On the challenges of developing a mass conserving system model

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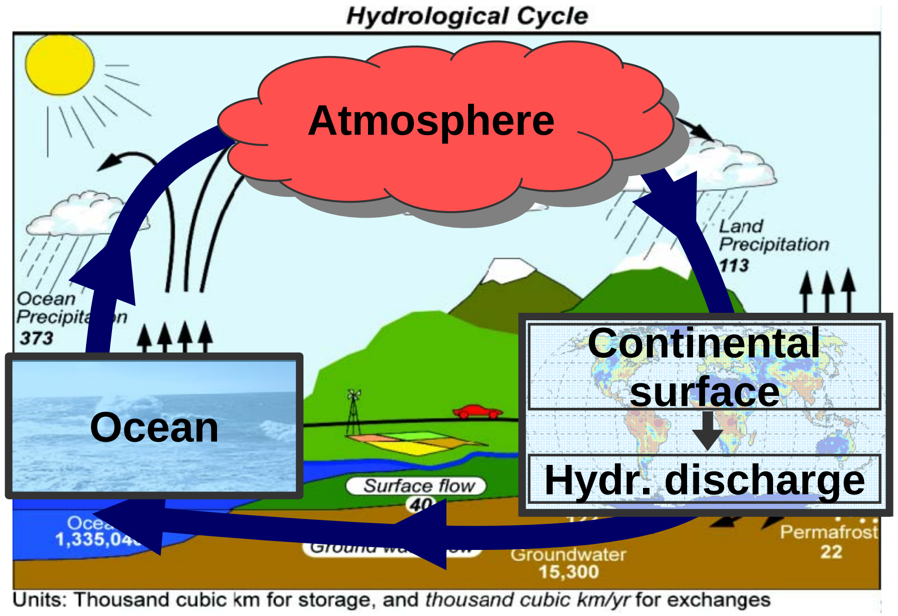
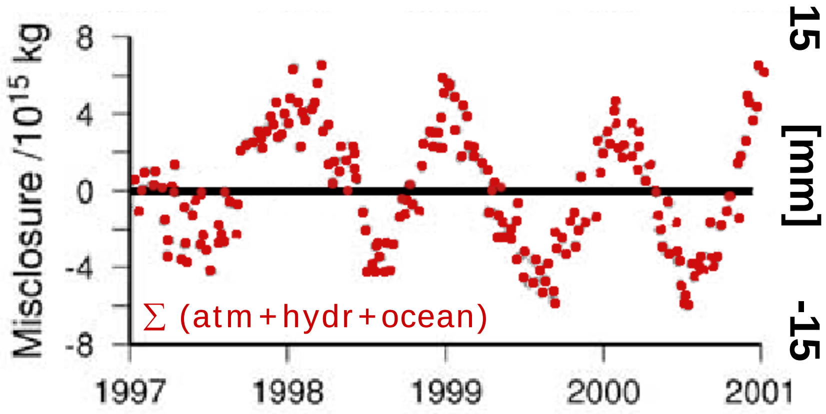
Conservation of total mass



(Trenberth et al., 2007)



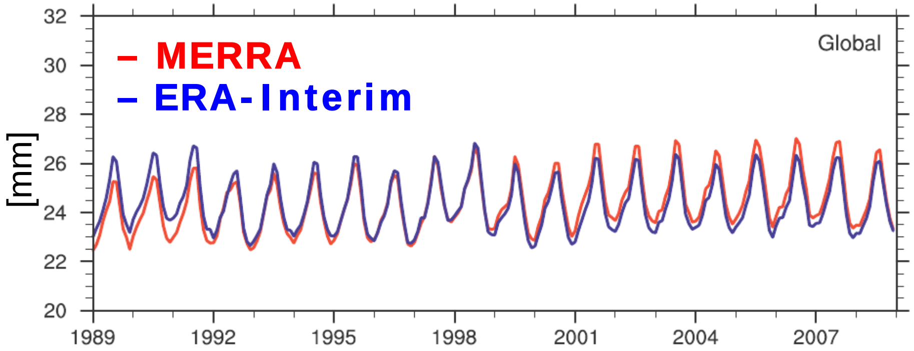
(Clarke et al., 2005)

- Assumption: mass = water mass
- Is total mass conserved by models?
- How large is the error in the total mass budget?

⇨ Substantial error in the mass budget

- How to deal with the misfit?
- How large is the error in individual subsystems?
- What is the reason for the error?
- Are the fluxes reasonable and physically consistent?

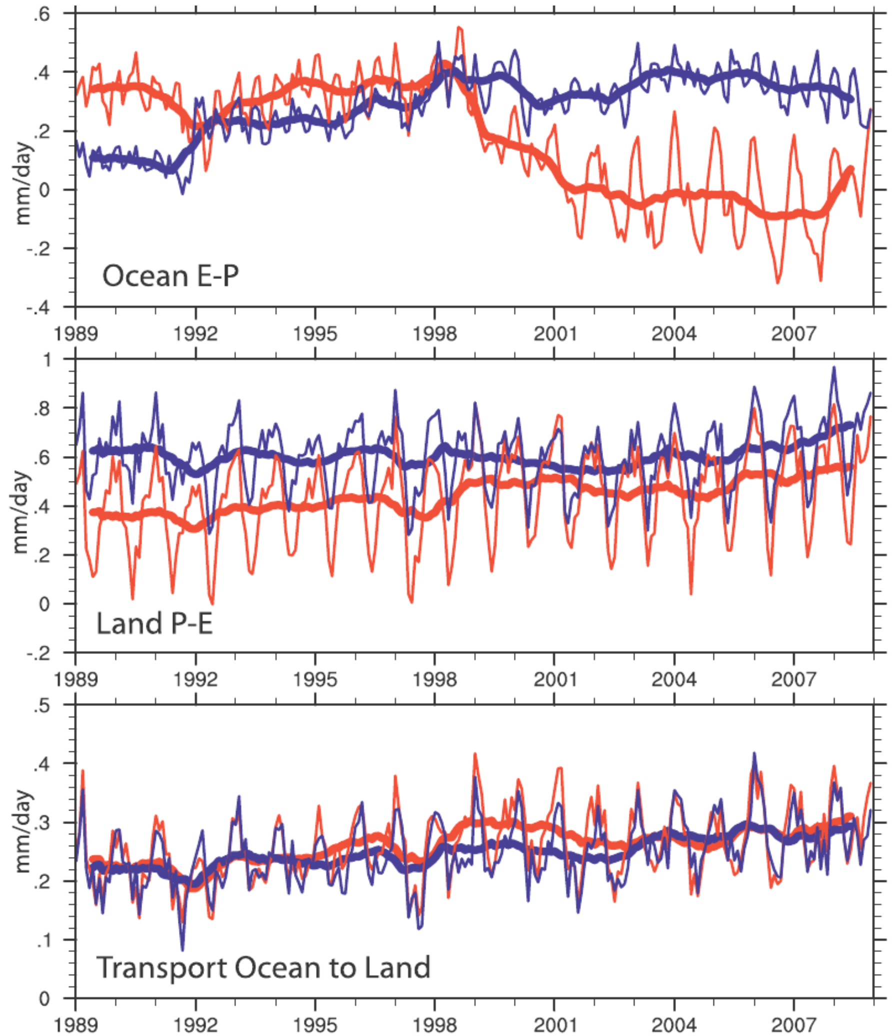
Atmospheric mass



total atmospheric water content (vapor, liquid, ice)

- Total atmospheric water storage is small
- Decadal variability is very small
  - E-P over ocean should equal P-E over land and …
  - … should equal the atmospheric ocean to land transport

(Both is generally not fulfilled!)



(Trenberth et al., 2011)

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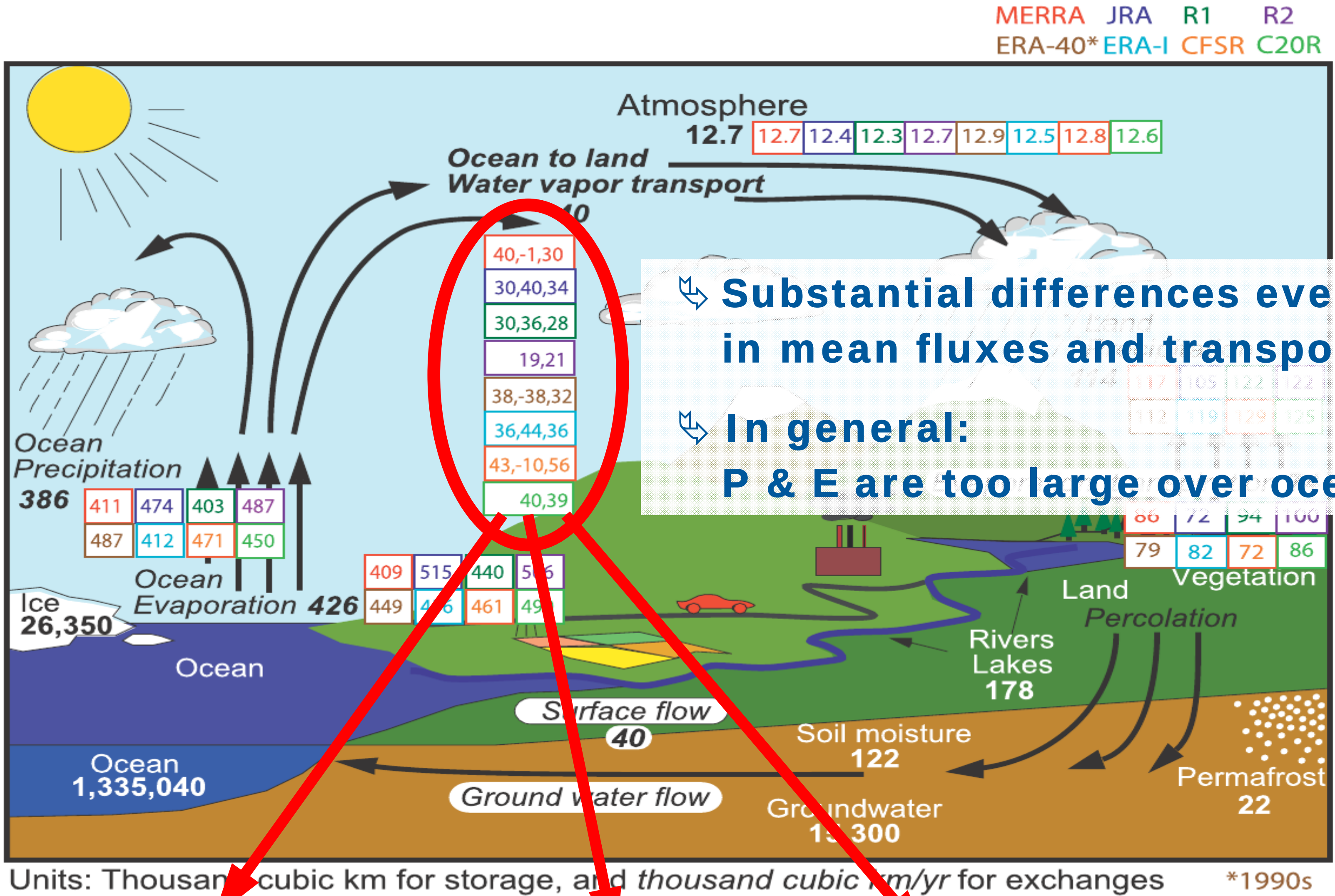
Atmospheric mass fluxes from 8 re-analyses



(Trenberth et al., 2011)

- Substantial differences even in mean fluxes and transports!
- In general:
  P & E are too large over oceans

atmospheric ocean to land transport

E-P from ocean

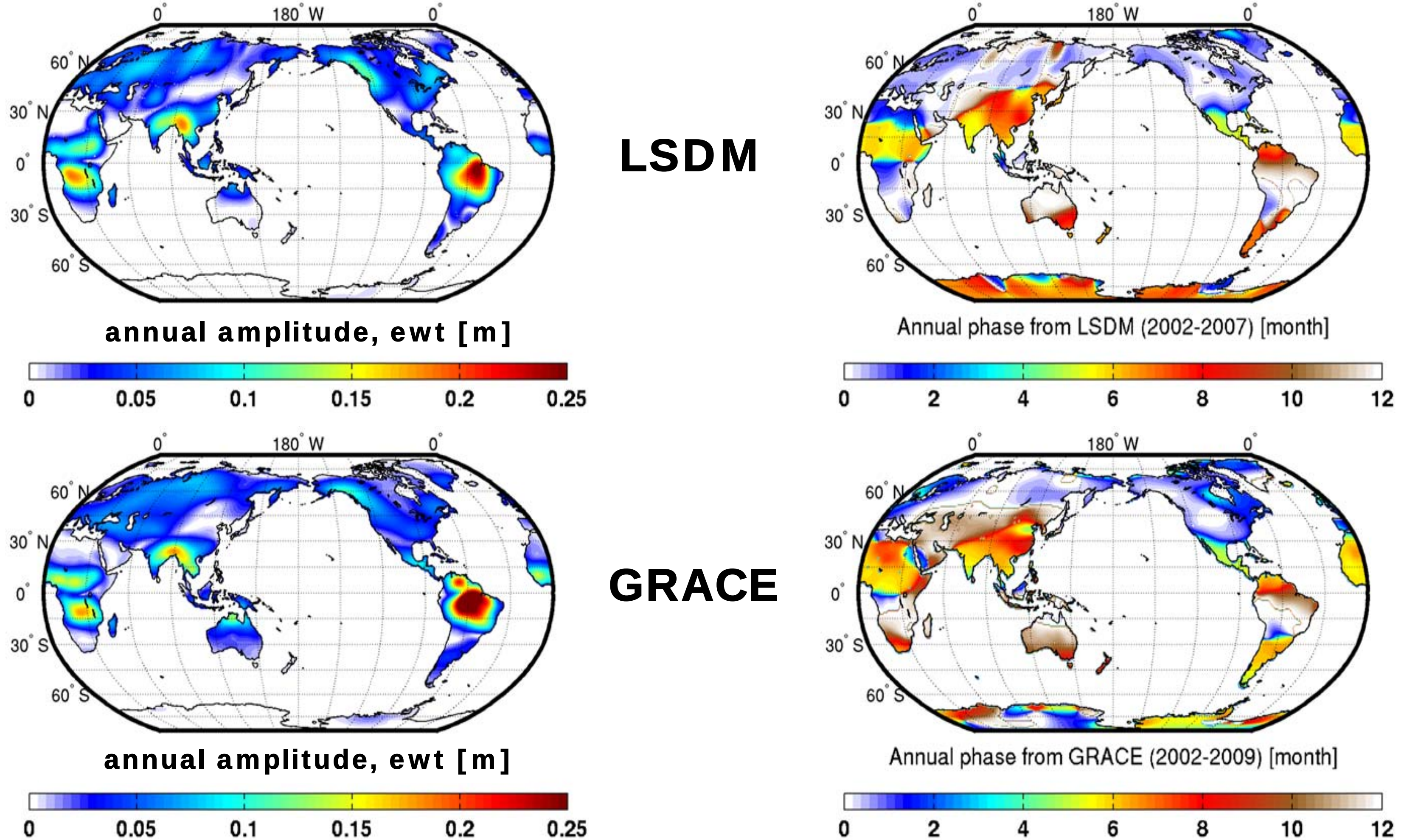
P-E from land

Atmospheric mass: Problems & solutions

- Due to insufficient absorption (clouds) too much heat propagates to the surface
  ↳ improve cloud/absorption modelling
- Main problem of re-analyses: Analysis increment (*"jumps"*)
  ↳ "*improve*" modelling (smaller misfit → smaller increments)
  ↳ avoid jumps by forward modelling (realistic vs. mass conserving run)
  ↳ demand mass consistent assimilation (e.g., apply mass conservation as constraint and/or exclude water vapour from the control vector)
- Anthropogenic effects not included (e.g., transient CO2 concentration)
  ↳ include
- Precipitation and evaporation are only diagnosed and have no effect on simulated atmospheric water content
  ↳ consideration of feedback mechanisms
  ↳ consistent P & E calculation via water vapour divergences???
  ↳ force mass conservation (like in ocean models)

Continental water storage

from hydrological discharge model LSDM (P-E from ECMWFop) and GRACE



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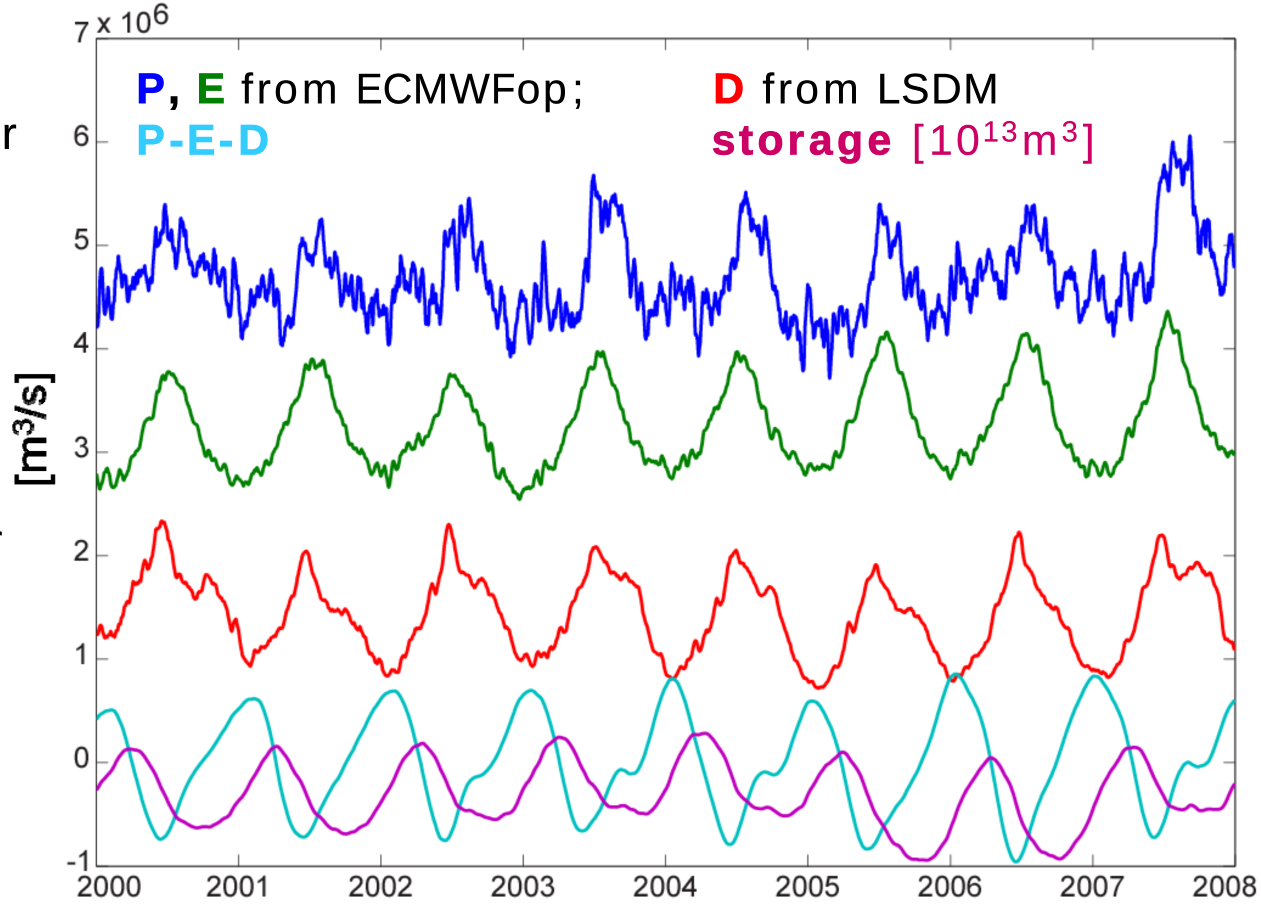
Continental water storage

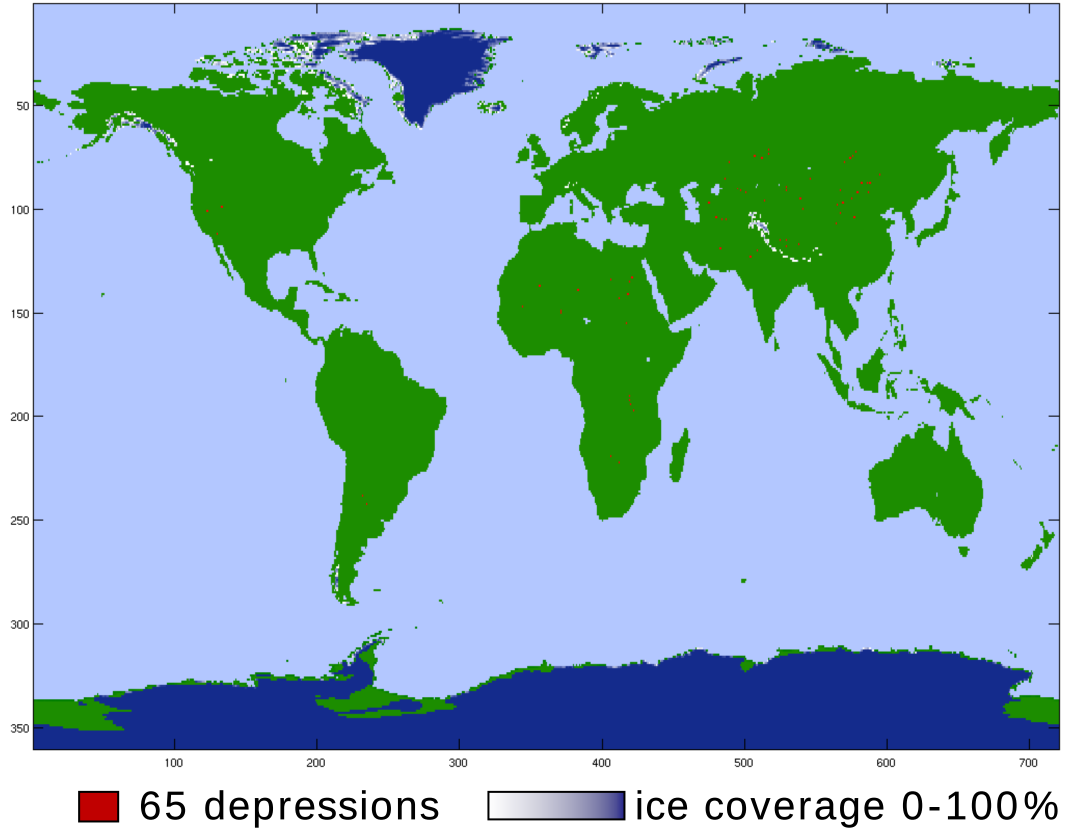
- good agreement of simulated (LSDM) and observed (GRACE) water storage variations
- annual variations dominate
- amplitudes in models "prescribed" by atmospheric freshwater fluxes
- model phases primarily determined by internal processes (snow melt, retention factors, ...)



Continental water storage

- land-ocean mask affects freshwater fluxes P, E, D
  ↳ use a consistent mask in all sub-systems
- most hydr. models do not include continental ice surfaces (Greenland, Antarctica)
  ↳ include land-ice model
- in general:
  T, P from re-analyses,
  E from internal calculation
  ↳ P, E inconsistent!
- water excess in topographic depressions
  ↳ routing to ocean (nearest coast grid cell)

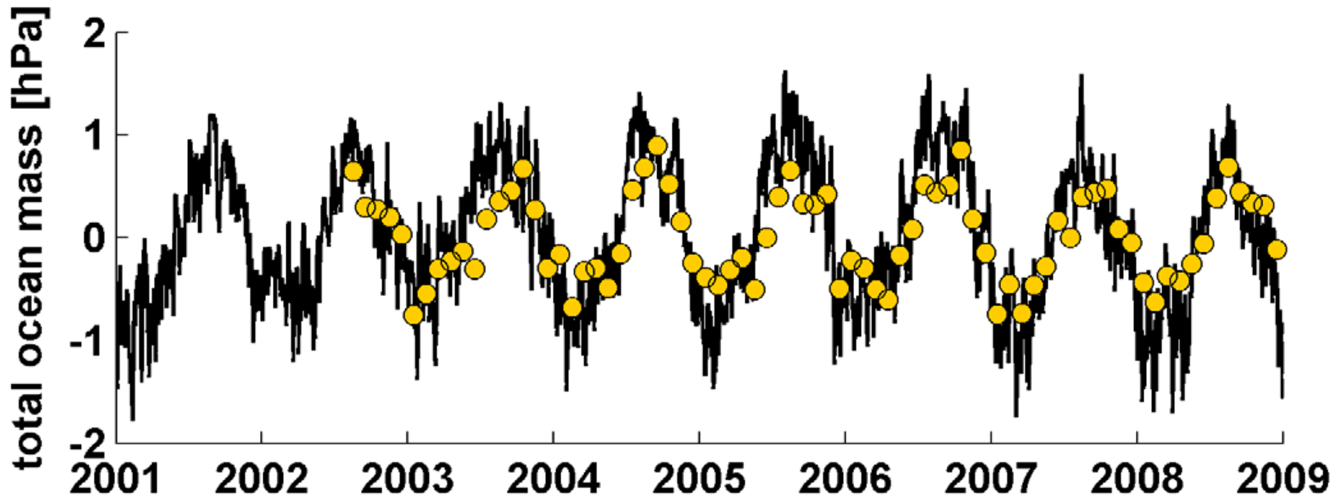
Example: Land Surface Discharge Model (LSDM, 0.5°x0.5°)



Variations of total ocean mass

OMCT model simulation

GRACE GFZ RL04, AOD1B restored, annual geocentre (Eanes, 2000), area filter (Swenson et al., 2003)



- total ocean mass from GRACE & ECMWF+HDM+OMCT
- cryospheric mass fluxes neglected
- linear trends removed

Mass conservation & freshwater fluxes in ocean models

continuity equation

$$\frac{1}{\rho}\frac{d\rho}{dt} + \vec{\nabla} \cdot \vec{v} = 0 \quad \text{(mass conservation)}$$

degenerates in z-models to

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad \text{(volume conservation)}$$

Greatbatch [1994]: correction $\delta\bar{\zeta}(t) = -\frac{1}{O}\int_V \frac{\delta\rho}{\rho_0} dV$

$$\Rightarrow m = \text{const}$$

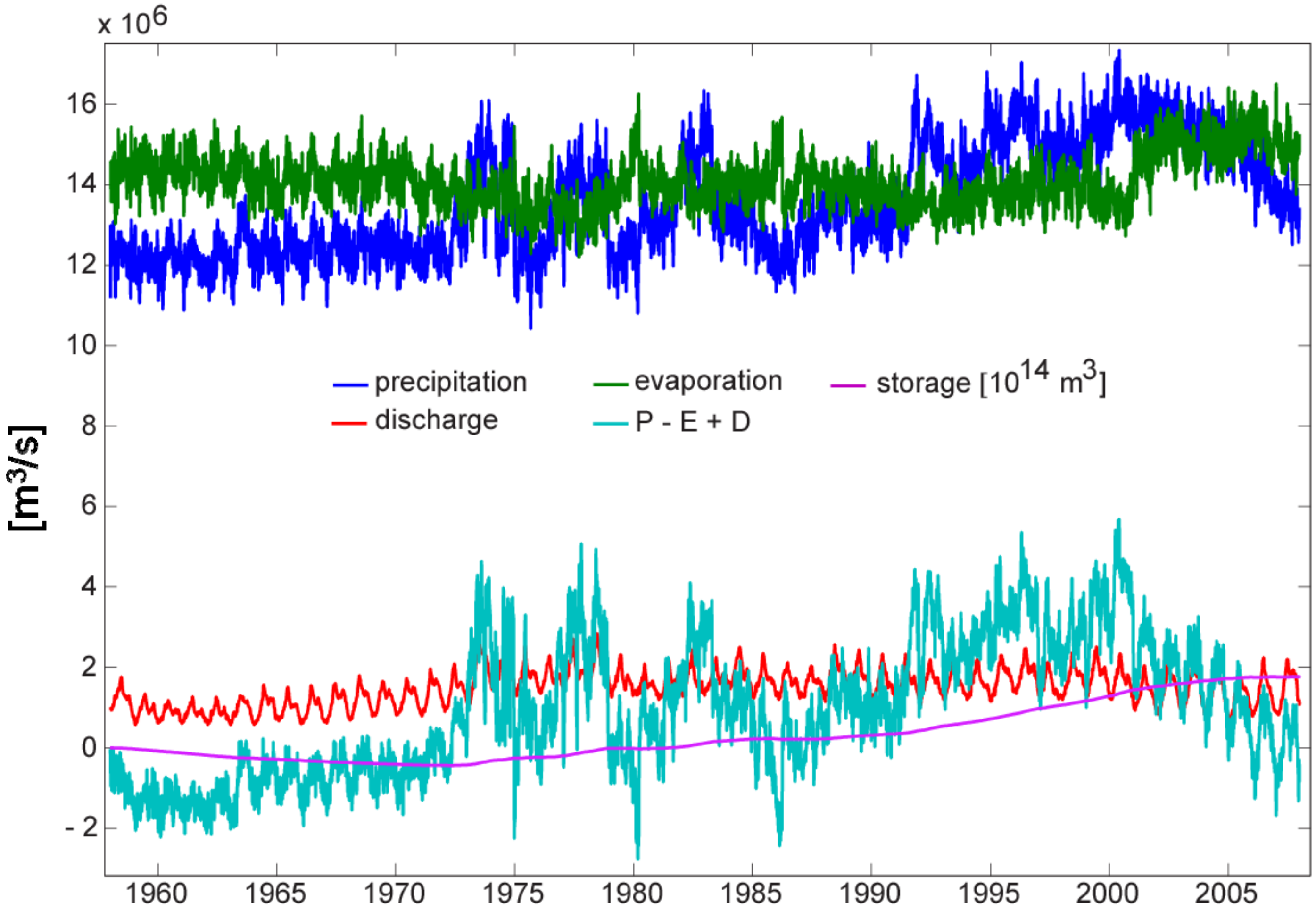
Ocean mass

- **Precipitation**
  (ECMWF)
  409 10^{12} m^3/y

- **Evaporation**
  (ECMWF)
  441 10^{12} m^3/y

- **Discharge**
  (LSDM)
  38 10^{12} m^3/y

- **P-E+D > 0**
  (6 10^{12} m^3/y
  ≈ +1cm/year



Mass conservation & freshwater fluxes in ocean models

consideration of freshwater fluxes

$$\boxed{m(t) = m_0 + \rho_{FW} \int_O (P - E + D)\, dO + \ldots}$$

with precipitation (P), evaporation (E) from re-analyses; continental FW fluxes (D) from hydrological models

↳ additional boundary condition required:

a) $m \neq f(t) \Rightarrow m = const$

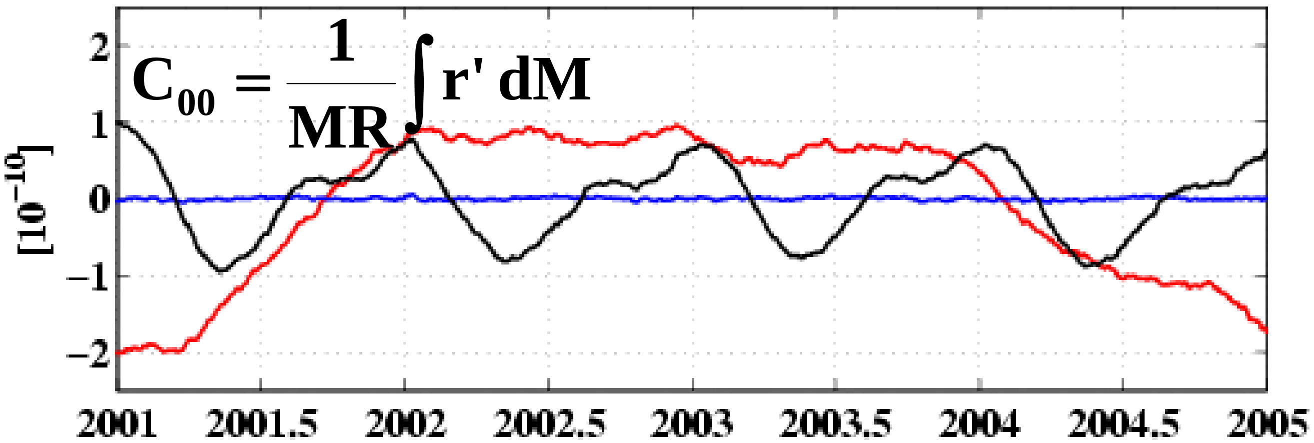
b) $\int_T \int_O (P - E + D)\, dO\, dt = 0 \Rightarrow T = ?$

Mass conservation & freshwater fluxes

Impact of various boundary conditions on oceanic mass distributions

↳ control runs:

1) volume conservation (**V=const**)
2) mass conservation over the period 2001-2004 (**M=const, T=4yr**)
3) “instantaneous“ mass conservation (**M=const, instant.**)



V=const

M=const (T=4yr)

M=const (instant.)

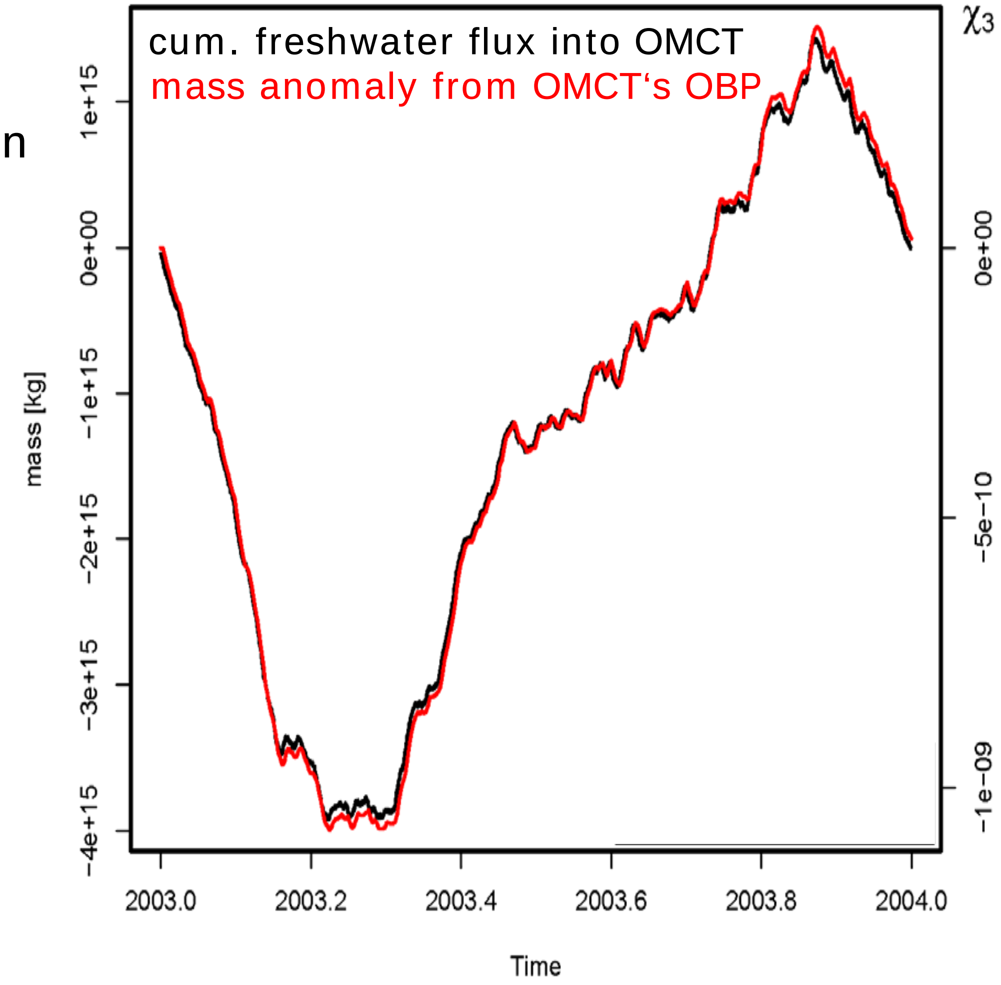
thermohaline, wind-, and pressure driven circulation

Ocean mass

- In ocean models mass conservation can be easily enforced by applying correction approaches (e.g., “Greatbatch”)

- Prescribed surface fluxes cause (un-)realistic ocean mass variations
  ↳ problem: definition of $\int_T \dots \, dt$

- Evaporation can also be diagnosed from the ocean model



Mass balance approaches

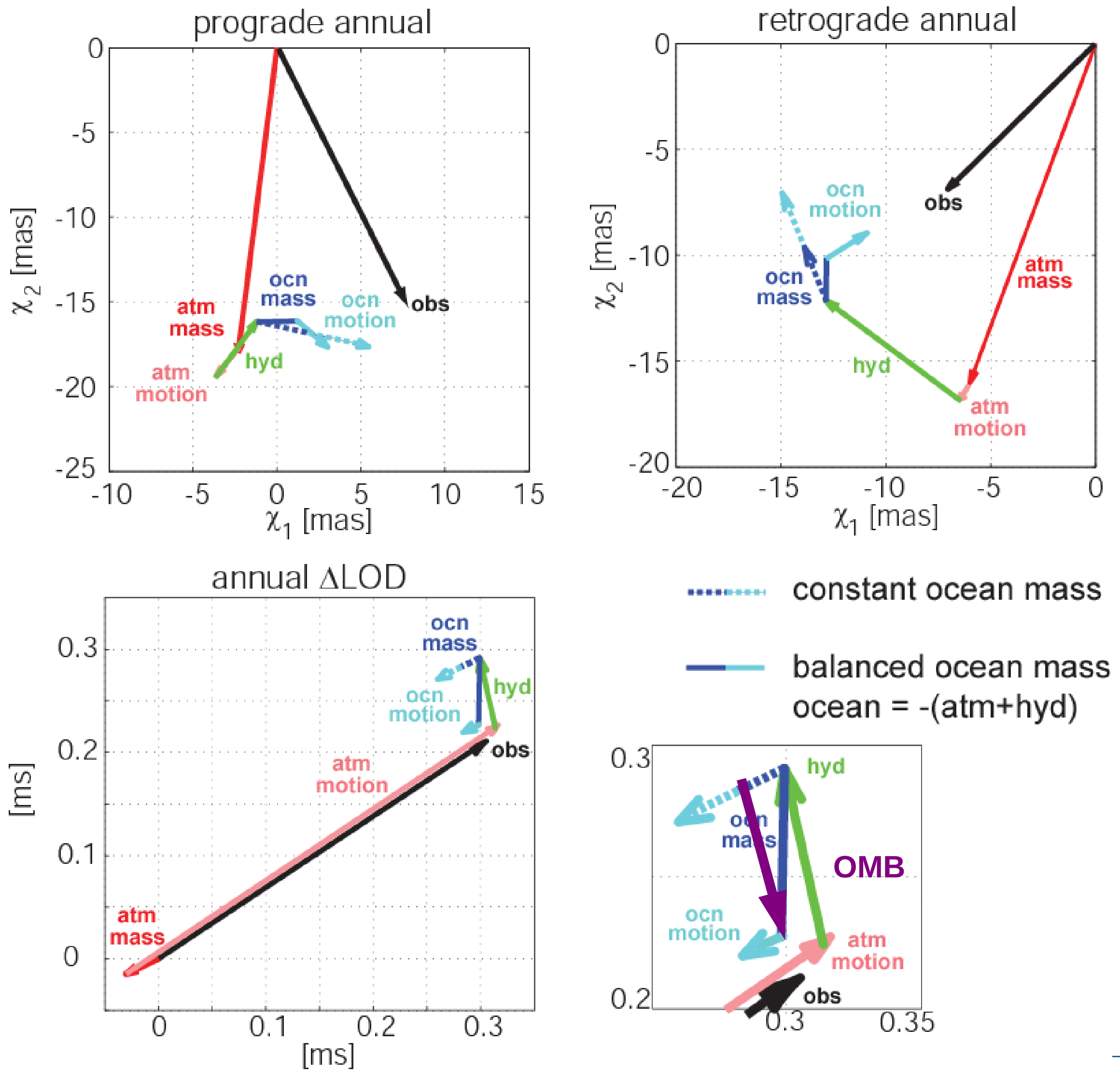
- **Global Mass Balance** (e.g., Chen 2005, Yan 2012)**:**
  add a homogeneous global layer to the atmosphere
  to compensate mass imbalance
  ↳ no impact on ΔJ2, polar motion
  ↳ effect on LOD

- **Ocean Mass Balance** (e.g., Dobslaw 2010)**:**
  atmospheric mass variations too small to compensate overall imbalance;
  add a homogeneous layer to the global ocean
  to compensate mass imbalance
  ↳ impact on polar motion and LOD

- **Global Gaussian Distribution** (e.g., Chen 2005)**:**
  add global layer with f=f(latitude)
  ↳ ...

- **...**

Influence of mass balance on annual EOP



left:

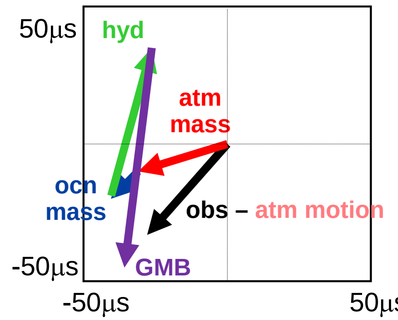
variable ocean mass balancing atmospheric + hydrological mass

(Dobslaw & Dill, 2010)

bottom right:

global mass balance (uniform global layer GMB) balancing atmospheric +hydrological+oceanic mass

(Yan & Chao, 2012)



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Summary

- Avoid mass imbalances by ...
  - consistent land-ocean masks in sub-models
  - mass conserving fluxes at common boundaries of sub-systems
- Atmospheric fluxes and total atmospheric mass variations are not consistent in re-analyses
- In general, in ocean and hydrologic discharge models consistent mass variations are enforced by applying correction approaches
- Global mass conservation can be enforced by ...
  - additional homogeneous mass layers (globally or only in the ocean)
  - calibration of global precipitation fields
  - utilizing independent global observations (e.g., applying GRACE gravity fields as constraints)
- Global mass balance approach influences modelled Earth rotation parameters
  - difference between various balance approaches ≈ 4% in DLOD
  - ocean only mass correction affects polar motion