University of BRISTOL

Data Assimilation in terrestrial carbon cycle modelling

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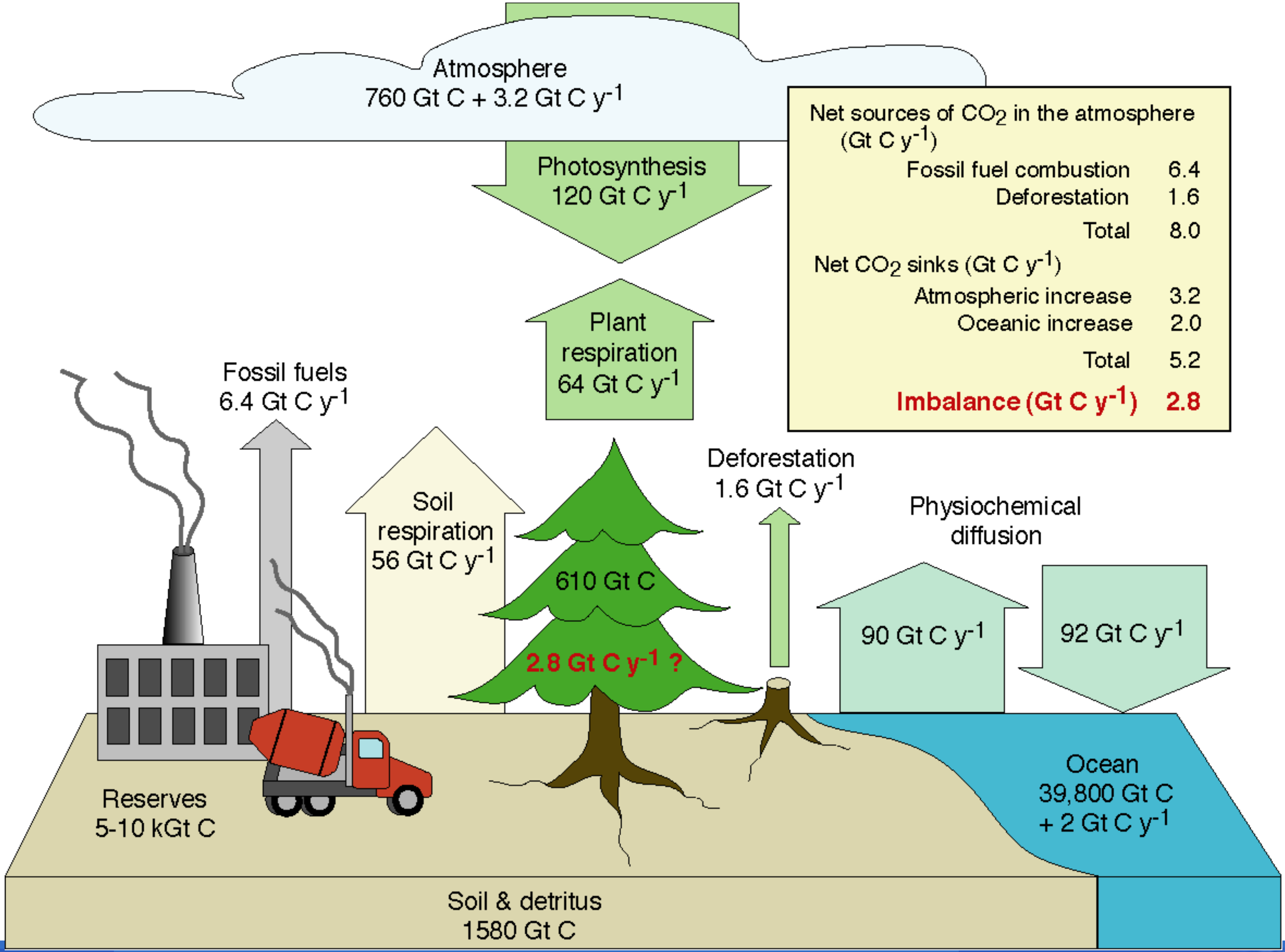
NATURAL ENVIRONMENT RESEARCH COUNCIL

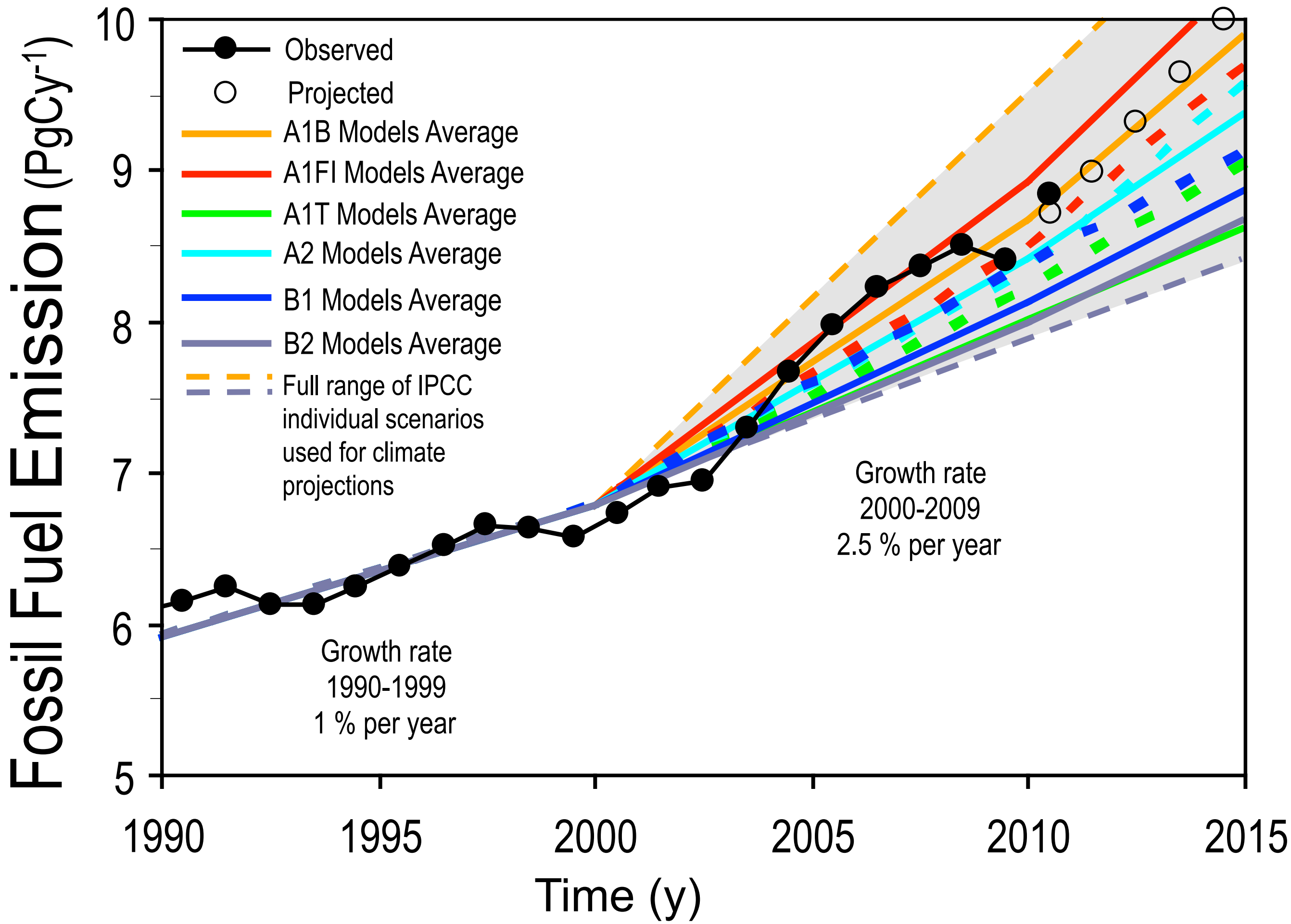
Outline

- Background to the carbon cycle
- CCDAS
- Particle filter method
- Results
- Comparison of particle filter and CCDAS
- Conclusions and future work

The Global Carbon Cycle



Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Updated from Raupach et al. 2007, PNAS; Data: Gregg Marland, Thomas Boden-CDIAC 2010; International Monetary Fund 2010

Fate of Anthropogenic CO_2 Emissions (2002-2011 average)

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

4.3±0.1 PgC/yr

46%

2.6±0.8 PgC/yr

28%

Calculated as the residual
of all other flux components

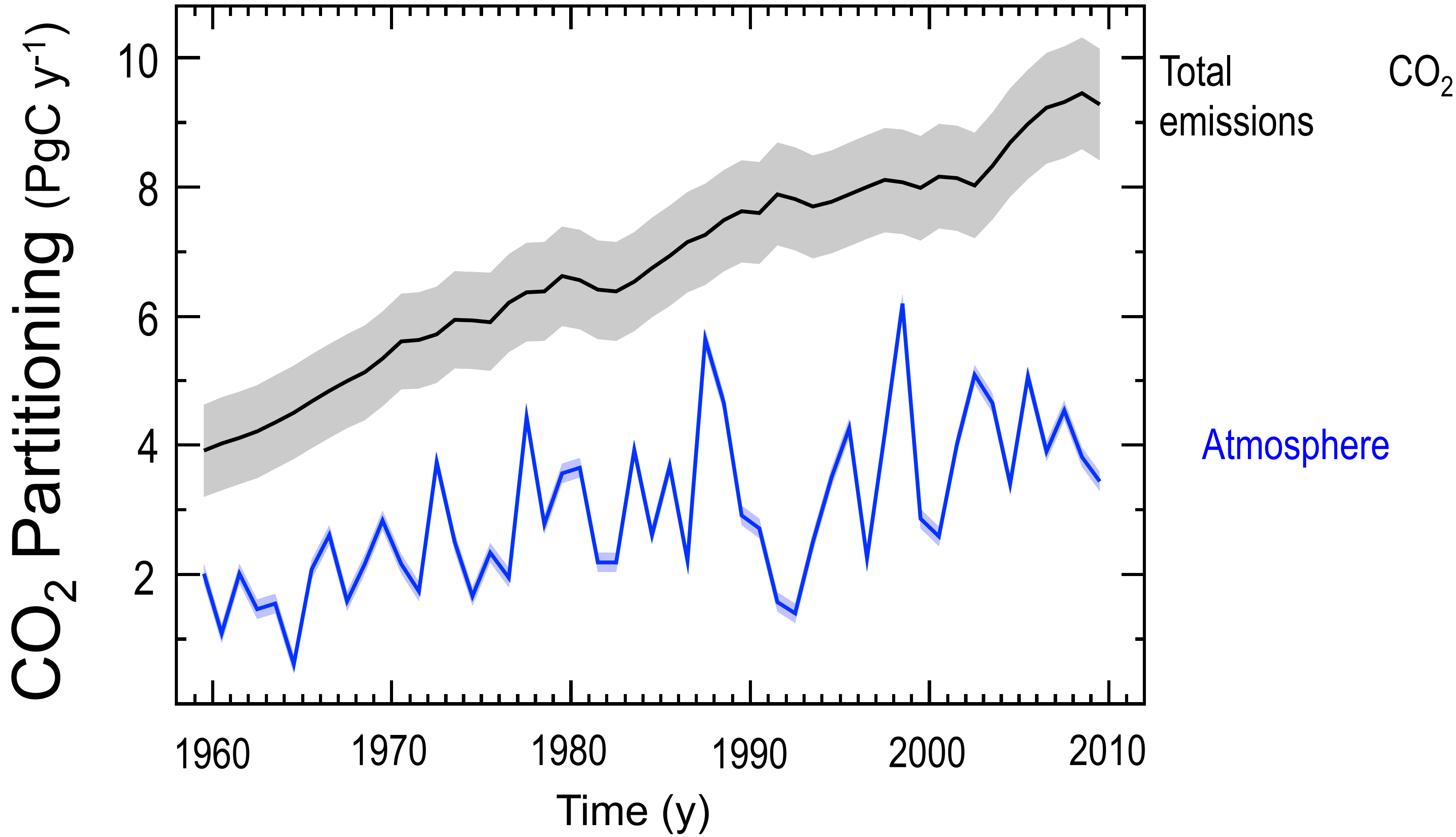
26%

2.5±0.5 PgC/yr

Source: Le Quéré et al. 2012; Global Carbon Project 2012

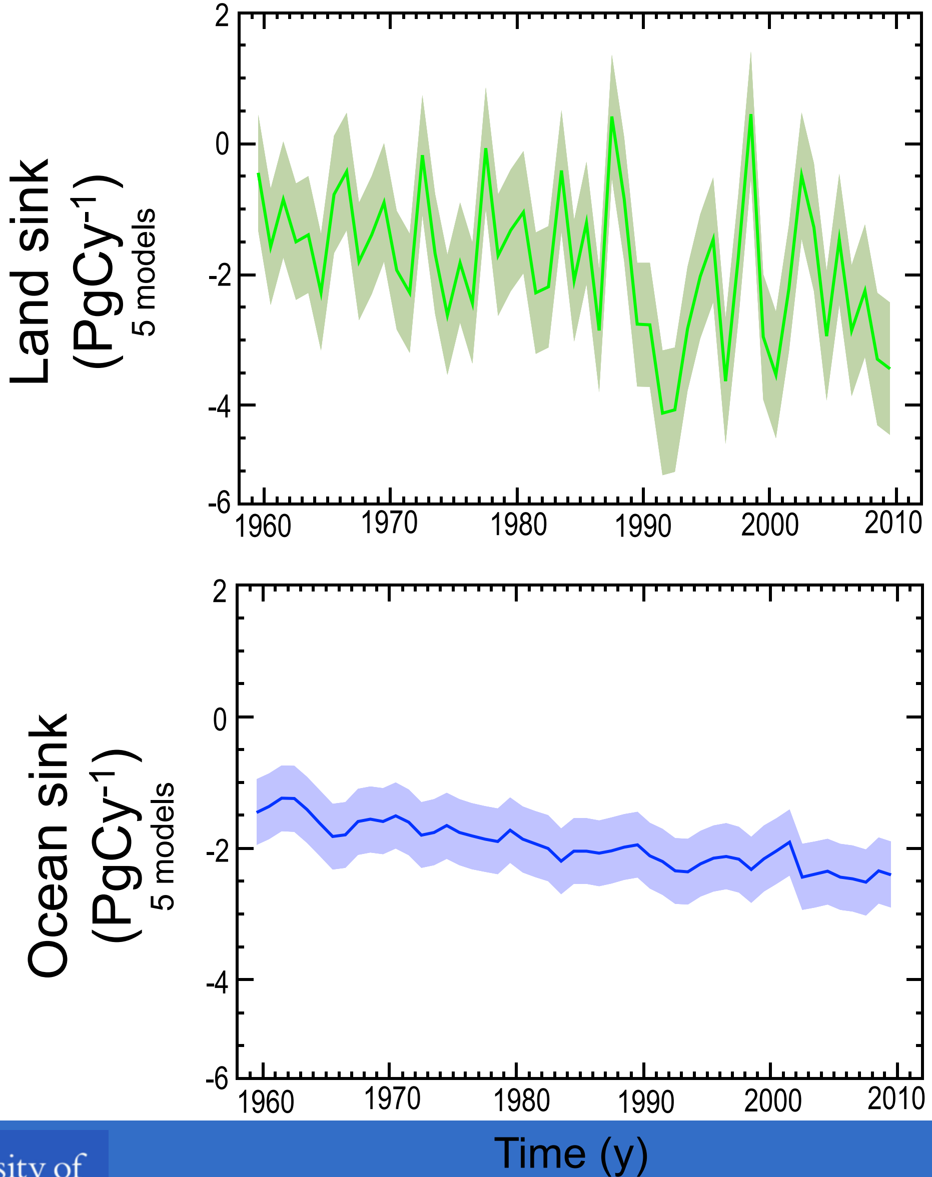
Key Diagnostic of the Carbon Cycle

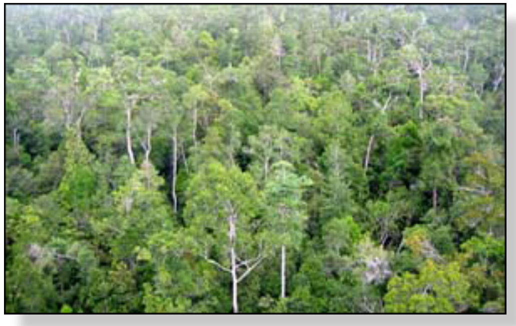
Airborne Fraction of total emissions



Updated from Le Quéré et al. 2009, Nature Geoscience; Data: NOAA 2010, CDIAC 2010

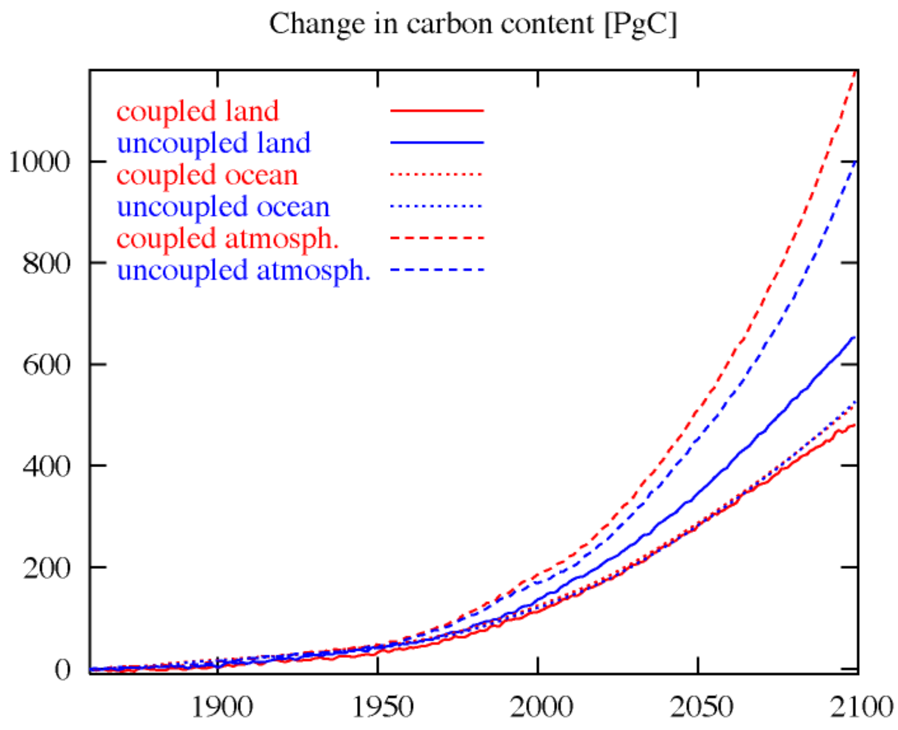
Modelled Natural CO_2 Sinks



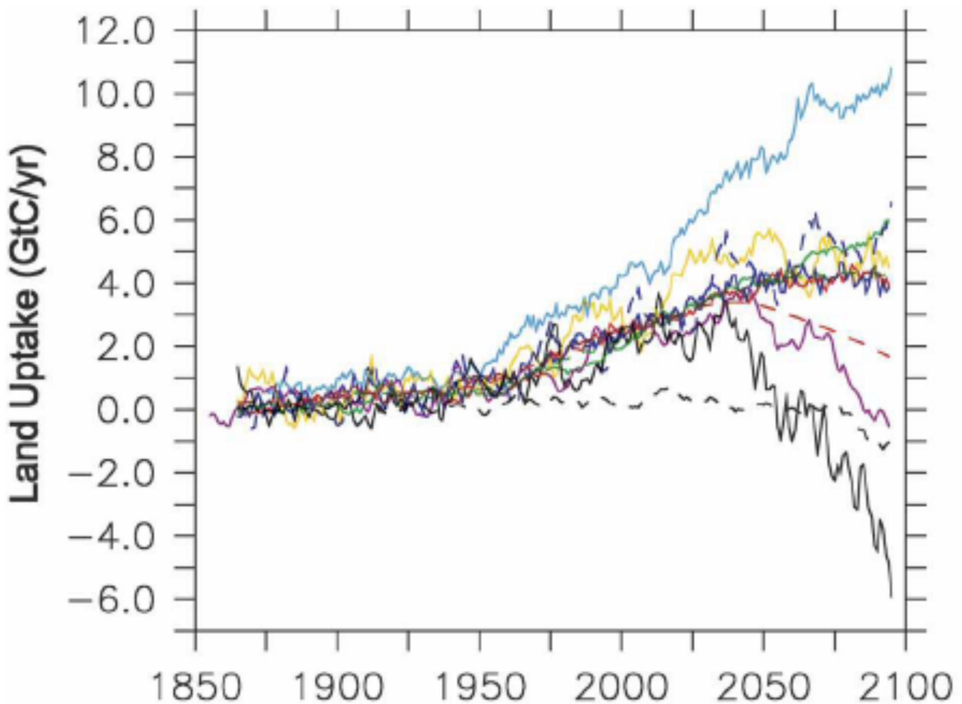


Updated from Le Quéré et al. 2009, Nature Geoscience

Carbon Cycle-Climate feedback

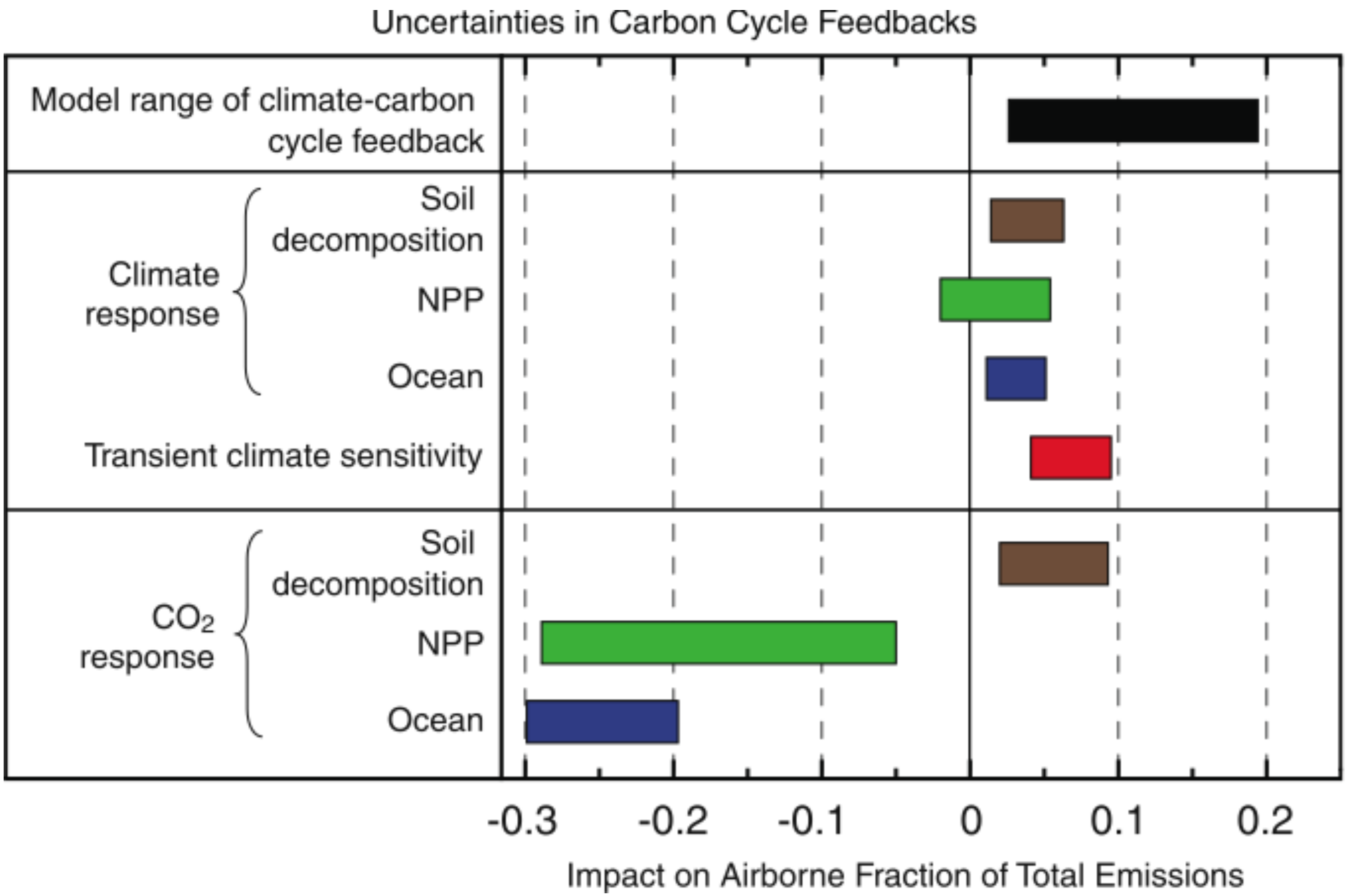


ECHAM5-MPIOM1-JSBACH
(Raddatz et al, 2007)



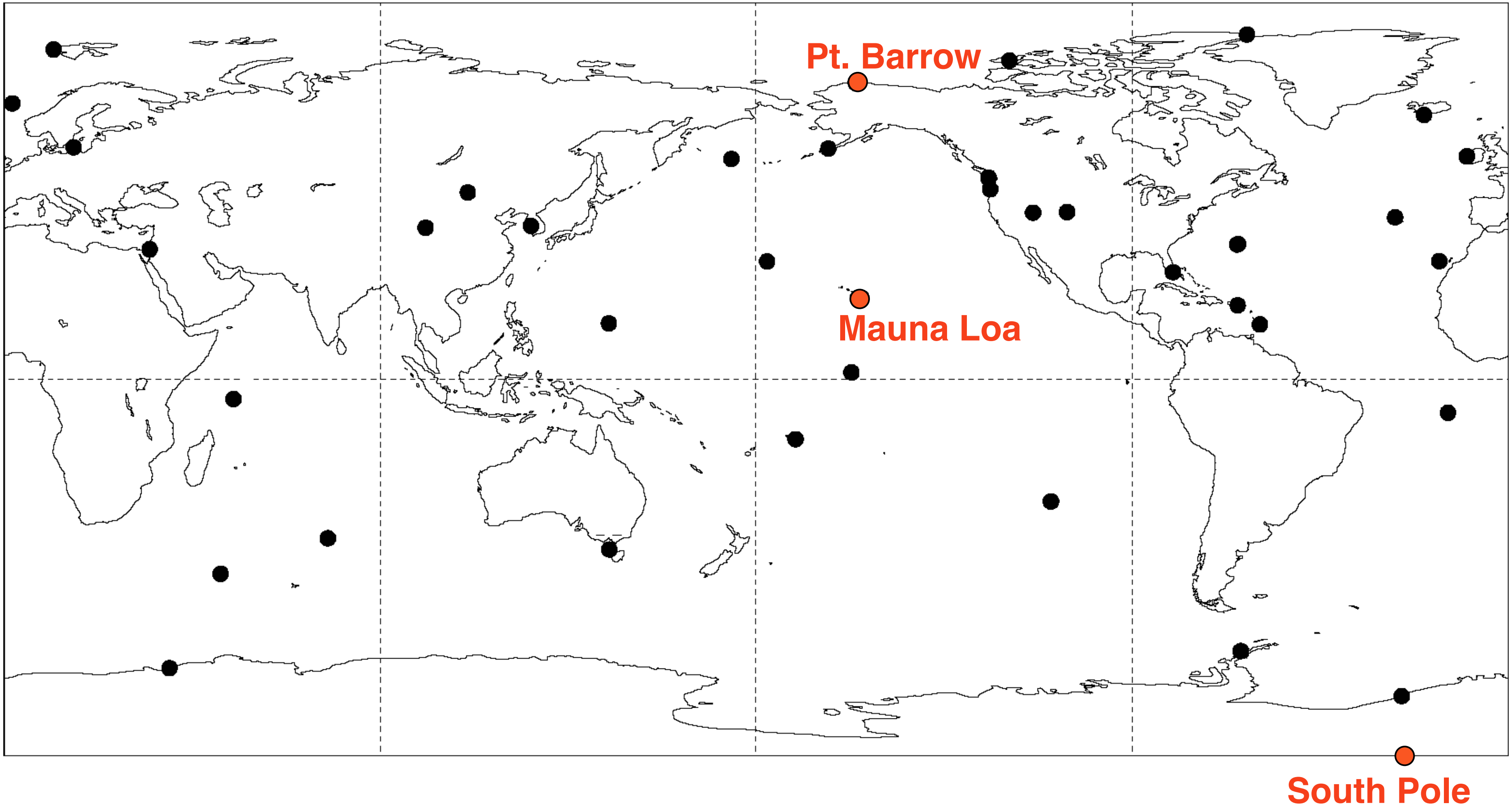
C4MIP results
(Friedlingstein et al. 2006)

Carbon Cycle-Climate feedback: breakdown of uncertainties

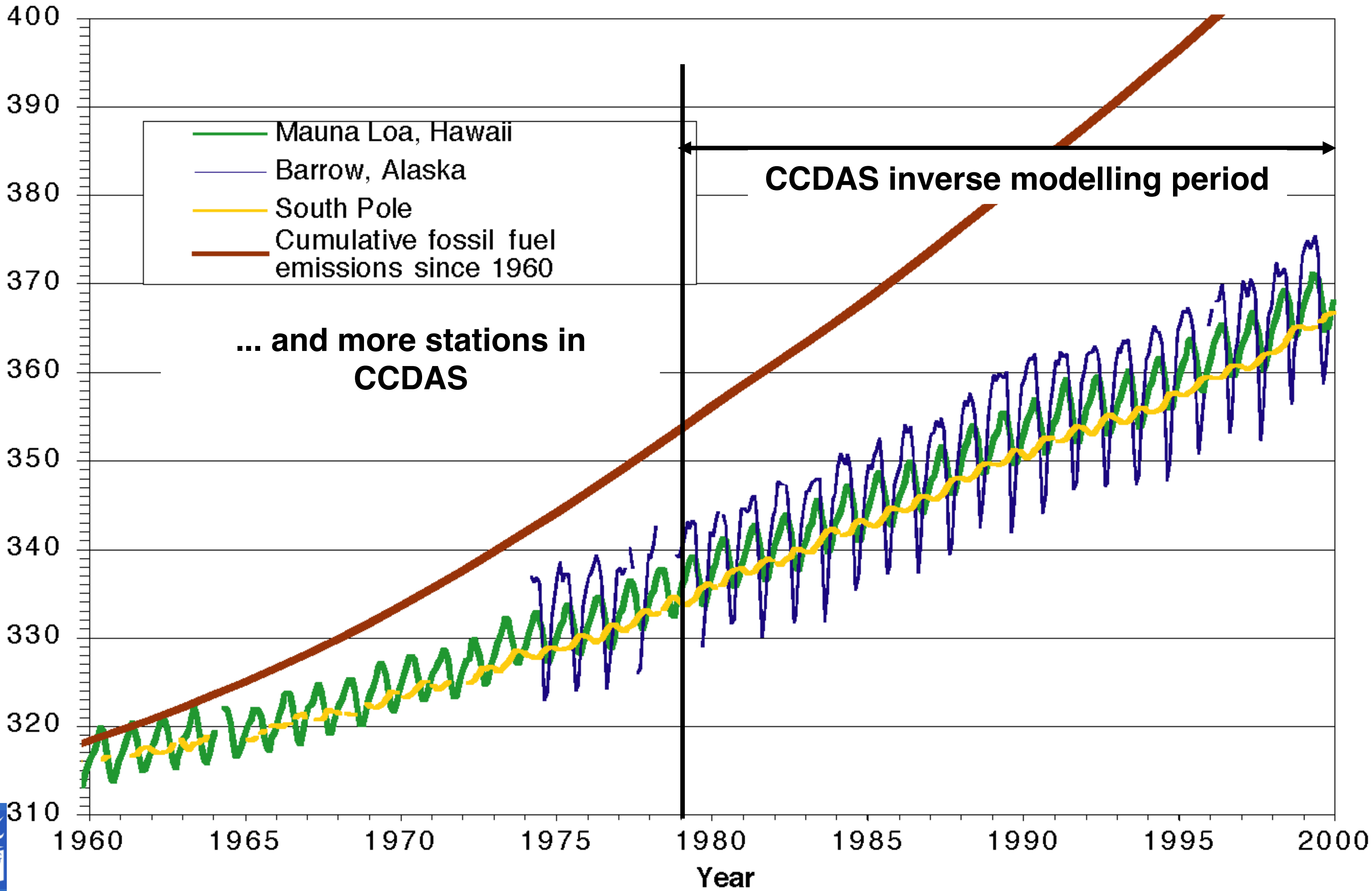


IPCC Climate Change 2007: The Physical Science Basis

The atm. CO_2 Station Network



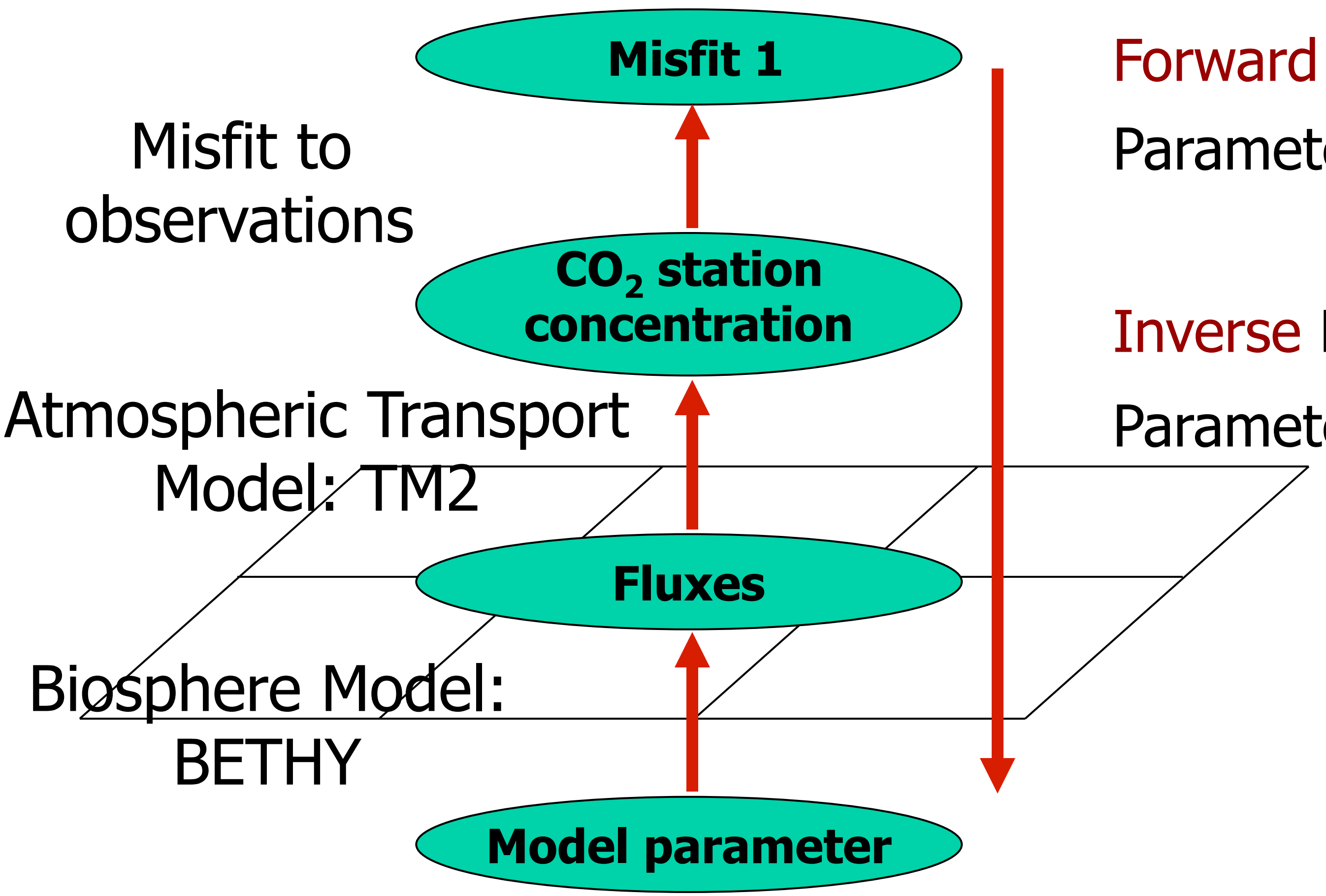
Atmospheric CO_2 Measurements



Need for Parameter Estimation

- Advanced models for coupled systems (e.g. land-atmosphere or ocean-atmosphere models) involve the coupling of many biological, chemical and physical processes
- Increase in the complexity of those models also leads to an increase in the number of parameters
- Prior parameter values usually based on “expert knowledge”
- If no reliable estimates can be provided for a parameter, it remains highly uncertain
- Uncertainty of the parameter might substantially contribute to the overall model output uncertainty
- Parameter optimisation methods can be used to constrain the parameters against observations

Assimilation of CO_2 with an inverse modelling system



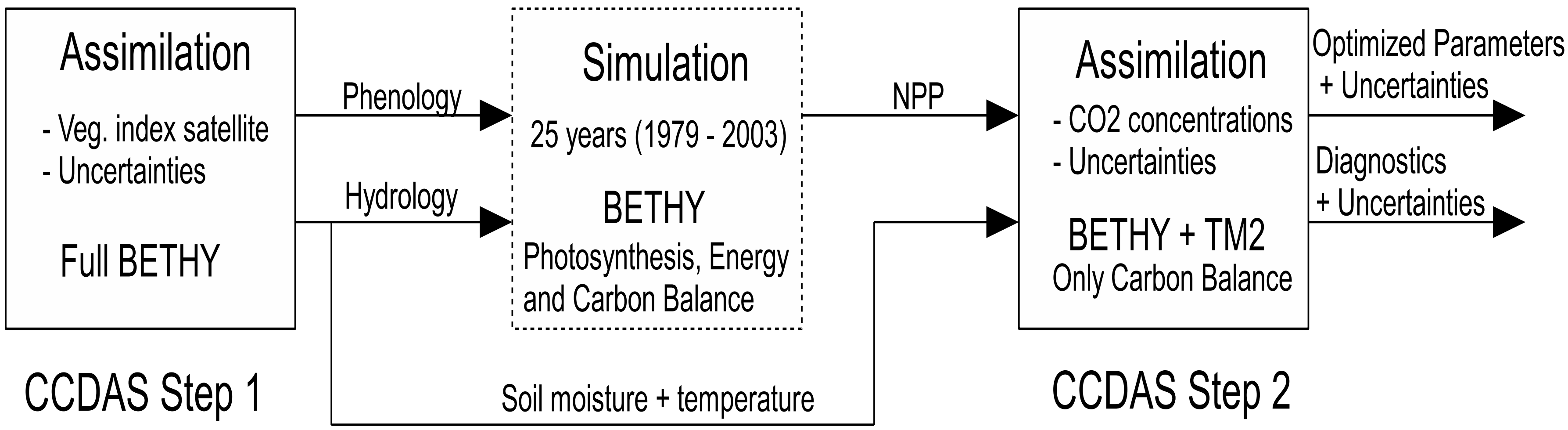
Forward Modeling:

Parameters –> Misfit

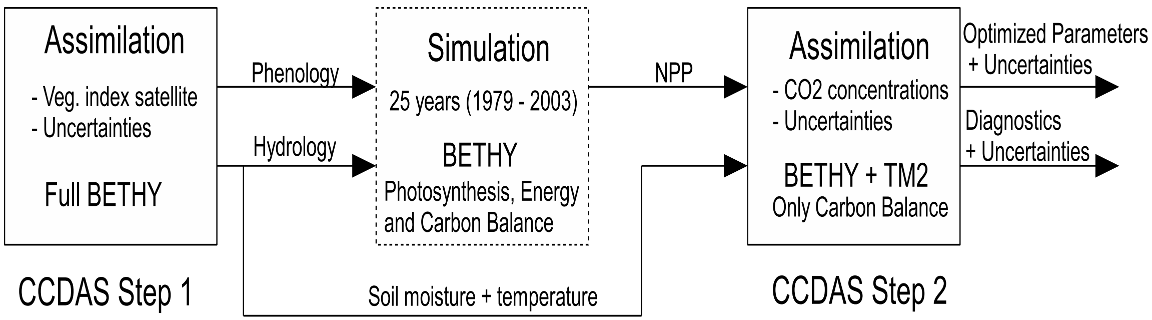
Inverse Modeling:

Parameter optimization

CCDAS


Assimilation
- Veg. index satellite
- Uncertainties
Full BETHY
CCDAS Step 1
Phenology
Hydrology
Simulation
25 years (1979 - 2003)
BETHY
Photosynthesis, Energy and Carbon Balance
NPP
Soil moisture + temperature
Assimilation
- CO2 concentrations
- Uncertainties
BETHY + TM2
Only Carbon Balance
CCDAS Step 2
Optimized Parameters + Uncertainties
Diagnostics + Uncertainties

CCDAS

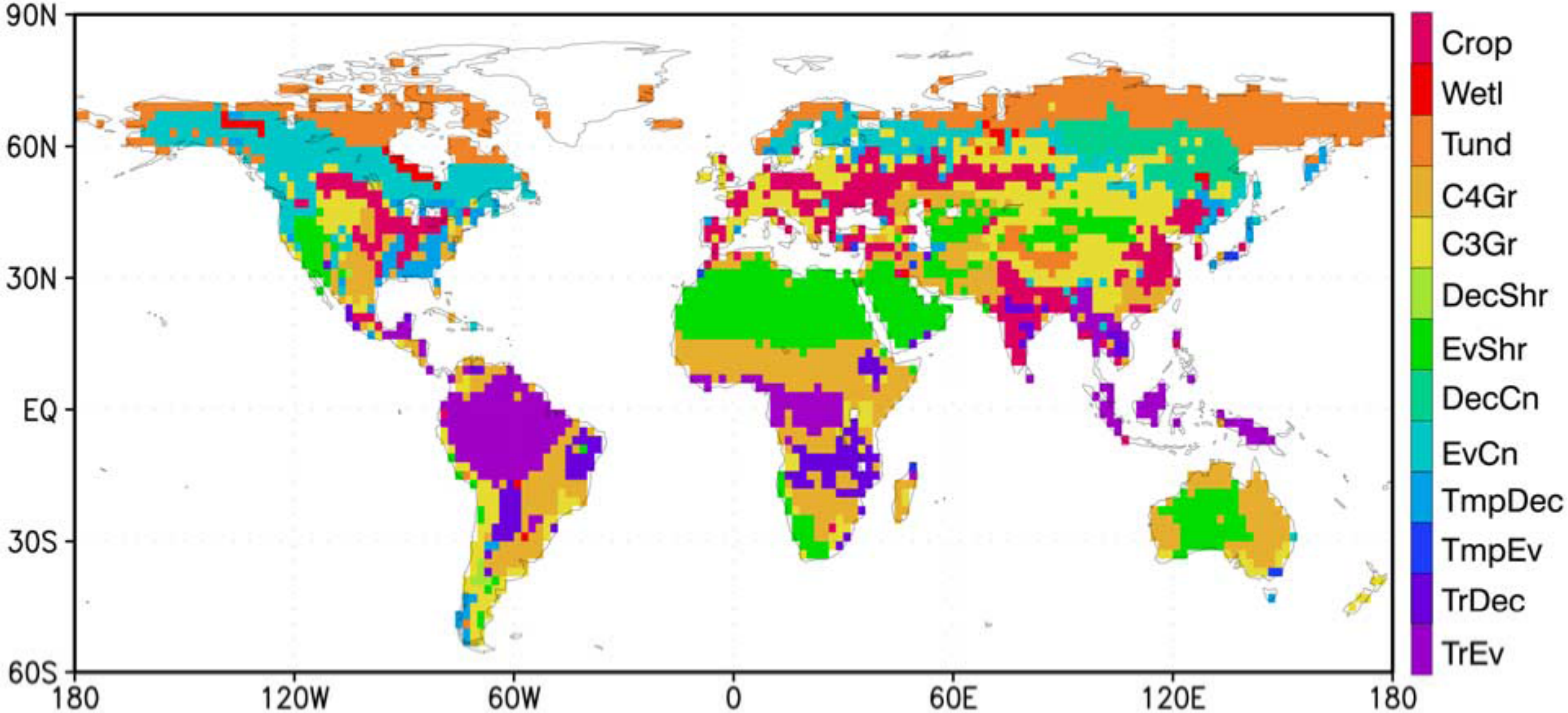


- Further simplification of step 2
- 13 plant functional types
- 6 process parameters
  - 5 global
  - 1 plant functional type dependent

Process parameters

Parameter	Description	Global	By PFT
$Q_{10,f}$	Soil respiration temperature factor, fast pool	X	
$Q_{10,s}$	Soil respiration temperature factor, slow pool	X	
τ_f	Fast pool soil carbon turnover time	X	
κ	Soil moisture dependence parameter	X	
f_s	Fraction of fast soil decomposition	X	
β	Net CO_2 sink factor		X

BETHY Plant Functional Types



Rayner et al. (2005)

CCDAS

- Iterative minimisation of the cost function

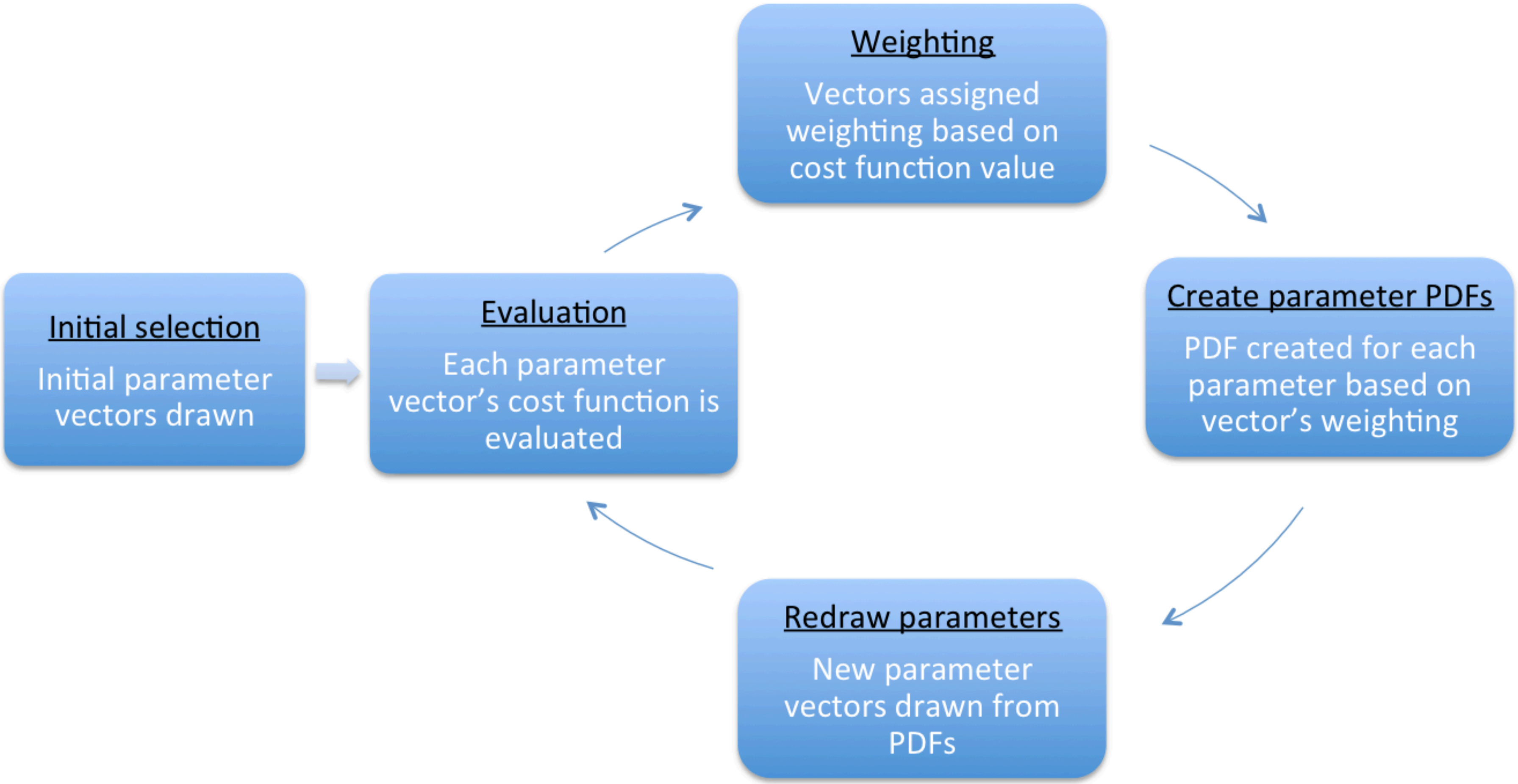
$$J(x)=\left((x-x_0)^T C_{x_0}^{-1}(x-x_0)\right)+\left(M(x)-c\right)^T C_c^{-1}\left(M(x)-c\right)$$

- Optimisation uses the gradient of J(**x**) with respect to the parameters
- Second order derivatives (Hessian) at minimum provide approximation of parameter uncertainties (a posteriori): $\mathbf{C}_{po}^{-1} = \partial^2 J(\mathbf{x}_{po}) / \partial \mathbf{x}^2$
- Uncertainties on target quantities (e.g. net flux, NEP) via linearisation of model (Jacobian matrix):

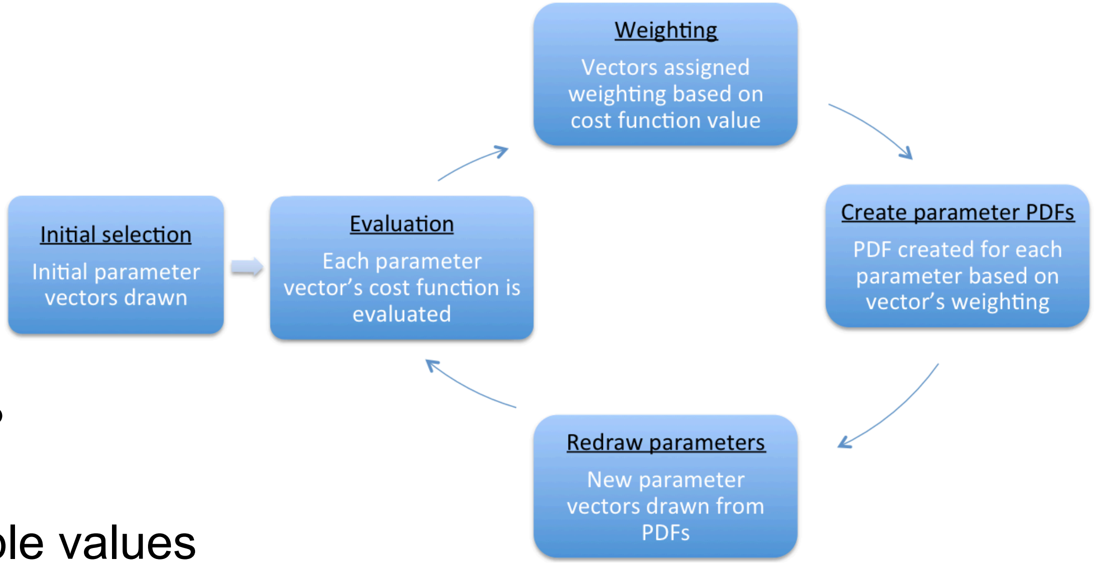
$$\mathbf{C}_{NEP} = \partial \mathbf{M}/ \partial \mathbf{x}\ \mathbf{C}_{po}\ \partial \mathbf{M}/ \partial \mathbf{x}^T$$

- All derivatives provided via automatic differentiation of model code (TAF)

Parameter estimation using a particle filter



Parameter estimation using a particle filter



1. Initial selection:

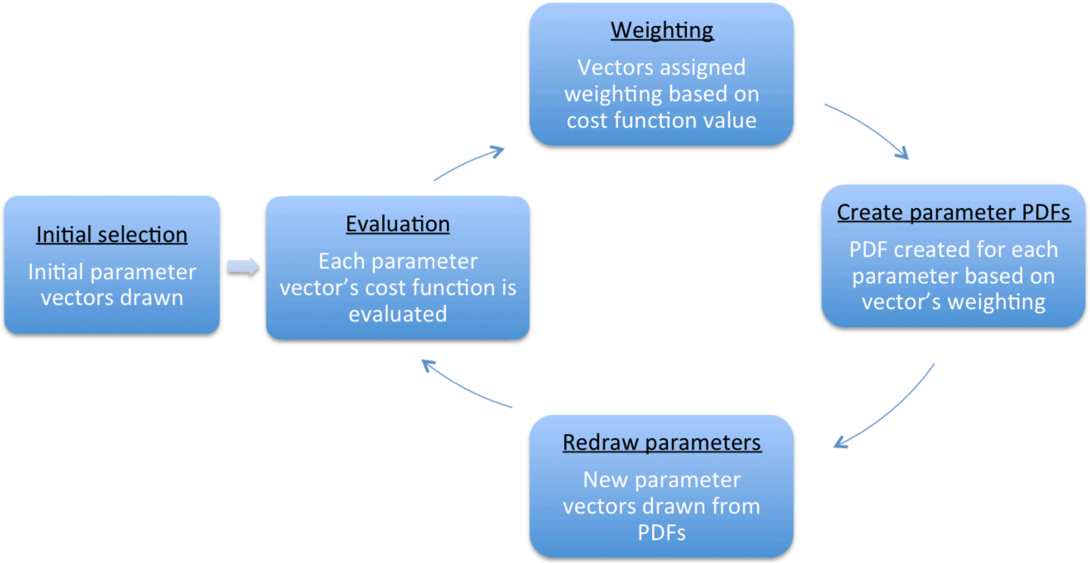
1. Uniform distribution
   - What to pick as limits?
2. Gaussian distribution
   - Physically unreasonable values

2. Evaluation:

Cost function is evaluated for each parameter

$$J(x) = \left(M(x) - c\right)^T C_c^{-1} \left(M(x) - c\right)$$

Parameter estimation using a particle filter



3. Weighting:

1. Gaussian:

$$w = \exp\left(-cf / cf_0\right)$$

2. Lorenz:

$$w = \frac{1}{1+cf}$$

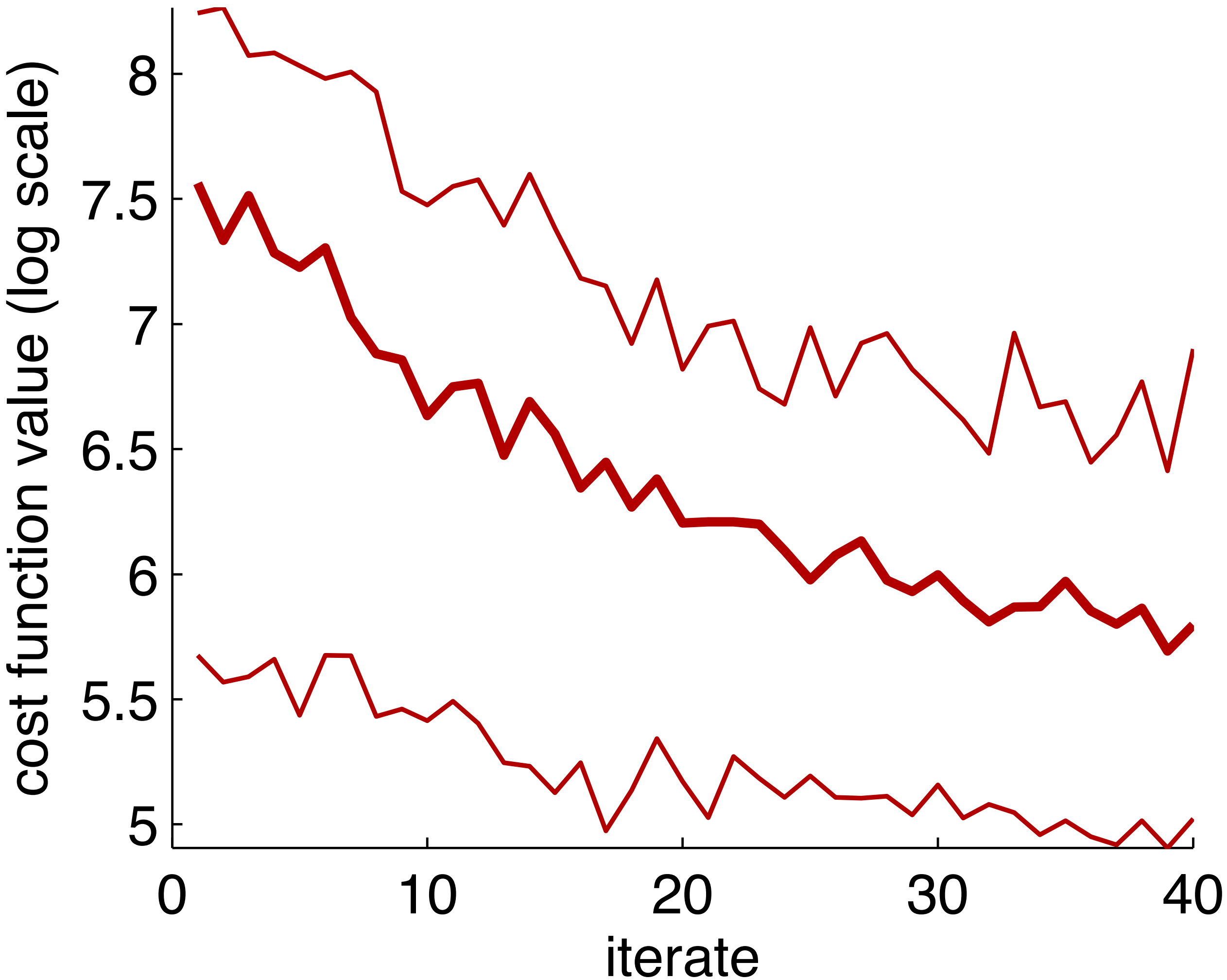
4. Create parameter pdfs:

1. Gaussian pdf
   - Weighted mean and weighted standard deviation
2. Constructed pdf
   - tricky

5. Redraw parameters:

Results

- 64 particles
- 40 iterations
- Gaussian initial sampling
- Gaussian resampling



Results

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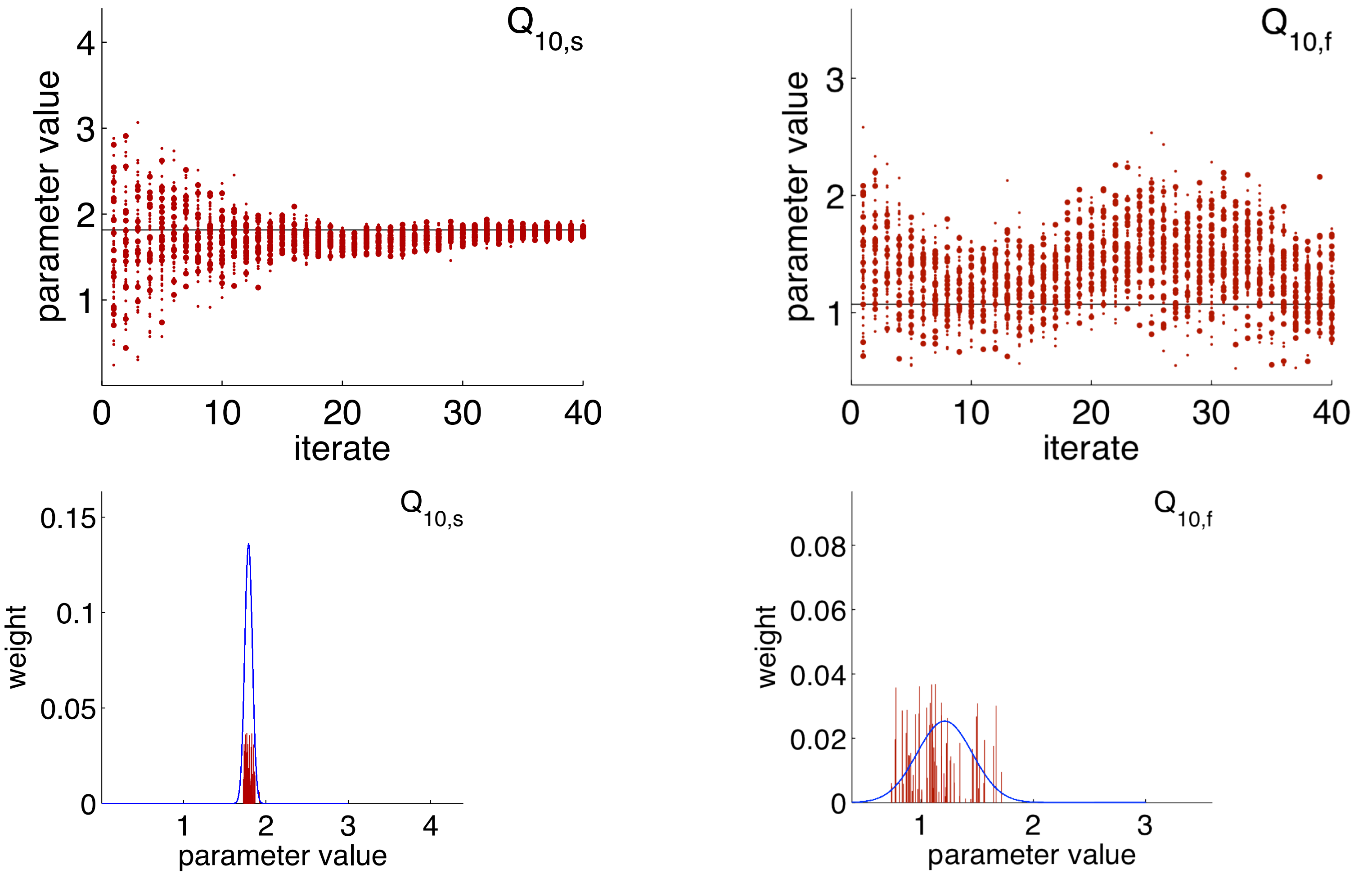


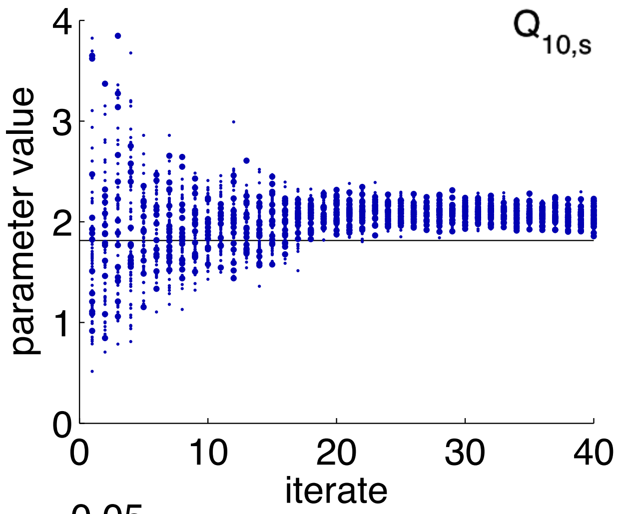
Parameter transformations

Perform the optimisation in a transformed parameter space, thus ensuring that when back-transformed the optimal parameter values are within the physically meaningful domain

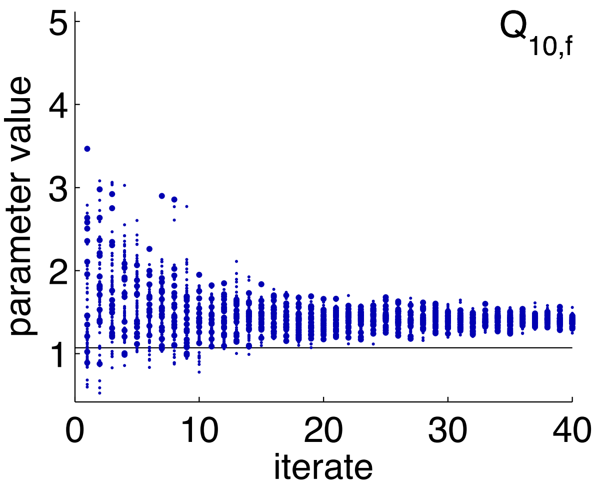
Different transformations:

- Log: limits parameters above a specified value
- Double bounded log: limits parameters between two values

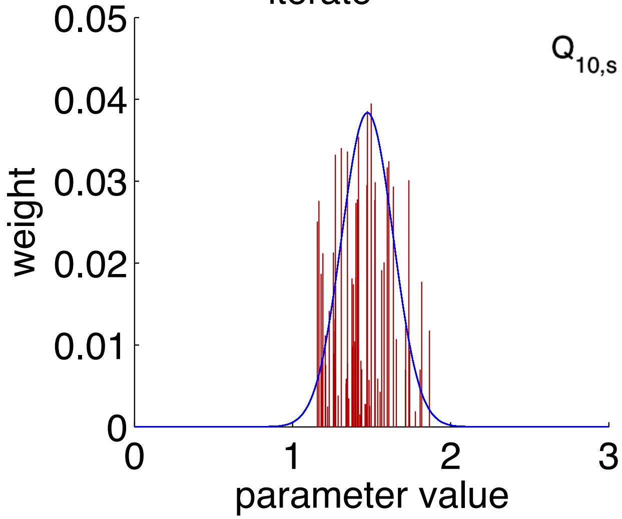
Results



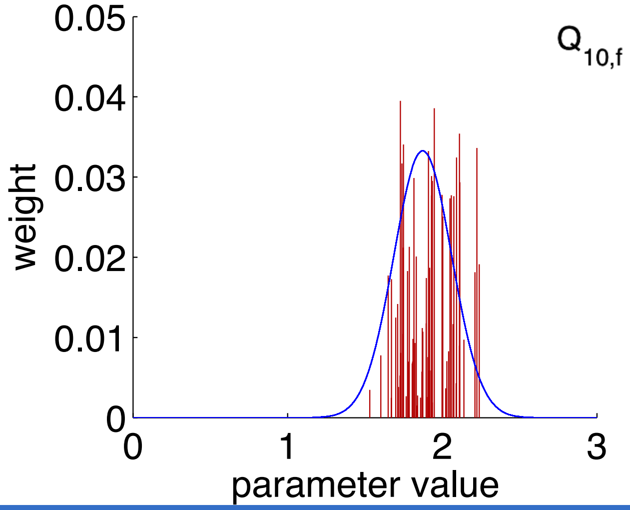
Q10,s
parameter value
iterate
0
10
20
30
40
1
2
3
4



Q10,f
parameter value
iterate
0
10
20
30
40
1
2
3
4
5



Q10,s
weight
parameter value
0
0.01
0.02
0.03
0.04
0.05
1
2
3



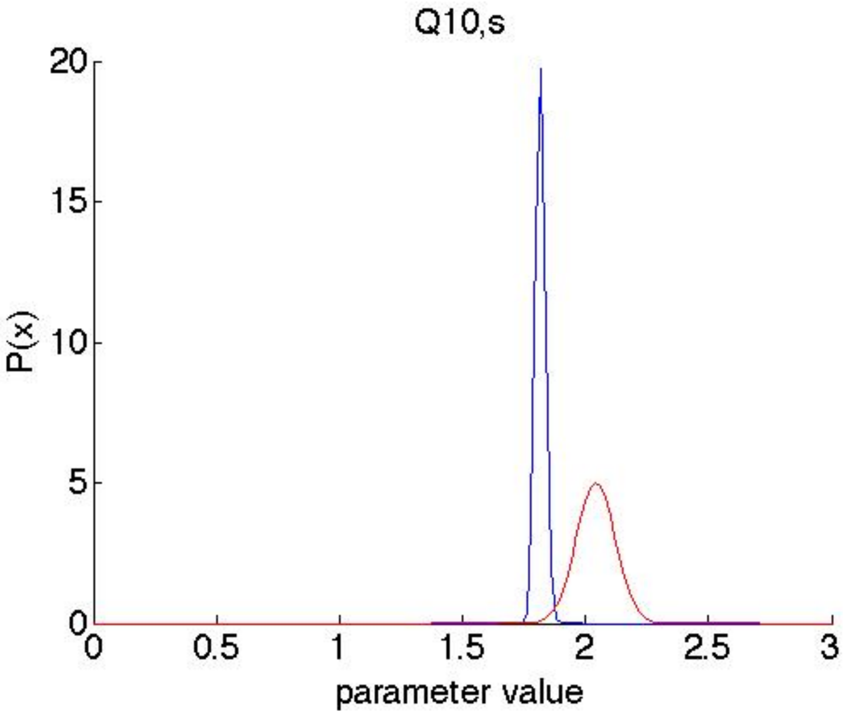
Q10,f
weight
parameter value
0
0.01
0.02
0.03
0.04
0.05
1
2
3

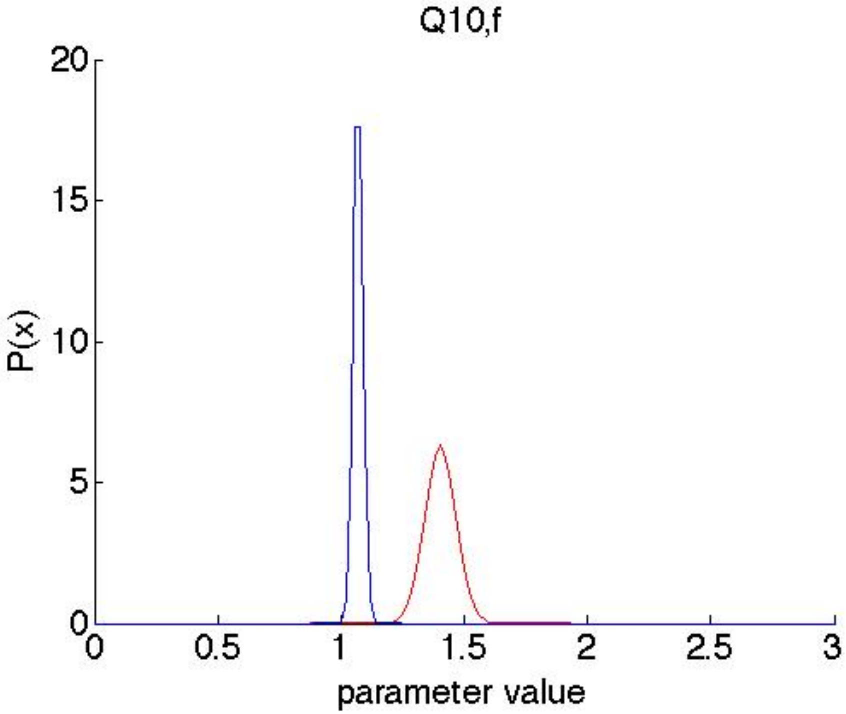
Comparison to CCDAS

	CCDAS	Particle Filter
Cost function Value	9667	17572

Parameter	Initial Value	CCDAS optimised value	Particle Filter optimised value	Initial uncertainty	CCDAS optimised uncertainty	Particle Filter weighted standard deviation
1 $Q_{10,f}$	1.5	1.069	1.40357865	0.75	0.016	0.063
2 $Q_{10,s}$	1.5	1.817	2.0419128	0.75	0.019	0.080
3 τ_f	1.5	3.435	12.8101455	3.0	0.120	1.146
4 κ	1	0.571	0.3050932	9.0	0.011	0.091
5 f_s	0.2	0.735	0.55894275	0.2	0.004	0.033

Comparison to CCDAS





CCDAS
Particle Filter

Conclusions

- Have set up a particle filter to estimate terrestrial carbon cycle parameters
- Have included parameter transformations to ensure physically meaningful optimal parameter values

Still need to

- Determine which set up provides the most consistent results
- Would like to have results closer to that of CCDAS