



SAGES

Scottish Alliance for Geoscience, Environment & Society

Constraining Climate Sensitivity using Top Of Atmosphere Radiation Measurements

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NCEO:
National Centre for Earth
Observation



Aims

- Discuss approach to generate atmospheric model parameters which give observed global-mean radiation measurements.
- Use results from these simulations to give probabilistic estimate of equilibrium climate sensitivity.
- Show some recent results on optimisation and behaviour of resulting models



Key results

- Successfully optimised HadAM3 to outgoing longwave (OLR) and Reflected Shortwave (RSR) observations.
- There is a relationship between equilibrium climate sensitivity and simulated outgoing radiation
- Uncertainty analysis on “plausible” HadAM3 models rules out Equilibrium Climate Sensitivity $> 5.6\text{K}$ (and $< 2.7\text{K}$)
- Can produce stable HdCM3 (Atmos/ocn) models whose responses appear not greatly different from standard model.



Philosophy

- Model is a tool which encapsulates our (best) knowledge of relevant physics of the system.
- Future predictions are based on models
- A model is useful for *specific* purpose if it is consistent with *relevant* observations
- Uncertainty in future predictions arises because many models are consistent with observations but make different predictions.
- What we need to do – *efficiently* produce model cloud which is consistent with observations



Observational Data (part 1)

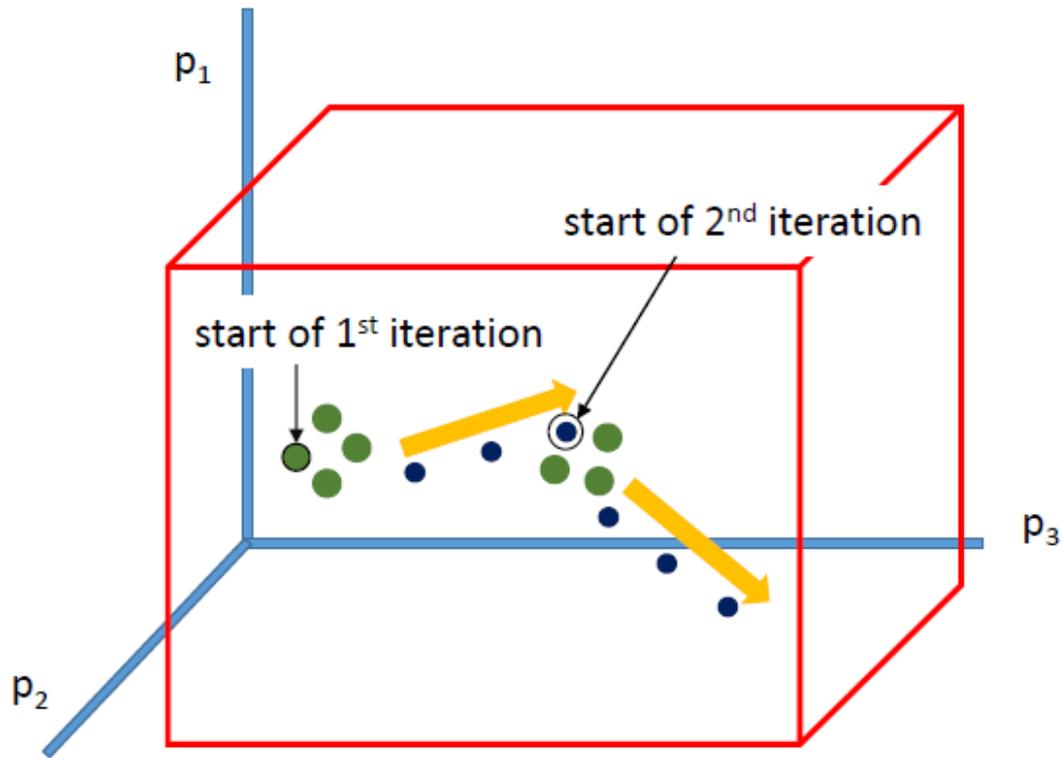
- Use the CERES (Clouds and the Earth's Radiant Energy System) record of Leob et al, 2009.
- CERES flying on TERA & AQUA satellites
- Measures Outgoing Longwave Radiation (OLR) and Reflected Solar Radiation (RSR)
- We only use the global-average 5-year mean values.



Experimental Design

- HadAM3 (Atmospheric model – Pope et al, 2000) simulations forced by observed Sea Surface Temperatures & Sea Ice.
- Modify four parameters in model which are known to affect climate sensitivity
- Simulations started Dec 1998 and ran through to April 2005 starting from same initial condition.
- Compare Model and Observations for 1st March 2000 to 28th Feb 2005

Schematic of Optimisation



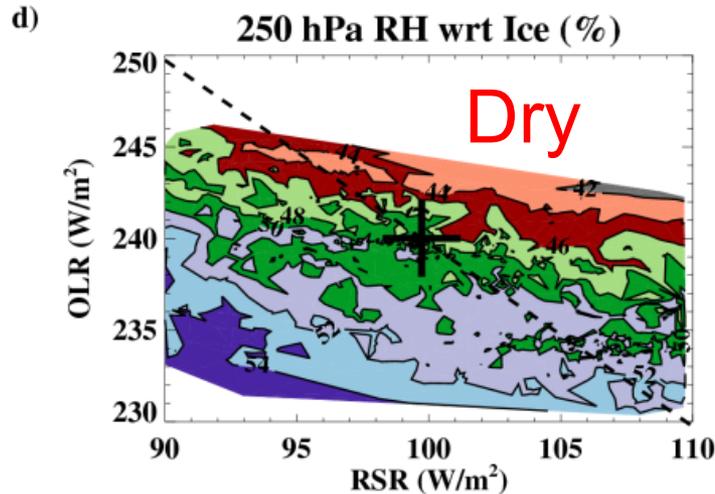
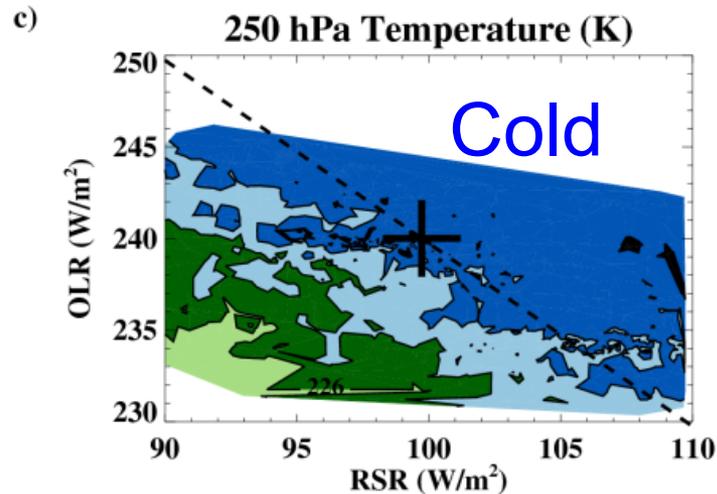
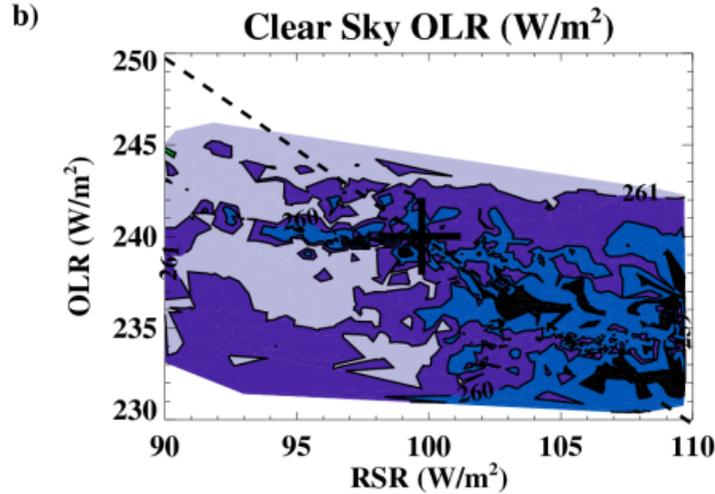
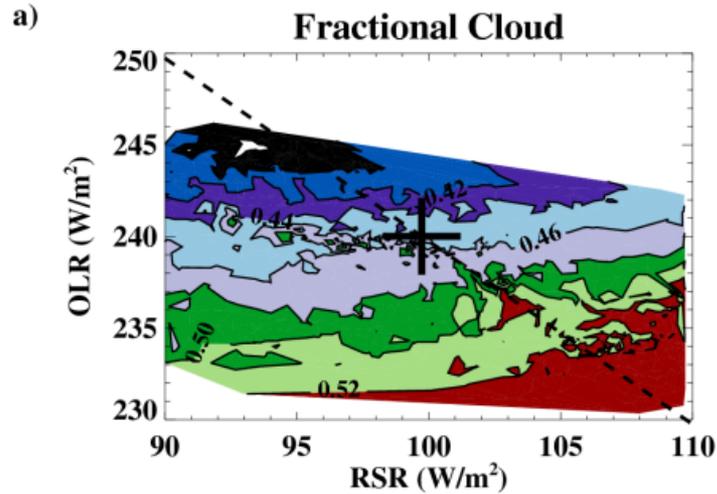


Optimisation

- Carried out 16 optimisation cases with initial values the extreme parameter choices with CERES target.
- Then carry out set of trials with various target values. We chose four values around the observed uncertainty value + observed values
- $\frac{3}{4}$ converged in about 3-4 iterations. Failure as much due to model blowup as failure in optimisation algorithm.
- Each successful iteration requires 7 simulations each of 6 years of atmospheric model. This is very efficient...



What is responsible for changes in RSR/OLR?



Little change in clear sky OLR due to compensation between RH and temperature.

Changes in radiation arise from cloud changes.

Warm

Wet

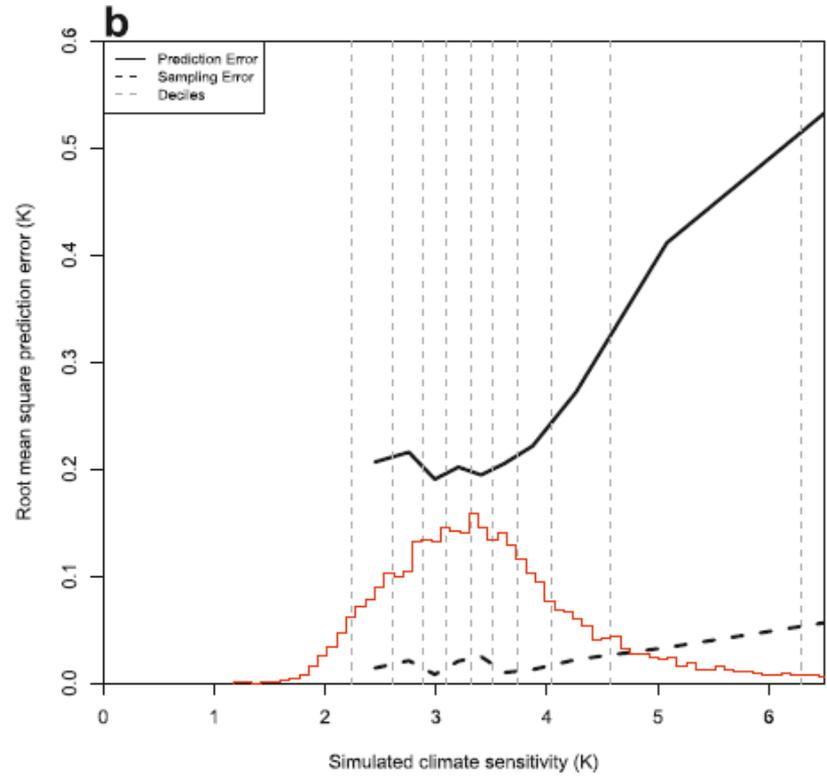
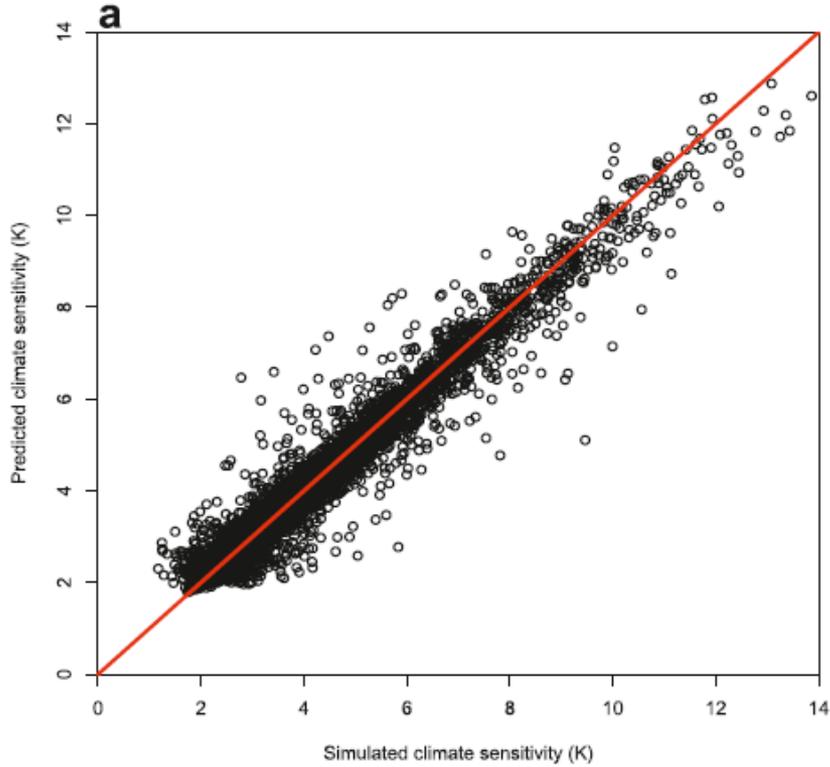


Estimating Climate Sensitivity

- Our experimental design doesn't give us an estimate of climate sensitivity
- But *climateprediction.net* done 14,000 doubled CO₂ slab model experiments (HadSM3) each 20 years long.
- Very brute force – each parameter at high, low and medium.
- Can estimate equilibrium climate sensitivity (ECS) for many parameters from these simulations.
- We constructed an **emulator** of ECS for HadSM3. Give the emulator model parameters and the emulator provides an estimate of climate sensitivity.
- Essentially sophisticated regression/interpolation and so generates some additional uncertainty.



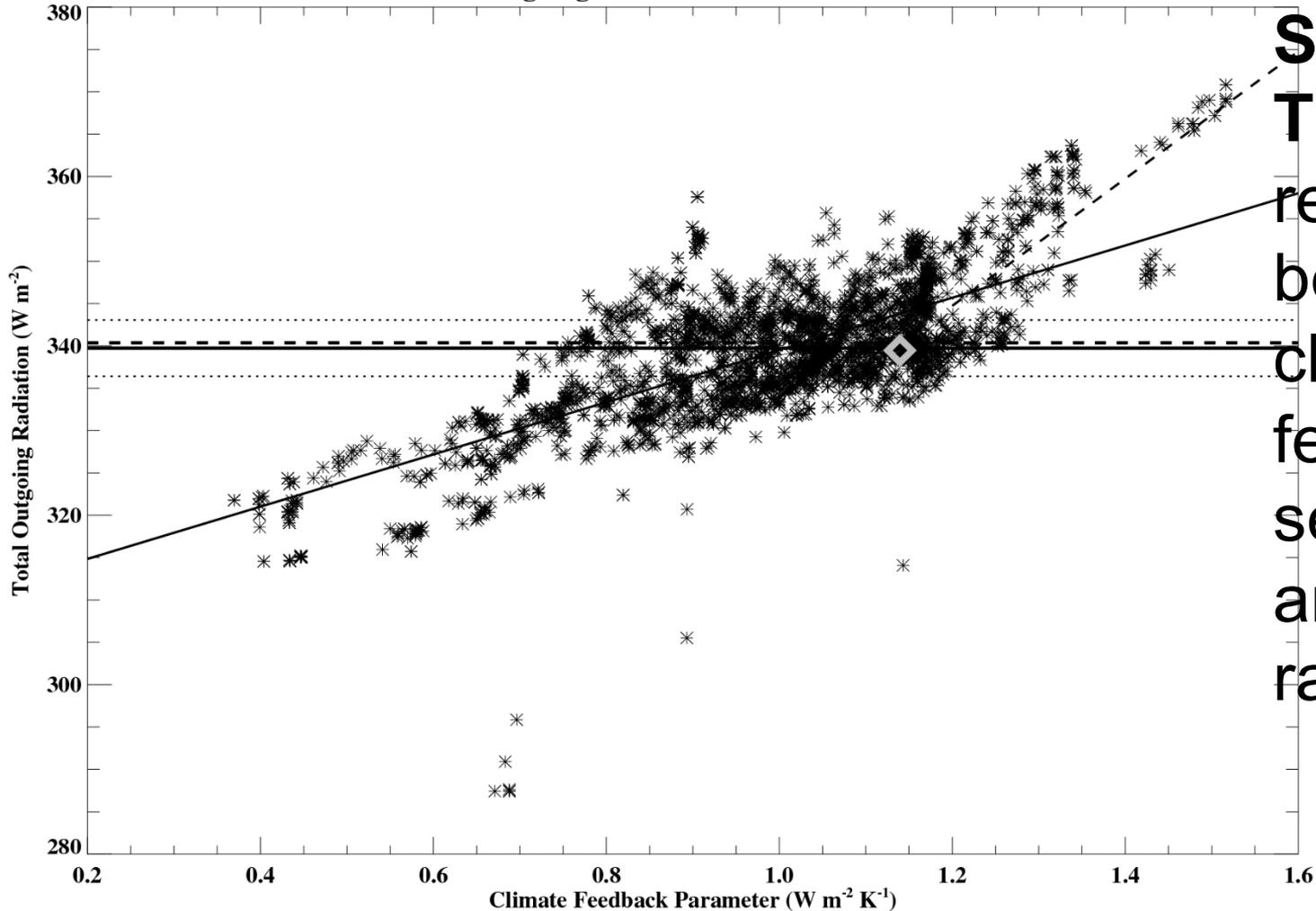
Emulation generates uncertainty





Feedback vs total outgoing radn

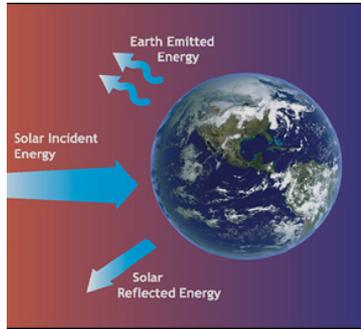
Total Outgoing Radiation vs Climate Feedback



Summary
There is a relationship between climate feedback/sensitivity and outgoing radiation

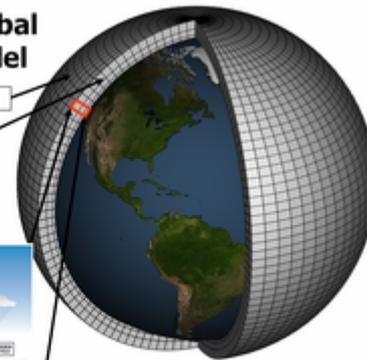
Probabilistic ECS estimate: Schematic

Simulated



Schematic for Global Atmospheric Model

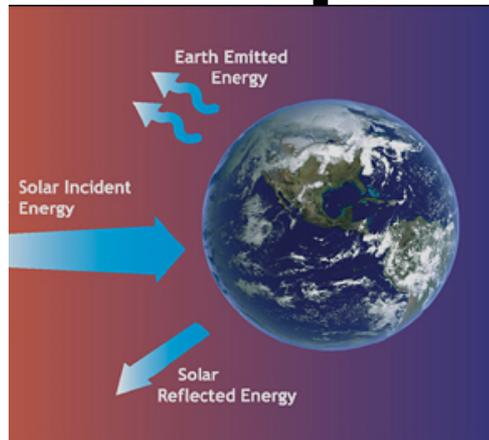
Horizontal Grid (Latitude-Longitude)
Vertical Grid (Height or Pressure)



Parameters

S

Prior



Observed

Likelihood

Uncertainty Estimate

Posterior



Uncertainty estimate for OLR and RSR

- Need estimate of uncertainty to decide what is a “plausible” simulation of OLR and RSR?
- Make estimates for sources of uncertainty and sum them assuming everything Gaussian.
- From “plausible” configurations can generate “plausible” range.
- Using (simple) Bayesian reasoning make probabilistic estimate of Equilibrium Climate Sensitivity.



Sources of Uncertainty

- Consider uncertainties that don't affect climate sensitivity but could affect the outgoing radiation.
- Observational uncertainty
- Forcing uncertainty
- Modelling uncertainty
- SST uncertainty as model is atmosphere only
- **NOT** including uncertainty in model structure
 - results are *conditional* on HadAM3 structure.



Observational uncertainty

- Reflected SW Radn (RSR): 1 Wm^{-2}
- Outgoing LW Radiation (OLR): 1.4 Wm^{-2}
- Then combined with uncertainty on total energy leaving the Earth (0.5 Wm^{-2}) mainly arising from uncertainty in incoming solar radiation.



Forcing and Aerosol Uncertainty

- Forcing Uncertainty (from IPCC AR4)
 - RSR: 1 Wm^{-2} (mainly aerosol uncertainty)
 - OLR: 0.25 Wm^{-2} (O_3 & GHG)
- Natural aerosol – RSR 1 Wm^{-2} from Penner et al, 2006 models are about 1 Wm^{-2}

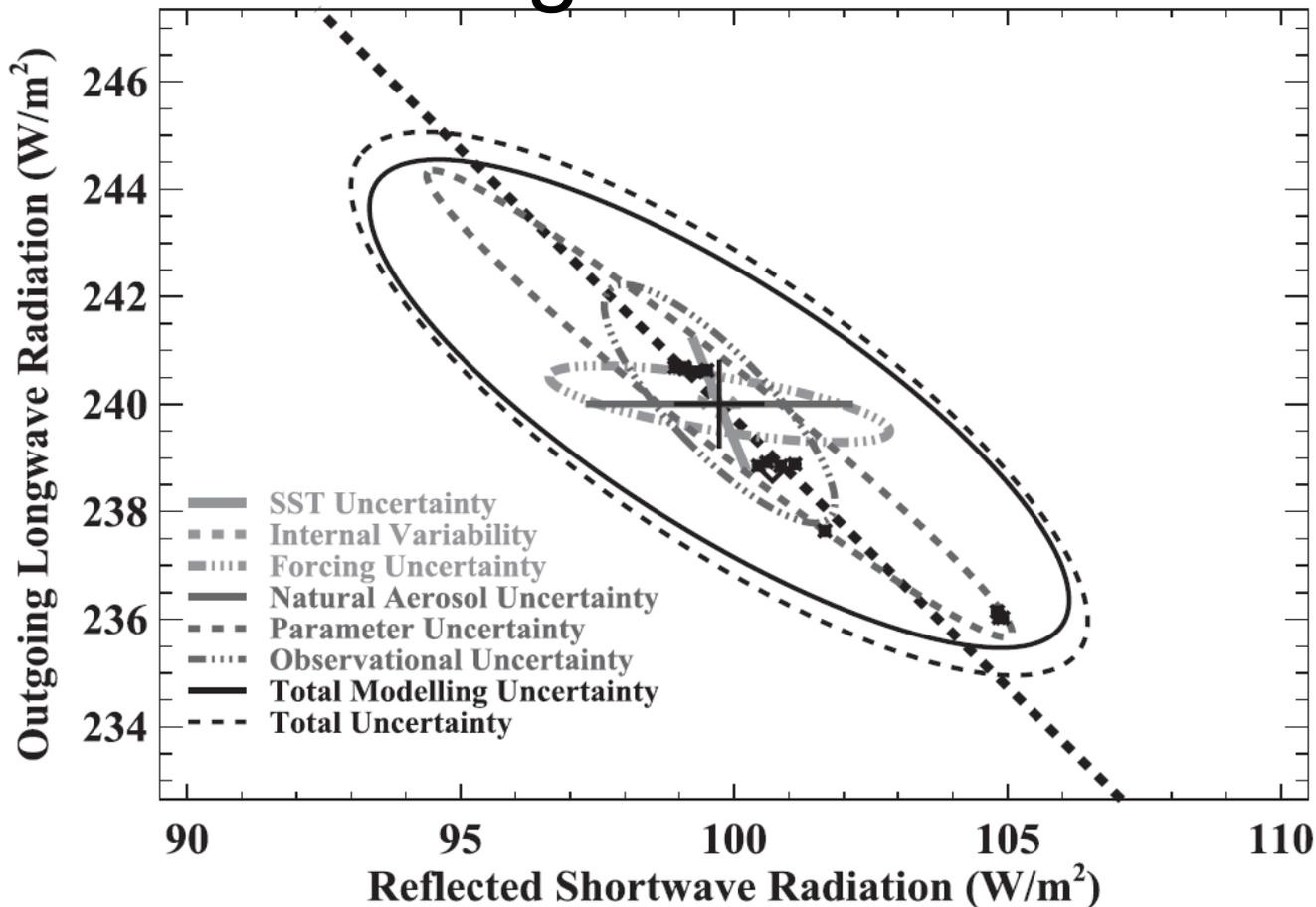


Modelling Error

- Internal climate variability: 0.1 Wm^{-2} in both RSR and OLR and is negligible.
- Parameter uncertainty – what about parameters that don't affect climate sensitivity but do affect radiation?
 - From *climateprediction.net* database find those model configurations that have a climate sensitivity from 3.2-3.4K (standard configuration is 3.3K). Gives 13 cases. Run the cases and compute covariance of RSR and OLR. Then treat as another source of uncertainty.

Sources of Uncertainty

95% Regions

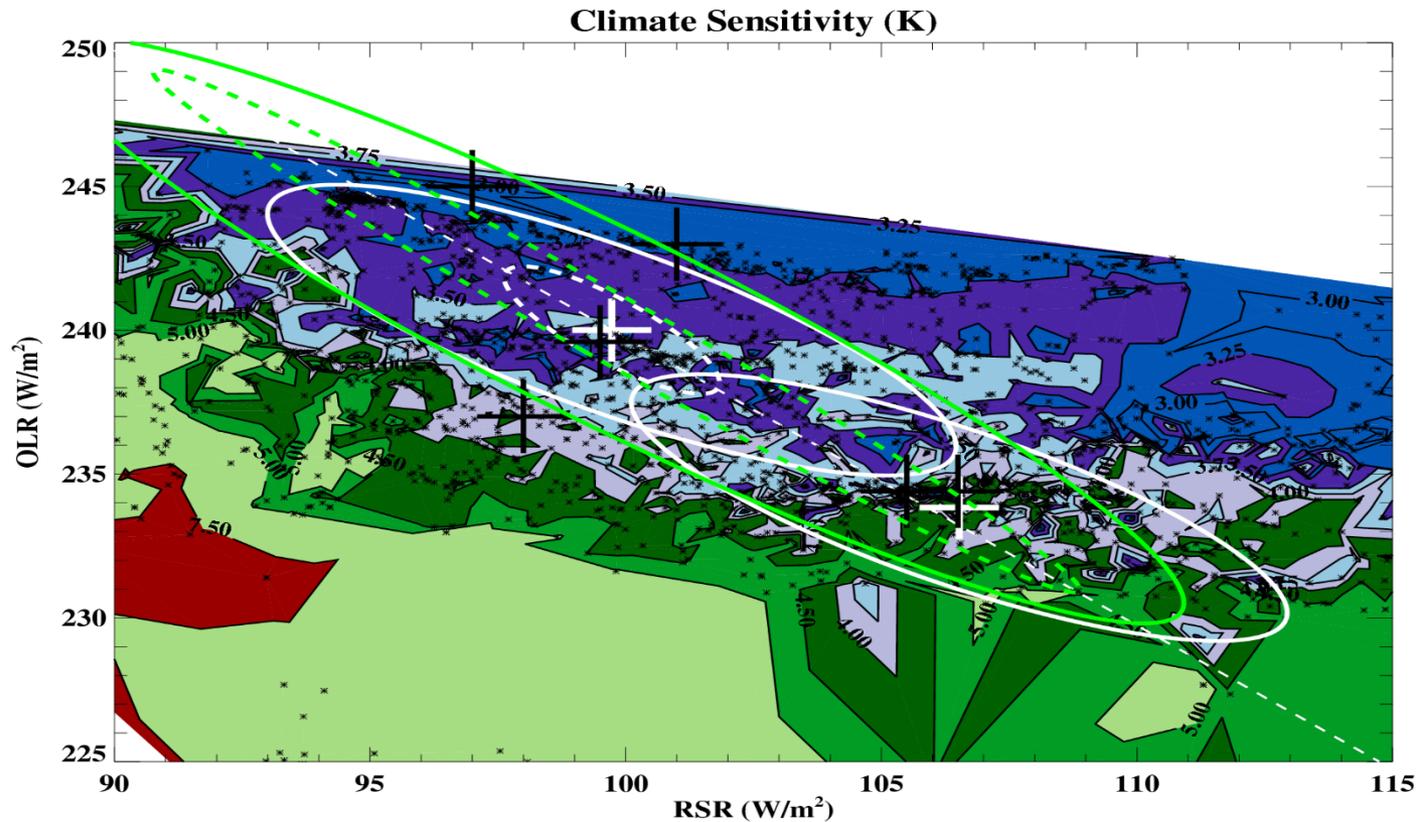


Dominant
Uncertainties
are:

1. Parameters
2. Forcing
3. Observations



Which Simulations are consistent with Observations?



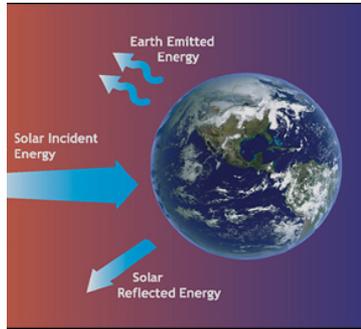
Find all configurations that have OLR and RSR consistent (95%) level with observations. What is the range of climate sensitivities?

CERES: 3.0-4.1 K

ERBE: 3.0-5.1 K

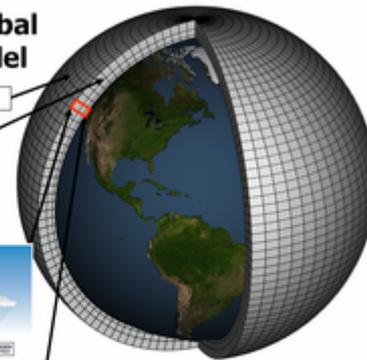
Probabilistic ECS estimate: Schematic

Simulated



Schematic for Global Atmospheric Model

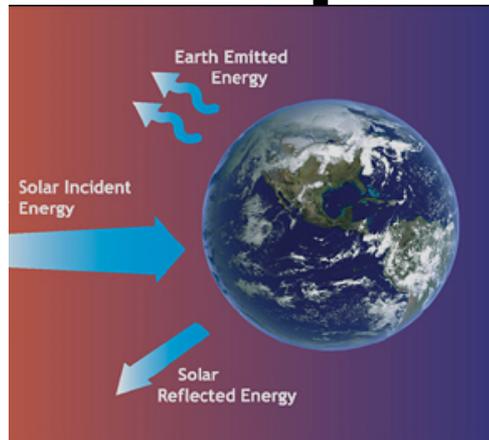
Horizontal Grid (Latitude-Longitude)
Vertical Grid (Height or Pressure)



Parameters

S

Prior



Observed

Likelihood

Uncertainty Estimate

Posterior



Computing a probability distribution

- Individual model realisations not randomly generated though have 16 different initial conditions and 5 different targets
- Explore several different prior assumptions on the individual realisations.

Uniform all configurations equally likely

Radiation OLR and RSR equally likely

Parameter Parameter values equally likely

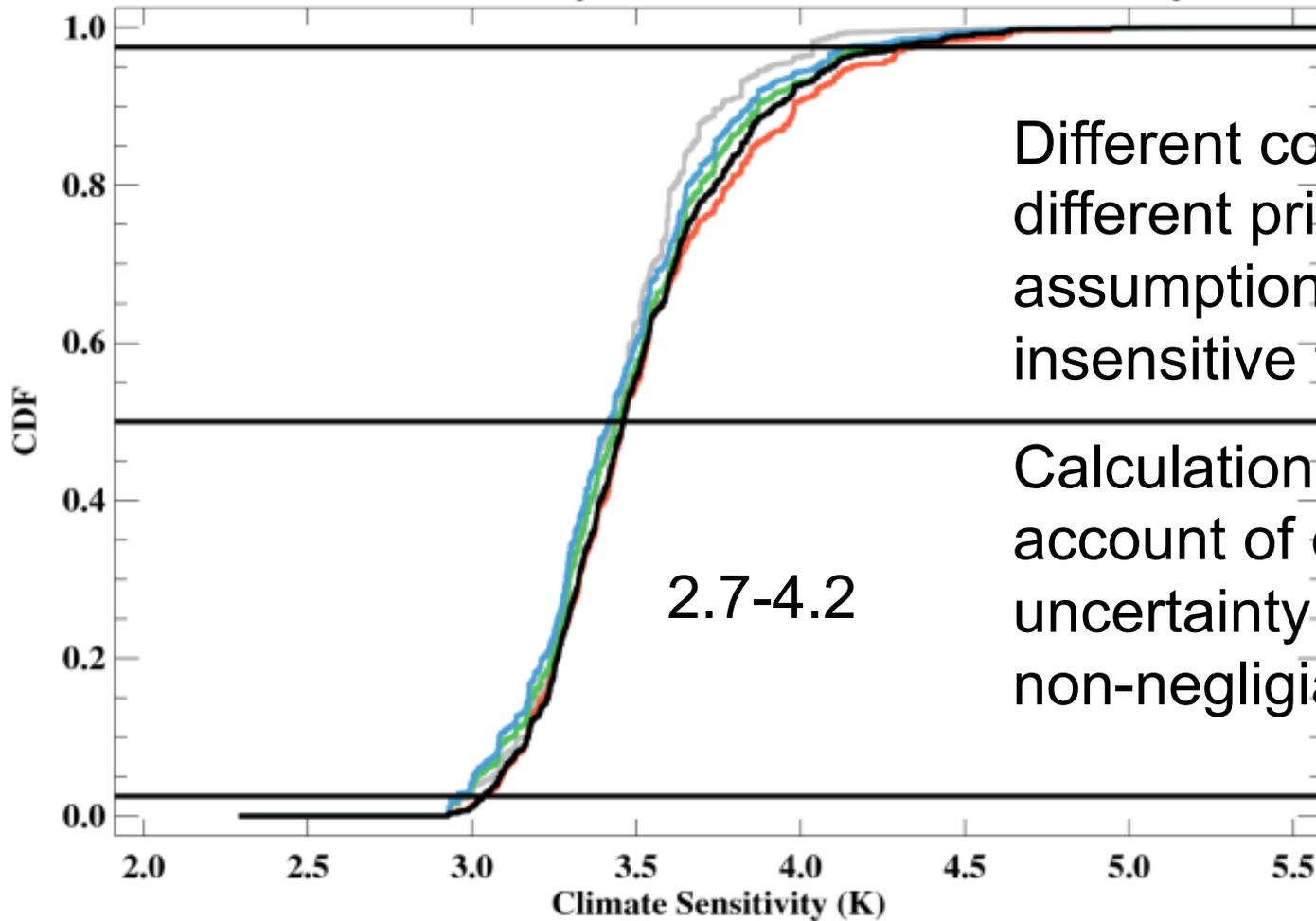
S ECS values equally likely in range

1/S All feedbacks equally likely in range



Cumulative Distribution Function

Cumulative Density Function for Climate Sensitivity

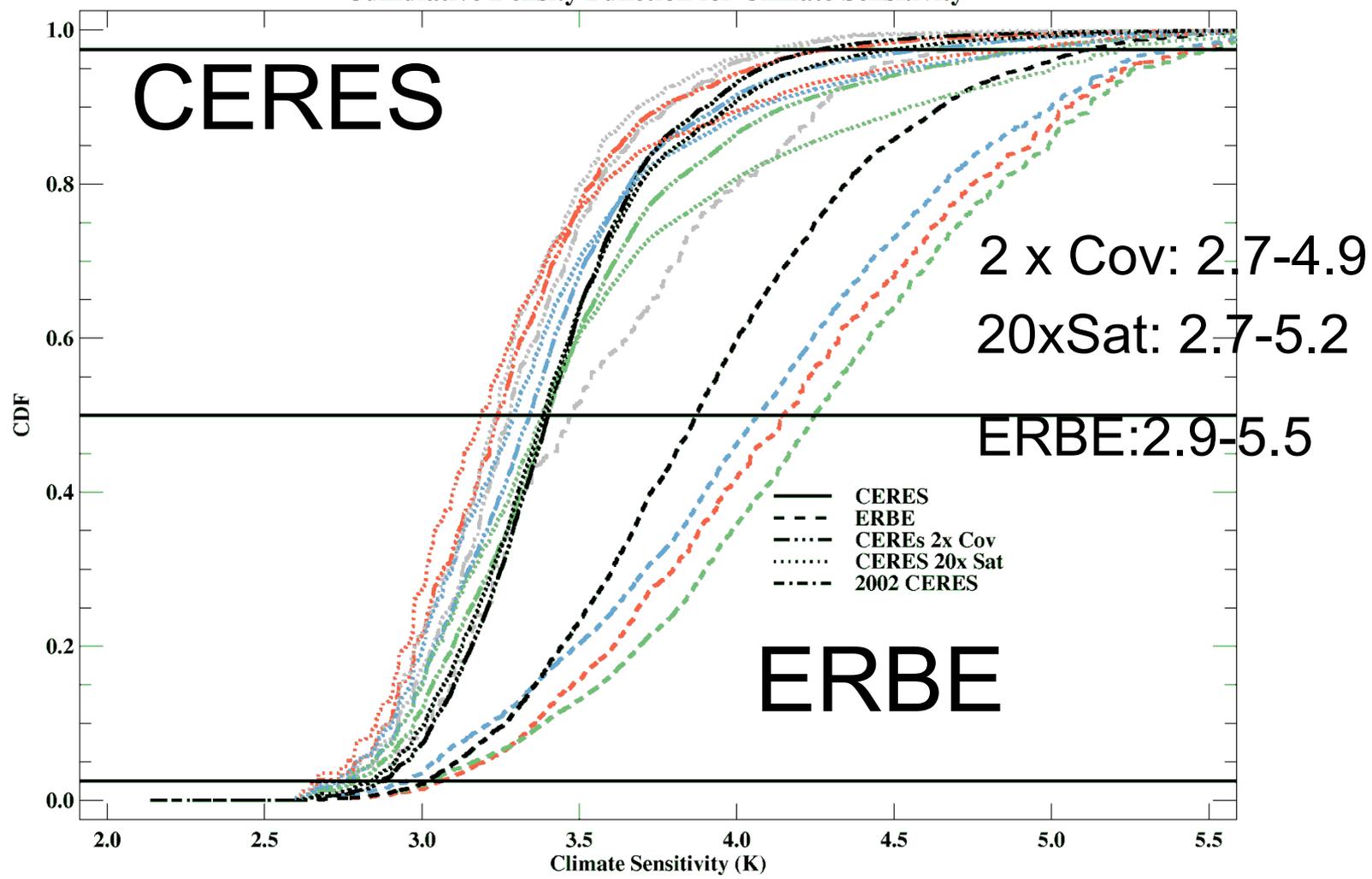


Different colours are different prior assumptions. Results insensitive to prior.

Calculation takes account of emulator uncertainty which is non-negligible.



Cumulative Distribution Functions: Sensitivity Studies

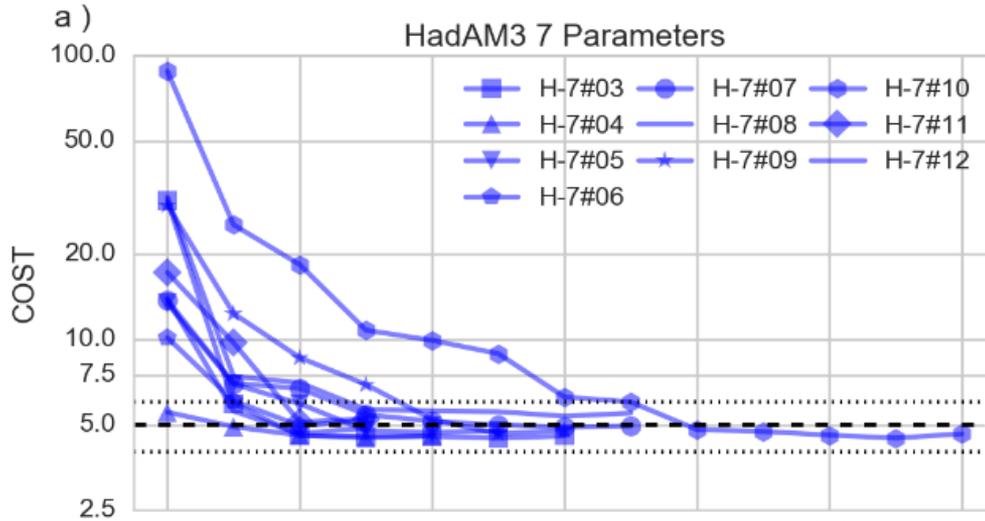




Recent Work

- Extended from 4 parameters to 14; trying 7 on the way. Increased the number of observations from 2 to 20.
- Issues
 - Weighting the observations – used covariance matrix as sum of observational error + 2xinternal var.
 - Now minimizing cost function which includes a net flux constraint.
 - Lots of parameters – tried random selection
 - Started from random extreme parameter choices

Optimisation



7-parameter

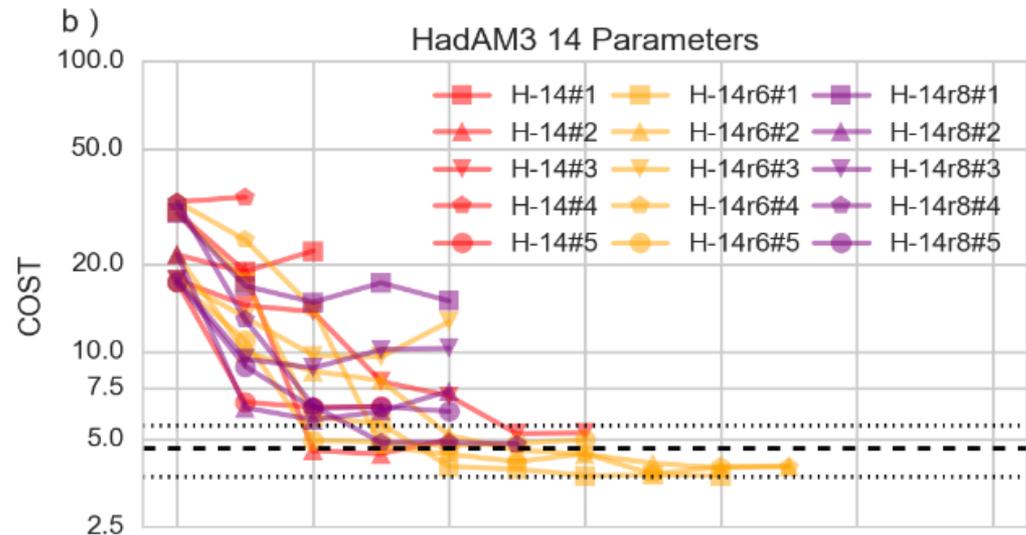
Mean of 5.6 iterations ~ 70 evaluations. Ended up similar cost function to standard version of HadAM3

14-parameter with three Algorithms:

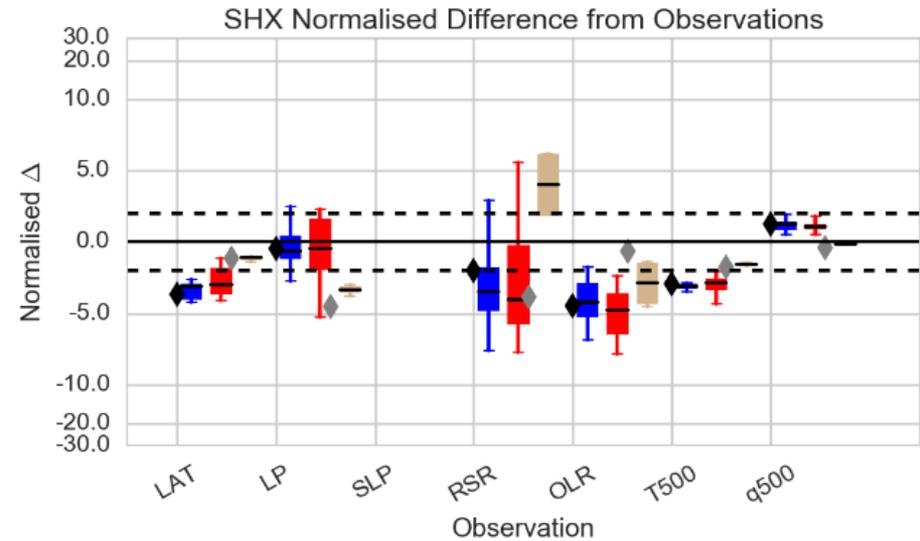
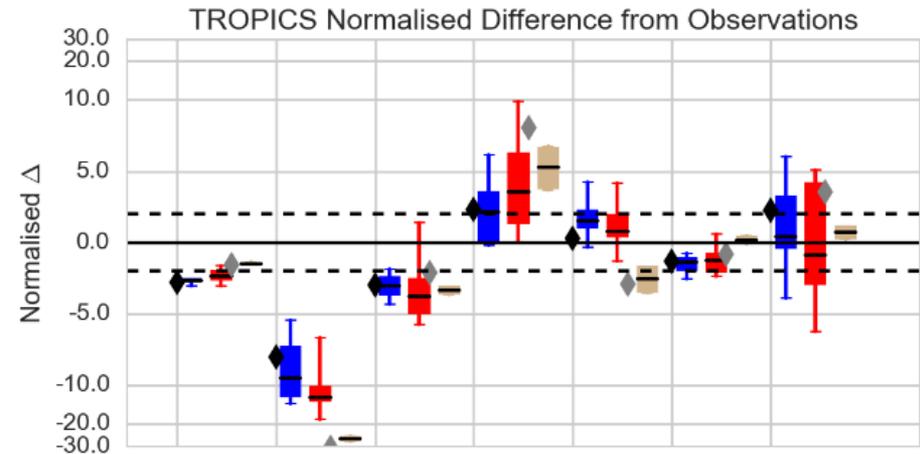
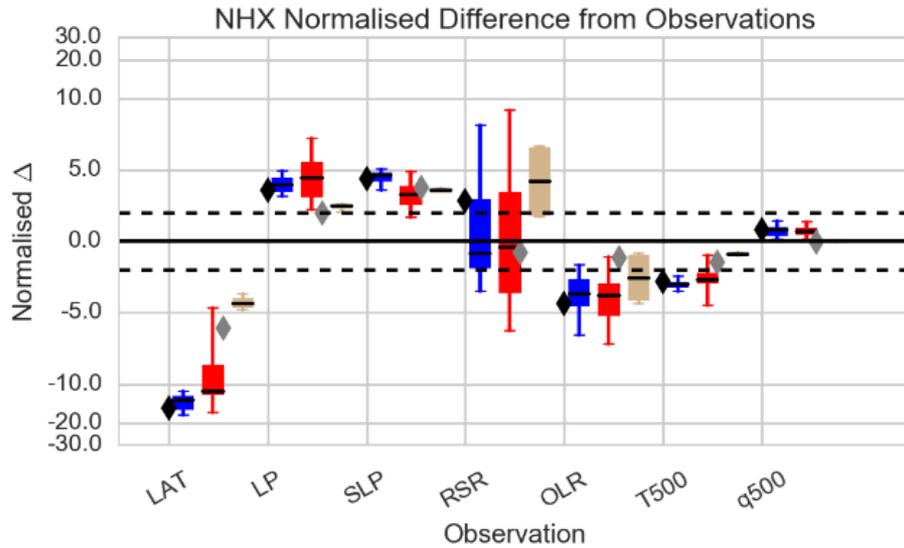
1) Each step perturb all 14
8 iter ~ 140 evaluations

2) Each step perturb 6 at random.
9 iter ~ 90 eval

3) Perturb 8 at random
21 iter ~ 240 eval

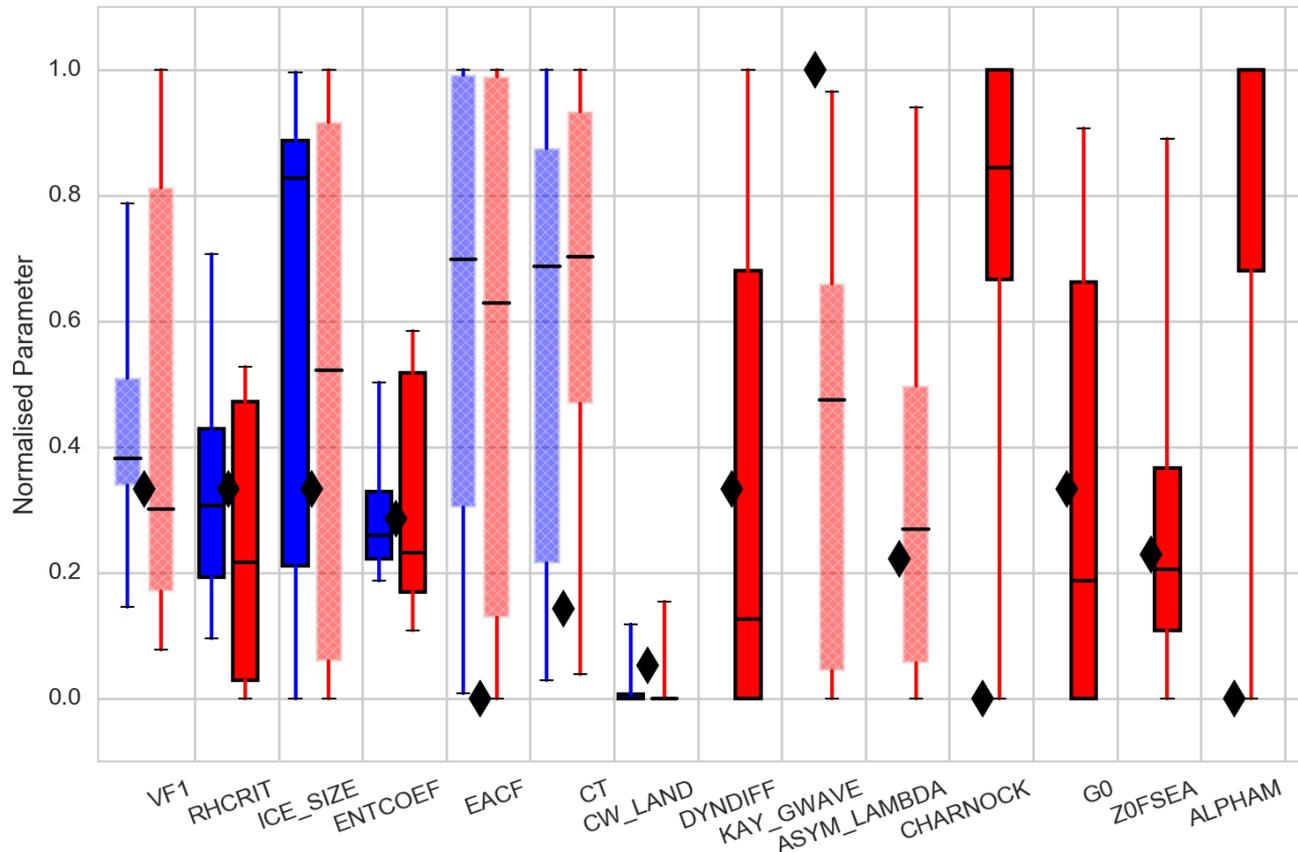


How does model do?



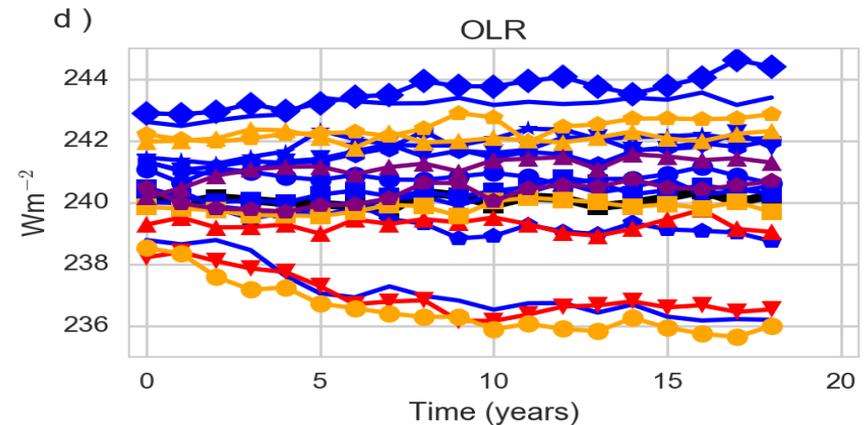
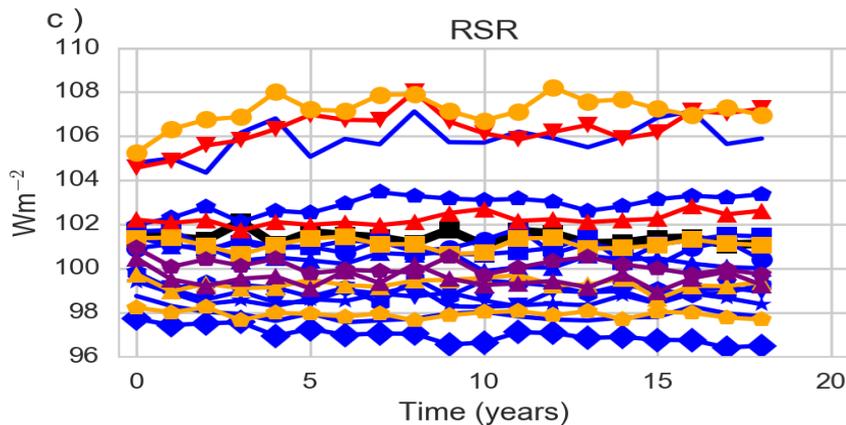
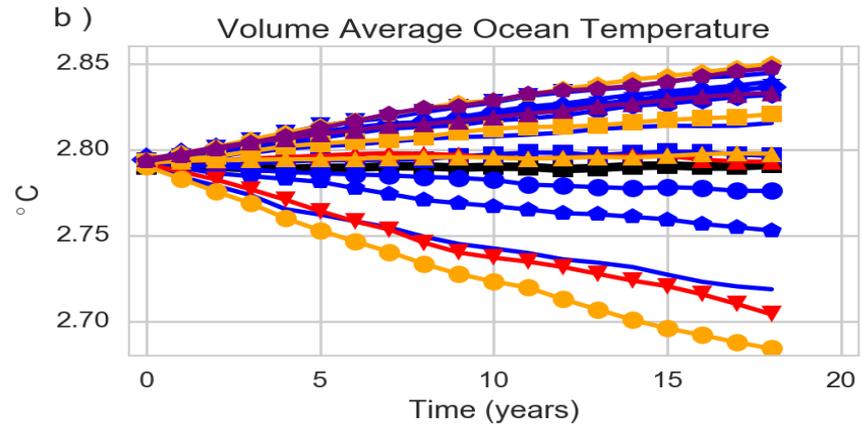
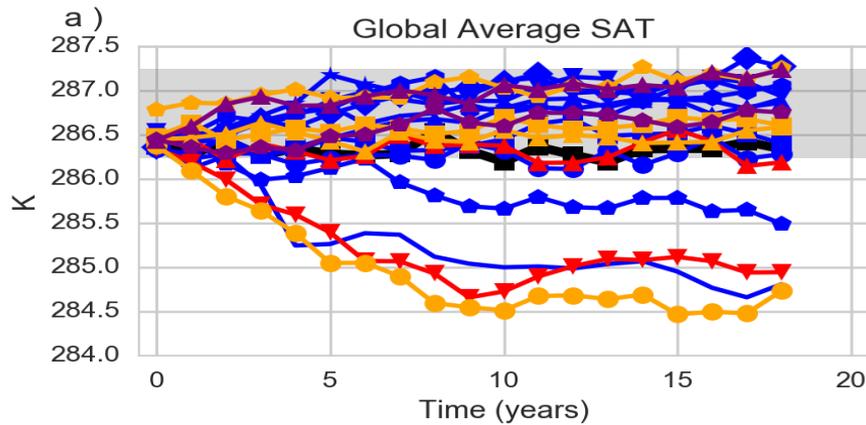
Showing difference from obs normalised by obs error + 2 * int var. Opt models all rather similar to std model.

Parameters constrained?



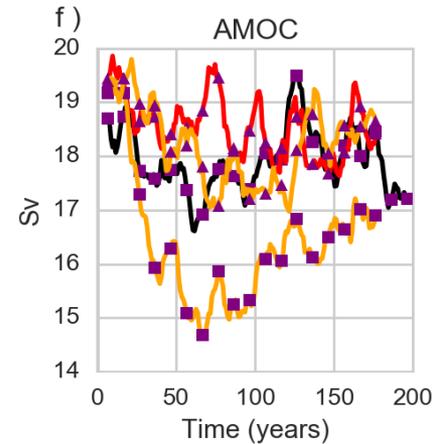
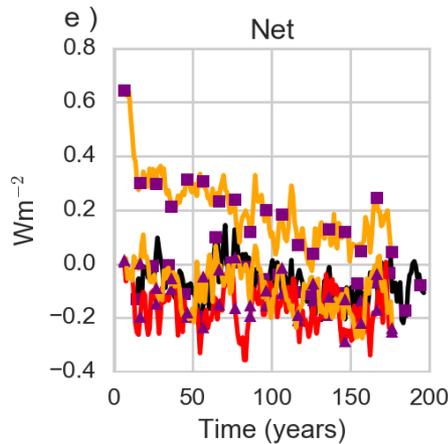
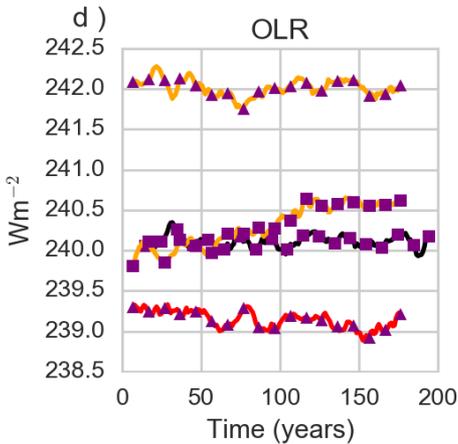
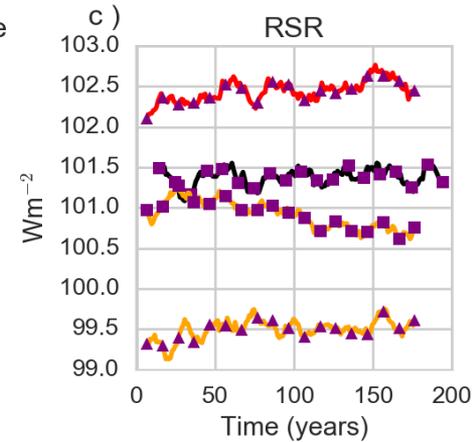
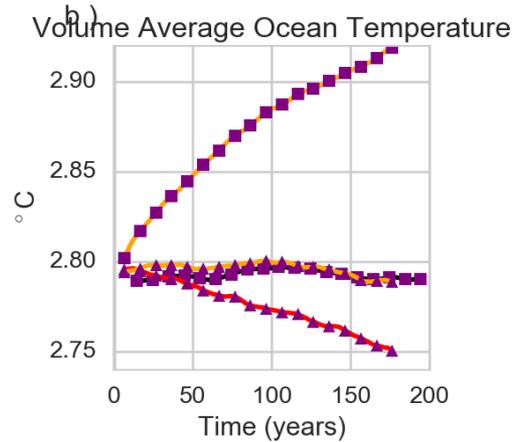
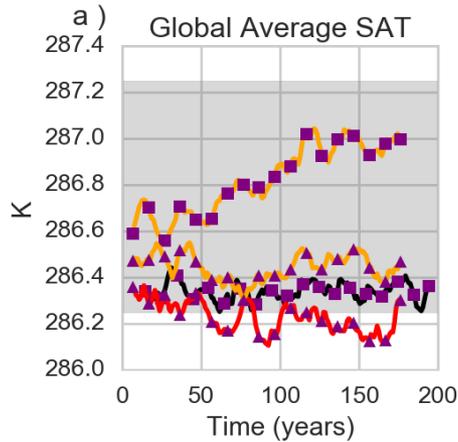
Some parameters constrained – many not. (If they are dark then constrained)

Couple Calibrated Models



Start from existing pre-industrial simulation of HadCM3. Get a broad range of outgoing fluxes. Ones that poor have large RSR – all rest scatter about same as obs error...

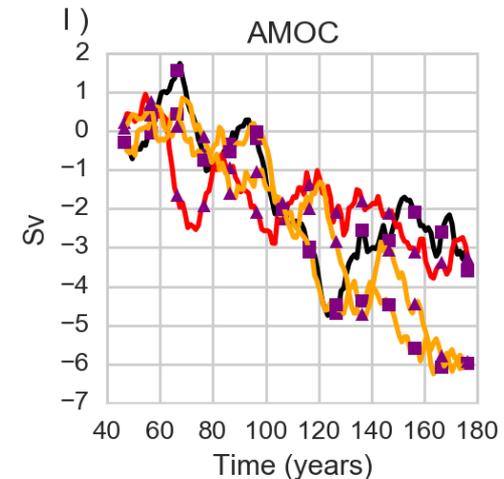
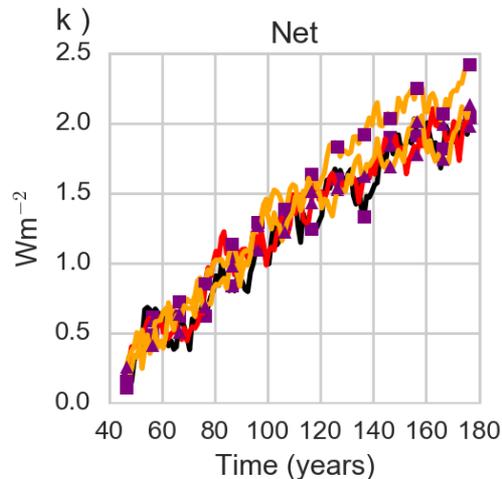
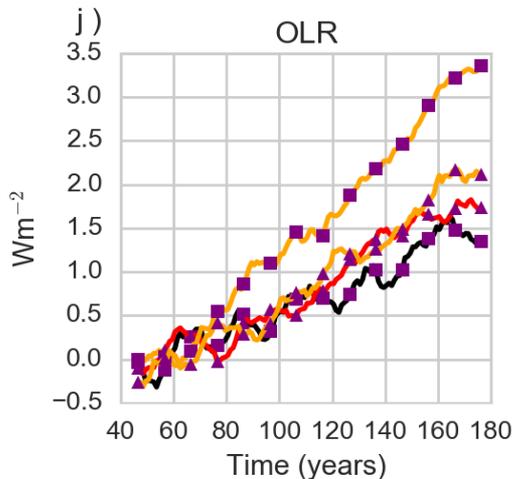
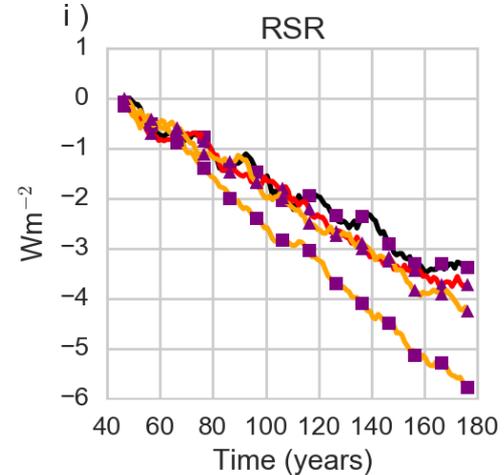
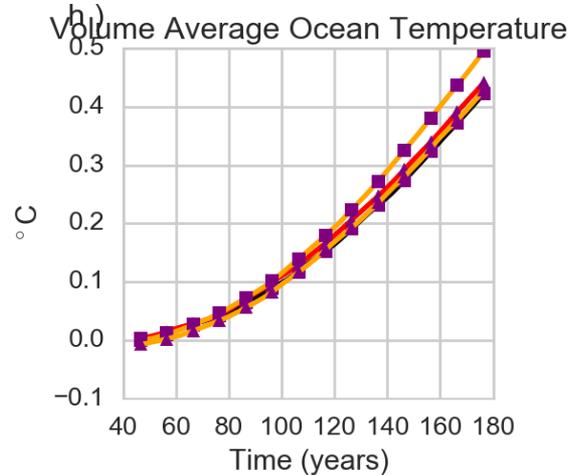
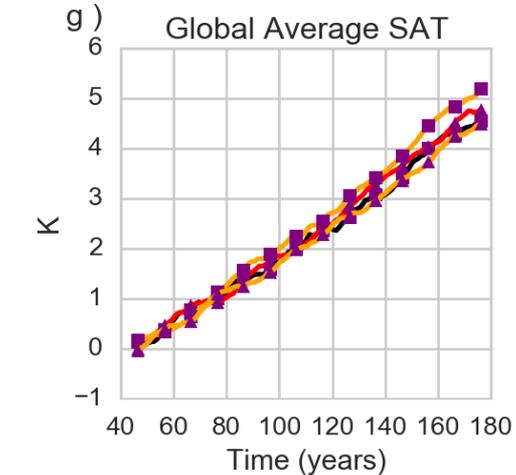
Extended Control Simulations



Extended three of the coupled models to 180 years (and the standard configuration).



Response to 1%/year CO2 increase

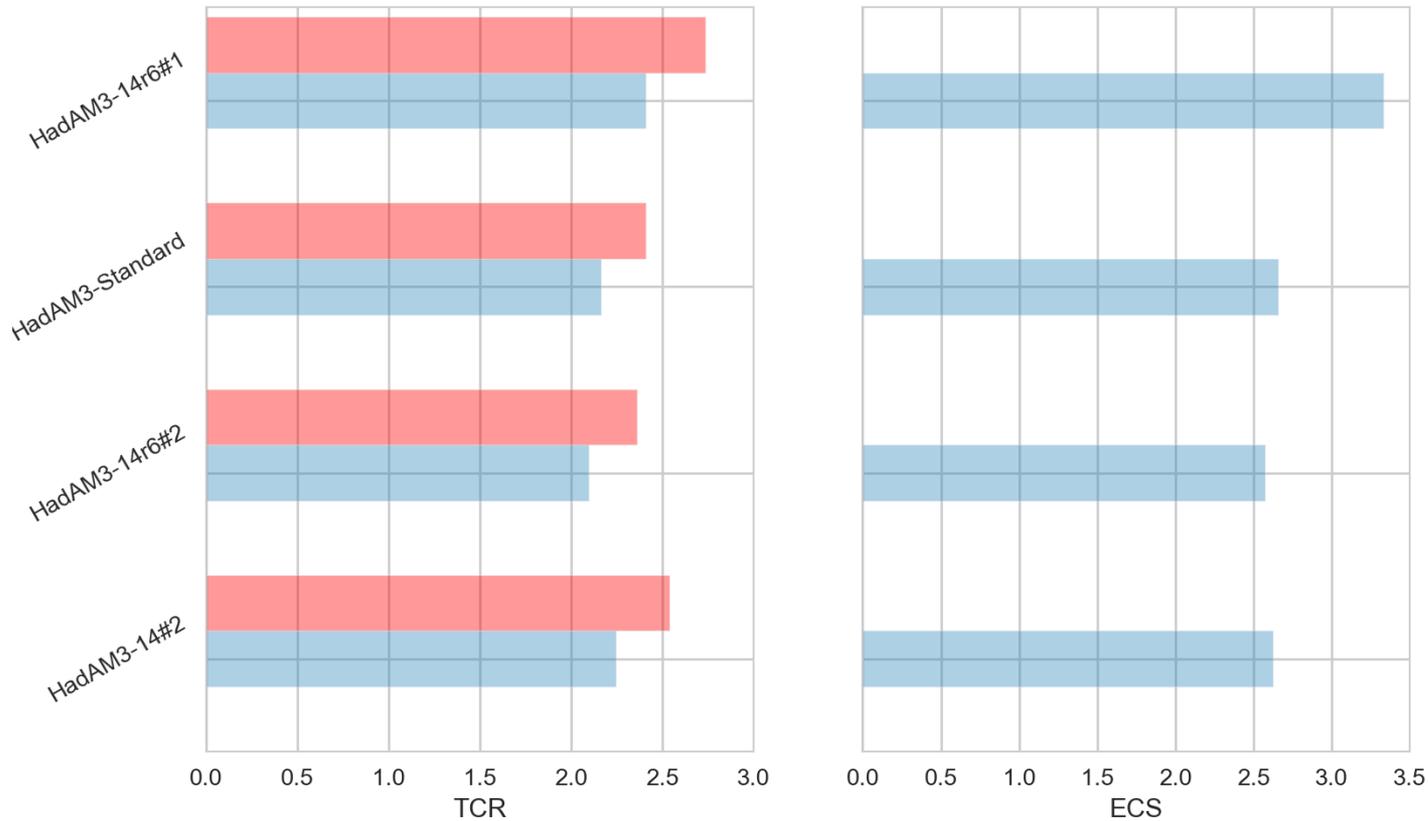


Response to 1%/year CO2 forcing. Start in year 40 of Control simulation and run for 140 years. 2xCO2 at year 70; 4xCO2 at year 140.



Transient Climate Response and Equilibrium Climate Response

- Compute TCR by fitting 2nd order polynomial (in time) to difference between 1% and control simulations
- TCR is value of fit at doubling (70 years)
- Also compute TCR at 4XCO₂ and half – test for fixed TCR
- Compute ECS following Gregory et al
$$\Delta N = F - \lambda(\Delta T) \Rightarrow F - \Delta N = \lambda(\Delta T) - \text{regress to compute } \lambda$$
$$\text{ECS} = 3.67/\lambda$$



TCR varies by, at most, about 10% from standard configuration. All variants show increase in TCR at 4xCO₂. ECS varies by about 20% from standard configuration.



Summary

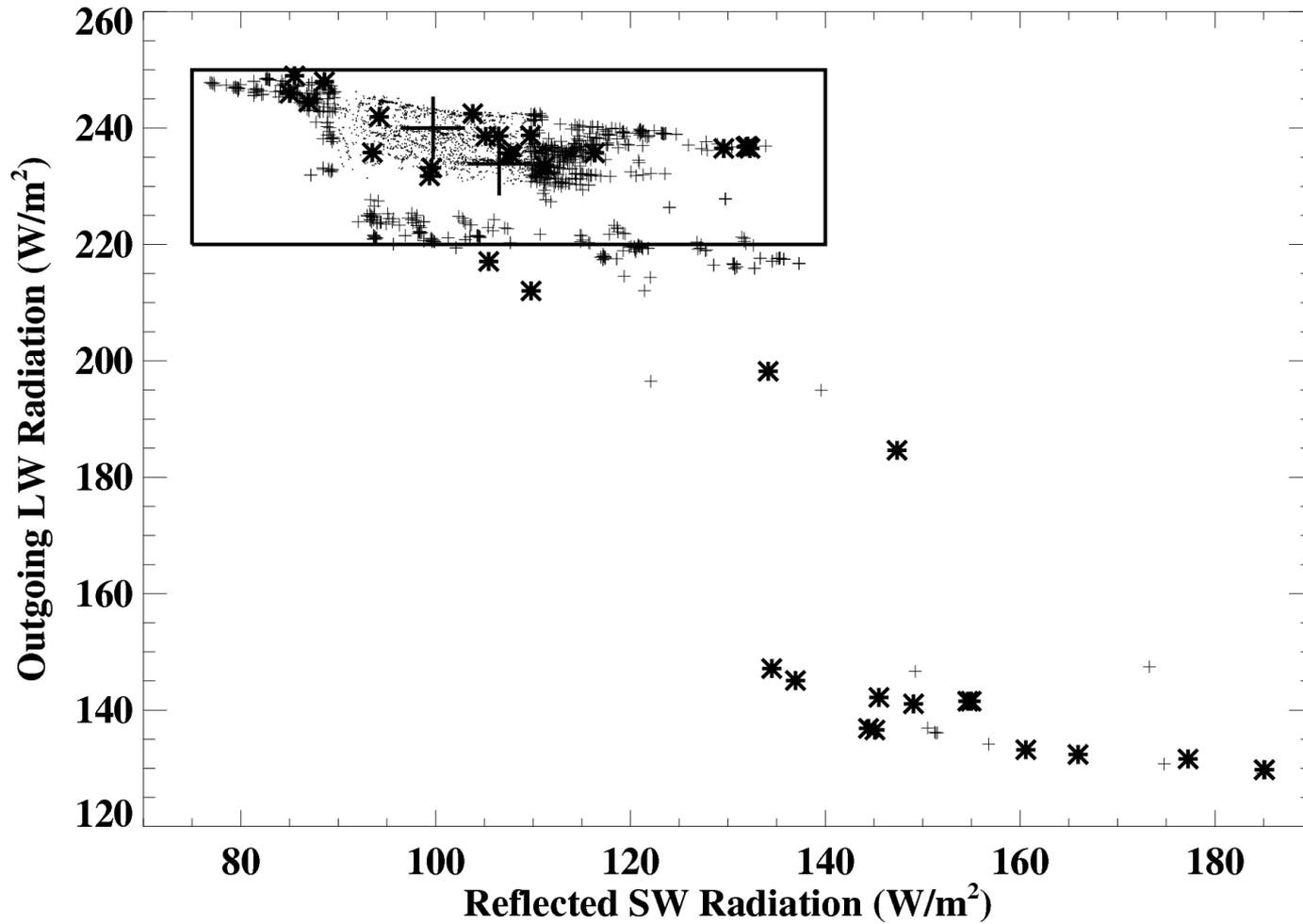
- Found could automatically tune HadAM3 to fit TOA radiation observations and, subsequently, a broad set of observations.
- Made an estimate of uncertainty in model-data difference which is dominated by uncertainty in unoptimised parameters, forcing and observations.
- Used this to make probabilistic estimate of climate sensitivity for HadAM3 giving 2.7-4.2 K for CERES with little sensitivity to prior assumptions. Using ERBE get 2.8-5.6K.
- Shown can optimise HadAM3 perturbing 14 parameters. Considerable sensitivity to algorithm.
- Coupled models produced mostly reasonable – some cool.
- Extended three of those coupled models and ran 1% CO₂ simulations. All models have similar TCR (~10%) and ECS (~20%) values.
- Suggests that **constrained** parameter perturbations give small uncertainty range in future climate projections...

Thanks and Questions



Failures

Failure Cases



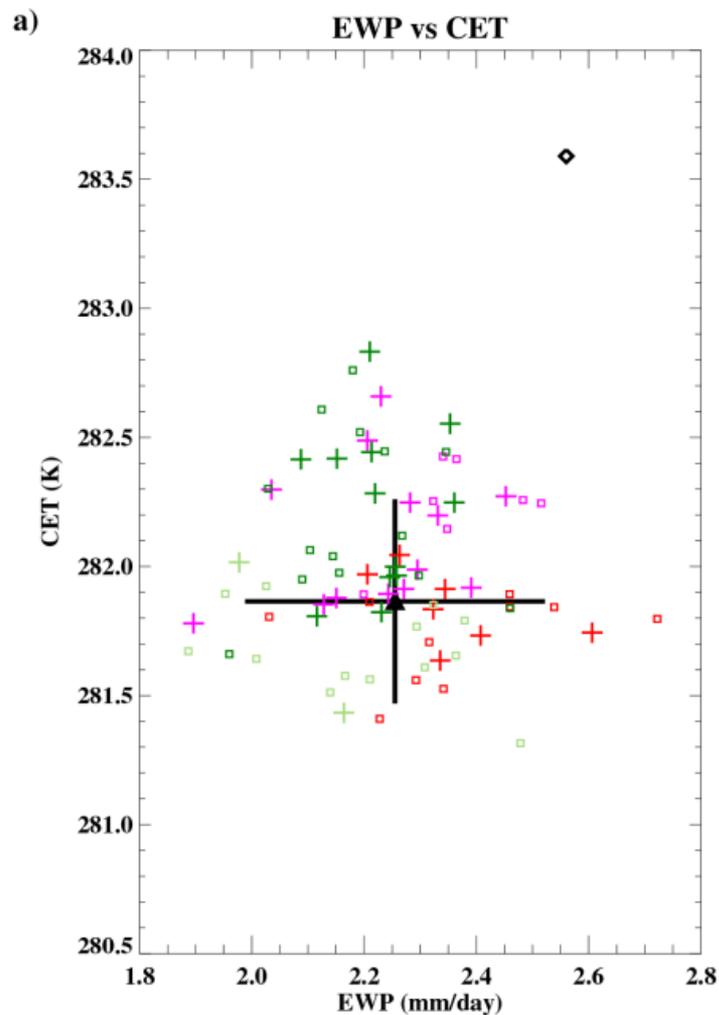
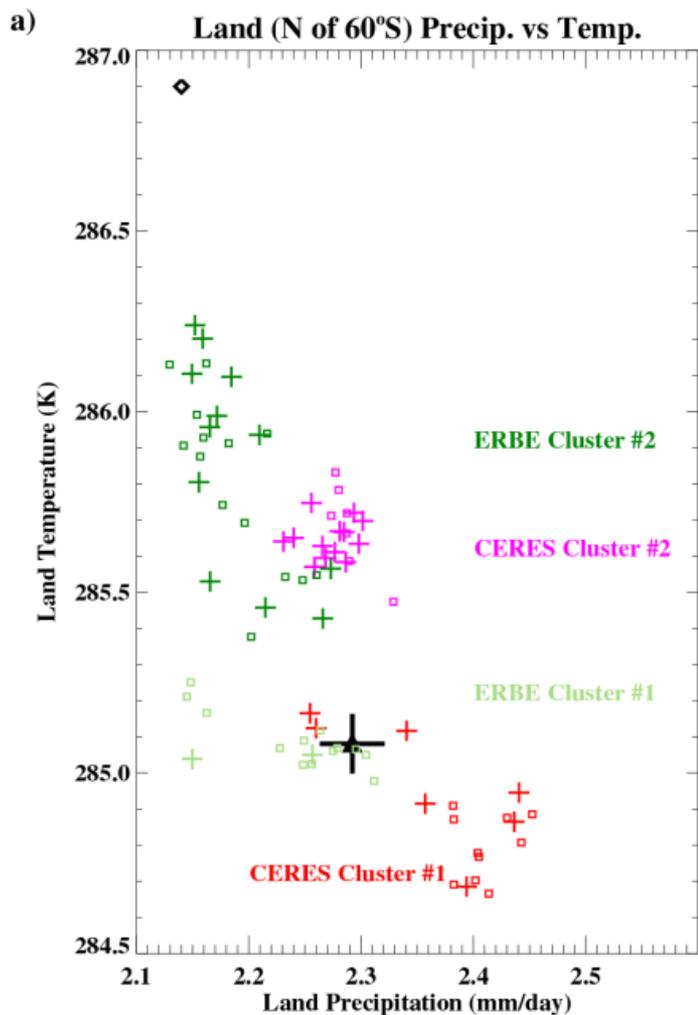


Equi-finality

- Can different parameter choice results in models with similar climatologies?
- Do this by looking at final configurations of CERES and ERBE optimisation cases + cases within 1 W/m^2 of target.

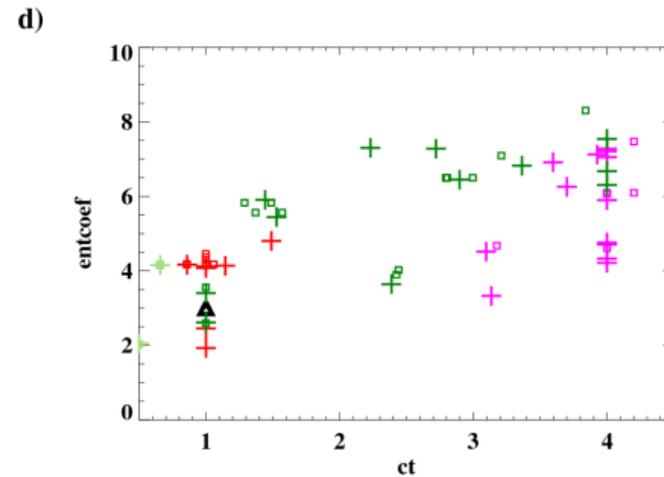
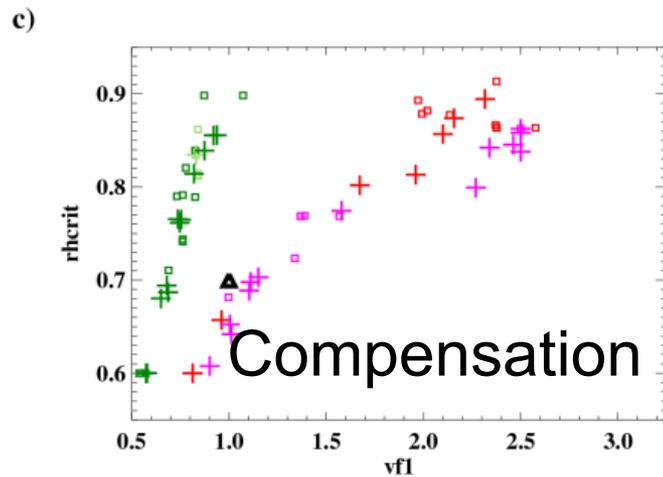
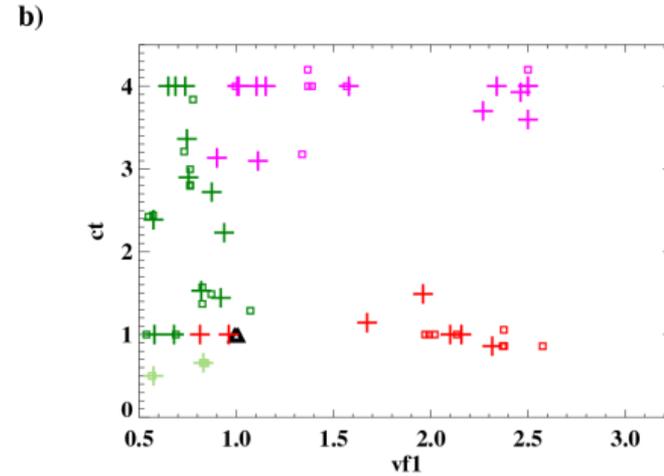
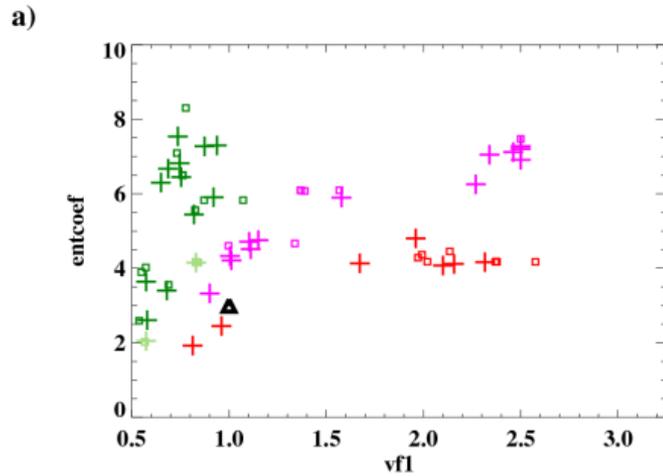


Precip vs Temp



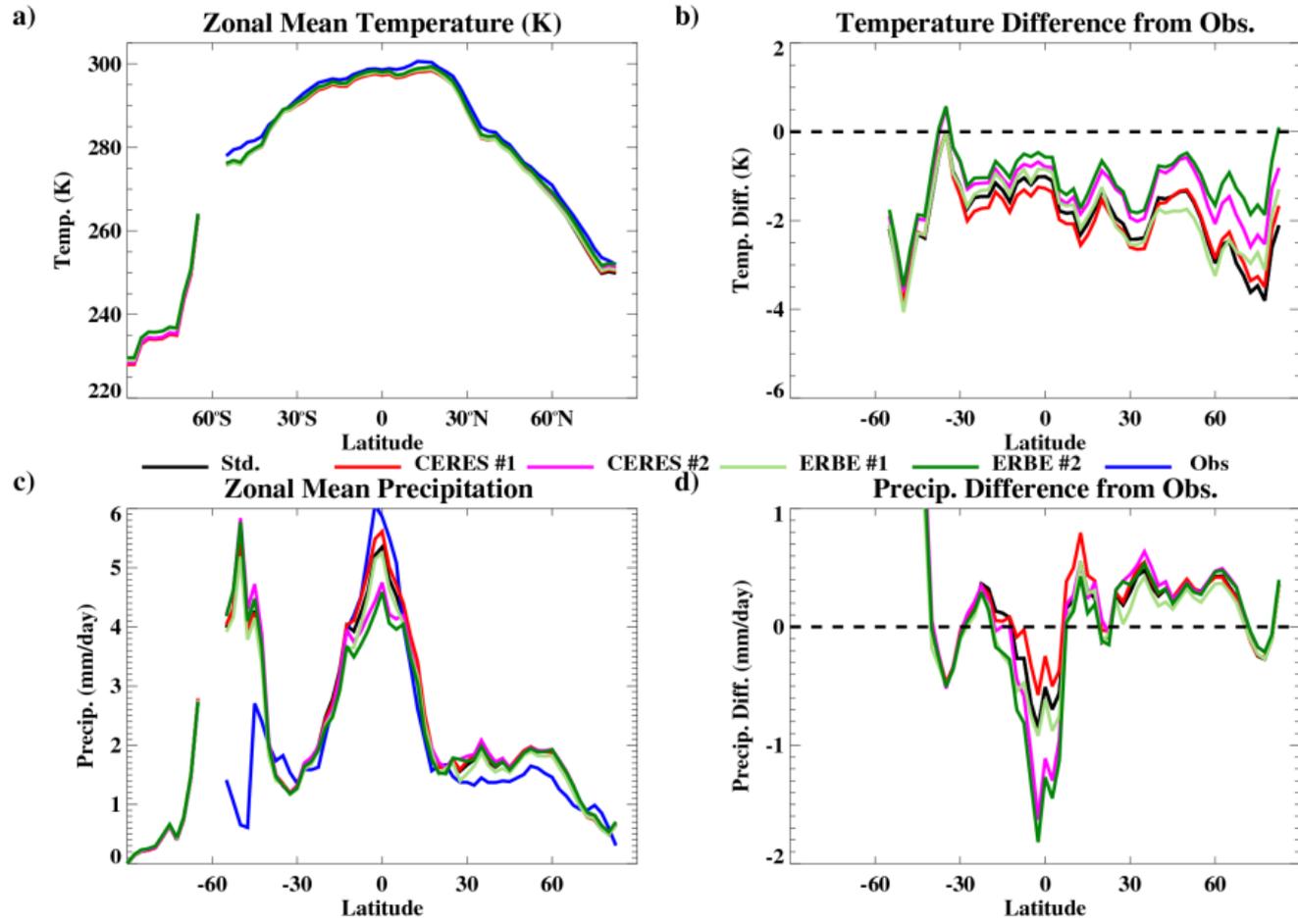


Parameter Values





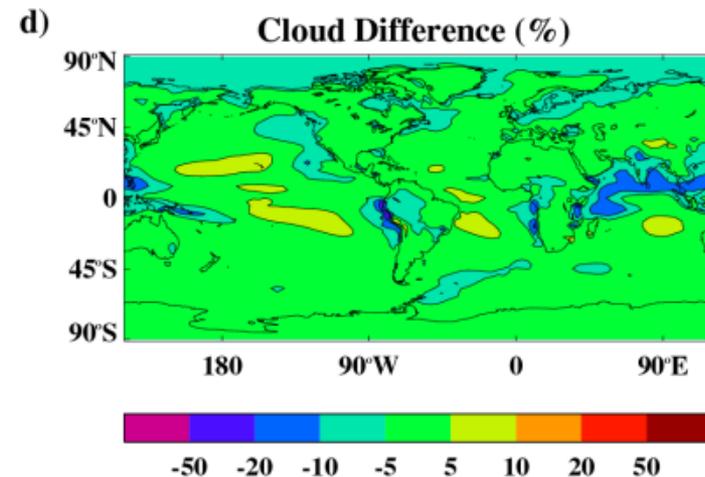
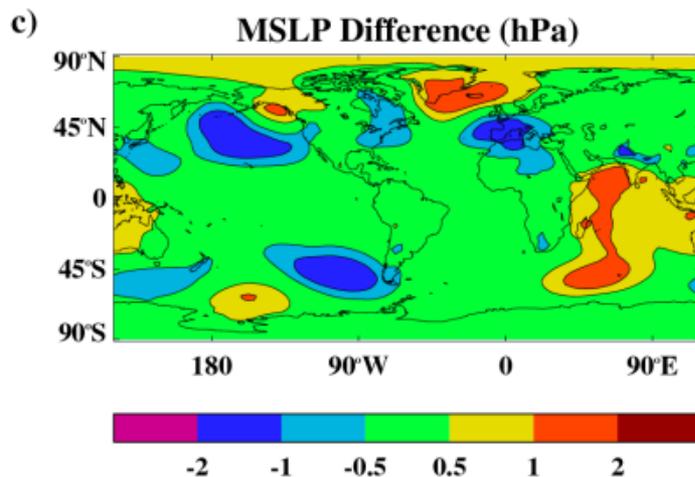
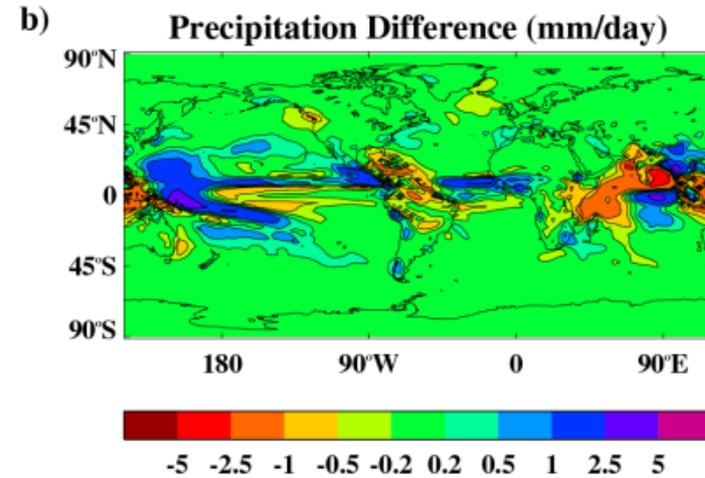
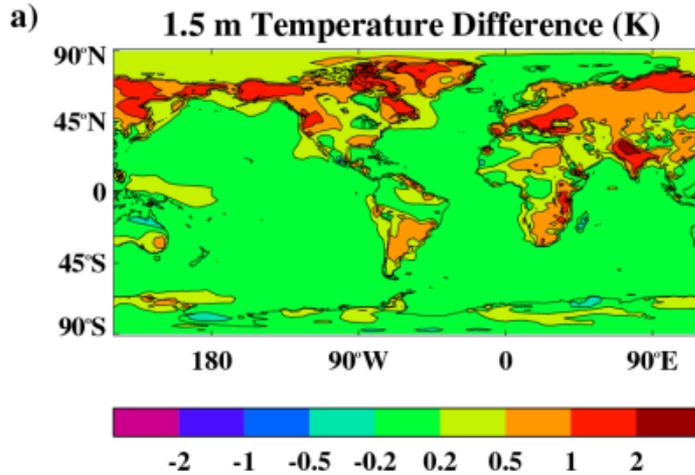
Land Zonal Means





Difference from Standard Config for CERES warm cluster

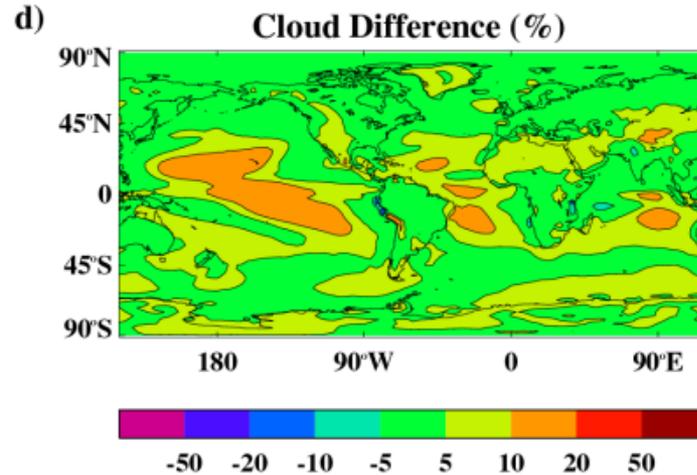
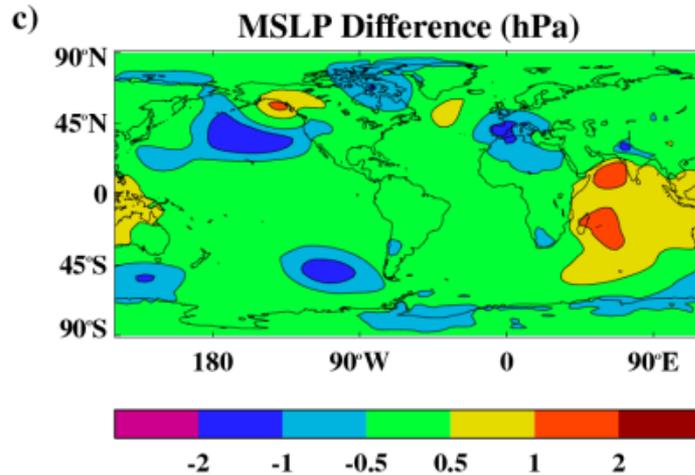
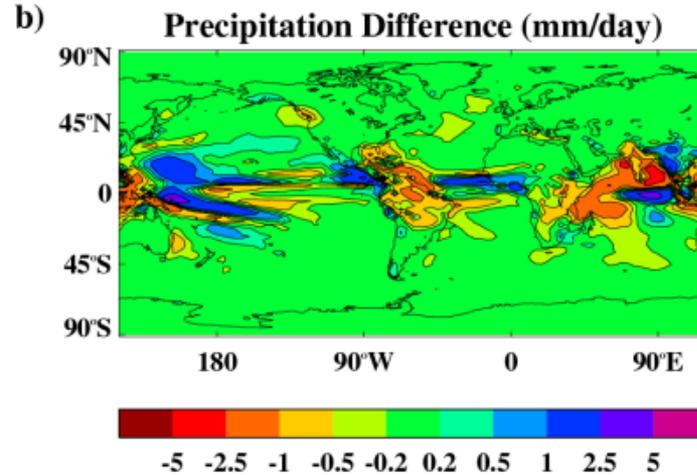
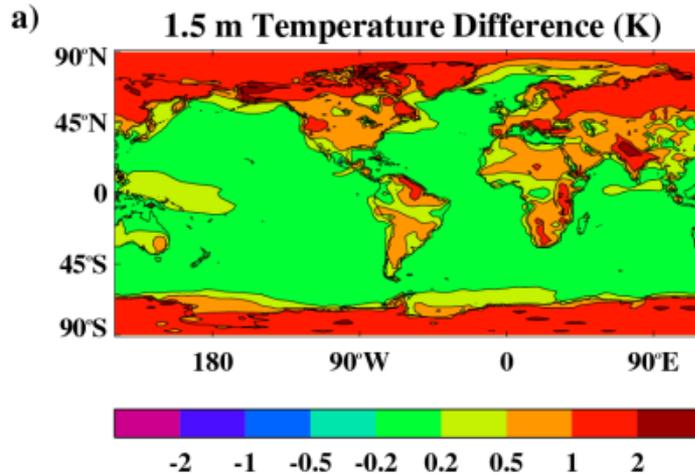
CERES Cluster #2 - Std Configuration





Difference from Standard Config for ERBE warm cluster

ERBE Cluster #2 - Std Configuration





Taylor Diagrams for 7/14 param cases

