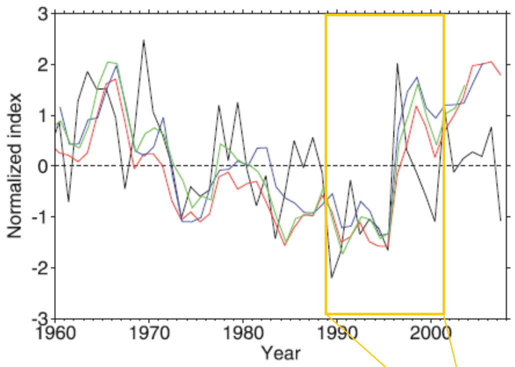
Walker INSTITUTE

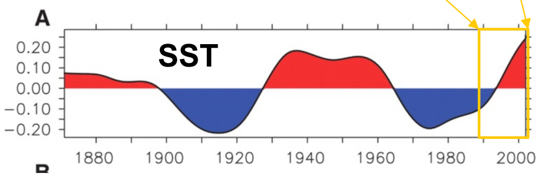
Strong evidence changes in ocean heat transport play a key role in AMV

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Robson et al, J. Clim, 2012 demonstrate the dominant role of a surge in northward ocean heat transport in explaining the rapid warming of the subpolar N. Atlantic in 1990s.

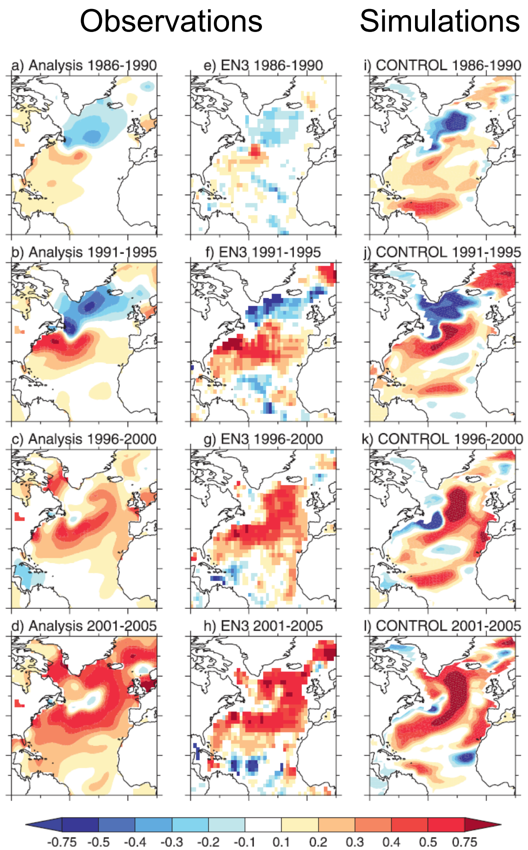
Independently supported by **Yeager and Danabasoglu, J. Clim, 2014.**





0-500m OHC

Figs from Robson et al, 2012

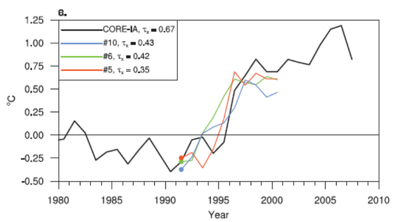


Initialised decadal predictions are a valuable tool to test models and attribution at a process level

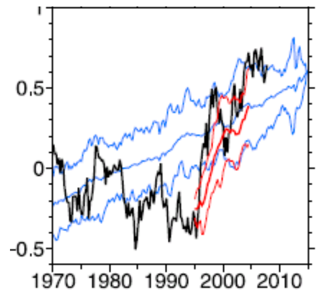
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

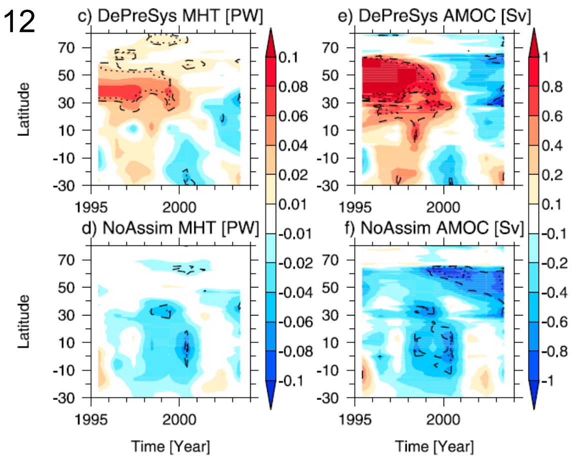
Rapid warming of N. Atlantic in 1990s was predictable due to the predictability of MOC & ocean heat transport.

Yeager et al, J. Clim, 2012

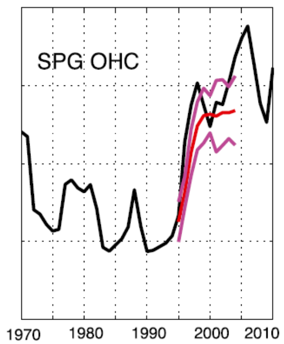


Robson et al, GRL, 2012



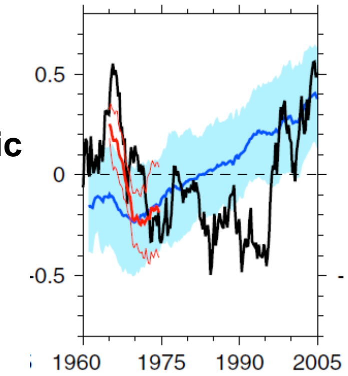


Msadek et al, J. Clim, 2014



Similar processes implicated in the N. Atlantic cooling (& freshening) in the 1960s

Robson et al, Clim. Dyn., 2014



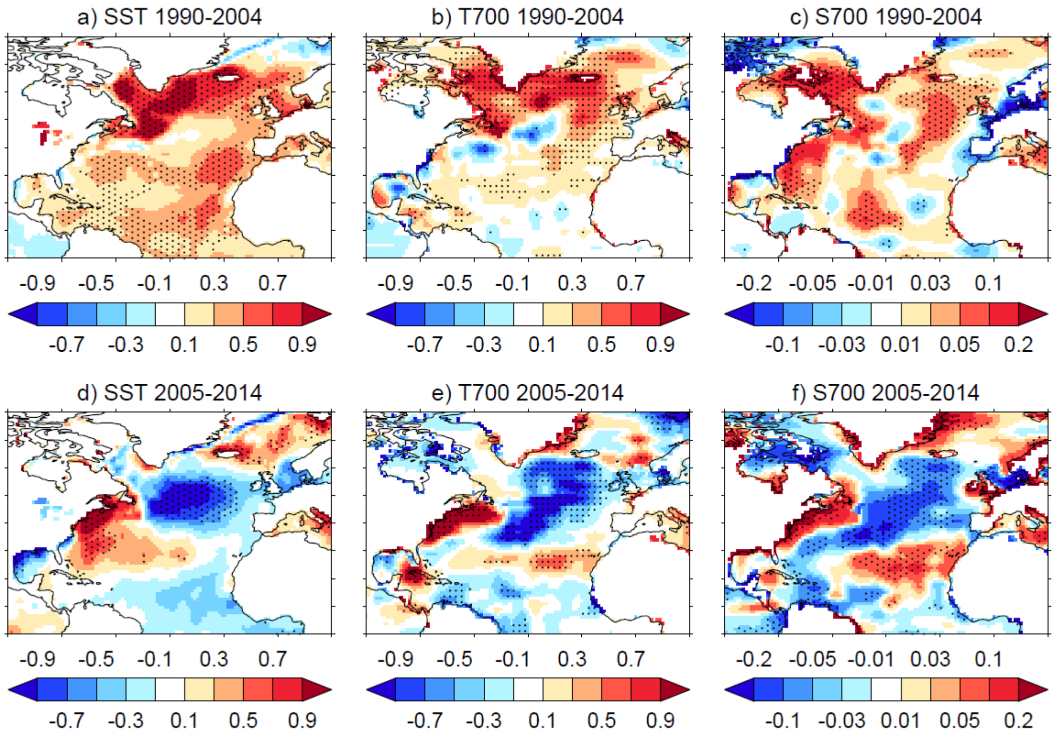
University of Reading

Return to the 1960s happening now?

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Linear trends 1990-2004

Linear trends 2005-14



University of Reading

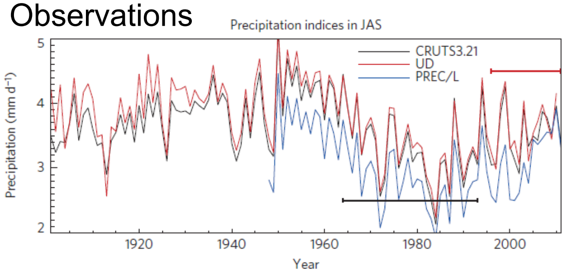
See Jon Robson's talk on Tuesday

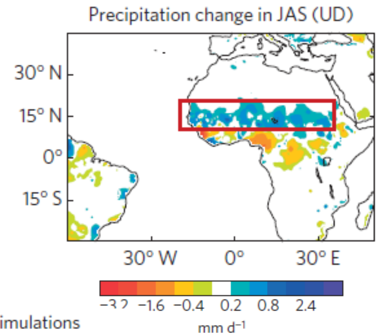
Walker INSTITUTE

Example 2: The recovery in Sahel rainfall

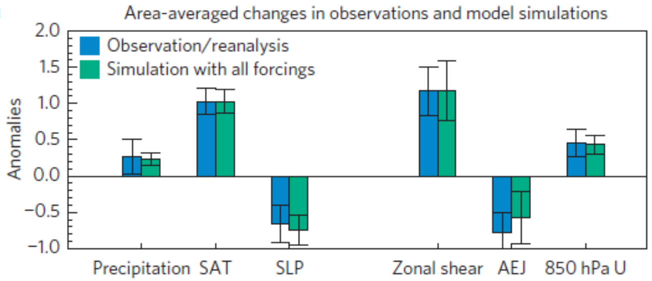
(Dong & Sutton, Nature Climate Change, 2015)

Observations





AGCM Simulations with ALL forcings

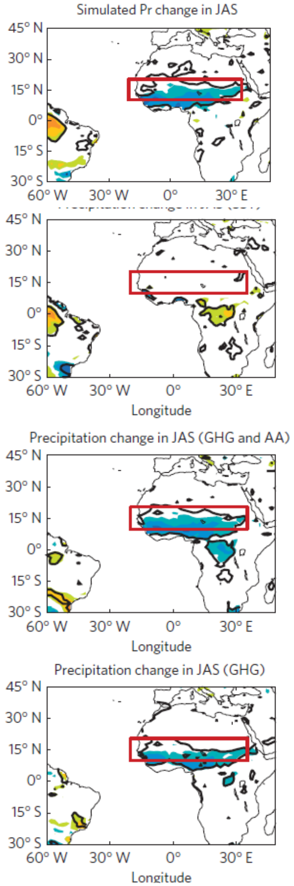


ALL

SST

GHG + AA

GHG



- *Multivariate changes* suggest an intensification & northward shift of the summer monsoon consistent between simulations and observations / re-analyses.

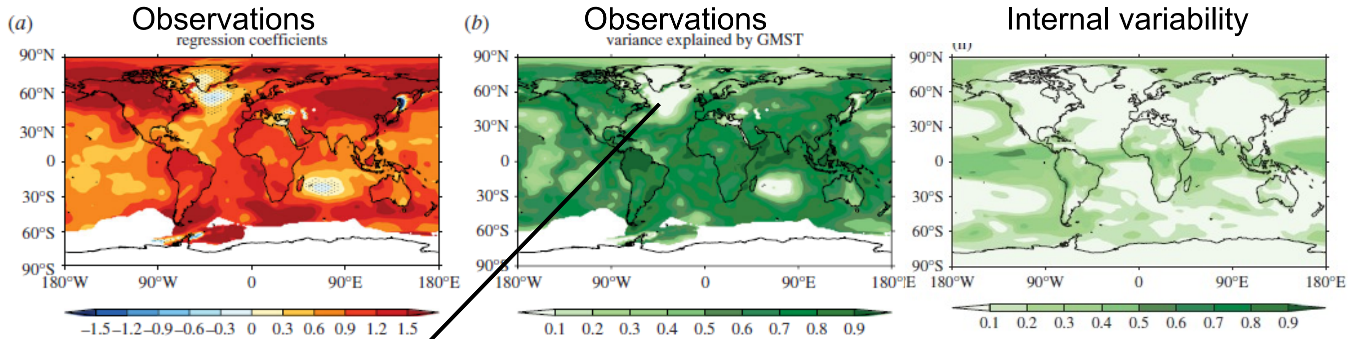
- Single forcing experiments suggest ***dominant role for direct impact of GHG increases***
- Model adequacy? Need to repeat with other models.

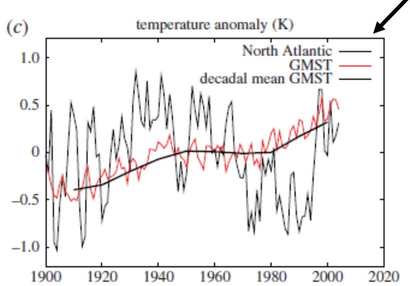
“Nearly-GCM-free” attribution

(Sutton et al, Phil Trans Roy Soc A, 2015)

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Regression of local decadal mean SAT on global mean surface temperature (GMST)

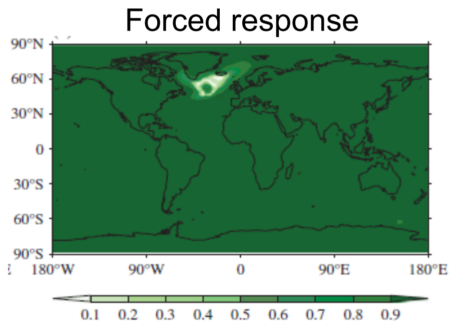




Strong evidence changes are caused by a forced response rather than internal variability.

Exceptions may indicate:

- large internal variability
- a non-linear response to forcing
- observational errors



University of Reading

Walker INSTITUTE

Conclusions

- There is a close link between **attribution** and **prediction** of decadal changes. Initialised predictions are a valuable tool for attribution.
- To have (any) confidence in decadal predictions we must demonstrate a capability to attribute past events to specific causes *robustly, at a process level.*
- These are tough problems. **Model adequacy** in **simulation of internal variability**, **forcings** and **responses** is a key issue.
- When comparing simulations to observations it is essential to use multivariate metrics ("**fingerprints**") to identify and discriminate between the processes involved.
- Very strong evidence that changes in ocean heat transport are first order important for **AMV** (contrary to Clement et al, 2015). We still need to unravel and quantify the respective roles of internal variability and forcings.

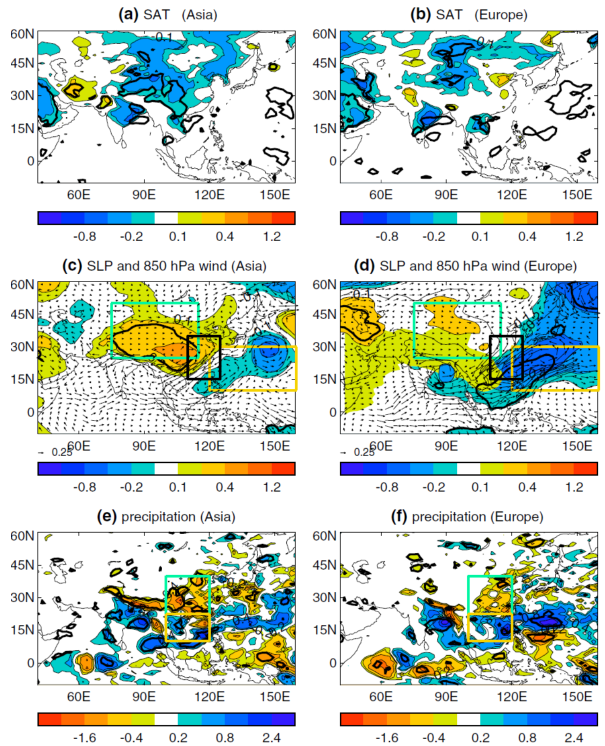
Extra slides

Preferred response of the East Asian summer monsoon to local and non-local anthropogenic sulphur dioxide emissions

Buwen Dong[1] · Rowan T. Sutton[1] · Eleanor J. Highwood[2] · Laura J. Wilcox[1]

Climate Dynamics, 2015

Illustrates challenges of attribution to regional aerosol emissions.



University of Reading

Walker Institute

Mechanisms influencing the cooling of the North Atlantic in the 1960s and 70s

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

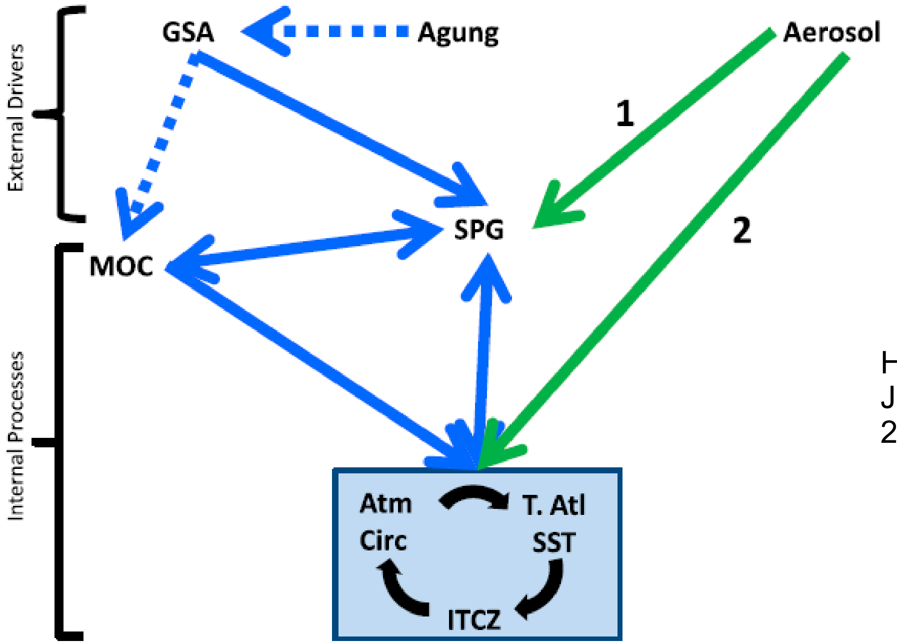


FIG. 9. Schematic describing the proposed mechanisms for explaining the observed North Atlantic cooling.

Hodson et al,
J. Climate
2014

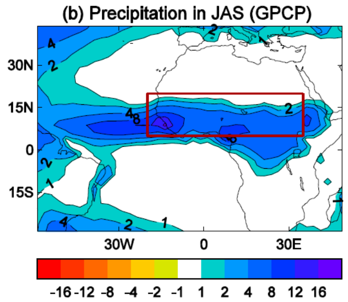
University of Reading

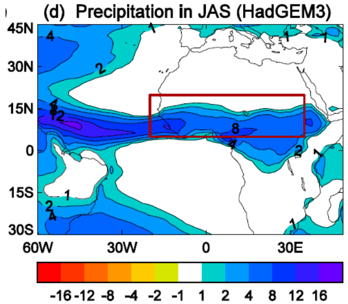
Walker INSTITUTE

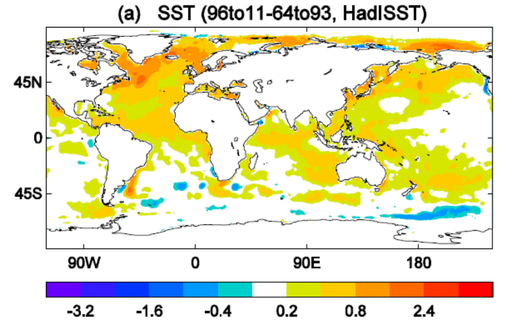
The recovery in Sahel rainfall

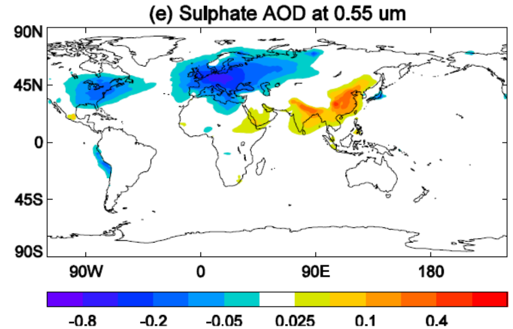
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

- Simulations with HadGEM3 (1.875 x 1.25, L85) investigated the impact of recent changes in a) SST, b) GHG, c) anthropogenic aerosols, separately and in combination.









GHG increases:

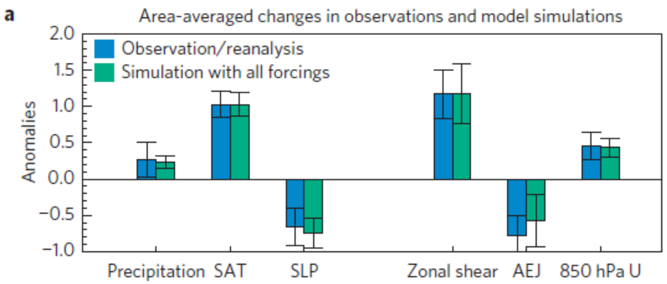
- 11% in CO_2
- 18% in CH_4
- 6% in N_2O

Dong & Sutton, NCC, 2015

University of Reading

Walker INSTITUTE

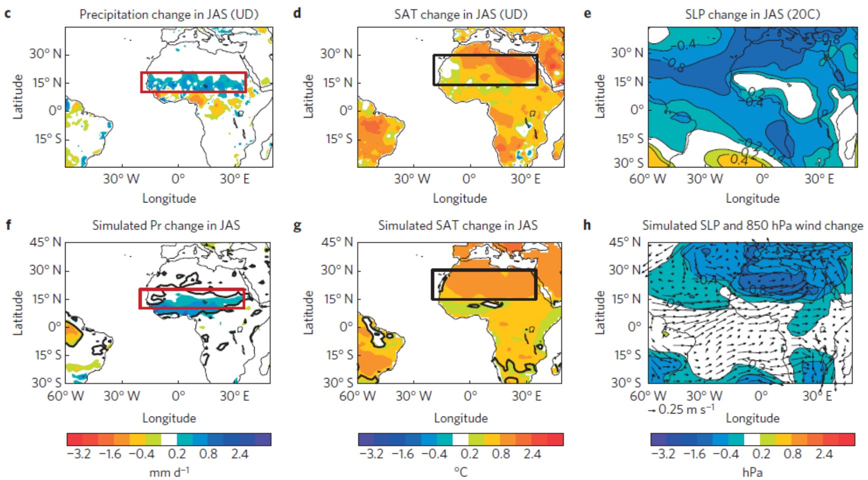
The recovery in Sahel rainfall



Multivariate changes suggest an intensification & northward shift of the summer monsoon consistent between simulations and observations / re-analyses

Observations

Simulations with ALL forcings



Dong & Sutton, NCC, 2015

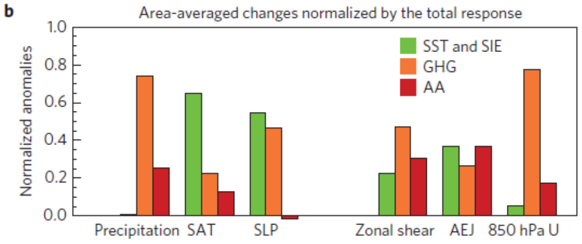
University of Reading

Walker Institute

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

The recovery in Sahel rainfall

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

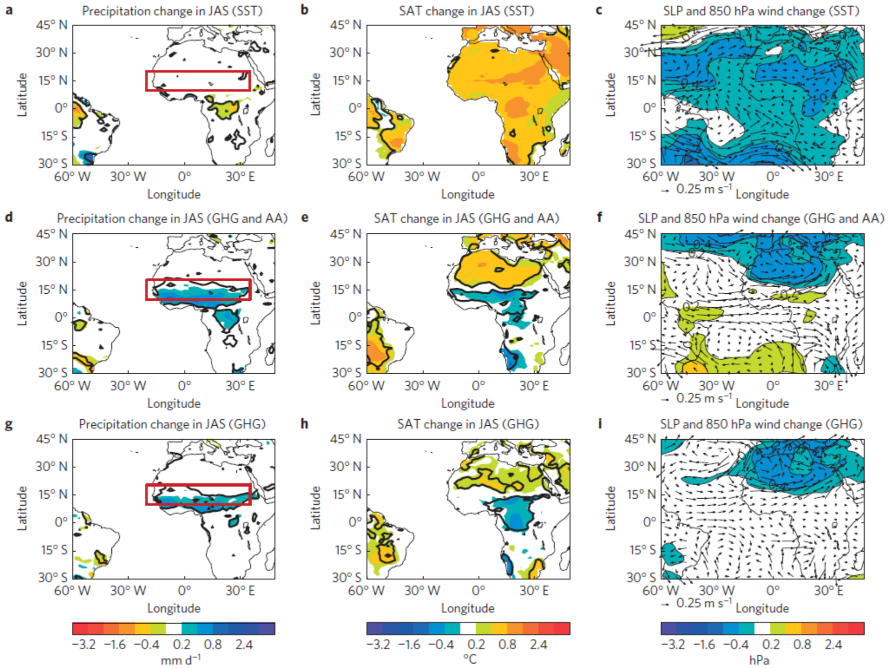


Attribution to specific forcing factors

SST

GHG & AA

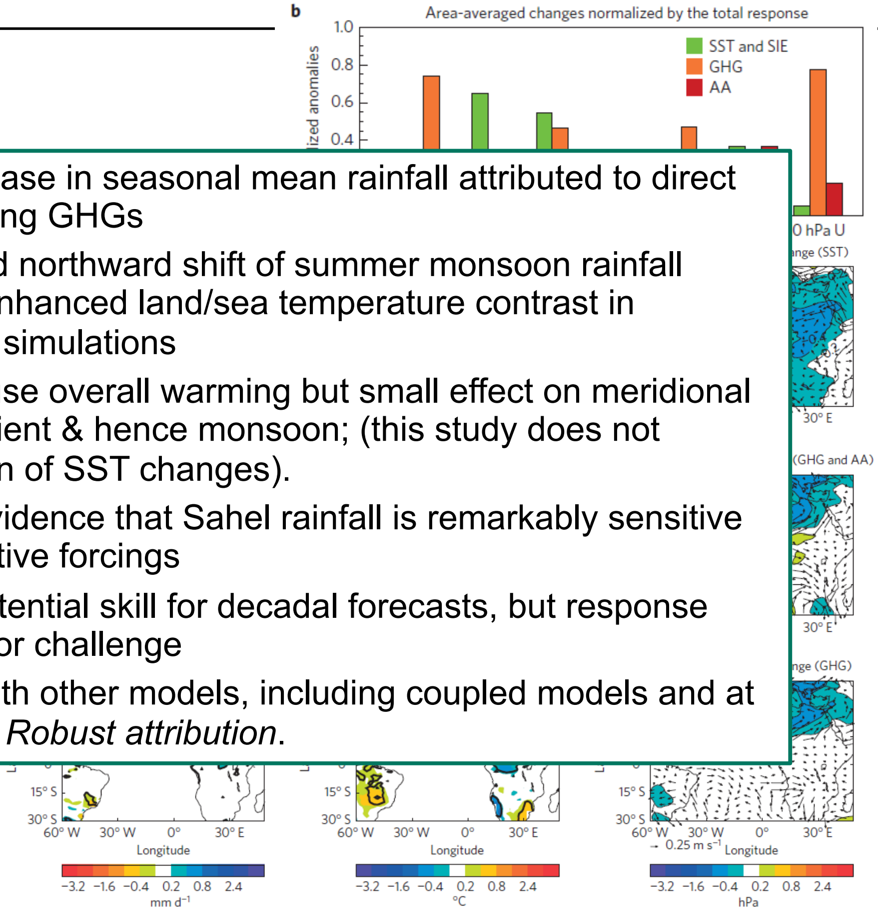
GHG



University of Reading

The recovery in Sahel rainfall

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

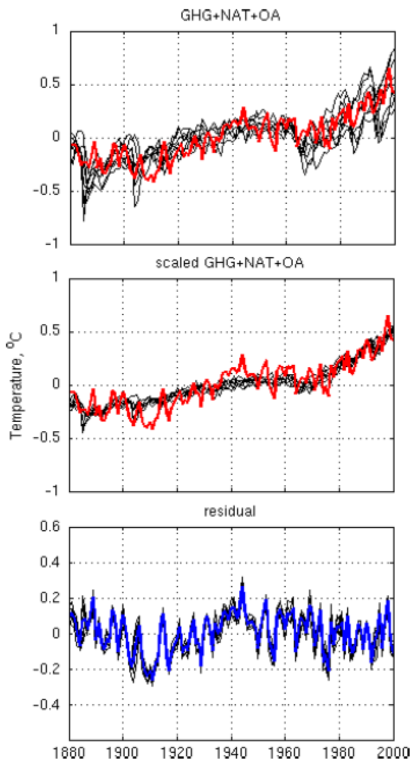


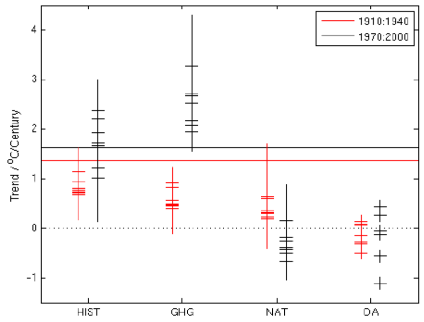
- ~75% of the increase in seasonal mean rainfall attributed to direct impact of increasing GHGs
- Intensification and northward shift of summer monsoon rainfall associated with enhanced land/sea temperature contrast in observations and simulations
- SST changes cause overall warming but small effect on meridional temperature gradient & hence monsoon; (this study does not address attribution of SST changes).
- Supports other evidence that Sahel rainfall is remarkably sensitive to changing radiative forcings
- Suggests high potential skill for decadal forecasts, but response uncertainty a major challenge
- Need to repeat with other models, including coupled models and at higher resolution. *Robust attribution*.

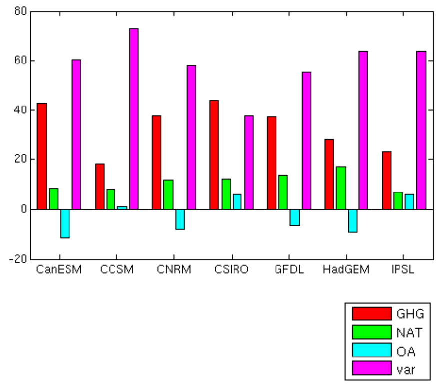
University of Reading

Attribution of the Early Twentieth Century Warming

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL







- Models warm less rapidly than obs in ETC
- Fitting over 1910-40 suggests similar contributions from GHG and NAT
- Fitting over 1880-2000 suggests smaller contribution from NAT
- Large residual suggests errors in forcings or responses (or large amplitude internal multidecadal variability)

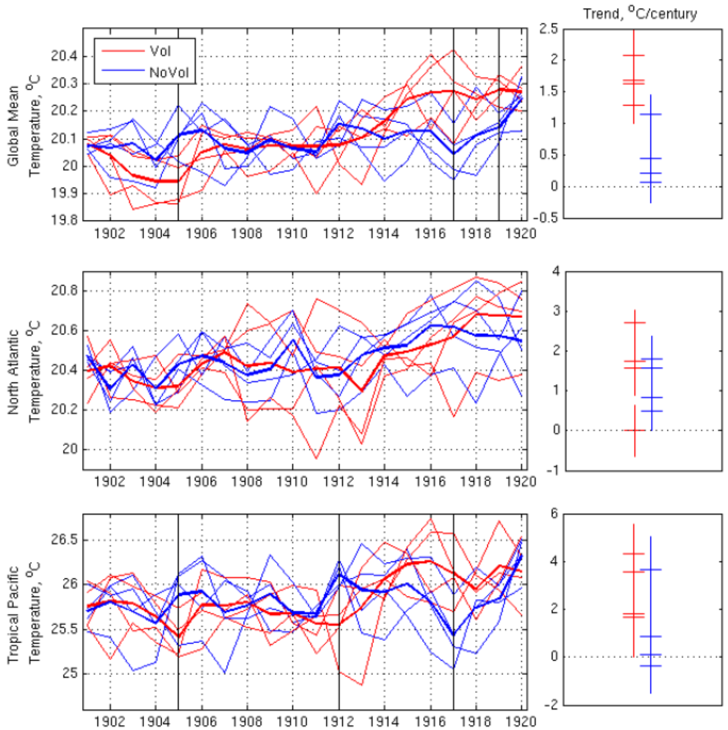
University of Reading

V. Thompson, PhD thesis, 2015

Walker INSTITUTE

Potential contribution of volcanic forcing to Early Twentieth Century warming

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL



Simulated response to 1902 Santa Maria eruption
Mean response ~ 0.2 ^{o}C

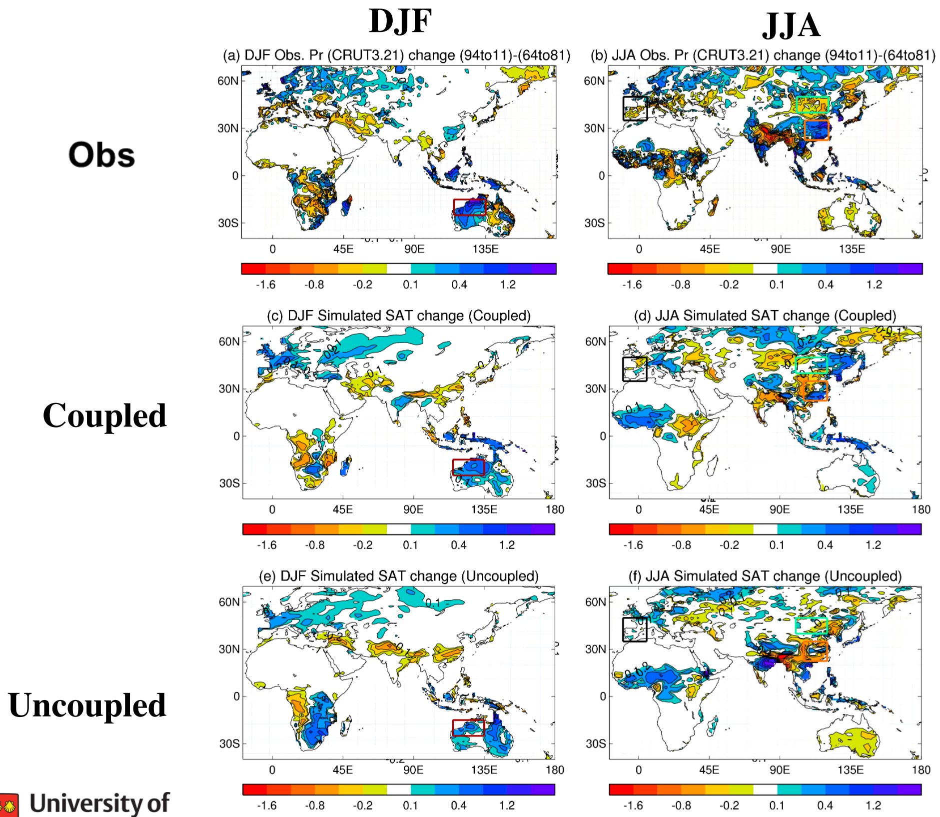
Rate of warming sensitive to ocean initial state.

V. Thompson, PhD thesis, 2015

University of Reading

Walker INSTITUTE

Seasonal mean precipitation changes between PD and EP for DJF and JJA



Contrasting precipitation change over East Asia in JJA.

Contrasting precipitation features over Australia in DJF.

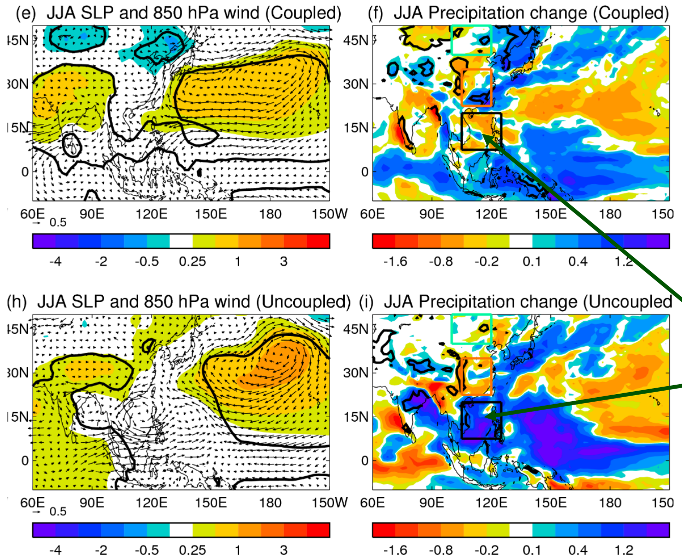
Significant differences in several monsoon regions.

Seasonal mean circulation and precipitation changes between PD and EP over East Asia in JJA

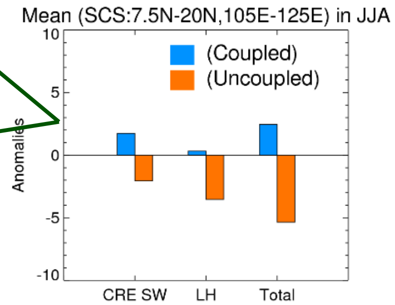
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Coupled

Uncoupled

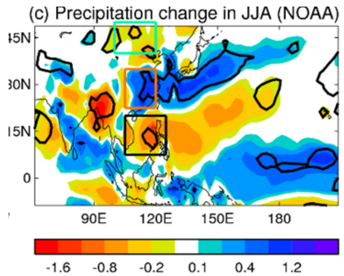


Contrasting precipitation features over East Asia and South China Sea in JJA



Obs

Changes between 1964-81 and 1994-2011

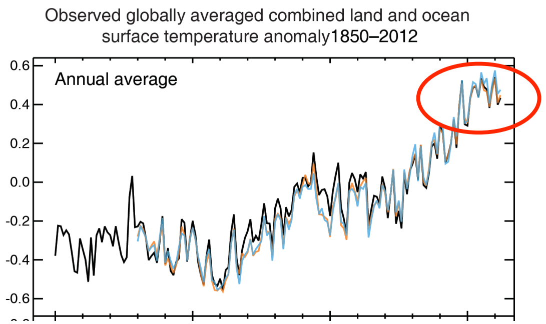


Local changes in the coupled response bear a similarity to observed changes

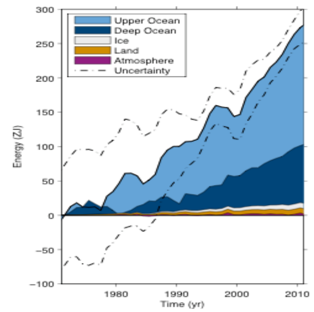
University of Reading

Walker INSTITUTE

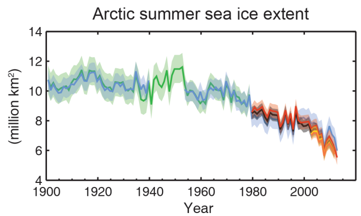
Example 1: The recent "pause" in global mean surface temperature rise

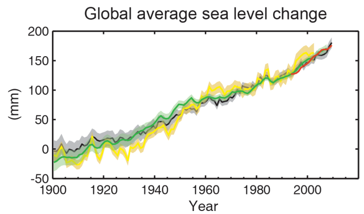


- little change in GMST over the last 15 years
- other important variables have continued to show significant changes
- *very likely* that the climate system continued to accumulate energy.



Figures from IPCC AR5





IPCC Assessment:

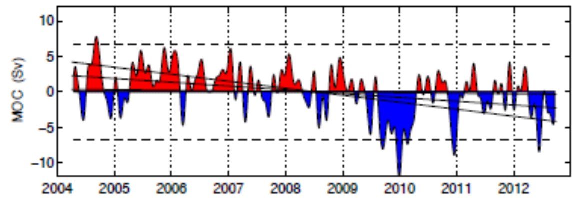
- Pause is "due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal variability, which includes a possible redistribution of heat within the ocean (*medium confidence*)."

- Improving quantification a focus of ongoing research
- Highlights the importance of multivariate Earth System monitoring

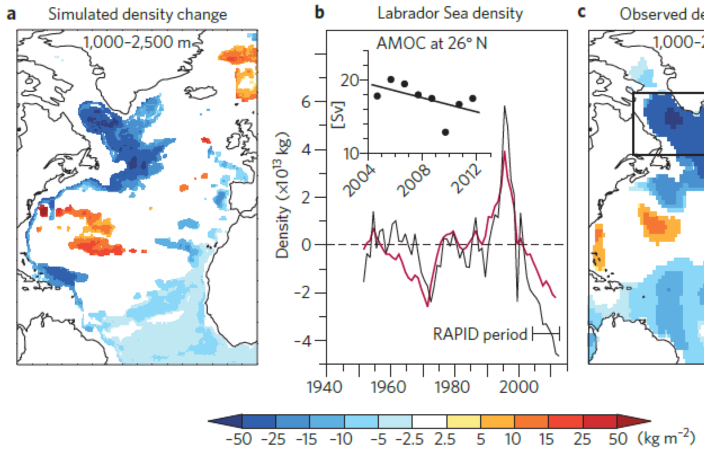
What next? Is the AMOC slowing down?

Smeed et al (2013) report a slow down in the MOC @ 26N over 2004-12

Other evidence suggests this is unlikely to be just a short term fluctuation



Potential density anomalies; 1000-2500m depth



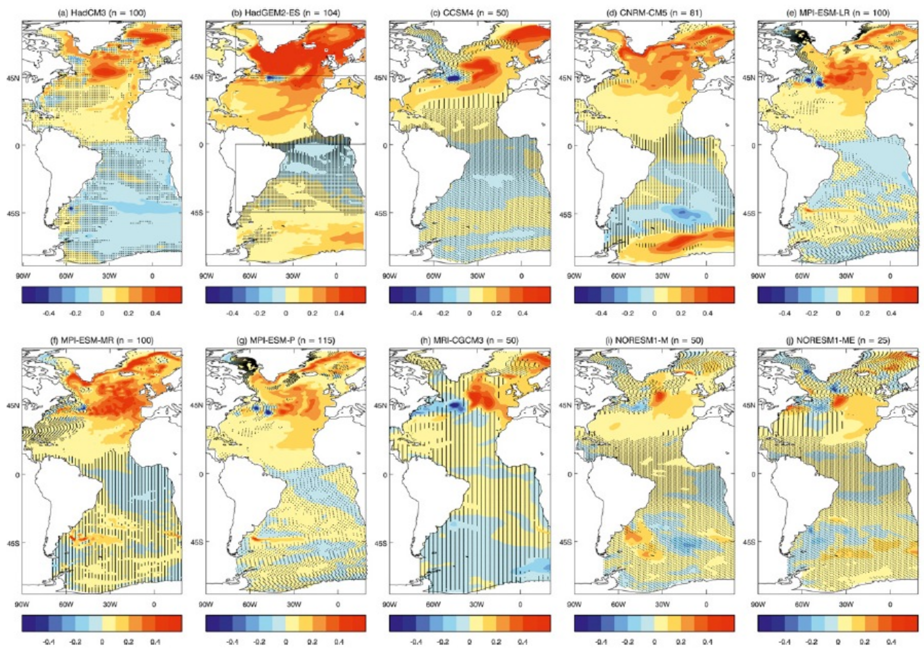
Robson et al, Nature Geoscience, 2014

What will this do to climate in Europe and elsewhere?

Internal variability is not only large, it is also uncertain.

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Different models show different timescales, amplitudes, and patterns of decadal variability



SST patterns associated with decadal variability in Atlantic MOC in different climate models

Roberts et al, 2013

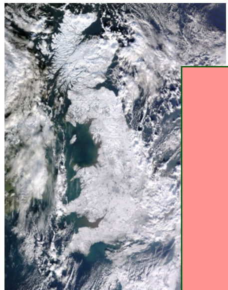
University of Reading

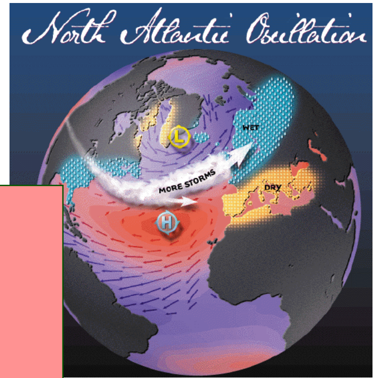
Walker INSTITUTE

Importance of circulation change in the atmosphere and ocean

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

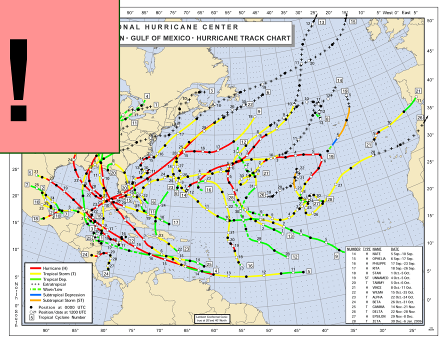
- Small changes in atmospheric circulation can have a major impact on regional climates and climate impacts





The new cloud feedback!

- A coupled ocean-
problem
- Dynamics rather
- Large internal variability & large response uncertainty; current climate models show low consistency
- Potential for poorly understood abrupt regime change



University of Reading

See e.g. Shepherd, Nat. Geosci, 2014

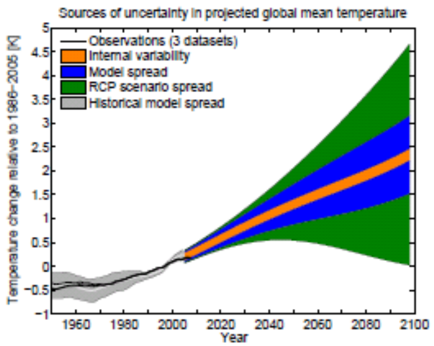
Walker INSTITUTE

Sources of uncertainty in climate predictions and projections

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

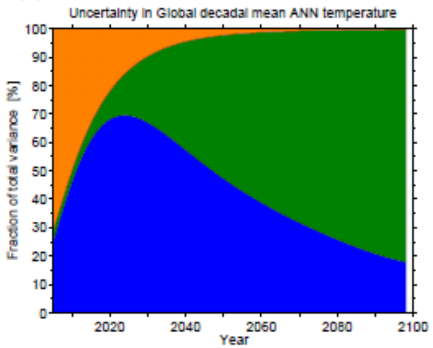
<u>decadal mean surface air temperature from CMIP5</u>

(a)

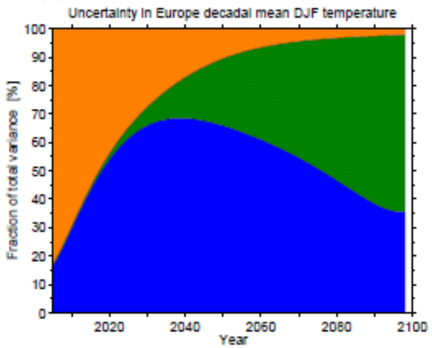


1. Forcing
2. Response
3. Internal variability

(c)



(d)



<u>Near-Term</u>:

- Internal variability
- Response uncertainty

<u>Long-Term</u>:

- Forcing (especially emissions) uncertainty
- Response uncertainty
- Internal variability

Hawkins & Sutton, 2009; 2011 + AR5

University of Reading

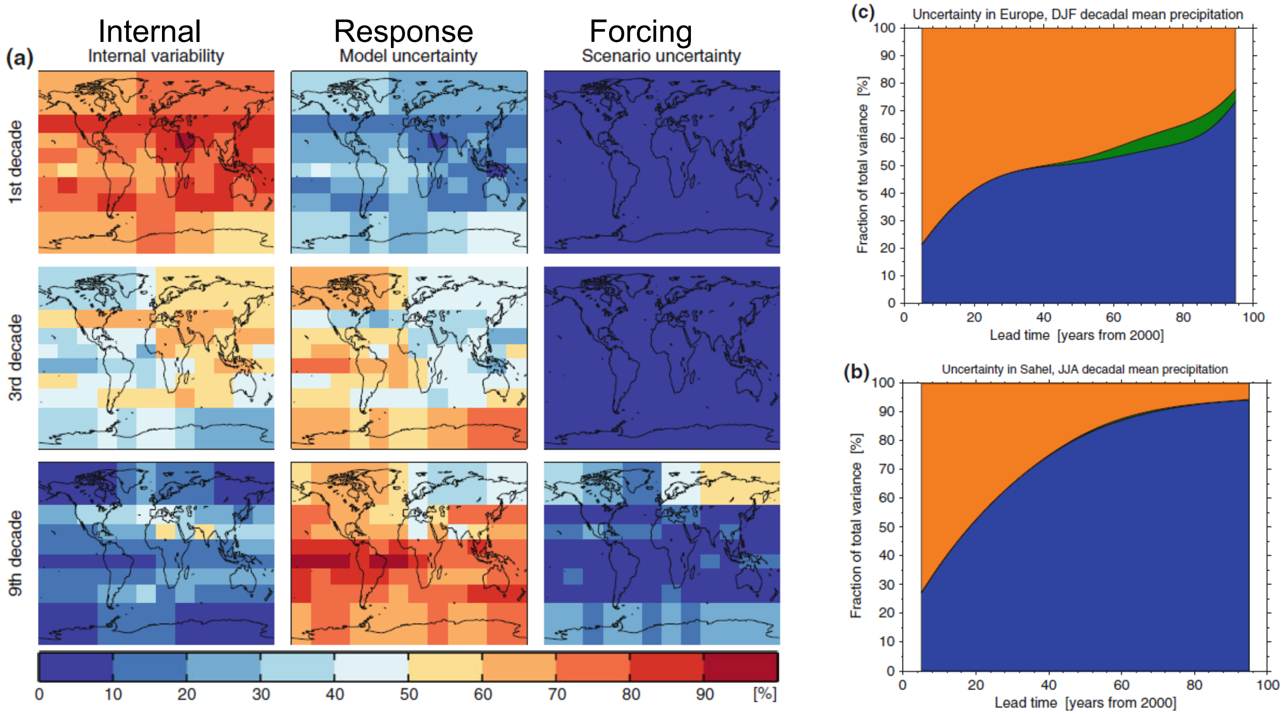
Internal variability increasingly important on smaller space and time scales

Walker INSTITUTE

Uncertainty in projections of regional precipitation change

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Fraction of variance in projected DJF precipitation change



University of Reading

Hawkins & Sutton, Climate Dynamics, 2011

Walker INSTITUTE

User needs for climate risk assessment

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

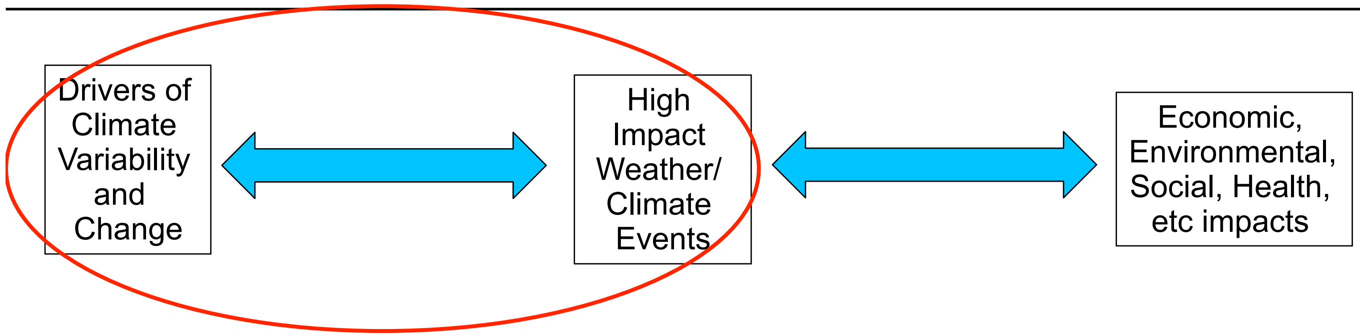
1. What possible weather/climate events could have a high impact on my business / activity?
   - What are the "*high-impact-for-me*" events?
   - Must recognise potential for unprecedented events.
2. What is the likelihood of "high-impact-for-me" events?
   - How will likelihood change on relevant planning time horizons?
   - e.g.: How will the likelihood in 2016-35 compare to 1986-2005?
3. What are the options to reduce risk / exploit opportunities?

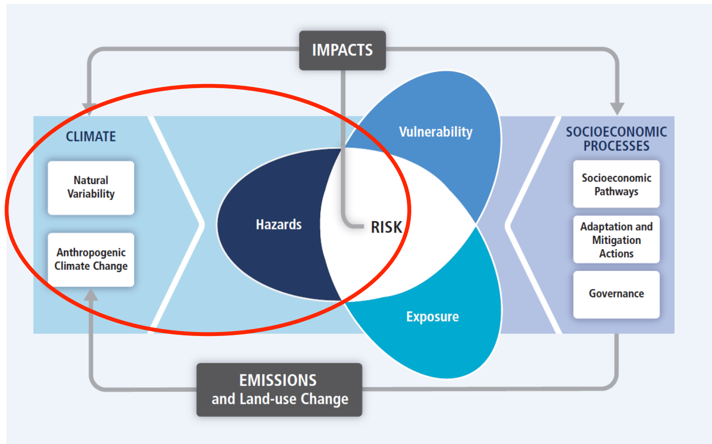
University of Reading

Walker INSTITUTE

Climate Risk Assessment

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL





IPCC AR5
WGII Fig
SPM.1

University of Reading

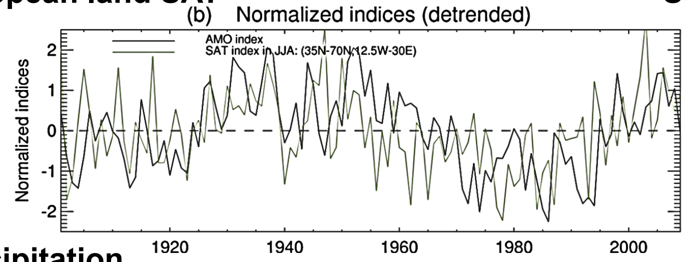
Walker INSTITUTE

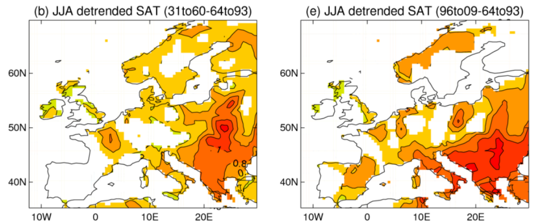
Multidecadal variability in European summer climate

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

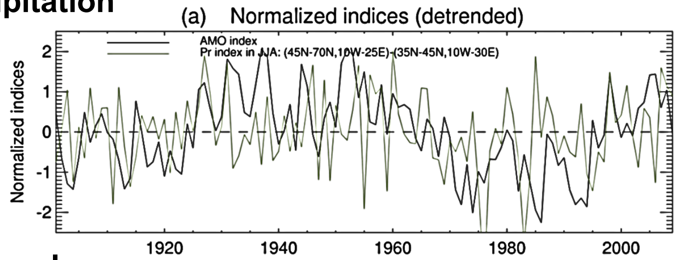
Sutton & Dong, Nature Geoscience, 2012

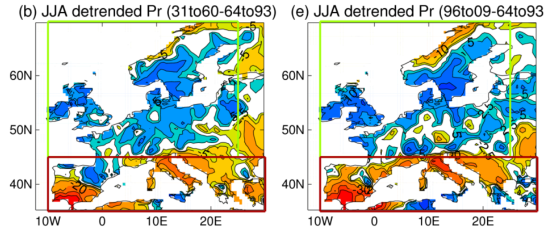
European land SAT



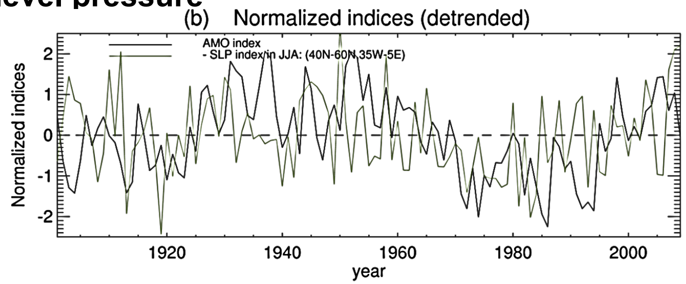


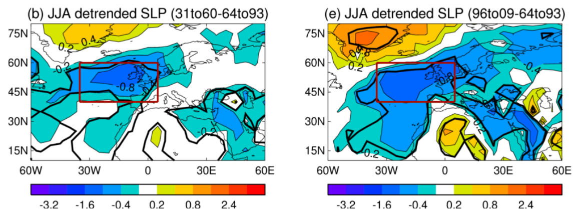
Precipitation





Sea level pressure





Comparison with model experiments suggests a causal influence of the Atlantic Ocean