Bayesian estimation of the climate sensitivity based on a simple climate model fitted to global temperature observations

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- Joint work with
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  - ⋆ Gunnar Myhre, CICERO
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  - ⋆ CICERO = Center for International Climate and Environmental Research in Oslo
- Work in progress, preliminary results

Climate sensitivity S

Definition:

Climate sensitivity $= S$
$=$ The temperature increase due to a doubling
of CO_2 concentrations compared to pre-industrial time (1750)

Radiative forcing

- CO_2 is only one of several factors that affect the global temperature
- Radiative forcing = The change in net irradiance into the earth relative to 1750
- Measured in Watts per square meter
- The global temperature depends on the radiative forcing
- The climate sensitivity measures the strength of this dependency

Aim of study

To estimate the climate sensitivity

- by modelling the relationship between
  - ⋆ estimates of radiative forcing since 1750 and
  - ⋆ estimates of global temperature

    based on measurements since 1850
- using a climate model based on physical laws

Climate model

Could use

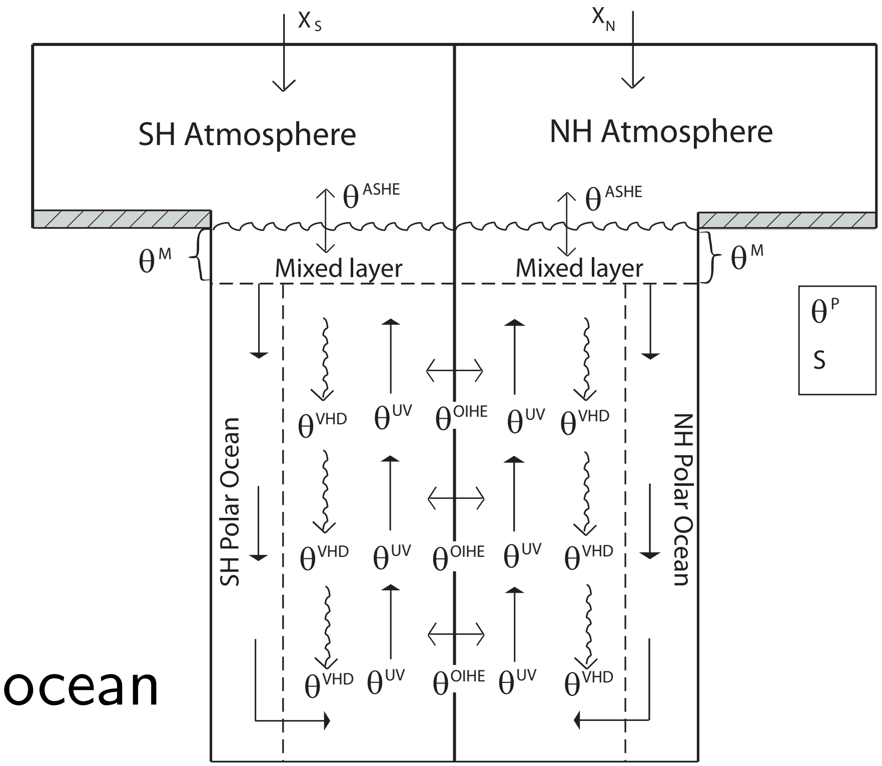
- an Atmospheric Ocean General Circulation Model,
  but complex and very computer intensive
- an approximation to an AOGCM,
  an emulator based on Gaussian processes
- a simple climate model, our approach

The "true" global state of the earth in year t

- TNH_t - Temperature at the northern hemisphere
- TSH_t - Temperature at the southern hemisphere
- OHC_t - Ocean heat content

Simple climate model

- Deterministic computer model (Schlesinger et al., 1992)
- based on
  - ⋆ energy balance
  - ⋆ upwelling diffusion ocean
- where the earth is divided into
  - ⋆ atmosphere and ocean
  - ⋆ northern and southern hemisphere
- with
  - ⋆ radiative forcing into the system
  - ⋆ energy mixing
    - ∗ between the atmosphere and the ocean
    - ∗ within the ocean



Simple climate model cont.

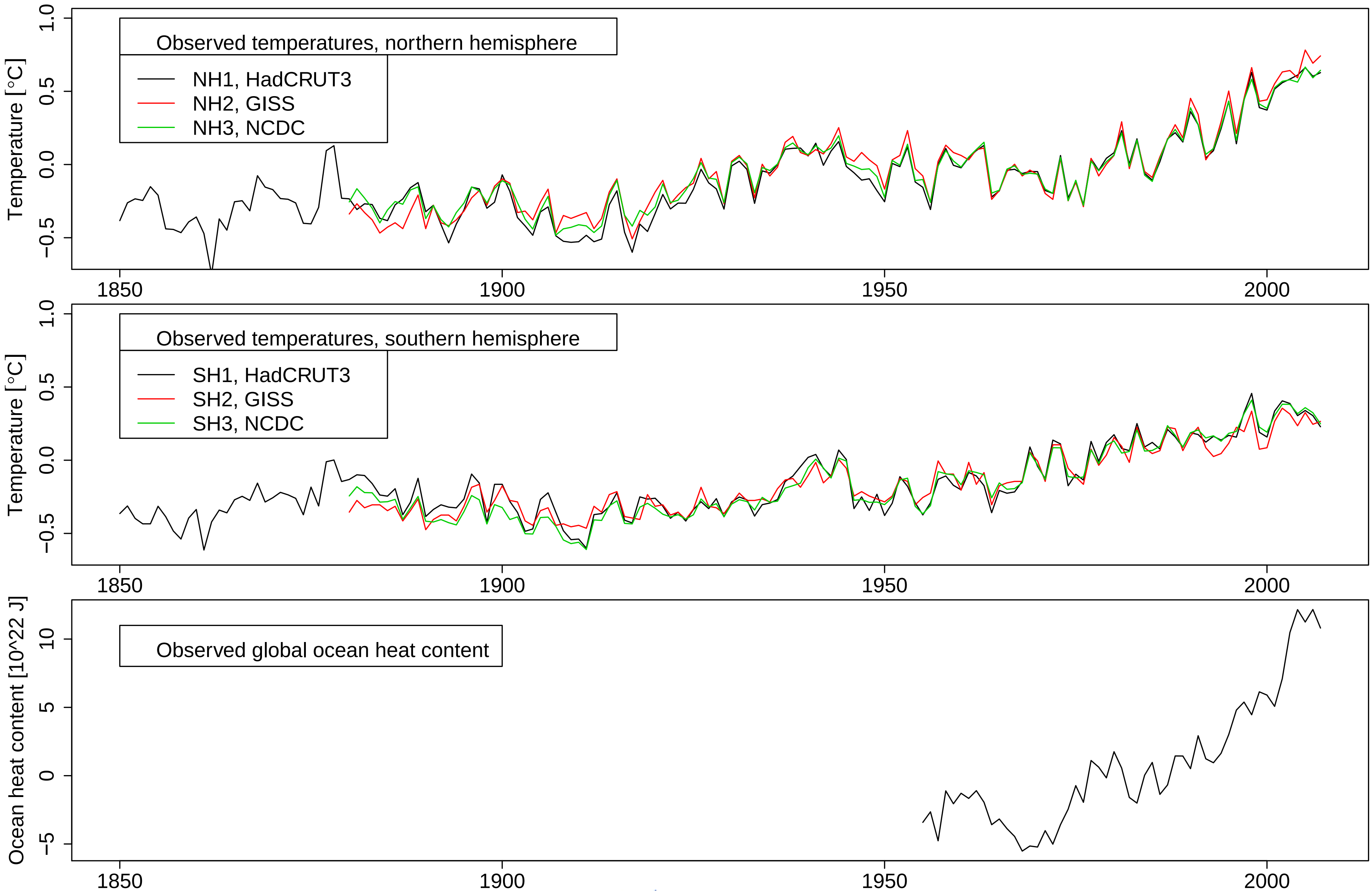
$\mathbf{m}_t(\mathbf{x}_{1750:t}, S, \boldsymbol{\theta})$

- Yearly time resolution
- Output
  - ⋆ temperature northern hemisphere
  - ⋆ temperature southern hemisphere
  - ⋆ ocean heat content
- Input
  - ⋆ $\mathbf{x}_{1750:t}$ - yearly radiative forcing from 1750 until year t, separate for northern and southern hemisphere
  - ⋆ S - the climate sensitivity, the parameter of interest
  - ⋆ $\boldsymbol{\theta}$ - 6-dimensional vector of other model parameters

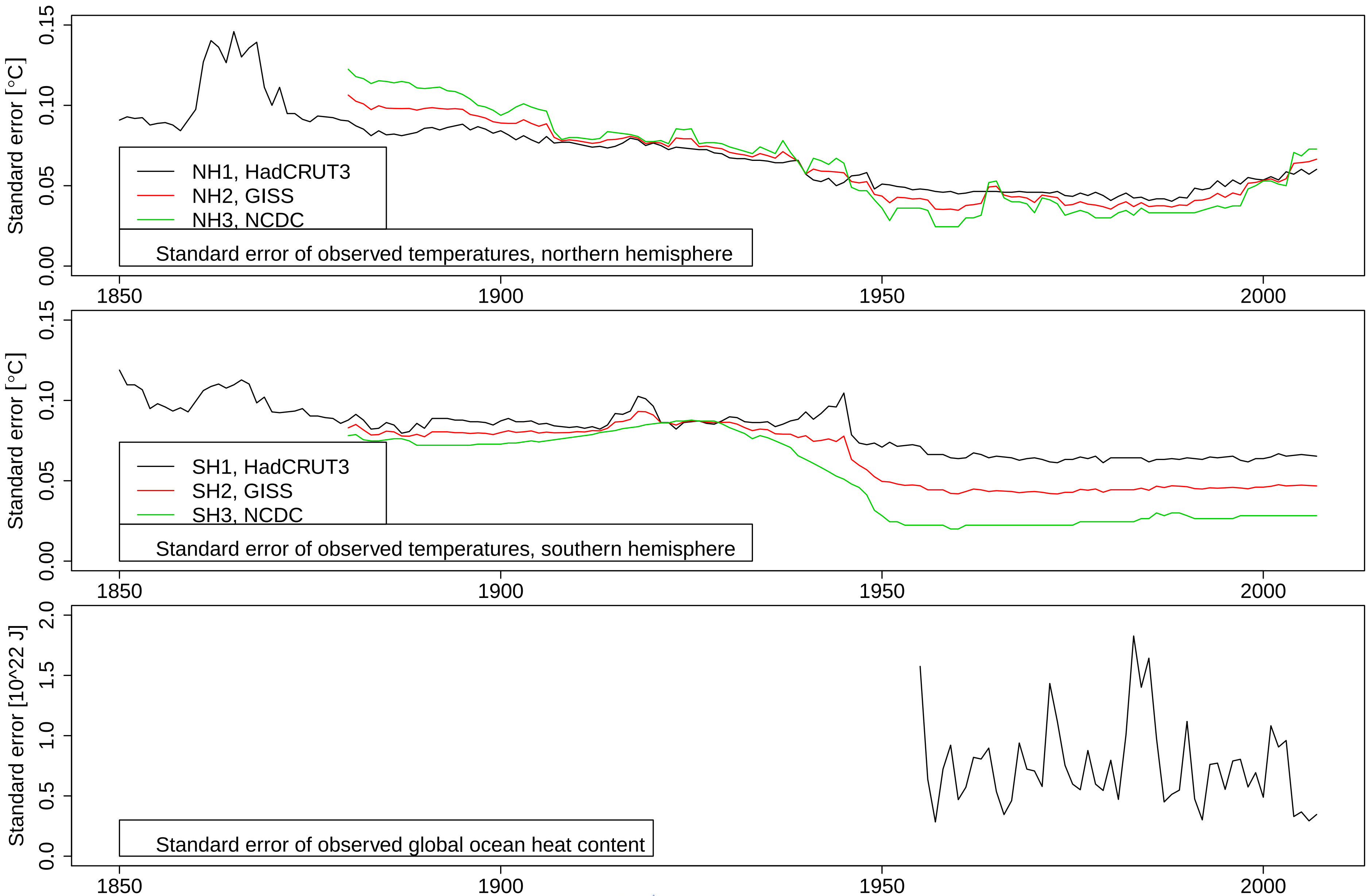
Response data

- $\mathbf{y}_t$ - 7-dimensional vector with yearly observed temperatures and ocean heat content
- Three pairs of series with temperature measurements for northern and southern hemisphere
  - ⋆ 1850-2007 (HadCRUT3, Brohan et al.,2006)
  - ⋆ 1880-2007 (GISS, Hansen et al. 2006)
  - ⋆ 1880-2007 (NCDC, Smith and Reynolds 2005)
- One series with ocean heat content measurements
  - ⋆ 1955-2007 (Levitus et al. 2009)
- These observations are not the truth, but are estimates of the underlying "true" global state of the earth
- $\mathbf{s}_t$ - 7-dimensional vector of corresponding standard errors

Observations



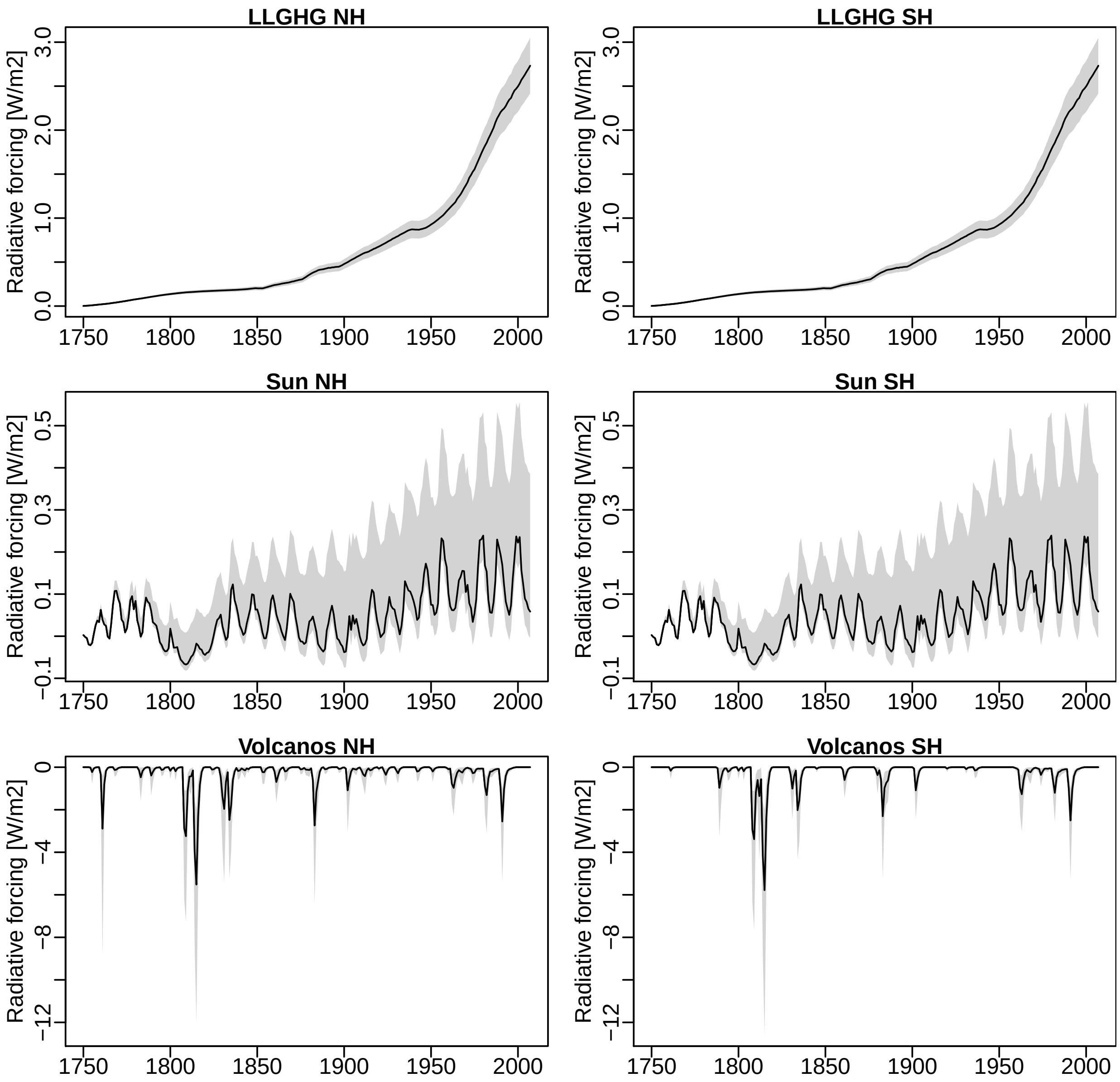
Standard errors



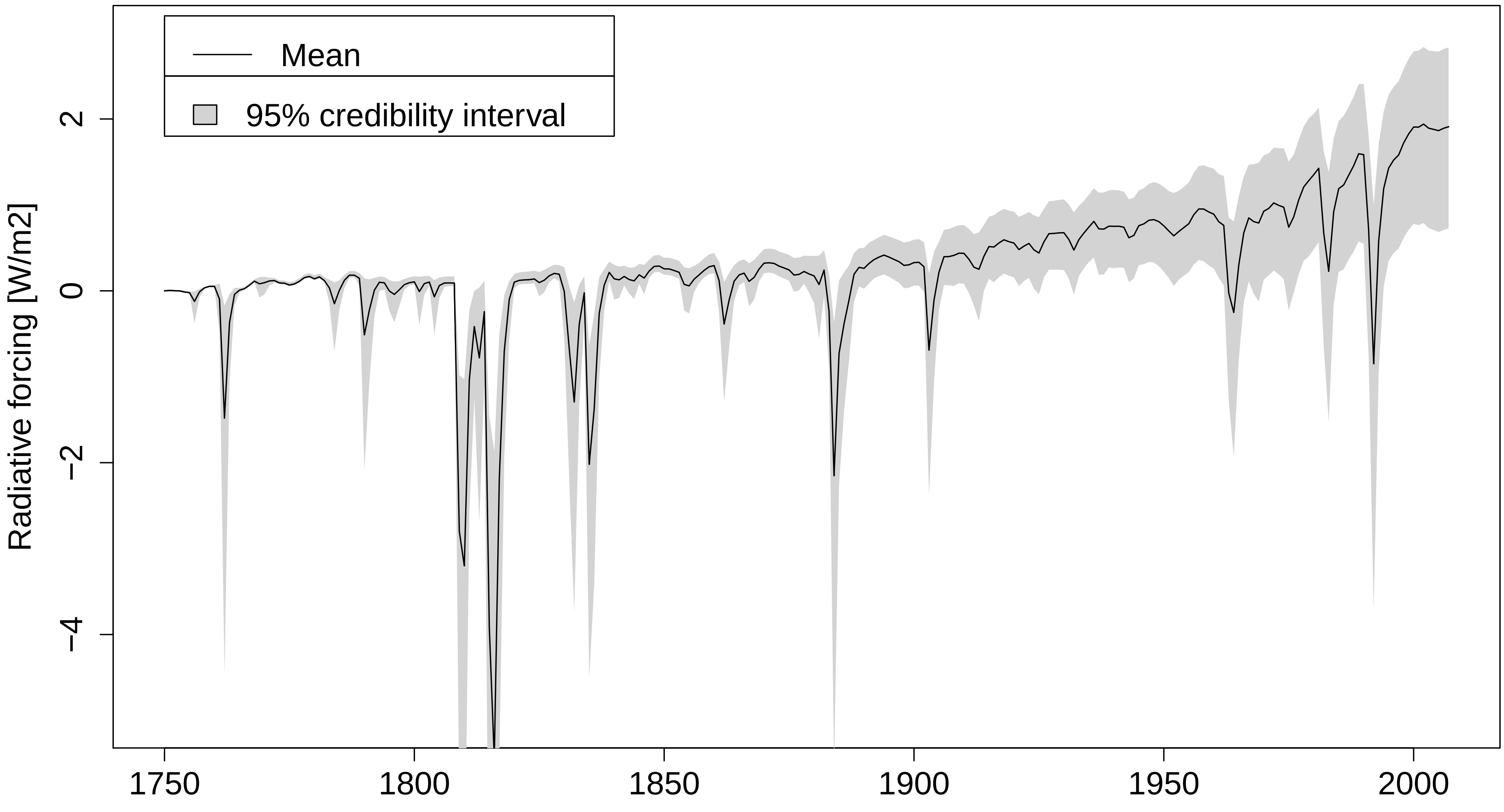
Radiative forcing

- We will specify our best knowledge about historical radiative forcing as prior distributions of 9 independent components, based on temperature-independent estimates of each component, including uncertainties
  - ⋆ long-lived greenhouse gases
  - ⋆ direct aerosols
  - ⋆ indirect aerosols
  - ⋆ solar radiation
  - ⋆ volcanoes
  - ⋆ land use
  - ⋆ tropospheric ozone
  - ⋆ stratospheric ozone
  - ⋆ stratospheric H_2O

Priors of components of radiative forcing



Prior of total radiative forcing



Model for "true" global state of the earth

$$\mathbf{g}_t = (TNH_t, TSH_t, OHC_t)^T$$

Combined deterministic + stochastic model

$$\mathbf{g}_t = \mathbf{m}_t(\mathbf{x}_{t:1750}, S, \boldsymbol{\theta}) + \mathbf{n}_t^m$$

- $\mathbf{n}_t^m$: model error, dimension 3

Model for observations

$$\mathbf{y}_t = \mathbf{A}\mathbf{g}_t + \beta_{\mathbf{0}} + \mathbf{n}_t^o$$

- $\mathbf{A}$: 7x3 matrix copying the northern and southern temperatures 3 times, to compare model with observations
- $\boldsymbol{\beta}_{\mathbf{0}}$: intercept, accounts for different reference periods, dimension 7
- $\mathbf{n}_t^o$: observational (measurement) error, dimension 7
- Can be difficult to separate model error and observational error, i.e. careful with too strict interpretation

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Model error

We assume $\mathbf{n}_t^m$ is VAR(1) (vector autoregressive process of order 1)

$$\mathbf{n}_t^m = \mathbf{\Phi}^m \mathbf{n}_{t-1}^m + \boldsymbol{\varepsilon}_t^m$$

$\mathbf{\Phi}^m$ is diagonal

$$\boldsymbol{\varepsilon}_t^m \sim N(\mathbf{0}, \mathbf{\Sigma}^{\boldsymbol{m}})$$

elements of $\boldsymbol{\varepsilon}_t^m$ are correlated

Observational error

- We assume $\mathbf{n}_t^o$ is a scaled VAR(1)

$$\mathbf{n}_t^o = diag(\mathbf{s}_t)\mathbf{n}_t^{o*}$$

where $\mathbf{s}_t$ is the vector of known observational standard errors and $\mathbf{n}_t^{o*}$ is VAR(1)

Estimation

- Bayesian approach (Kennedy and O'Hagan 2001), using MCMC
- Vague prior for S
- Informative priors for $\mathbf{x}_{t:1750}$ and $\boldsymbol{\theta}$
- Vague priors for other parameters

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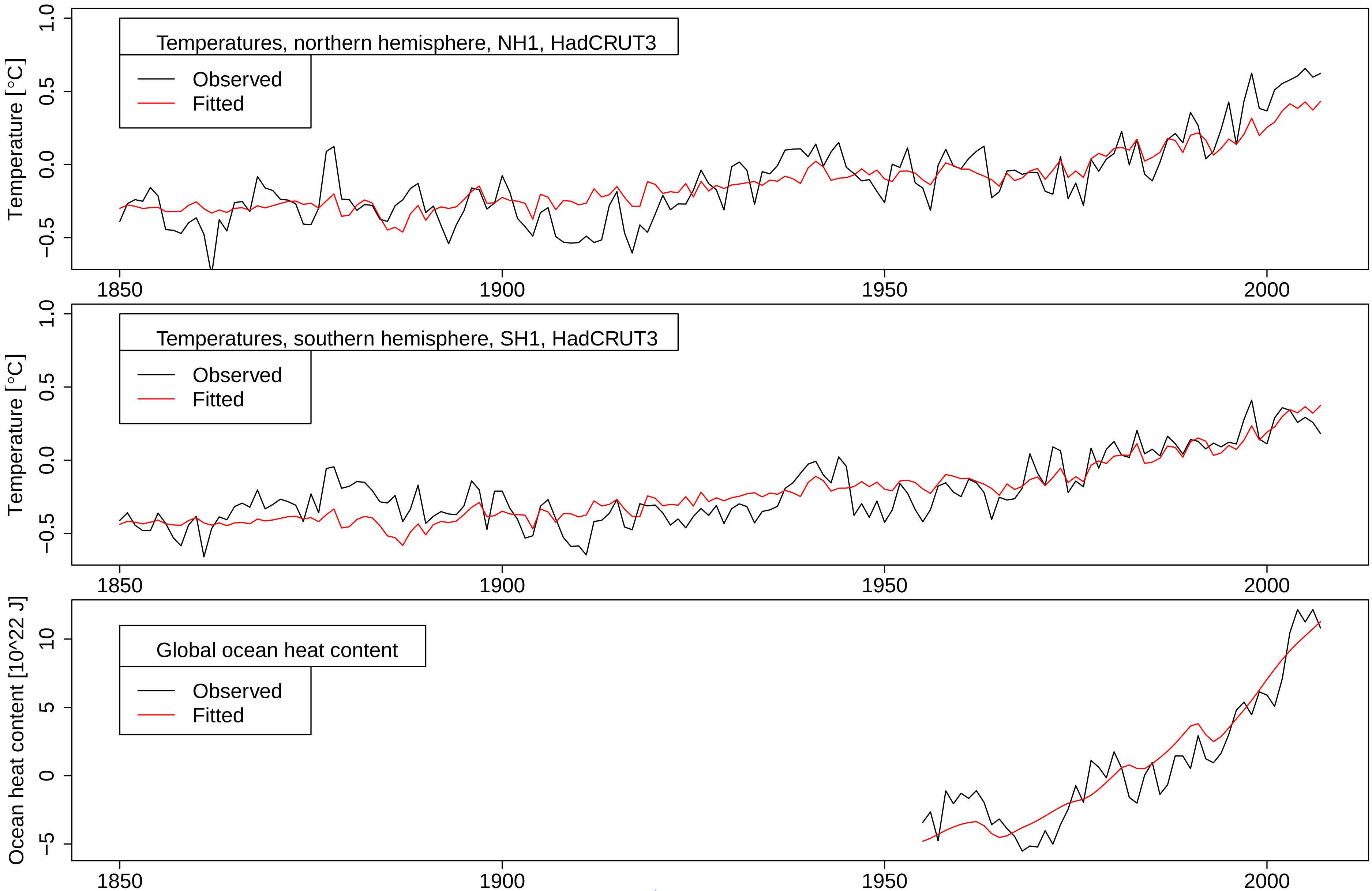
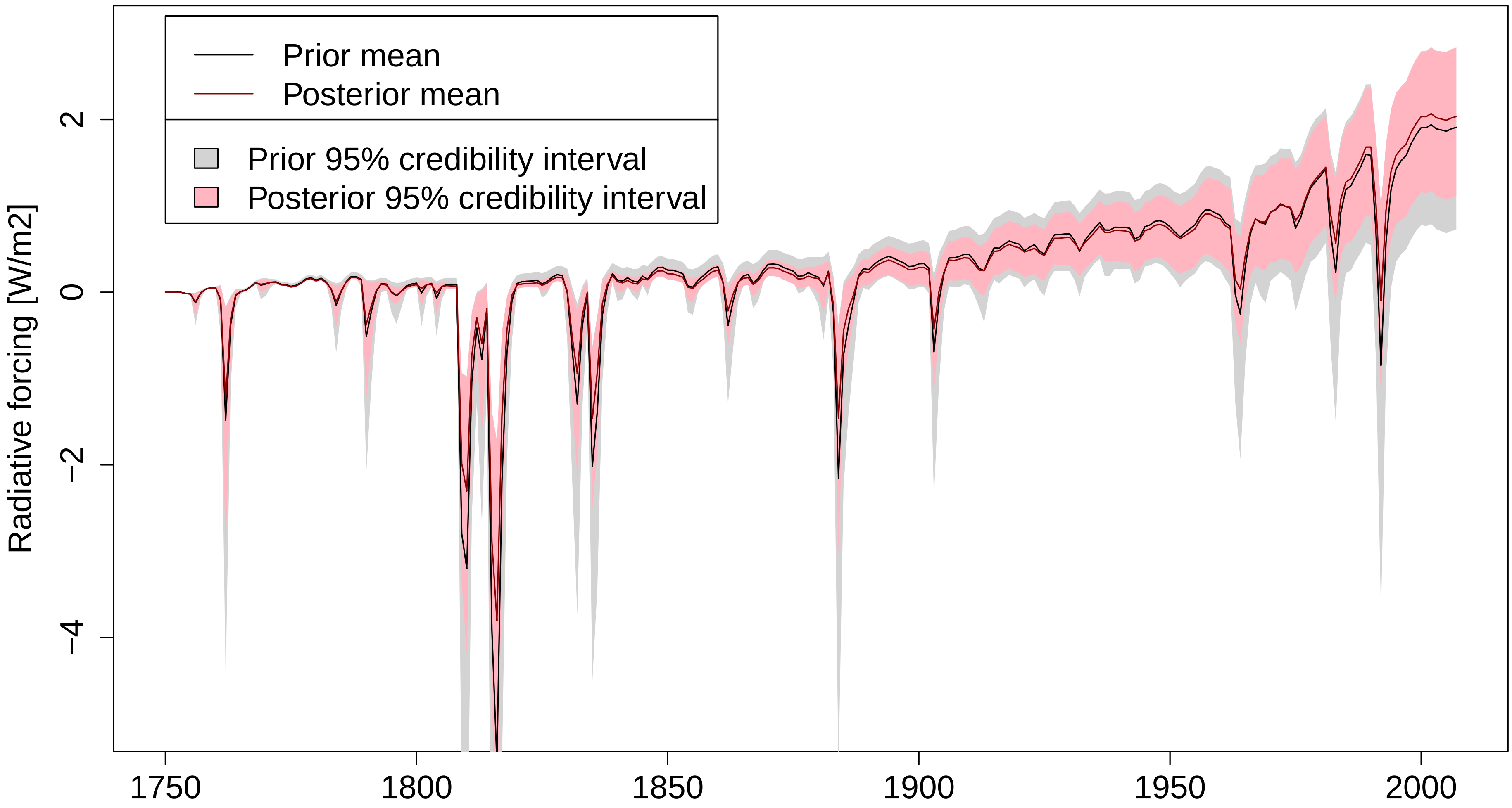
Observed and fitted response values



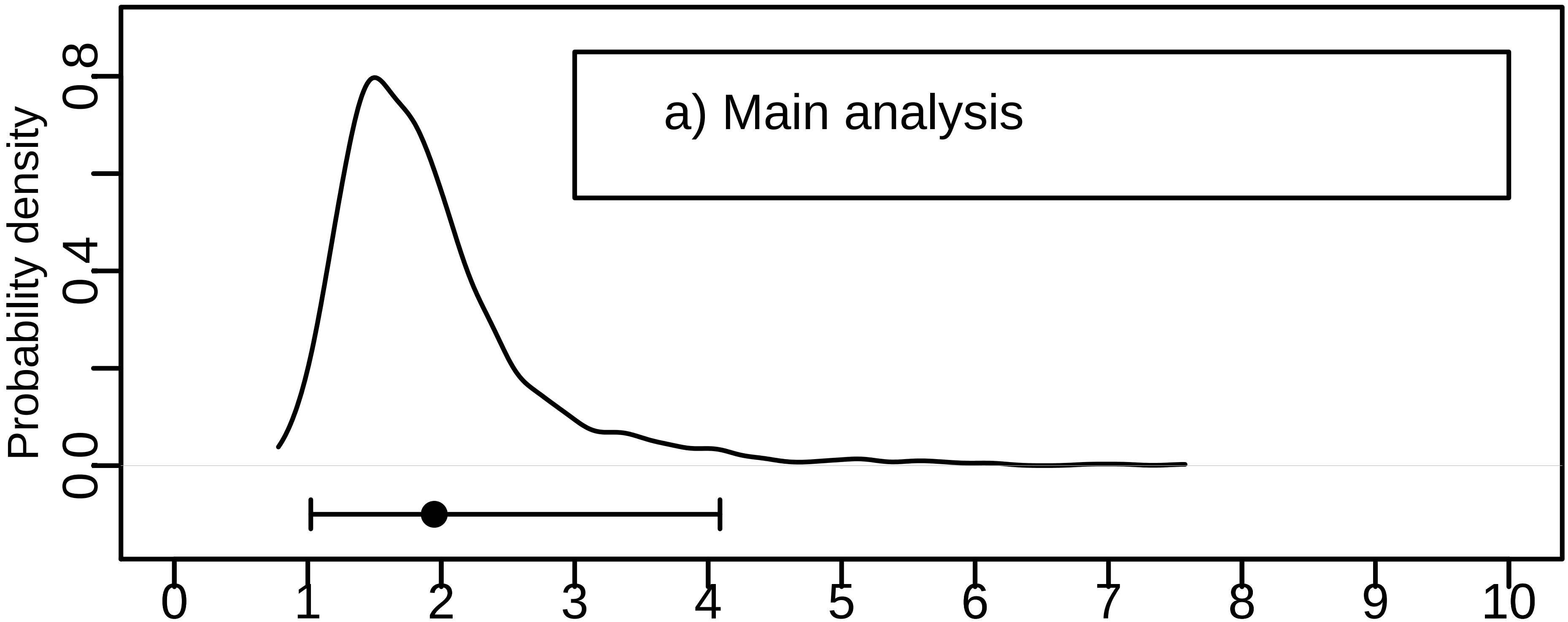
Posterior vs. prior of radiative forcing



Model and observational errors

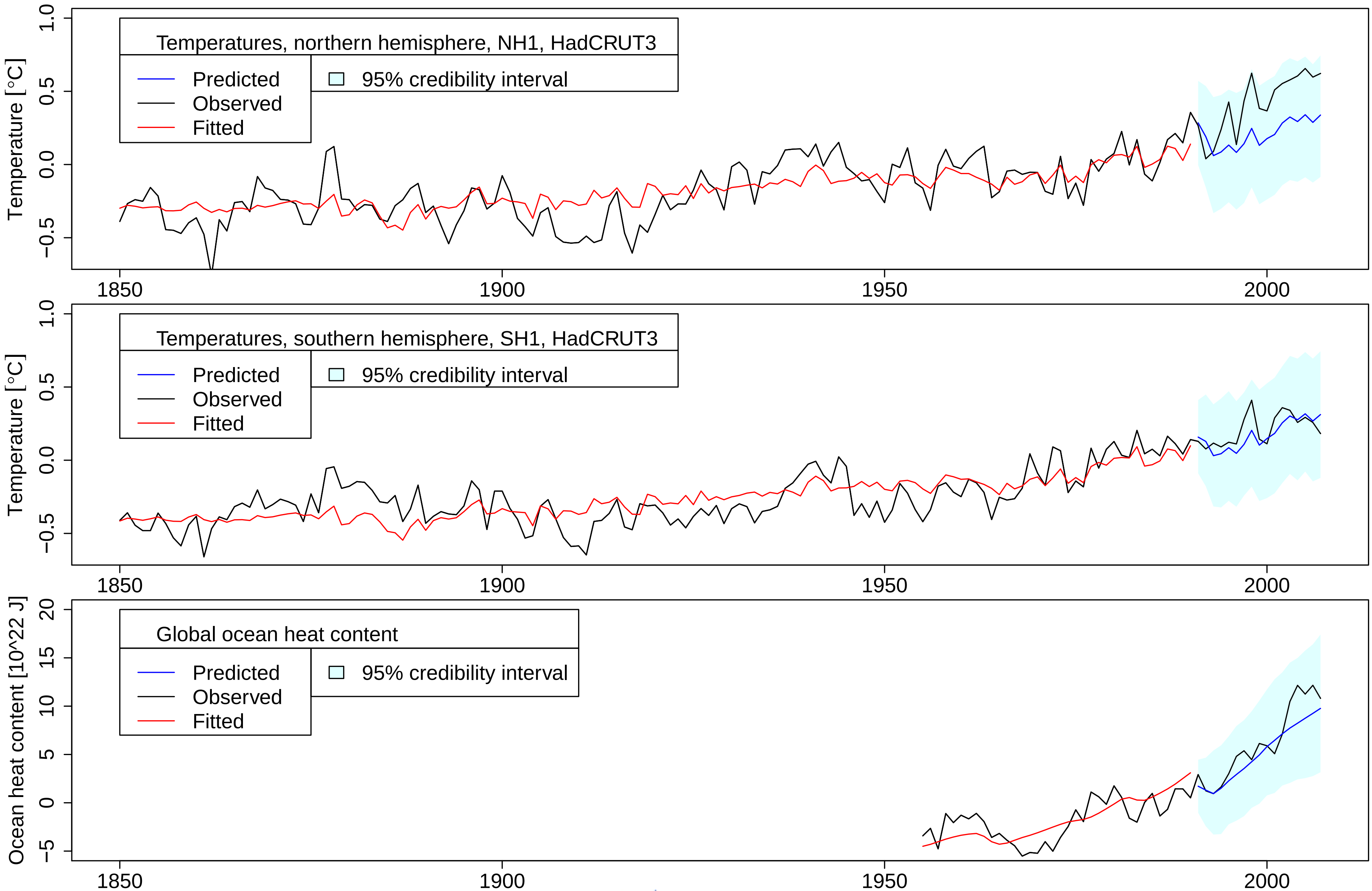
- Positive autocorrelations - ϕ's between 0.5 and 0.7
- Positive correlations between temperature errors
- Temperature errors and ocean heat content errors are uncorrelated

Posterior of the climate sensitivity S



Degrees Celcius

Re-estimation 1850-1990 + prediction 1991-2007



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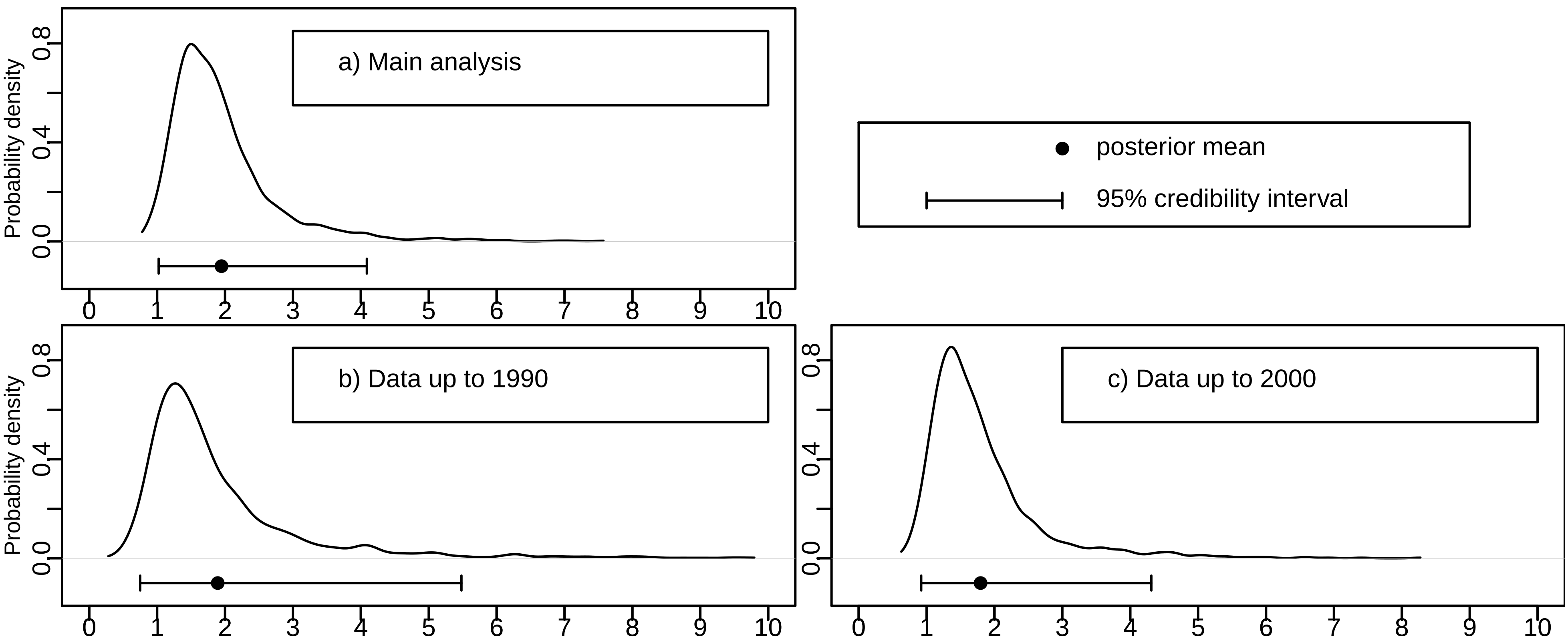
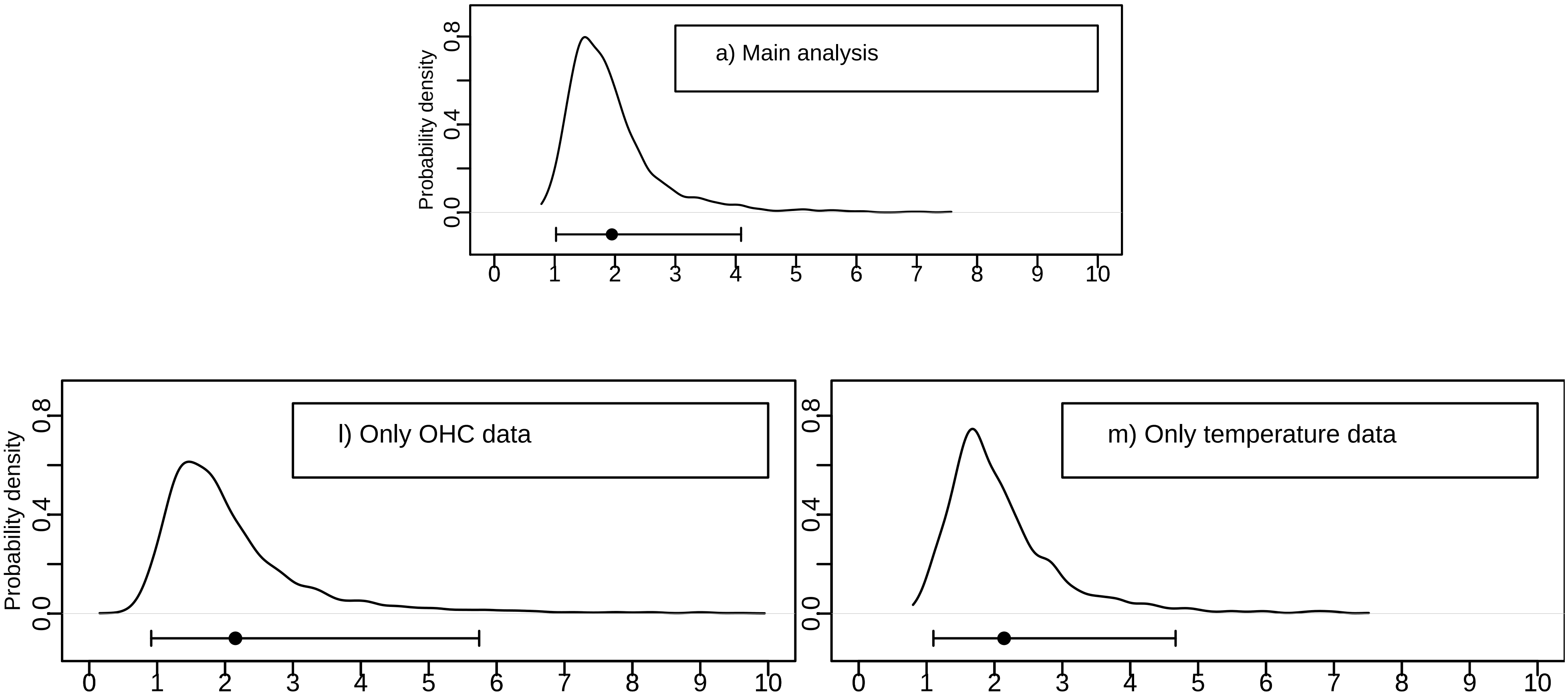
Posteriors for reduced data

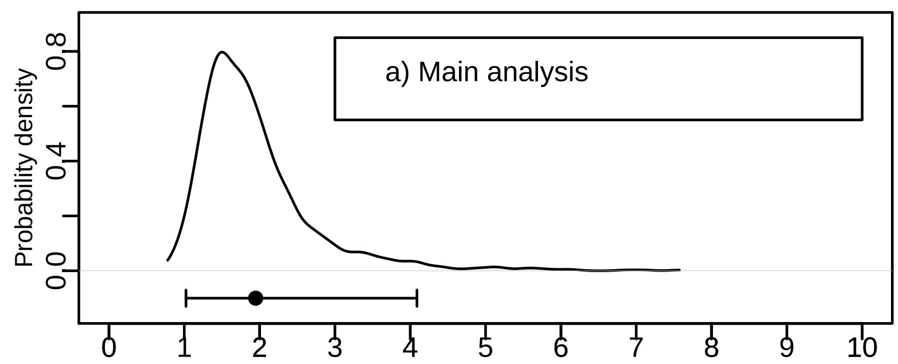


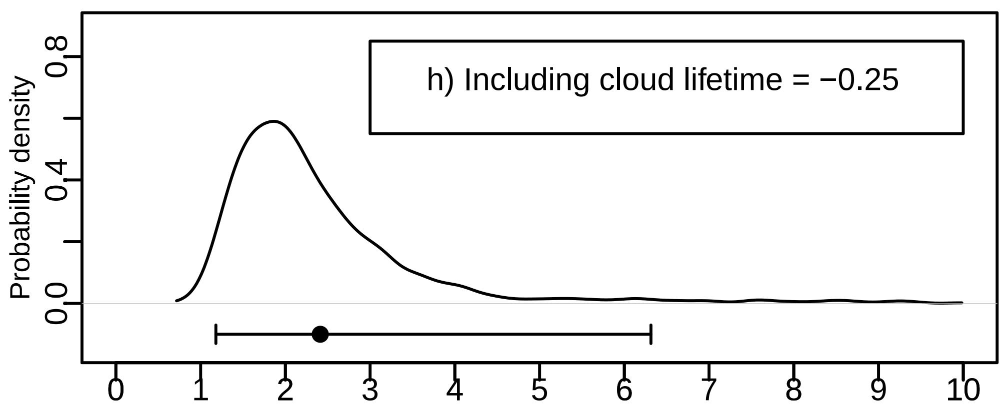
Posteriors for only temperature or OHC

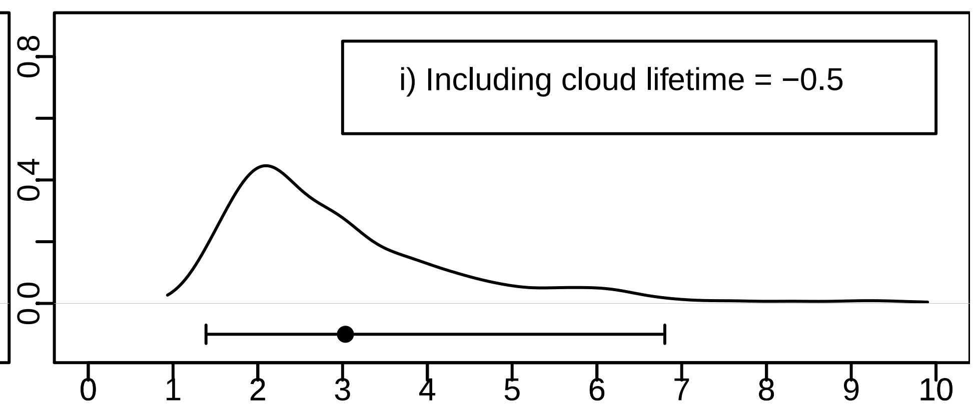


Posteriors including cloud lifetime effect

- Aerosols change the lifetime of clouds
- Cloud lifetime is *not* included a radiative forcing by IPCC (2007)
- But plays a similar role in our approach







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Further work

- Include the cloud lifetime effect with uncertainty
- Update priors of forcing,
  more precise estimates of historical forcing will be available soon
- Include data from 2008 and 2009

Thank you for your attention!

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Other approaches i)

Tommassini, Reichert, Kunsch, Buser, Knutti and Borsuk (2009) in Applied Statistics

$$\mathbf{y}_t = \mathbf{m}_t(\mathbf{x}_{t:1750}, S, \boldsymbol{\theta}) + \mathbf{n}_t^o$$

- Similar model $\mathbf{m}_t$
- Only one temperature series
- No autocorrelation in observational error $\mathbf{n}_t^o$ for temperature
- No intercept
- No model error term, all model error due to error in forcing
- No informative prior for forcing
  $x_t = \mu_t + \phi_t =$ mean $+$ random

Other approaches ii)

Sanso and Forest (2009) in Applied Statistics

- Medium complex climate model - computer intensive
- Emulator
- Response is aggregated temperature data
  - ⋆ mean(1946-1955) - mean(1905-1995),
    mean(1956-1965) - mean(1905-1995),
    mean(1966-1975) - mean(1905-1995),
    mean(1976-1985) - mean(1905-1995),
    mean(1986-1995) - mean(1905-1995)
  - ⋆ Earth divided into four zonal bands
  - ⋆ 20 dimensional vector

Other approaches iii)

Gregory, Raper, Stott and Rayner (2002) in Journal of Climate

$$S = 3.71 \cdot \Delta T / (\Delta RF - \Delta OHC)$$

- ΔT = mean temp 1957-1994 - mean temp 1861-1900
- ΔRF = mean RF 1957-1994 - mean RF 1861-1900
- ΔOHC = mean OHC 1957-1994 - mean OHC 1861-1900