Predicting Climate Change

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Predicting climate change

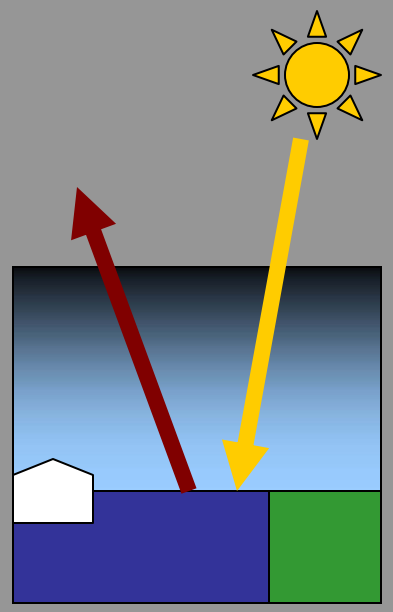
- Simple model of climate system, used as the basis of a "probabilistic" forecast
- Generating a "probabilistic" forecast
  - Problems in quantifying climate sensitivity
  - Benefits of exploiting 20th Century attributable warming due to GHG, transient response over next century
- Non-stabilization scenario vs stabilization scenario
- Various methodologies/approaches being explored
  - Monte Carlo methods
  - Statistical Emulators
  - Ensemble Kalman Filters

Probabilistic climate forecasting

- Benefits of *probabilistic* climate forecasts
  - difficulties in pinning down long term warming
  - Easier to look at current warming rates
- Takes uncertainties seriously
- Much more relevant for risk management approaches

Simple climate model

- **Energy Balance Model**
  - Forcing, F
  - Temperature change, ΔT
- **Two system parameters**
  - Effective heat capacity, c_{eff}
  - Feedback parameter, λ



System in Equilibrium:
No heating

$$c_{eff}\frac{d\Delta T}{dt} = F - \lambda \Delta T$$

Simple climate model

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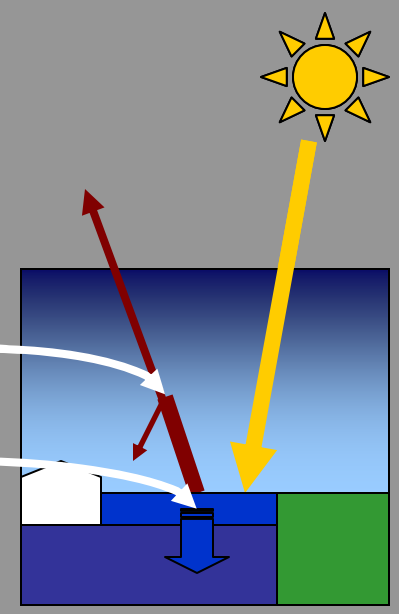

Forced system:
Heating of surface, ocean

$$c_{eff}\frac{d\Delta T}{dt} = F - \lambda\Delta T$$

Climate system uncertainty

- Uncertainty in initial conditions
  - Uncertainty in the measured state of the system
- Uncertainty in forcings
  - Uncertainty in the boundary conditions of the system
    - » Solar radiation
    - » Composition (GHG, volcanic effects)
- Uncertainty in physical response
  - Uncertainty in the parameters governing the system
  - Uncertainty in model formulation

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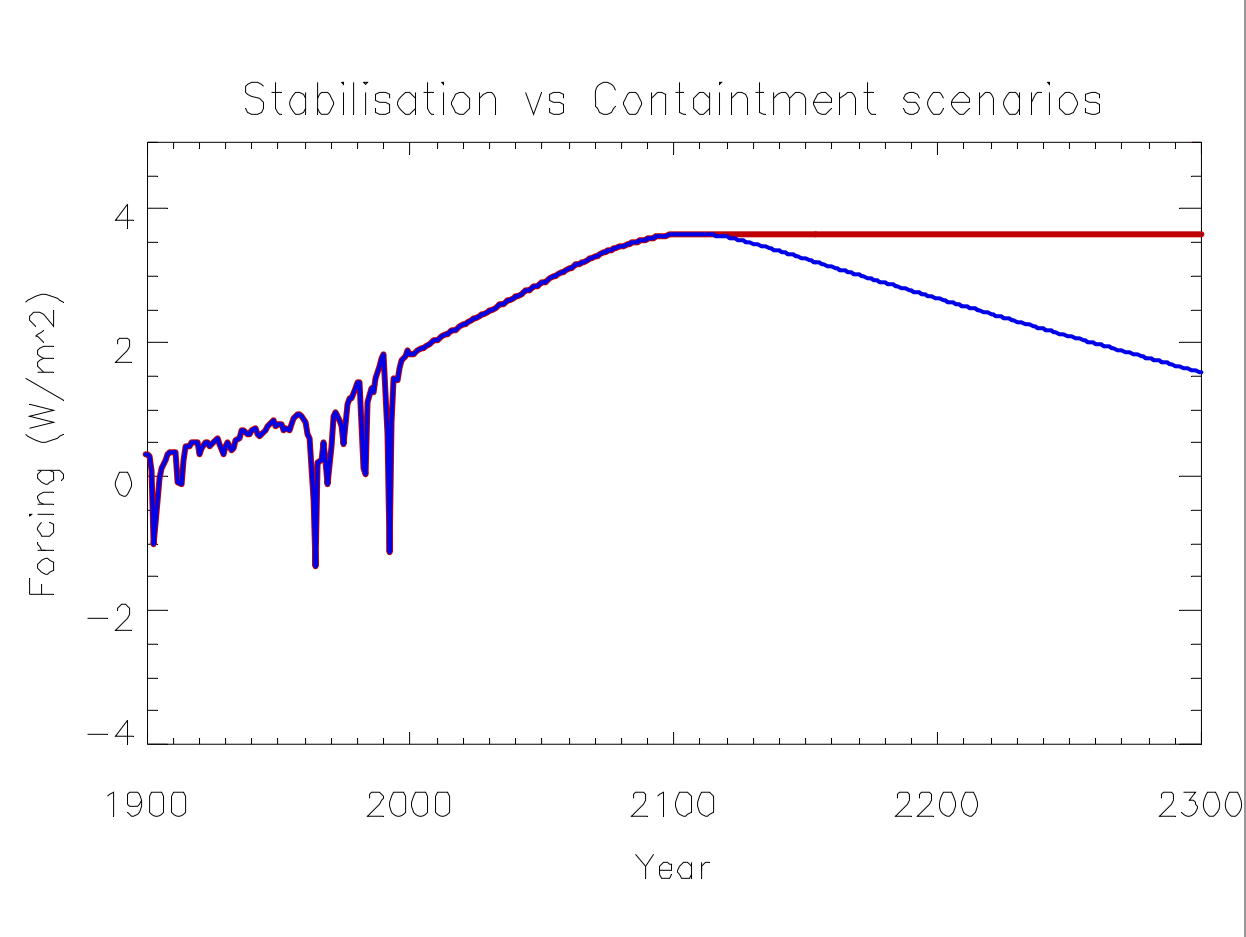
Climate system uncertainty

- UN Framework Convention on Climate Change states as its goal:
- "stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system."
- This (perhaps inadvertently, in 1990) places stabilization of GHGs at the centre of international attempts to address climate change.
- Is this a good idea?

Climate system uncertainty

- We will consider "probabilistic" forecasts of climate change under two scenarios
  - Indefinite stabilization at 550ppmv
  - Scenario in which concentrations peak at 550ppmv, before declining to pre-industrial levels by about 2300
- To examine how the likelihood of a large temperature increase is sensitive to the duration of elevated GHG.
- This lets us know whether posing the UNFCCC's goal in terms of stabilization of GHG is a good idea.

Warming under different scenarios



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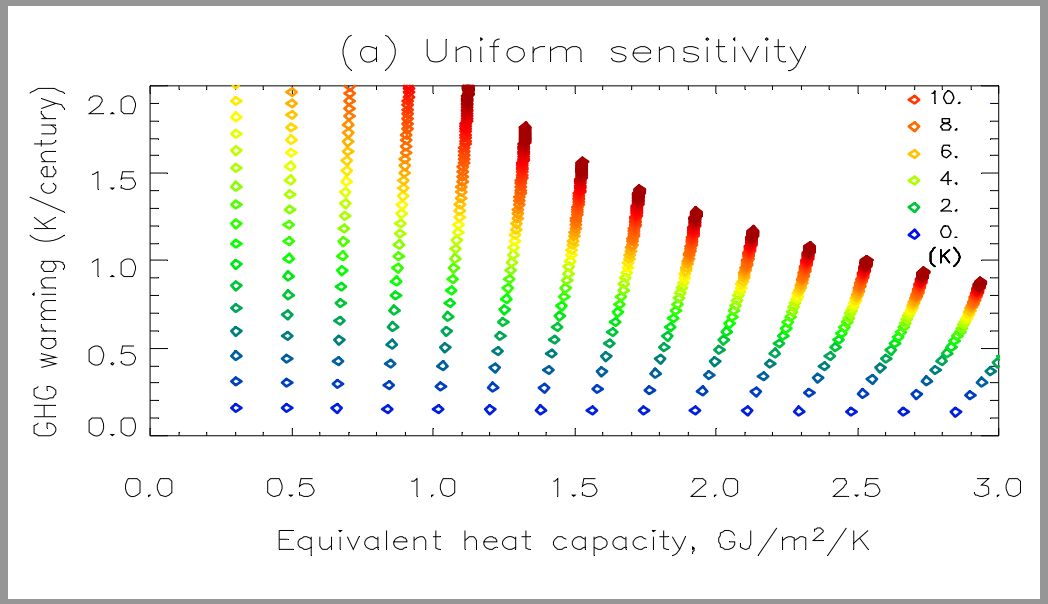
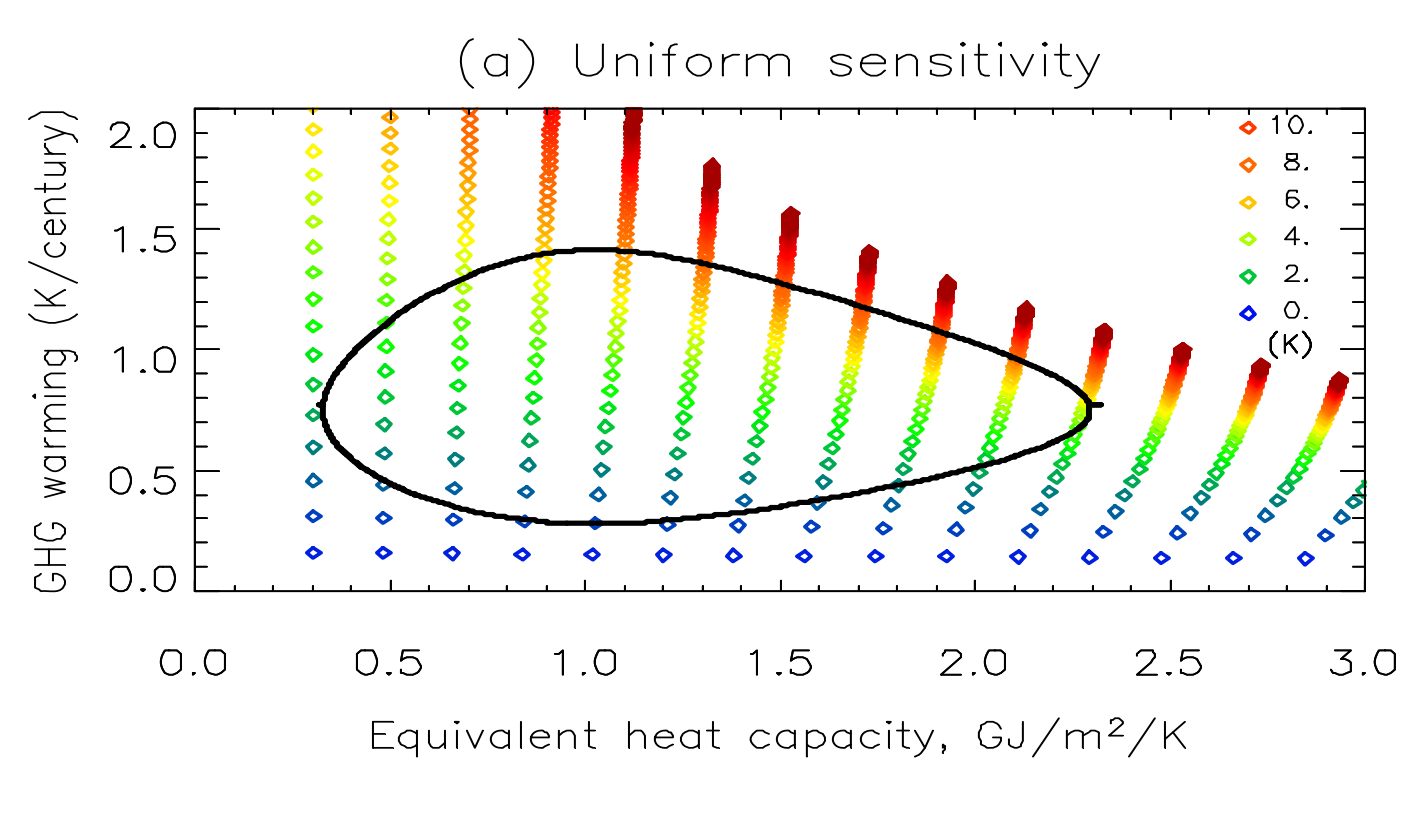
A simple perturbed-physics ensemble

- Perturbed-physics ensemble generated by varying
  - climate sensitivity ($S=1/\lambda$) (colours)
  - Heat capacity of the climate system (horizontal axis)
- Plotted against the warming these models would give for the 20th century, under historical climate forcings



Applying a data constraint



With 20th century attributable warming (Stott & Kettleborough, 2002) and ocean heat uptake (Levitus *et al.*, 2005) data as a constraint (5-95%)

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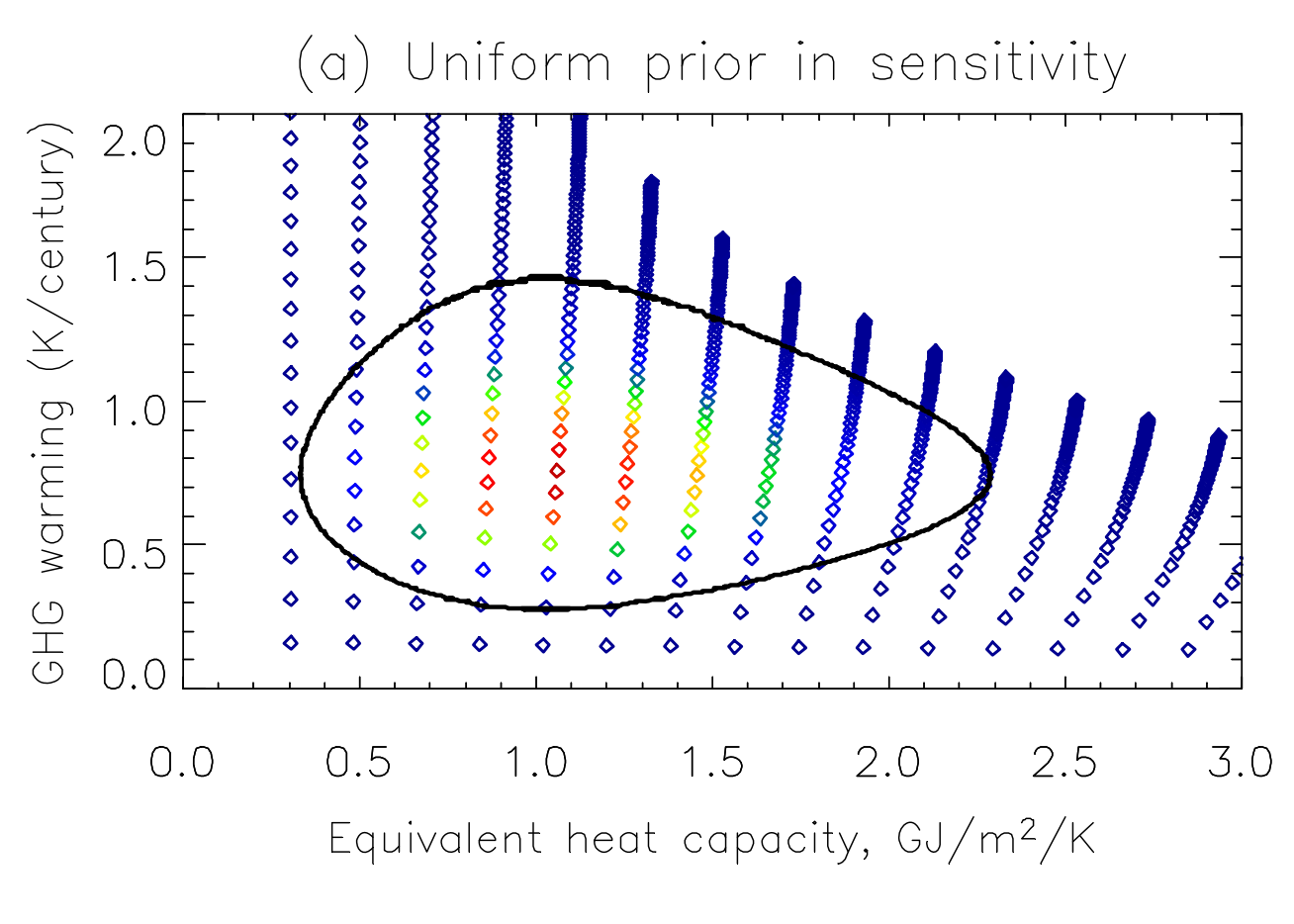
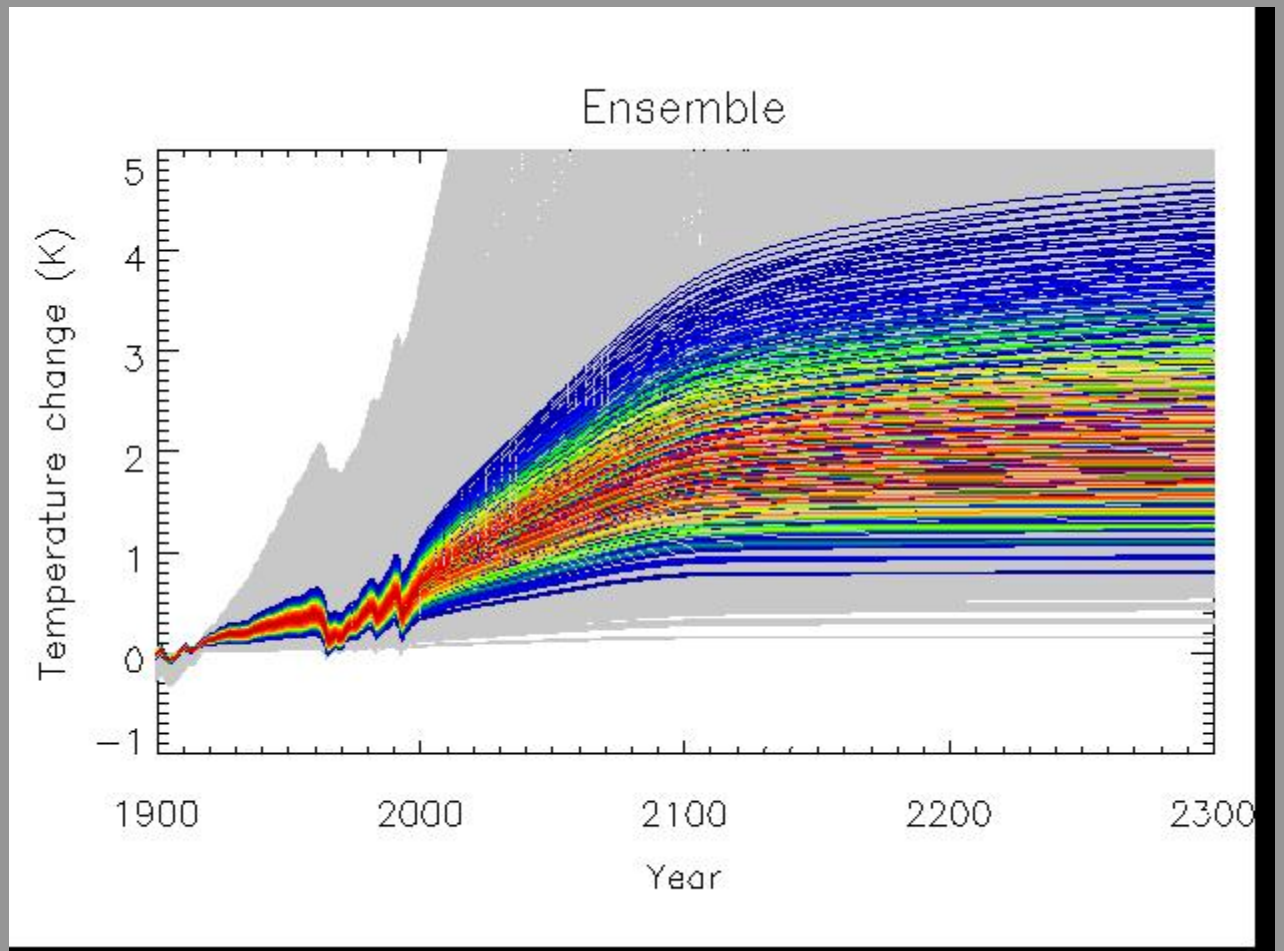
Likelihood weighting



Warming under different scenarios



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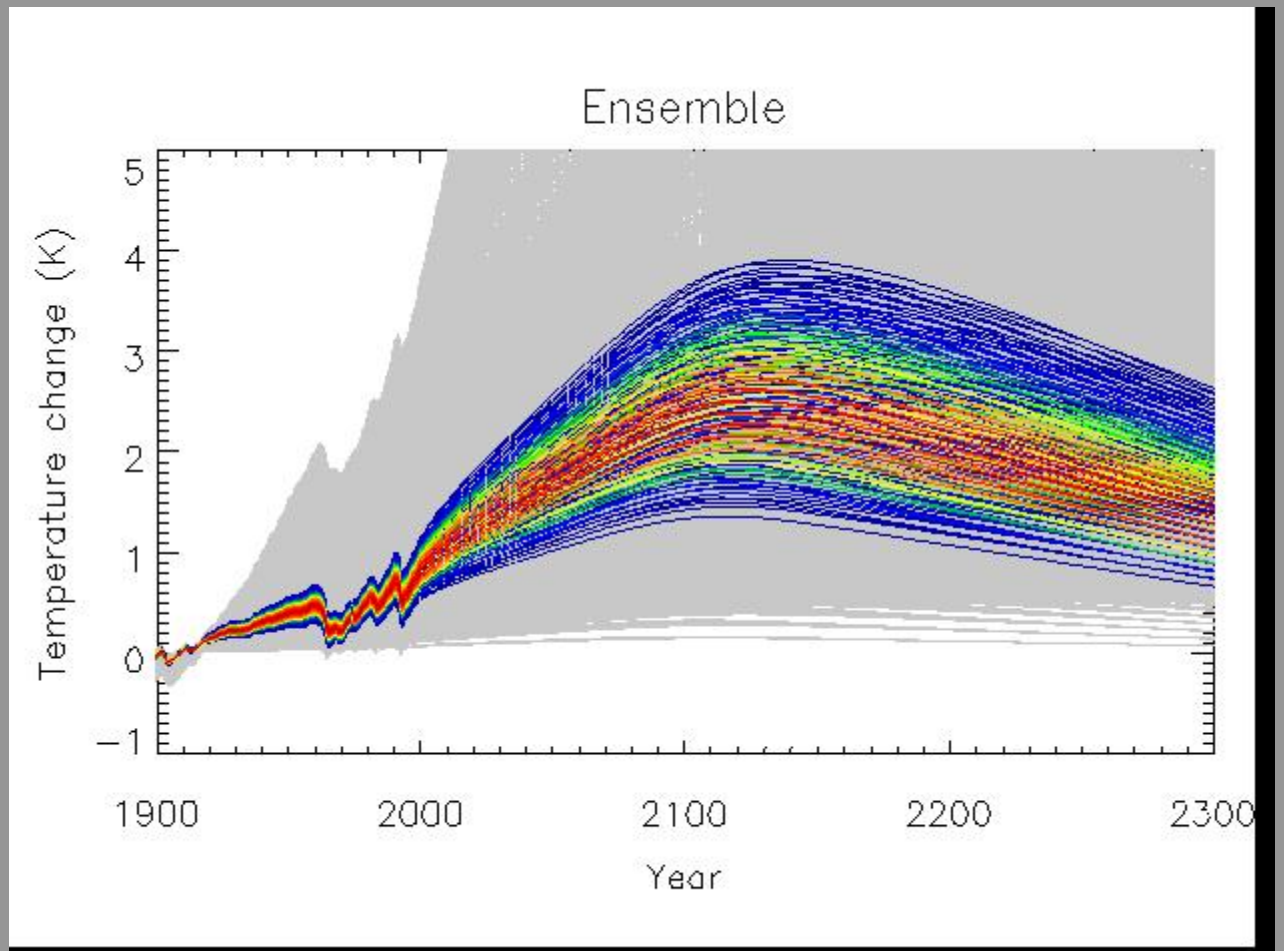
Warming under different scenarios



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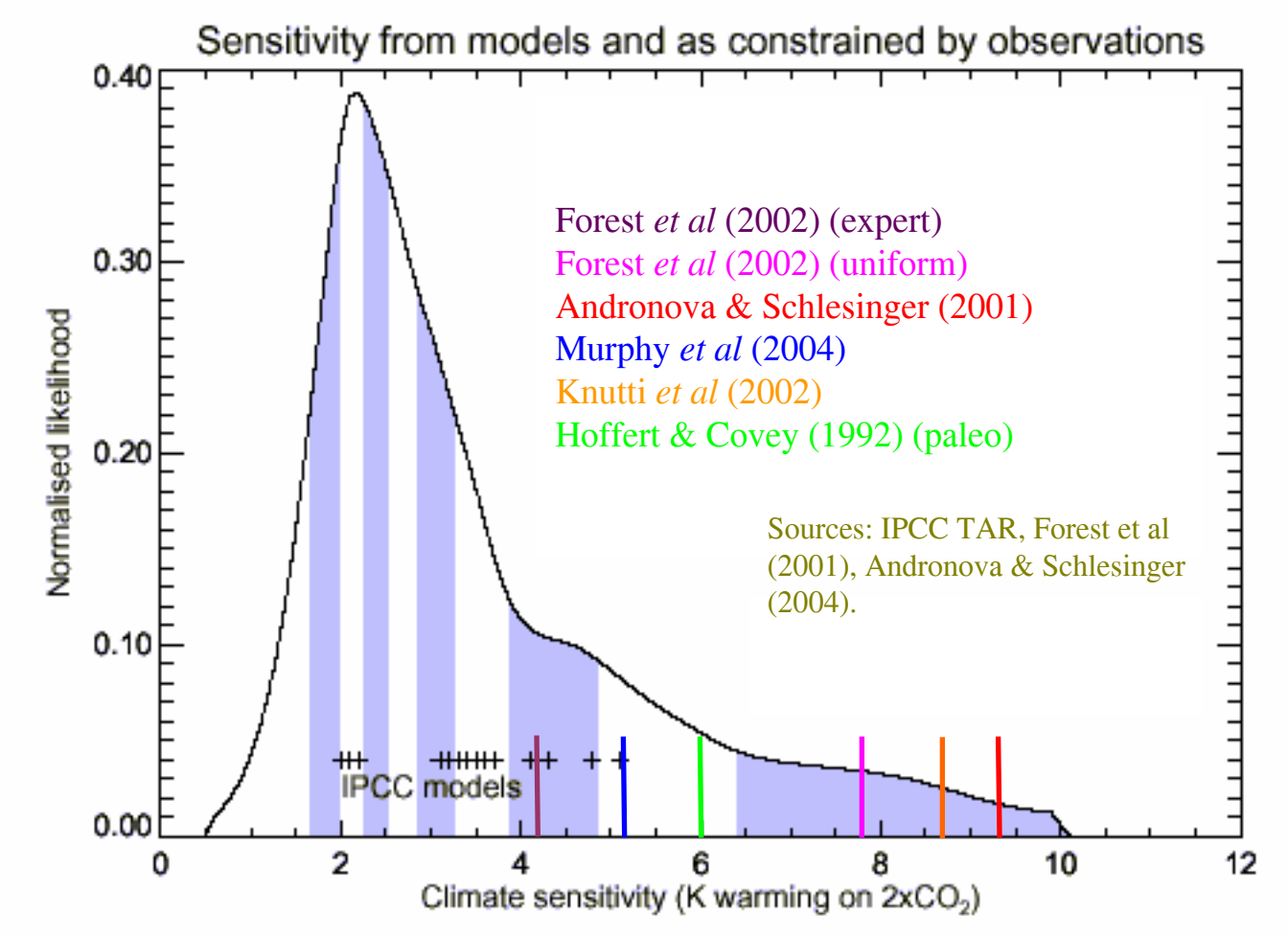
Quantifying metrics of global change

- This is borne out by the literature:
  - Recent attempts to quantify S have failed to converge on an upper bound
  - The transient response, on the other hand, is well understood

Uncertainty in long term warming to $2xCO_2$



Attributable GHG warming is linearly related to TCR

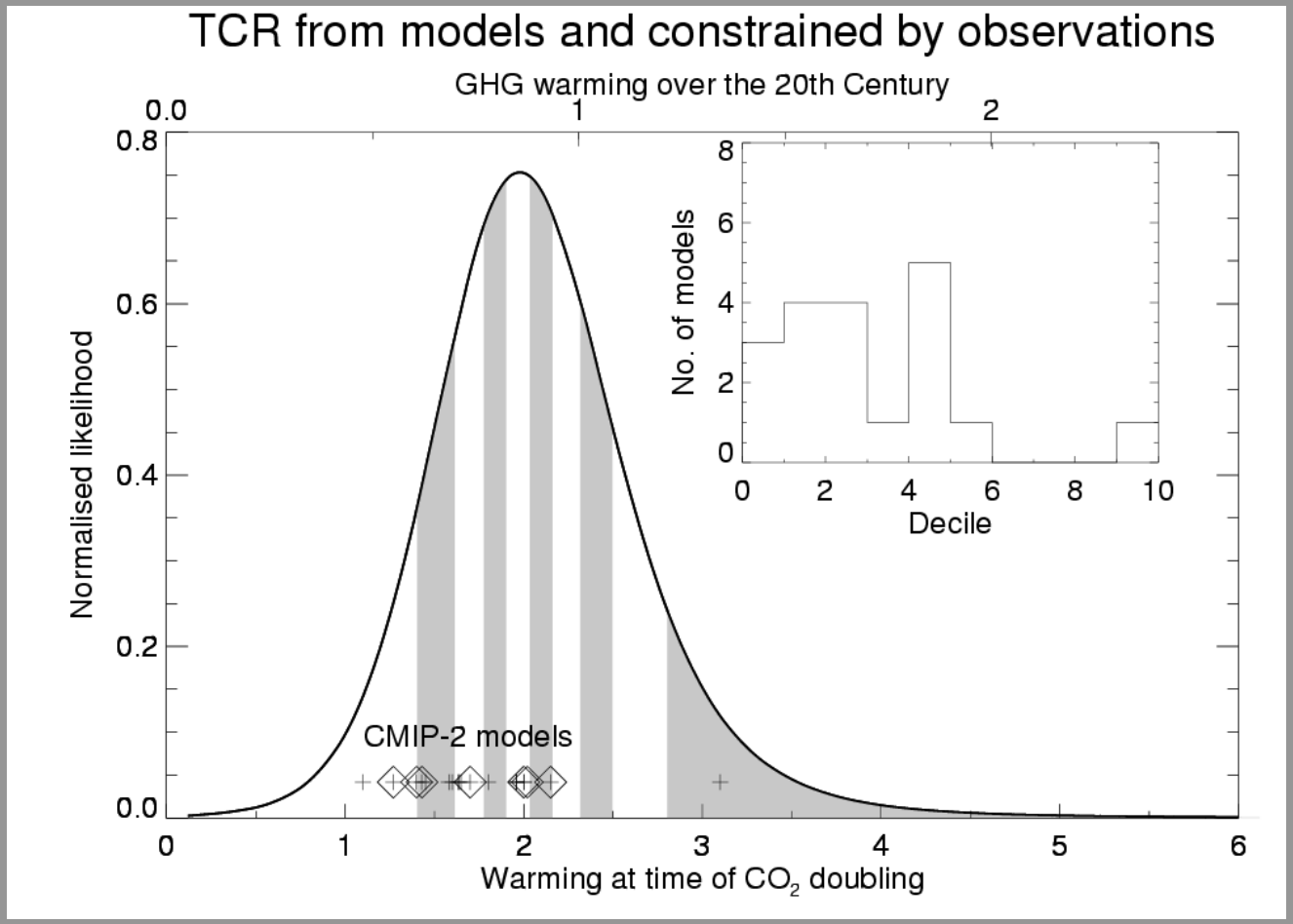


Figure from Jamie Kettlebrough

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This problem arises for two reasons

- Because of the role of (subjective) prior beliefs in the generation of these sorts of Bayesian forecasts (Bertrand's Paradox)

- Because of the lack of any observable quantity that scales with *S*

Fundamental difficulties in observing senstivity

- The things we can observe scale with λ not S. Since $S=1/\lambda$, this means that a Gaussian uncertainty on our observable leads to an inverse Gaussian on the distribution for S.
- Paleoclimate studies potentially give us observables that scale with S, but in this case we know the temperature response better than the forcing, which causes trouble (since $S \sim \Delta T/F$): we get another inverse Gaussian.

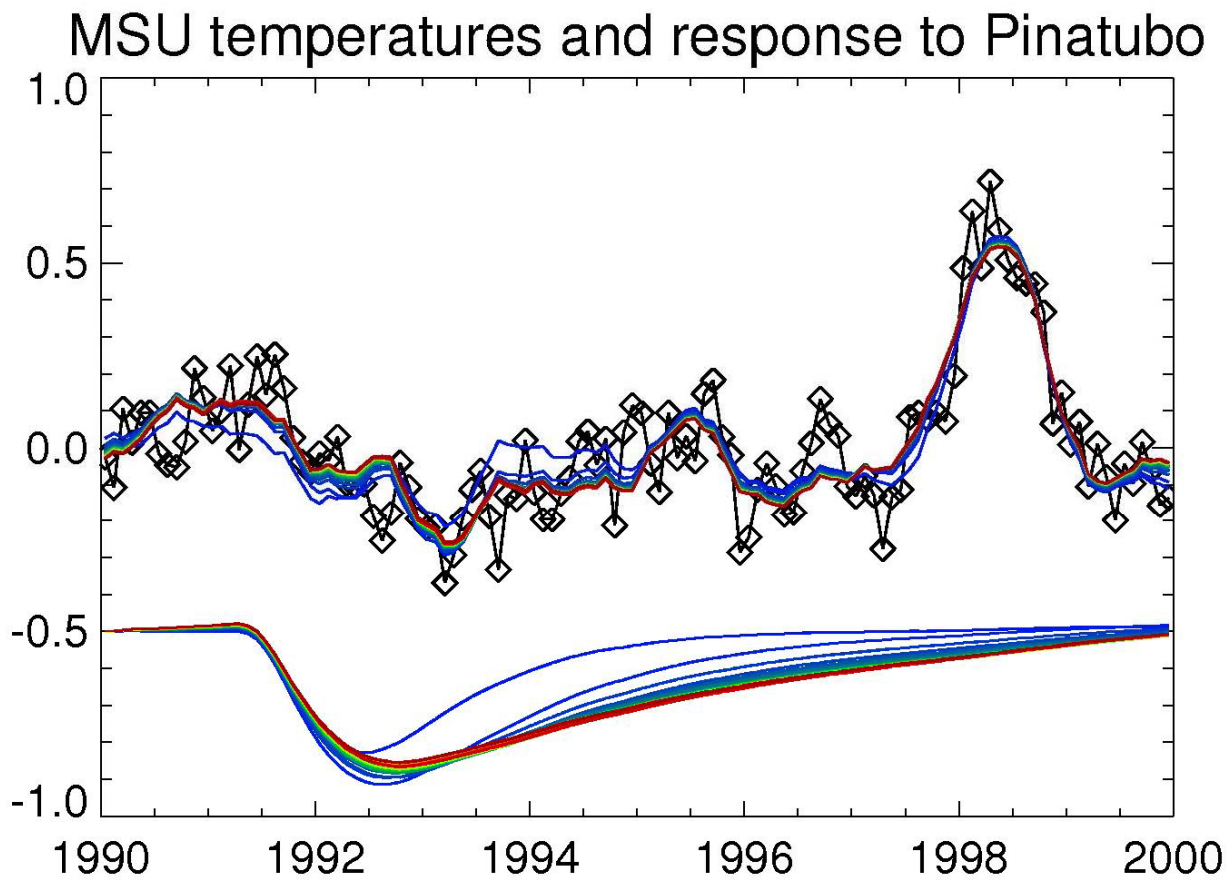
Transient observables scale with λ for large S

$$c\frac{dT}{dt} = F - \lambda T$$

$$T = \int \frac{F}{c}\left(1 - \frac{\lambda t}{c} + \ldots\right)dt$$

- For large *S* (small *λ*) or short times, response varies as…
- So the first sensitivity-dependent term to appear in the transient response scales with S^{-1} (*λ*), not *S*, (particularly for Pinatubo (Wigley et al, 2005)).

EBM responses to Pinatubo forcing



Also fitting ENSO, background climate and effective heat capacity

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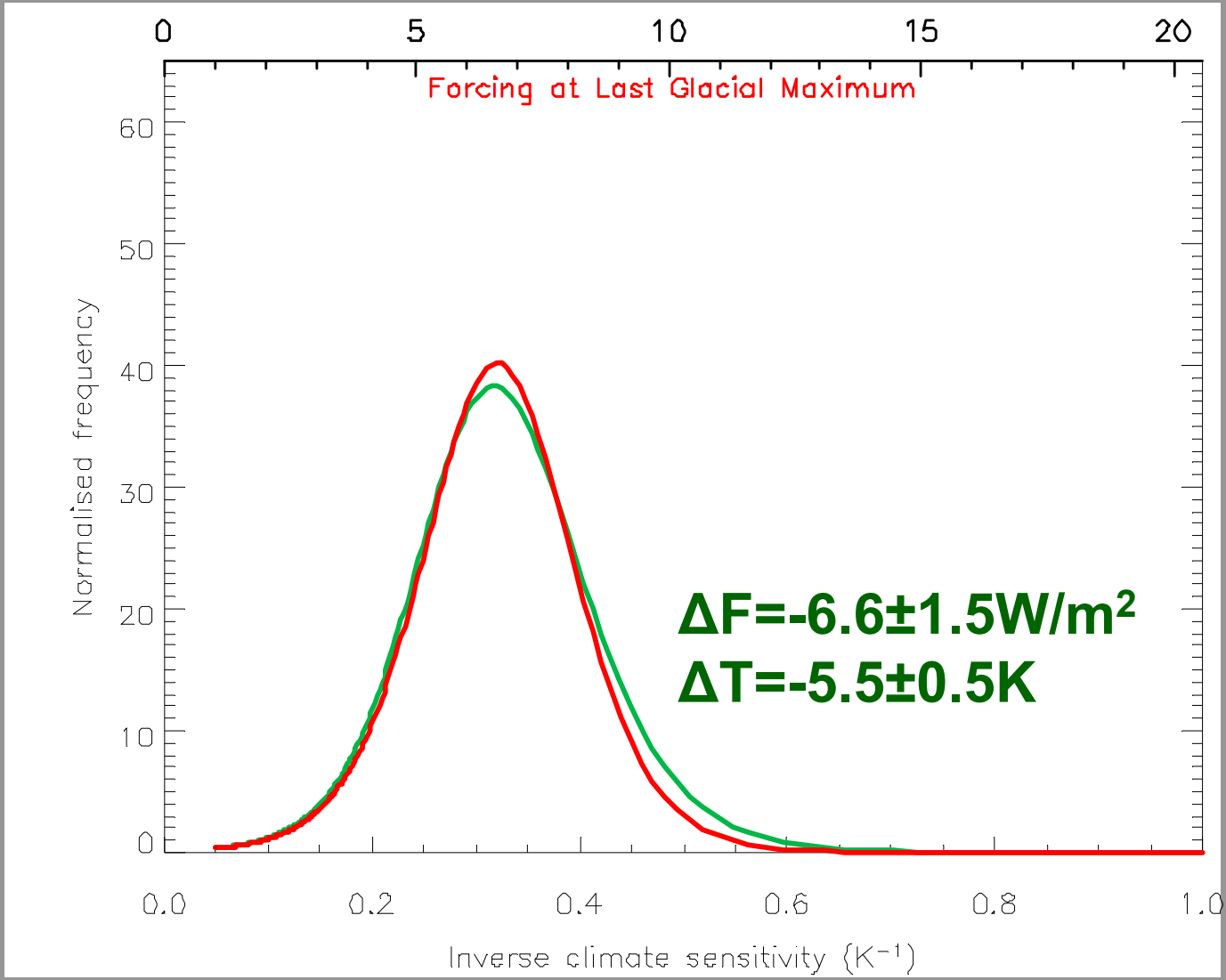
Paleo constraints

- We lack data to say what the global mean change is during LGM ("or any other period")
- Reconstructions flawed, MARGO suggests that results are proxy-dependent
- Forcing uncertainties are a problem

- Long time scales☑
- Data constraints☒
- Forcing uncertainties ☒

Are these high sensitivities ruled out by temperatures in the Last Glacial Maximum?



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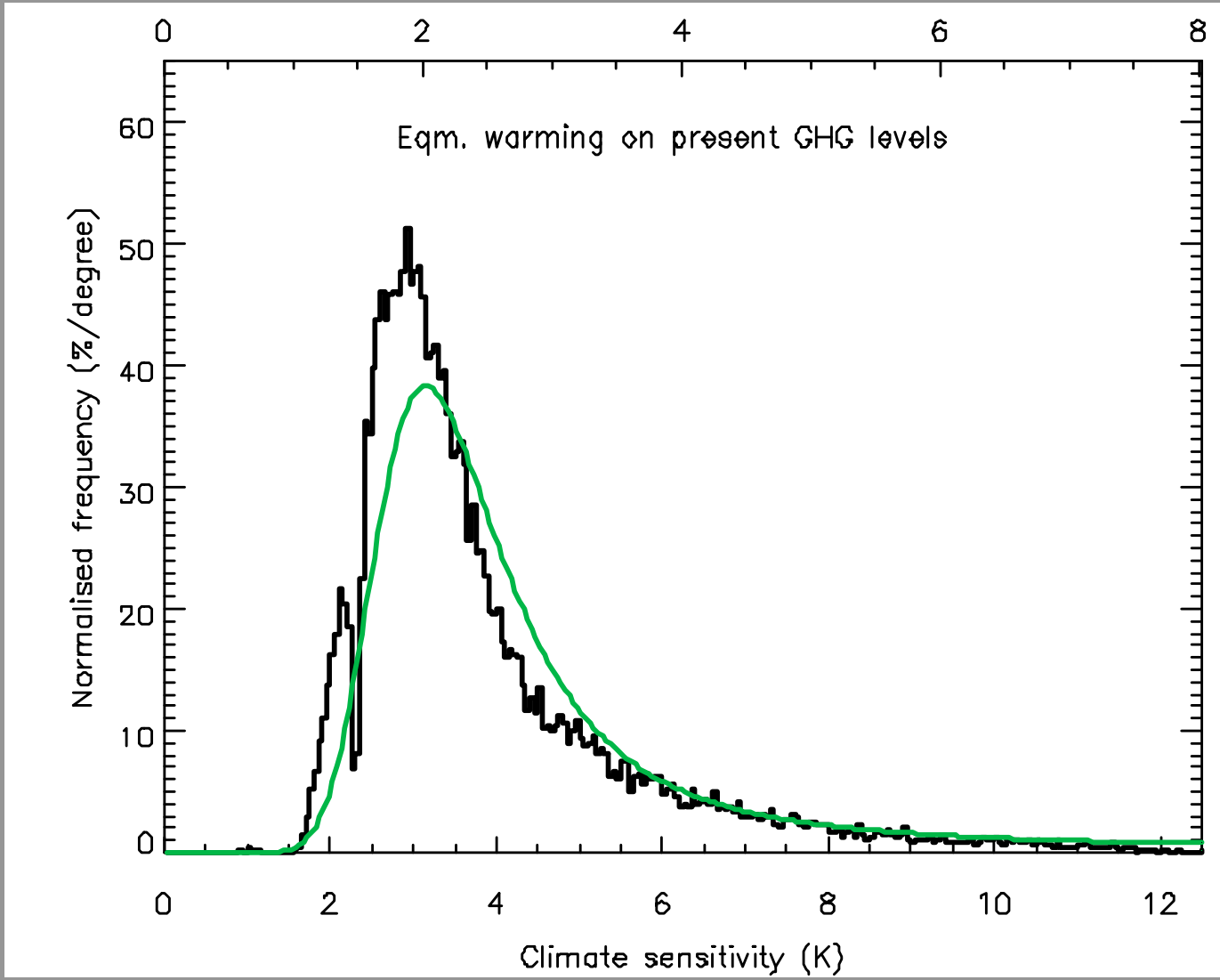
No: symmetric uncertainty in past forcing → asymmetric, open-ended range for sensitivity



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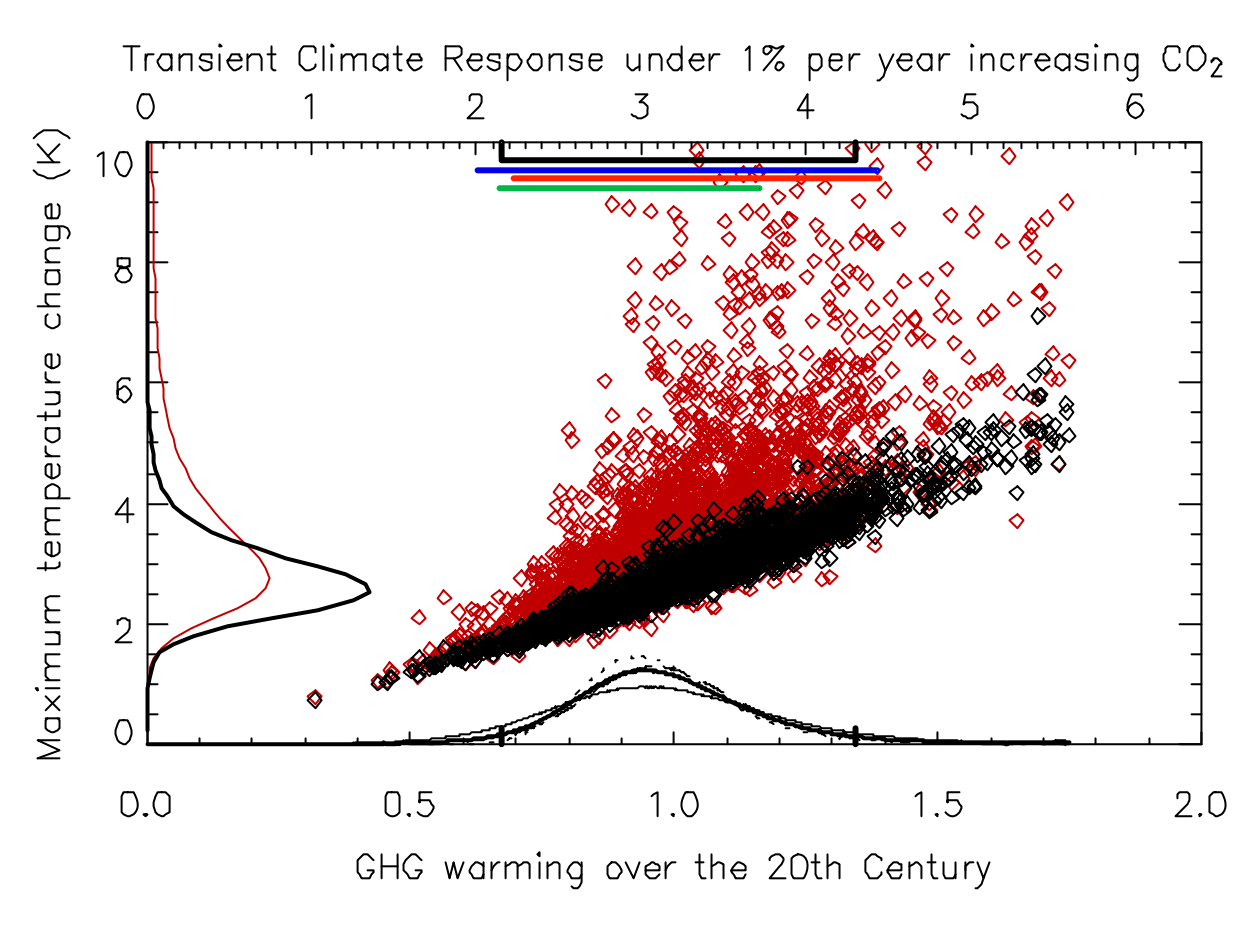
Results

- The fat tail arises in part because its hard to observe anything that scales with equilibrium warming
- On the other hand, past warming rates scale quite linearly with future warming rates

$$c_{eff}\frac{d\Delta T}{dt} = F - \lambda \Delta T$$

Remaining neutral in observable quantities



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Some doubts about Article 2 of the Rio Convention

- Article 2 of the Rio Convention commits the parties to take actions to "stabilise greenhouse gas concentrations at a level (TBD) to avoid dangerous interference" in the climate system.
- Is stabilisation of GHG a sensible way to think about "avoid[ing] dangerous interference" in the climate system, given that it is
  - impossible to observe directly
  - difficult to construct a reliable pdf?
- It's probably worthwhile considering alternatives, such as phase-out scenarios, which are better constrained by observations.

JM fellowship work 1

- We can treat the inability to estimate an upper bound on sensitivity as an opportunity to explore other, possibly more policy-relevant, alternatives to stabilization scenarios

- Am keen to work this in to economic and impacts models, where appropriate

Exploiting the TCR in “scenario” design

- The equilibrium response is NON-linearly related to past (attributable) warming
- The transient response is linearly related to past (attributable) warming

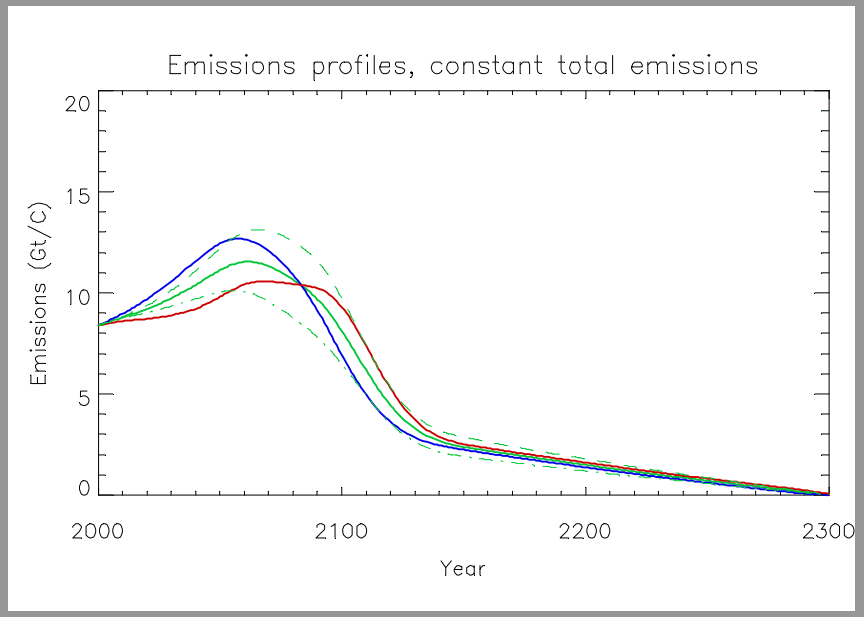
- Consider maximum warming under emissions scenarios in which emissions drop back to zero** by 2300.
  - **Zero basically means within the uncertainties associated with the carbon cycle (by 2300)

Policy possibilities using the TCR?

- May allow us to exploit
  - linear relation between TCR, Attributable warming
  - Not completely unreasonable assumptions about carbon futures
  - Lagged nature of the emissions/response in the climate system
- To develop tighter confidence intervals for inputs into economic models, impacts, policy. Most suitable for problems in which the observational constraint problem is relevant.
- Potentially leading to better constrained ideas about the price of carbon (very early in this analysis).

TCR phase out scenarios

- The exact path (timing of the peak) may not matter as much as the total amount of carbon
- Emissions scenarios:
  - peaking early
  - peaking for 550ppm in 2100
  - peaking late
  - +20% (dashed)
  - -20% (dash-dotted)
- Investigating this with MAGICC
- Emissions → 0 in 2300.



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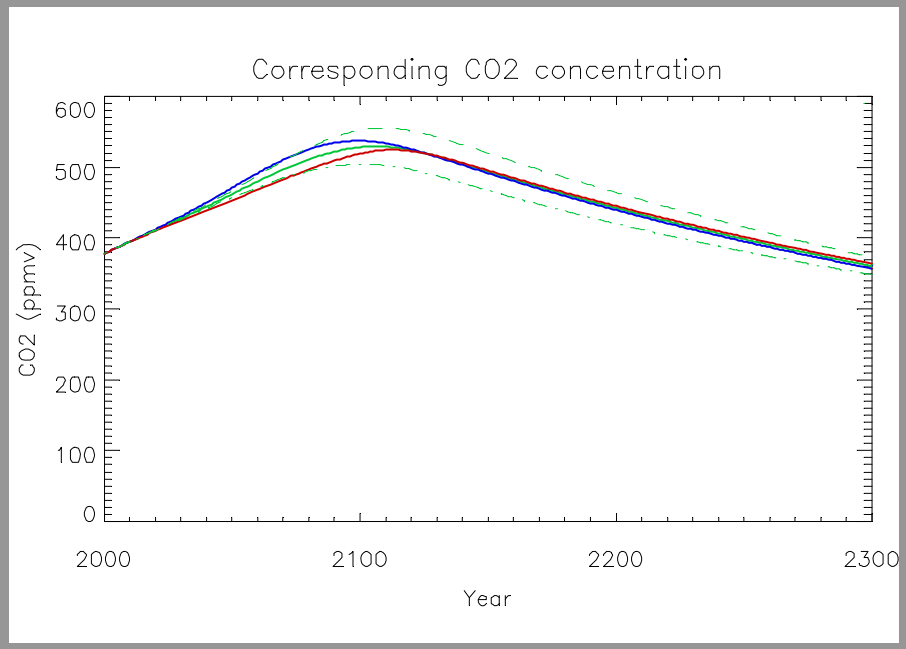
Phase out concentrations

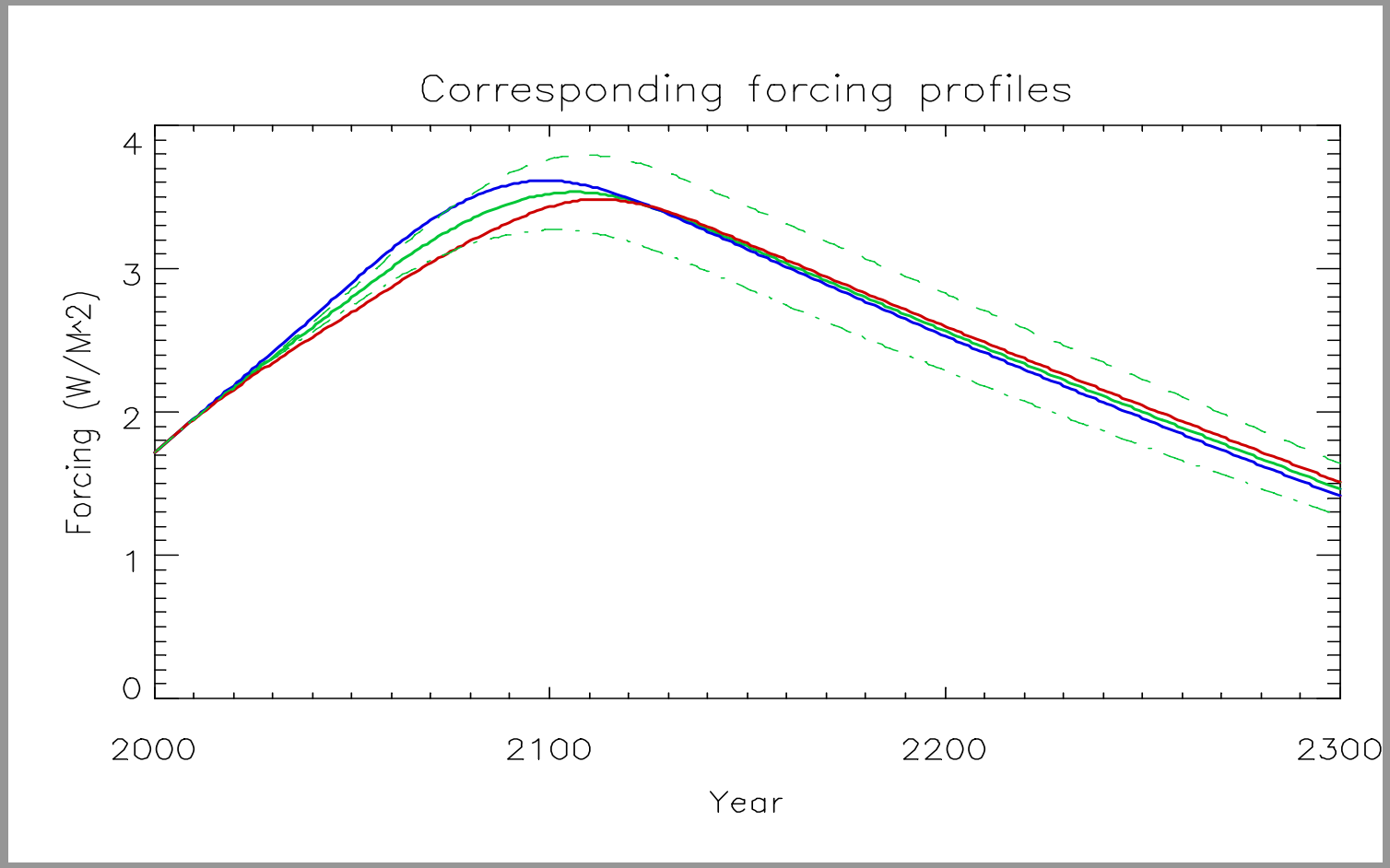
- Concentrations are strongly dependent on the carbon cycle model used.
- This analysis uses Nordhaus's 1991 approach, such that:

$$Q_{(t)} = (1-\lambda)Q_{(t-1)} + \varphi e_{(t-1)}$$

  - where:
    - » Q=carbon stock,
    - » e=emissions
    - » λ=1/120,Φ=0.64
- Not exactly a comprehensive carbon cycle model…



Forcing under phase outs



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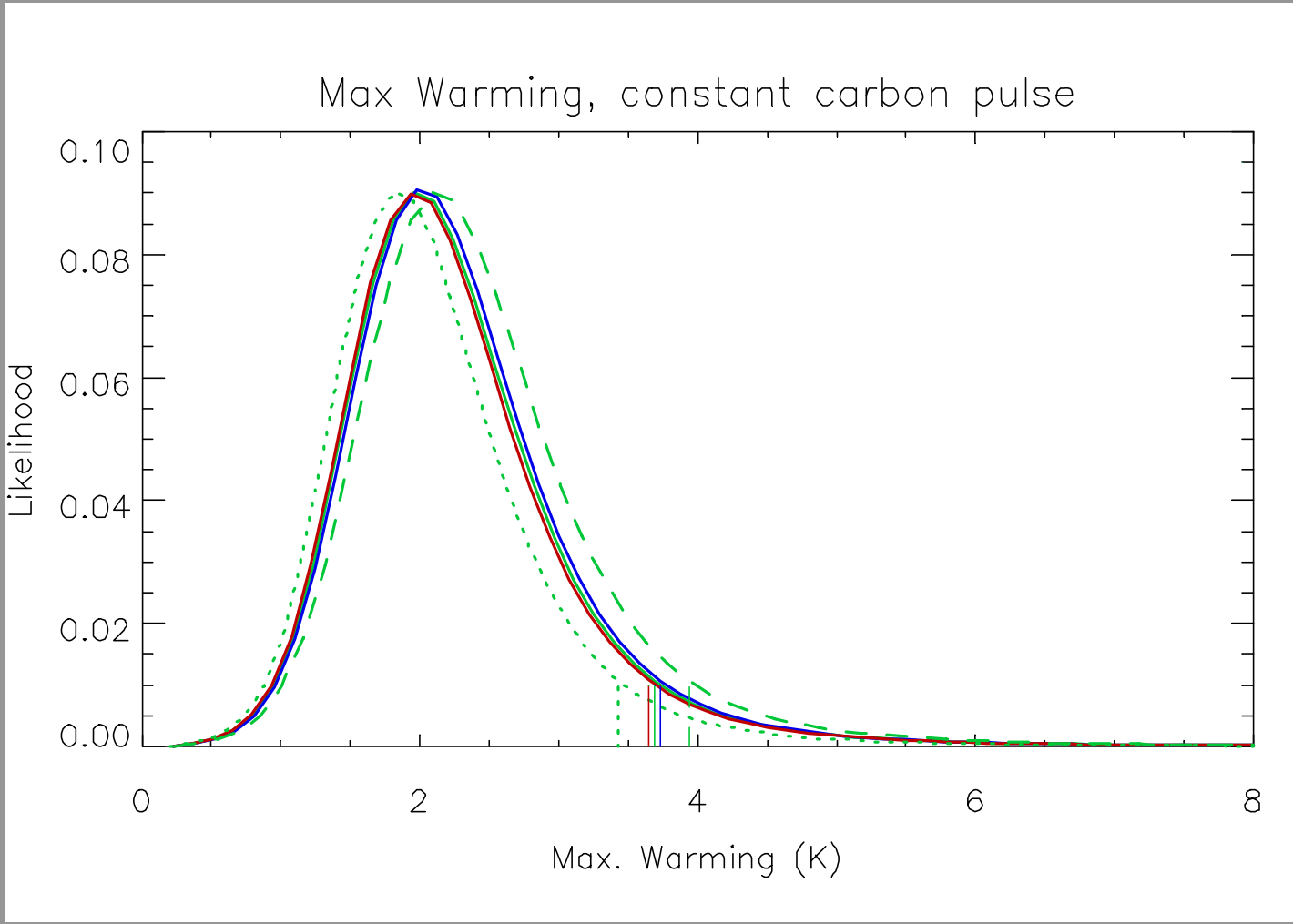
Maximum warming under phase outs



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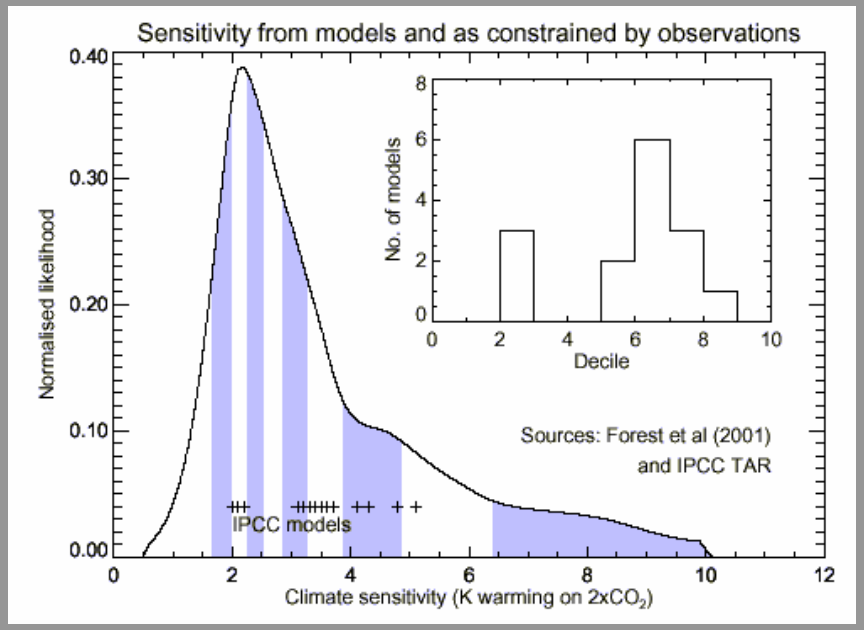
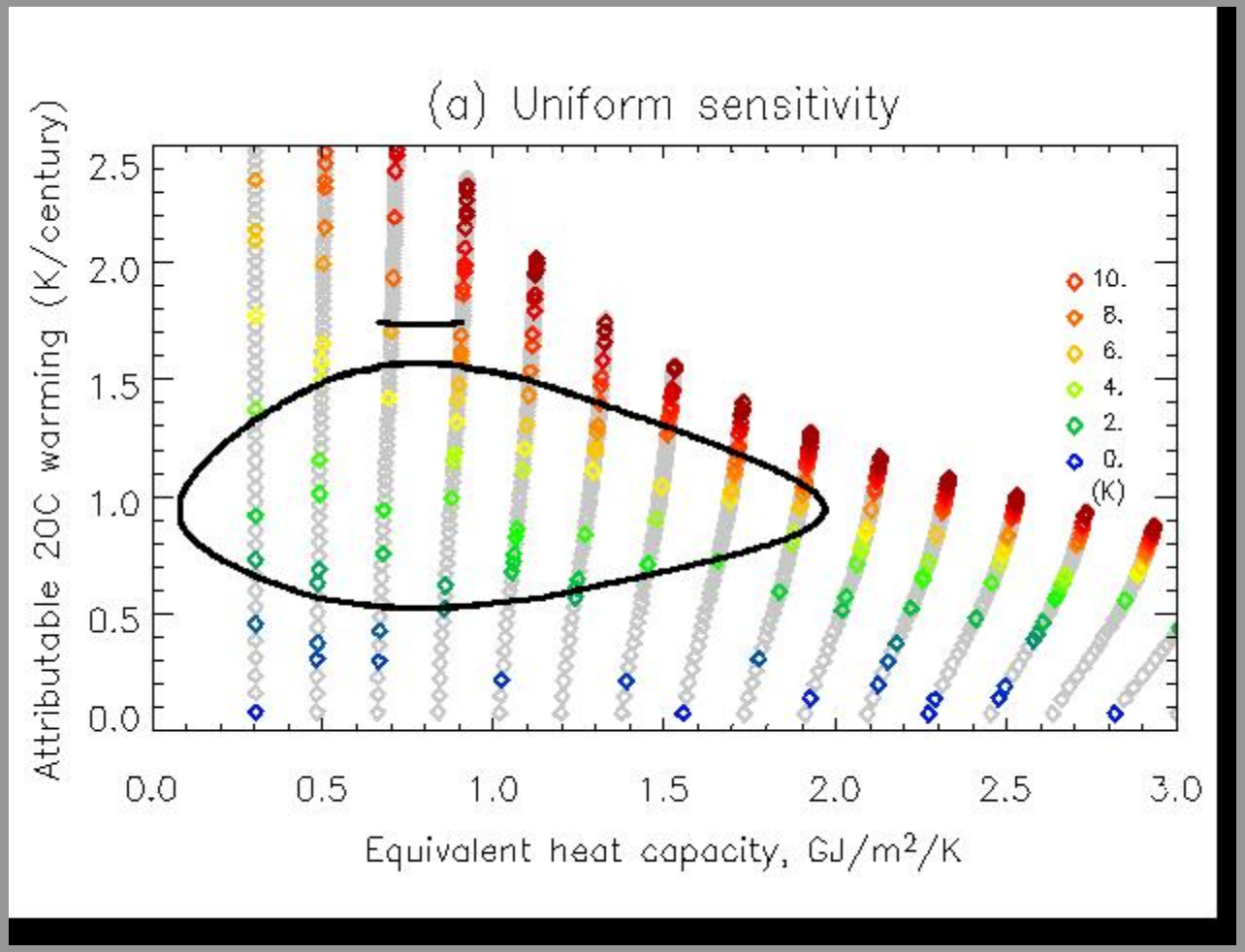
Monte Carlo Approaches (climate*prediction*.net)

- Ideally we want to span the range of senstivities using GCMs
- BUT, GCMs are expensive to build, and every modelling group wants to build the "best guess" model
- To span the range, we need to deliberately de-tune the models by perturbing the model physics within the ranges of uncertainty specified by the modellers.



Perturbed Physics Ensembles with patchy sampling (1)



The sampling is incomplete, but random in S (20% coverage)

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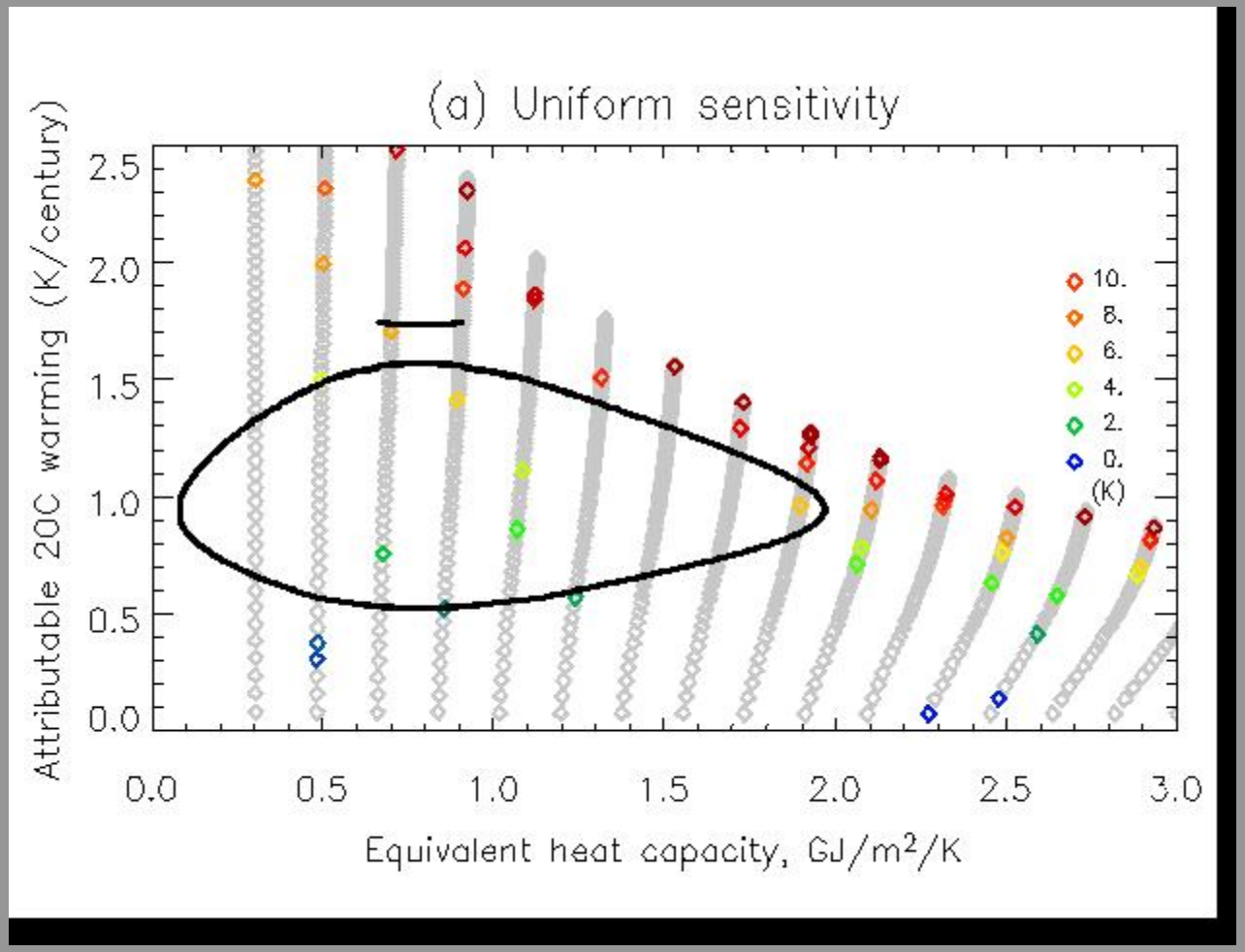
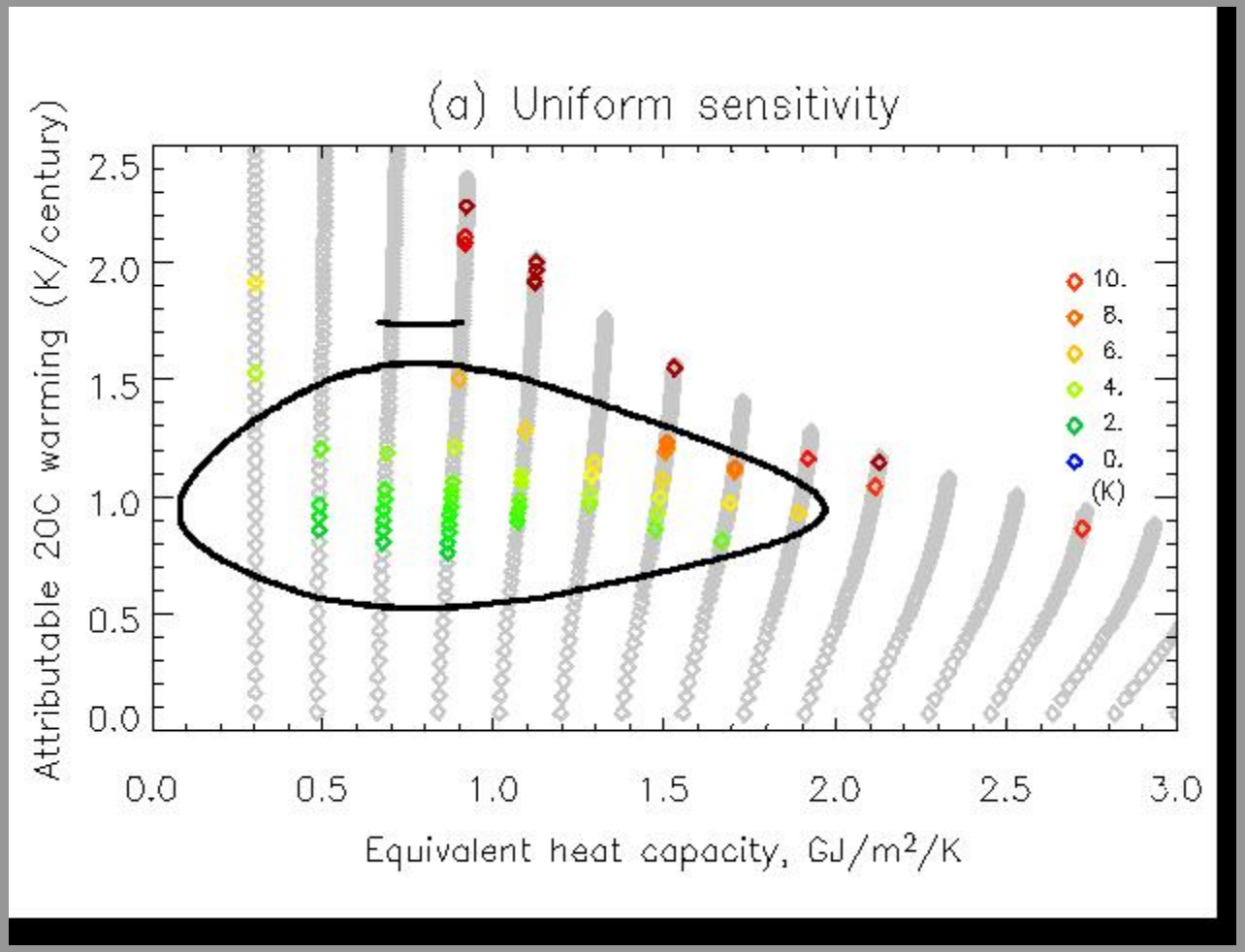
Perturbed Physics Ensembles with patchy sampling (2)



The sampling is incomplete, but random in S (3.5% coverage (128 runs from 3600))

Perturbed Physics Ensembles with patchy sampling (3)



The sampling is incomplete, likelihood weighted with a prior in *S* (3.5% coverage)

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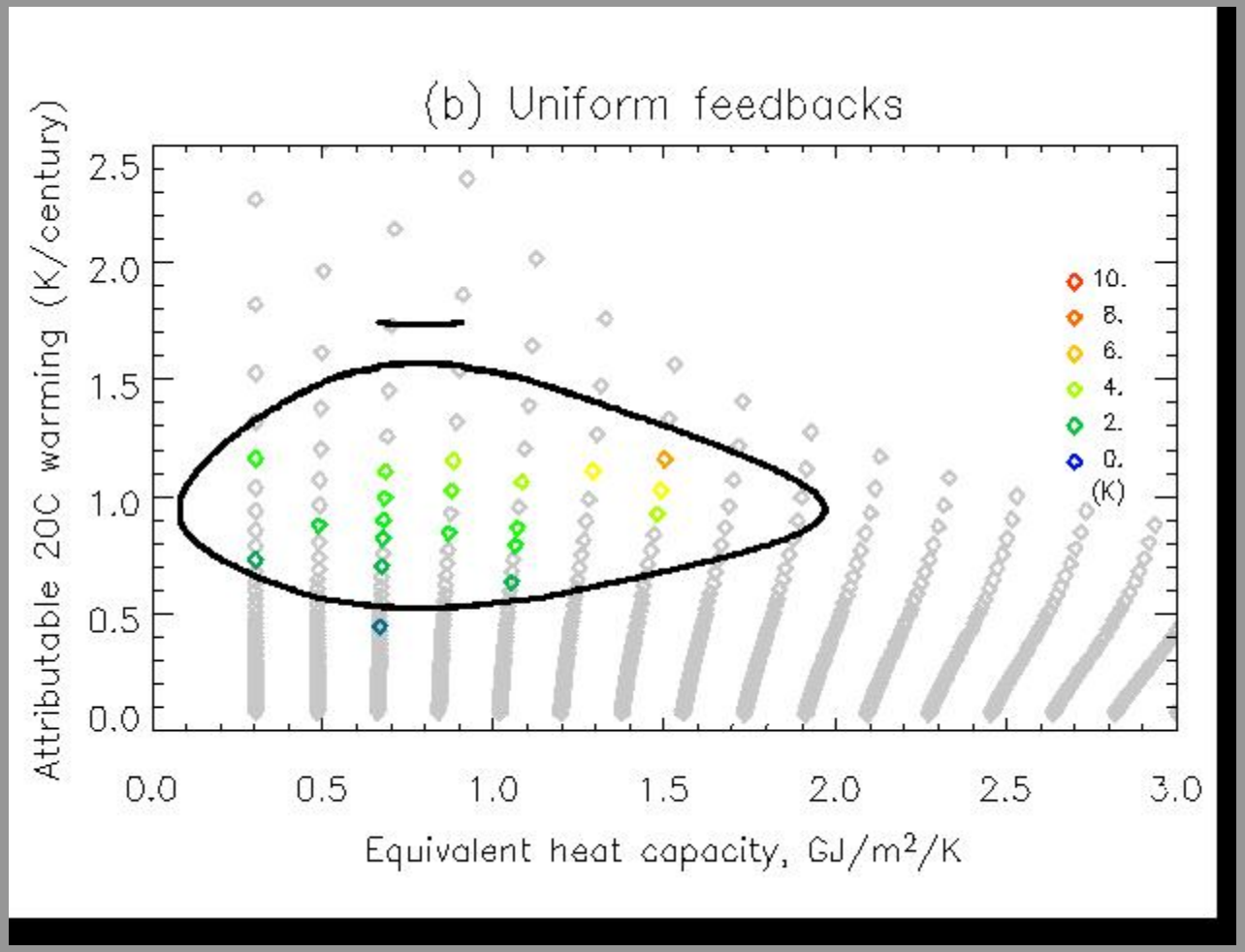
Perturbed Physics Ensembles with patchy sampling (4)



The sampling is incomplete, likelihood weighted, using a *1/S* prior (3.5% coverage)

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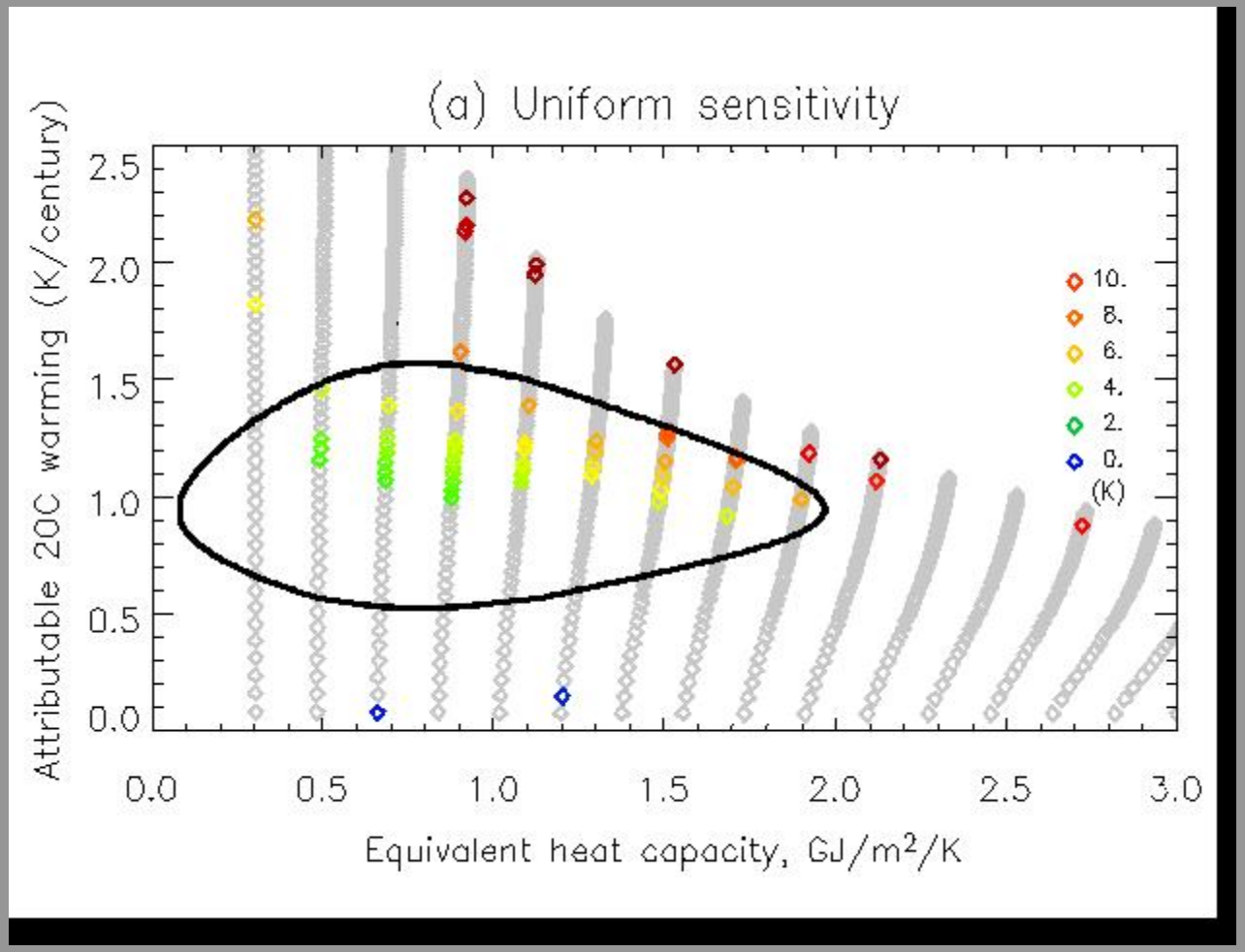
It's almost certainly even worse than that!



The sampling is incomplete, likelihood weighted, with a prior in *S* (3.5% coverage) biased warm by 1°C

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Non-linearity

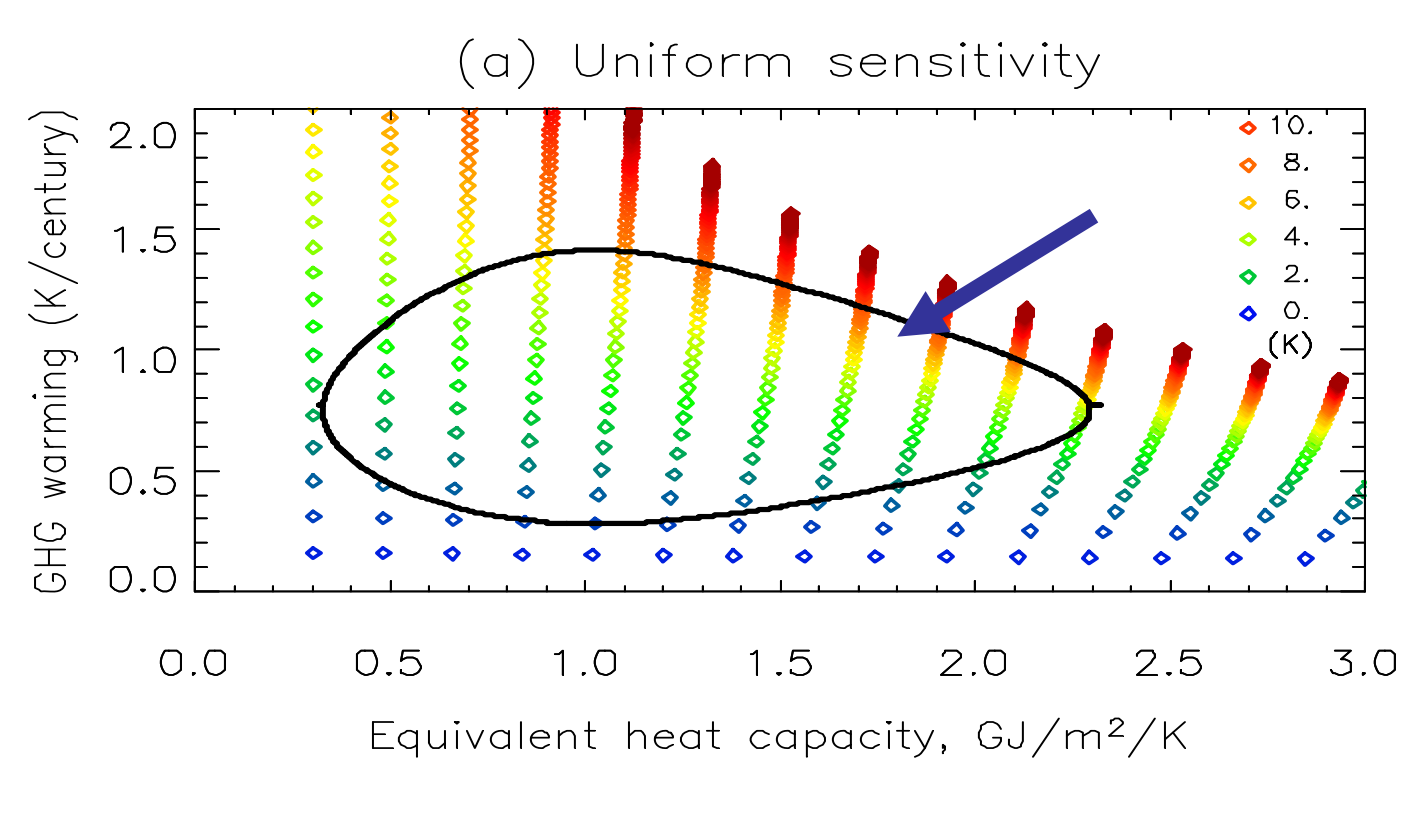
- And that was our best case, in which we were looking at something that is basically a linear system.
- When we go to regional or sub-annual scales, we can expect sampling, biasing and non-linearity to complicate even the best "low-fat" methods of simulating a fully-perturbed physics ensemble.
- This is why climate*prediction*.net is valuable: because it provides a more thorough sampling of GCM phase-space than any other experiment, by several (3) orders of magnitude

JM fellowship work

- Further explore methodological issues involved in "probabilistic" climate forecasting, especially
  - Interpretation of single climate models
  - Interpretation of model ensembles

- Attempt to explore the policy implications (and opportunities!) of this work

Constraints implied by observations



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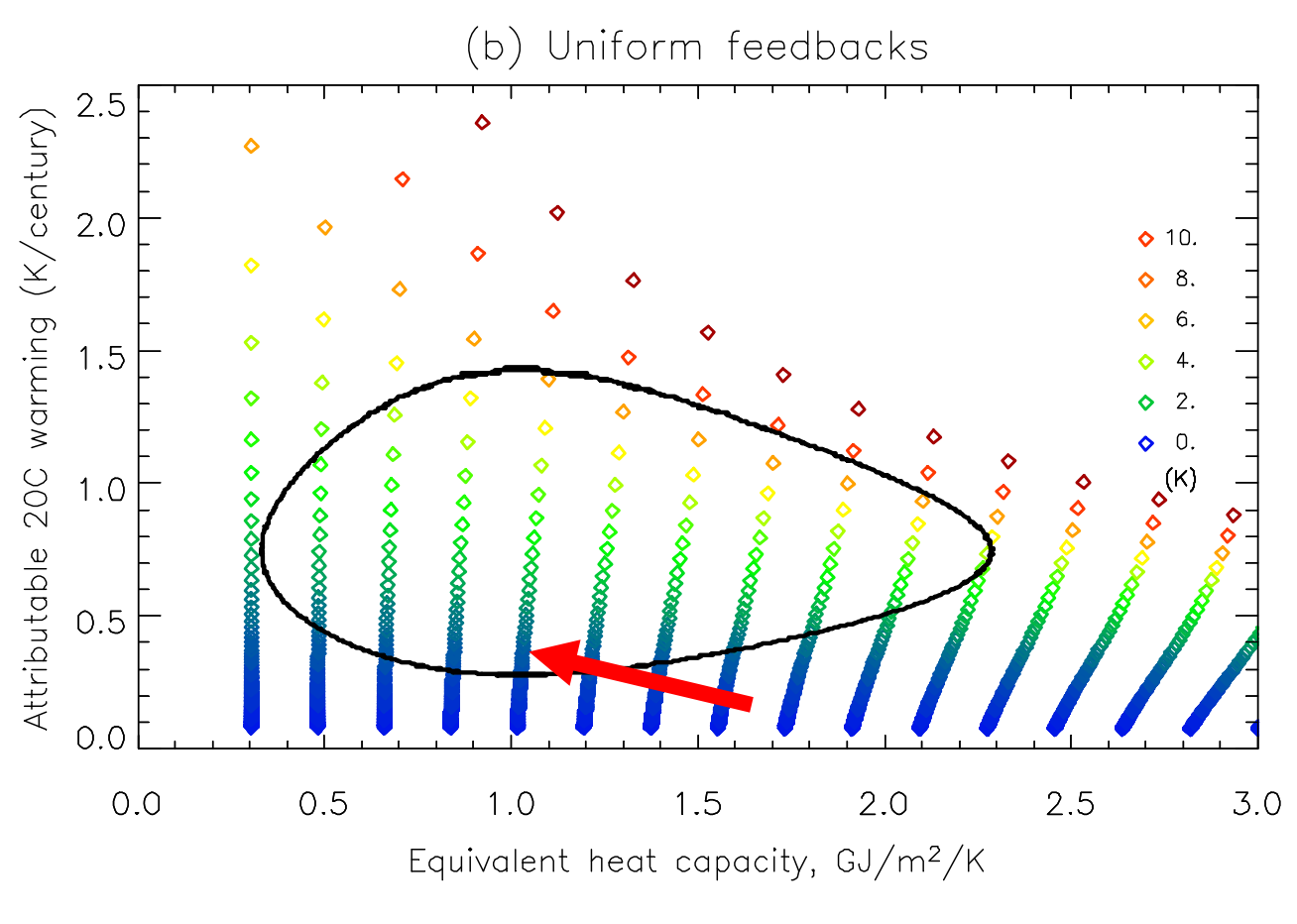
Using a different prior gives a different result



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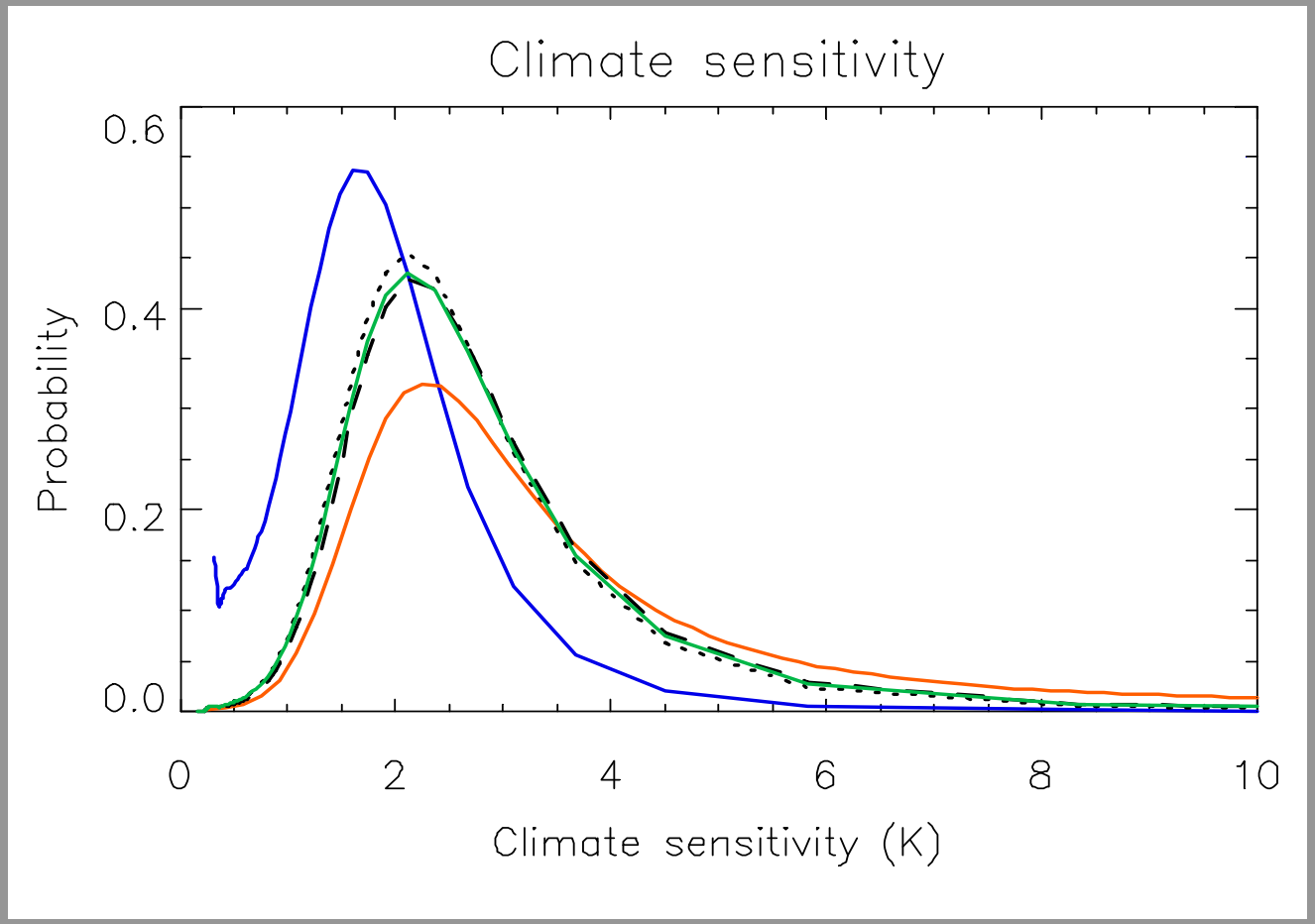
Differences in the predictive distributions used to build the forecast gives the reported range in sensitivities



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Bertrand's Paradox (1889)

- Bertrand intended to highlight problems with the classical definition of probability in the case of a problem with an infinity of possible outcomes
- Depends strongly on the prior assumptions you use in setting up the problem
- Many, equally plausible priors result from the underdetermined nature of "randomness"
- We recommend using the principle of indifference over the forecast variable of interest to avoid claiming spurious "knowledge" from the prior alone
- This amounts to choosing a uniform prior in the forecast variable of interest