Using CCDAS for Integration: Questions and Ideas

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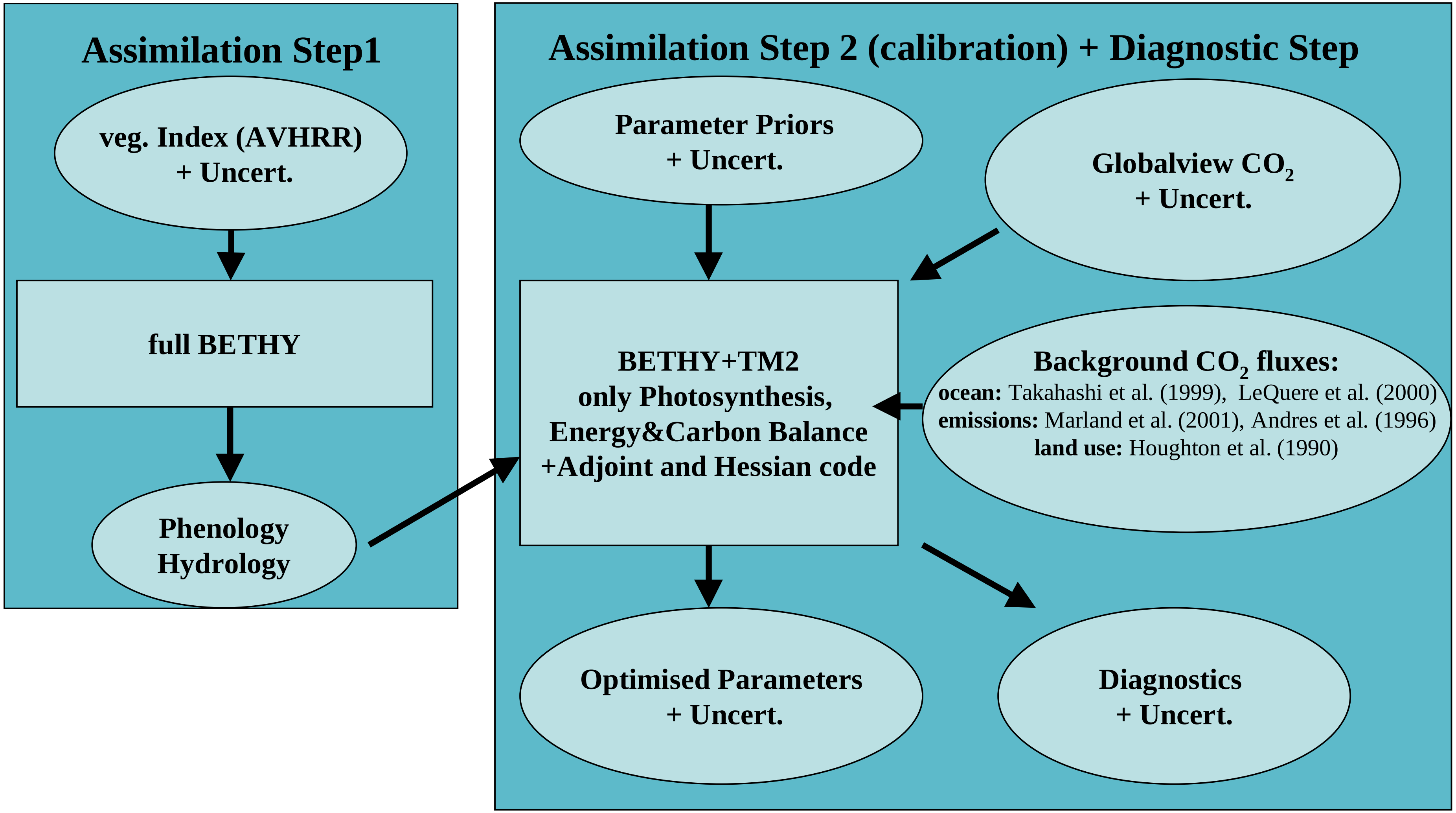
Overview

- More observations
- Efficient sensitivities of diagnostics
- More processes
- Many parameters
- Conclusions/Left-out issues

Carbon Cycle Data Assimilation System (CCDAS) current form



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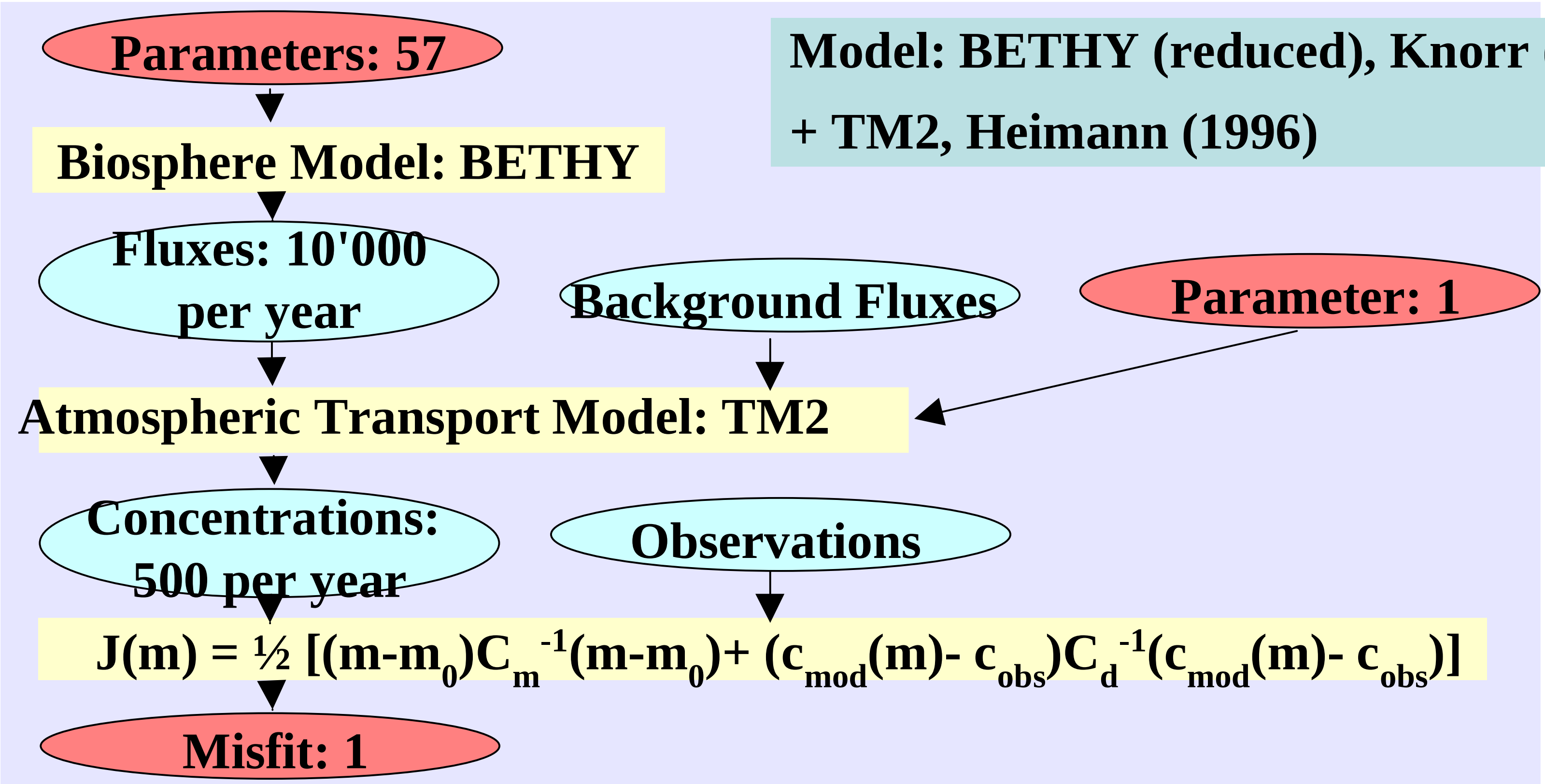
Calibration of biosphere model

within Carbon Cycle Data Assimilation System (CCDAS)

Model: BETHY (reduced), Knorr (2001)

+ TM2, Heimann (1996)



* **ocean:** Takahashi et al. (1999), LeQuere et al. (2000); **emissions:** Marland et al. (2001), Andres et al. (1996); **land use:** Houghton et al. (1990)

Adding more observations

within Carbon Cycle Data Assimilation System (CCDAS)

$$J(m) = \tfrac{1}{2}\,(m-m_0)C_m^{-1}(m-m_0)$$

$$+ \tfrac{1}{2}\,(c_{mod}(m)- c_{obs})C_c^{-1}(c_{mod}(m)- c_{obs})$$

$$+ \tfrac{1}{2}\,(f_{mod}(m)- f_{obs})C_f^{-1}(f_{mod}(m)- f_{obs})$$

$$+ \tfrac{1}{2}\,(I_{mod}(m)- I_{obs})C_I^{-1}(I_{mod}(m)- I_{obs})$$

$$+ \tfrac{1}{2}\,(R_{mod}(m)- R_{obs})C_R^{-1}(R_{mod}(m)- R_{obs})$$

$$+ \text{etc} \ldots$$

Flux Data

Inventories

Atmospheric Isotope Ratios

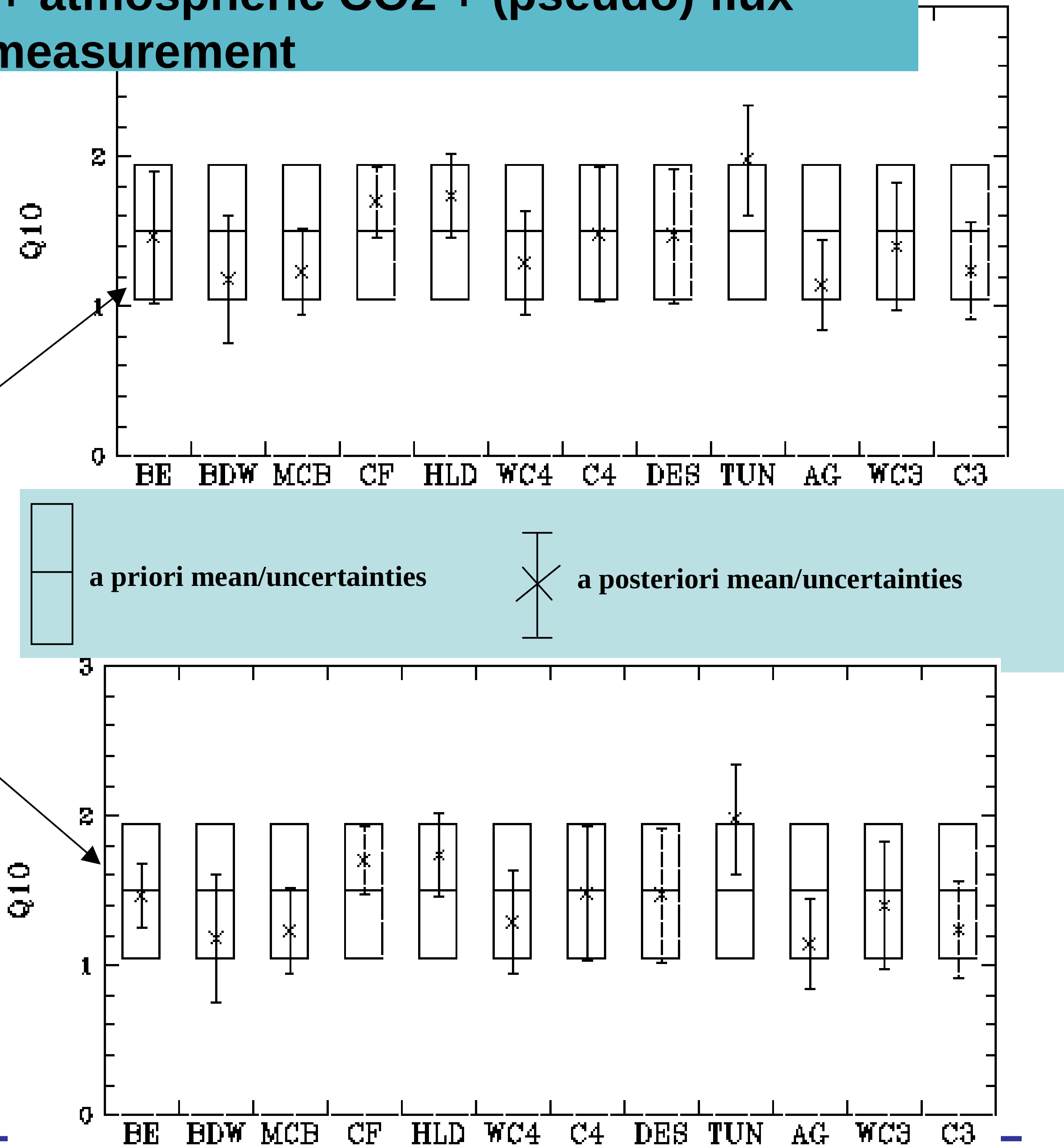
- Can add further constraints on any quantity that can be extracted from the model (possibly after extensions)
- Covariance matrices are crucial: Determine relative weights!
- Uses Gaussian assumption; can also use logarithm of quantity (lognormal distribution), ...

Example: A priori info + atmospheric CO2 + (pseudo) flux measurement

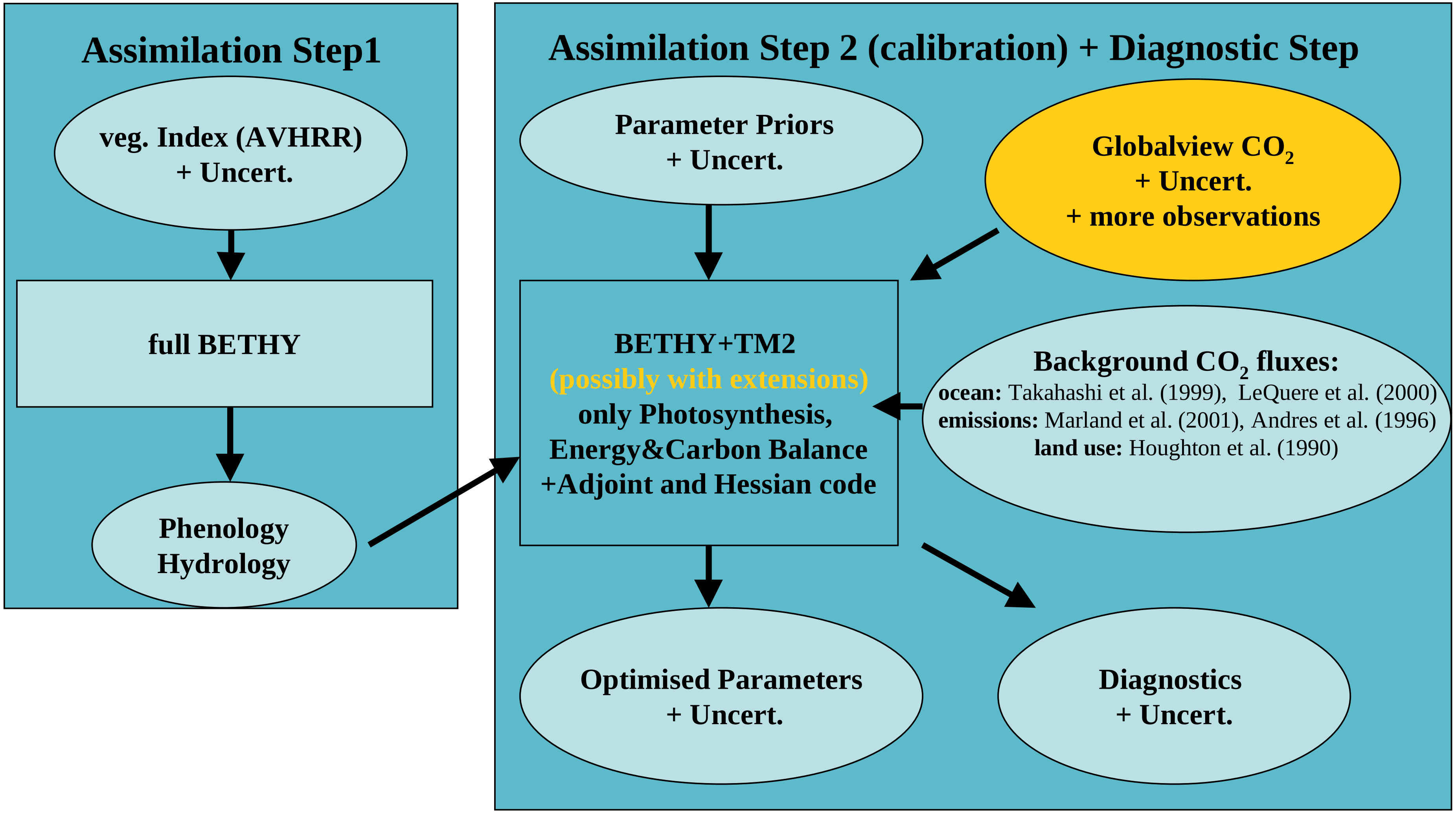
Comparison shows impact of a (pseudo) flux measurement in the broadleaf evergreen biome on Q10 estimated by an inversion of SDBM:

***Upper panel*:**
only concentration data

***Lower panel*:**
concentration data + pseudo flux measurement (mean: as predicted sigma: 10gC/m^2/year)



Carbon Cycle Data Assimilation System (CCDAS) with more observations



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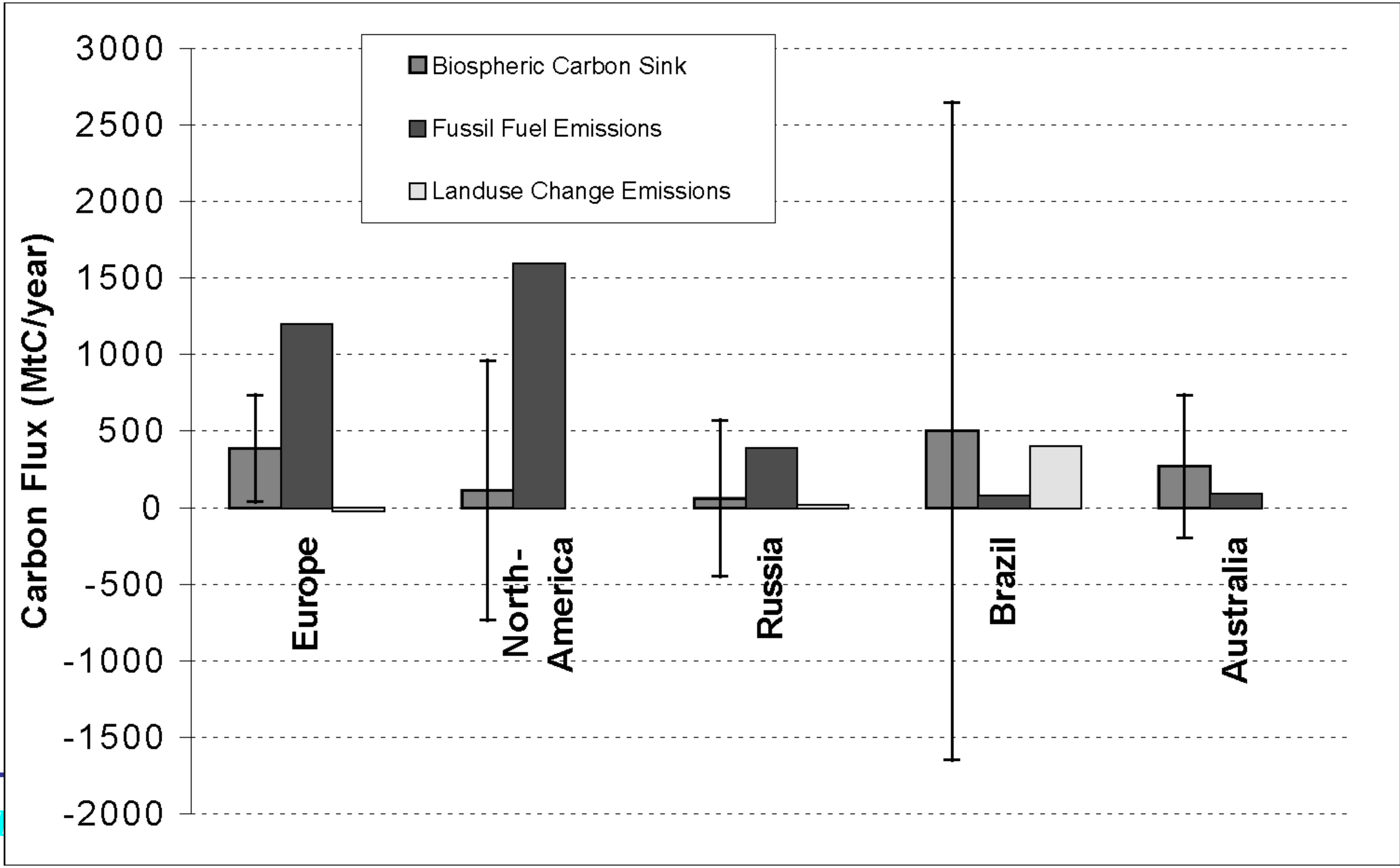
Typical Diagnostics

Regional Net Carbon Balance and Uncertainties



Sensitivity of diagnostics?

- How do diagnostics change, when some of the input is modified, e.g. background fluxes: fossil fuel emissions, ocean fluxes

- Standard approach would be a new CCDAS run with modified input
- Optimisation is iterative procedure using, say, 100 runs of model and adjoint

- Efficient alternative for modified parameters via implicit function theorem (second order adjoint, Le Dimet et al. 2002)
  Optimisation for input field b yields optimal parameters x satisfying:

$$(d/dx)\ J(x,b) = 0$$

  This defines x as an implicit function of input field b, i.e. x(b) AND the sensitivity of the optimal parameters w.r.t. input field, dx/db is:

$$(d/dx)\ [(d/dx)\ J(x(b),b)]\ dx/db + (d/db)\ [(d/dx)\ J(x,b)] = 0$$

Sensitivity of diagnostics?

- The sensitivity of the optimal parameters w.r.t. input field, db/dx is:

$$(d/dx)\,[(d/dx)\,J(x(b),b)]\,dx/db + (d/db)\,[(d/dx)\,J(x(b),b)] = 0$$

- Sensitivity dx/db takes observational constraint into account

- To solve for dx/db, second derivative code required for
  (d/dx) [(d/dx) J(x(b),b)] : Hessian (is computed by CCDAS anyway)
  (d/db) [(d/dx) J(x(b),b)] : Has to be generated and evaluated

- Parameter sensitivity dx/db to be multiplied by diagnostic sensitivity df/dx:

$$df/db = df/dx\ dx/db$$

- Approach to be demonstrated within CarboOcean with:
  f : European budget
  b: ocean fluxes on 8 by 10 global map
  Deliver sensitivity maps to support design of observation system;
  indicate ocean regions with high impact on European balance

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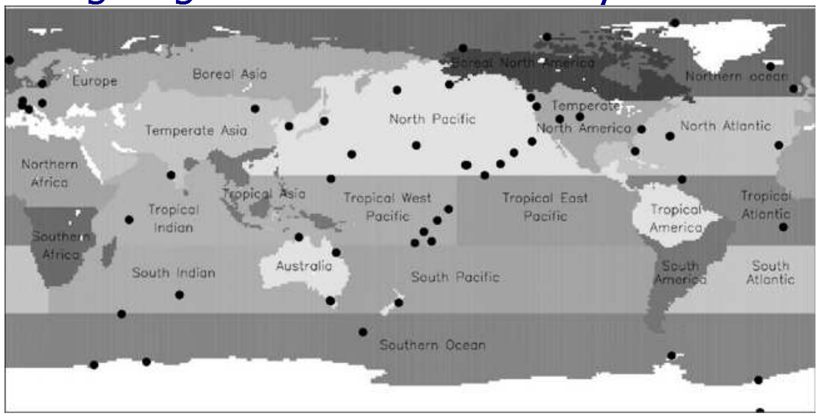
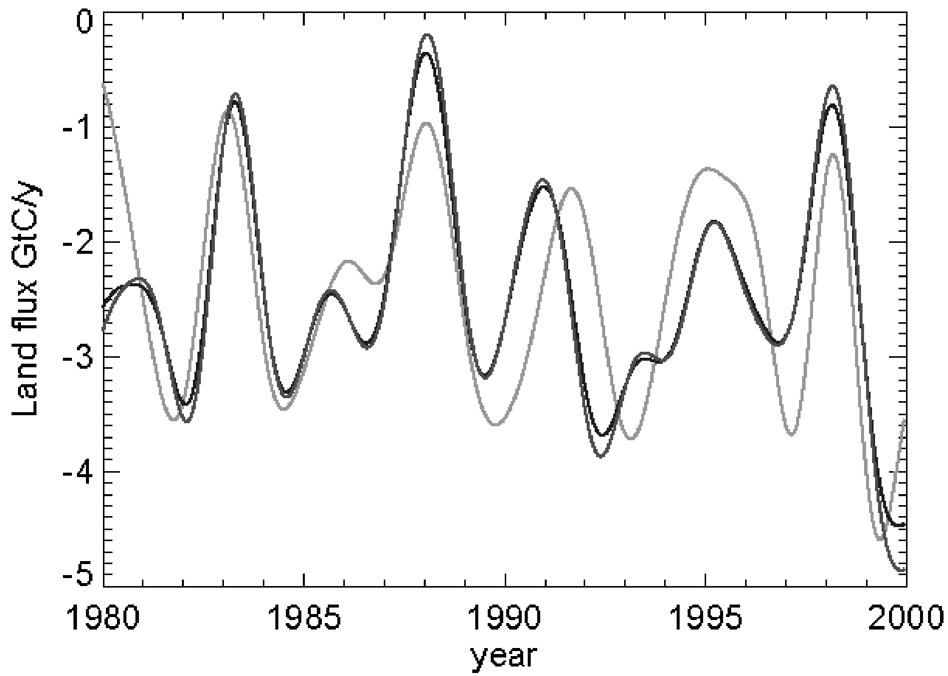
Including the ocean

- A 1 GtC/month pulse lasting for three months is used as a basis function for the optimisation
- Oceans are divided into the 11 TransCom-3 regions
- That means: 11 regions * 12 months * 21 yr / 3 months = 924 additional parameters
- Test case:
  - all 924 parameters have a prior of 0. (assuming that our background ocean flux is correct)
  - each pulse has an uncertainty of 0.1 GtC/month giving an annual uncertainty of ~2 GtC for the total ocean flux

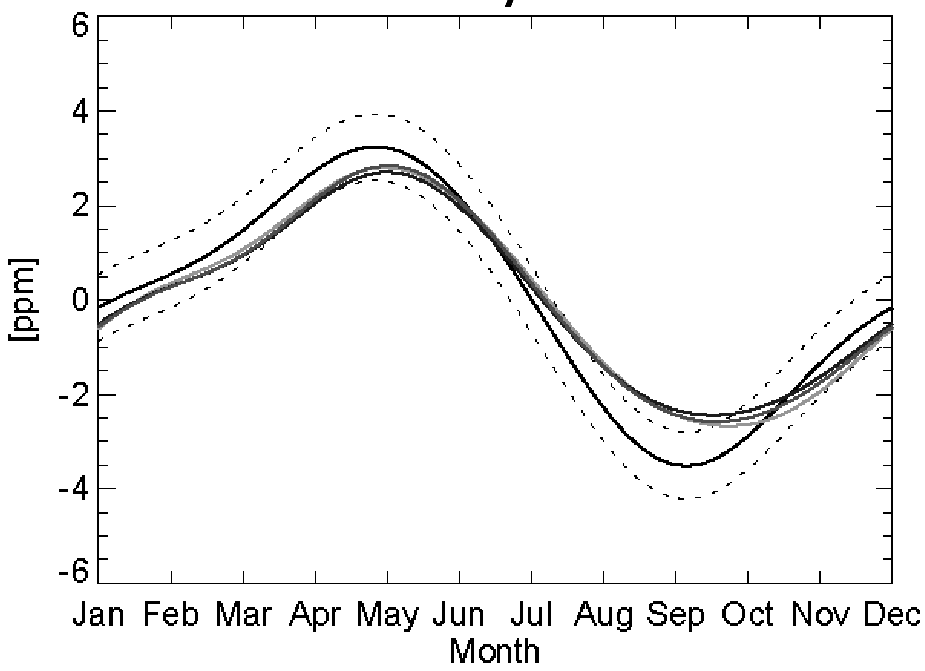


Including the ocean

Global land flux



Seasonality at MLO



Observations

High resolution standard model

Low resolution model

Low-res incl. ocean basis functions

Extending the model

- Study uses extremely simplified form of an ocean model:

  flux(x,t) = Σ coefficient(i) * pattern(i,x,t)

- Optimising coefficients for biosphere patterns
  allows the optimisation to compensate for errors (missing processes) in BETHY
  (weak constraint 4DVar, see ,e.g., Zupanski (1993))

- It is preferable to include a process model.
- Candidates: fire, marine biogeochemistry, ...

- Also: Improvement of BETHY: More sophisticated soil model
  or Transport Model: TM2 -> TM3, interannual winds, higher resolution...

Extending the model: Spin-up

- CCDAS uses a ß-factor as PFT-specific parameter; determines net flux:

  average NPP = ß (average soil respiration)

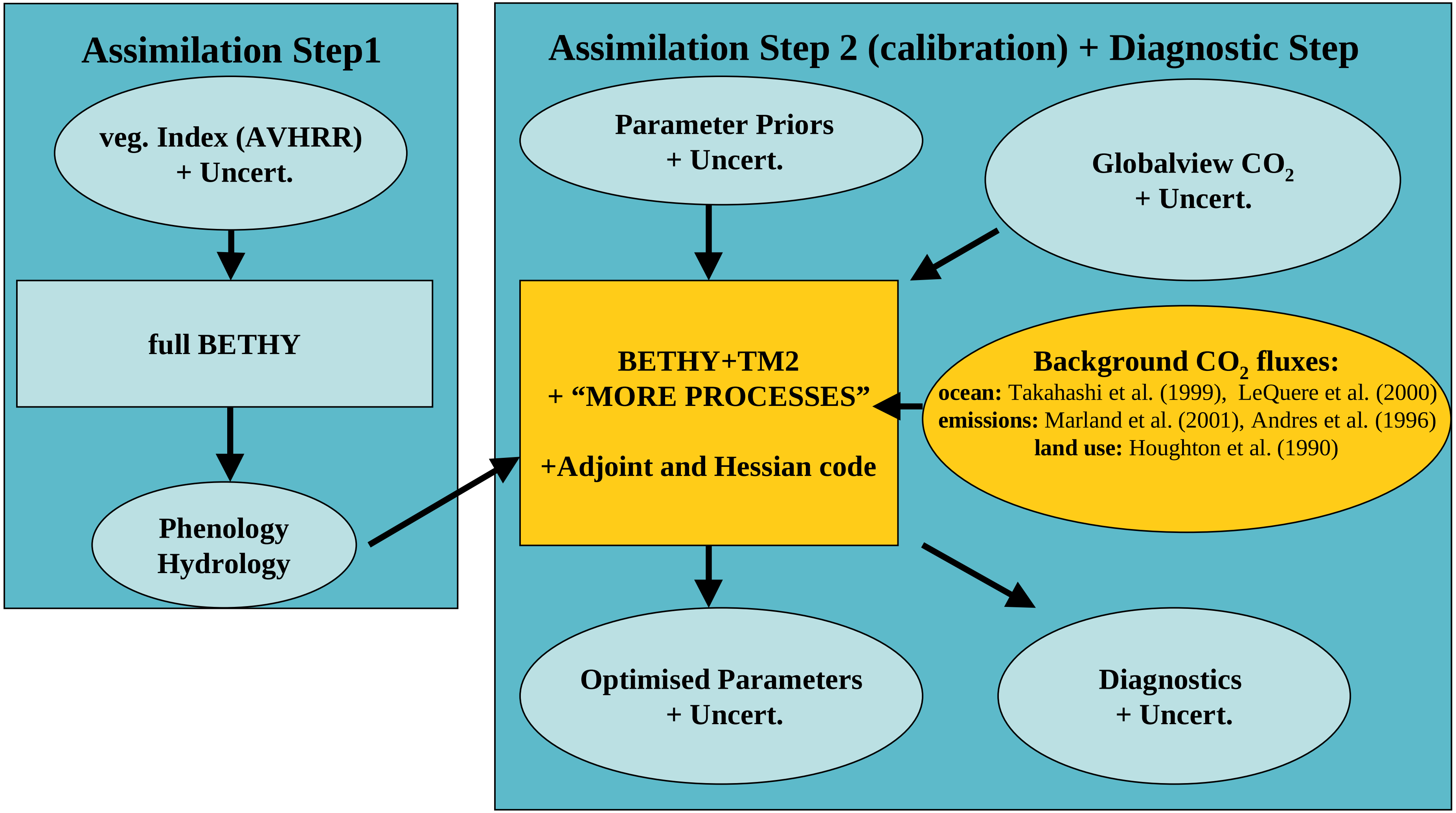
- ß avoids spin-up of slow carbon pool, with all the complications involved
- Alternative model-formulation may require a spin-up of several 1000 years
- Parameter sensitivities need to take account of spin-up period
- Simplest way is to run the adjoint through the spin-up
- Alternative way via implicit function theorem for final year of spin up:

  s = model (s, x)   s: equilibrium state; x: parameters

  ds/dx = d (model)/ds ds/dx + d(model)/dx

- Need to compute d(model)/ds and d(model)/dx only for final iteration
- Concept demonstrated for spin-up of box model of atmospheric transport (LNCS, submitted, see http://FastOpt.com)

Carbon Cycle Data Assimilation System (CCDAS) with more processes



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Handing of many parameters

- CCDAS setup including the ocean patterns has about 1000 parameters
- A higher level of parameter regionalisation in the standard set-up (on to-do list) will also increase number of parameters

- Adjoint optimisation can handle many parameters (NWP/Oceanography: millions of unknowns)

- Standard set-up of CCDAS computes full Hessian matrix to infer covariance of parameter uncertainties (57 x 57 matrix)
- For many-parameter set-ups, computation and inversion of Hessian expensive
- But: full covariance matrix of parameter uncertainties is not needed
- Need only uncertainties in 'interesting directions', e.g. the direction that projects on European budget
- Must devise and implement efficient (matrix-free) algorithm for uncertainty propagation that focuses on 'interesting directions'
  Is also useful for traditional flux inversions when Jacobian is too large to compute (continuous measurements, satellite CO2)

Conclusions

- CCDAS
  is a prototype
  can be extended to assimilate more observations (and quantify their impact)
  can be extended by more processes (and deliver their optimal parameters)
  can be used in prediction mode
  can support observation-system design
  is based on modern software (Fortran 95)
  looks well-suited as tool for integration

- Indicated a few technical issues:
  Uncertainties without full Hessian
  efficient sensitivity to input quantities
  spin up

- Some of the issues not addressed:
  Prior estimates for parameters and uncertainties crucial -> Jens Kattge @ Jena
  Two-step procedure sub-optimal (information from the second step missing in the first)
  Relies on a single TEM: do test and compare different formulations
  but cannot not quantify uncertainty via differences among TEMs
  (as Transcom for atm. transport) -> Marko Scholze @ Bristol

- More info, papers, etc: http://CCDAS.org, http://FastOpt.com