Uncertainties in (energy) budgets

Thanks to Michael Mayer, John M. Edwards, Patrick Hyder, Andrea Storto, Marianne Pietschnig, Sebastian Stichelberger, Eric Boisseson, Patrick Laloyaux, Elke Rustemeier, Markus Ziese

4GA Bern Dec 2017

Motivation, Outline

- Integral budget constraints allow for indirect estimation of difficult to measure quantities.
  - TOA global mean radiation imbalance = OHCT+Icemelt
  - Estimation of net surface energy flux pattern
- Biases and drifts in state quantities such as temperature often have their root in erroneous transports
- CMIP6 puts more emphasis on budget components – reference data needed
- Ocean, ice and coupled reanalyses open new possibilities

- Improvements for coupled energy budget formulation
- Regional budget evaluations
- Precipitation evaluation ->DWD talk
- Carbon ->UVSQ talk

Improving the net surface energy flux evaluation

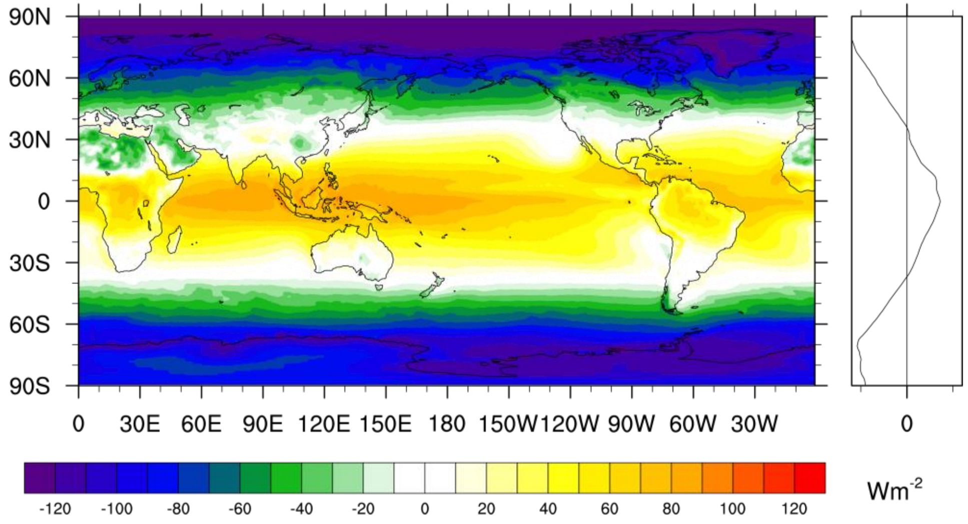
- Use vertically integrated atmospheric total energy budget equation to infer F_S indirectly

$$F_S = Rad_{TOA} - \nabla \cdot F_A$$

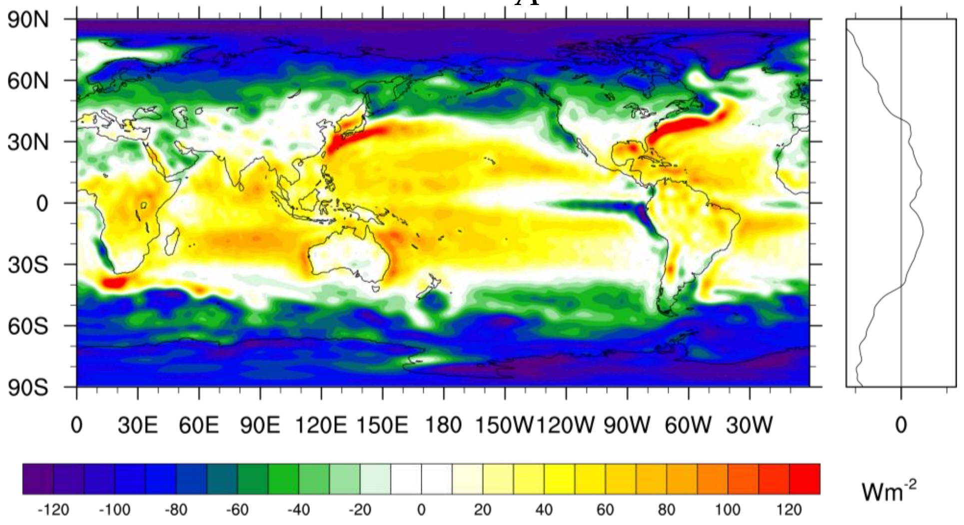
with $$F_S = LH + SH + Rad_S$$

- Divergence term requires mass-consistent winds

Rad_{TOA}



$\nabla \cdot F_A$



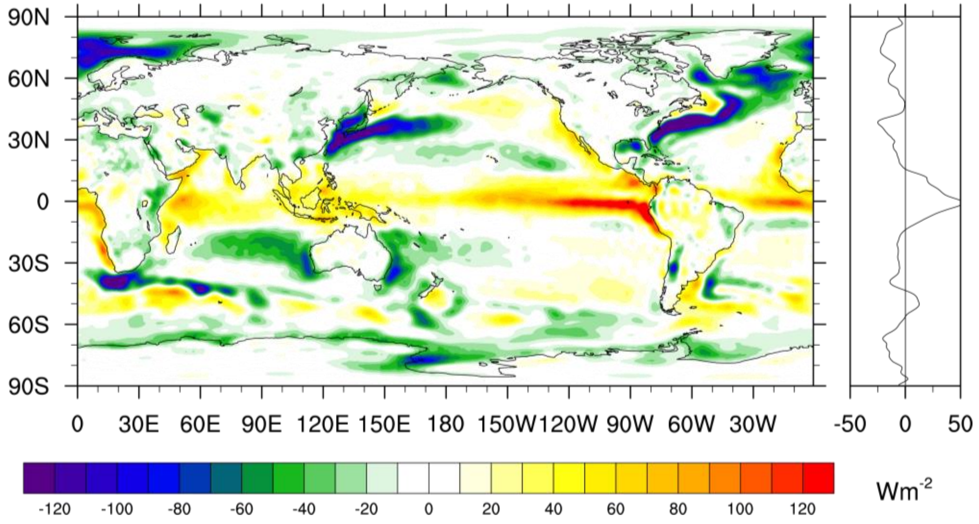
Current practice

- Vertically integrated atmospheric total energy budget equation can be used to infer net surface energy flux
- Divergence term requires mass-consistent winds

$$F_S = Rad_{TOA} - \nabla \cdot F_A$$

with $F_S = LH + SH + Rad_S$

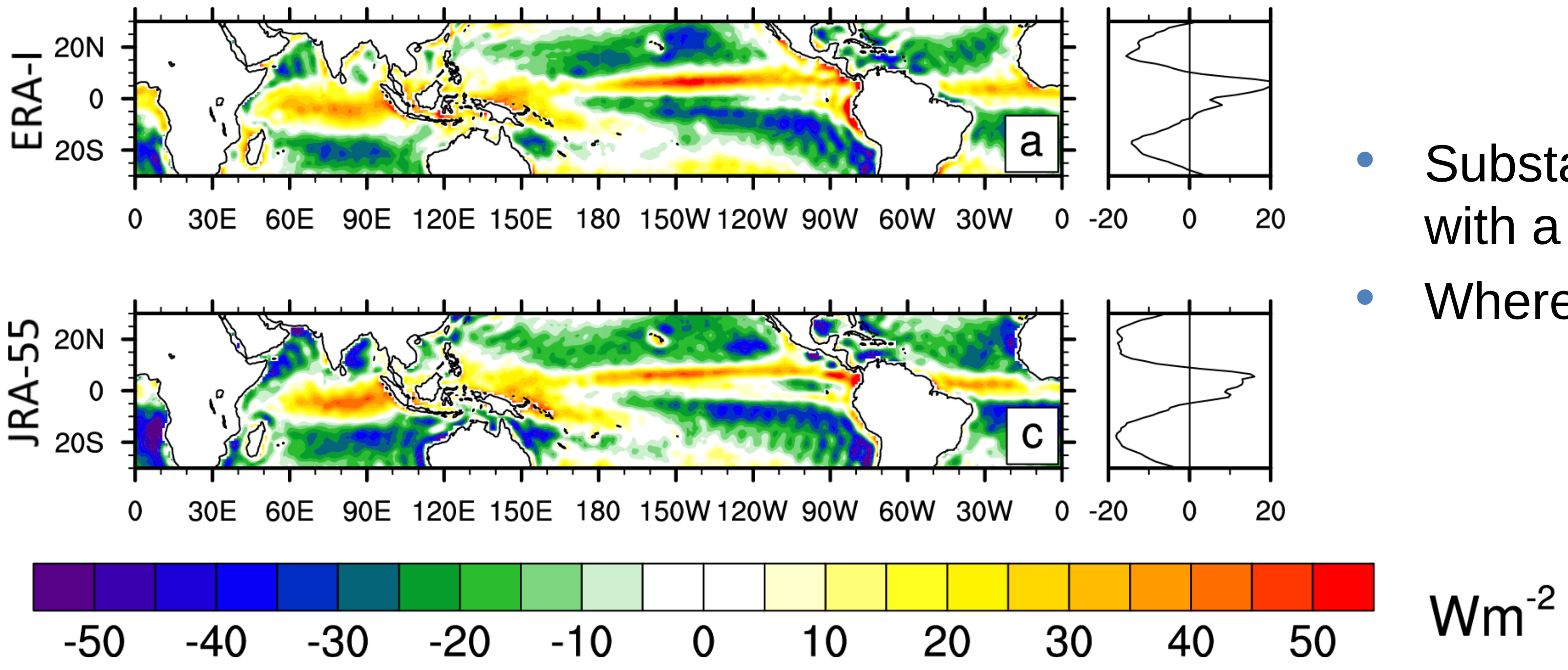
Inferred F_S



The patterns look nice and realistic, but…

Comparison to independent surface flux product

- Compare implied F_S from satellite TOA radiation and reanalysis transports to independent surface flux products
- here: difference to CERES sfc radiation plus OAflux turbulent fluxes



- Substantial differences in the tropics, with a pronounced P-E pattern
- Where does this pattern come from?

Take a closer look at budget equation

- Vertically integrated atmospheric total energy budget equation

$$F_S = Rad_{TOA} - \nabla \cdot F_A$$

Take a closer look at budget equation

- Vertically integrated atmospheric total energy budget equation

$$F_S = Rad_{TOA} - \frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2 (m+k)] dp$$

Take a closer look at budget equation

- Vertically integrated atmospheric total energy budget equation

$$F_S = Rad_{TOA} - \frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2 (m+k)]dp$$

- Divergence term can be decomposed as follows:

$$\frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2 (m+k)]dp = \frac{1}{g}\int_0^{p_s} \vec{v}_2 \cdot \nabla (m+k)dp + \frac{1}{g}\int_0^{p_s} (m+k)(\nabla \cdot \vec{v}_2)dp$$

Moist static energy
$(= c_p T + L_v q + \phi)$

Kinetic energy

Advection term

Mass divergence term

Take a closer look at budget equation

- Vertically integrated atmospheric total energy budget equation

$$F_S = Rad_{TOA} - \frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2 (m+k)]dp$$

- Divergence term can be decomposed as follows:

$$\frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2 (m+k)]dp = \frac{1}{g}\int_0^{p_s} \vec{v}_2 \cdot \nabla (m+k)dp + \frac{1}{g}\int_0^{p_s} (m+k)(\nabla \cdot \vec{v}_2 q)dp$$

Moist static energy $(= c_p T + L_v q + \phi)$

Kinetic energy

Advection term

Mass divergence term

Vertically integrated mass divergence reduces to moisture flux divergence (if dry mass is conserved!)

Take a closer look at budget equation

- Vertically integrated atmospheric total energy budget equation

$$F_S = Rad_{TOA} - \frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2(m+k)]dp$$

- Divergence term can be decomposed as follows:

$$\frac{1}{g}\int_0^{p_s} \nabla \cdot [\vec{v}_2(m+k)]dp = \frac{1}{g}\int_0^{p_s} \vec{v}_2 \cdot \nabla(m+k)dp + \frac{1}{g}\int_0^{p_s} (m+k)(\nabla \cdot \vec{v}_2 q)dp$$

Moist static energy
$(= c_p T + L_v q + \phi)$

Kinetic energy

→ Mass divergence term involves absolute m, i.e. temperature itself!

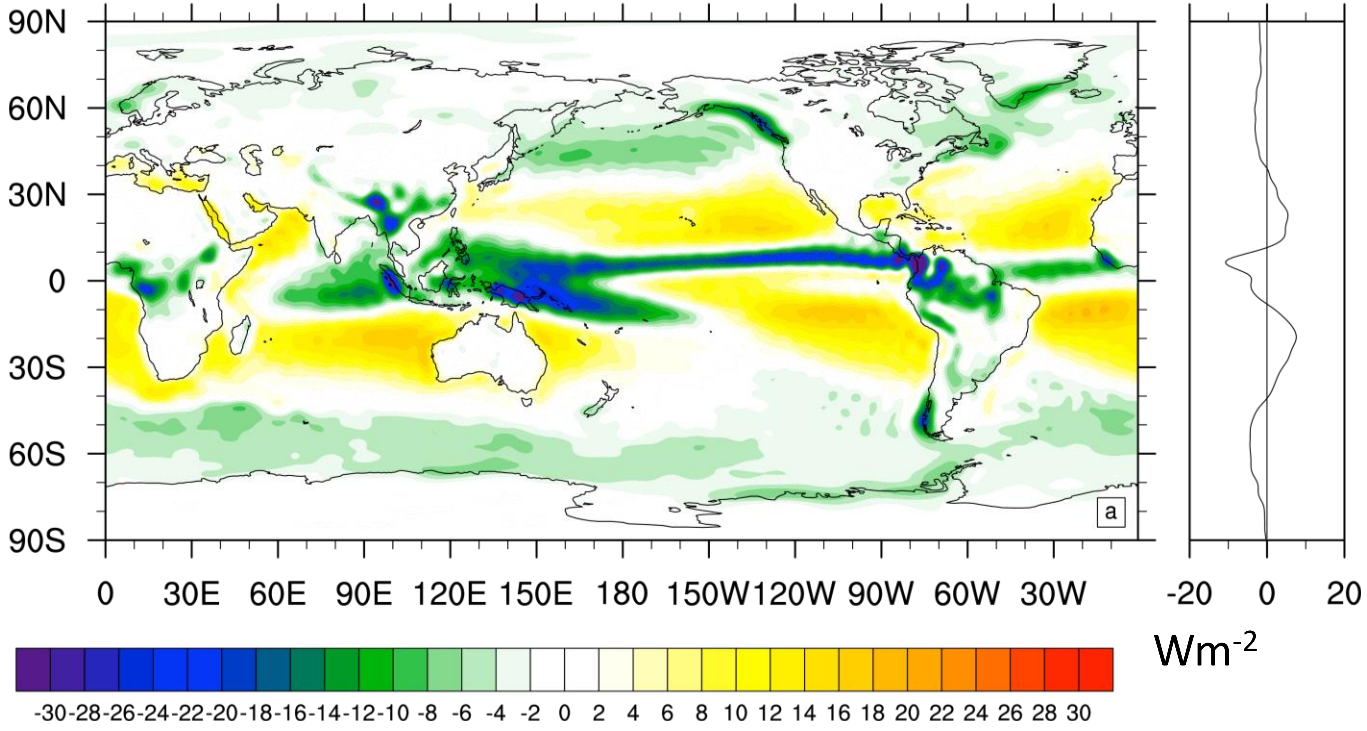
ECMWF

universität wien

- Dependency of F_S on reference temperature can be written as:

$$\Delta F_S = \frac{1}{g}\int_0^{p_s}(m_{Kelvin}+k)(\nabla\cdot\vec{v}_2 q)dp - \frac{1}{g}\int_0^{p_s}(m_{Celsius}+k)(\nabla\cdot\vec{v}_2 q)dp = \underbrace{\frac{c_p \times 273.16}{g}}_{h_0}\int_0^{p_s}(\nabla\cdot\vec{v}_2 q)dp$$

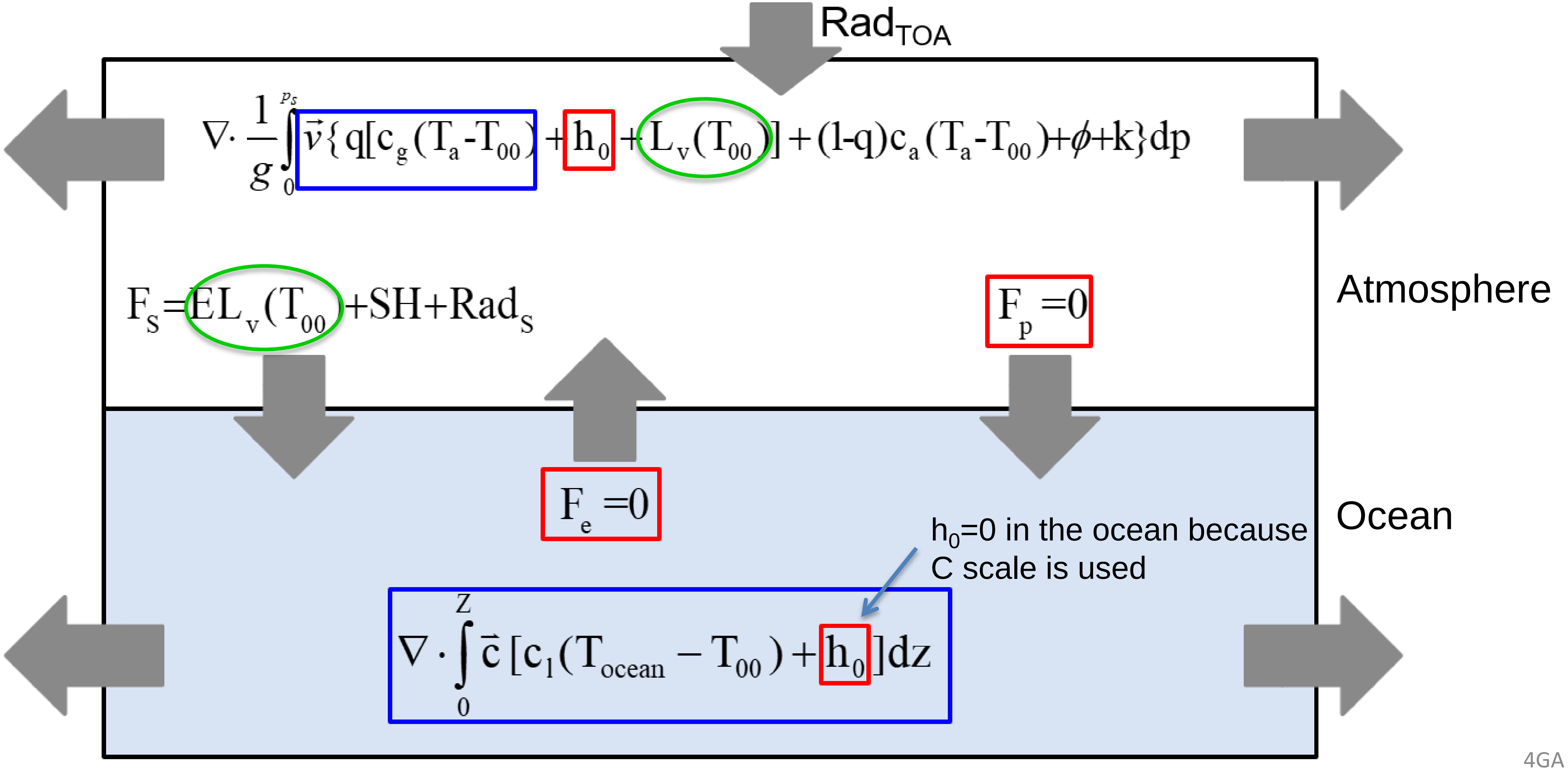
Field of ΔF_S shows large values with a P-E structure:



What is correct? Shouldn't F_S be independent on employed temperature scale?

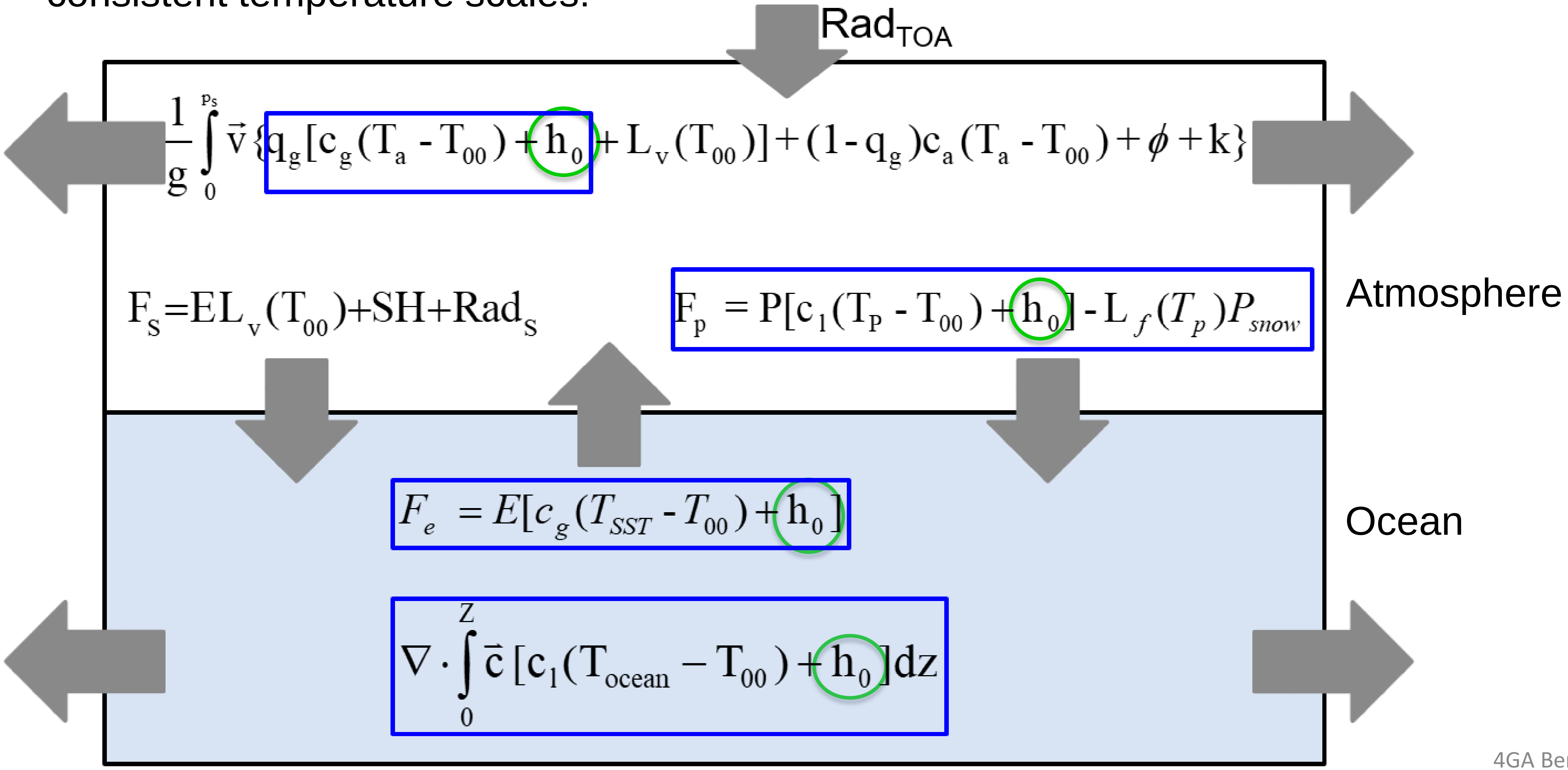
Reason for inconsistency

- Latent heat is treated consistently in 3D energy fluxes, but moisture enthalpy fluxes are NOT!



More complete budget

- Need to include moisture enthalpy fluxes in lateral AND surface fluxes – using consistent temperature scales!



More complete budget

- Need to include moisture enthalpy fluxes in lateral AND surface fluxes – using consistent temperature scales!

Rad_{TOA}

$$\nabla \cdot \frac{1}{g}\int_0^{p_s} \vec{v}\{q_g[c_g(T_a - T_{00}) + L_v(T_{00})] + (1-q_g)c_a(T_a - T_{00}) + \phi + k\}dp$$

$$F_S = EL_v(T_{00}) + SH + Rad_S$$

$$F_p = P[c_l(T_P - T_{00})] - L_f(T_p)P_{snow}$$

Atmosphere

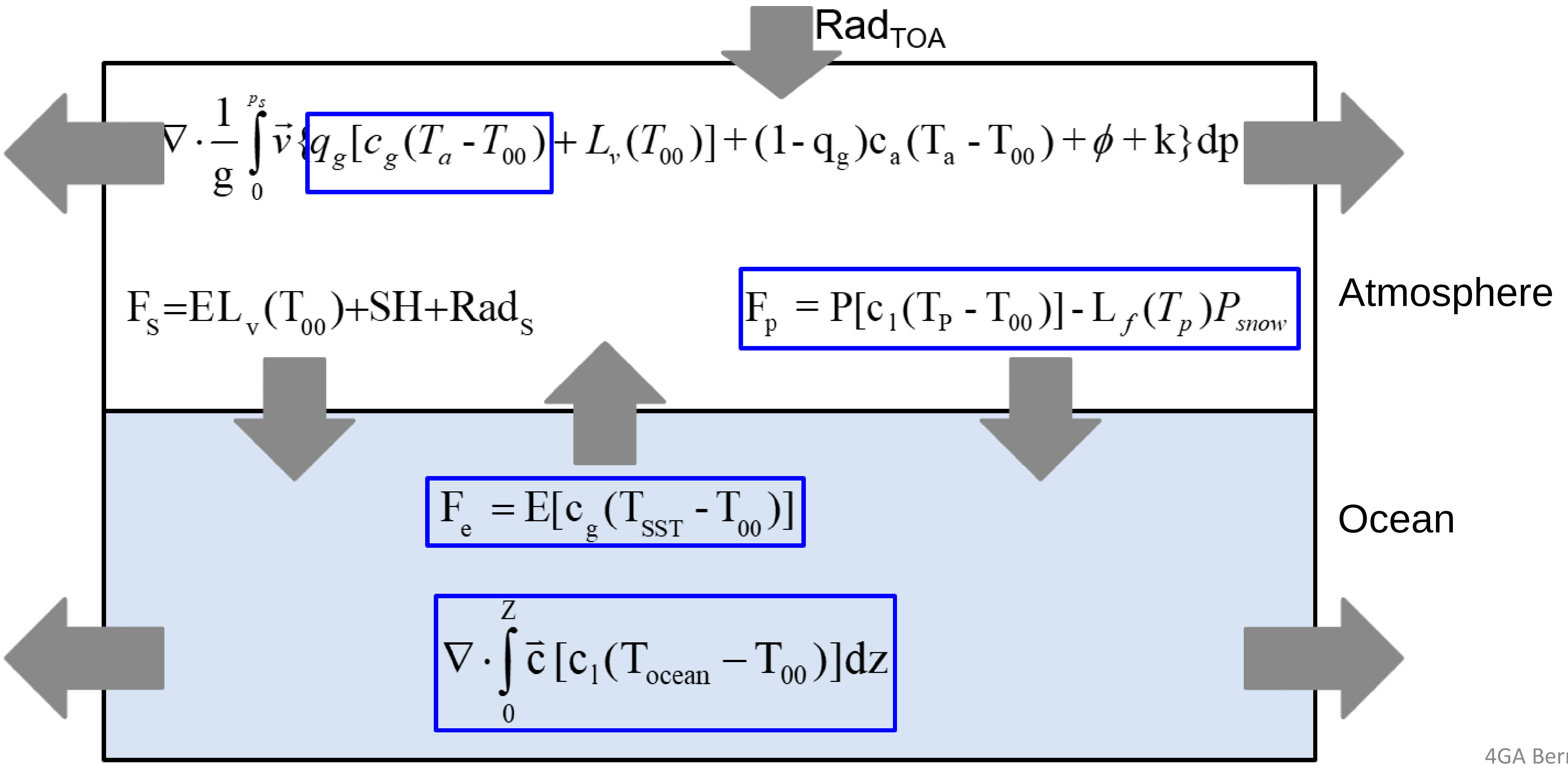
$$F_e = E[c_g(T_{SST} - T_{00})]$$

Ocean

$$\nabla \cdot \int_0^Z \vec{c}\,[c_l(T_{ocean} - T_{00})]dz$$

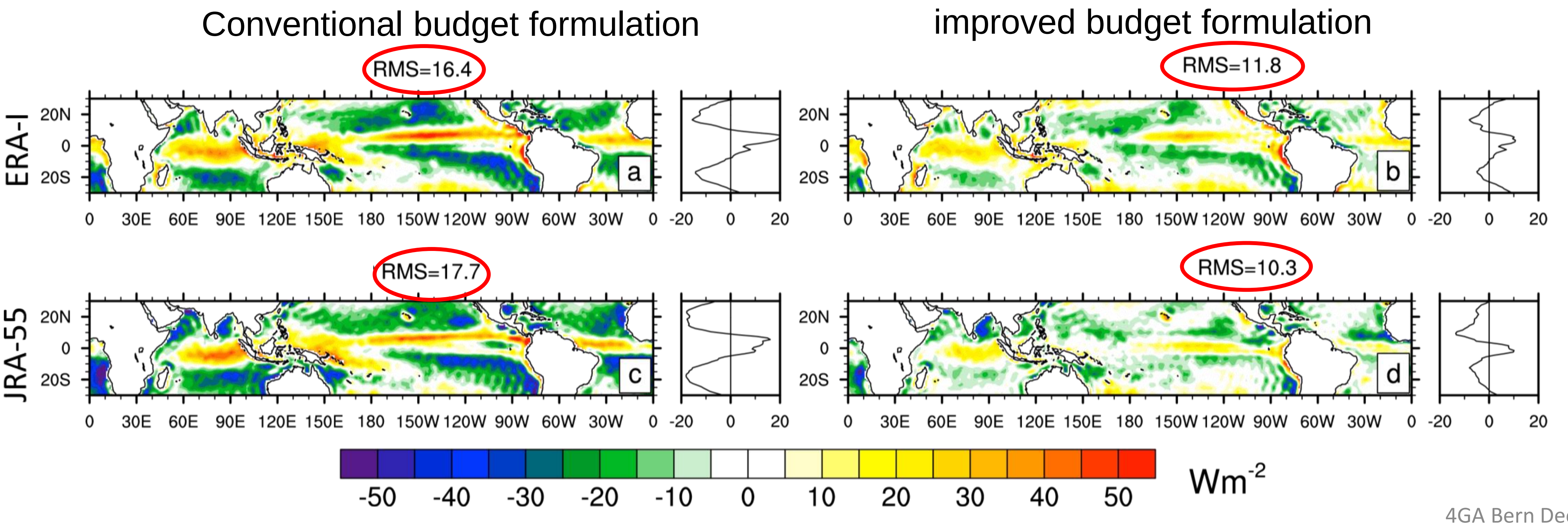
Practical evaluation

Either take into account F_p and F_e when inferring F_S



Improvement of results

- More consistent budget formulation improves agreement
  → RMS difference drops by 30-40%
- Improvement seen also with several other flux products

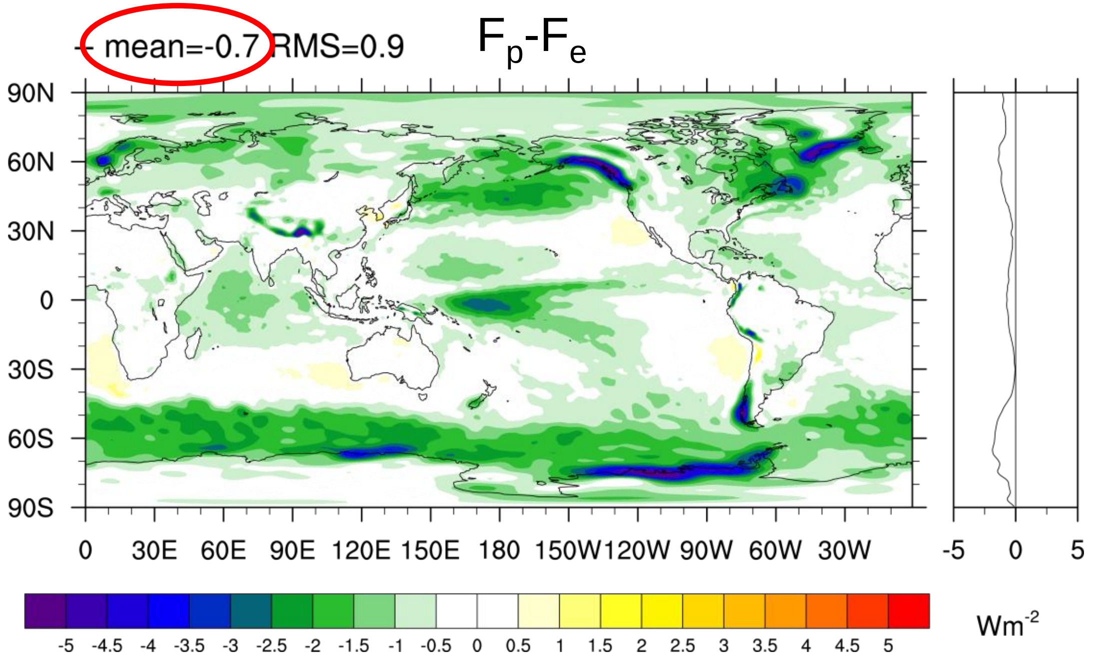


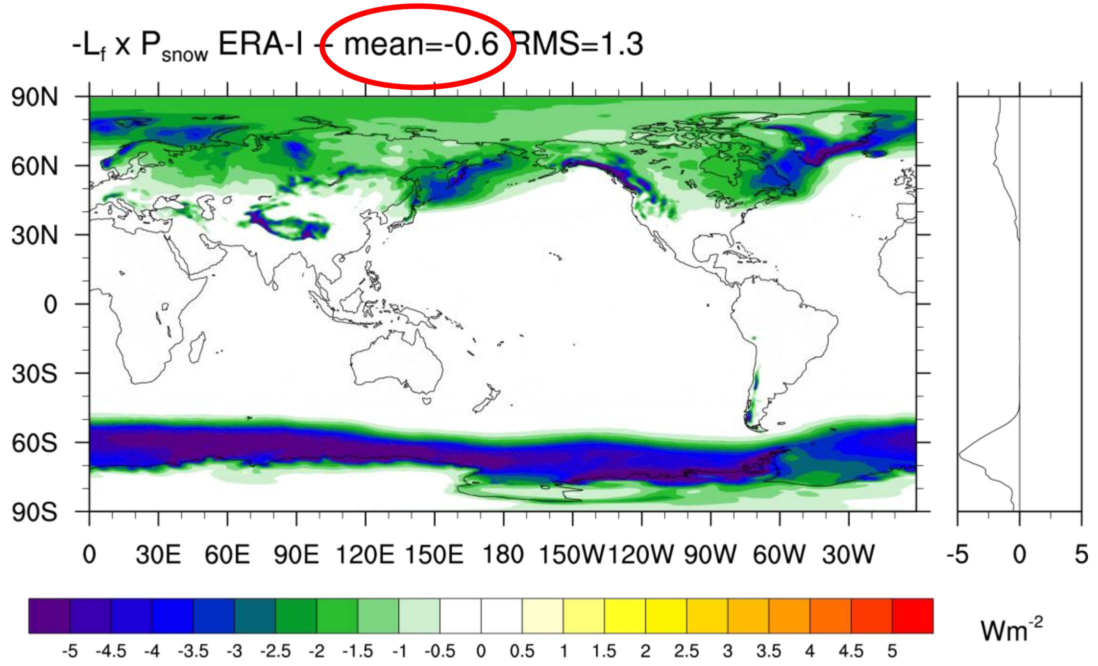
ECMWF

universität wien

Surface enthalpy fluxes

- Although small compared to h_0-effect, F_p, F_e, and F_{snow} exhibit pronounced spatial pattern
- Additional implications for global mean fluxes





Mayer, M., L. Haimberger, J. Edwards, and P. Hyder, 2017: Towards consistent diagnostics of the coupled atmosphere and ocean energy budgets. J. Climate. doi:10.1175/JCLI-D-17-0137.1, in press.

Oceanic Heat Content Estimation

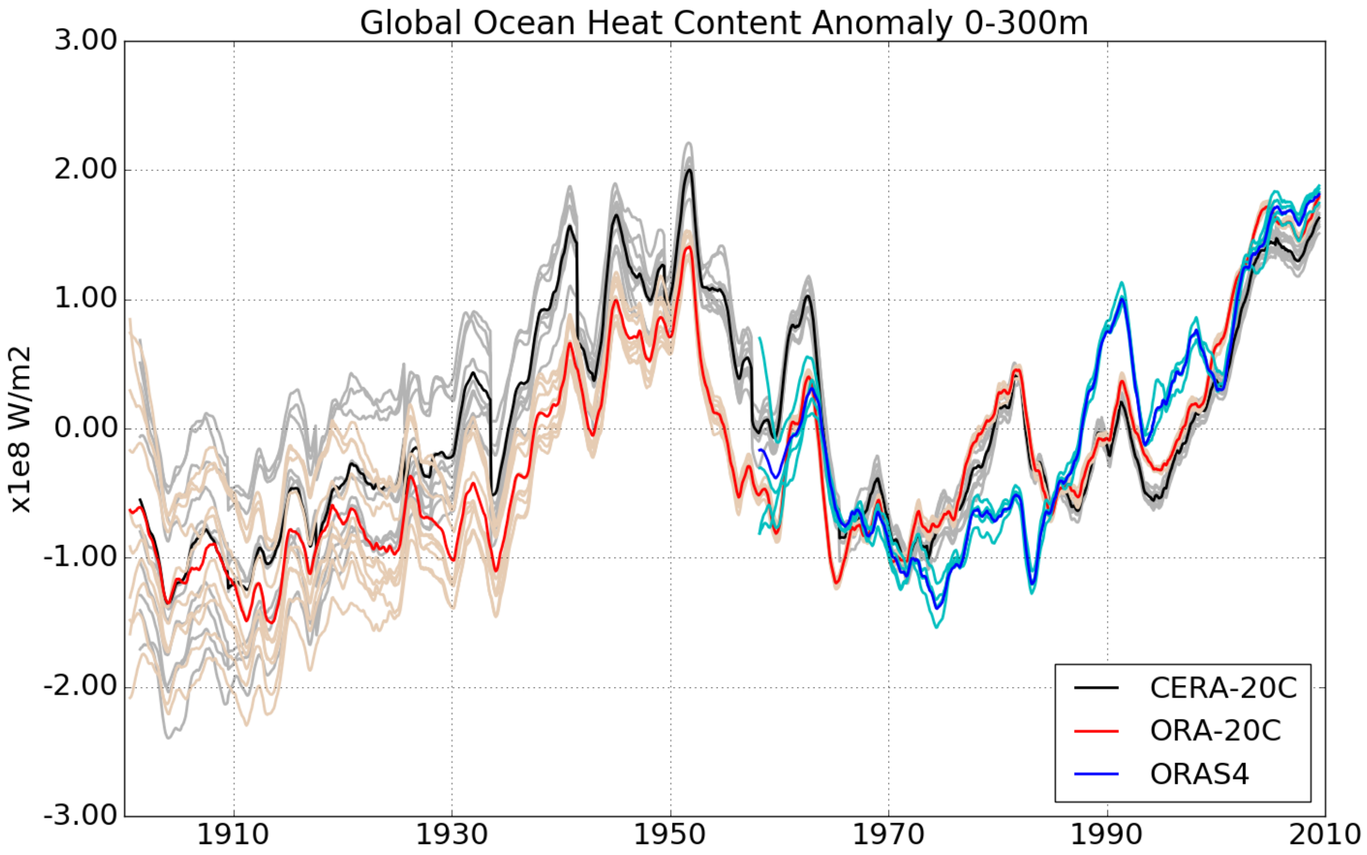
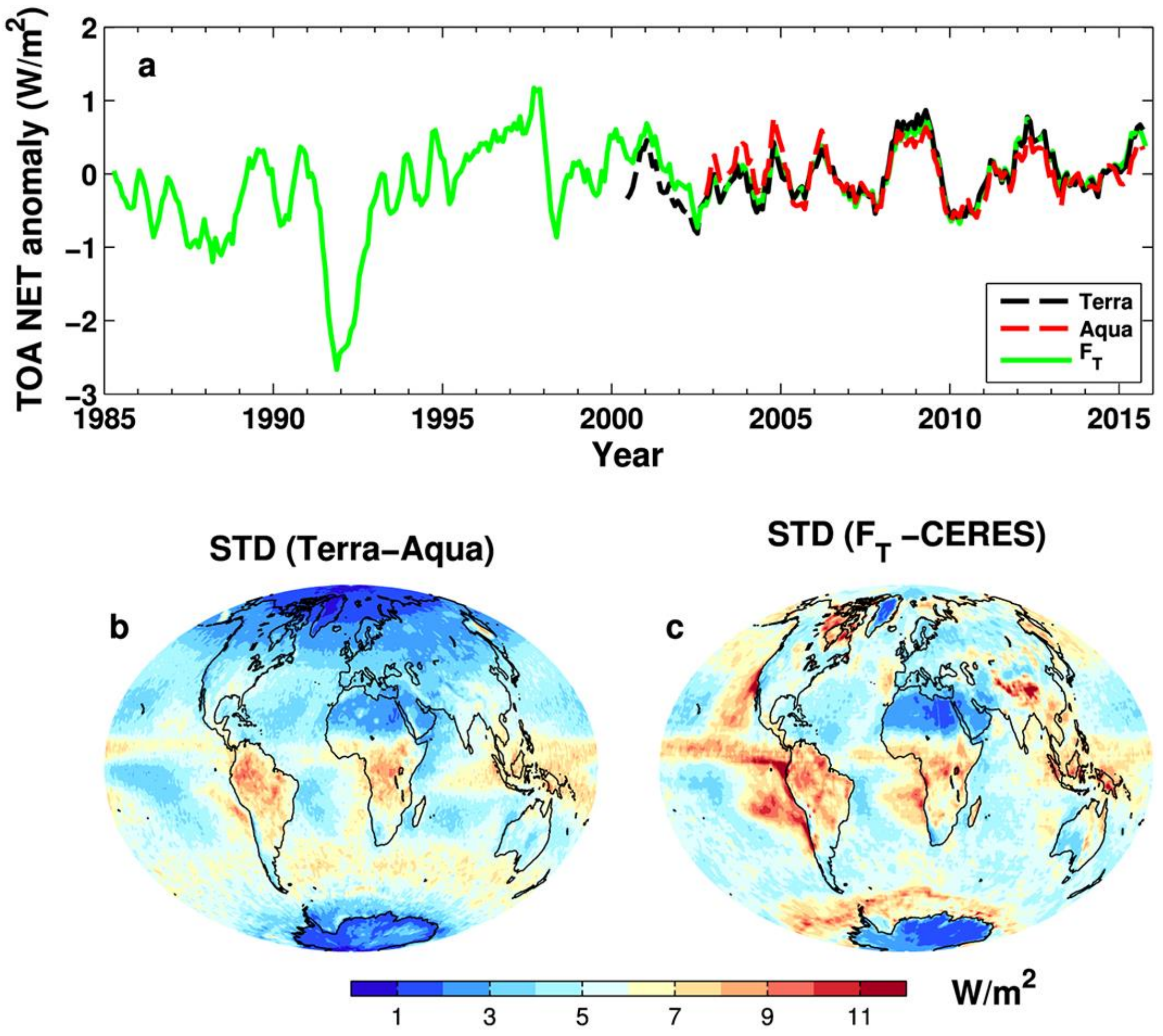


Fig. 6: Global 0-300m OHC anomalies with respect to 1958-2010. ORA-20C ensemble (10 members) are in light red, with the ensemble mean in red. CERA20C ensemble (10 members) in grey, with the mean in black, ORAS4 ensemble (5 members) in light blue with the ensemble mean in blue. An OHC increase of 1×10^8 J/m2 corresponds to a temperature increase of 0.08K averaged over the top 300m.

De Boisséson, E., Balmaseda, M. A. and Mayer, M., 2017: Ocean heat content variability in an ensemble of twentieth century ocean reanalyses. Clim. Dyn., DOI 10.1007/s00382-017-3845-0

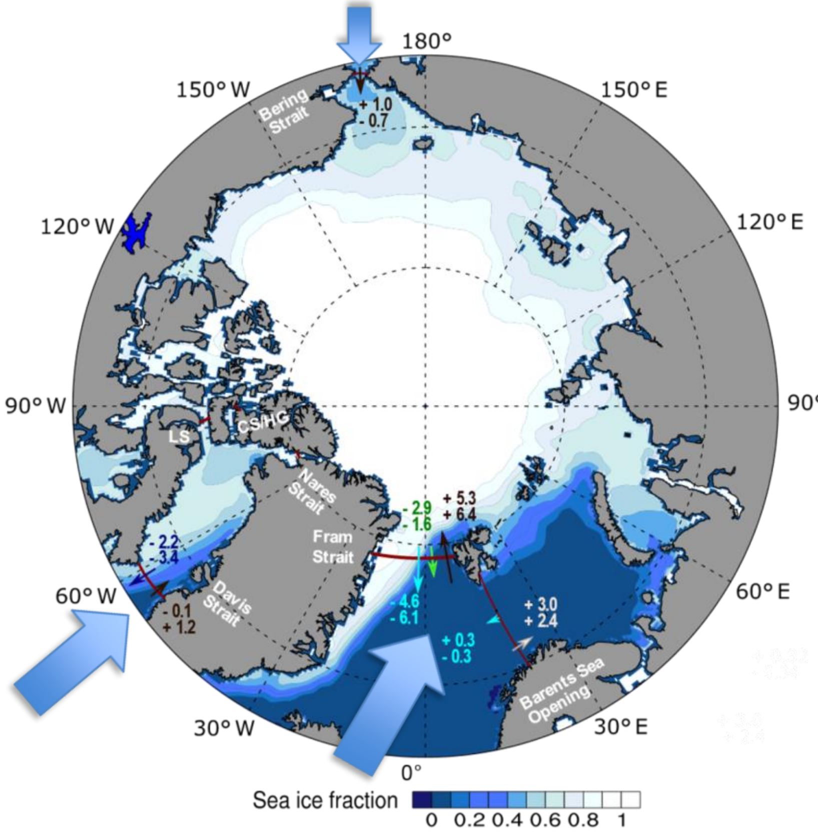
Rad_{TOA} from CERES and from reconstructions



Next step: Evaluate how well do improved budget estimations for Fs, revised Rad_{TOA}, Ocean heat content estimates correlate?

Liu, C., et al. (2017), Evaluation of satellite and reanalysis-based global net surface energy flux and uncertainty estimates, J. Geophys. Res. Atmos., doi:10.1002/2017JD026616.

Energy and Freshwater fluxes through Arctic Gateways



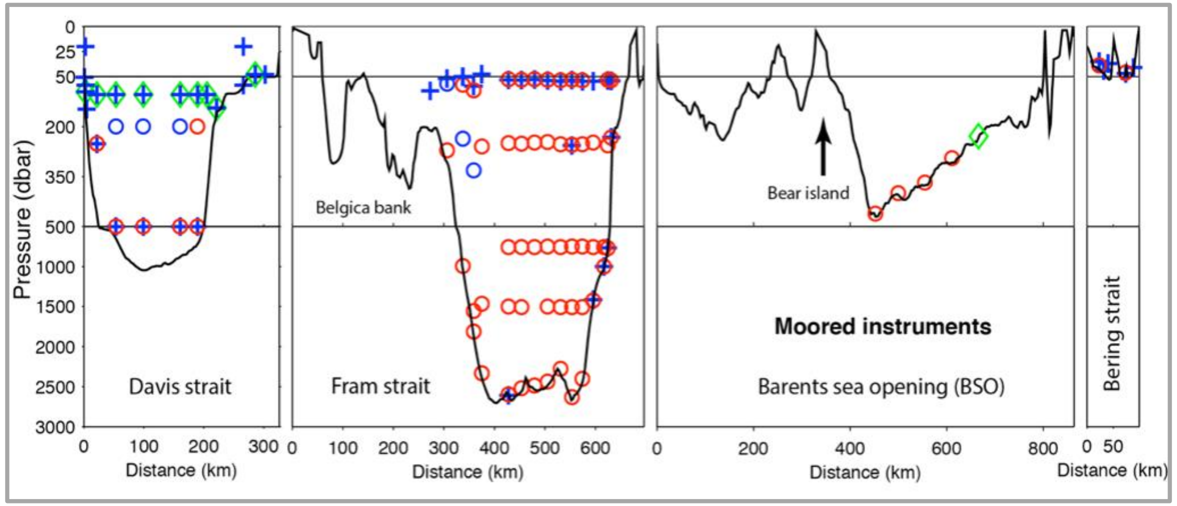
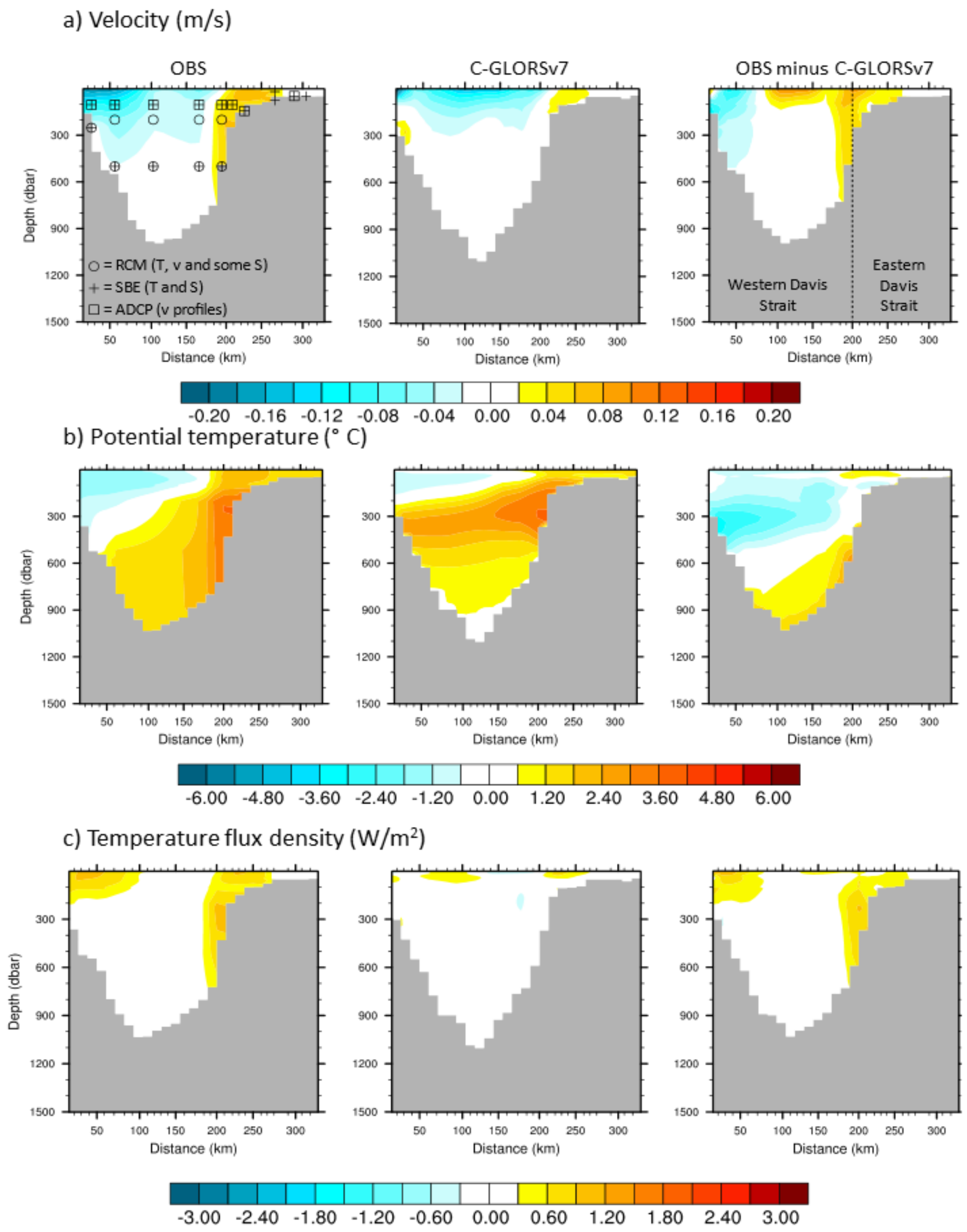


Fig 2: Location of 138 instruments at 41 mooring sites in the Arctic Gateways. Blue crosses: Temperature and salinity measurements (SeaBird microCATs). Blue circles: Current and Salinity meters (Aanderaa single point current meters). Red circles: Current meters. Green diamonds: ADCP (Acoustic Doppler Current Profiler). Source: Tsubouchi et al. 2017



Volume and temperature fluxes through Davies strait

- Fluxes from moored array vs. CGLORSv7 09/2005-08/2006
- Common reference temperature for both
- Temperature fluxes positive from moored array, near neutral from C-CLORS

Pietschnig et al. 2017,
Ocean Science Discussions

Net Heat and Freshwater Transport comparison

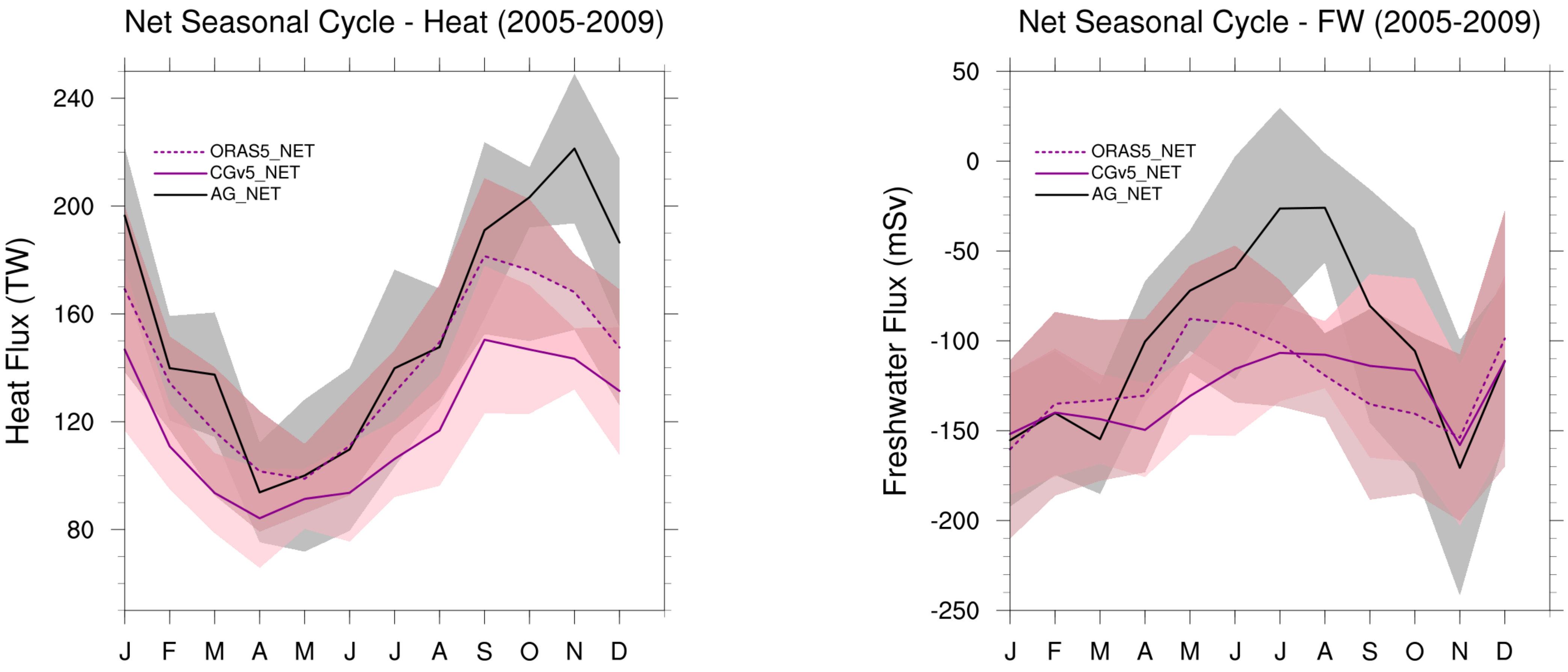


Fig. 4 a) Seasonal cycle of net northward heat fluxes estimated from moored observations, CMCCv5, and ORAS5 ocean reanalyses from data covering 2004-2009. b) seasonal cycle of net northward freshwater fluxes. Shading indicates standard deviation of the 7 monthly averages.

Conclusions

- Inconsistency in present energy budget formulation revealed and fixed
  → this is a diagnostic problem and hence affects all reanalysis products
  → also much cleaner comparison to climate models
- Effects of surface enthalpy fluxes should be taken into account in models
  → Explicitly required for CMIP6 – reanalyses should follow, especially when coupled
- Recommendations for better usability of archived energy budget terms:
  - Mass consistent total energy divergence
  - Divergence of moisture enthalpy transports should be stored separately
- Regional evaluation of lateral oceanic transports
- Next steps:
  - see if improved formulation improves OHCT-F_S-RAD_{TOA} correlation
  - Noise near orography – how to best avoid it to get F_S over land?

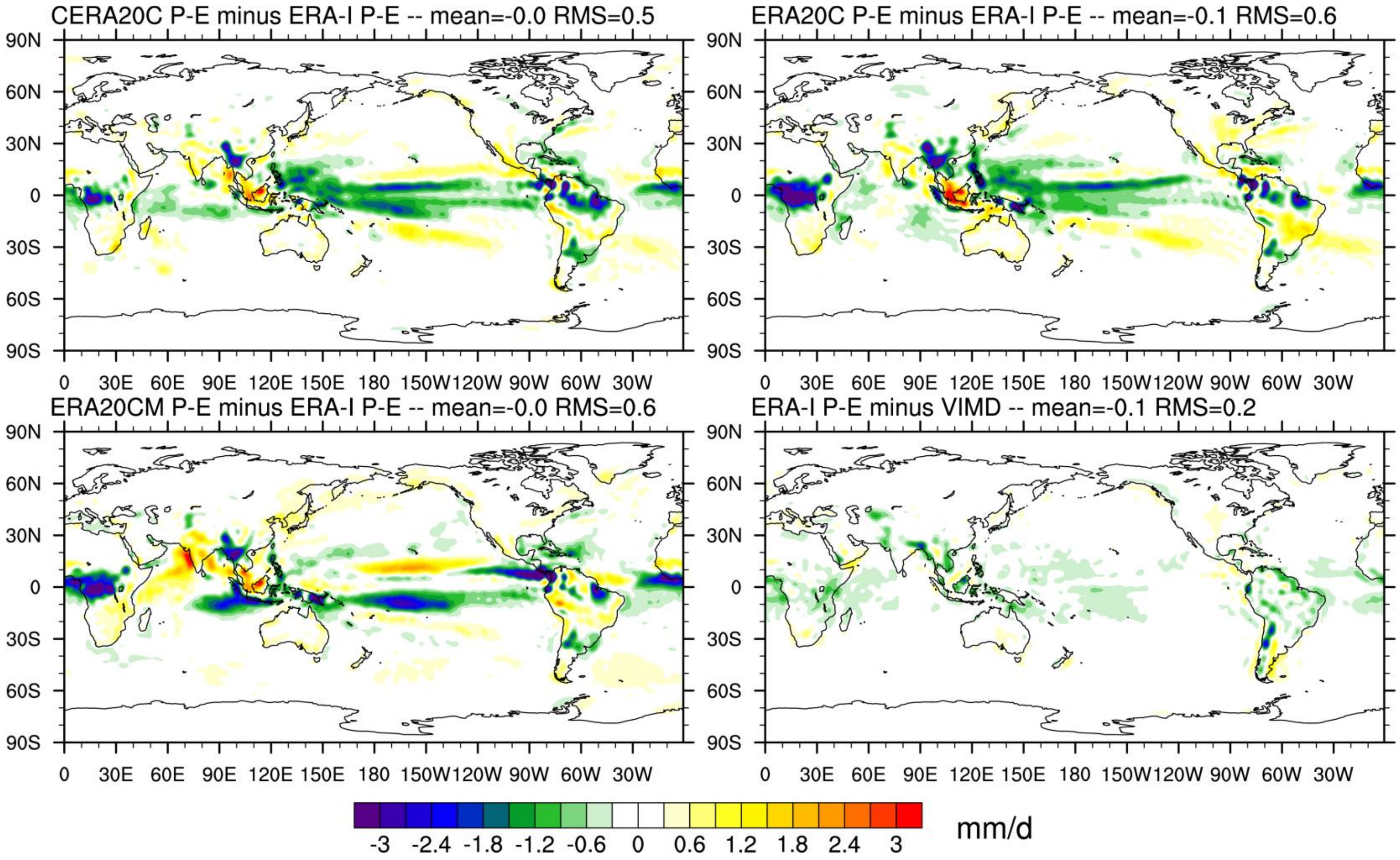


Fig. 9: P-E differences CERA20C minus ERA-Interim averaged over period 1979-2010 (upper left), Differences ERA20C minus ERA-Interim (upper right), Differences ERA20CM minus ERA-Interim (lower left), Difference between ERA-Interim P-E and vertically integrated moisture flux divergence (lower right), yielding a measure of uncertainty for ERA-Interim P-E .

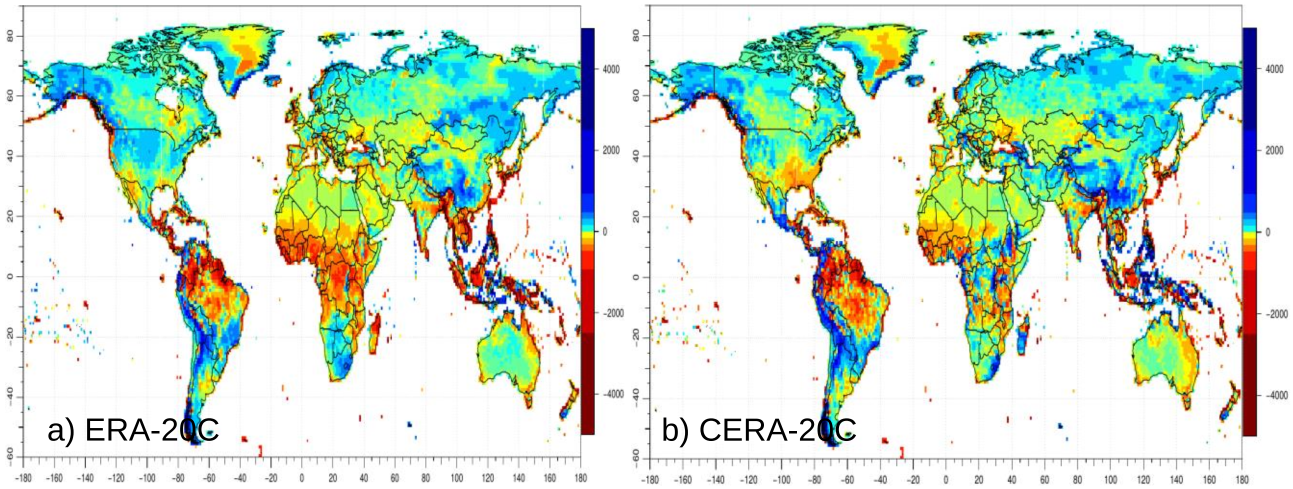
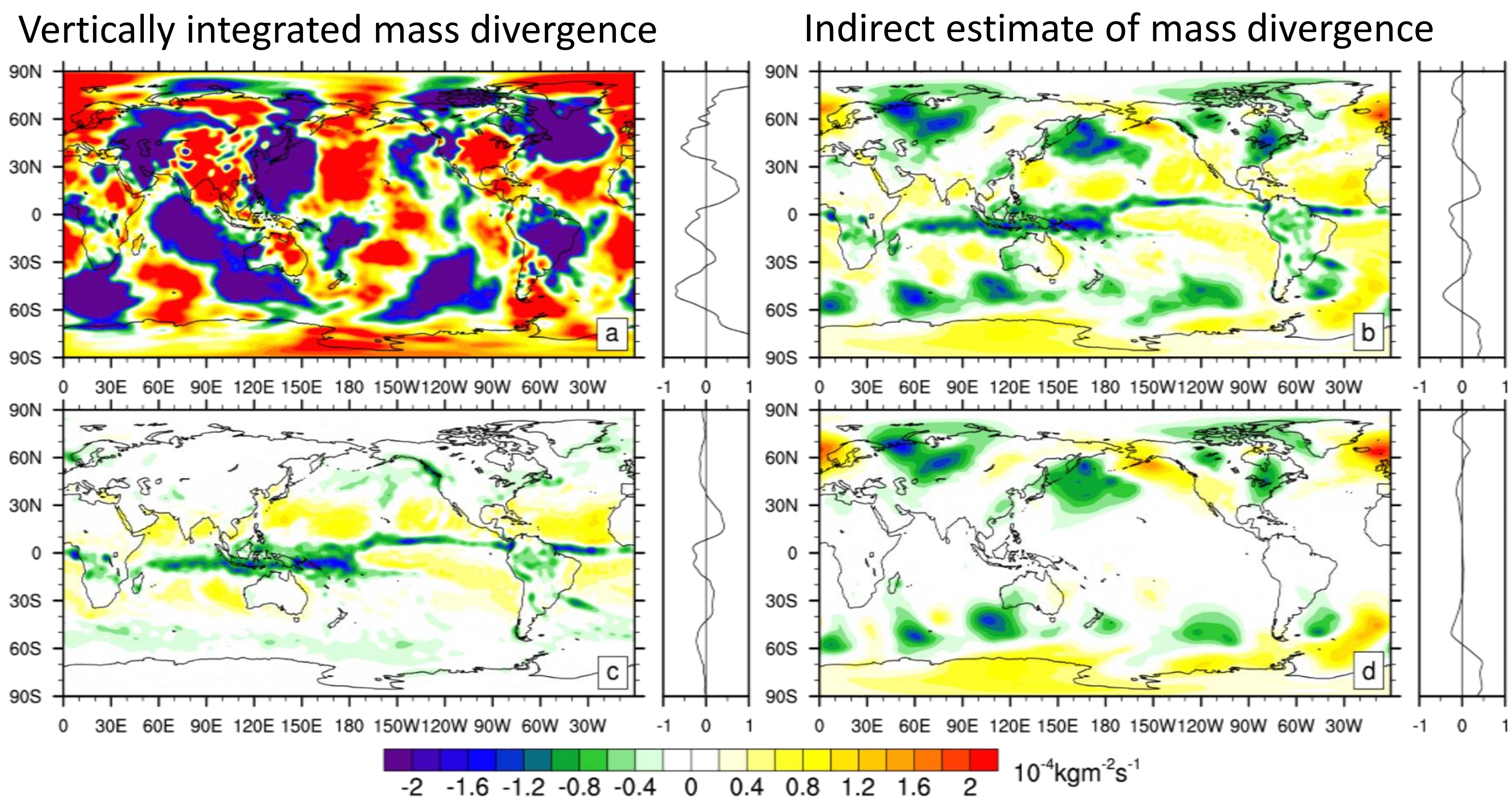
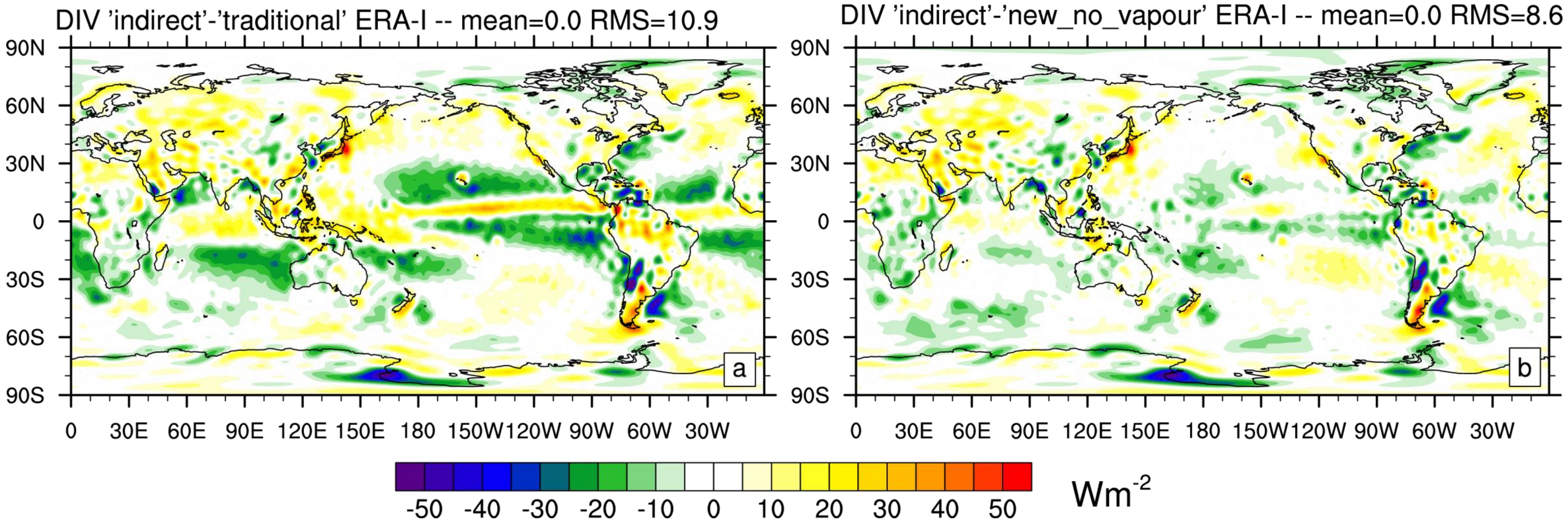


Figure 7 BIAS of short term precipitation forecasts from ERA-20C a) and the CERA-20C ensemble mean b) against Full Data Monthly V7 (Schneider et al., 2014). Time interval considered: 1901-2000 on 1° spatial resolution with annual temporal resolution.

Mass budget in ERA-Interim



Improved self-consistency of ERA-Interim budget



Error introduced by consistent vapour enthalpy removal