Climate prediction and its uncertainties

School of Geographical Science, University of Bristol
October 2005

Dave Frame

Department of Physics, University of Oxford

climate*prediction*.net

Oxford University

Talk layout

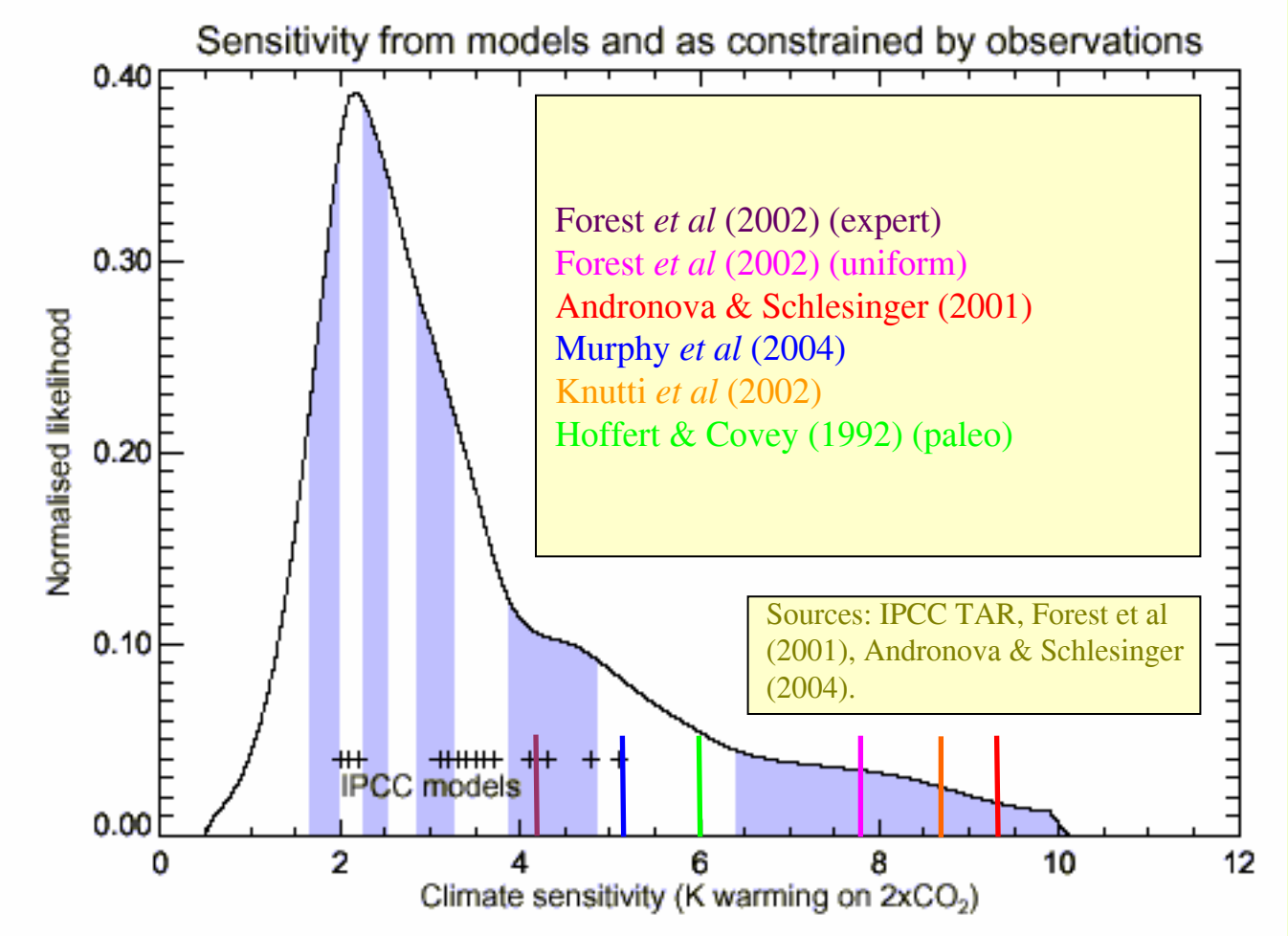
- Currents in climate prediction: Observationally-constrained *probabilistic* climate forecasts
  - difficulties in pinning down sensitivity
  - Monte Carlo approaches
- Transient / "phase-out" scenarios as possible(?) alternatives to stabilization scenarios
  - transient scenarios give us a warming rate
  - maximum warming under a "phase out" scenario is much better constrained by observations than is sensitivity
- Policy issues

Constraining climate sensitivity: probabilistic approaches

Attempting to constrain perturbed-physics ensembles with observational data.

- **Observational constraints from ocean heat content changes.**
- **Observational constraints from Detection and Attribution studies.**
- **Physical constraints from perturbed-physics ensembles.**
- **Inferring probabilistic climate forecasts from these.**

Uncertainty in climate sensitivity



Likelihood-weighted ensembles of climate models

- In ensembles of opportunity (CMIP etc.), individual models are tuned to agree with observations and with each other
- In PPE (deliberately detuned models), results depend on the choice of parameter perturbations

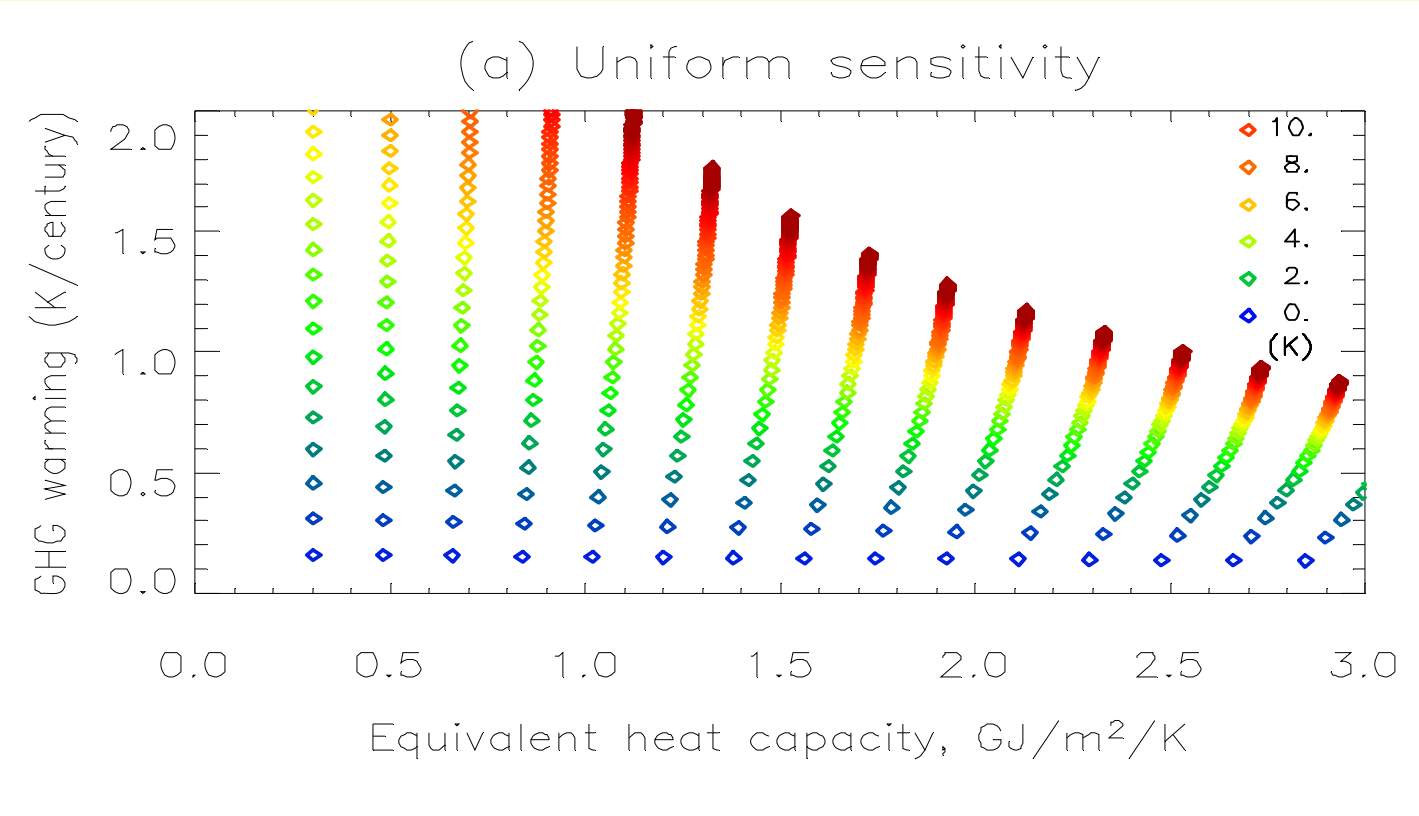
- An example: energy balance model PPE constrained
  - by attributable warming (Stott & Kettleborough) data and
  - by ocean heat content (Levitus) data
  - uses GHG forcing diagnosed from HadCM3; doesn't consider other contributions.

Comparing individual simulations with observations

- Use detection and attribution analysis to estimate attributable greenhouse warming, ΔT_{GHG} (linear trend 1900-2000), allowing for uncertainty in forcing. [Data from Stott & Kettleborough (2002).]
- Estimate effective heat capacity c_{eff} from observed $\Delta Q_{1957-1994}/\Delta T_{1957-1994}$, allowing for uncertainty in both. [Data from Levitus *et al* (2005); CRU.]
- Sample sensitivity and heat capacity in a simple climate model.

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

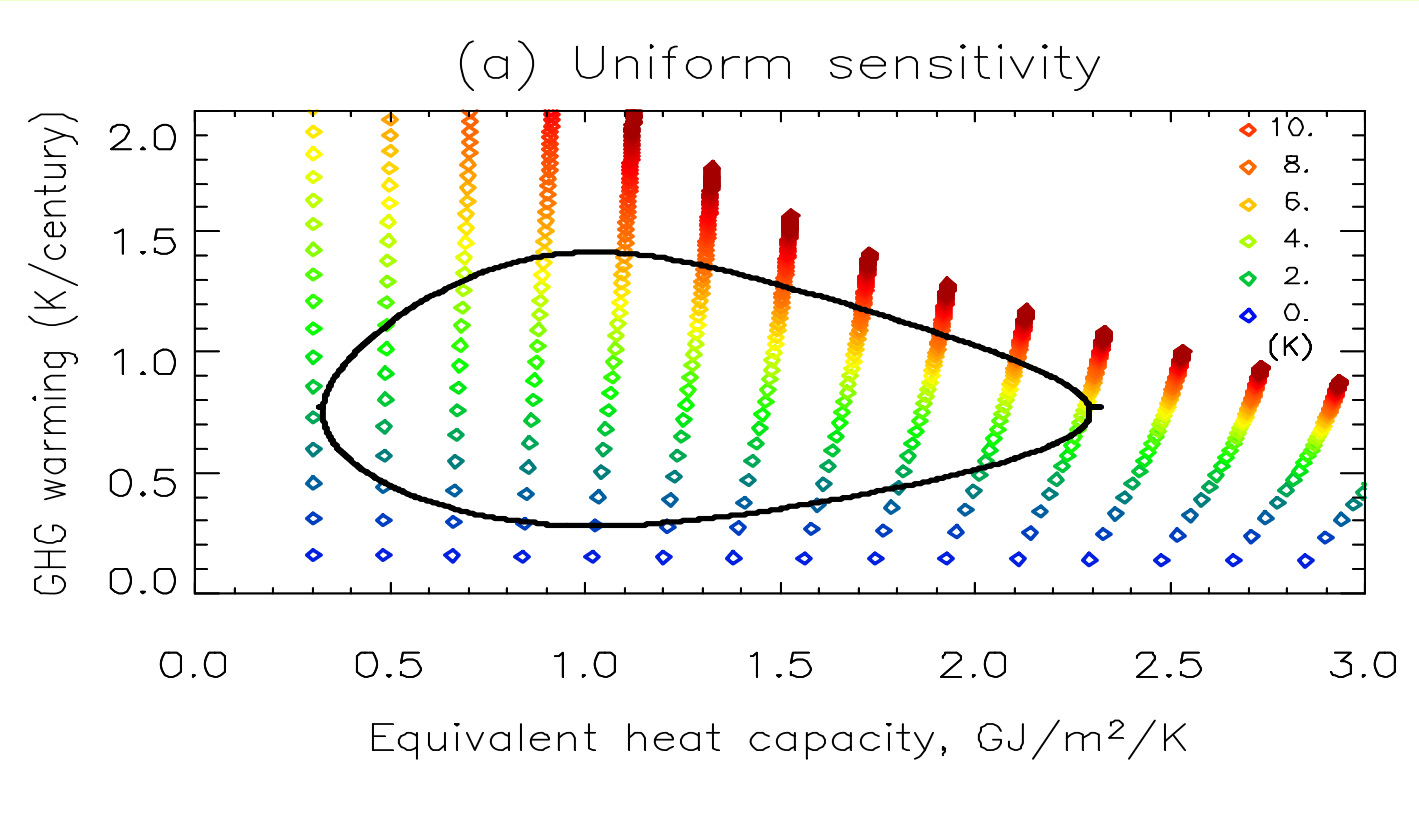
Sampling sensitivity and heat capacity in a simple climate model (Hansen et al, 1985)



climateprediction.net

Oxford University

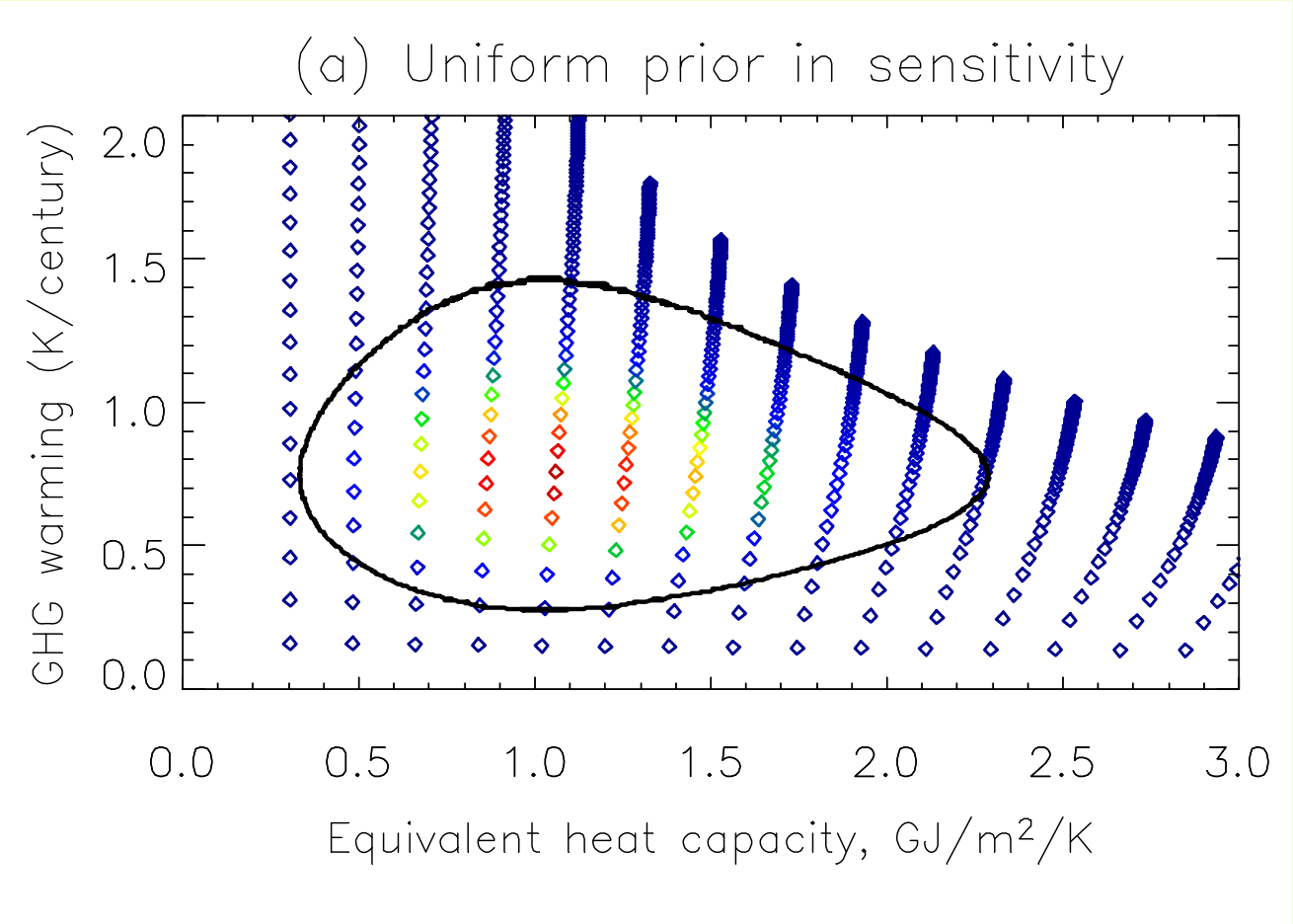
Uniform sampling in sensitivity



climateprediction.net

Oxford University

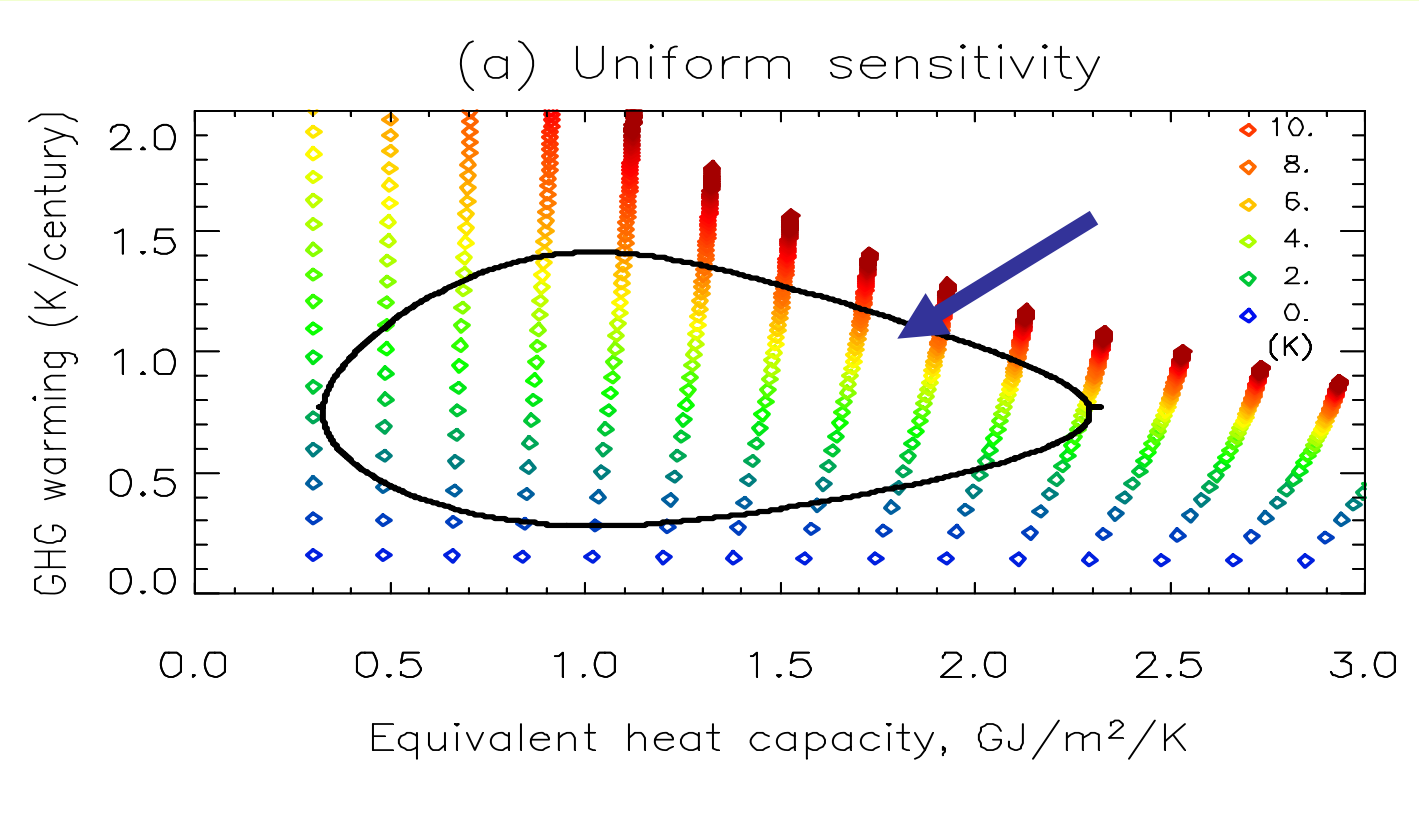
Likelihood weighting



climateprediction.net

Oxford University

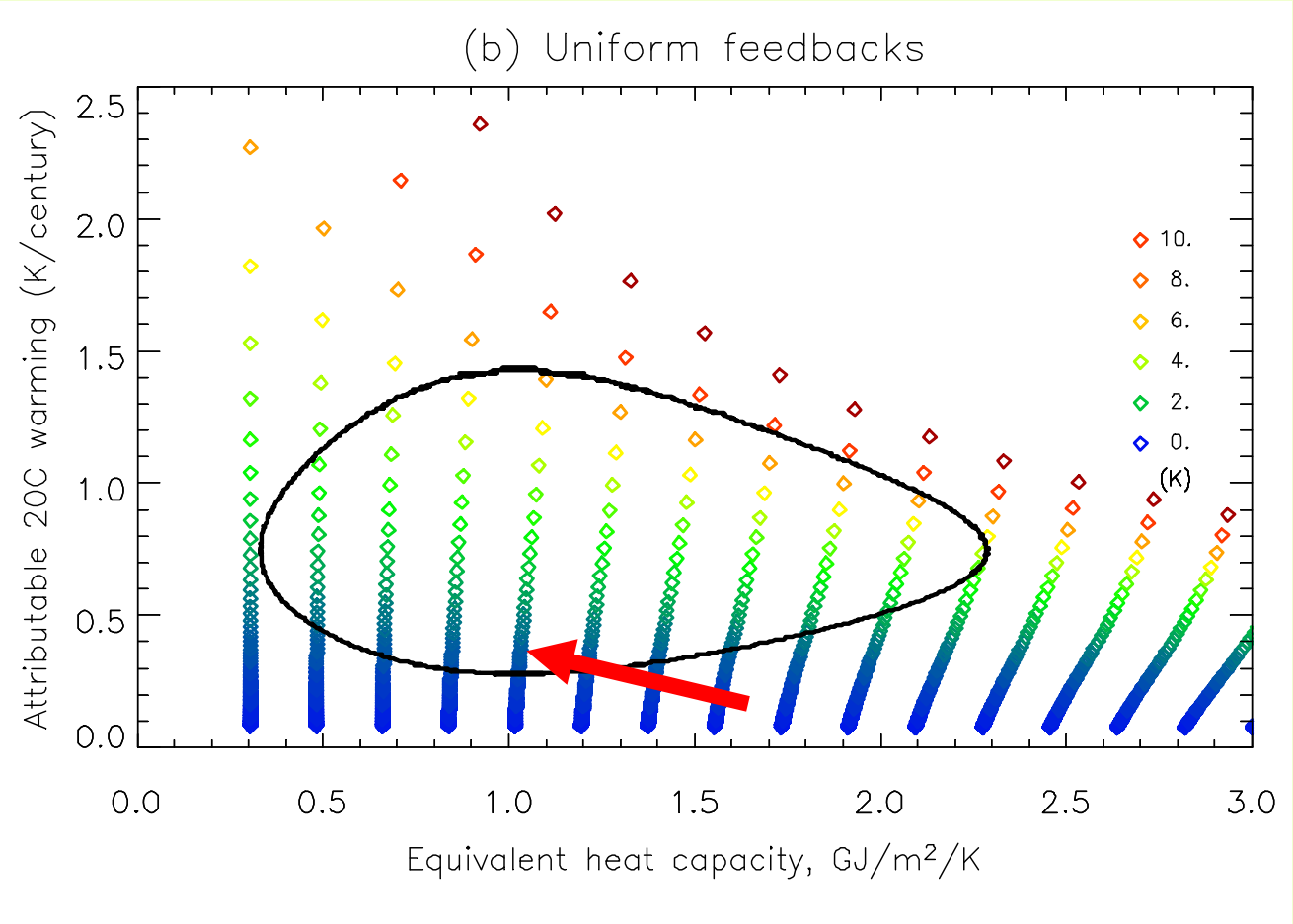
Constraints implied by observations



climateprediction.net

Oxford University

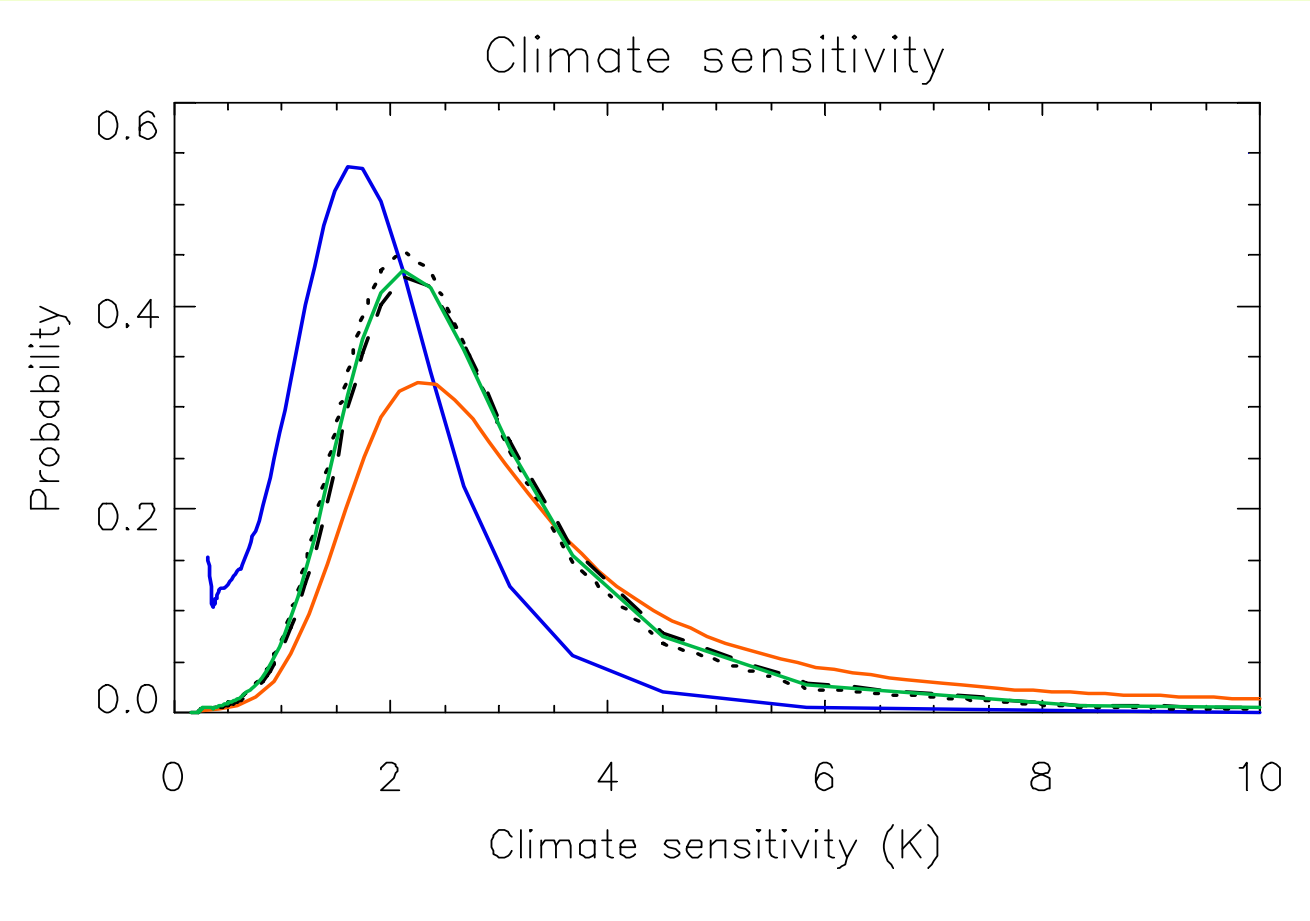
Using a different prior gives a different result



climateprediction.net

Oxford University

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



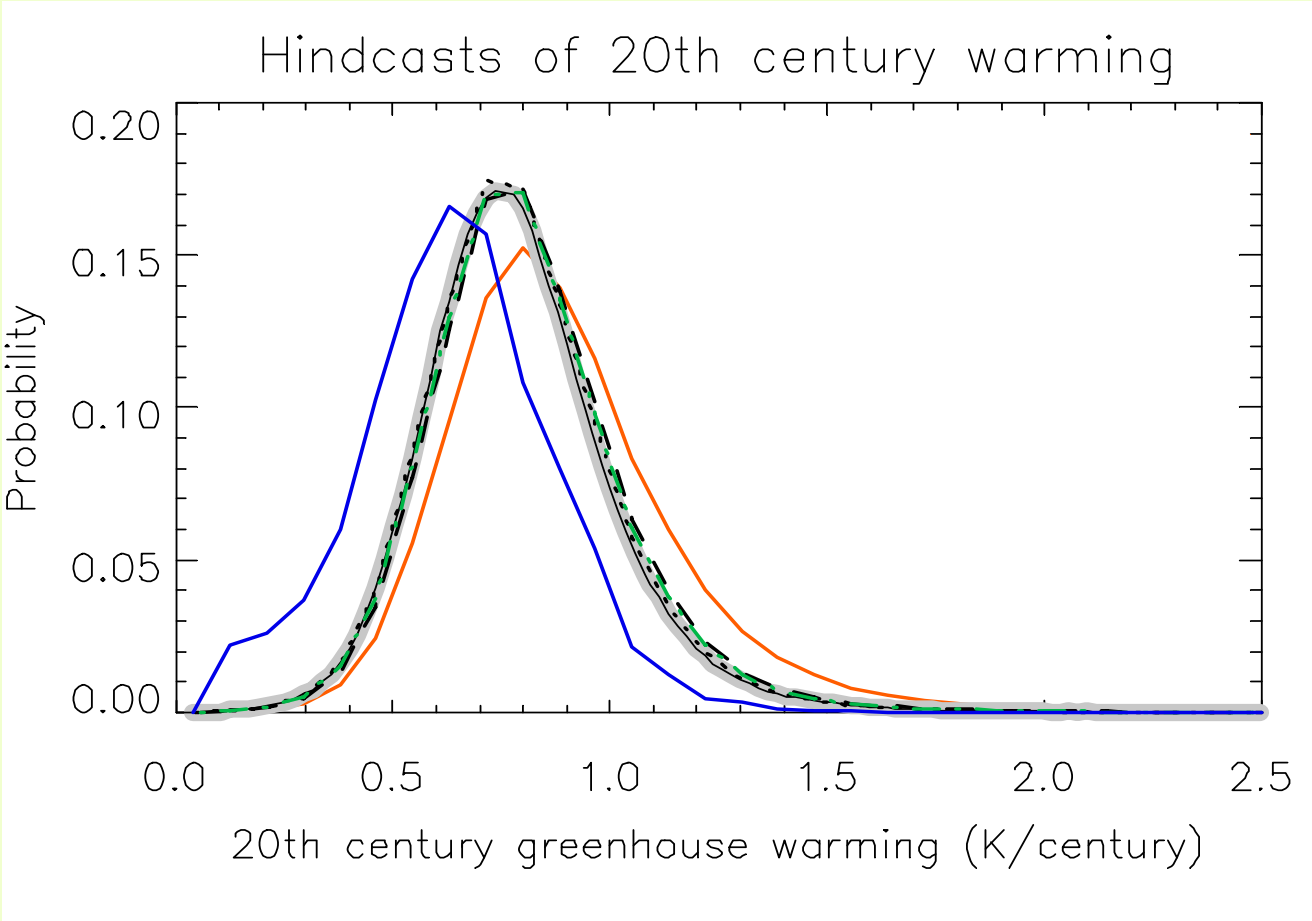
climateprediction.net

Oxford University

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

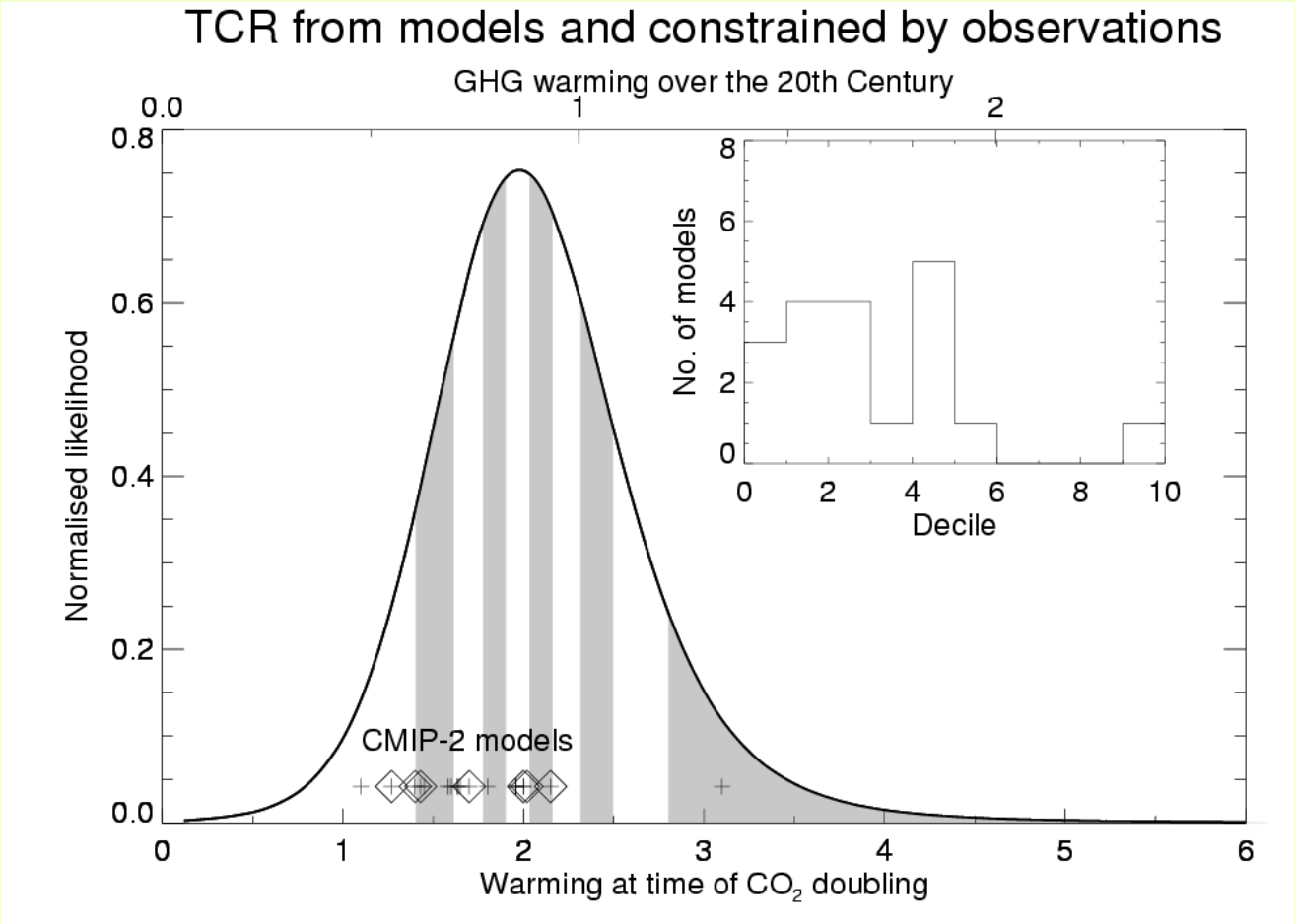
Hindcasts are quite closely related to (variants of) TCR because…



climateprediction.net

Oxford University

… Attributable GHG warming is linearly related to TCR



climateprediction.net

Figure from Jamie Kettlebrough

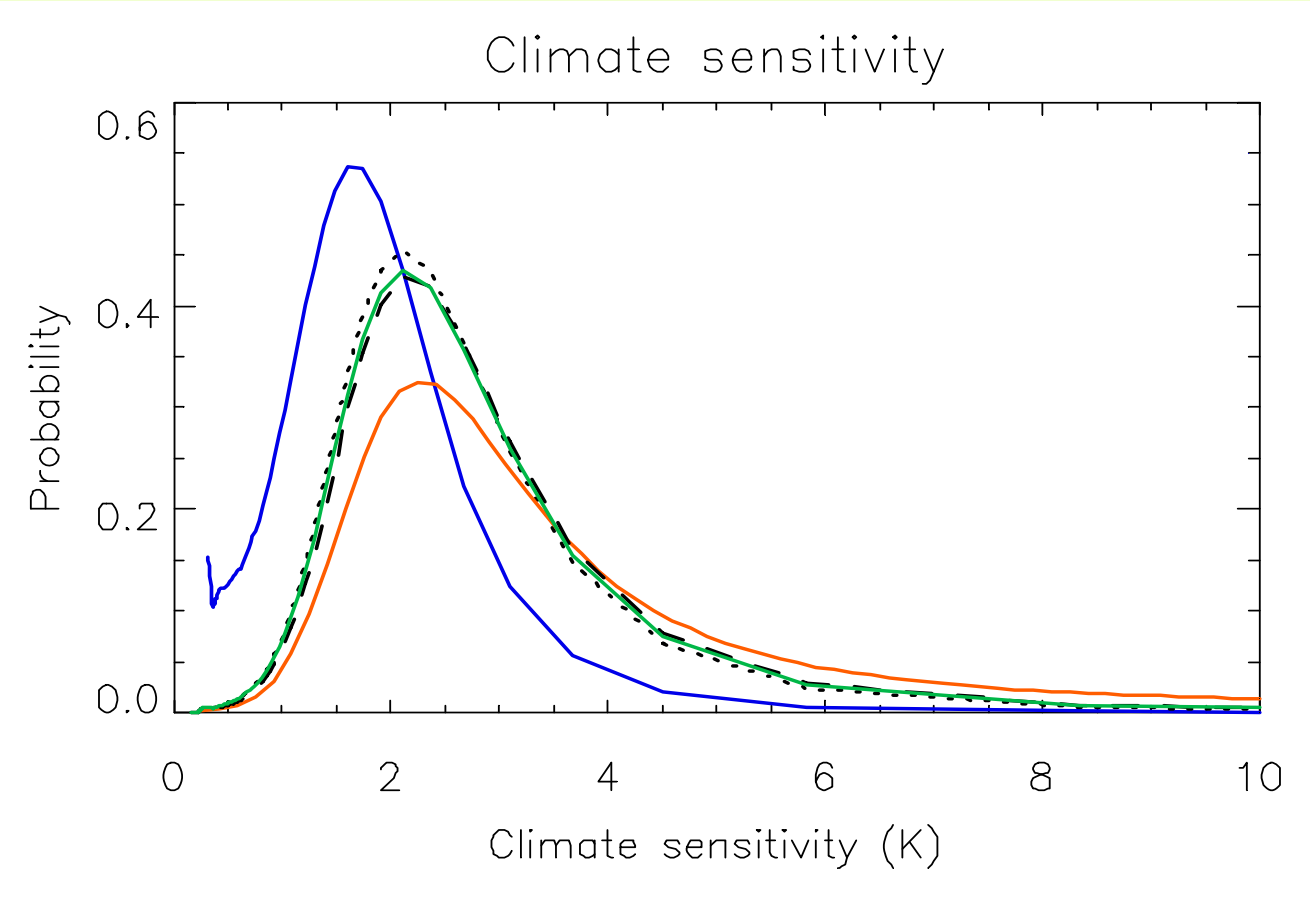
Oxford University

Summary

- **So Attributable warming provides a particularly nice "observable" on which to condition our transient climate change experiments**

- **Identifying such a nice "observable" for climate sensitivity is much harder.**

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



climateprediction.net

Oxford University

Fundamental difficulties in observing senstivity (a short detour)

- 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.

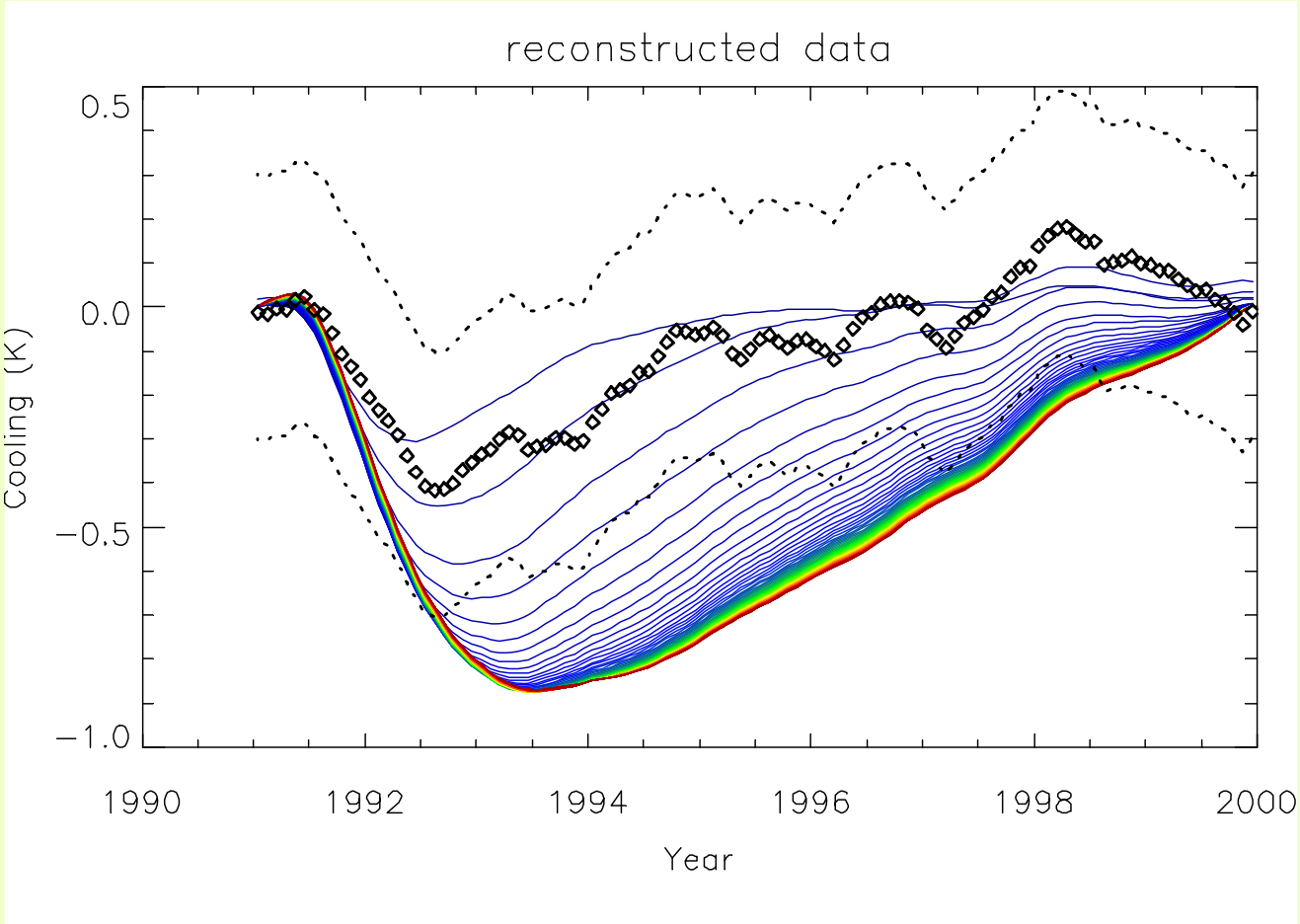
Transient observables scale with λ for large S

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

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

- 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)).

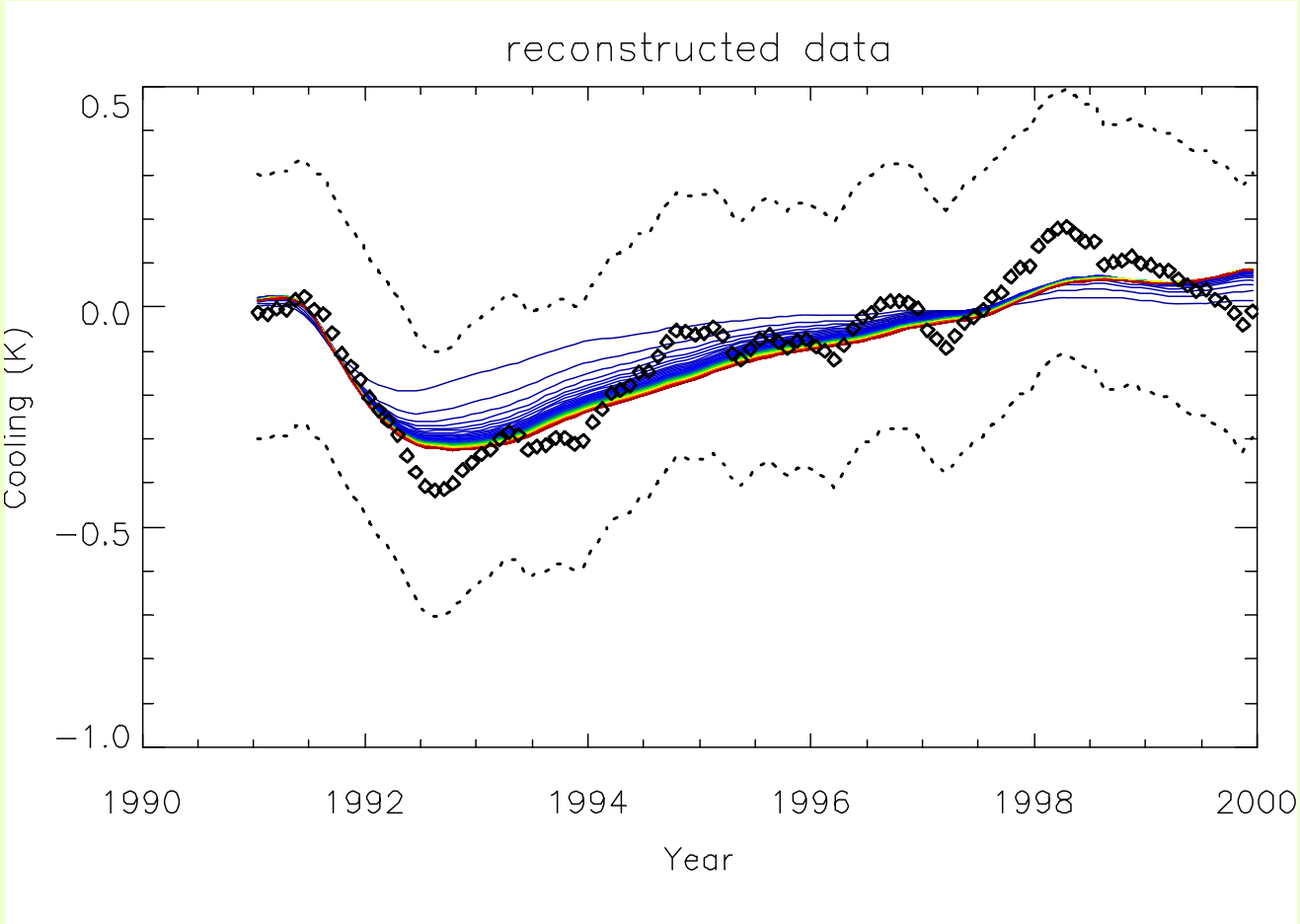
Have been claims that volcanoes provide a constraint on sensitivity (low heat uptake)



climateprediction.net

Oxford University

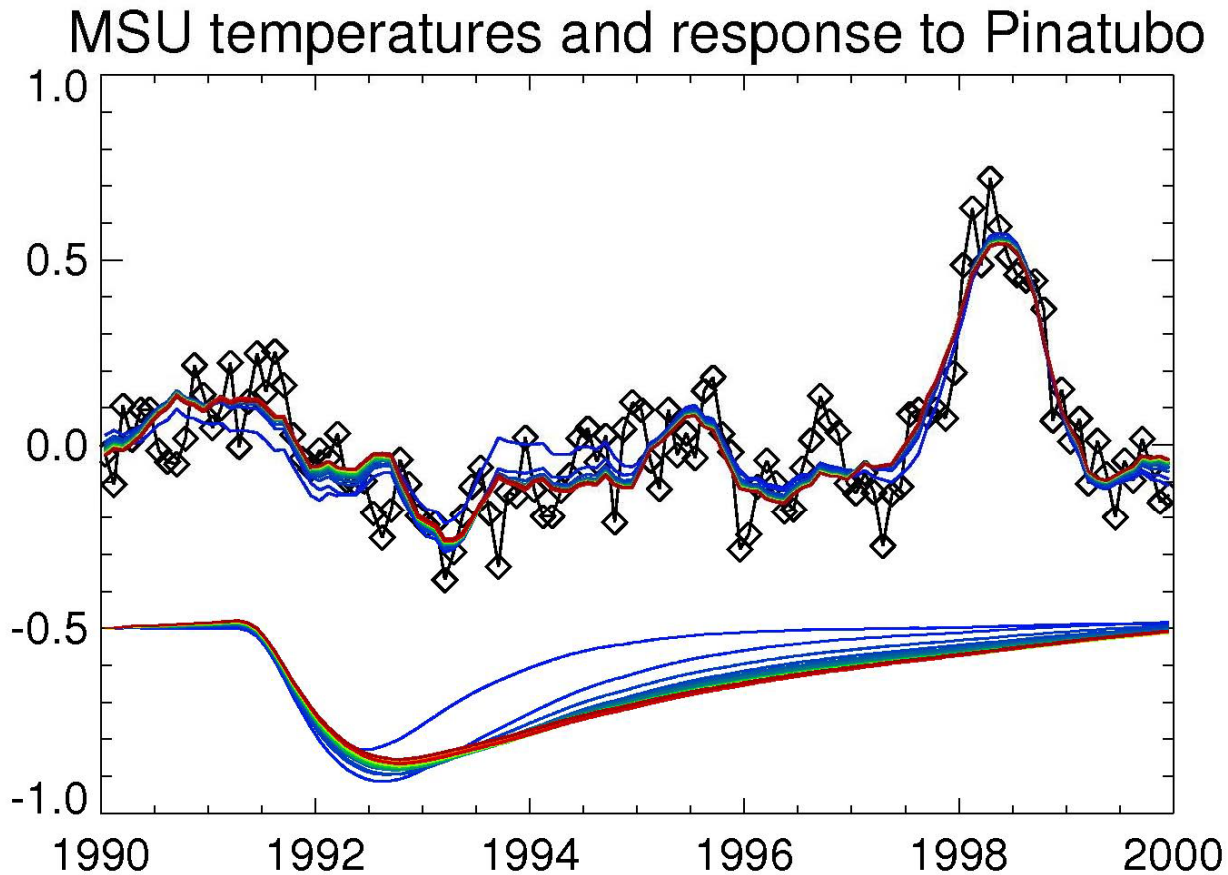
Have been claims that volcanoes provide a constraint on sensitivity (high heat uptake)



climateprediction.net

Oxford University

EBM responses to Pinatubo forcing



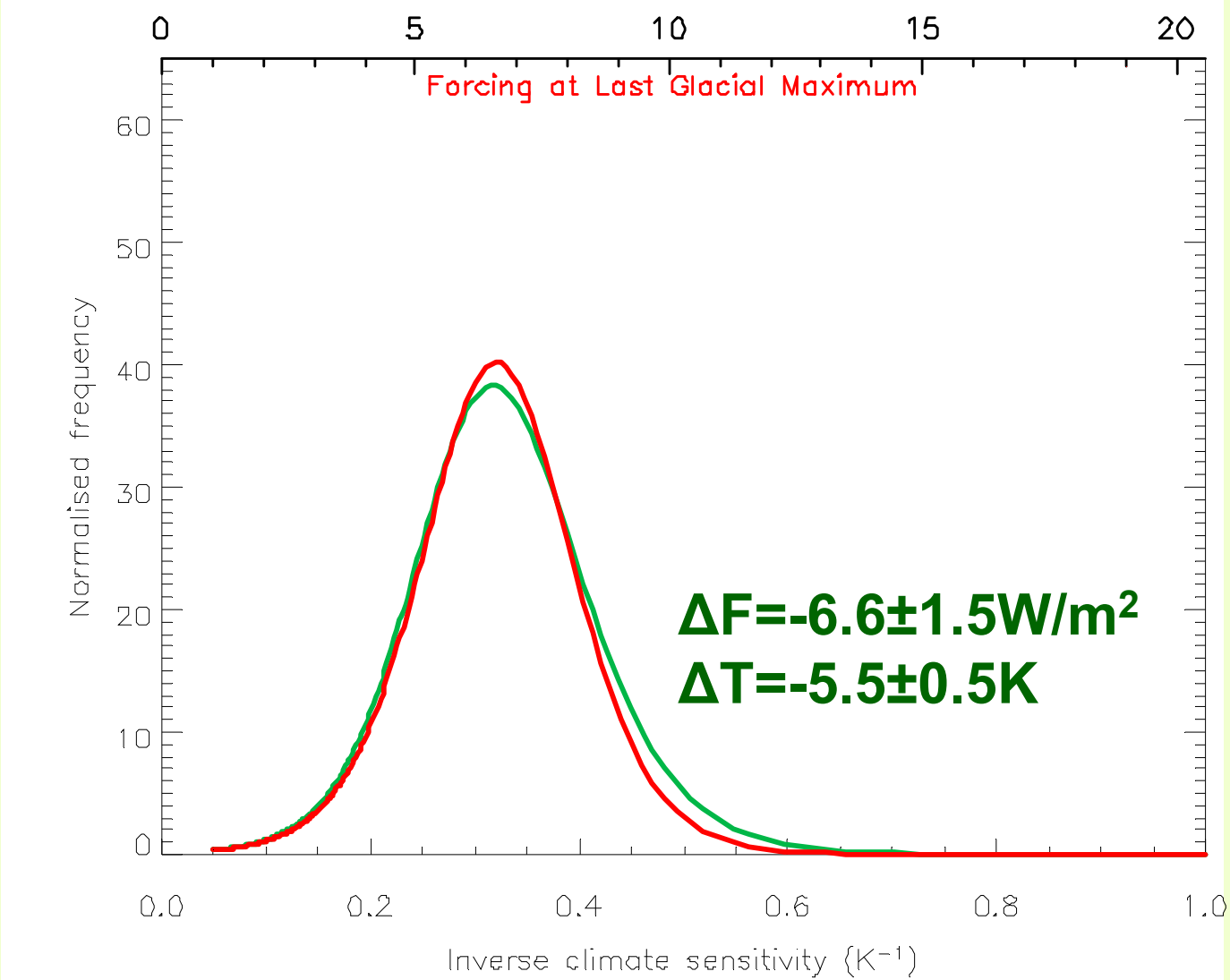
Also fitting ENSO, background climate and effective heat capacity

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?

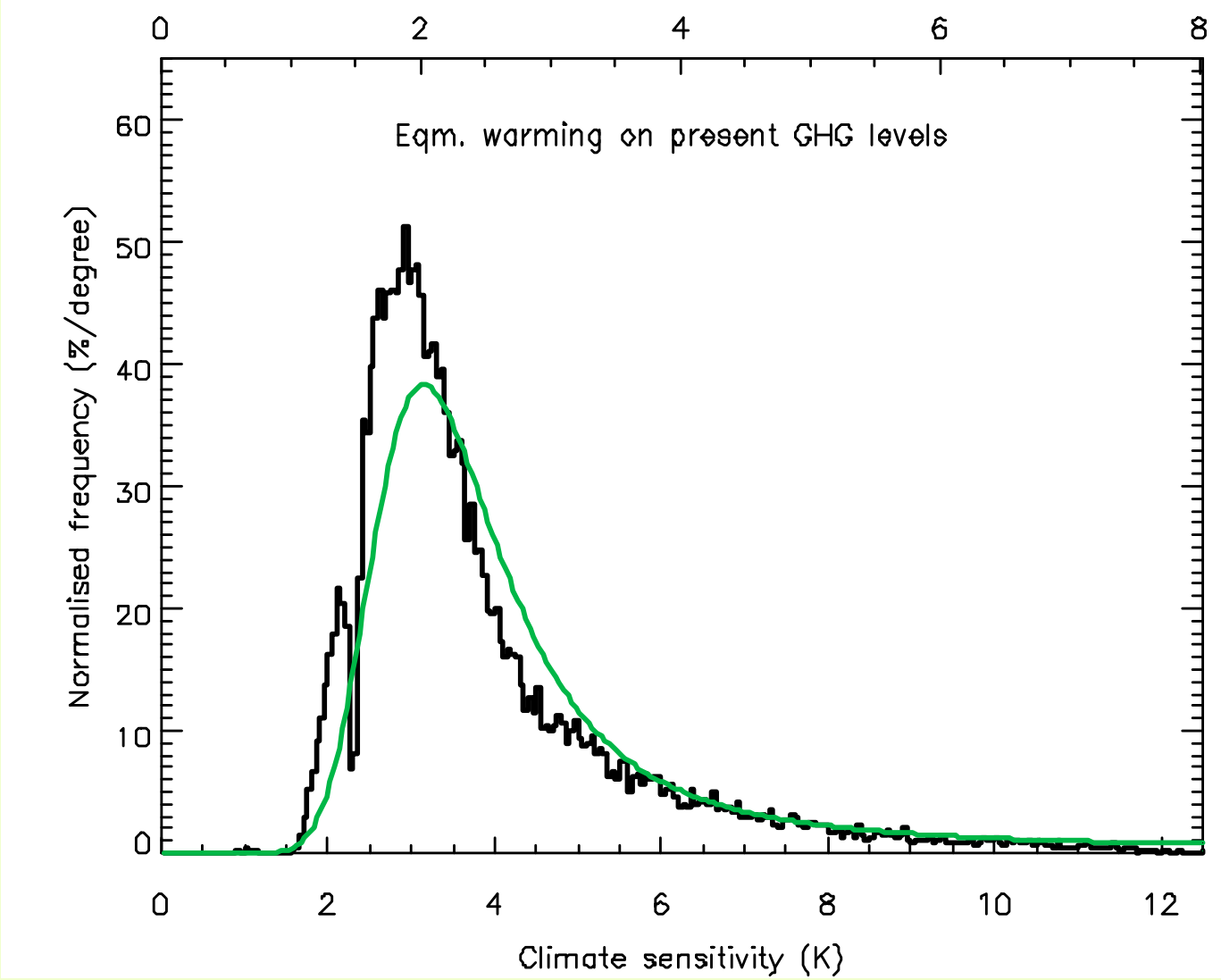


Numbers courtesy of Stefan Rahmstorf and Gavin Schmidt, realclimate.org

climateprediction.net

Oxford University

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

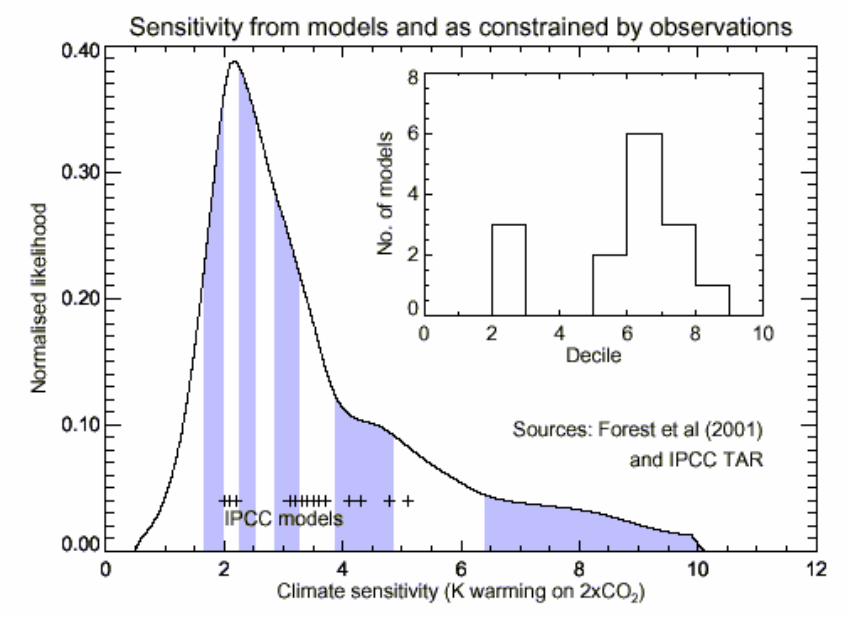


climateprediction.net

Oxford University

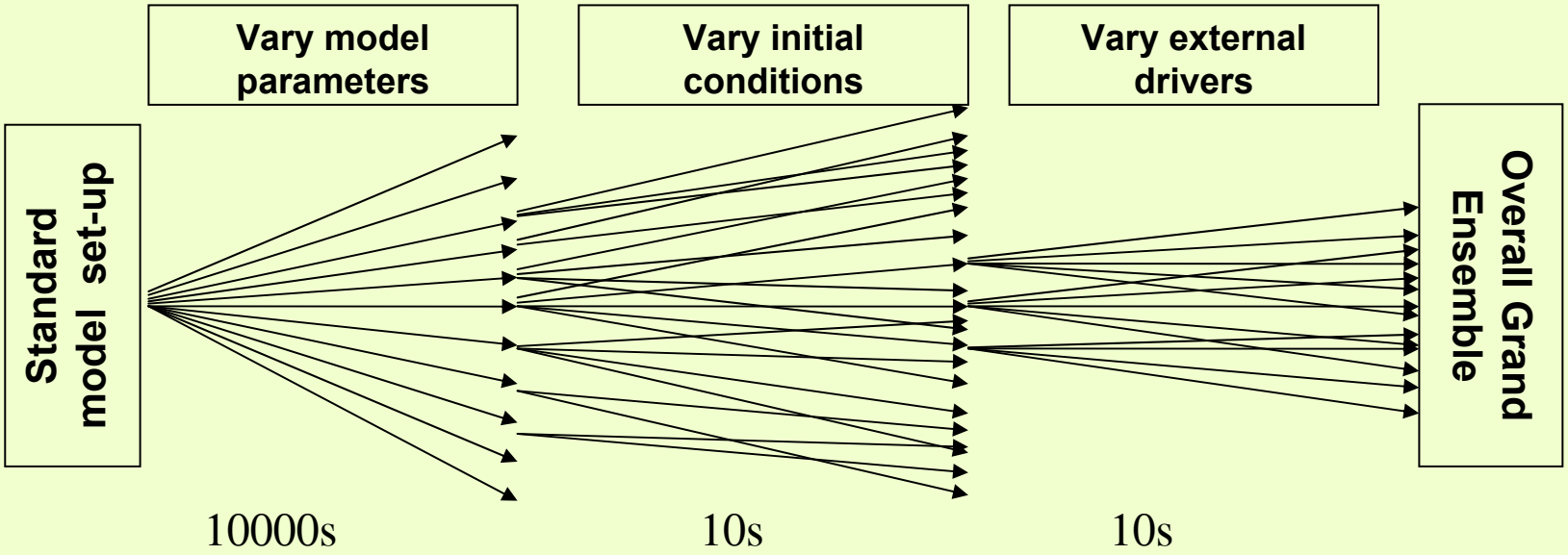
Monte Carlo Approaches

- 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.



The "cascade of uncertainty" in climate change prediction

- **How do we find alternative, equally realistic, climate models to explore the full range of possible responses to increasing carbon dioxide?**

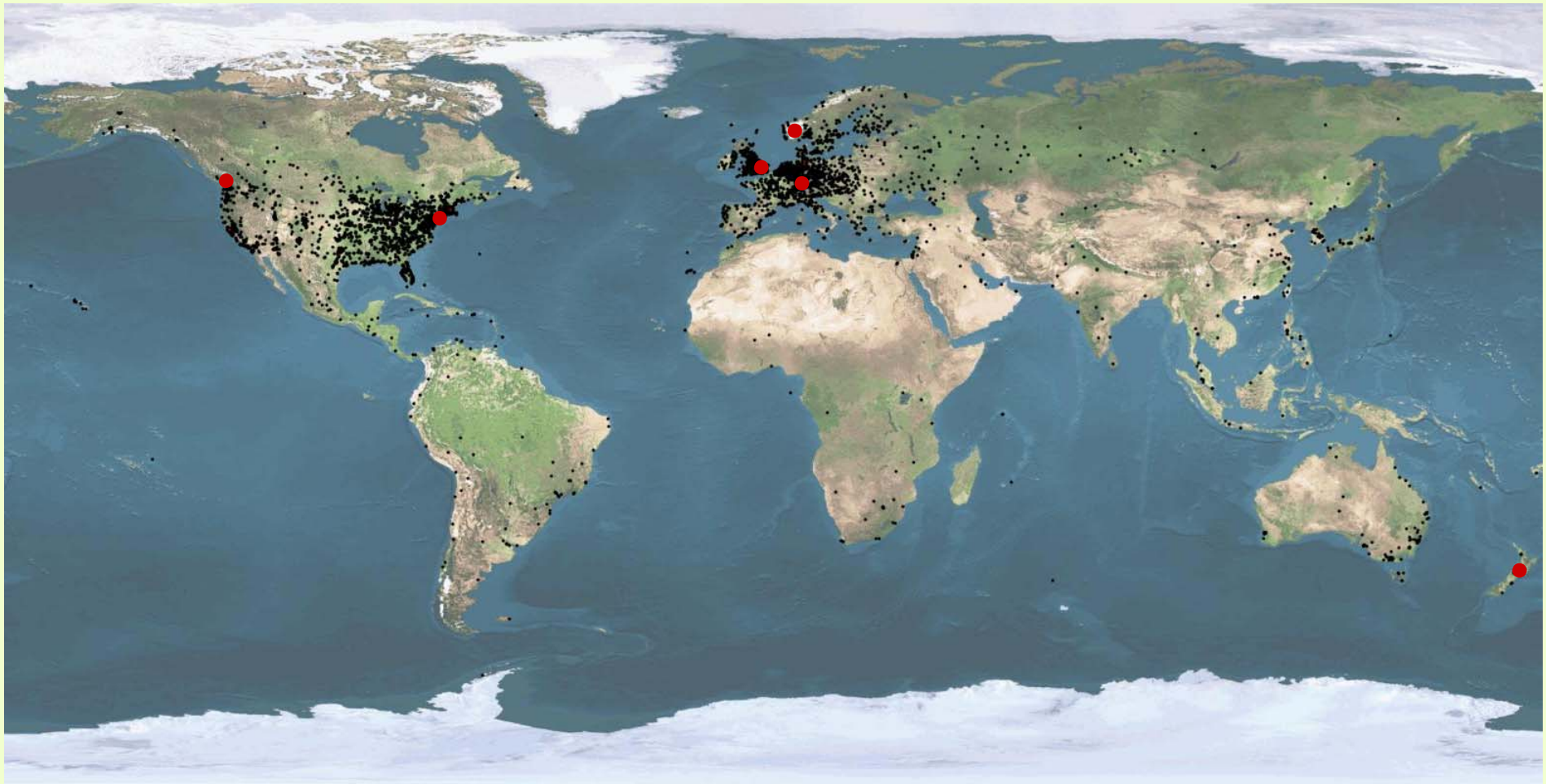


Model Versions **Simulations**

climateprediction.net

Oxford University

Climate*prediction*.net: an example of a Grand Ensemble of GCMs



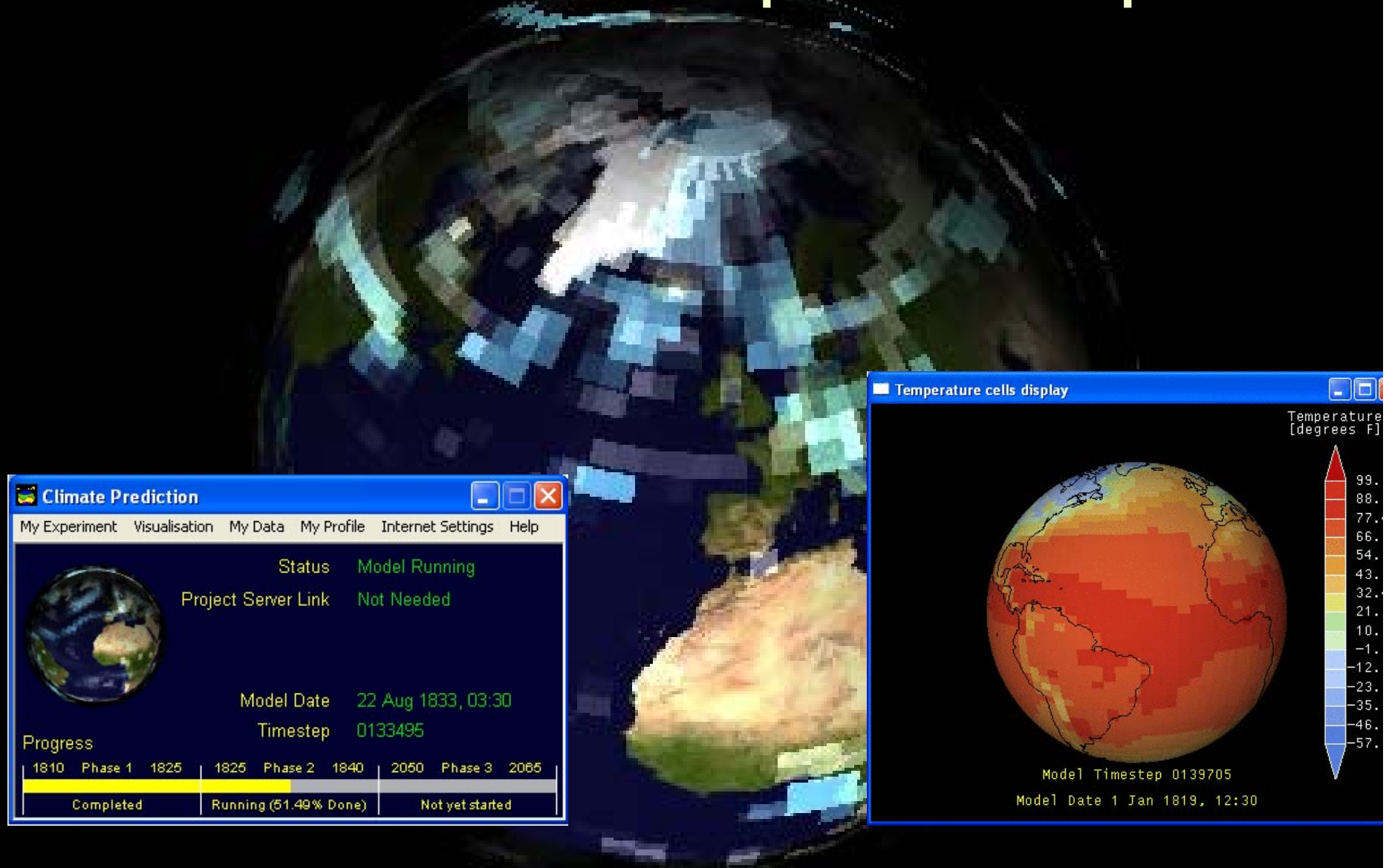
~30,000 active volunteers, 130 countries, ~110,000 full runs

Upload servers

climate*prediction*.net

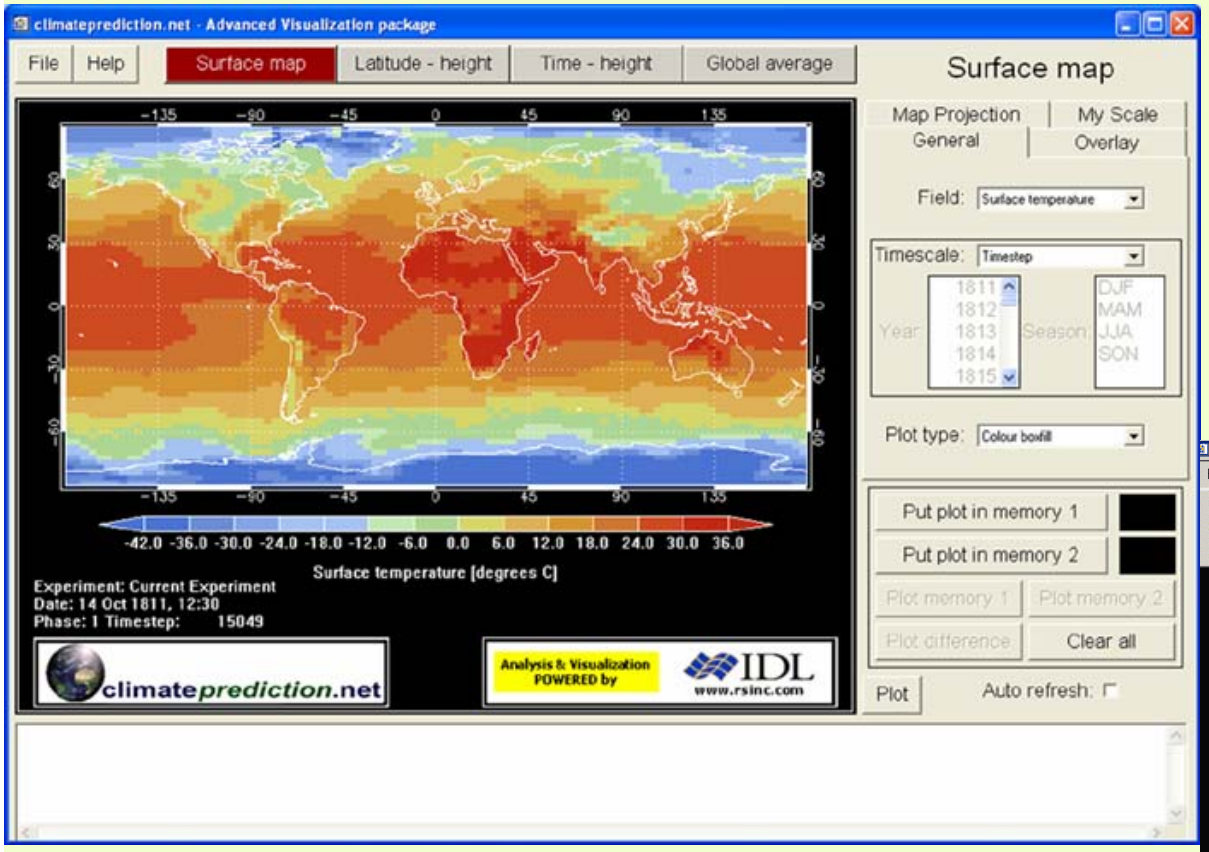
Oxford University

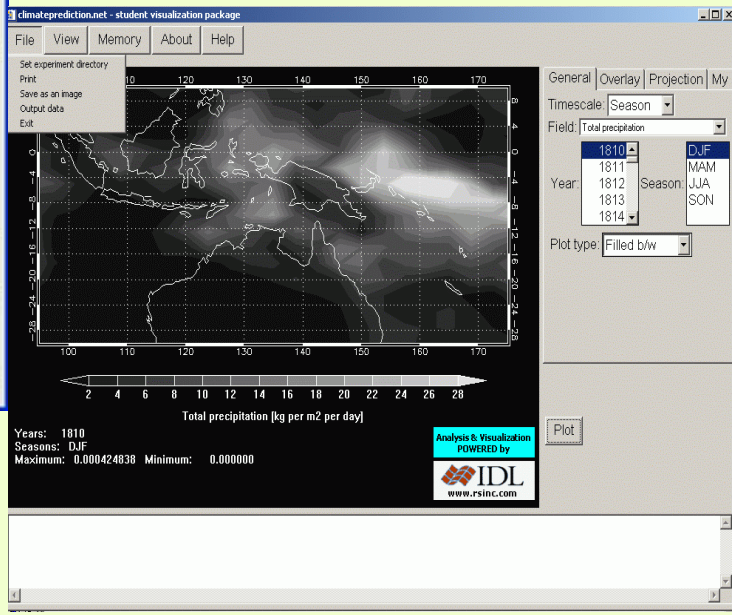
Members of the public download and run a full 3-D climate model on their personal computers



Model Phase 3, Timestep 0134187

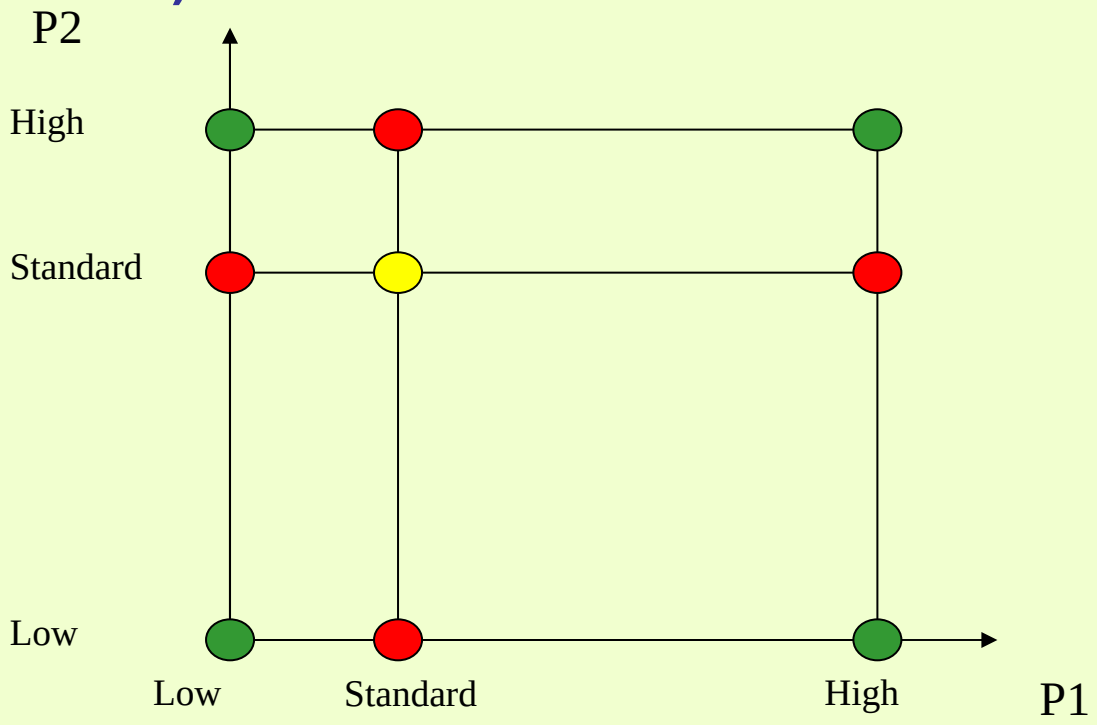
Software provided for school and undergraduate projects



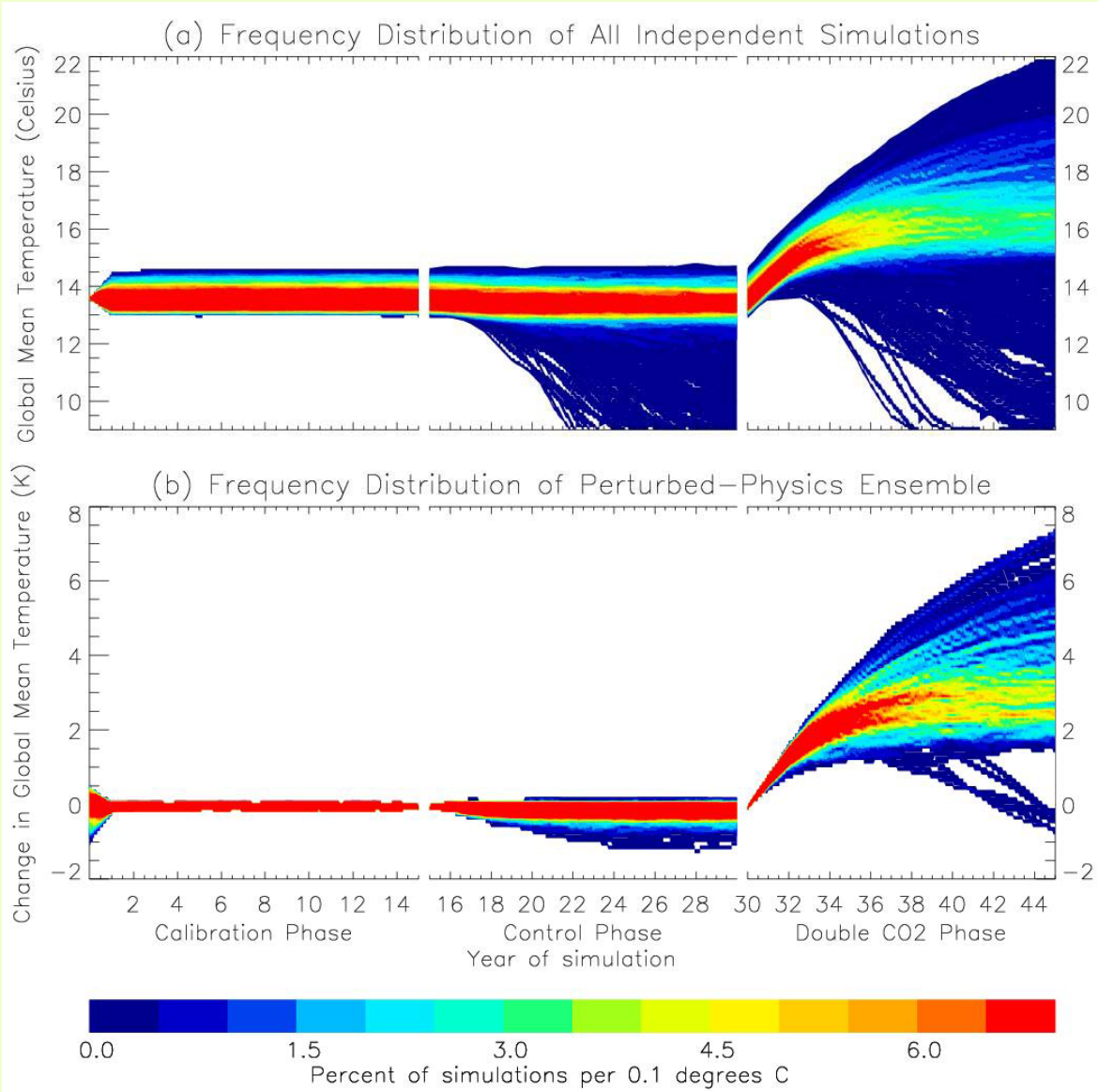


Exploration of parameter space, focussing on identifying non-linear interactions

- Perturbations to 21 atmospheric/surface parameters
- Three values each, including combinations
- Initial exploration of 6 parameters (clouds and convection)



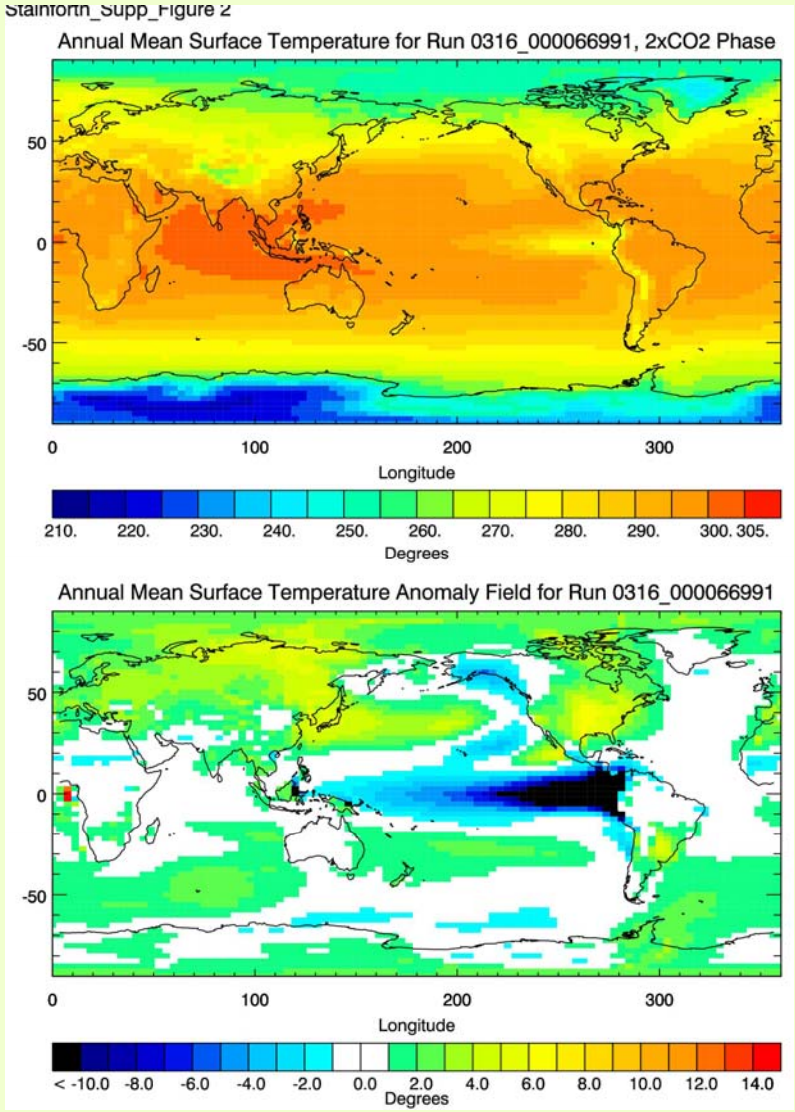
Time-evolving distribution: red=dense



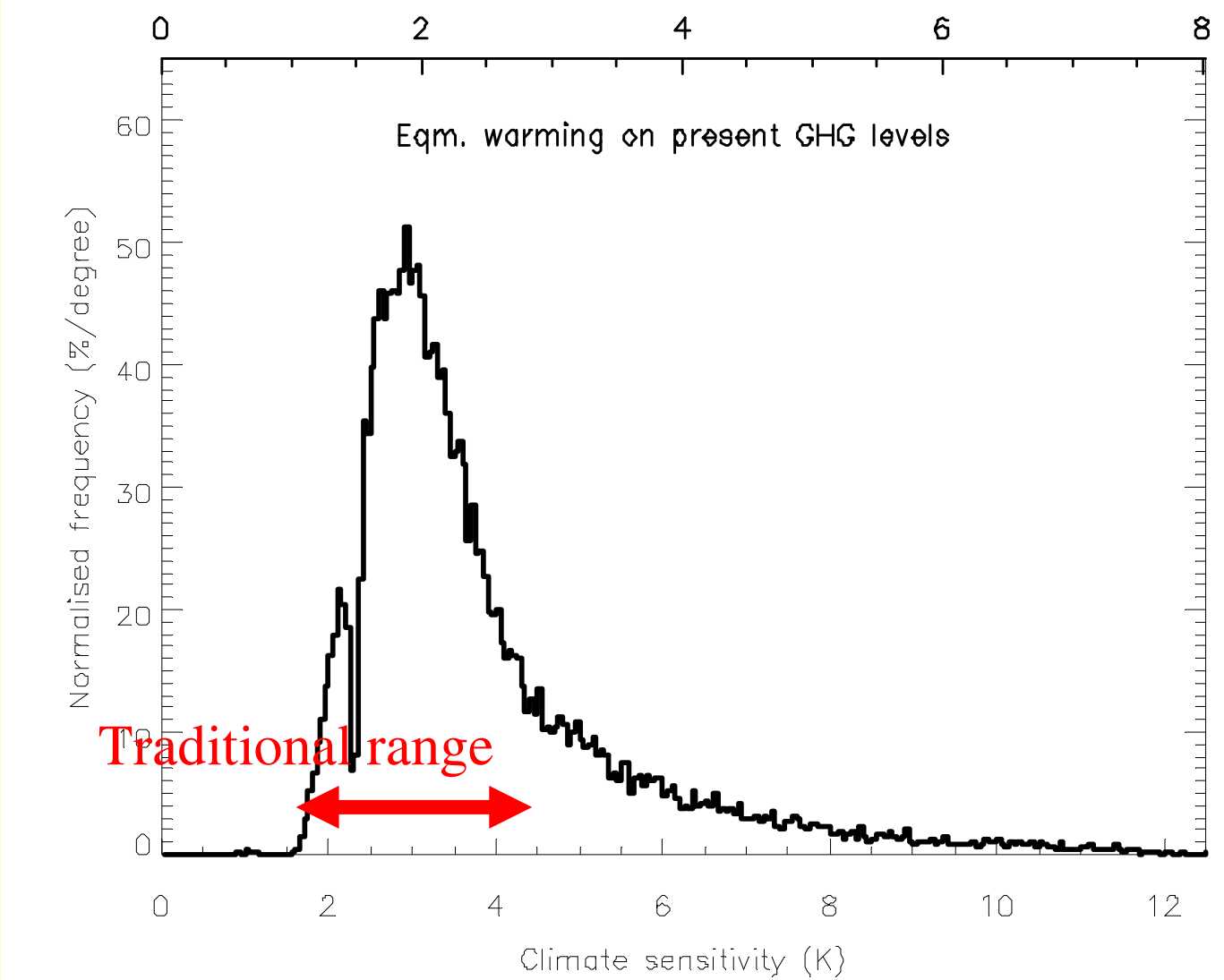
Remove models that are unstable in the control.

Few remaining negatively drifting $2xCO_2$ model versions are an unrealistic consequence of using a slab ocean.

Not The Day After Tomorrow: why we got some negative sensitivities…



47334 simulations passing initial quality control



climateprediction.net

Oxford University

Result was a double edged sword…

FREE METRO

Check out our great going out guide

Thursday, January 27, 2005 www.metro.co.uk

Life, starts Page 17

Smoke billows into the sky above the port of Dudinka in Russia yesterday

11°C That's how much hotter scientists believe the world will get ... and it will be worse in Britain

BY SUZY AUSTIN

THE world is likely to heat up by an average of 11°C by the end of the century, the biggest ever study of global warming showed yesterday.

And the effect could be even more marked in Britain, where temperatures could soar by up to 20°C unless greenhouse gases are cut.

Such a rise – far higher than the 2°C previously forecast – would see Britain endure tropical temperatures, flooding and devastating drought.

It would change the weather patterns of the world, melt the polar ice caps and warm the oceans, causing a surge in sea levels threatening the lives of billions of people.

The findings come from a study which tapped into the processing power of 100,000 home computers in 150 countries.

Researchers racked up the equivalent of 8,000 years of processing time as they ran 60,000 potential scenarios through the network, far more than the 128 scenarios the powerful computers at the Met Office can check in a year.

Each scenario was based on the assumption that carbon dioxide levels had reached double those of pre-Industrial Revolution times by the middle of this century.

Researcher David Stainforth, from Oxford University, said: 'An 11 degree warmed world would be a dramatically different world.

'Warming is not constant at all latitudes and tends to be greater at high latitudes.

'With a world warmed by 11 degrees there would be large areas of high latitude that could be 20 degrees warmer than they are today.

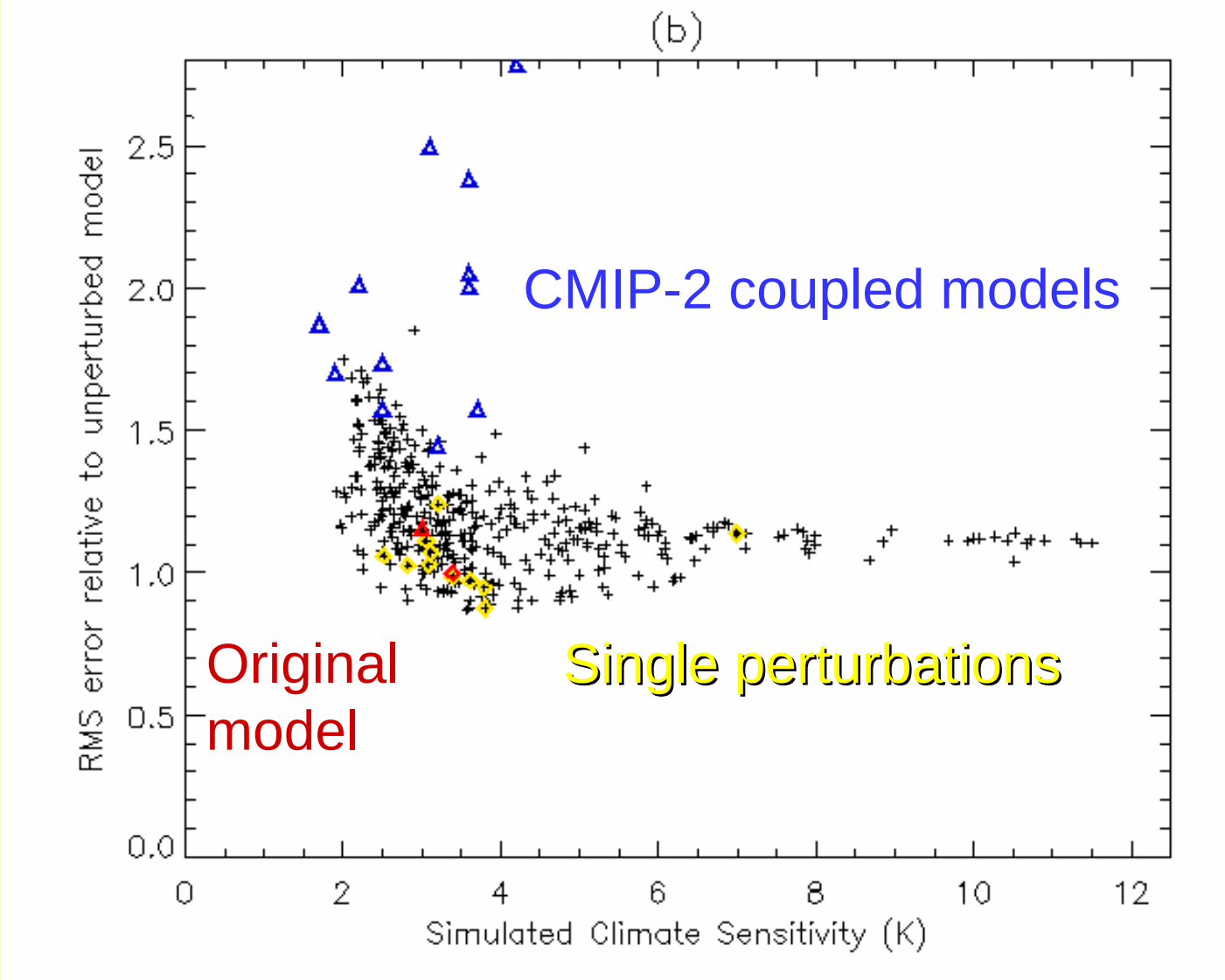
'I think it would probably not be a tropical paradise. The UK would be at the high end of this change, well into the teens as the temperature changes. I don't think we'll be building many snowmen in winter, or going sledging.'

The findings could mean world leaders need to toughen their commitment in the Kyoto agreements to cut CO_2 emissions to 5.2 per cent below 1990 levels by 2012.

The warning came as Tony Blair used the World Economic Forum in Switzerland to call for action on global warming and to pressure America to sign up to Kyoto.

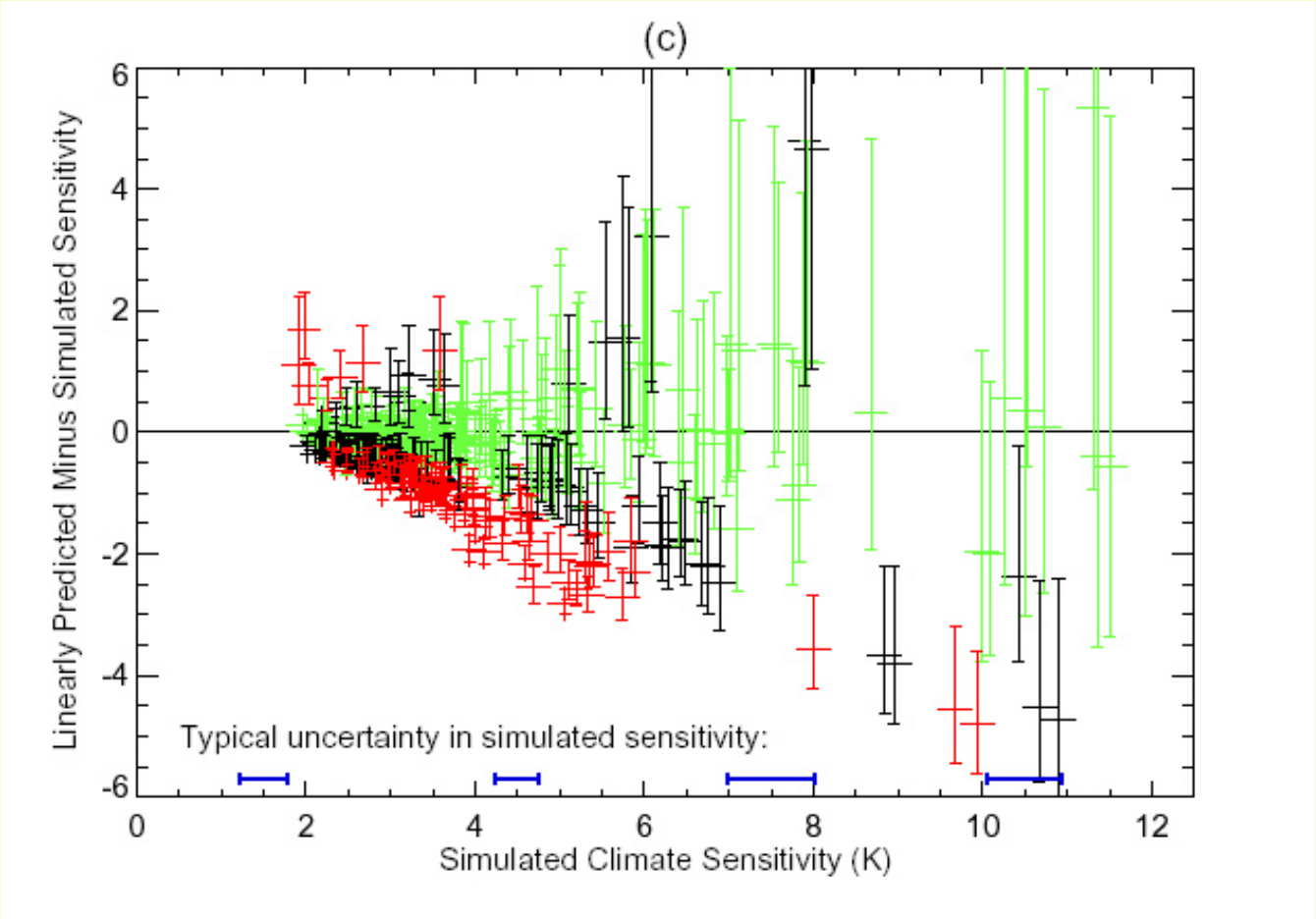
Blair's call – Page 5

PPE generates high sensitivity models that are hard to rule out



Stainforth et al, 2005

Perturbations add non-linearly



Initial results

- On-going task to compare models against observations (Piani *et al.*)
- Building on CMIP-II's experience
- Models that give us high sensitivities not yet ruled out by observations
- There are a number of interesting models that give us a range of sensitivities (<2K to >11K) that do not appear to be worse climate models than HadCM3

Next steps, analysis

- Systematic quality control process
  - Models vs physics, vs other models
  - Models vs observations
- More full analysis of the entire ensemble
- Several subprojects already suggested
  - New variables (precip, mslp, etc.)
  - Regional analyses
- Ultimately want this to become a dataset like CMIP-II or a satellite dataset – a community resource (we just have to build the infrastructure, first!)

Next steps, experimental development

- **Sulphur cycle experiment**
  - **Perturbations to the S-cycle, sensitivity experiment to changes in aerosols, similar to current experiment**
- **Coupled model spinups**
  - **Perturbations to ocean to give range of Kv, thermohaline behaviours**
- **Coupled model hindcast experiment**
  - **run 1950-2000 using historical forcings as a test of the models from the slab phase(s)**
- **Coupled model 21st century experiment**
  - **run 2000-2100 using range of future forcings, having run the hindcast and found models which are both interesting (phase 1) and good (phase 2)**
  - **Predictive experiment with the goal of a "probabilistic" forecast**

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

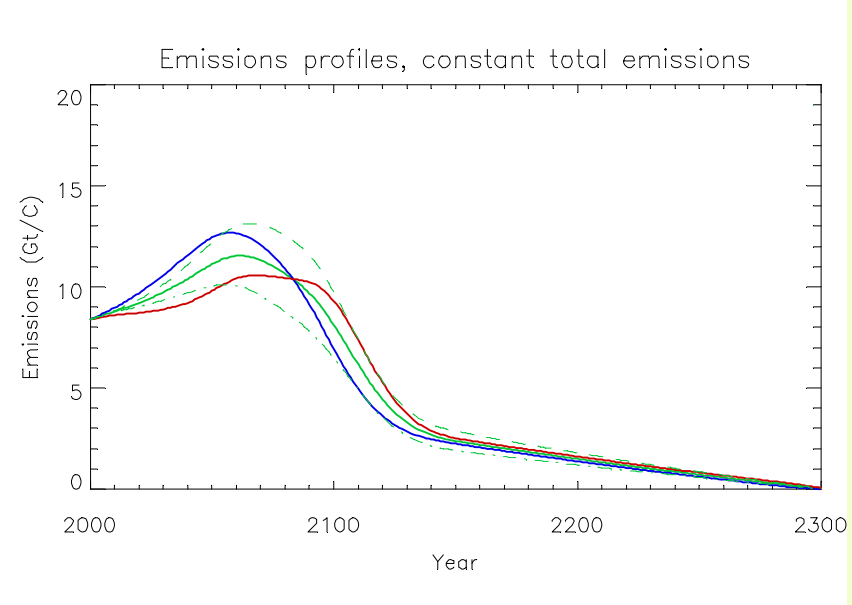
- Consider maximum warming under emissions scenarios in which emissions drop back to zero** by 2300.
  - **Zero basically means within the uncertainties associated with the carbon cycle (by 2300)

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 IAMs, etc. 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.

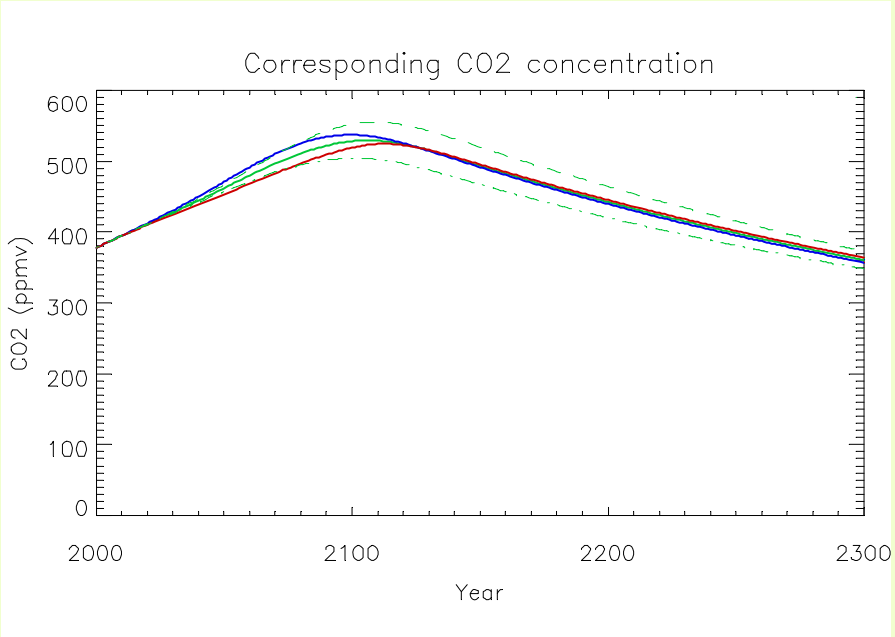


Phase out concentrations

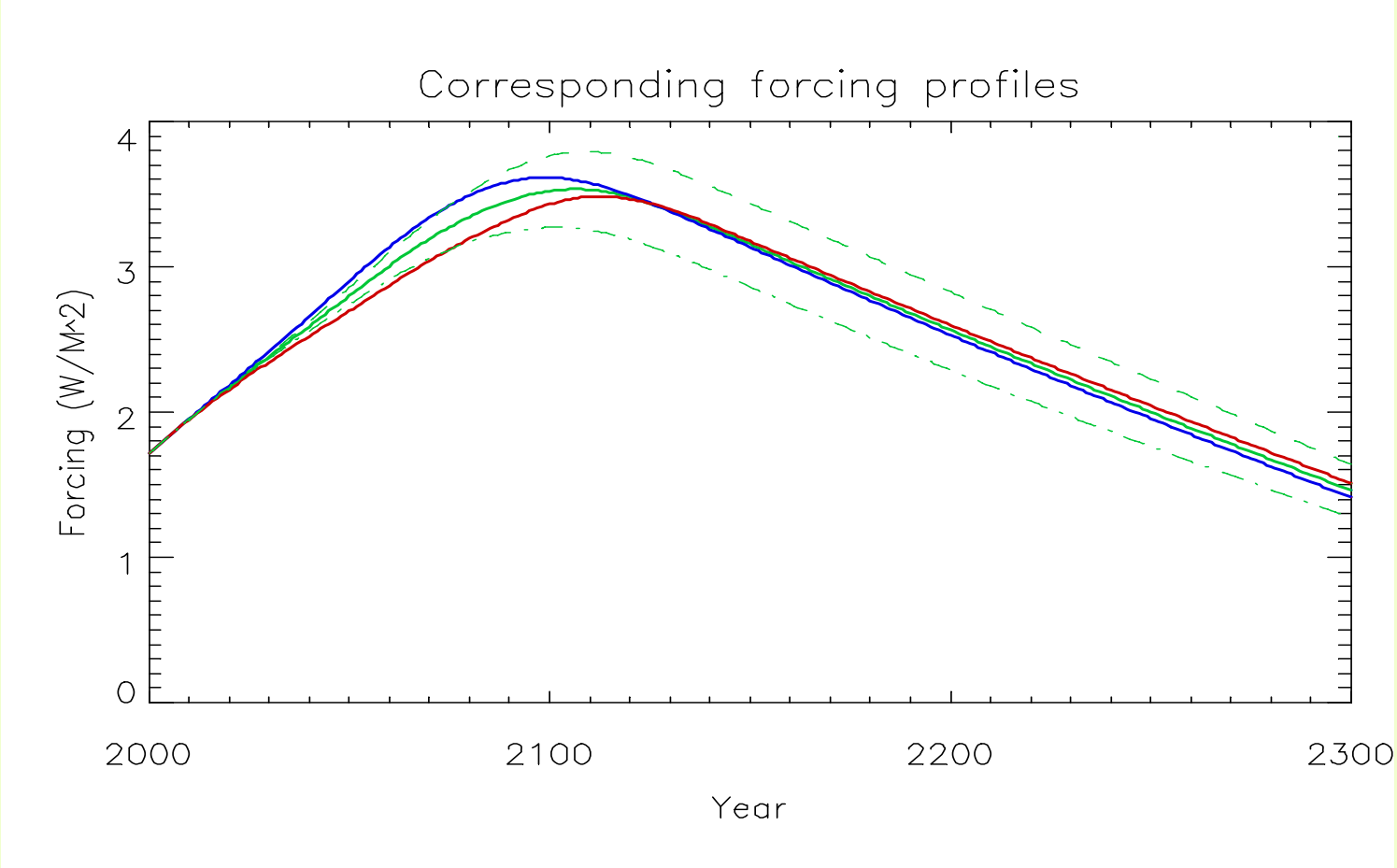
- Concentrations are strongly dependent on the carbon cycle model used.
- This analysis uses Nordhaus's 1991 approach, such that:

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

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



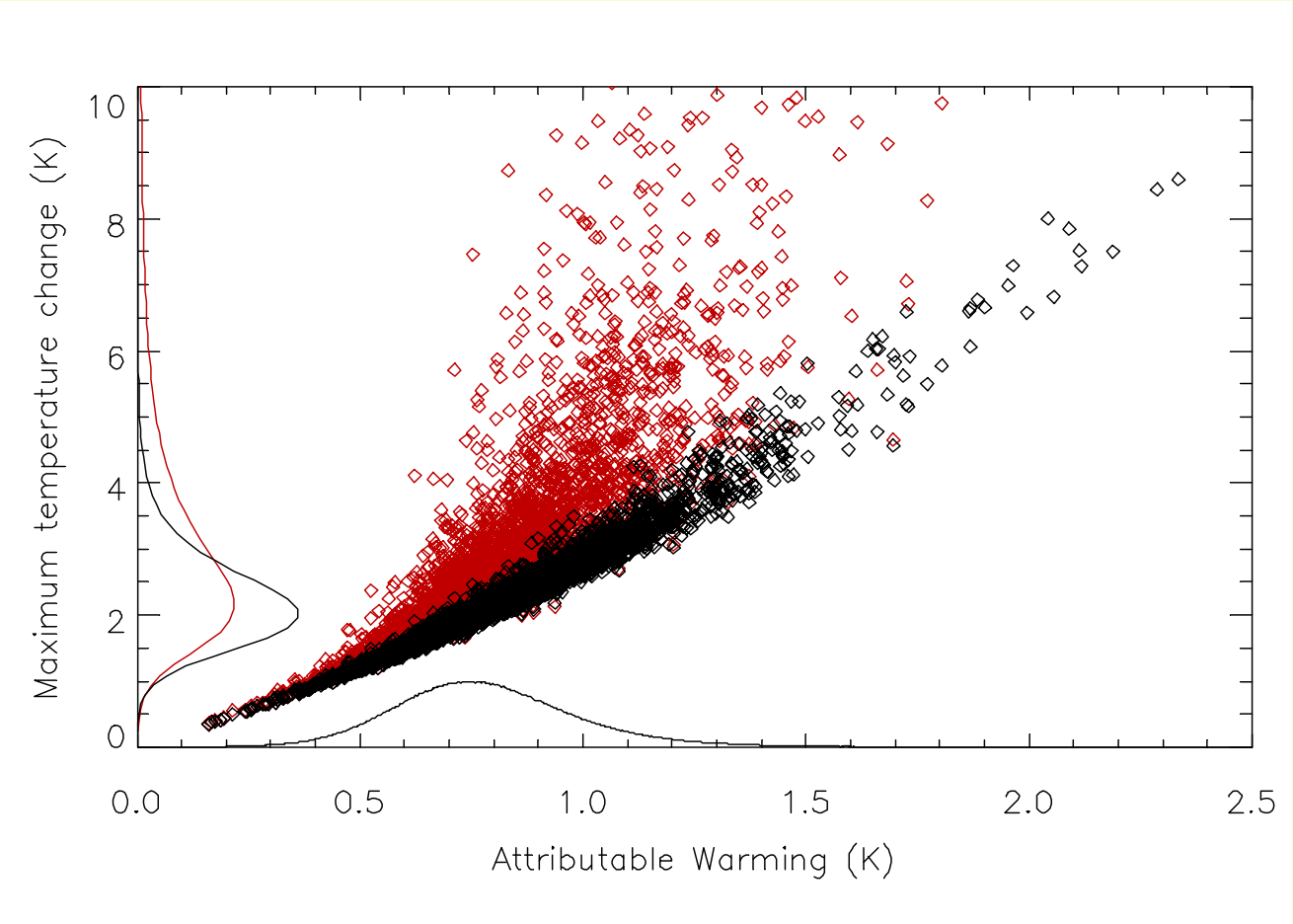
Forcing under phase outs



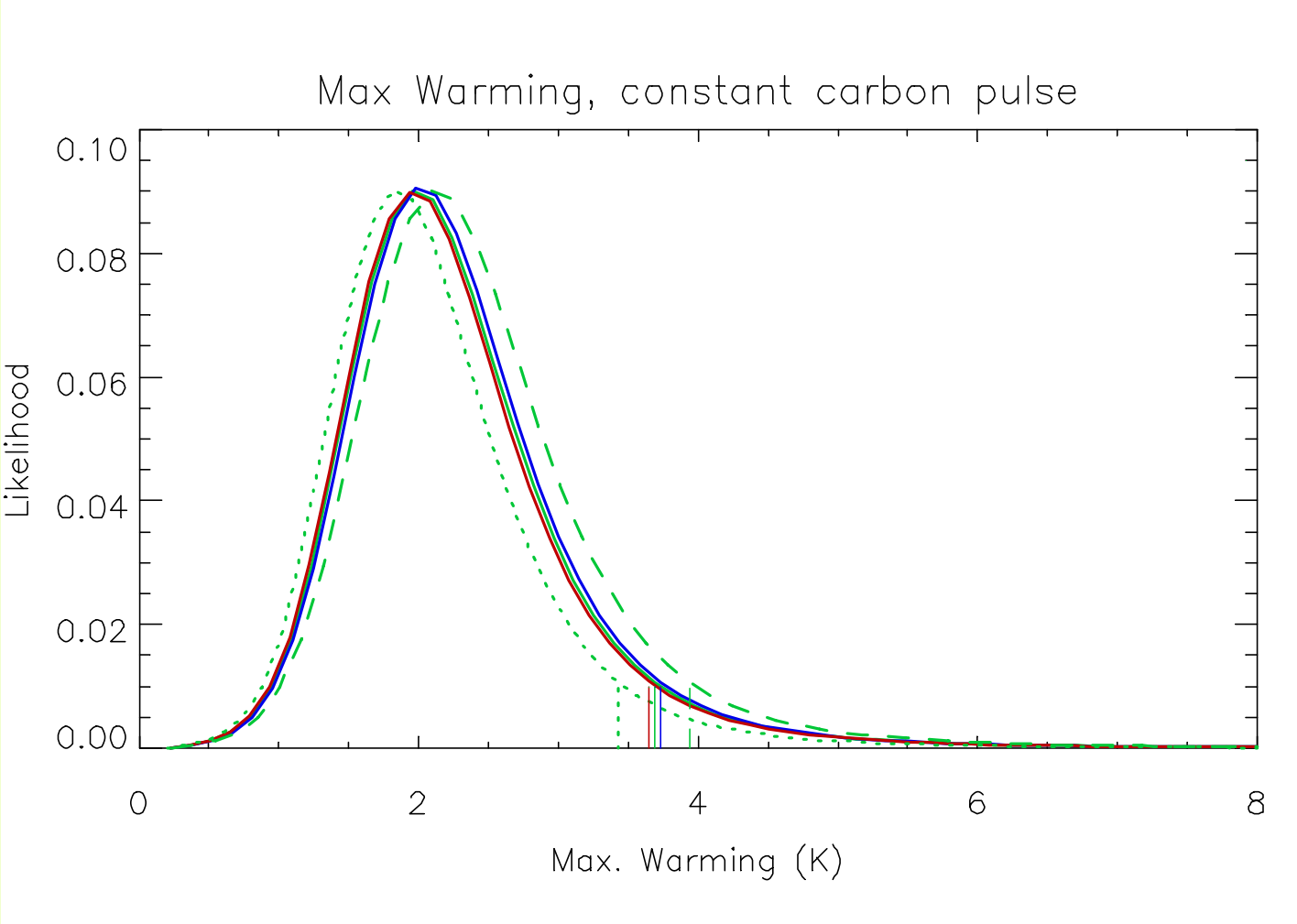
climateprediction.net

Oxford University

Remaining neutral in observable quantities



Maximum warming under phase outs



climateprediction.net

Oxford University

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.