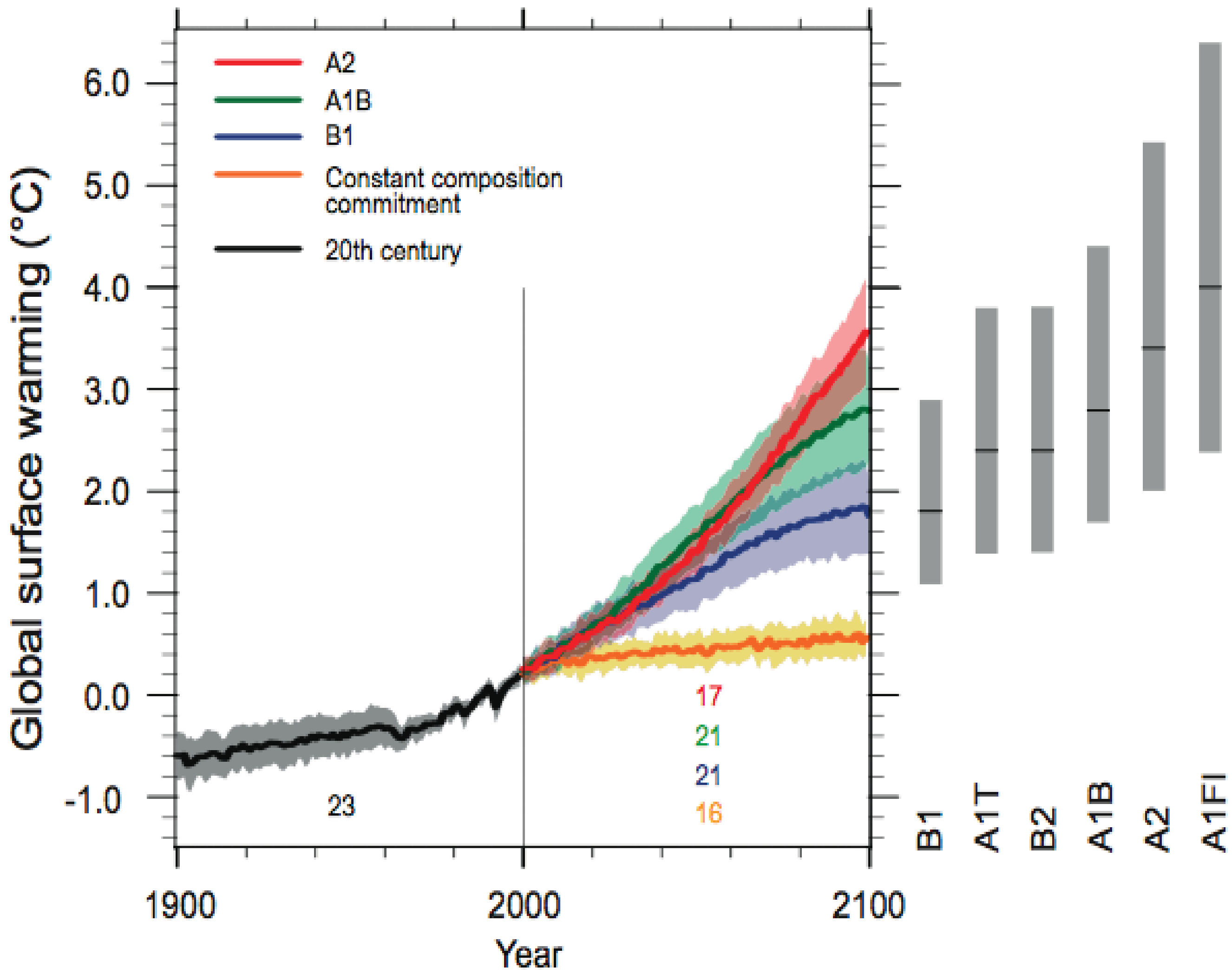
Climate Change: model uncertainty

- What we know
- What we don’t know; uncertainty at small scale; uncertainty in response of ESS
- Reasons for this

- Climate change is happening and we know what’s causing it
- We use GCMs to make projections
- Uncertainties in projections; in evolution of the climate system, and in response of ESS
- Reasons for this….types of uncertainty; emergence versus reductionism in approaches to complexity
- Policy implications
- Climate sensitivity and landscape sensitivity

Projections of Future Changes in Climate

Best estimate for low scenario (B1) is 1.8 C (*likely* range is 1.1 C to 2.9 C), and for high scenario (A1FI) is 4.0 C (*likely* range is 2.4 C to 6.4 C).



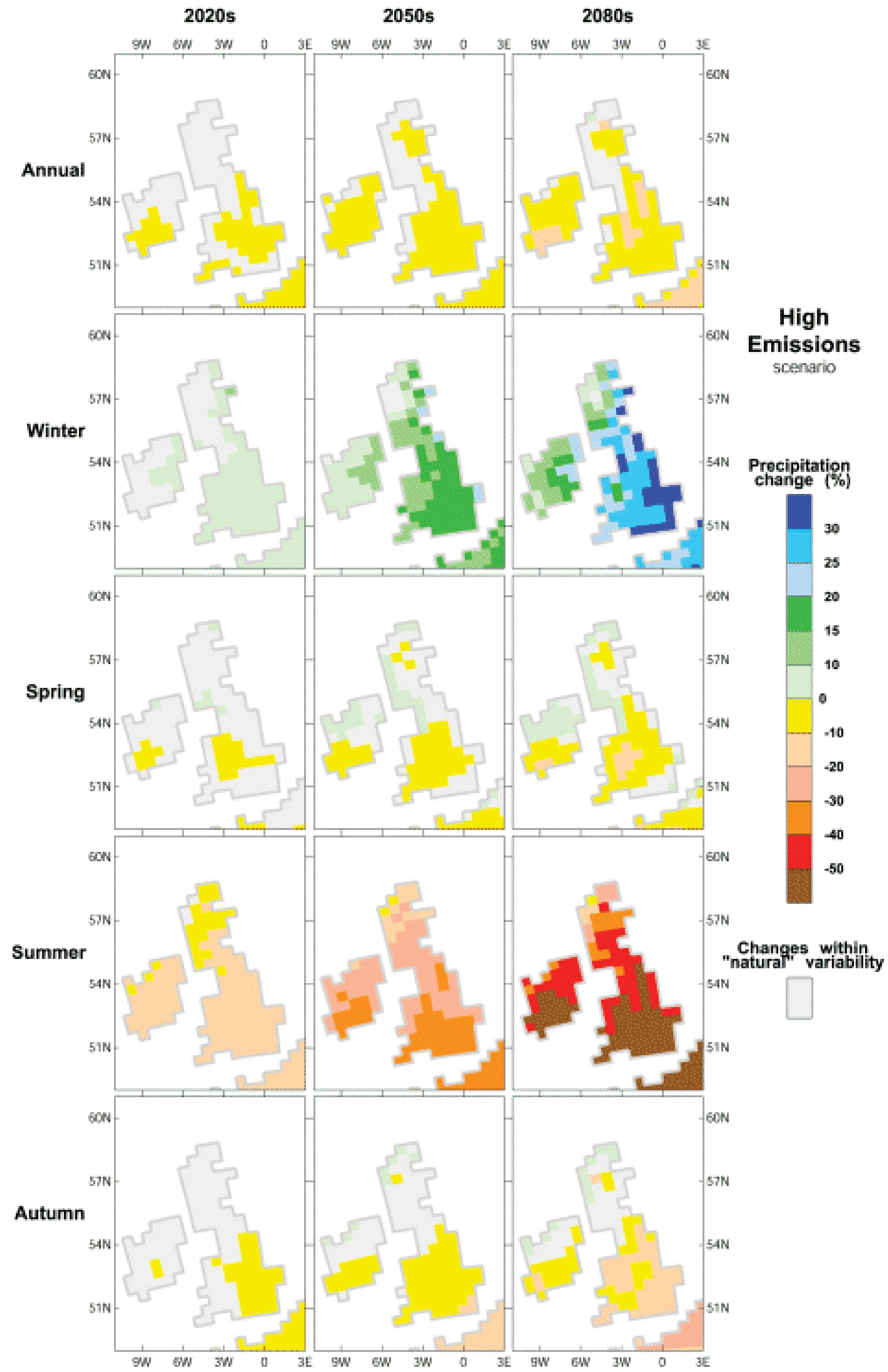
Uncertainty at small scale

What happens if we rely on GCMs to develop RCMs?

UKCIP 02

Used to develop planning policy:
Local Goverment performance framework: NI 188 planning to adapt to climate change

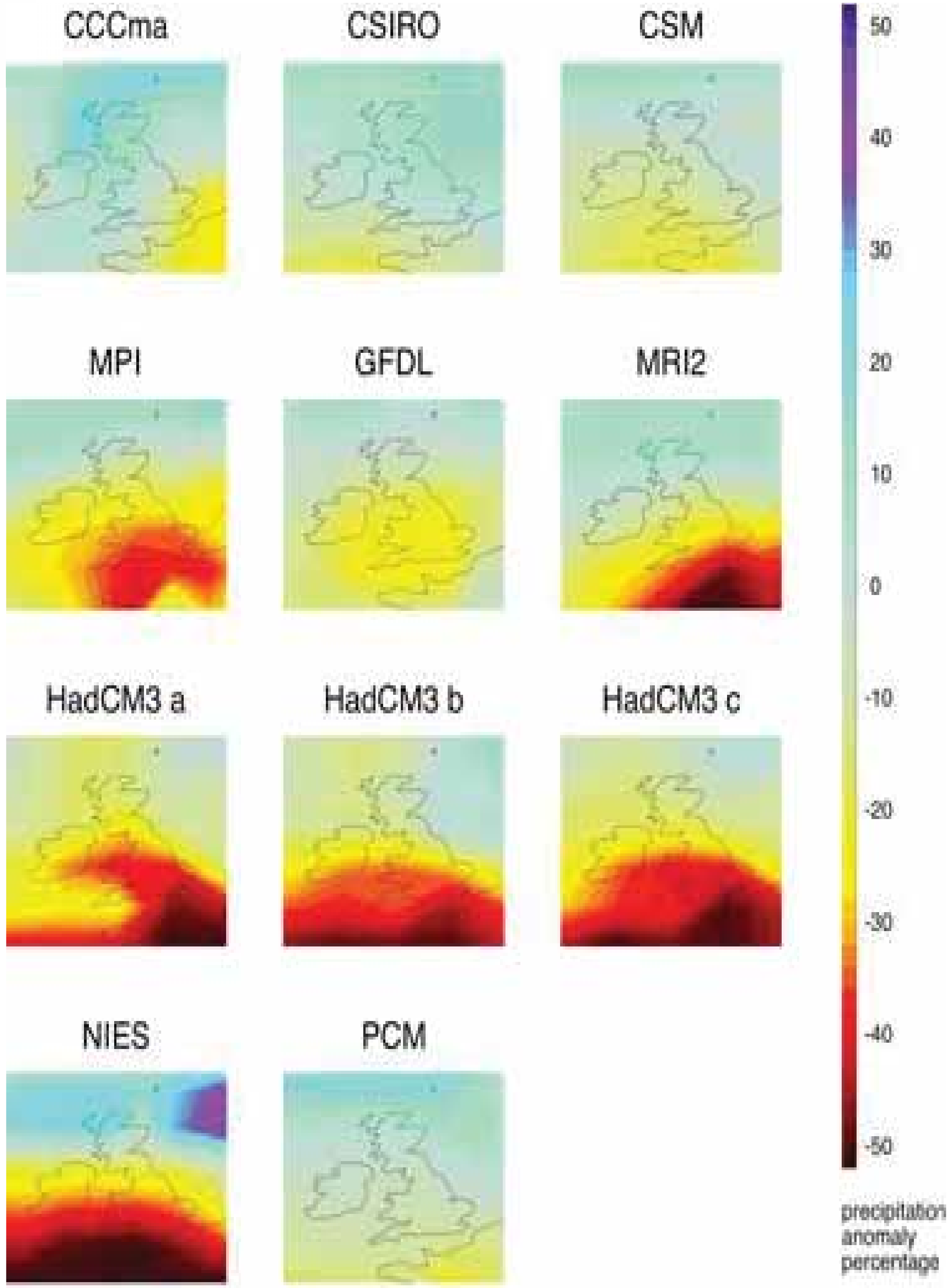
BUT.........



Source: UKCIP02 Climate Change Scenarios (funded by DEFRA, produced by Tyndall and Hadley Centres for UKCIP)

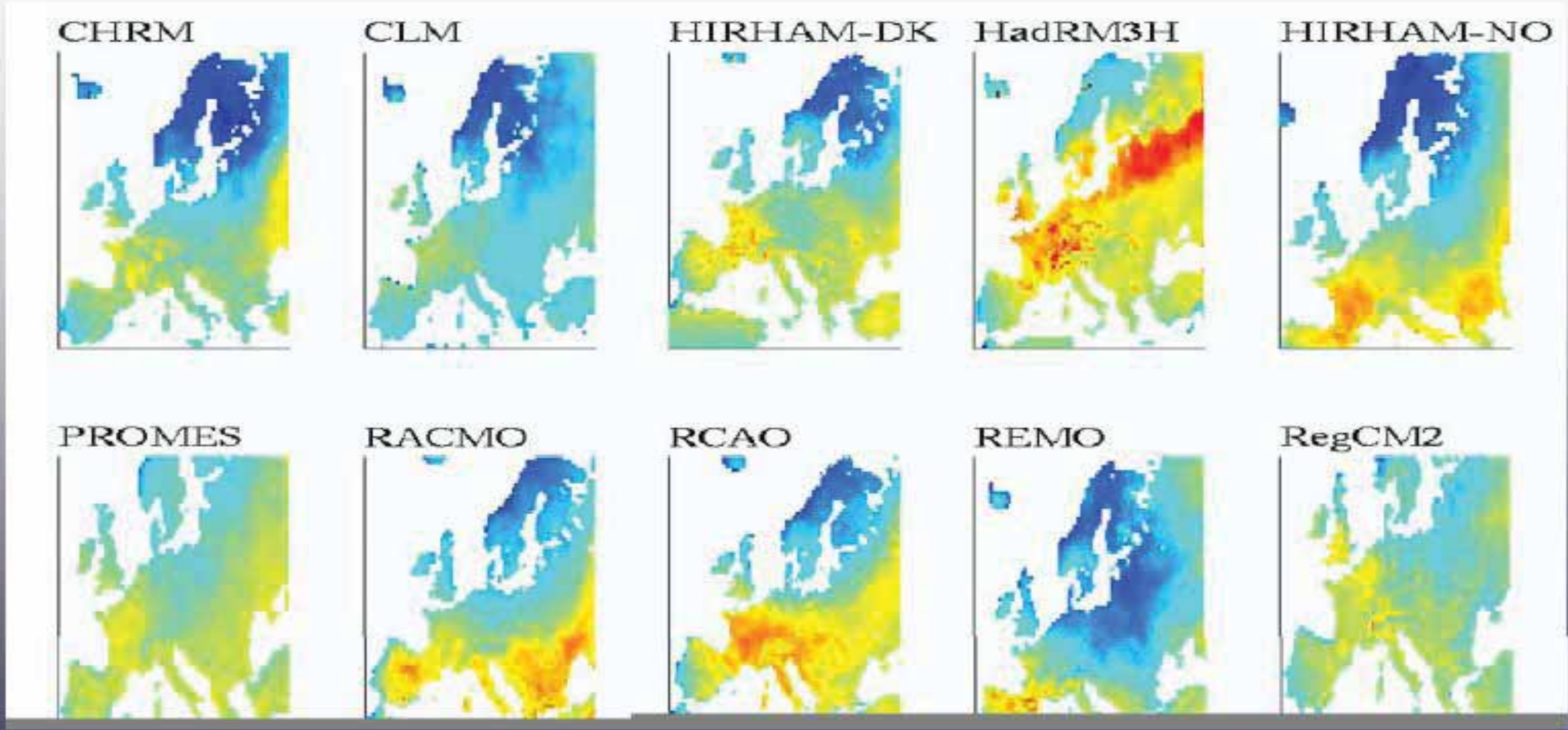
Model uncertainty

- Different climate models will produce a different climate response even when forced by an identical emissions scenario
- UKCIP02 scenarios are “drier” over UK than some other climate models



Source: UKCIP02 Climate Change Scenarios (funded by DEFRA, produced by Tyndall and Hadley Centres for UKCIP)

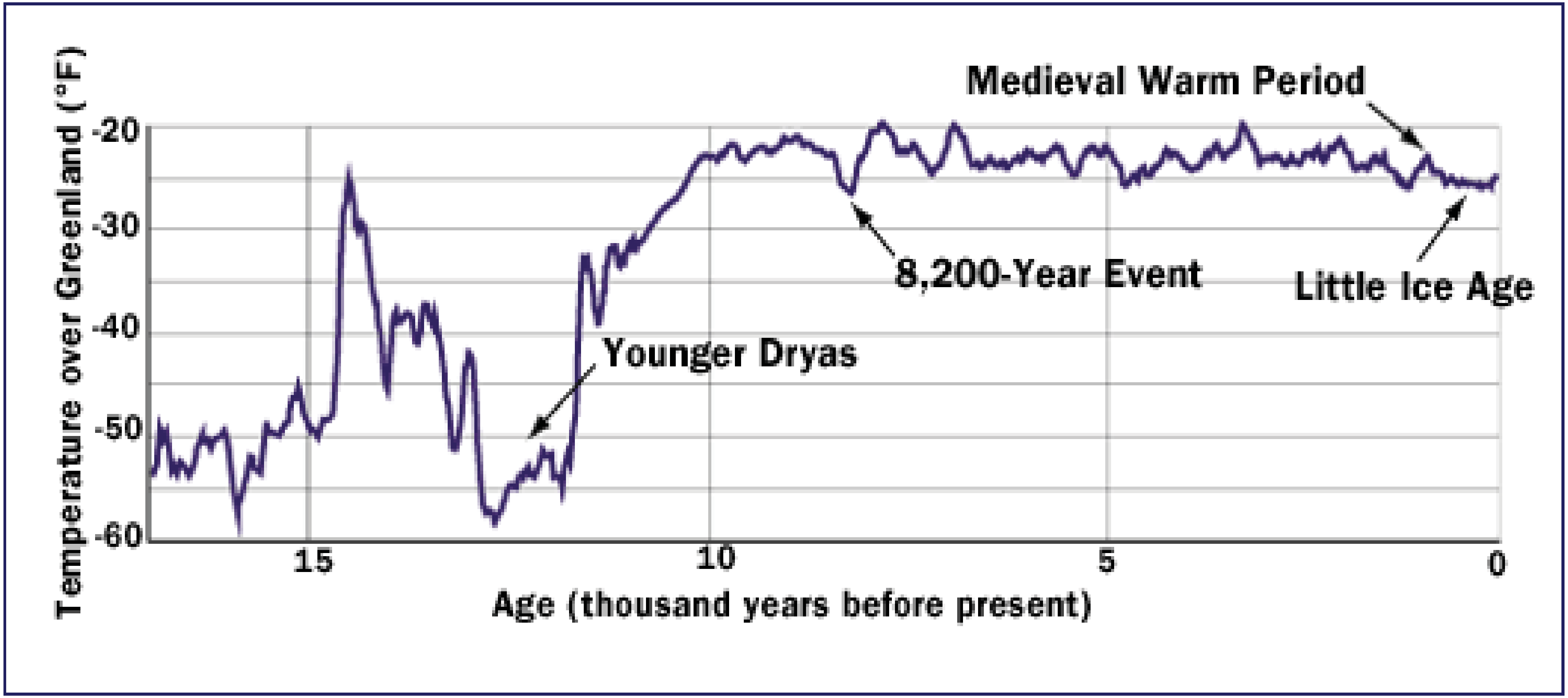
Increases in 95%-ile summer Tmax in 10 parallel RCM experiments



Mark New 2008

Uncertainty in dynamic evolution of the climate system

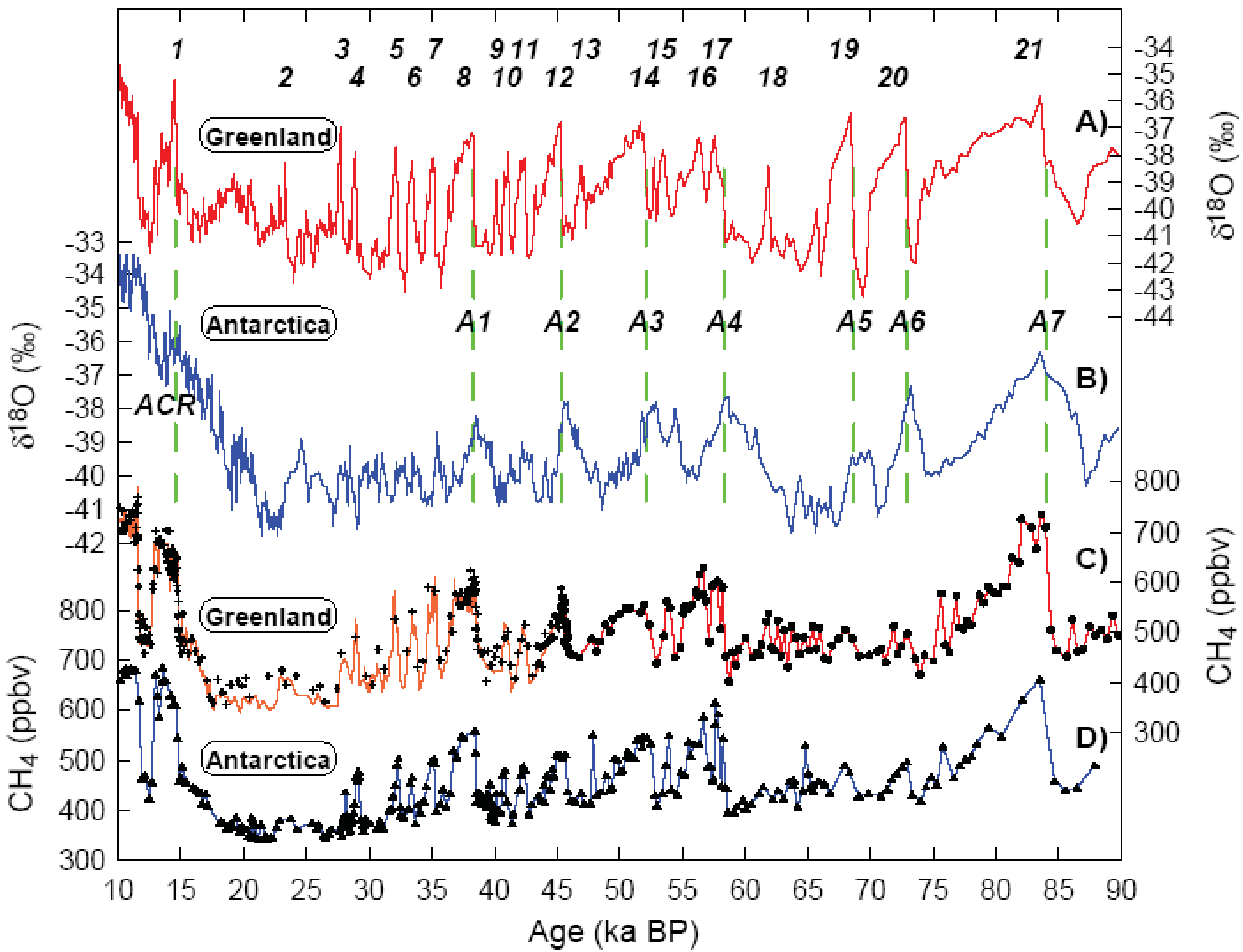
Implications for climate sensitivity?



The climate has undergone change in the past

The variability of (global?) climate change over the past 17 Ka

Dansgaard-Oeschger events



Broecker writing in 1999 bemoaned the limitations of the climate models to recreate some aspects of past climates and wrote:

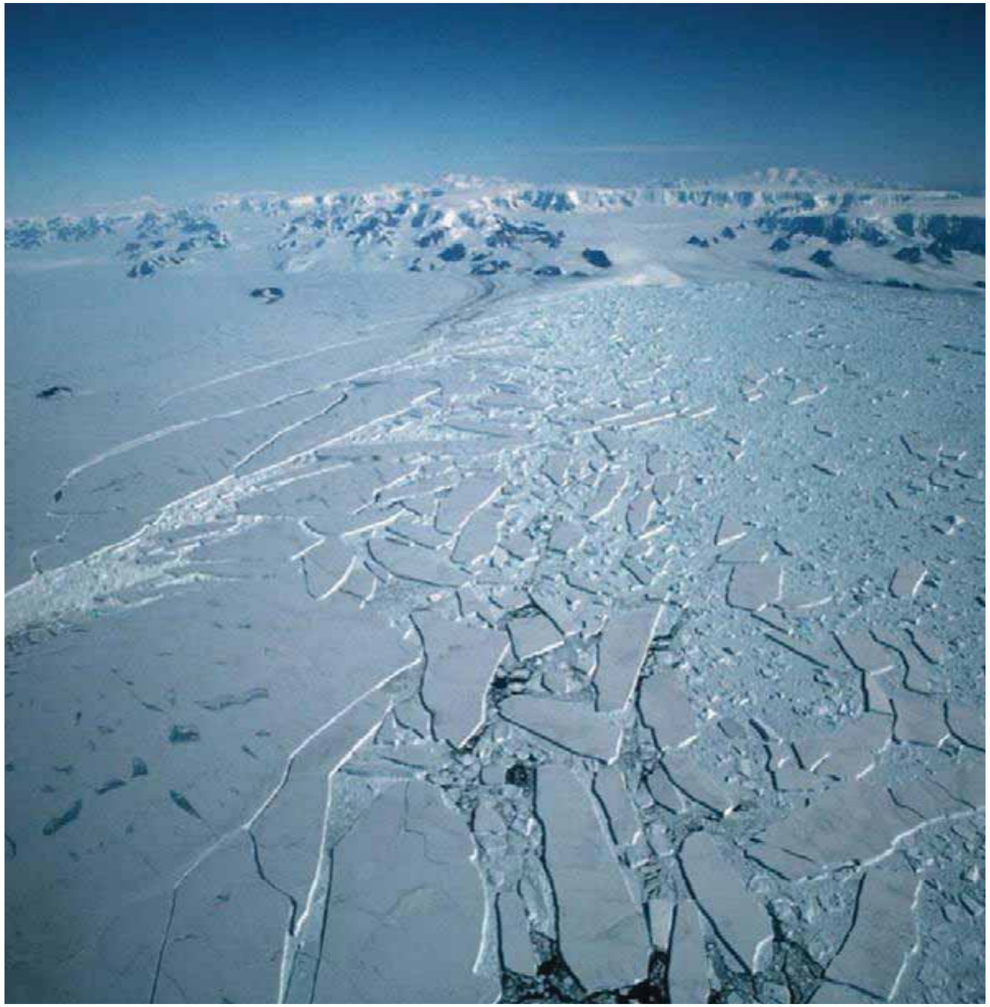
"No one understands what is required to cool Greenland by 16 °C and the tropics by 4 ± 1 °C, to lower mountain snowlines by 900 m, to create an ice sheet covering much of North America, to reduce the atmosphere's CO_2 content by 30%, or to raise the dust rain in many parts of Earth by an order of magnitude. If these changes were not documented in the climate record, they would never enter the minds of the climate dynamics community".

Is model construction failing to predict future rapid change?

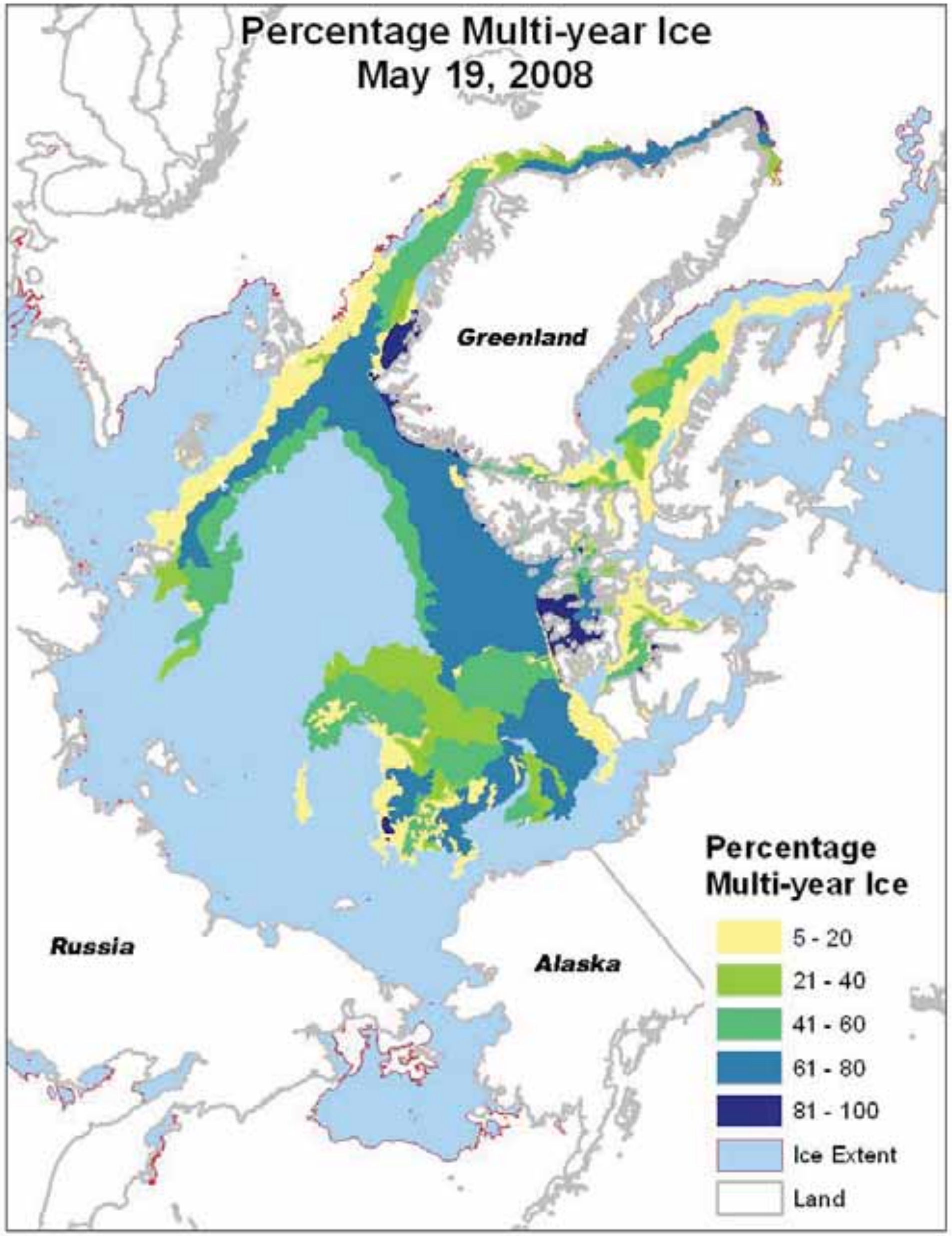
Problems with models: future climate change

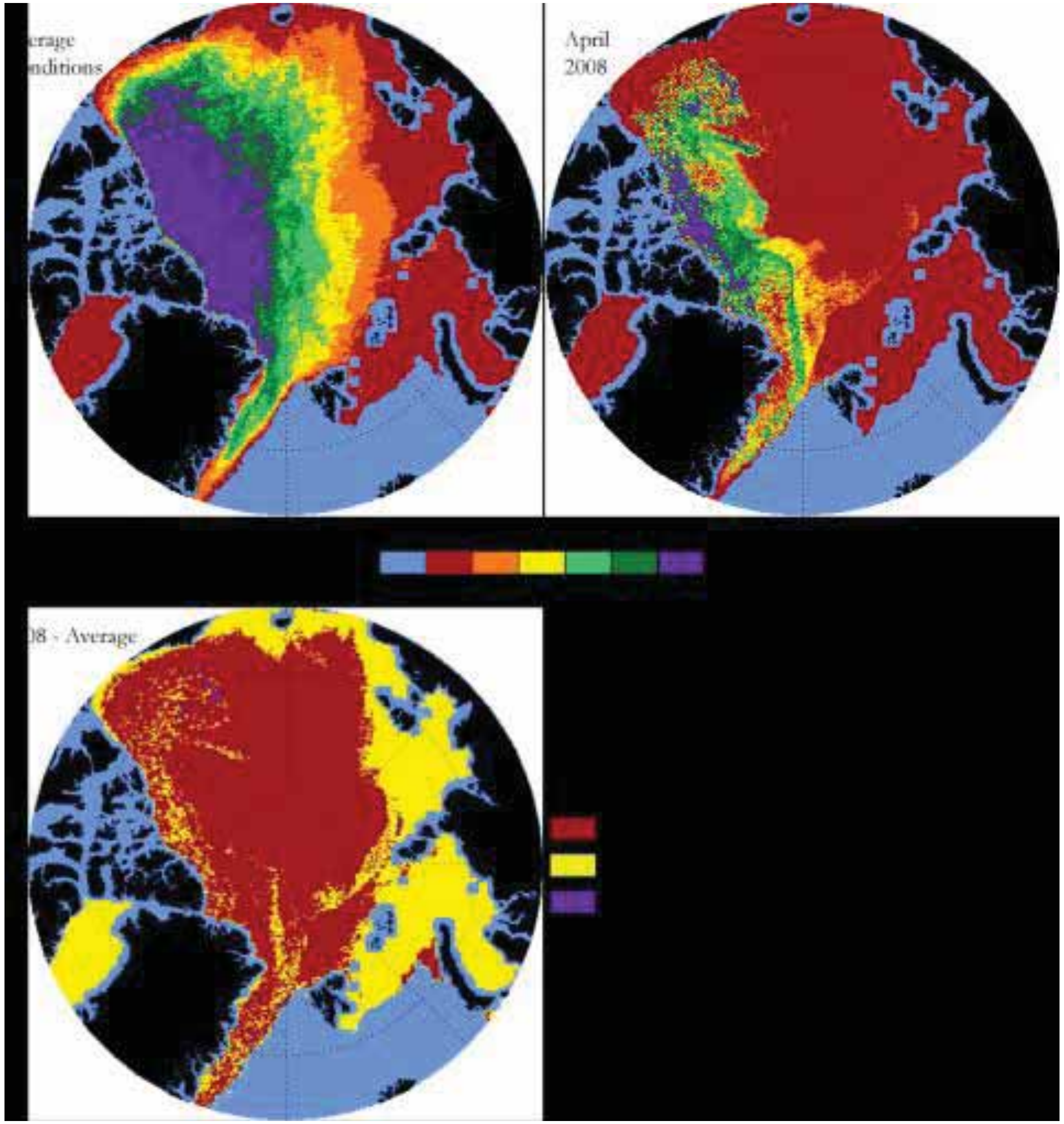
- Climate system much more sensitive, non-linear and dynamic than previously believed

- May display emergent behaviour



Is change already faster than forecast?


Percentage Multi-year Ice
May 19, 2008
Greenland
Russia
Alaska
Percentage Multi-year Ice
5 - 20
21 - 40
41 - 60
61 - 80
81 - 100
Ice Extent
Land


April
2008
Average

One Example of Threshold?

Reductions in sea ice drive T increases

Lawrence et al. 2008

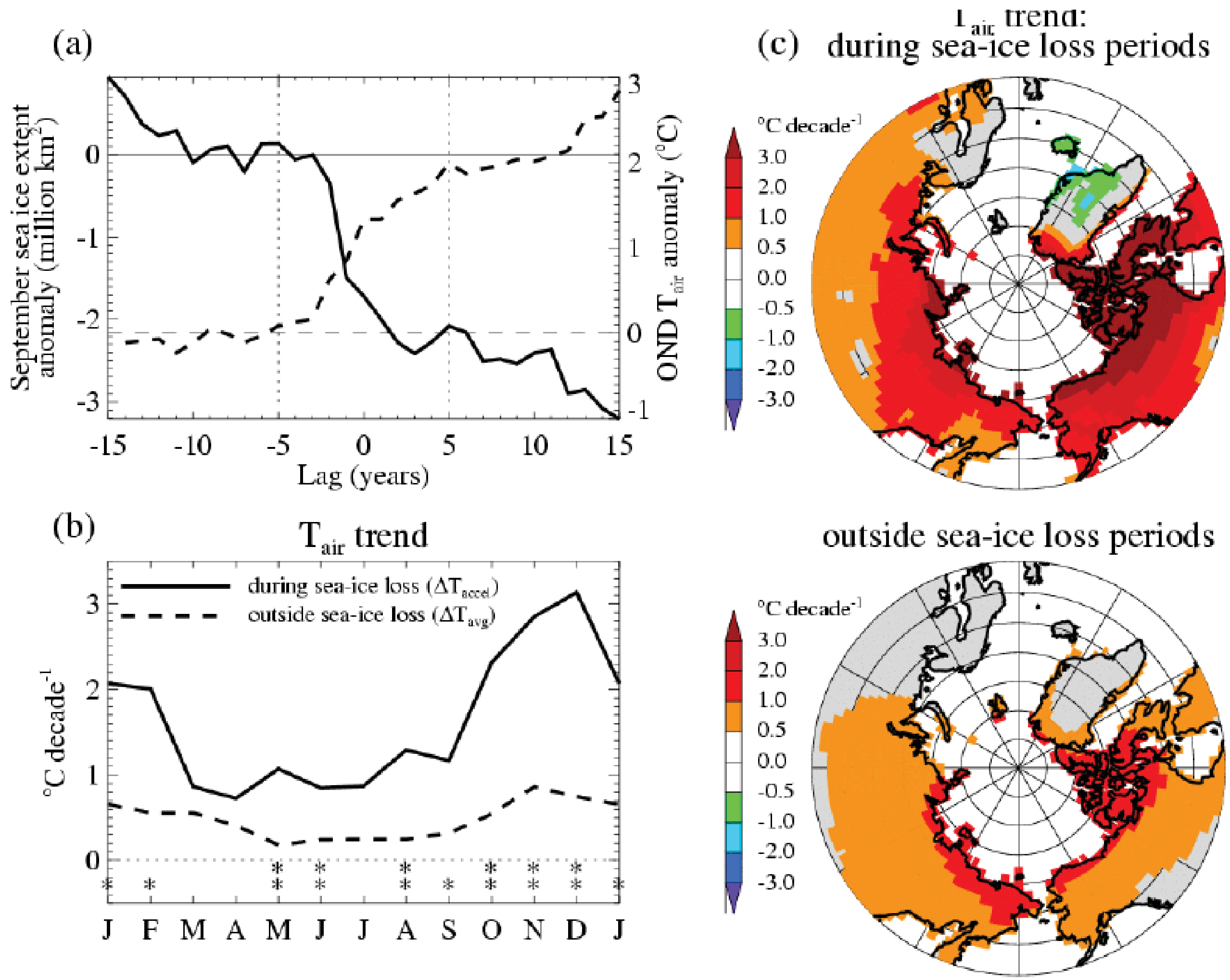
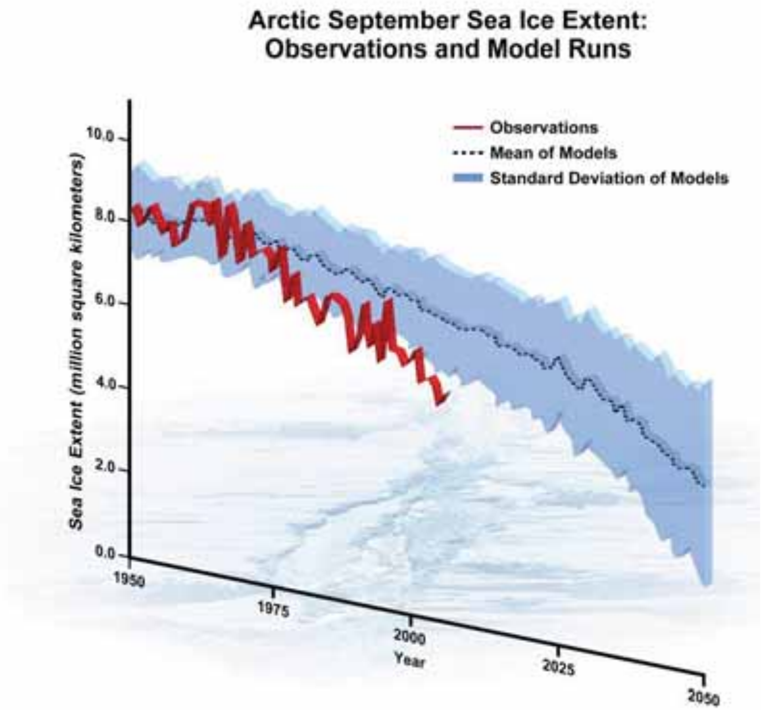
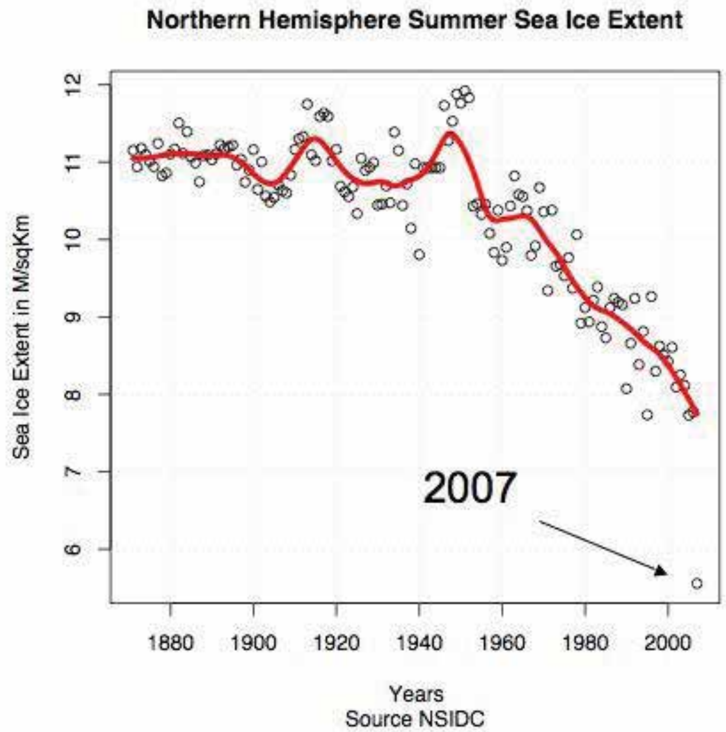


Figure 1: (a) Composite lagged time series of September sea ice extent (solid line) and OND T_{air} (dashed line) over Arctic land area (65°-80°N, 60°-300°E). Composites are centered around the mid-points of the nine rapid sea ice loss events seen in the CCSM3 A1B simulations. Results shown as anomalies from the average of years −10 to −5. (b) Average monthly Arctic land air temperature trends during rapid sea ice loss periods and outside sea ice loss periods. Trend is statistically significant at the 90% (*) and 95% (**) levels. (c) Maps of air temperature trends for OND during and outside abrupt sea ice loss periods.

Example: models unable to recreate trends in sea ice reduction

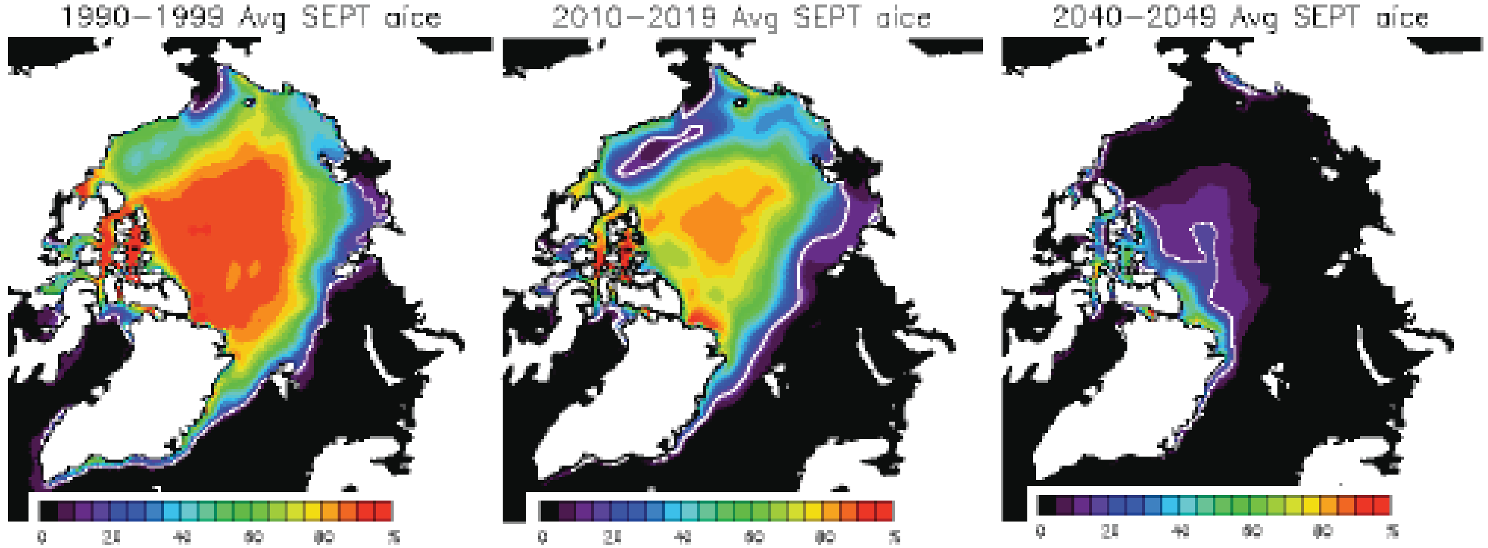


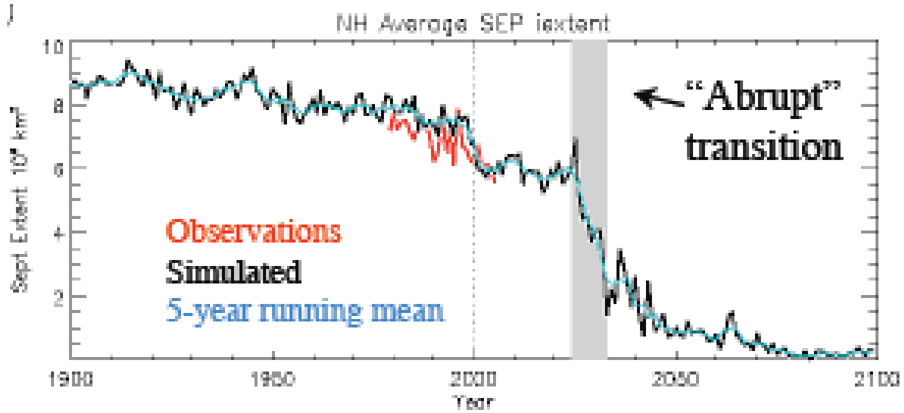
Stroeve et al. 2007, GRL



Modelled sea ice reduction shows abrupt transition

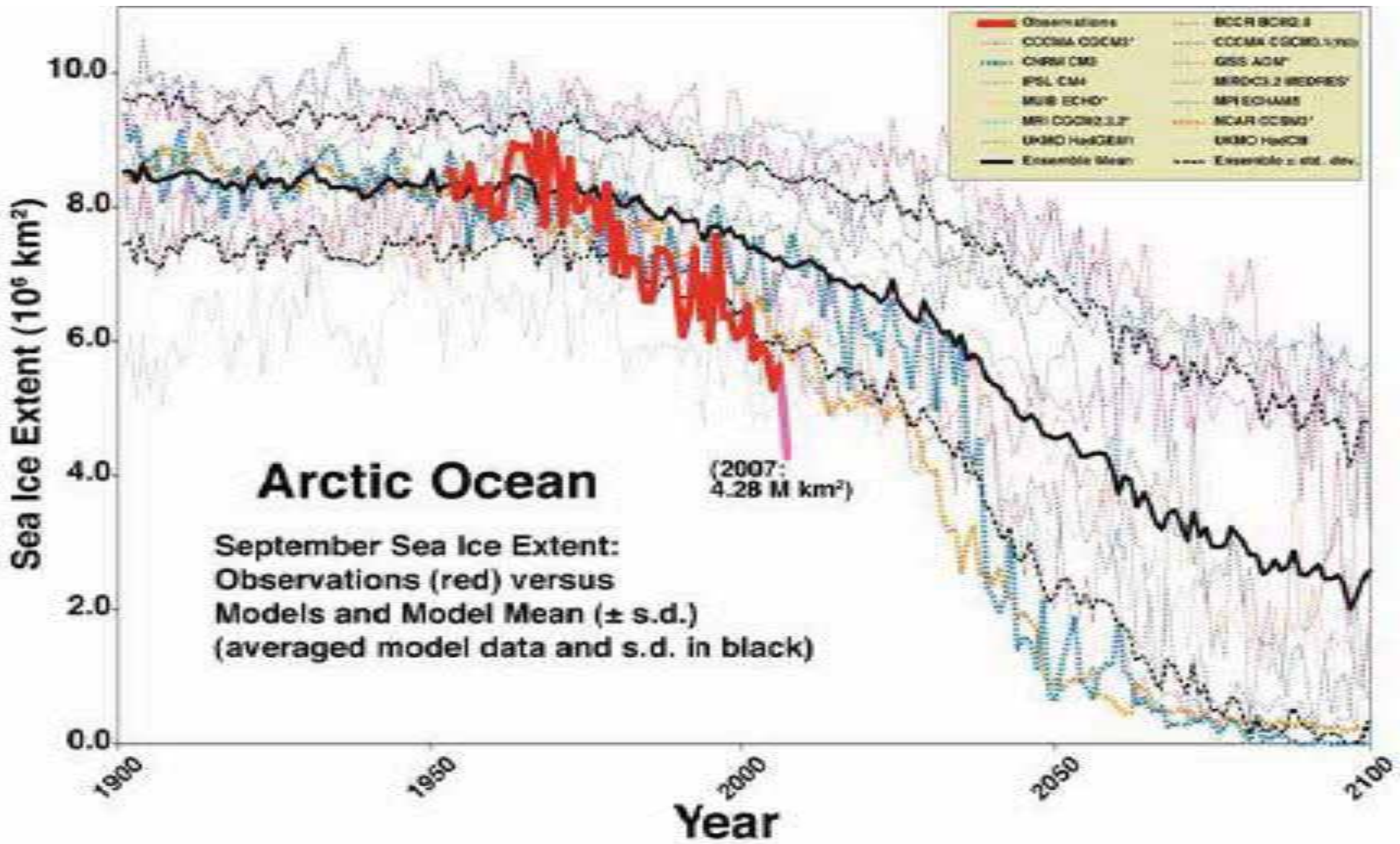
September Sea Ice Conditions





- Gradual forcing results in abrupt ice transitions
- From 80 to 20% extent in 10 years.
- Winter maximum shows
  - Smaller, more gradual decreases

(Holland et al., 2006)


Sea Ice Extent (10⁶ km²)
10.0
8.0
6.0
4.0
2.0
0.0
1900
1950
2000
2050
2100
Year
Observations
Ensemble Mean
Arctic Ocean
(2007: 4.28 M km²)
September Sea Ice Extent:
Observations (red) versus
Models and Model Mean (± s.d.)
(averaged model data and s.d. in black)

Reasons for uncertainty

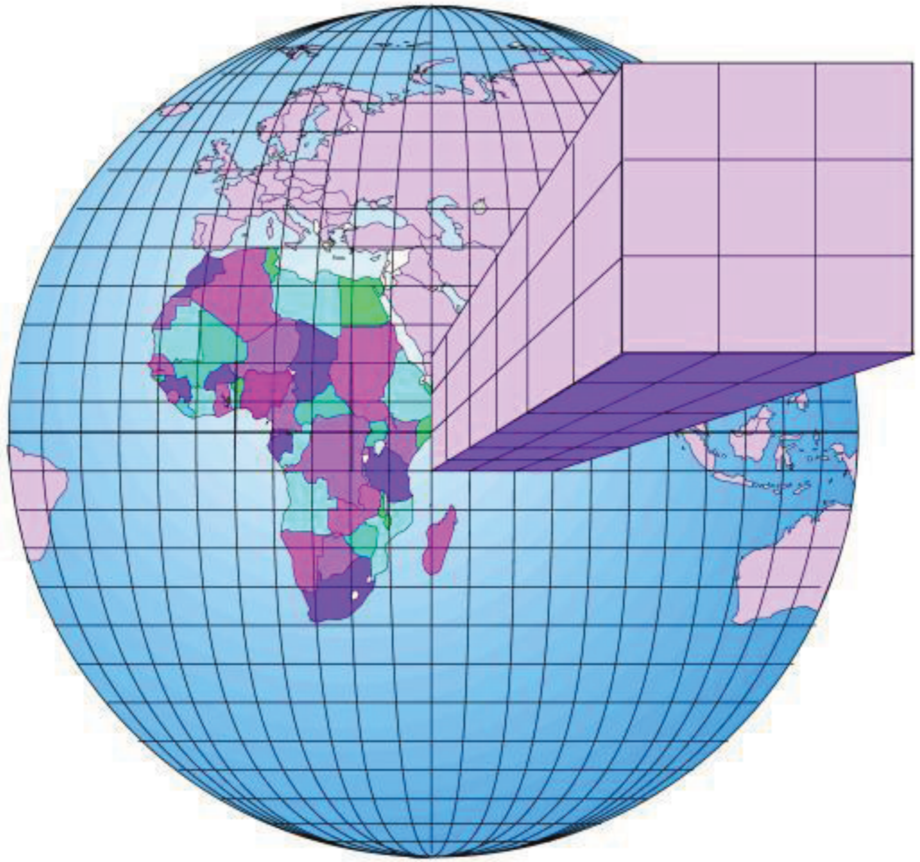
- The construction of GCMs

Types of Models

- Energy Balance Models (EBMs) – Surface temperature as a result of energy balance
  - Zero-Dimension – Whole Earth
  - One-Dimension – Earth in zonal bands with latitudinal heat transfer
  - Two-Dimensions – Lat/Long or Latitude/Altitude changes
- Statistical –Dynamical Models (SDMs)
  - Use parameterized input equations to describe changes through time
- Radiative Convective Models (RCMs)
  - Radiative processes in vertical columns
- General Circulation Models (GCMs)
  - Use physical laws to drive all changes
  - Coupled Ocean-Atmosphere GCMs

What do models consist of?
Parameterisations

- Some climate processes, e.g. clouds, occur at scales smaller than the individual grid boxes
- These processes are not explicitly resolved by the basic equations
- Such processes are represented through other variables which are explicitly resolved in the basic equations (parameterisation)
- Includes radiation, convection, diffusion, land-use
- **GCMs treat the climate system as a reductionist problem**



Reasons for uncertainty

- Model uncertainty
- Forcing uncertainty

Sources of GCM uncertainty

Theoretical Limitations

- Initial Condition Uncertainty (links between system elements; matters only if chaos exists at all spatial scales within the system; emergence likely)

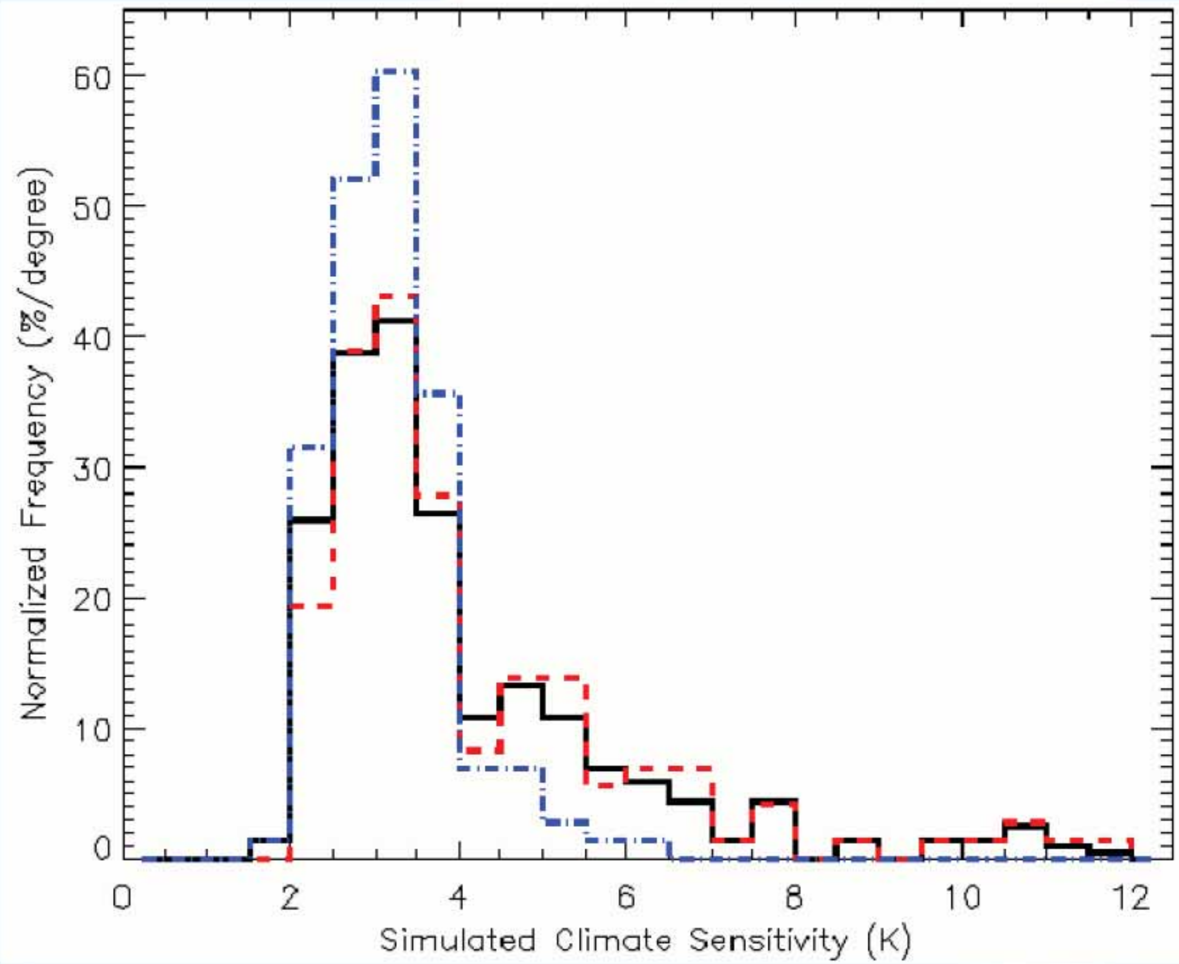
Practical Limitations

- Forcing Uncertainty
- Model Inadequacy (understanding of processes poor; parameterisation required)
- Model Uncertainty (even with ensembles of model runs, no guarantee that uncertainty not built in to models)

"The present generation of climate models may not have captured significant aspects of past climates because the experiments have not been run, because exploration of model and initial condition uncertainty has been insufficient, because their resolutions are too low or because they do not include the relevant fundamental processes"

Harrison and Stainforth, *Eos*, 2009.

Climate sensitivities from climate*prediction*.net



The frequency distribution of simulated climate sensitivity using all (2,578) model versions (black), all model versions except those with perturbations to the cloud-to-rain conversion threshold (red), and all model versions except those with perturbations to the entrainment coefficient (blue).

Sensitivity is the equilibrium response of the global mean temperature of doubling atmospheric levels of carbon dioxide.

Stainforth et al, Nature, 27 Jan '05

Reasons for uncertainty

- How do we treat complexity in nature?
- Philosophy of science

Introduction

- Emergence and Reductionism seen as two competing explanatory methodologies
- Much debated in physics, chemistry, biology, ecology
- Perhaps less so in some other subjects
- Implications for the success of climate modelling and the ways in which we have attempted to predict future evolution of the climate system

Reductionism

- **Define:** understanding of complex systems can be gained by examining the component parts of the system

- **Ontological reductionism** argues that all that exists are the fundamental constituents of matter, or entities that are determined by them

- **Epistemological reductionism**, on the other hand, argues that theories and conceptions about macroscopic entities can be reduced to theories about fundamental constituents

- Reductionism therefore suggests that a fundamental theory is 'deeper', and has more explanatory power and provides a deeper understanding of the world than one using alternative methods

Problems with reductionism

- Intertheoretic reductionism (where one subject is reduced to the fundaments of another) is often problematic

- Chemistry cannot be derived from the Schrödinger wave equations (Hendy 1998) and quantum wave functions cannot be used to support chemical inferences (Silberstein 2002)

- **Logical flaw:** The most fundamental theory which science possesses (and to which all other phenomena might be expected to reduce) is quantum theory, in which the system states display entanglement. This means that the state of the system is not constructed by the states of its parts.

- Reductionism therefore provides us with analysis, rather than synthesis, of complex systems

- Other practical problems too (non-linearity; equifinality; intractability etc.)

What is the alternative?

Emergence

- Define: Structures that are not amenable to reductionist analysis. Suggest that explanation is scale-dependent in that our best understandings follow from the examination of parts of complex systems at the scale at which we are interested

- Macroscopic phenomena “possess…*relatively autonomous qualities* and (satisfy) a set of *relatively autonomous relations* which effectively constitute a set of *macroscopic causal laws*” (Bohm 1957, p.50; emphasis in original)

- “The behaviour of large and complex aggregates of elementary particles…is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear” (Anderson, 1972, p.396)

- “The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question” (Anderson, 1972, p. 393)

- Deutsch (1998 p. 24) sums up the shortcomings of reductionism by suggesting that it “misrepresents the structure of scientific knowledge. Not only does it assume that explanation always consists of analysing a system into smaller, simpler systems, it also assumes that all explanation is of later events in terms of earlier events; in other words, that the only way of explaining something is to state its *causes*” (emphasis in original)

Since the macroscopic structures of a complex system are insensitive to microscopic changes in that system we can only understand the large-scale by analysing the *emergent* phenomena operating at that scale

Emergent properties are *qualitative* structures rising from the organization of *quantitative* phenomena (Bohm, 1997)

The idea of emergence becomes a powerful tool against the reductionists’ argument since some systems may be ‘more than the sum of their parts’ requiring higher level theories to understand them

Implications of this uncertainty

Implications

- Future change may be very rapid (as it has in the past)
- GCMs may not be able to predict such change
- Models not good at recognising regional variability in response to feedbacks
- Responses such as sea level change may be very rapid

Climate change as emergent behaviour

- Emergent behaviour is characteristic of dynamic systems where the large-scale behaviour of the system is effectively independent of the behaviour of the small-scale components of that system.

- This means that reductionism may not be a valid response to complexity in natural systems.

- Does this mean that our General Circulation Models (GCMs), which are reductionist, are unable to account for the likely future dynamic evolution of the climate system?

- Their inability to mimic the rapid climate shifts in the past (and some broad scale elements of the present climate system) may mean that they are not preparing us for threshold responses

- However, It is not only the crossing of thresholds (sea ice?) that we should be aware of

- Rapid climate change could occur by modulating the frequency and duration of climate cycles that are already well-known (eg ENSO, NAO)

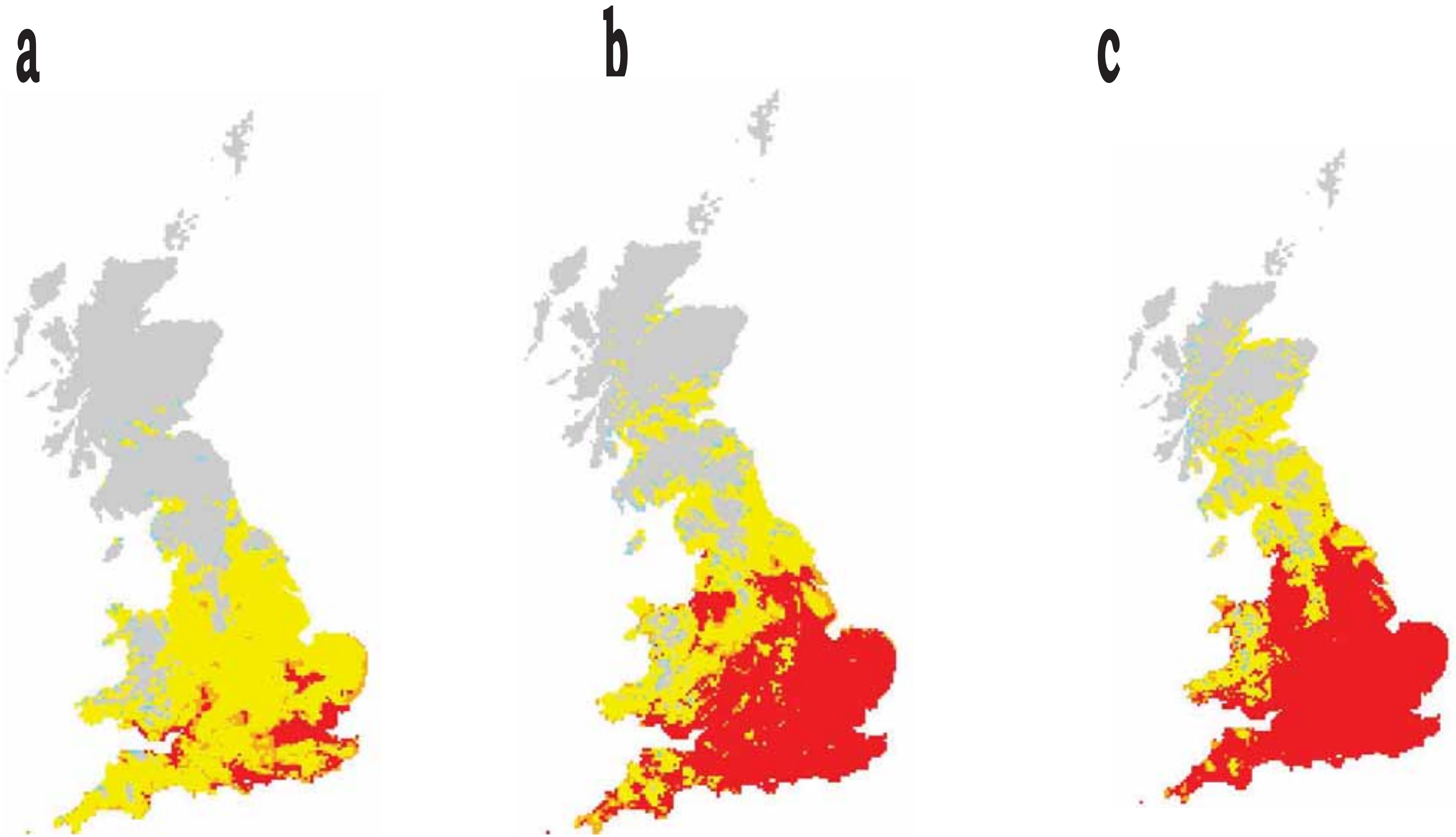
- Could also be strengthening long-term oscillations associated with climate variability which have previously tended to operate on long timescales (e.g. Dansgaard-Oeschger type events)

- Could even have the emergence of completely new modes of oscillation under conditions of AGW caused by reorganisation of the oceans

Example of consequences: Planning for impacts of Climate Change on Health

- Vector borne disease (malaria, tick infestation)
- Salmonella organisms due to high temperature
- Water contamination (algal blooms)
- Increased mortality follows hotter summers but decreased mortality with warmer winters
- Increased air pollution with blocking anticyclones

Figure 3.2. Projected future risk maps for malarial transmission under a medium-low (a, b and c) and a medium-high (d, e andf) climate change scenario. Maps show risk for the period 2020s (a and d), 2050s (b and e) and 2080s (c and f). Based on UKCIP02.



Robert Maynard 2007

So, future change not well modelled

- Especially at regional scale, and especially when dealing with precipitation

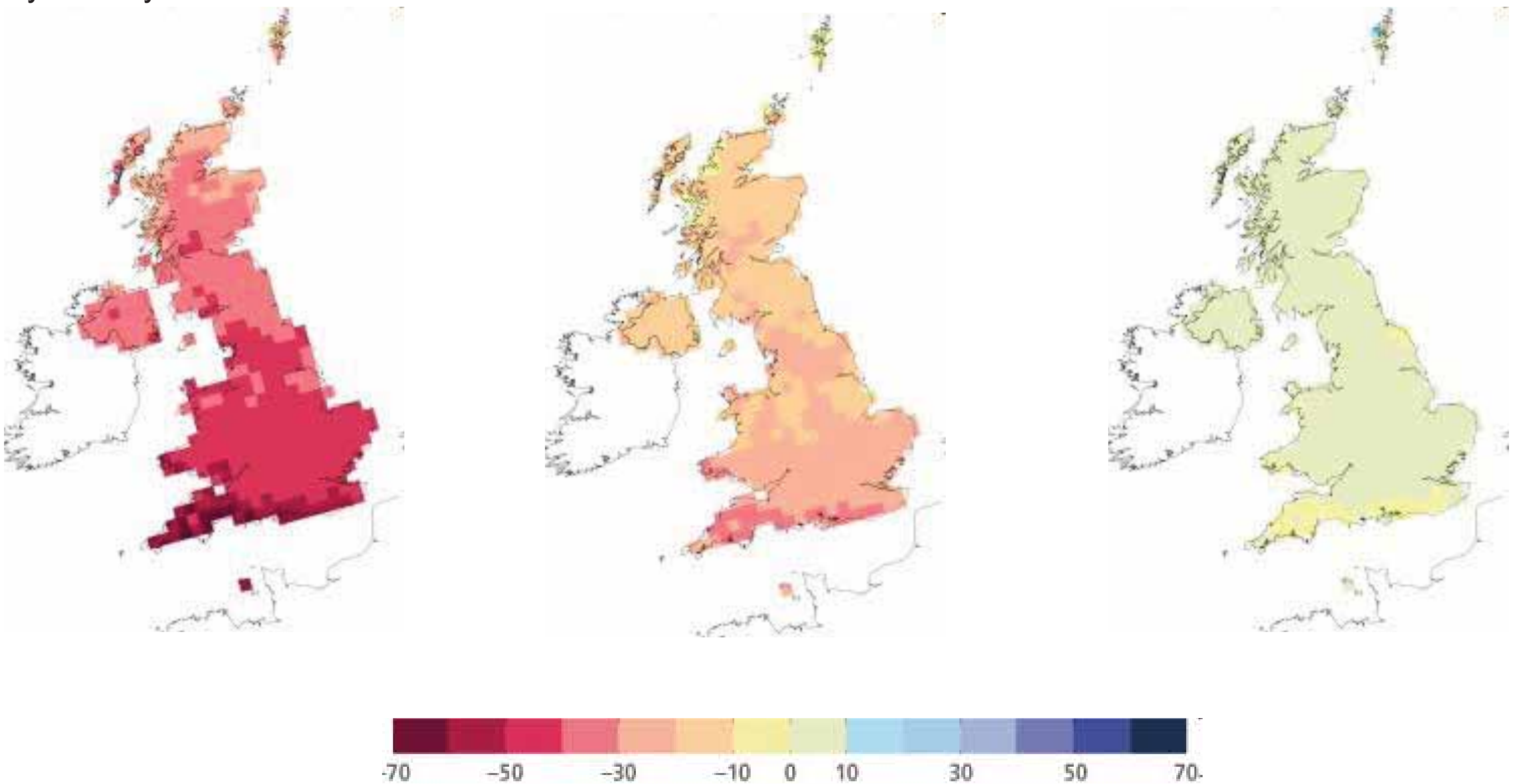
- “Why would anyone think that combining conflicting models might yield a decision-relevant PDF?” (Lenny Smith 2008)

UKCP09: Change in summer mean precipitation (%) for the 2080s under a medium emissions scenario

10% probability level:
very unlikely to be less than

50% probability level:
central estimate

90% probability level:
very unlikely to be greater than



The problem with modelling: UKCIP09

- Two questions: 1) Can we produce ***objective*** probabilities for detailed future climate?

  2) Can we produce ***relevant subjective*** probabilities for detailed future climate?

- We cannot produce objective probabilities (UKCIP accept this).

- We only have one climate so we can't derive statistics for climate change in the 21st century. We have many observations of weather but no observations of how the earth's climate could change under any emission scenario for the 21st century.

- Since we don't have many versions of the earth on which to experiment we use models. There is general agreement that the models are not equivalent to the real earth's climate2 so multiple simulations of a model don't give objective probabilities.

- So what about relevant subjective probabilities?

- The UKCIP08 state that their probabilistic climate projection is “a subjective probability, providing an estimate based on the available information and strength of evidence (similar to horse-racing odds)”.

- The problem here relates to the basis of subjectivity (the “prior” in Bayesian statistics)

- If these “probabilities” were in fact horse racing odds they would be subjective in the sense that they would relate to a particular book keeper and based on his skill and knowledge of the previous behaviour of the horses, the course and of competing book makers.

- But small scale climate forecasts relevant for adaptation decisions, cannot claim the same kind of basis in “expert” opinion. No climate scientist has seen even one, let alone multiple examples of how the earth’s climate could respond to any given scenario of 21st century GHG scenario.

- The subjectivity in the UKCIP08 climate projections comes from the choice of a particular climate model and the choice of how to explore the uncertainties in that model (which is incomplete and inconsistent with other IPCC models).

- Using a different model would give fundamentally different results and that different choices of how to explore uncertainty would completely change the subjective probabilities.

- “It has already been shown that uncertainty within the one model chosen is much greater than explored in the simulations underpinning UKCIP08. The inclusion of some data from other models available worldwide can not resolve these issues” (Dave Stainforth 2009).

- “Why would anyone think that combining conflicting models might yield a decision-relevant PDF?” (Lenny Smith 2008)

- As a result there is no clear way for decision makers to use the UKCIP08 probabilities.

- They are not objective so there is no basis for using them to derive cost functions and thus optimize decisions.

- Neither are they usefully subjective as it is unlikely that any UKCIP08 user will have sufficient knowledge to judge the basis for subjectivity; unlike members of the city judging different economic forecasts.

- Furthermore, if the process were repeated with a different model or with the next generation of models, we have good reason to believe the probabilities would change substantially. In a very real sense they are therefore not decision relevant probabilities.

Ensembles

- In UKCP09 ensembles were used (not so in UKCIP02)

- Ensembles can use different initial conditions (important for daily forecasts but in general less so for longer time scales), use different physics formulations within a single model (the most important aspect of ensemble creation in UKCP09), and use a number of different individual models (the key approach in the 2007 IPCC AR4).

- In practice more than one approach is used within a single ensemble

Ensemble uncertainty

- In an ideal ensemble each probability distribution of each parameter at each future time will provide a true representation of the outcomes possible, and of their likelihoods, under existing uncertainties

- Therefore each member of the ideal ensemble delineates ranges of values within a probability distribution of a parameter, each range having equal probability.

- Thus if somewhere within an ensemble individual neighbouring members predict temperatures of, say, 8.5°C, 9.1°C and 10.3°C then within this perfect ensemble the probability of the temperature lying within the range 8.5 to 9.1°C is the same as that of it lying between 9.1 and 10.3°C, and similarly for all other ranges identified by the ensemble.

- However an ensemble is of finite size and therefore may be too small to explore the full range of possible outcomes, including those beyond the highest and lowest values given by any members. In this perfect ensemble there is therefore the same probability that the observed value of the parameter will lie below the lowest value given as in the range between any two neighbouring members, with the same applying to highest values also.

- This was tested in the early days of ensemble development

- What happened was that far more of the observations than expected statistically lay outside the highest and lowest values of the distributions and far too few within the ranges prescribed by the members themselves (up to 80% of the observations lay outside the ranges of the ensembles).

- In these early ensembles the spread of values produced by an ensemble was far *too narrow*, with the level of forecast uncertainty *underestimated* by the ensembles, a result only partly dependent upon the relatively small size of the ensembles (typically similar to the size used in the AR4, or perhaps a little smaller – nine members was a common early ensemble size).

- Despite this, experienced forecasters thought that the ensemble spread was *too wide*. The level of confidence thought to exist in model predictions by experienced forecasts was thus misplaced – the forecasters were *overconfident* in these predictions.

- In UKCP09 only the Hadley Centre model is used, although information from 12 other models is employed in informing the calculation of the distributions. UKCP09 ensembles have 11 members.

- The ensemble size come near to matching that of climateprediction.net, with the likely certainty that all distributions in UKCP09 are *too narrow*.

Downscaling from GCMs

- Downscaling is a way to obtain higher spatial resolution output based on GCMs
- Options include:
  - Combine low-resolution monthly GCM output with high-resolution observations
  - Use statistical downscaling
    - Easier to apply
    - Assumes fixed relationships across spatial scales
  - Use regional climate models (RCMs)
    - High resolution
    - Capture more complexity
    - Limited applications
    - Computationally very demanding

Statistical Downscaling

- Statistical downscaling is a mathematical procedure that relates changes at the large spatial scale that GCMs simulate to a much finer scale
  - For example, a statistical relationship can be created between variables simulated by GCMs such as air, sea surface temperature, and precipitation at the GCM scale (predictors) with temperature and precipitation at a particular location (predictands)

Regional Climate Models (RCMs)

- These are high resolution models that are “nested” within GCMs
  - A common grid resolution is 50 km
    - Some are higher resolution
  - RCMs are run with boundary conditions from GCMs
- They give much higher resolution output than CCMs
  - Hence, much greater sensitivity to smaller scale factors such as mountains, lakes

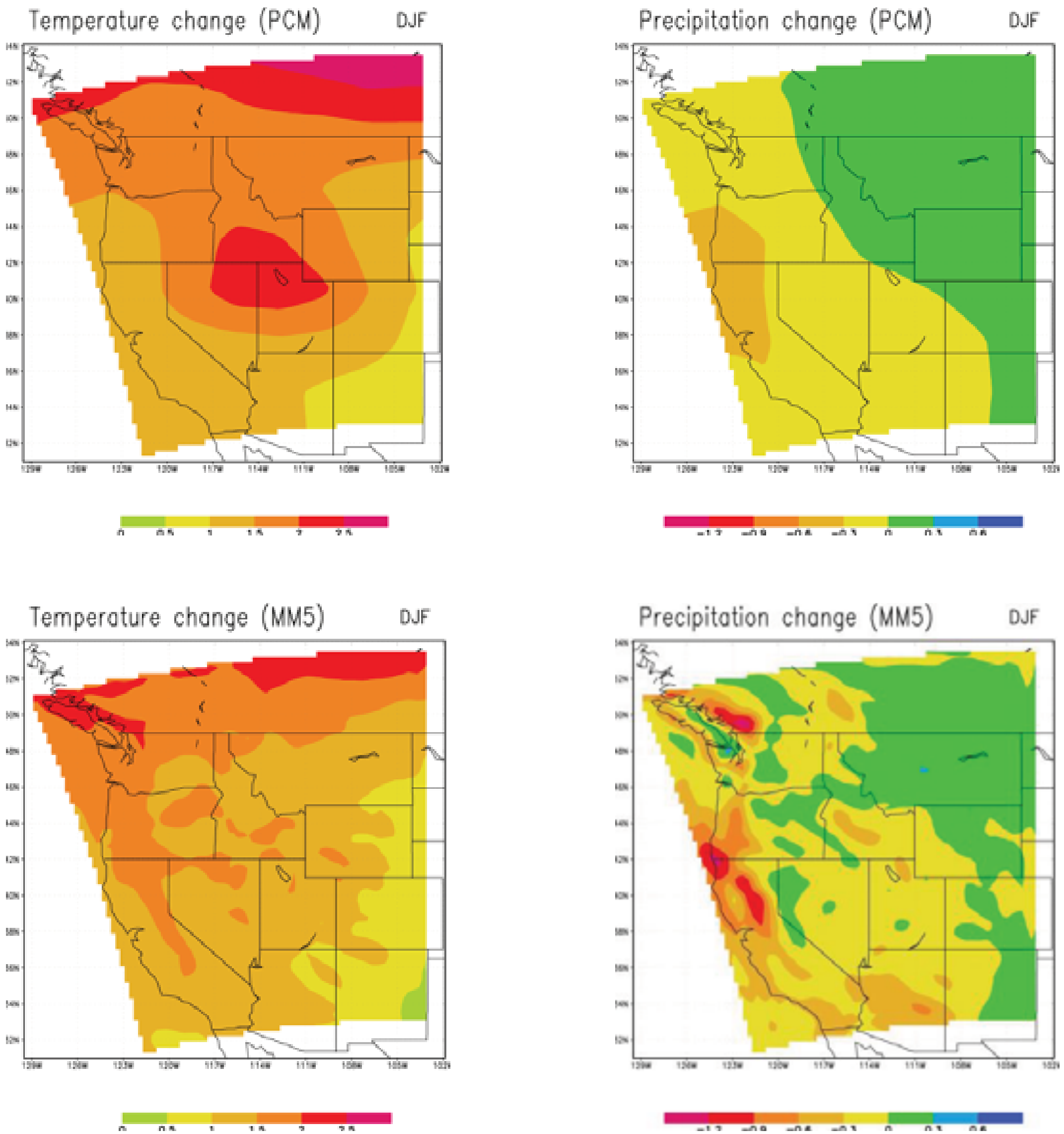
GCM vs. RCM Resolution

Temperature

Precipitation

GCM

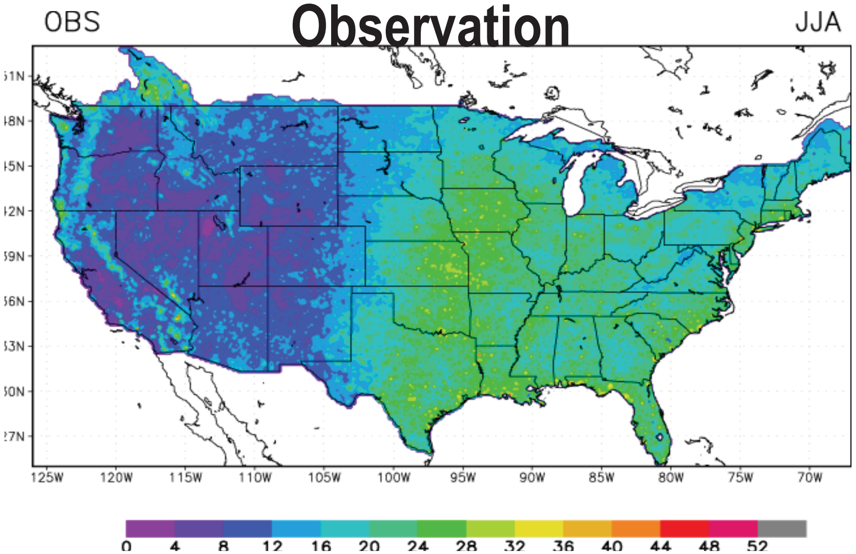
RCM

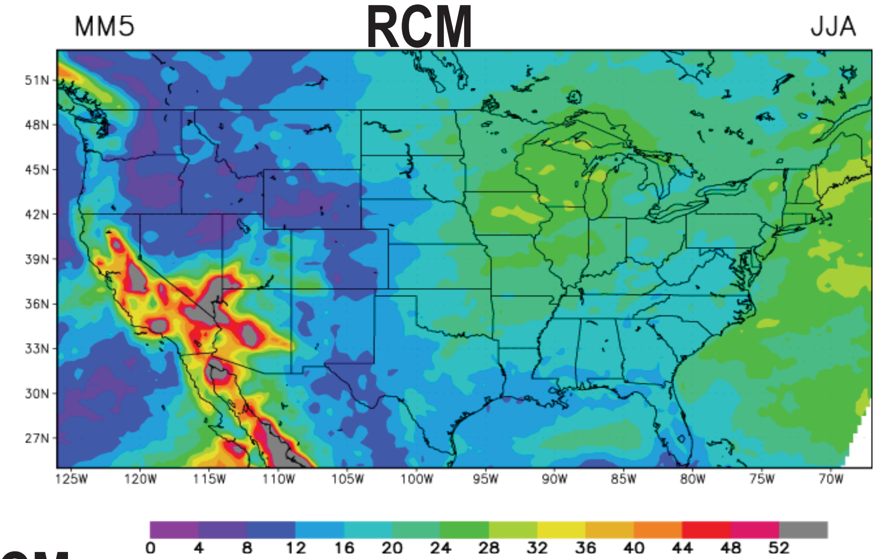


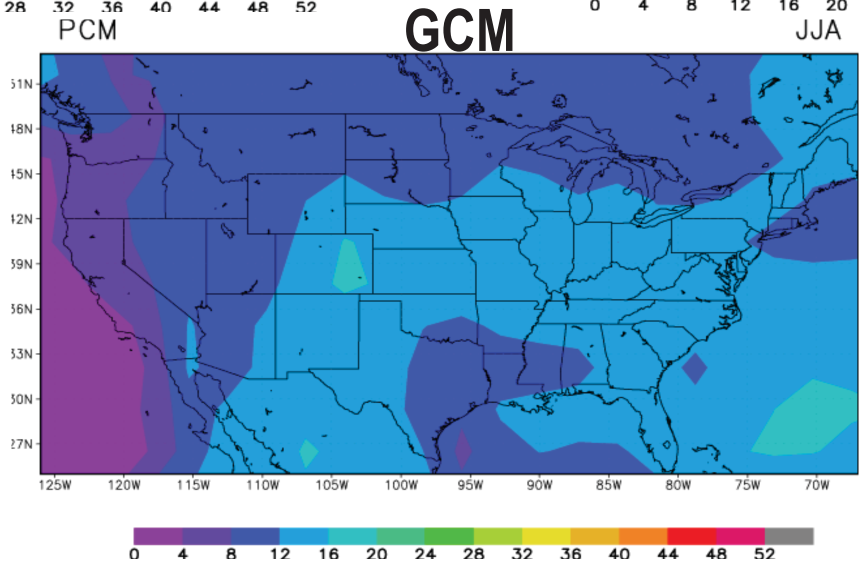
Implications for user groups

- Modelling at the regional scale has associated uncertainties
- Climate change risk management must accept and take account of these problems
- Developing baseline data sets is an important step

Extreme Precipitation (JJA)







Combine Monthly GCM Output with Observations

- An approach that has been used in many studies
- Typically, one adds the (low resolution) average monthly change from a GCM to an observed (high resolution) present-day “baseline” climate
  - 30 year averages should be used, if possible
    - e.g., 1961-1990 or 1971-2000
    - Make sure the baseline from the GCM (i.e., the period from which changes are measured) is consistent with the choice of observational baseline

Combining Monthly GCMs and Observations

- This method can provide daily data at the resolution of weather observation stations
- Assumes uniform changes within a GCM grid box and over a month
  - No spatial or daily/weekly variability

Statistical Downscaling (continued)

- Is most appropriate for
  - Subgrid scales (small islands, point processes, etc.)
  - Complex/heterogeneous environments
  - Extreme events
  - Exotic predictands
  - Transient change/ensembles
- Is not appropriate for
  - Data-poor regions
  - Where relationships between predictors and predictands may change
- Statistical downscaling is much easier to apply than regional climate modeling

Statistical Downscaling (continued)

- Statistical downscaling assumes that the relationship between the predictors and the predictands remains the same
- Those relationships could change
- In such cases, using regional climate models may be more appropriate

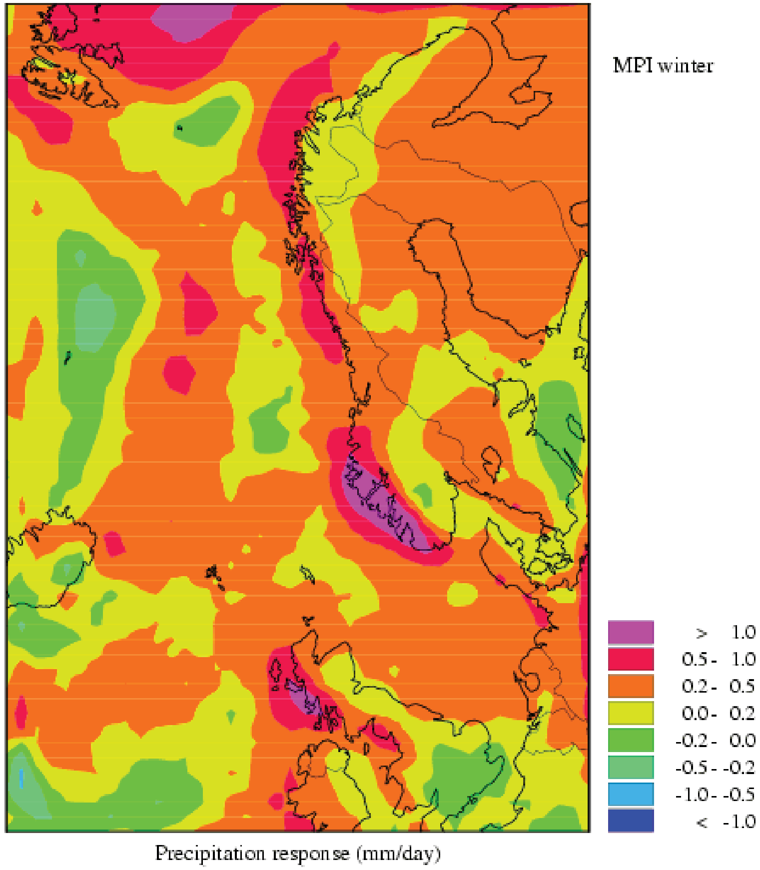
RCM Limitations

- Can correct for some, but not all, errors in GCMs
- Typically applied to one GCM or only a few GCMs
- In many applications, just run for a simulated decade, e.g., 2040s
- Still need to parameterize many processes
- May need further downscaling for some applications

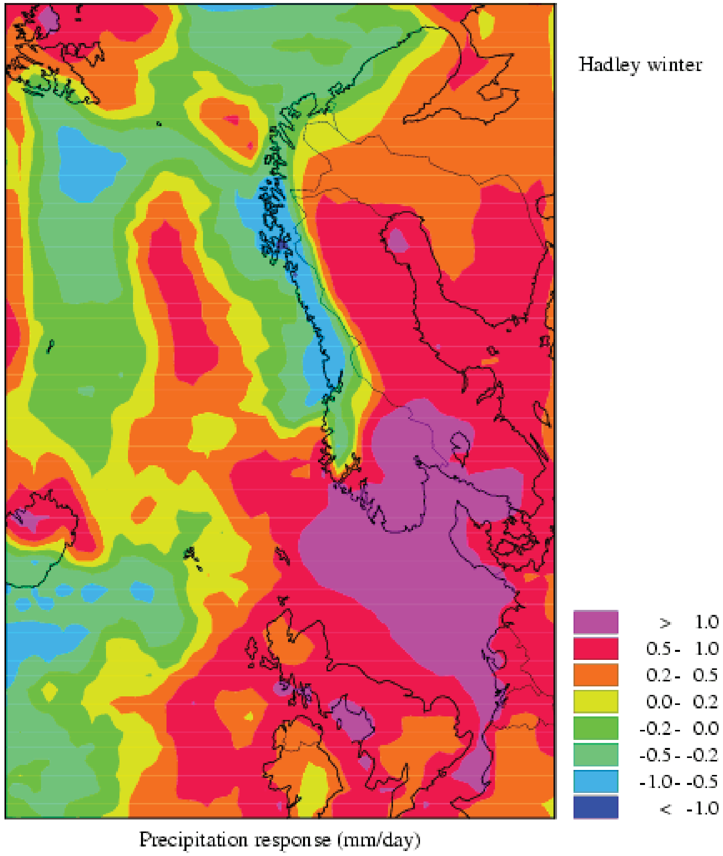
Climate System Unpredictability and model deficiency

RegClim Regional Climate Model (HIRHAM)
Precipitation response winter DJF (mm/day)

MPI (GSDIO, 1980-1999 +50)



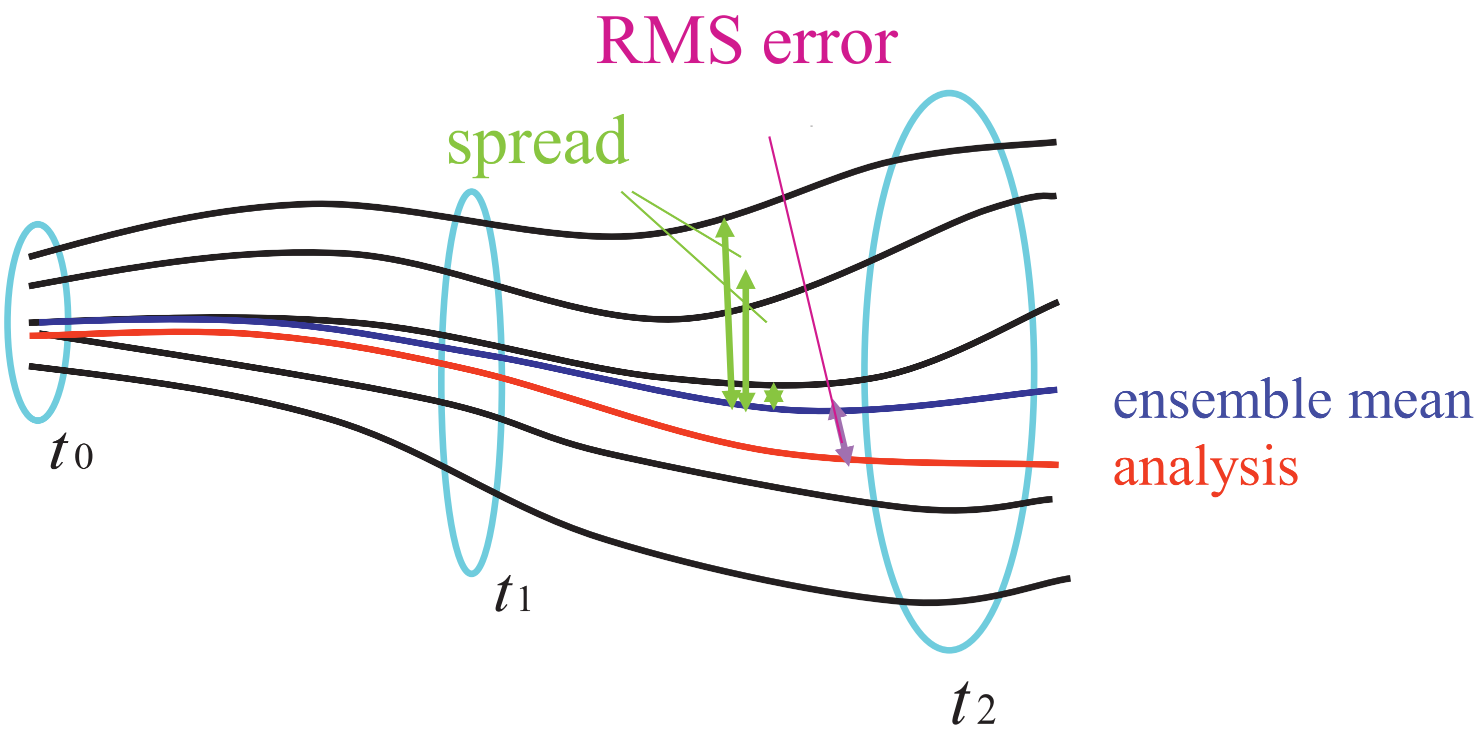
Hadley (A2, 1961-90 + 110)



Is this due to model uncertainty only?
Can sample uncertainty be an explanation too?

Glenn Shutts

Representing initial state uncertainty by an ensemble of states



- Represent initial uncertainty by ensemble of atmospheric flow states
- Flow-dependence:
  - Predictable states should have small ensemble spread
  - Unpredictable states should have large ensemble spread
- ***Ensemble spread should grow like RMS error***

Glenn Shutts

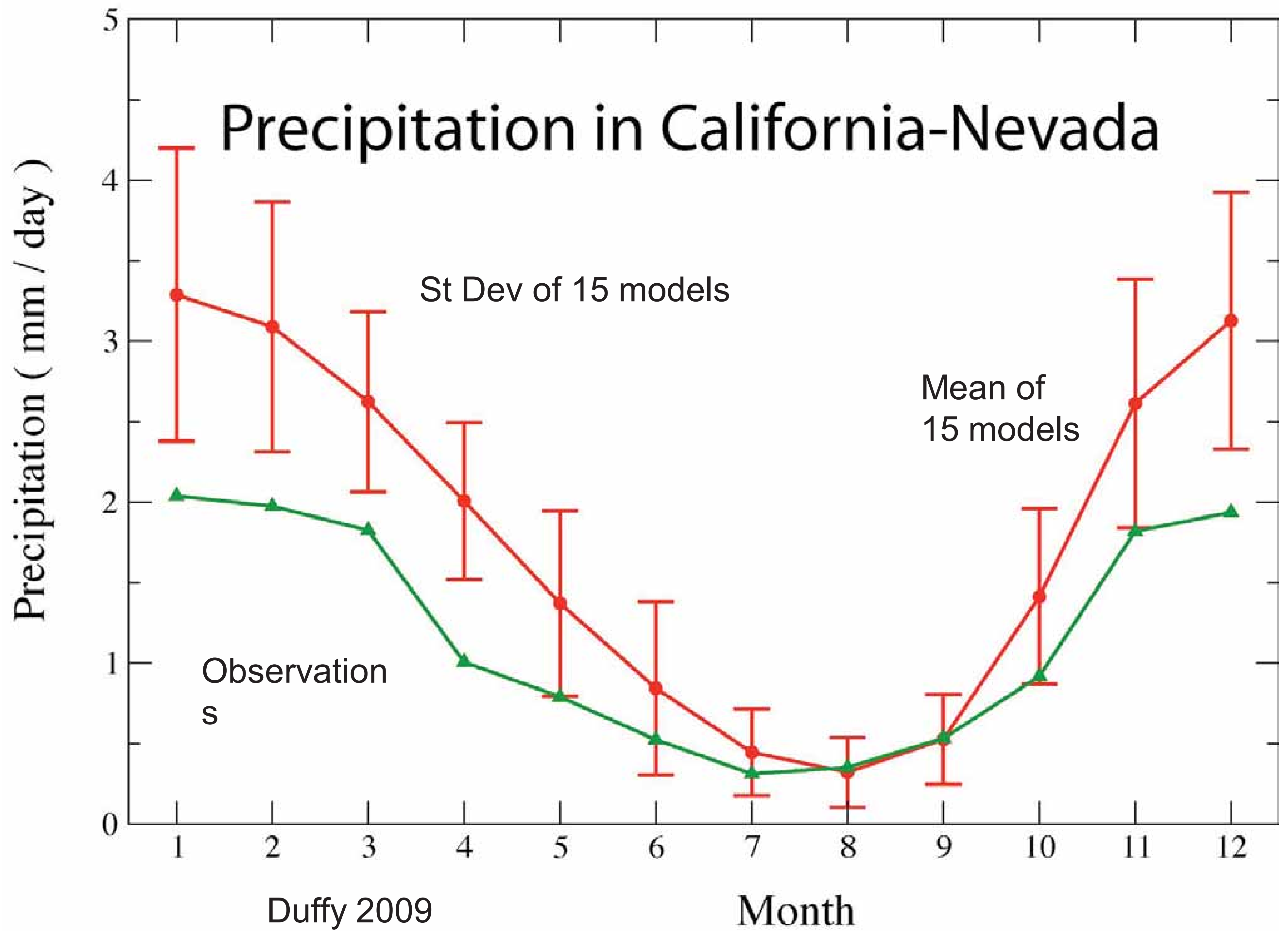
Manifestations of model error

In medium-range:

- Under-dispersion of ensemble system (Over-confidence)
  - Can extreme weather events be captured?

On seasonal to climatic scales:

- Not enough internal variability
  - To what degree do detection and attribution studies for climate change depend on a correct estimate of internal variability?
- Underestimation of the frequency of blocking
- Tropical variability, e.g. MJO, wave propagation
- Systematic error in T, Precip, …


Precipitation in California-Nevada
St Dev of 15 models
Mean of 15 models
Observations
Precipitation (mm / day)
Month
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12
Duffy 2009

Uncertainty in action: Assessing flood risk

Climate scenarios:		*Hydrological change:*		*Change in flood risk:*		
Climate model	→	Catchment hydrology model	→	Flood inundation model:	→	Risk map
				Probability of flooding		
				+		
				Loss estimation		

Increasing uncertainty →

Climate projections of runoff

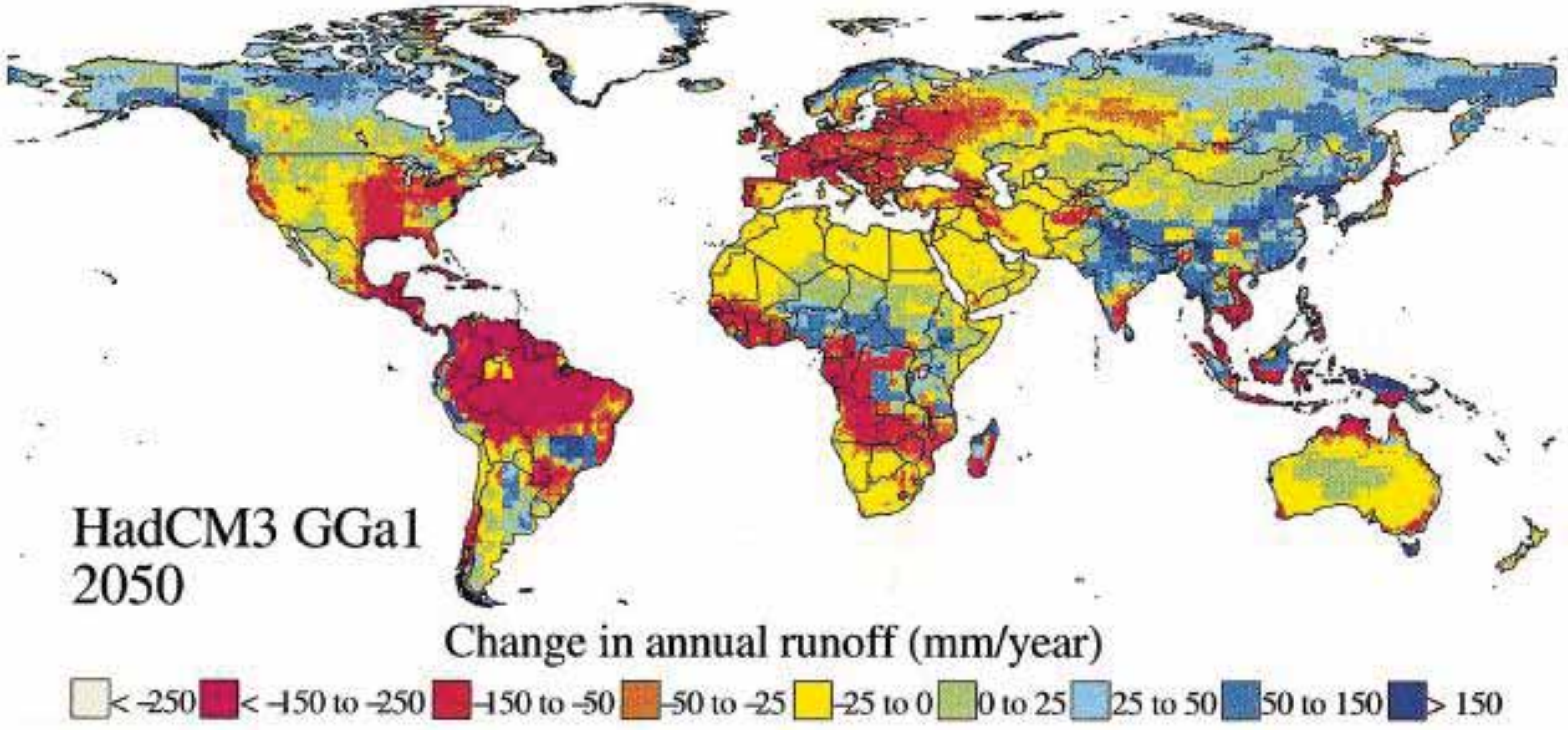
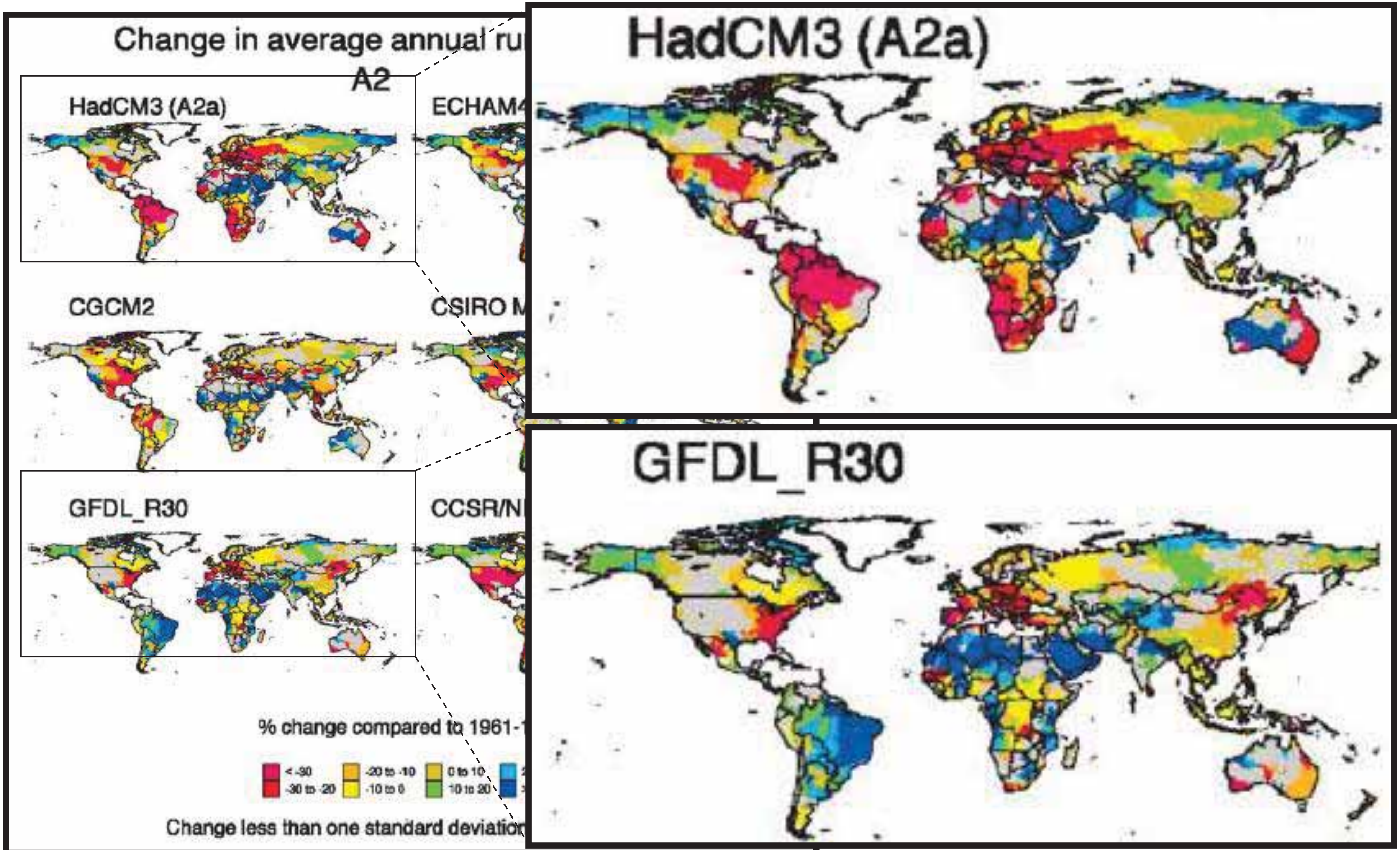
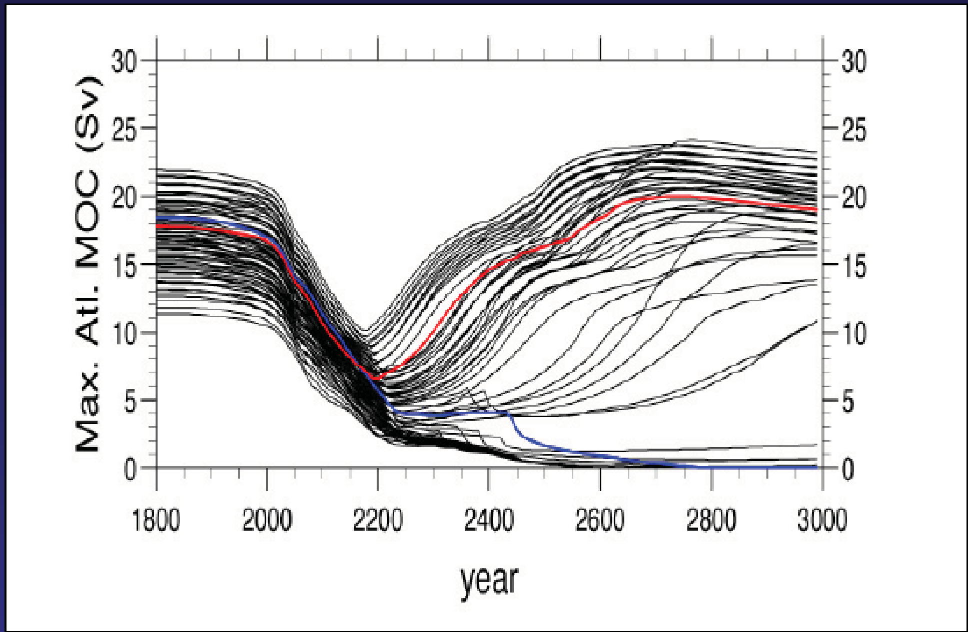


Fig. 2. Change in average annual runoff by the 2050s.

Climate projections of runoff



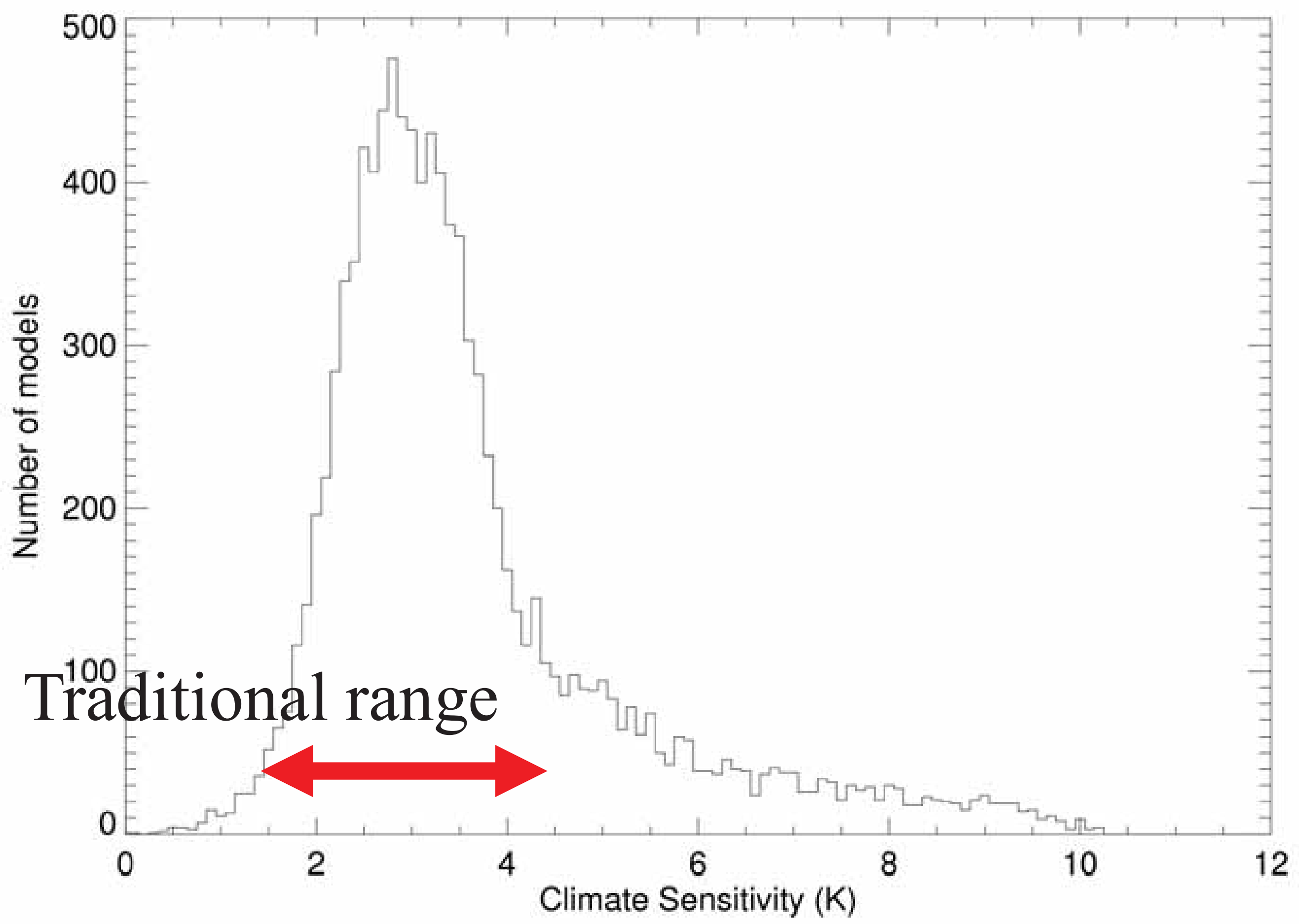
Challenge 3: Climate Uncertainty



AMOC simulated with GENIE-1 (Marsh et al., 2007)

How the climate will change in the future is far from certain. For a particular model, different outcomes will be obtained for different parameter settings in the model ("parameter uncertainty"). The figure shows how the Atlantic Meridional Overturning Circulation (AMOC) might change in the future (for a given warming scenario) in the GENIE model, depending on how various parameters in the model are chosen. To properly assess the model's response, about 10,000 – 100,000 runs would be needed to span the parameter space using naïve Monte Carlo methods.

Future temperatures (warming)?
High risk of substantial warming even with today's greenhouse gas levels: what is a safe stabilisation limit?



climateprediction.net

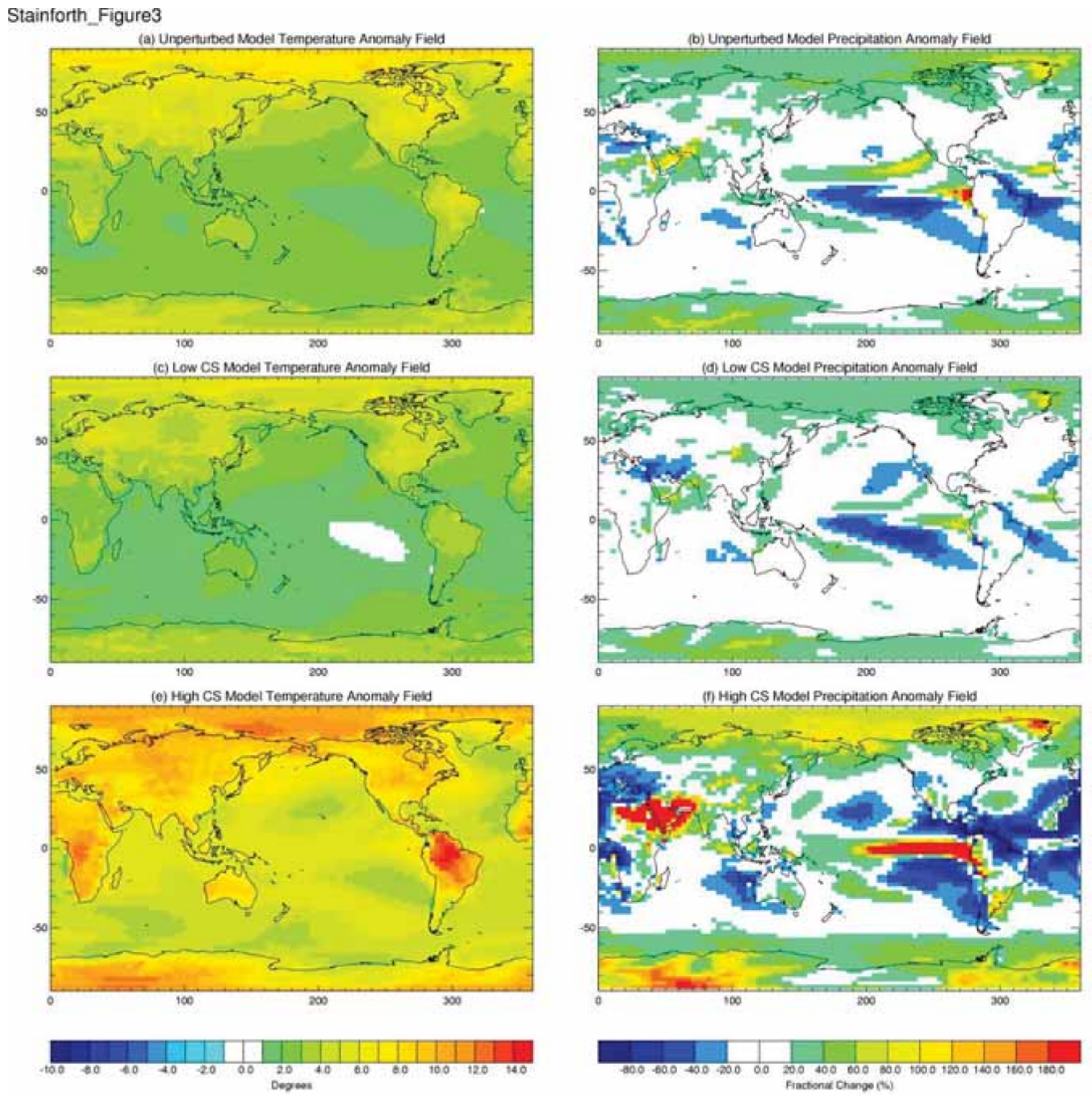
Sylvia Knight

Regional responses: temperature and precipitation

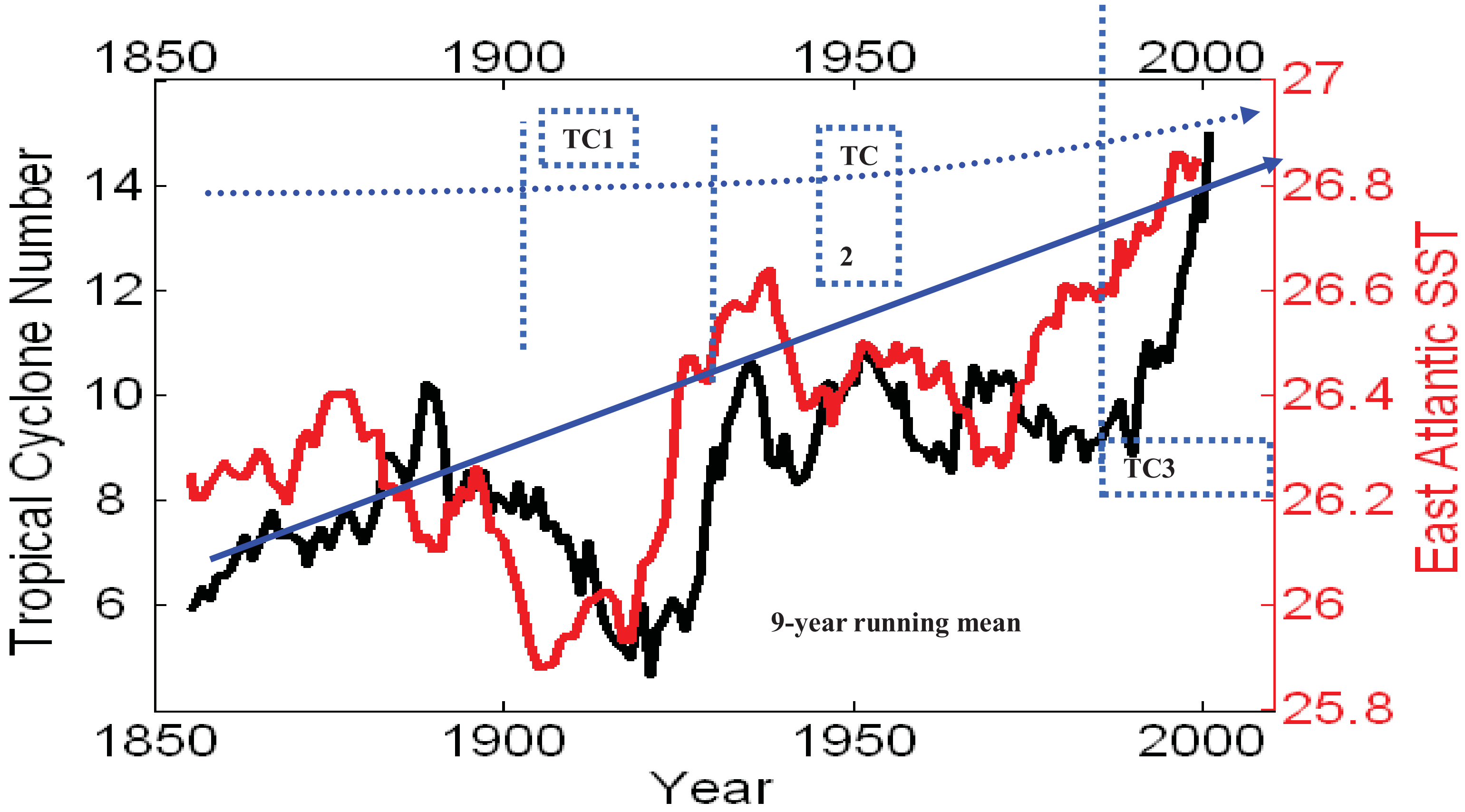
Standard model version

Low sensitivity model

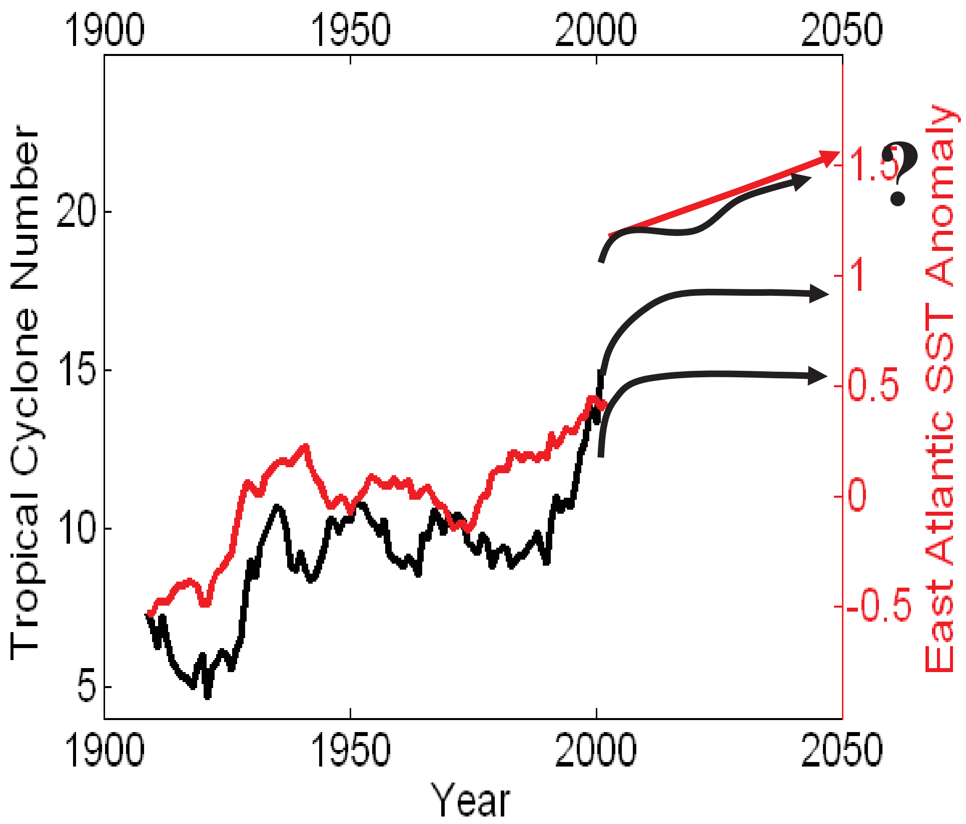
High sensitivity model



Uncertainties in Hurricane Trends



Holland 2006



- Likely that high levels of hurricane activity will stay at similar level.
- Over next 20 years, Oochi et al 2006 suggest increased North Atlantic activity, small increase in intensity globally (other views too!)
- All depends on ENSO

Holland 2006

ENSO

AGW may affect ENSO as both associated with large changes in the earth's heat balance.

Problem: GCMs poorly represent key physical processes (eg clouds and ocean processes) and predictability rare beyond 12 months

Additionally, no GCM reliably simulates El Niño and GHG warming together.