Some advances on Coupled Energy Budget Diagnostics

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Der Wissenschaftsfonds.

Outline

- Everybody's talking about coupled modelling/assimilation, but how about coupled budget diagnostics?
- CMIP6 design document has strong focus on this (Griffies et al 2014)
- On-going work:
  - Improvement of existing diagnostic methods
  - Recent trends in energy flows through the Arctic climate system
  - Comparison of in-situ-based to reanalysis-based ocean transports through the main Arctic straits

Part 1: Improvement of diagnostic methods

Inconsistencies in atmospheric budget diagnostics

- Vertically integrated atmospheric total energy budget equation

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

- This equation is commonly used to indirectly estimate F_S using radiation from satellites and transports from reanalyses

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- Divergence term can be decomposed as follows:

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

Moist static energy

Kinetic energy

Vertically integrated mass divergence reduces to moisture flux divergence

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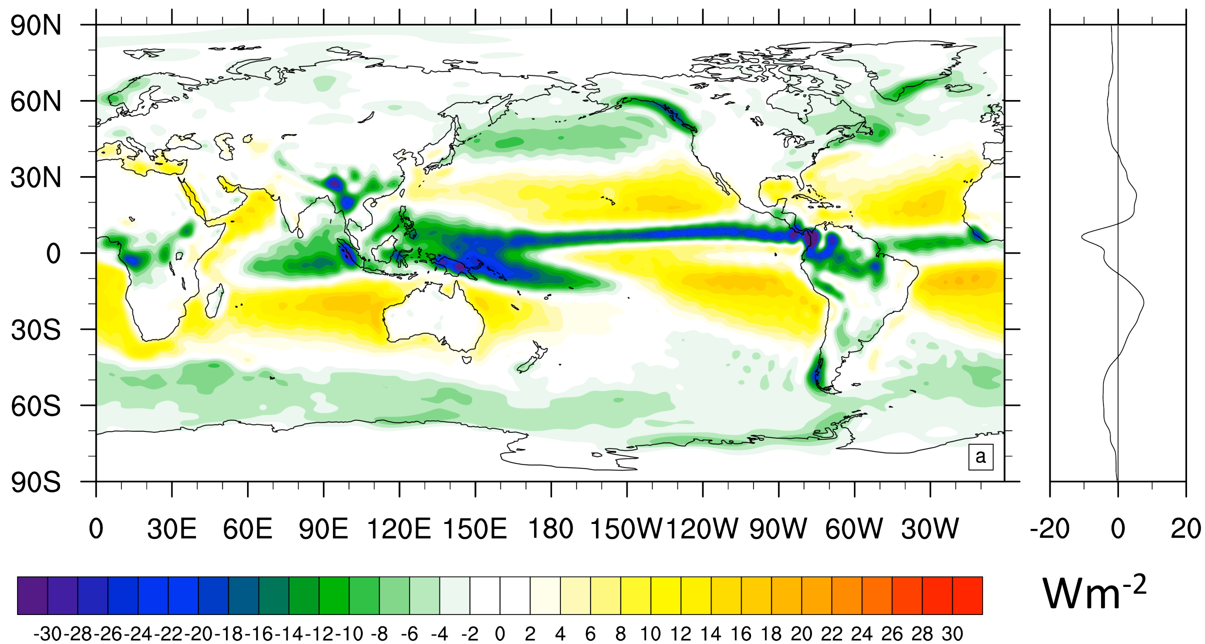
→ Last term on rhs involves absolute h, i.e. temperature itself!

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

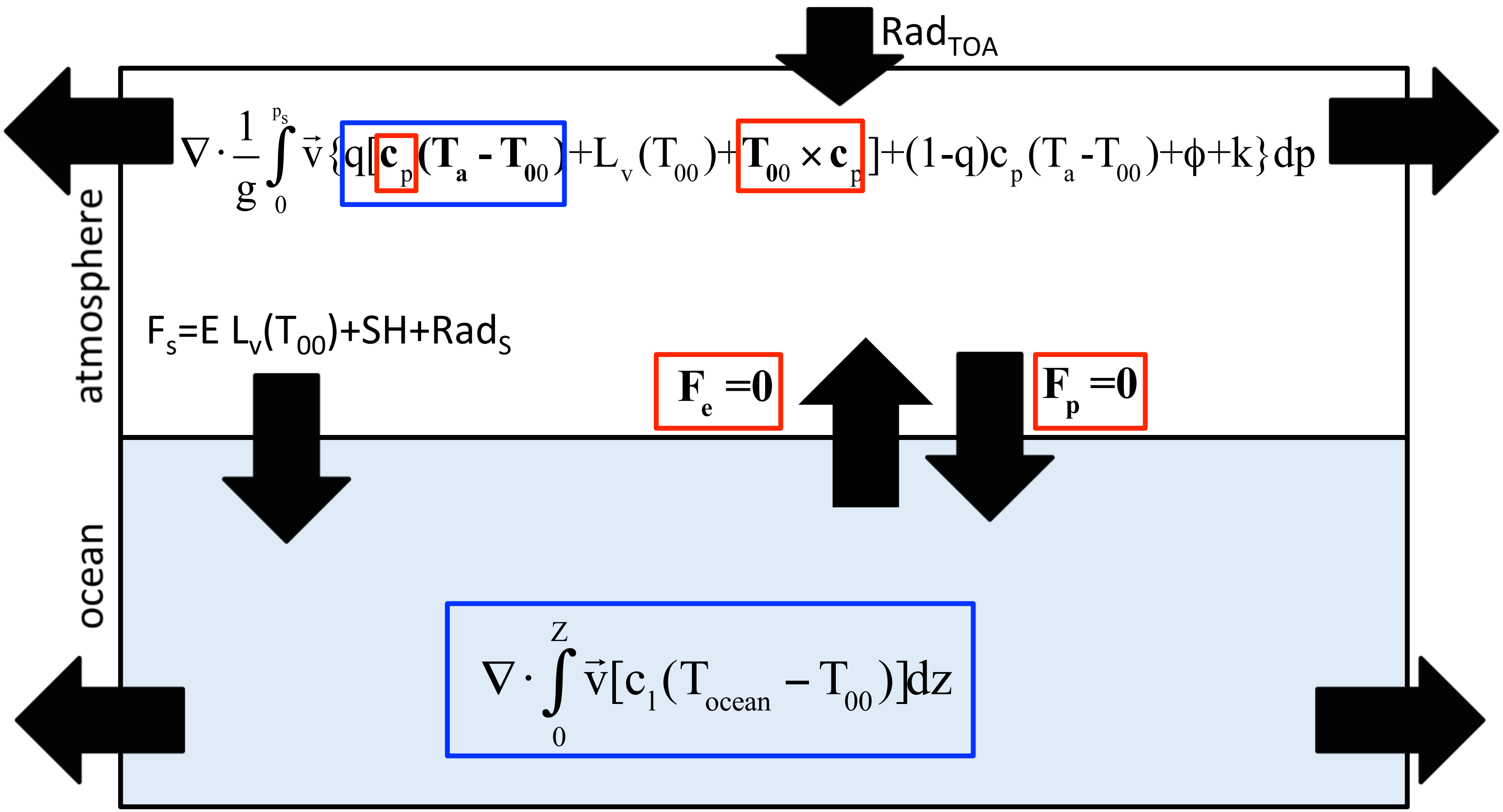
$$\Delta F_S = \frac{1}{g}\int_0^{p_s} (h_{\text{Kelvin}} + k)(\nabla \cdot \vec{v}_2 q)\,dp - \frac{1}{g}\int_0^{p_s} (h_{\text{Celsius}} + k)(\nabla \cdot \vec{v}_2 q)\,dp = \frac{c_p \times 273.16}{g}\int_0^{p_s} (\nabla \cdot \vec{v}_2 q)\,dp$$

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



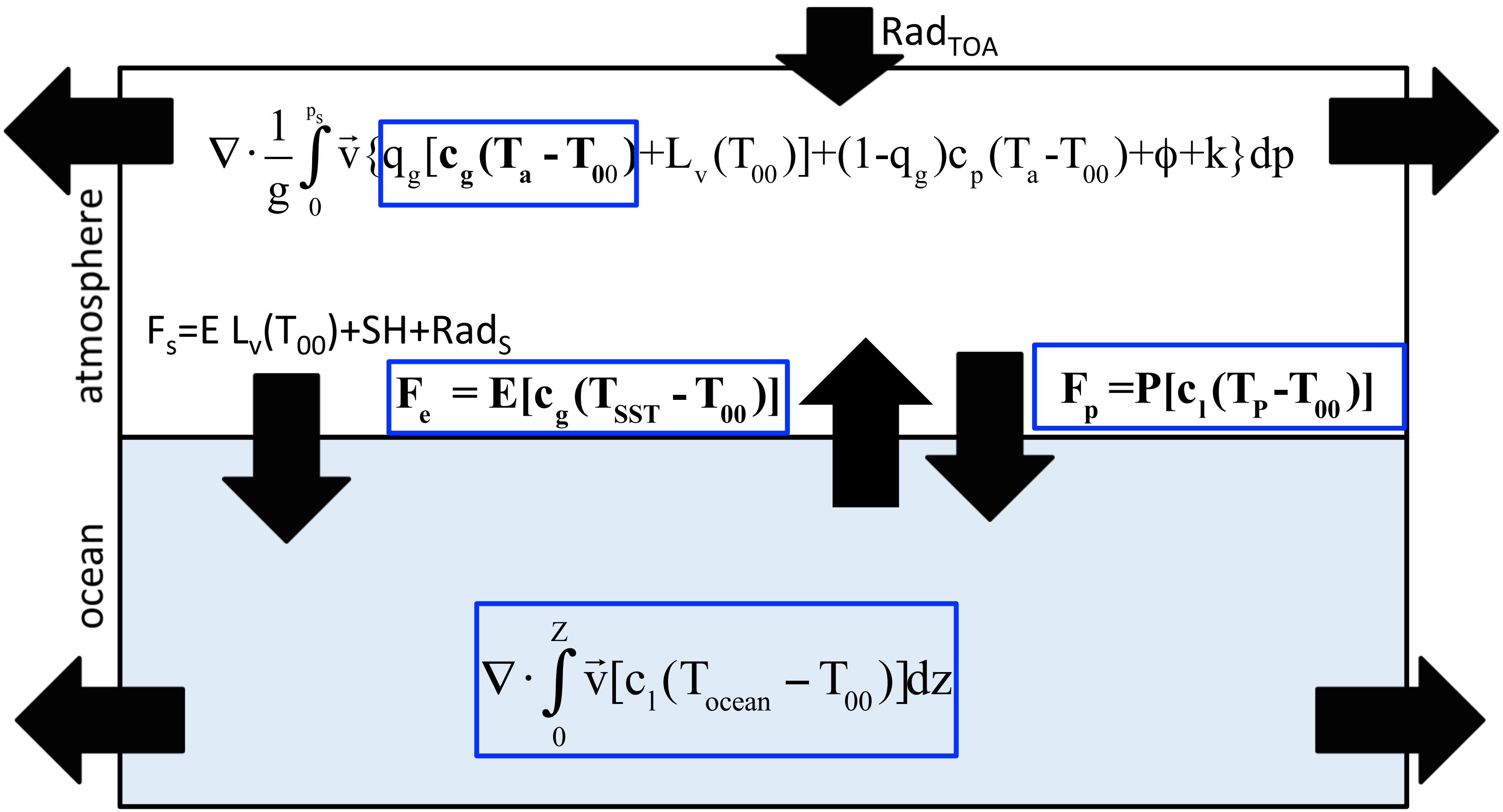
- What is correct? Shouldn't F_S be independent on temperature scale?

- Reason for inconsistency: Moisture enthalpy fluxes are included in lateral transports, but NOT those associated with P and E!



Improved methods I

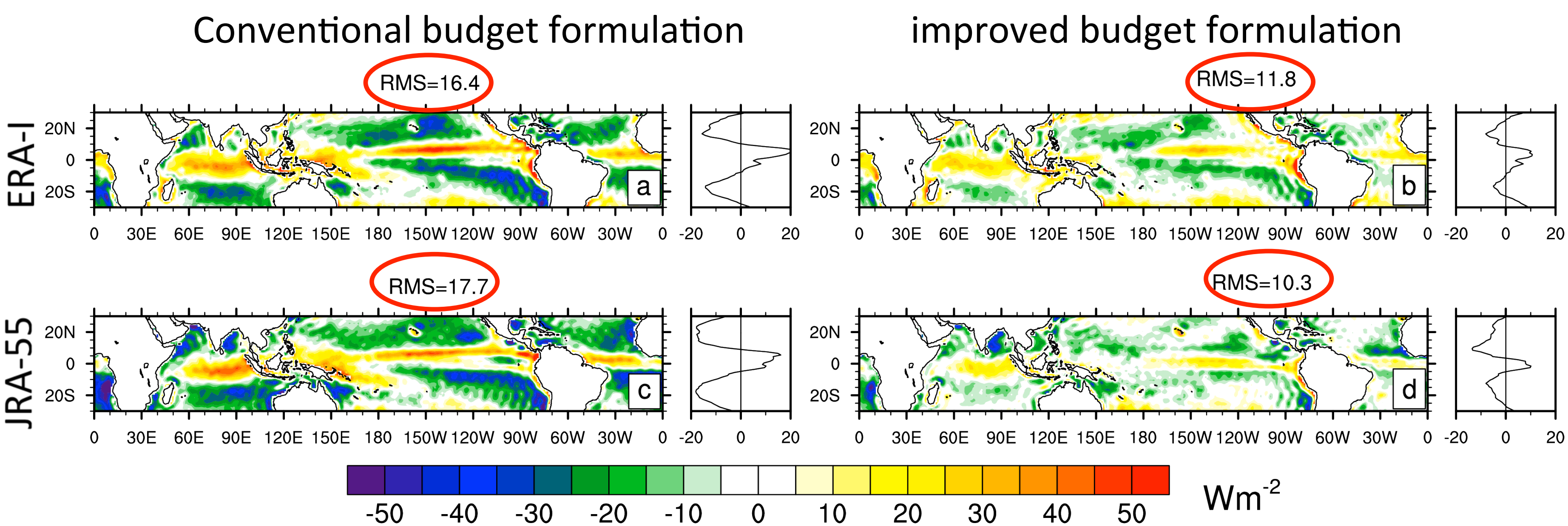
- Need to include moisture enthalpy fluxes in lateral AND surface fluxes!



- When including F_e and F_p, implied F_S becomes independent of reference temperature

Improved methods II

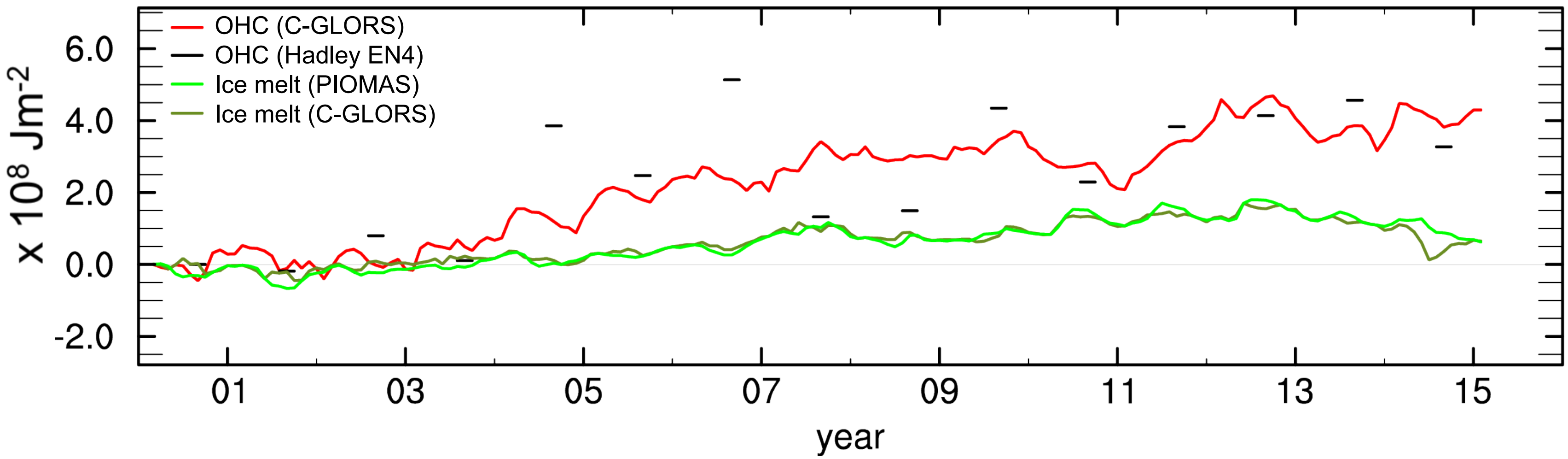
- Compare implied F_S from satellite TOA radiation and reanalysis transports to independent surface flux products
- here: difference to CERES sfc radiation plus OAflux turbulent fluxes
- More consistent budget formulation improves agreement – RMS difference drops by 30-40%



Part 2: Recent trends in energy flows through the Arctic climate system

Long-term evolution

- Accumulated arctic cap (70N-90N) energy anomalies



- Strong upward trend in OHC (equivalent to 0.95 Wm^{-2})
- in-situ based OHC from Hadley EN4 very unstable due to lack of obs

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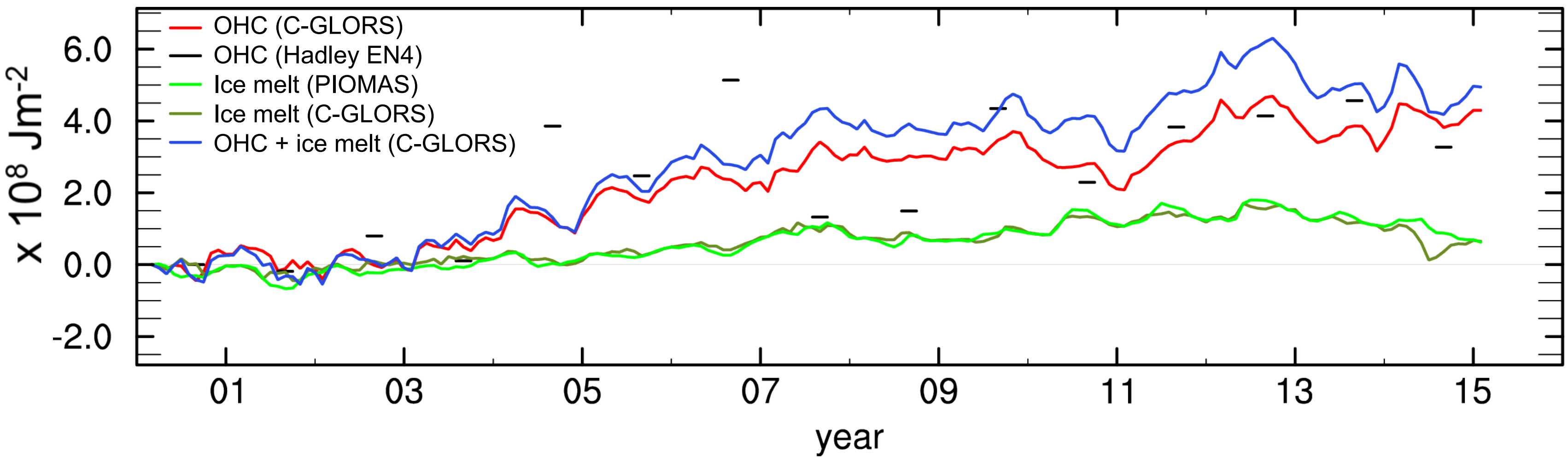
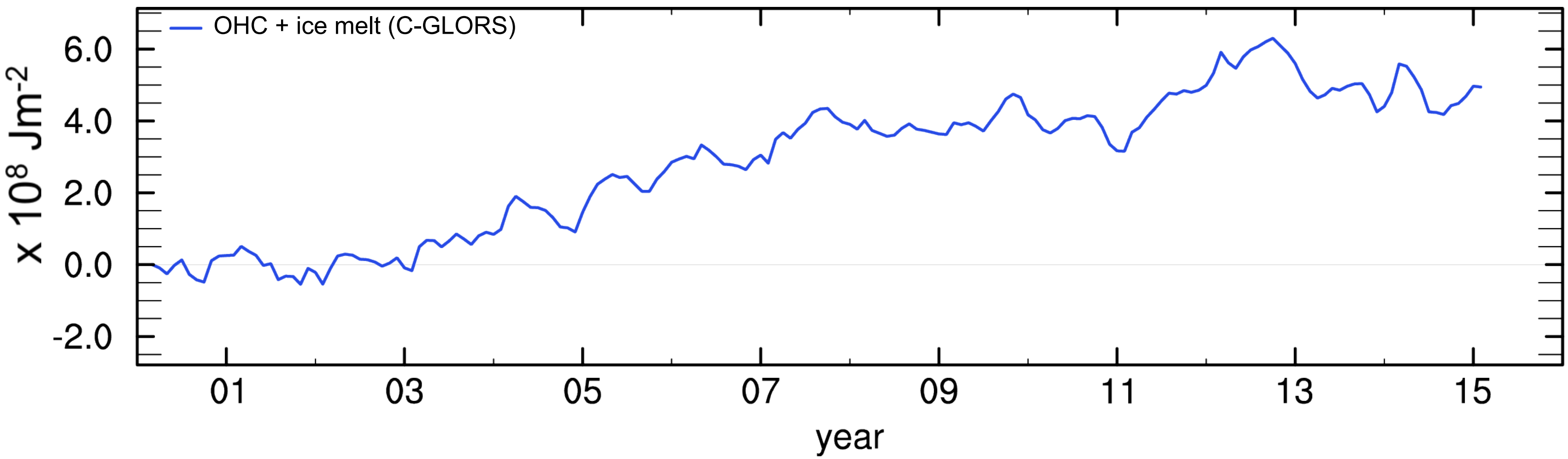


- Strong upward trend in OHC (equivalent to 0.95 Wm^{-2})
- in-situ based OHC from Hadley EN4 very unstable due to lack of obs
- Comparatively little energy going into melt (about 0.1 Wm^{-2})

Long-term evolution

- How well do boundary fluxes replicate energy accumulation?



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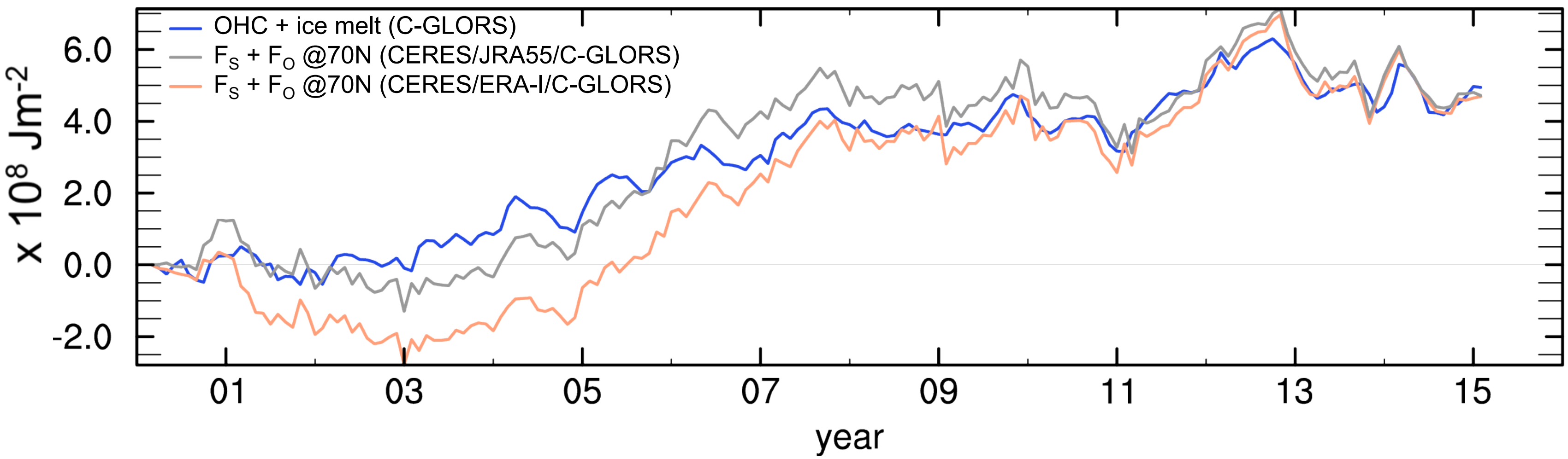
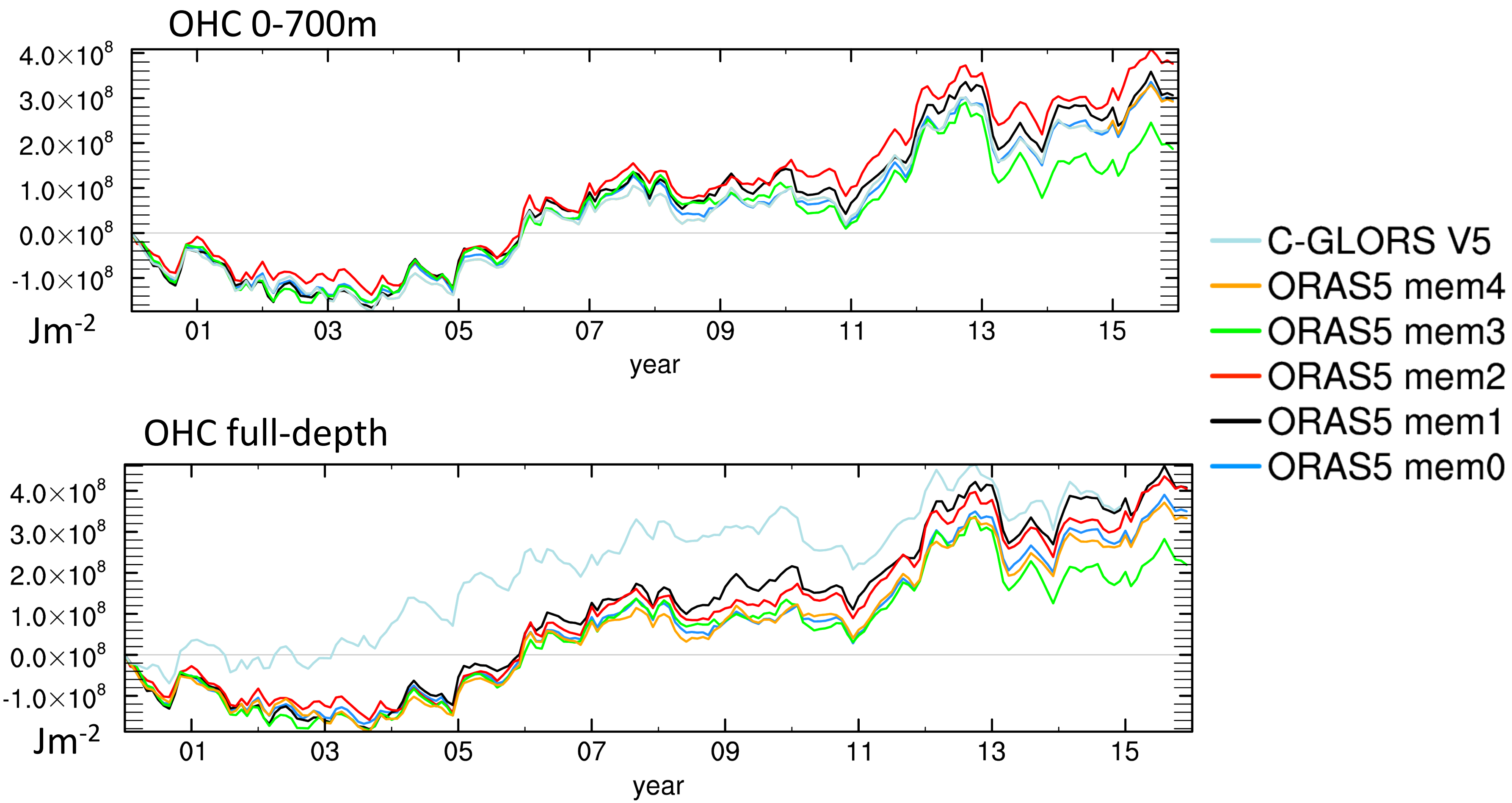


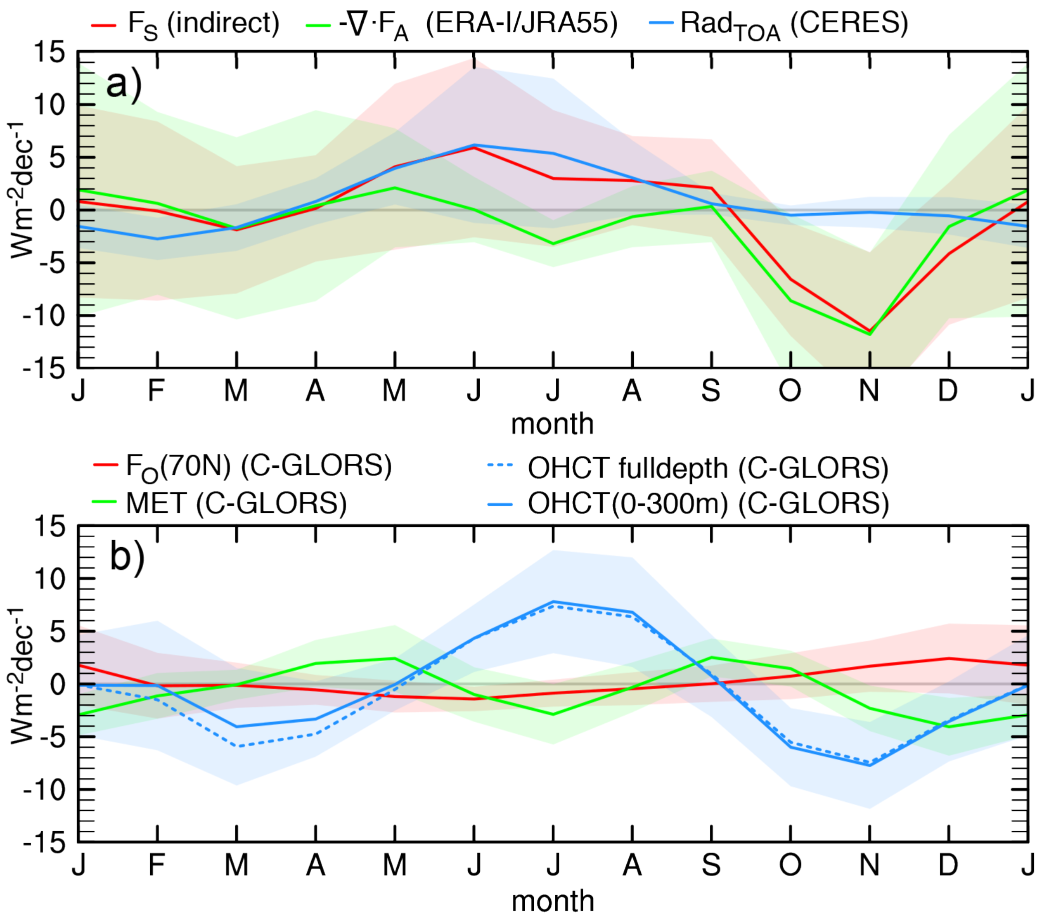
- Periods of weak and enhanced ocean energy take-up agree quite well
- Varying contributions from radiation and lateral transports

Preliminary look at ORAS5

- Very good agreement in upper 700m, below not so good



Arctic average seasonal trends 2000/03 – 2015/02



- Clear trend of atmospheric transports and surface fluxes in fall
- Significant amplification of oceanic annual cycle
- Weak trends in ocean heat transport

Mayer, M., L. Haimberger, M. Pietschnig, and A. Storto (2016), Facets of Arctic energy accumulation based on observations and reanalyses 2000–2015, Geophys. Res. Lett., 43, 10,420–10,429, doi:10.1002/2016GL070557.

Part 3: Comparison of in-situ-based to reanalysis-based ocean transports through the main Arctic straits

Ocean Reanalysis vs. ARCGATE

- “ARCGATE” project at AWI: derive fluxes from permanently moored observations - volume, mass and freshwater
- Compare fluxes through the main Arctic gateways to C-GLORS ocean reanalysis

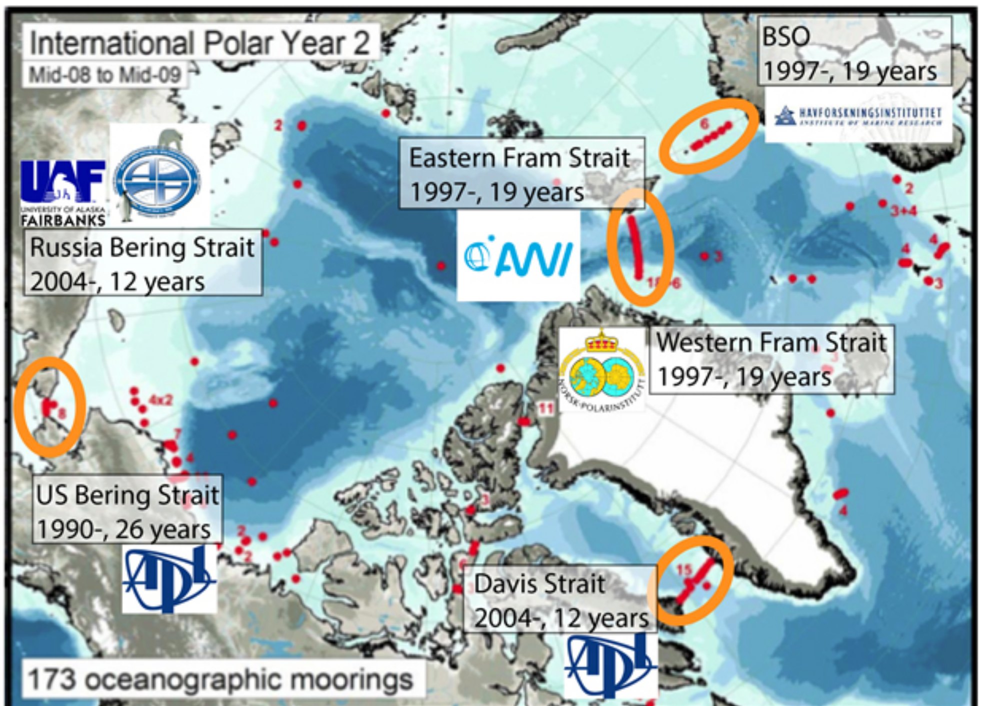
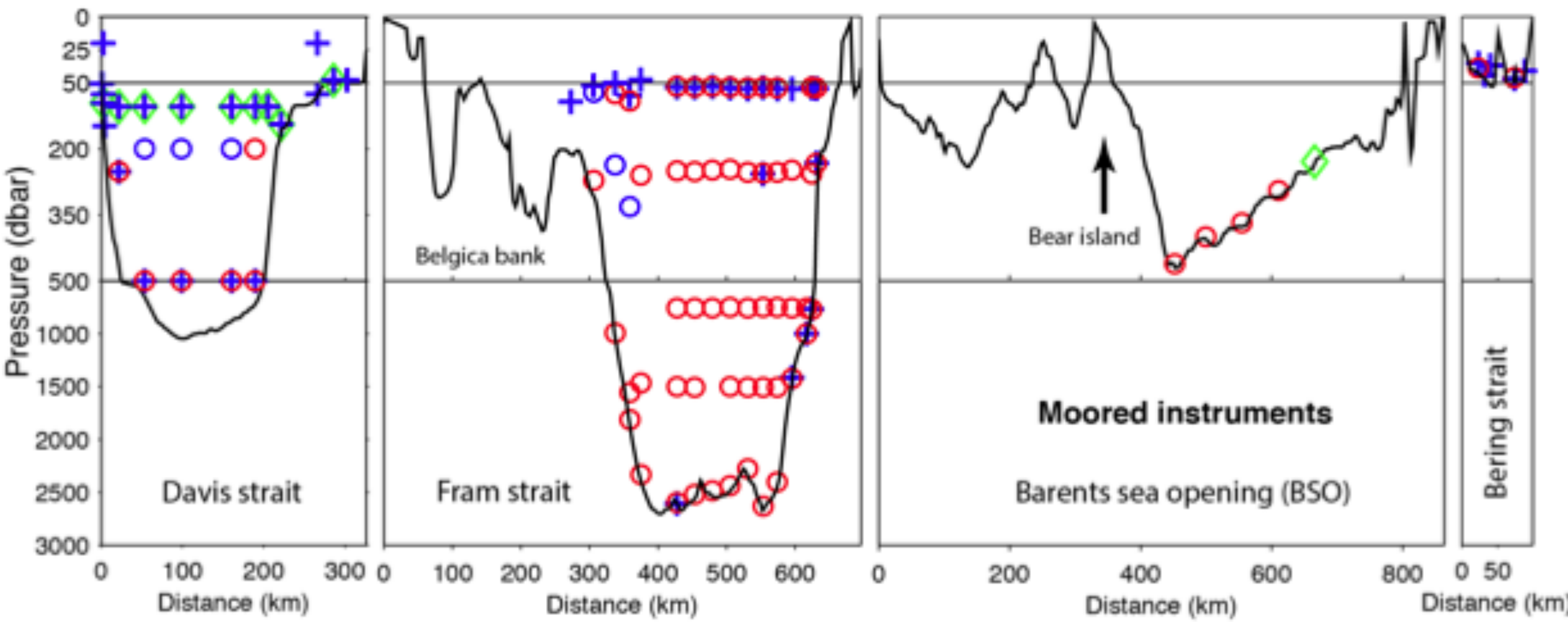


Figure from: https://www.awi.de/en/science/climate-sciences/physical-oceanography/projects/arcgate.html

ARCGATE instrumentation

- Locations of moored instruments in each Arctic gateway
- Measurements complemented with ship observations (BSO)



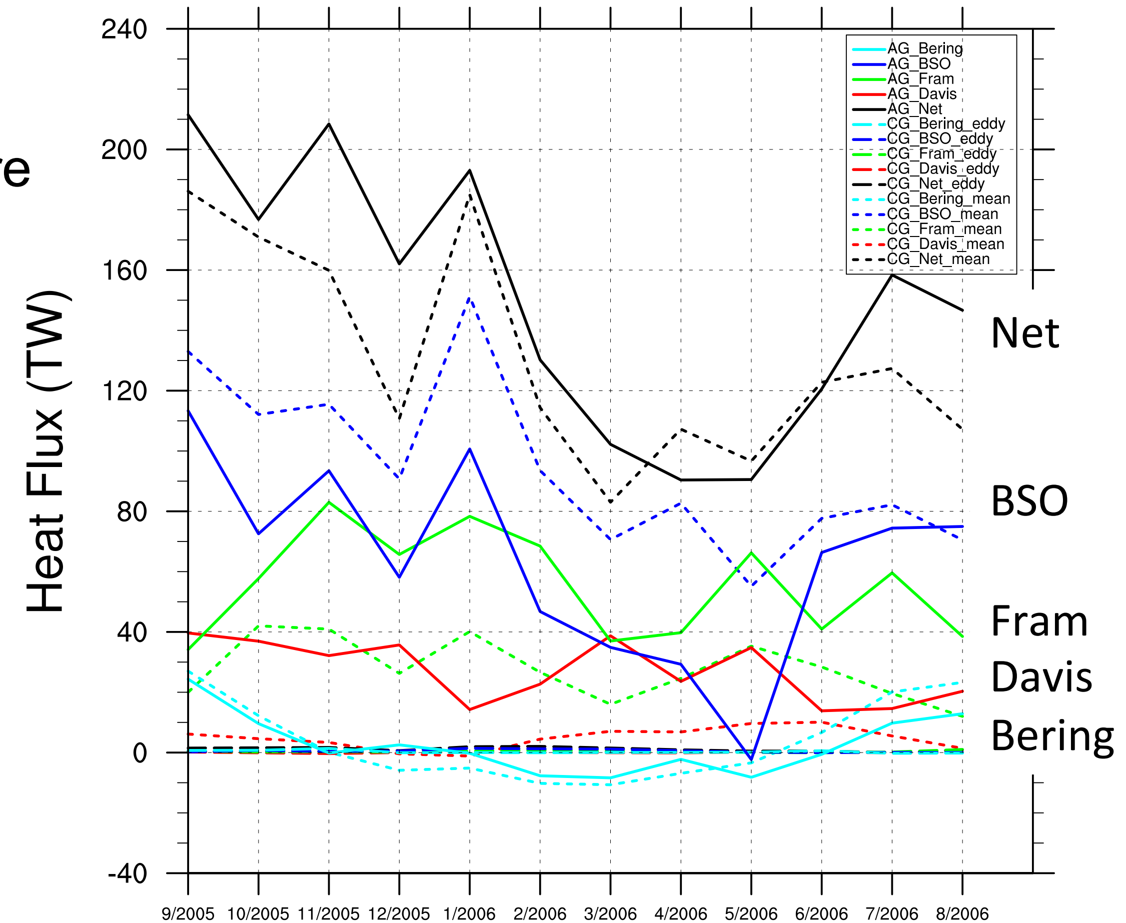
Courtesy of T. Tsubouchi (Tsubouchi et al. 2016)

Comparison of heat transports

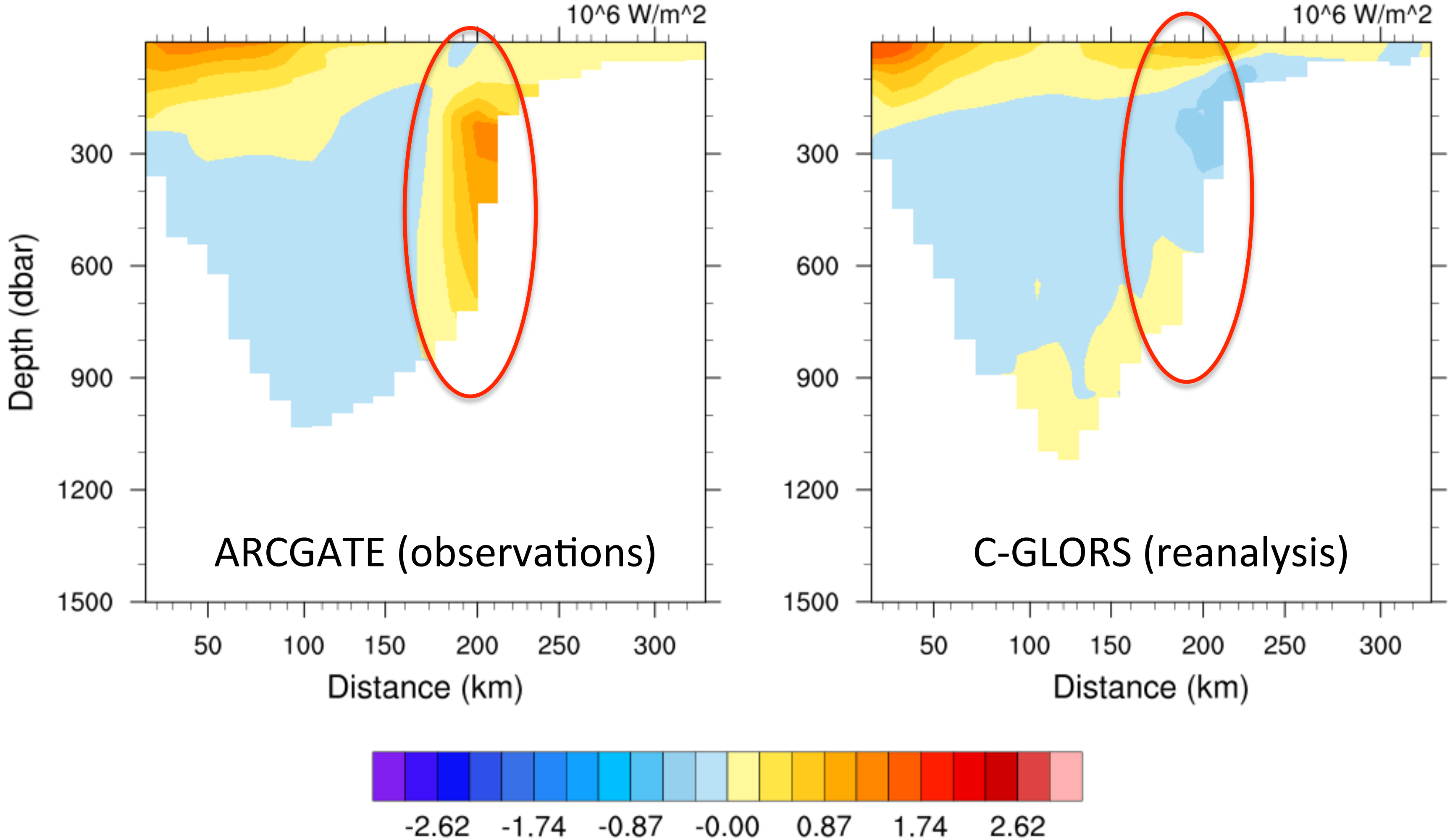
- Use monthly T and velocity fields
- Same reference temperature

$$\overline{T\mathbf{v}} = \overline{T_{ref}}\overline{\mathbf{v}} + \overline{T'\mathbf{v}'}$$

- Net mass flux close to zero
- Largest differences in
  - Barents Sea Opening
  - Davis Strait



Davis Strait: Heat Flux



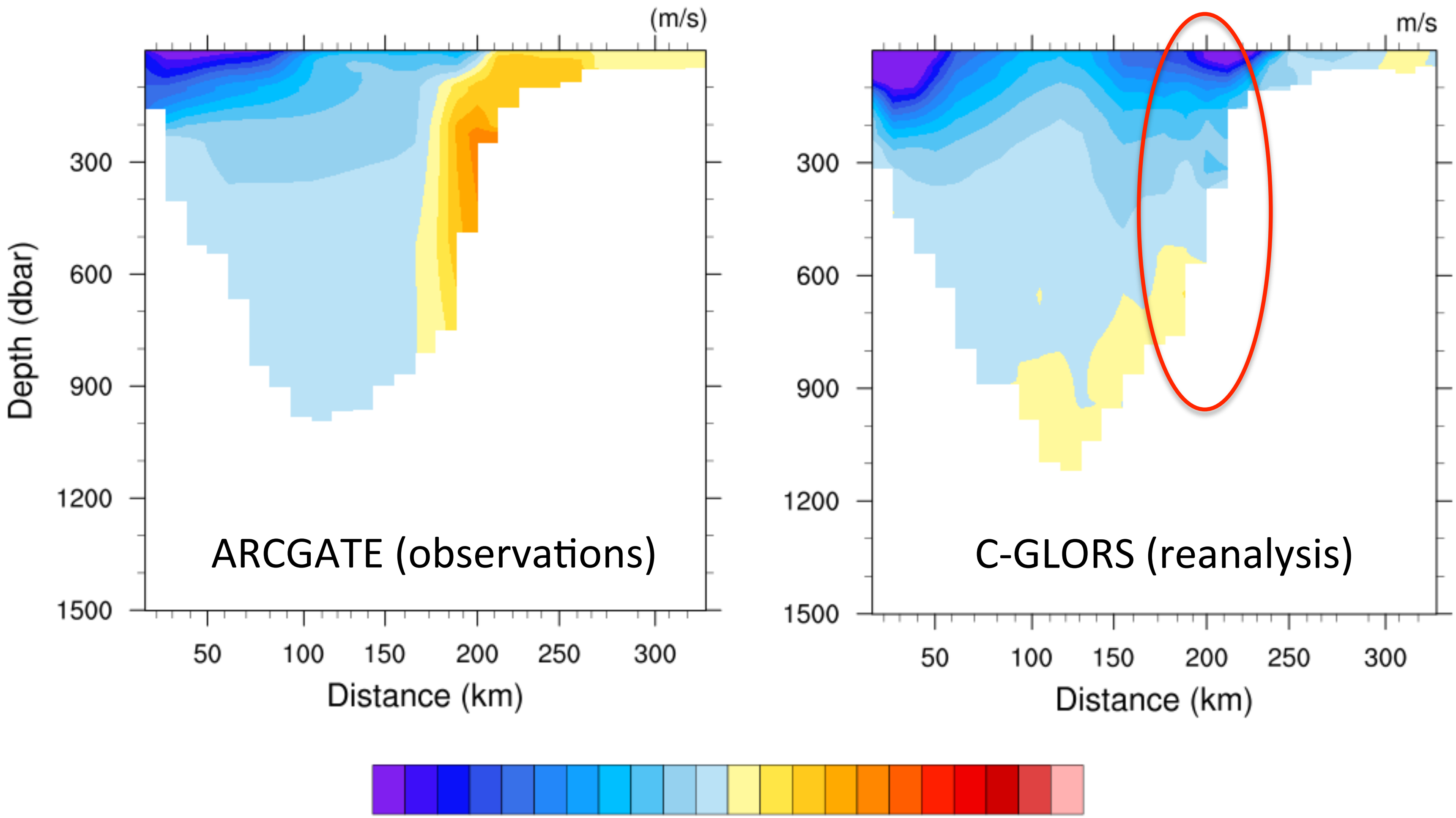
From Pietschnig et al. (2017) to be submitted

Conclusions and Outlook

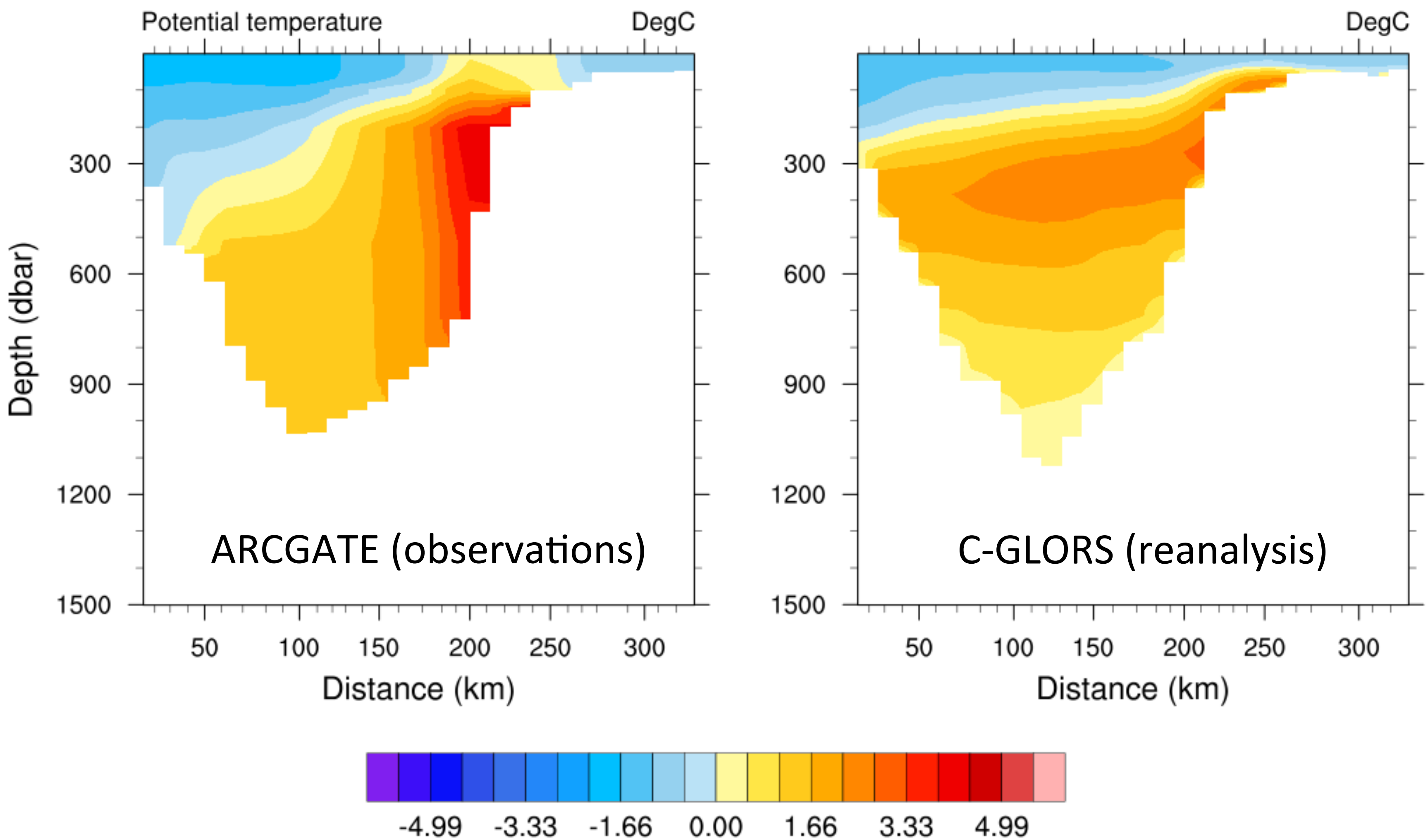
- Further scrutinize energy budget formulations – there are also other missed terms like latent heat flux due to snow fall
  → Activity can be seen as steps towards CMIP6 requirements
  → paper in preparation
- Arctic trend paper recently published in GRL
  → explore this further using ORAS5
  → also extend study period backward using CERA-20C
- Extend study period of ARCGATE comparison to full six years
  → Assessment of variability
  → Include also other products
  → paper in preparation

→ This diagnostic work links WP2 and WP4

Davis Strait: Volume Flux



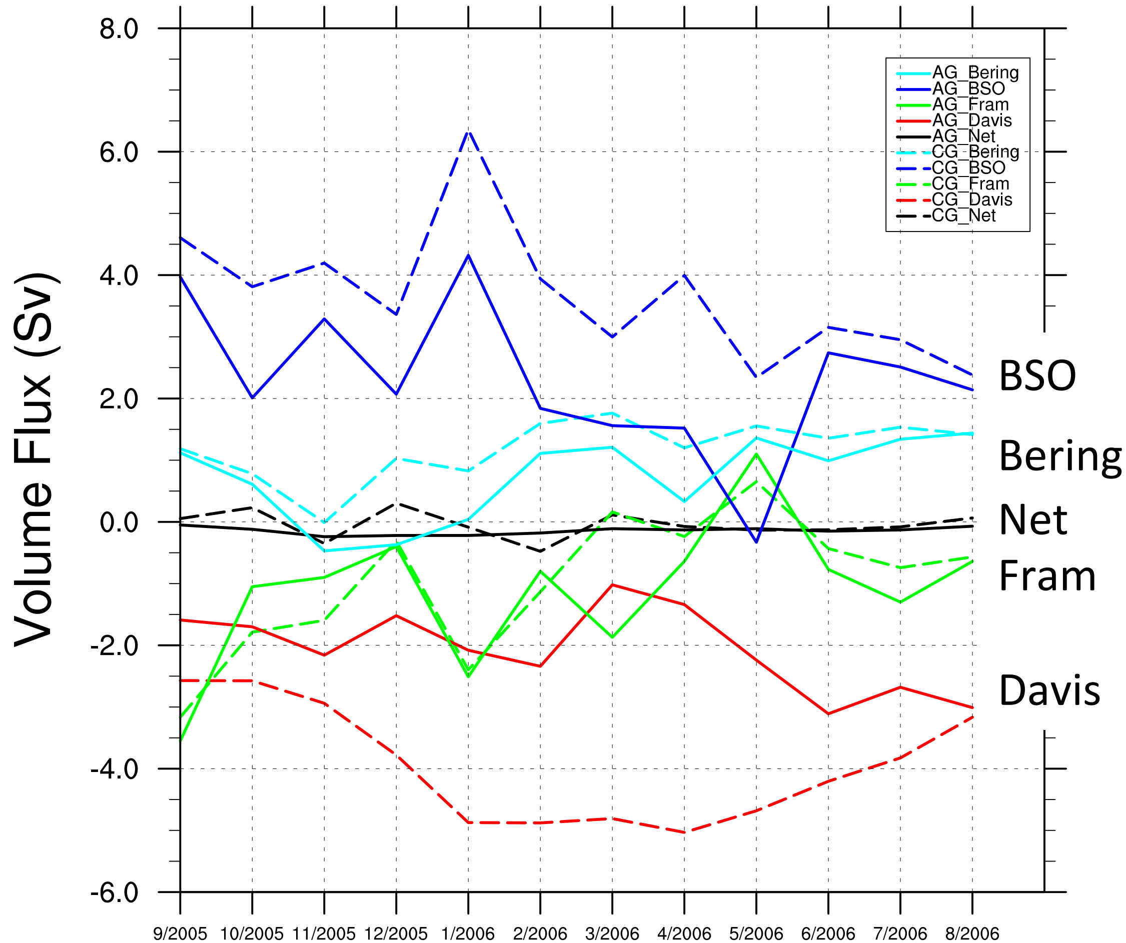
Davis Strait: Temperature



Comparison of volume transports

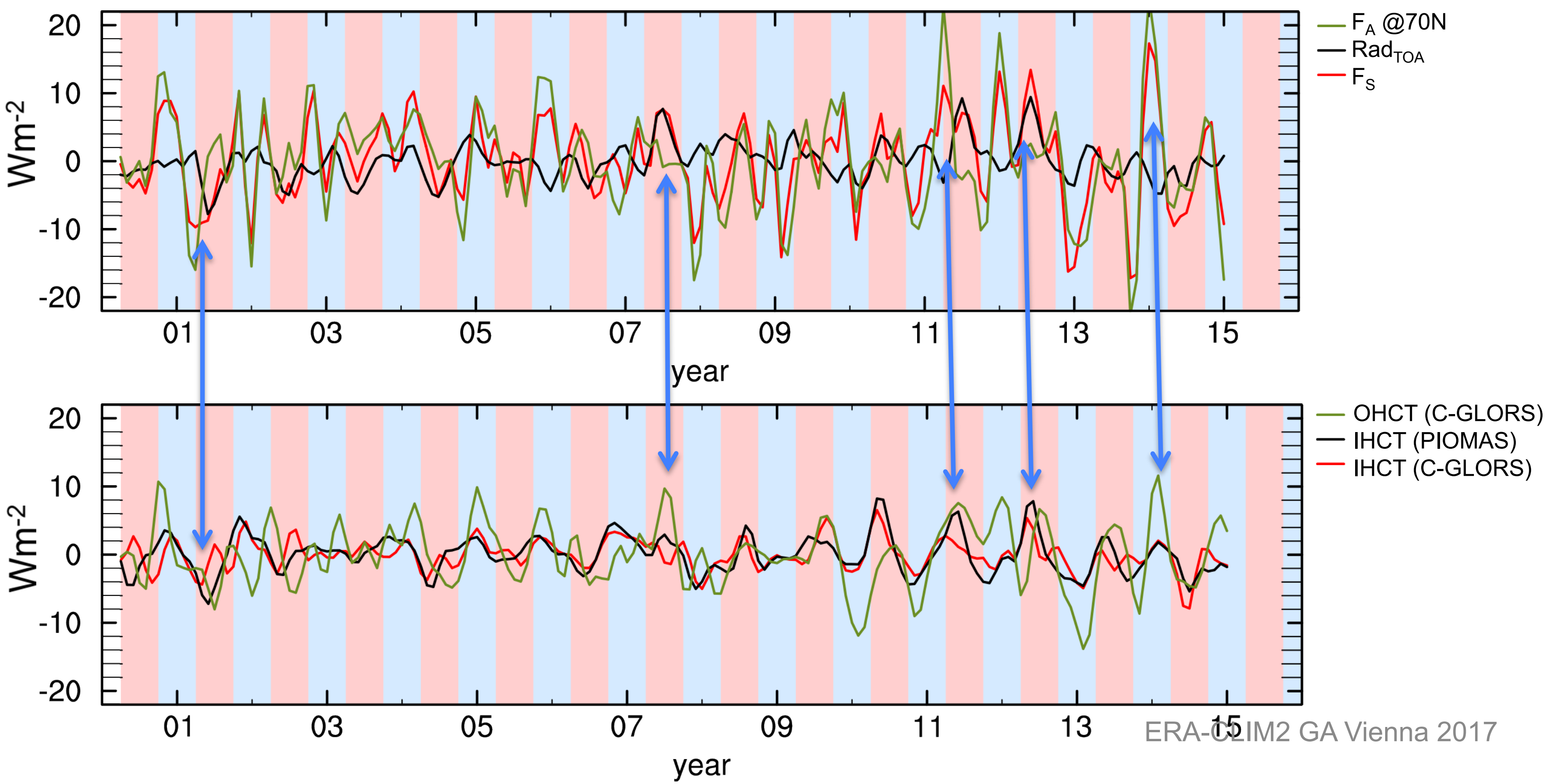
- Pos. = Arctic inflow
- 1 Sv = 10^6 m^3/s
- Reanalysis (dashed)
- Observations (solid)

- Largest differences in
  - Barents Sea Opening
  - Davis Strait
- Net flux close to 0 Sv
  - approx. – 0.1 Sv

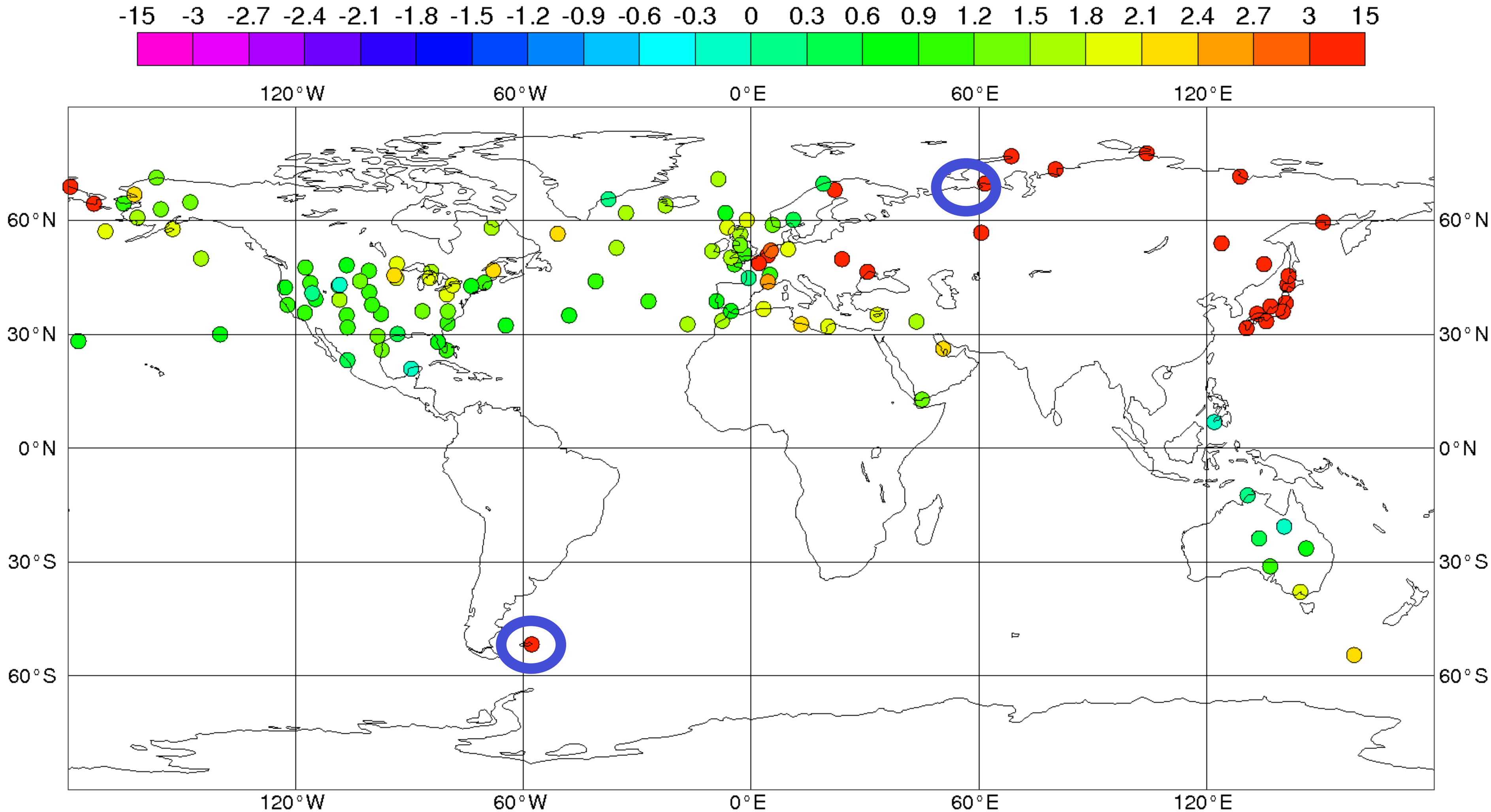


Variability: Budget time series for 70N-90N

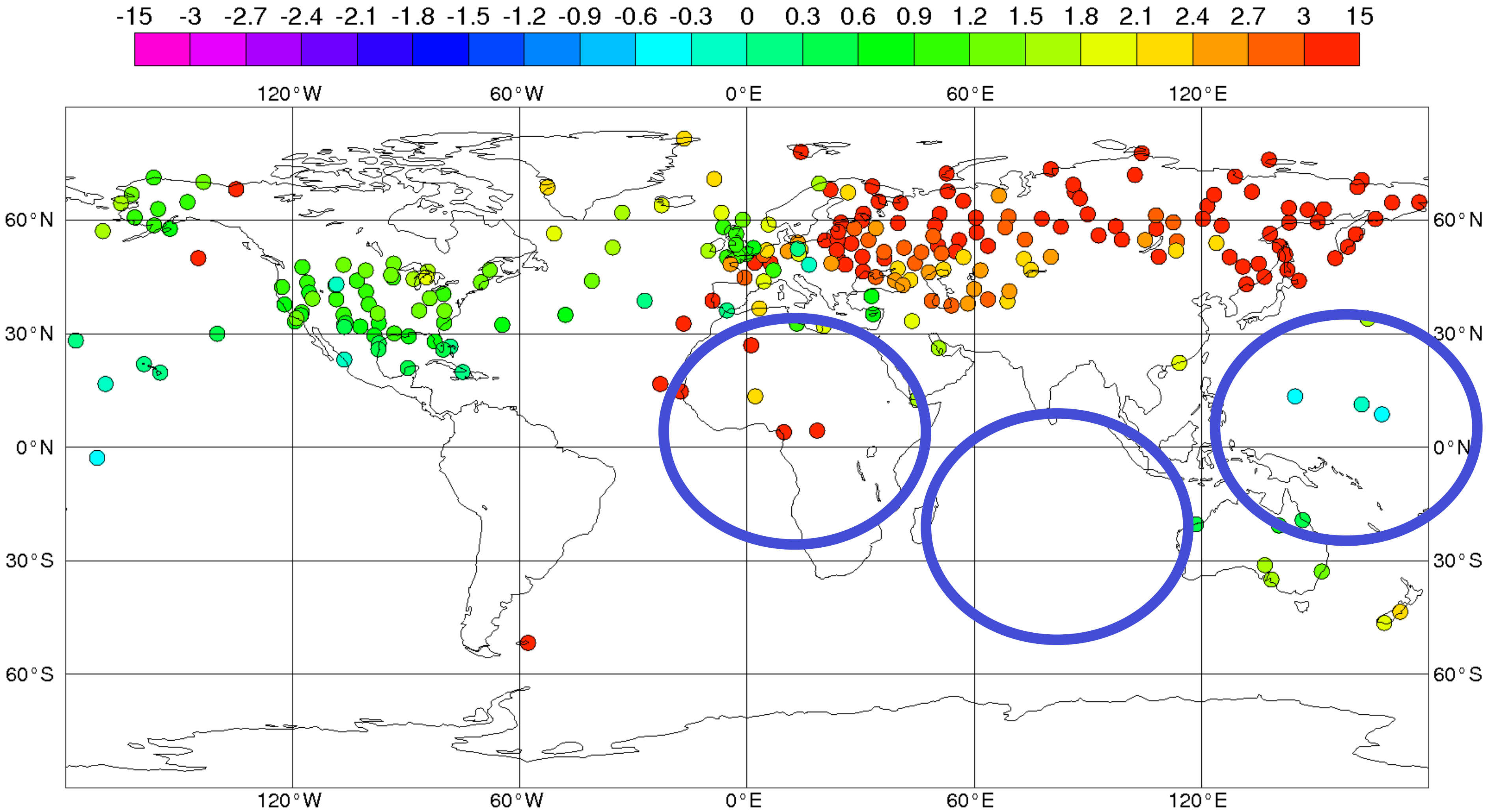
- Also clear relationship between surface flux and ocean energy terms!



Radiosondes – CERA-20C, 300hPa, 1949-1950

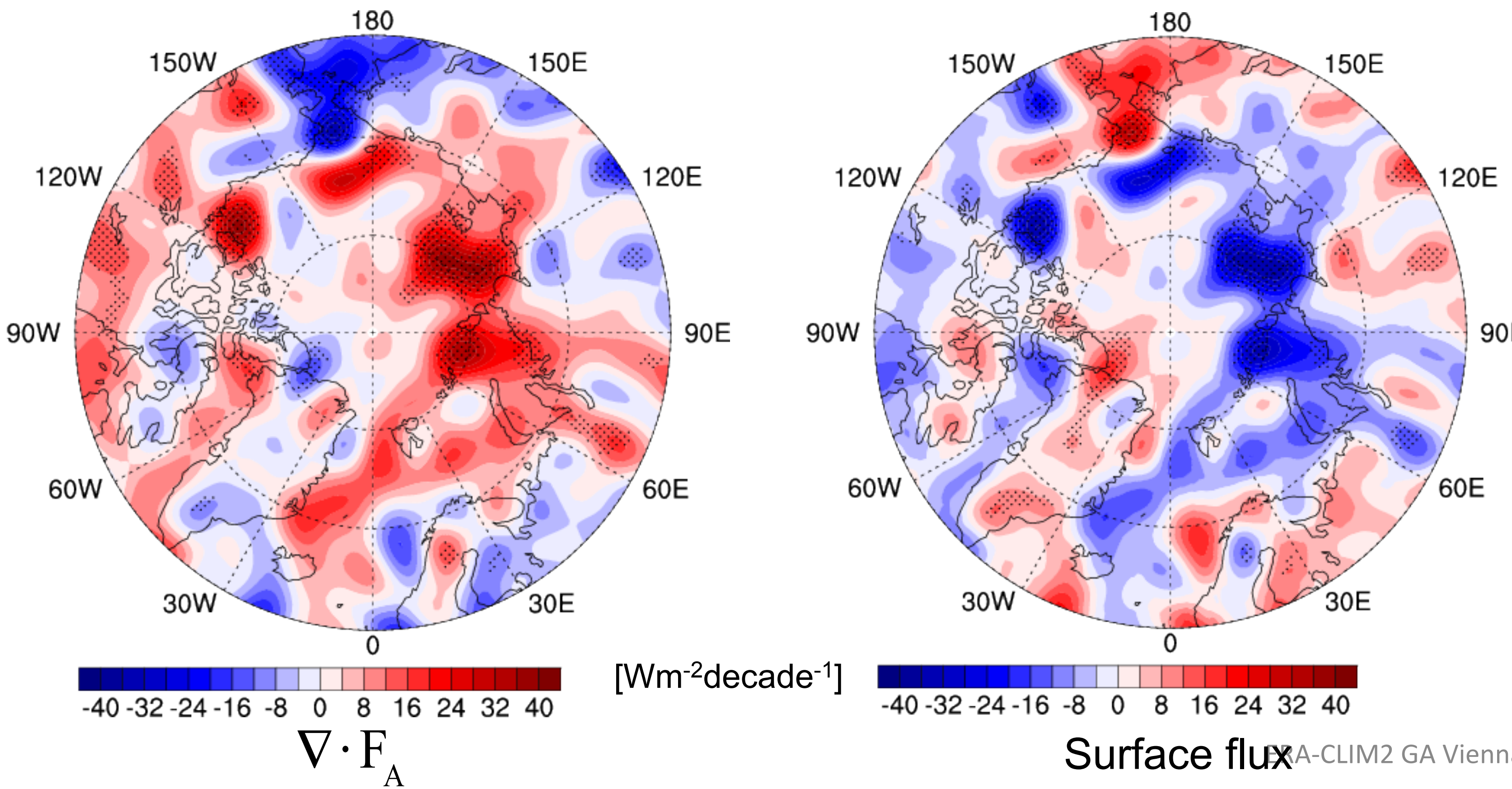


Radiosondes – CERA-20C, 300hPa, 1954-1955



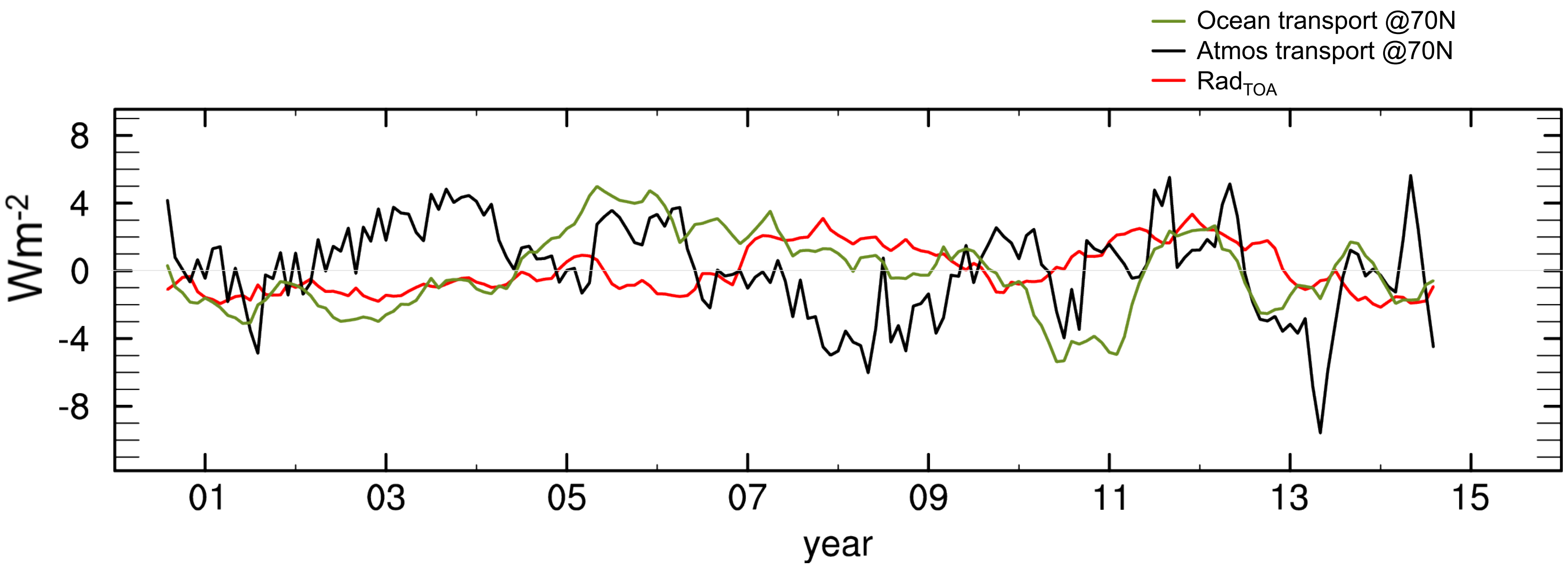
October trends

- Clear connection between October trends of atmospheric energy divergence and surface fluxes

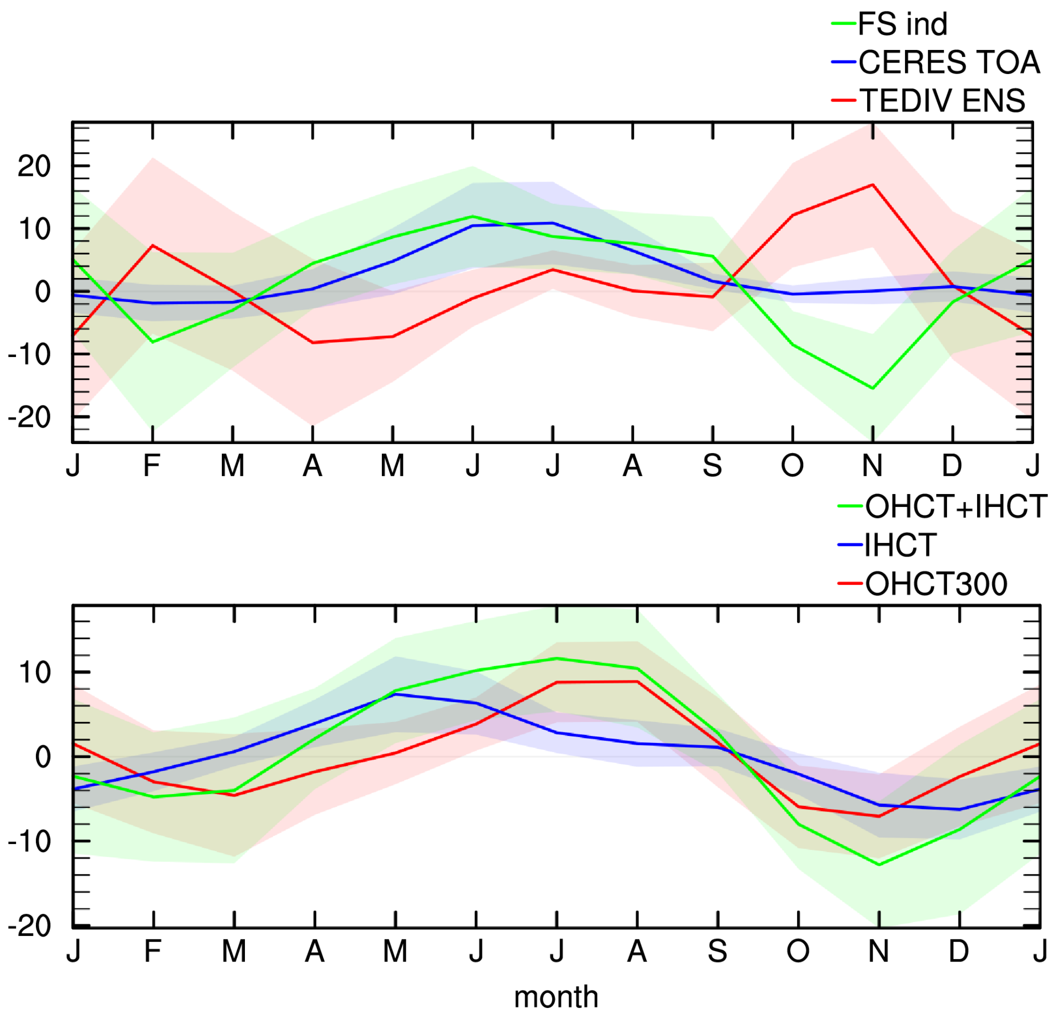


Contributions to storage rate

- Above zero flux anomalies mean enhanced storage contribution
- Increased TOA energy input after 2007
- Considerable variation in atmospheric and oceanic heat transports



Trends 2000/03 – 2012/02



The state of the coupled Arctic energy budget (70-90N)

- Add up atmosphere, ocean, ice equations and integrate over polar cap

$$\left\{Rad_{TOA}\right\} + F_A(70N) + F_O(70N) + F_I(70N) = \left\{OHCT\right\} + \left\{IHCT\right\} + \left\{AET\right\} + \\ + imbalance$$

- 2000-2014 averages:

Net heat flux into polar cap [Wm^{-2}]		**Heat storage [Wm^{-2}]**	
Rad_{TOA} (CERES)	-116.1±0.4		
F_A across 70N	95.3 (92.3,98.7)	atmosphere	0.1±0.1
F_O across 70N	19.9 (18.5,22.5)	Ice melt	0.3±0.3
F_I across 70N	≈3 (Serreze et al 2007)	Ocean heat content	0.7±0.5
Sum of fluxes	**2.1±0.9**	**Storage sum**	**1.1±0.6**

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- **Sampling uncertainty is small, but structural uncertainties are likely large!**

Atmospheric energy budget

- Energy conservation in the vertically integrated atmosphere:

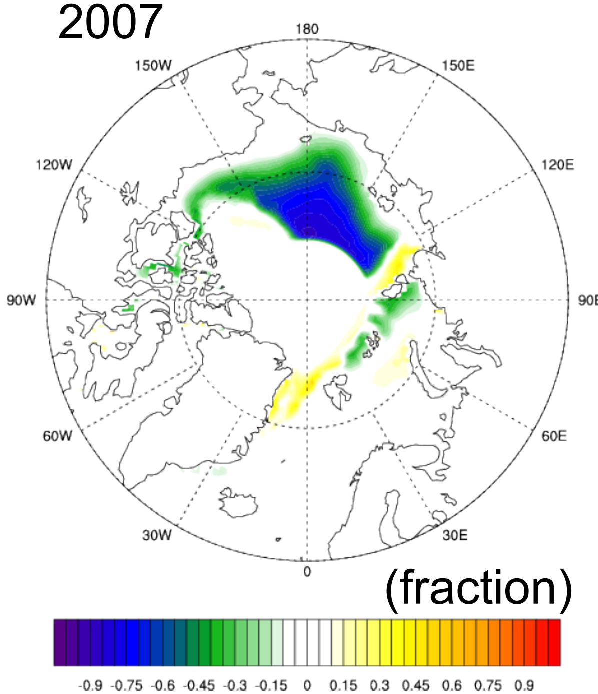
$$\underbrace{\frac{1}{g}\int_0^{p_s}\nabla\cdot\overbrace{(c_pT+\phi+k+Lq)\mathbf{v}_2}^{F_A}dp}_{\text{DIVFA}}=\underbrace{(ASR+OLR)}_{Rad_{TOA}}-\underbrace{\frac{\partial}{\partial t}\frac{1}{g}\int_0^{p_s}(c_pT+\phi_S+k+Lq)dp}_{\text{AET}}-\underbrace{(LH+SH+Rad_S)}_{F_S}$$

- Compute DIVFA and AET from analyzed reanalysis fields: ERA-Interim, MERRA, JRA55
- Difficulty with computation of DIVFA: mass budget in reanalysis
- Rad_{TOA} and F_S from reanalysis or independent satellite data: CERES (soon: ERBE before 2000)

Example

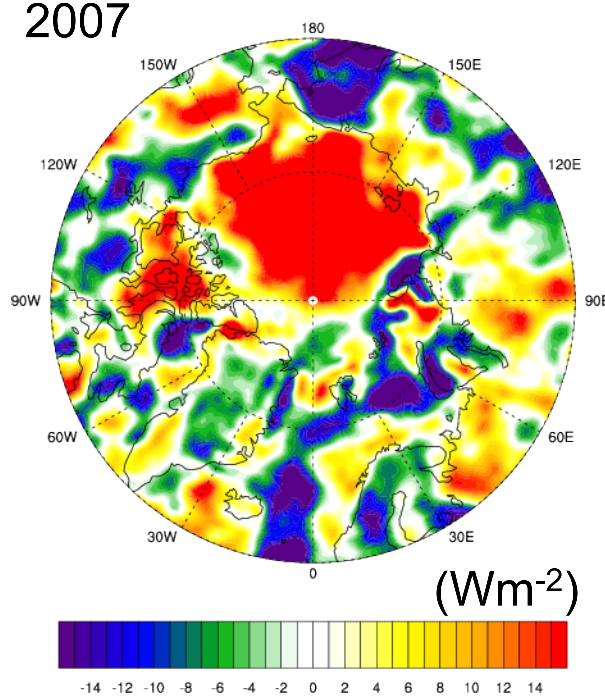
- Extreme case of very low sea ice extent in fall 2007
- Surface energy fluxes and Rad_{TOA} in JJA 2007 clearly resemble the pattern of sea ice anomalies in Sep 2007

Sea ice anomalies Sep 2007



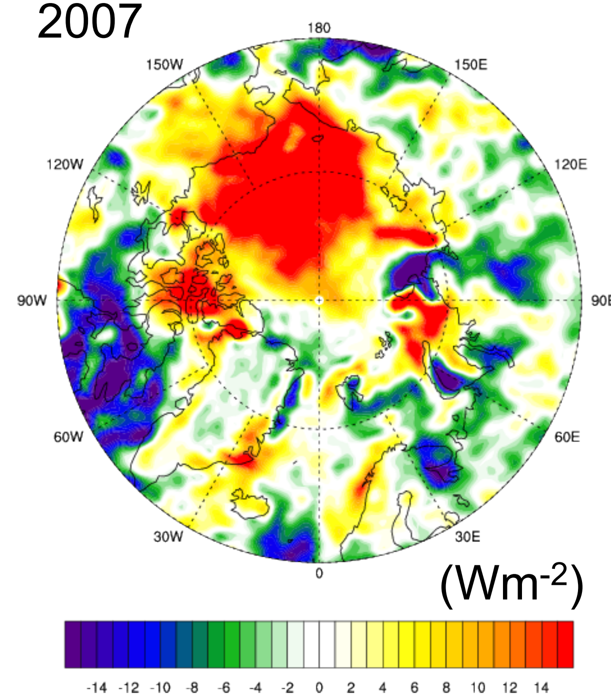
(data: ERA-I)

Surface flux anomalies JJA 2007



(data: CERES+ERA-I)

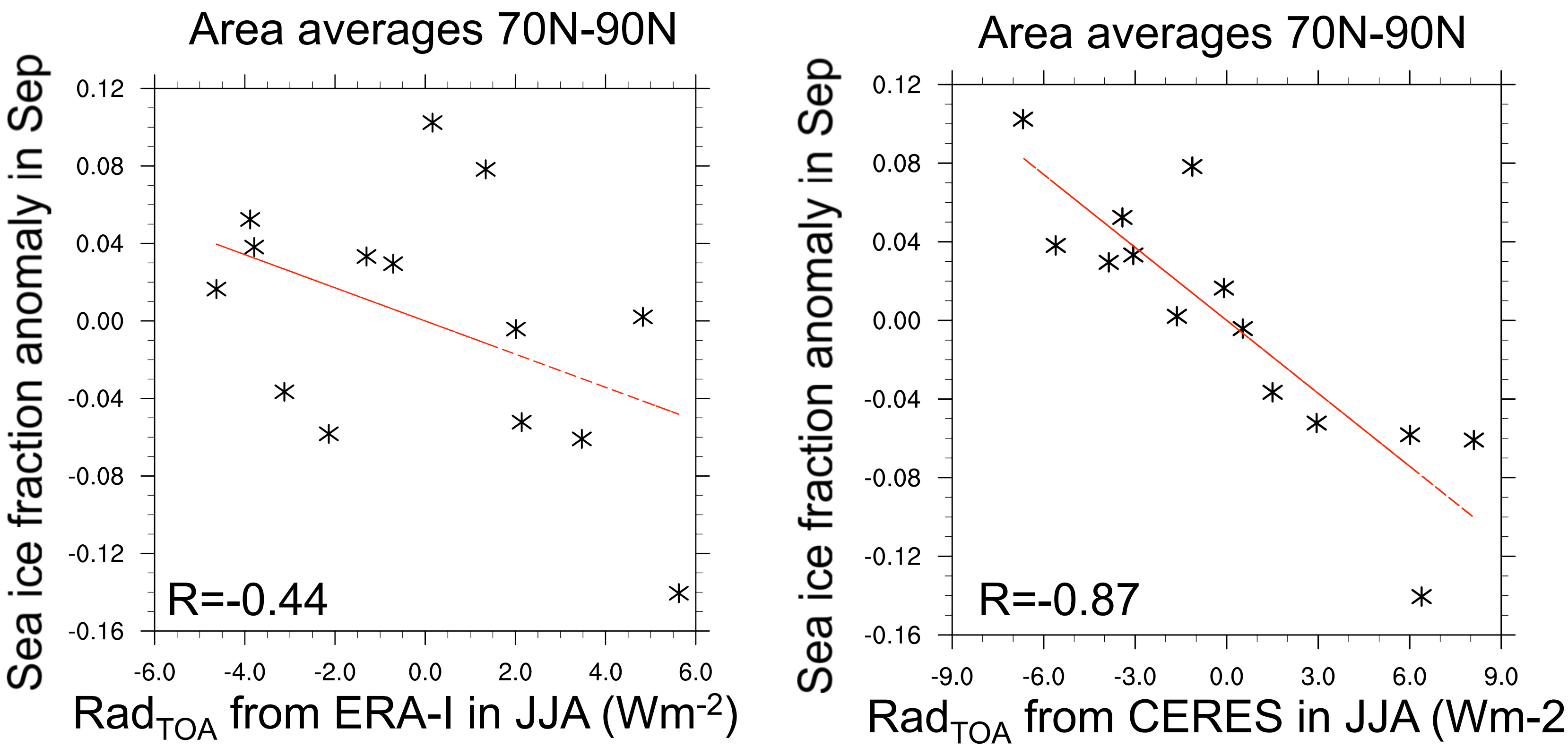
Rad_{TOA} anomalies JJA 2007



(data: CERES)

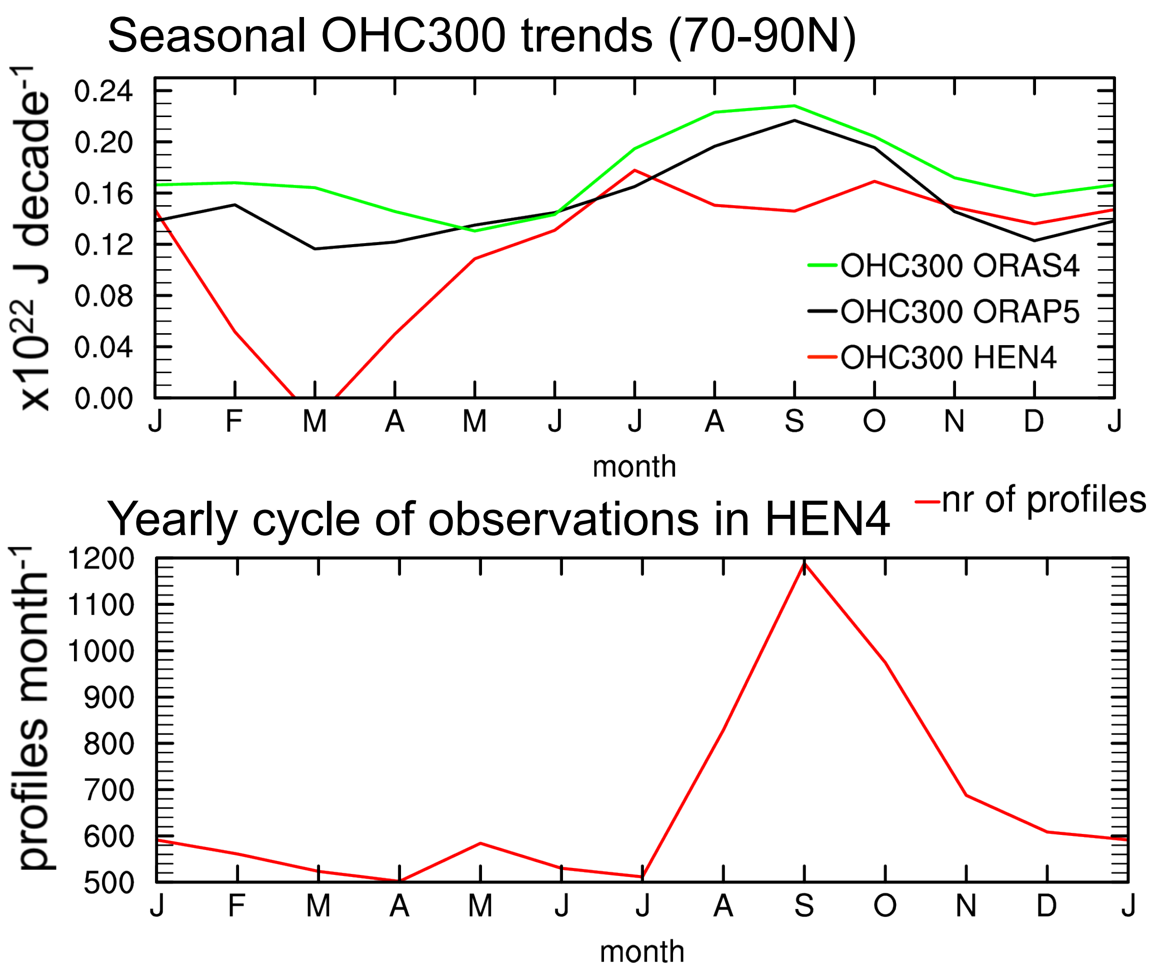
Radiation at TOA and sea ice extent

- Summer (JJA) Rad_{TOA} clearly has strong impact on September sea ice extent
- Reanalysis has difficulties to show this, probably due to cloud biases



Upper ocean heat content trends 2000-2014

- Different estimates for end-of-melt-season OHC trends agree quite well
- Lack of spring trends in Hadley EN4 demonstrates importance of dynamical ocean reanalysis to carry information forward in time



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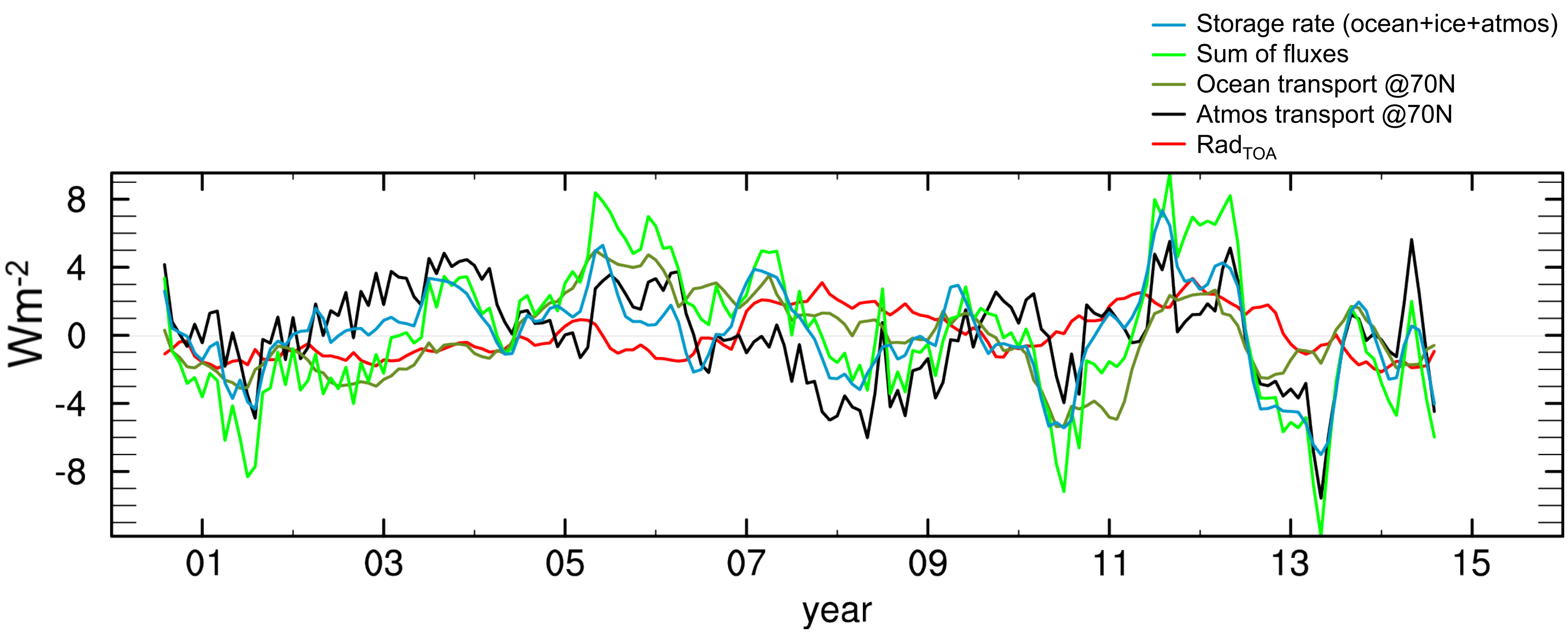
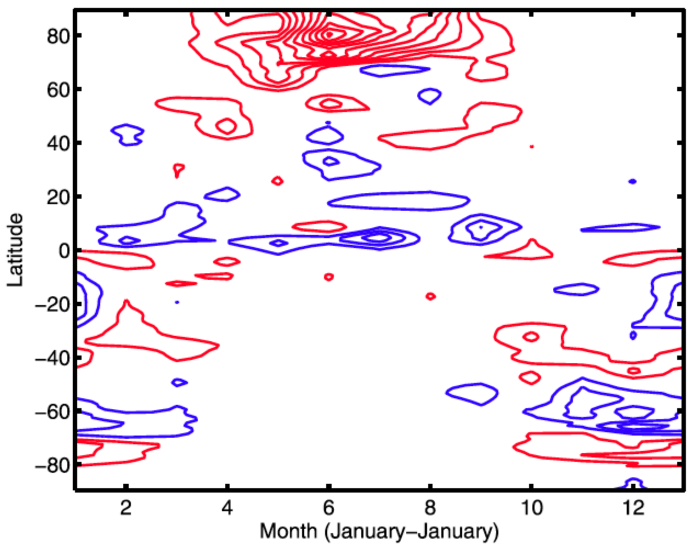


Motivation and outline

- Arctic climate system is subject to rapid changes and large interannual variability
  - How does this affect its energy budget?
  - Investigate the observations-based coupled energy budget of atmosphere and ocean, including sea ice

→ Quantify accumulation of energy in the Arctic

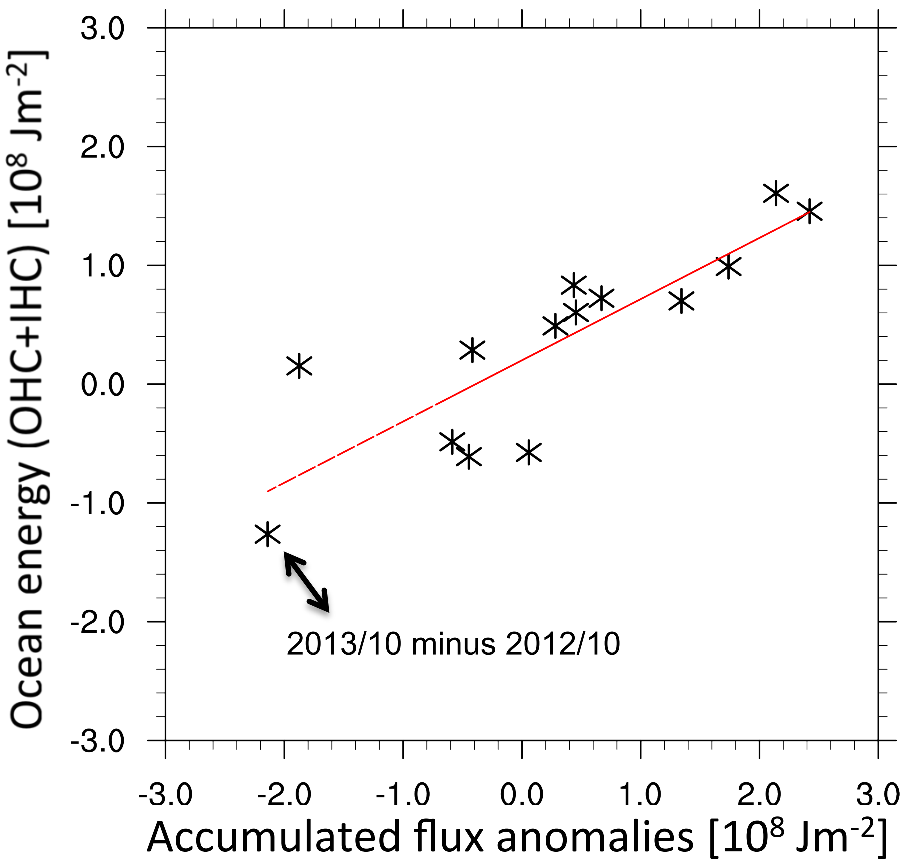
→ Diagnose variability and trends in energy flows 2000-2015



Decadal trends of reflected SW radiation 2000-2013 (from Hartmann and Ceppi 2014)

Storage anomalies vs flux anomalies

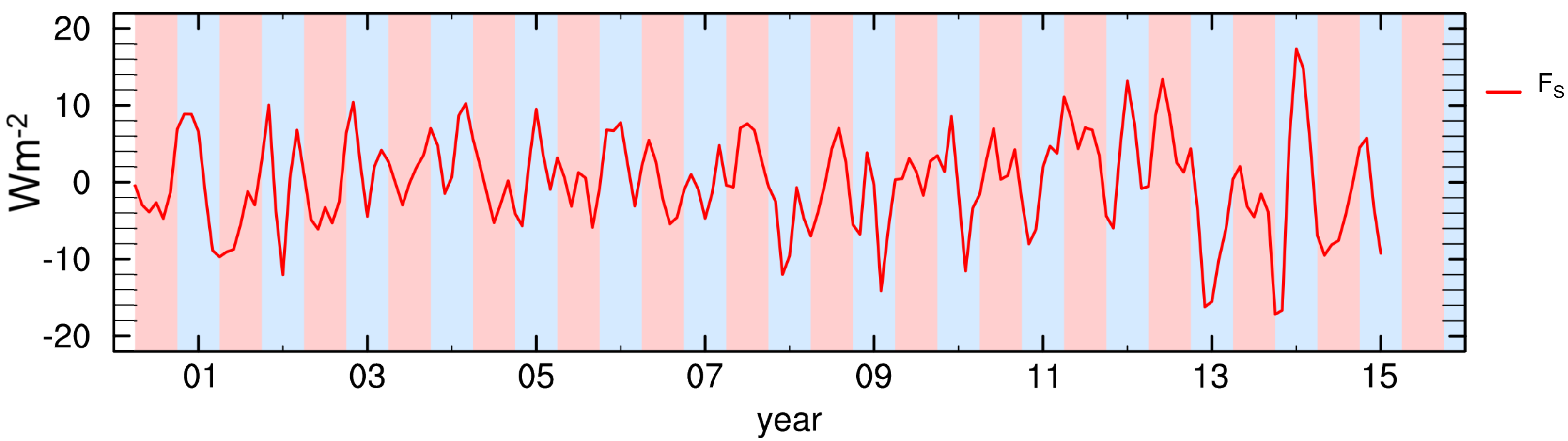
Year-to-year (Oct-Oct) storage (2000-2014)

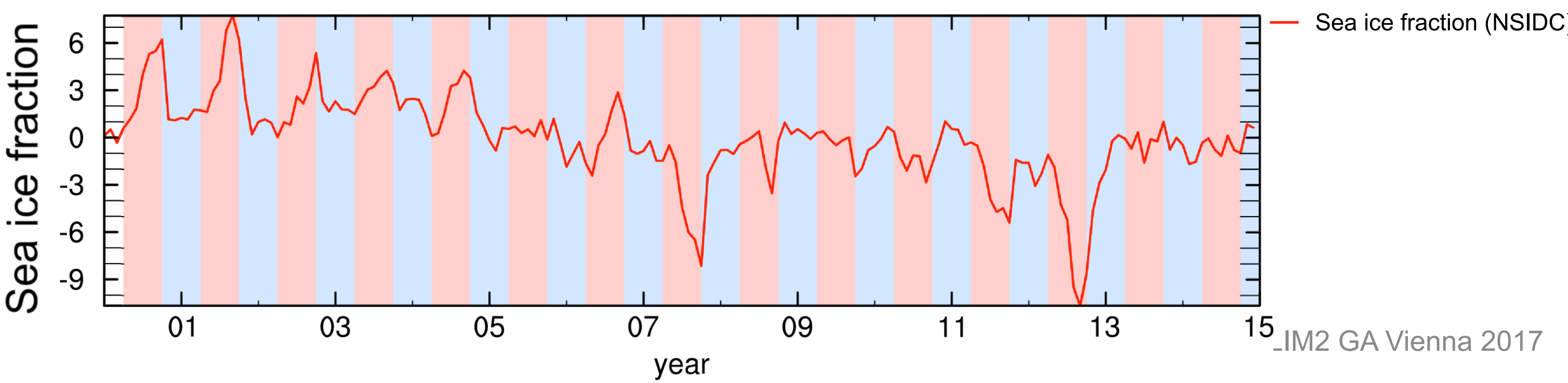


- Good qualitative agreement between annual variation of accumulated energy changes in the arctic cap (r=0.83)
- Ocean energy variance lower than flux variance → regression coefficient only ~0.5 Jm^{-2}/Jm^{-2}

Variability: Budget time series for 70N-90N

- Clear relationship between surface energy flux and sea ice extent





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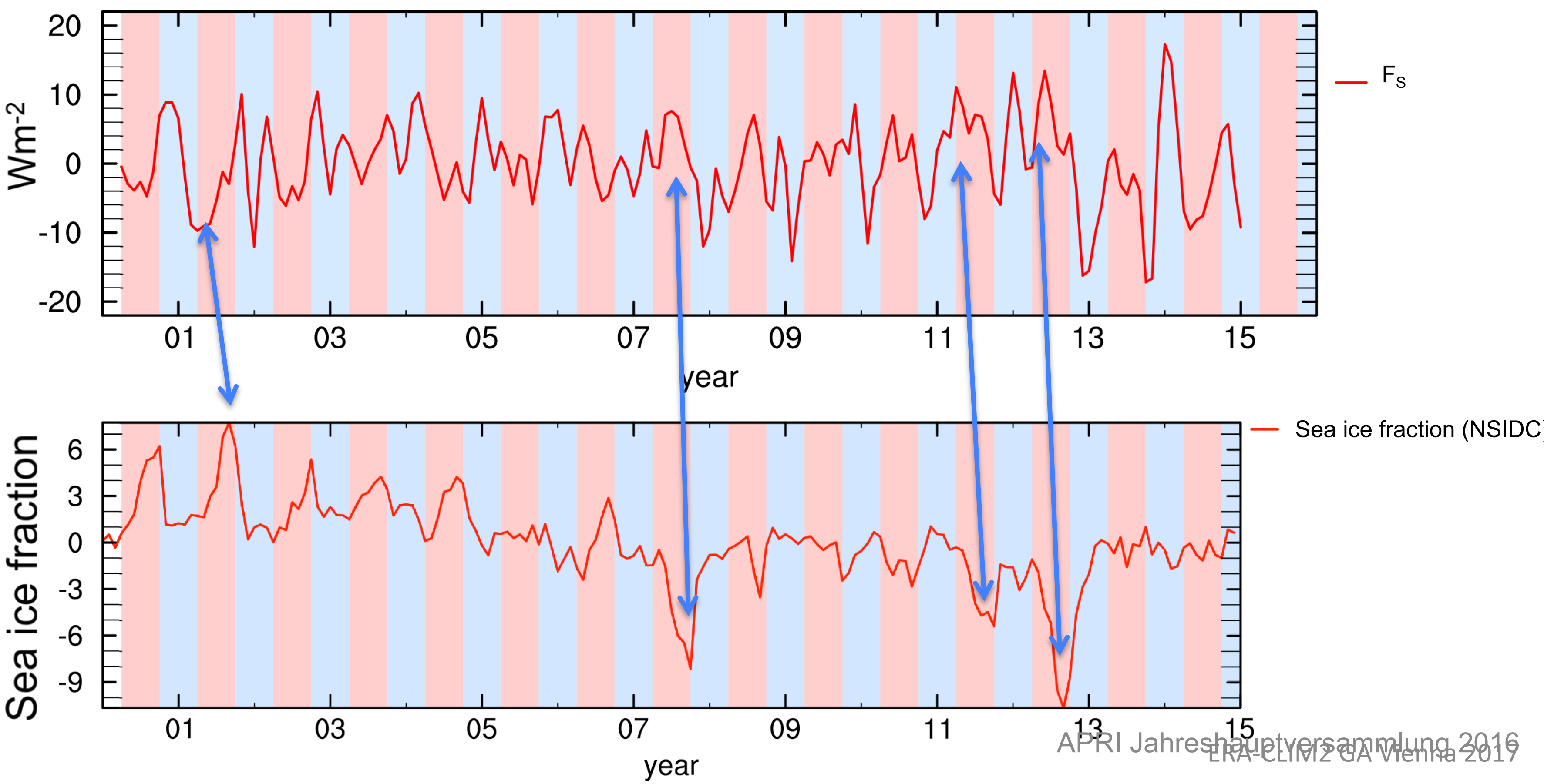
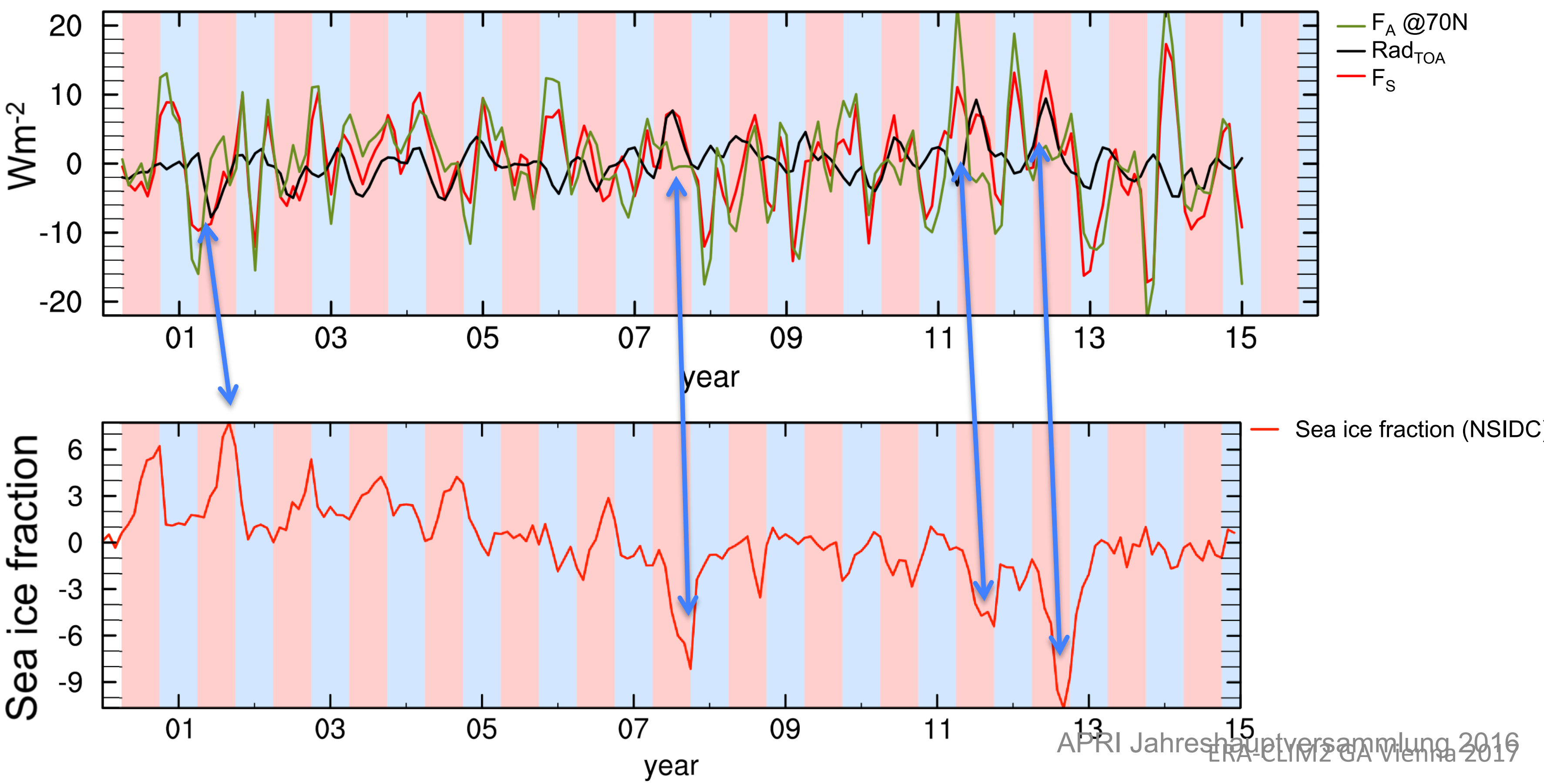


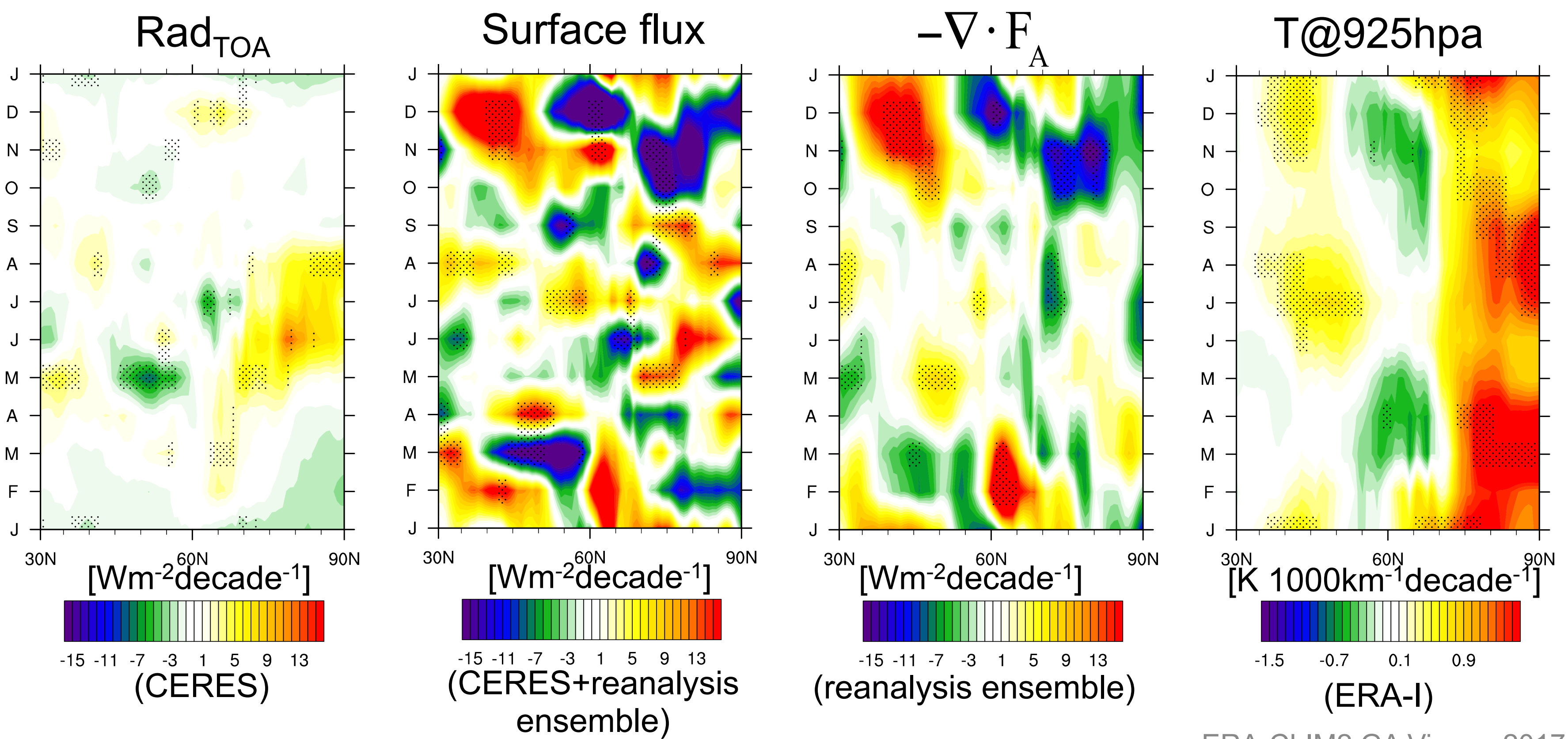
Variability: Budget time series for 70N-90N

- Clear relationship between surface energy flux and sea ice extent
- Atmospheric energy transport exhibits strong variability, especially associated with low ice extents in 2011, 2012



Seasonal trends: atmosphere

- Positive summer trend of F_S driven by Rad_{TOA} → ice-albedo feedback
- Negative autumn trend of F_S driven by atmospheric energy convergence – associated with decreased baroclinicity



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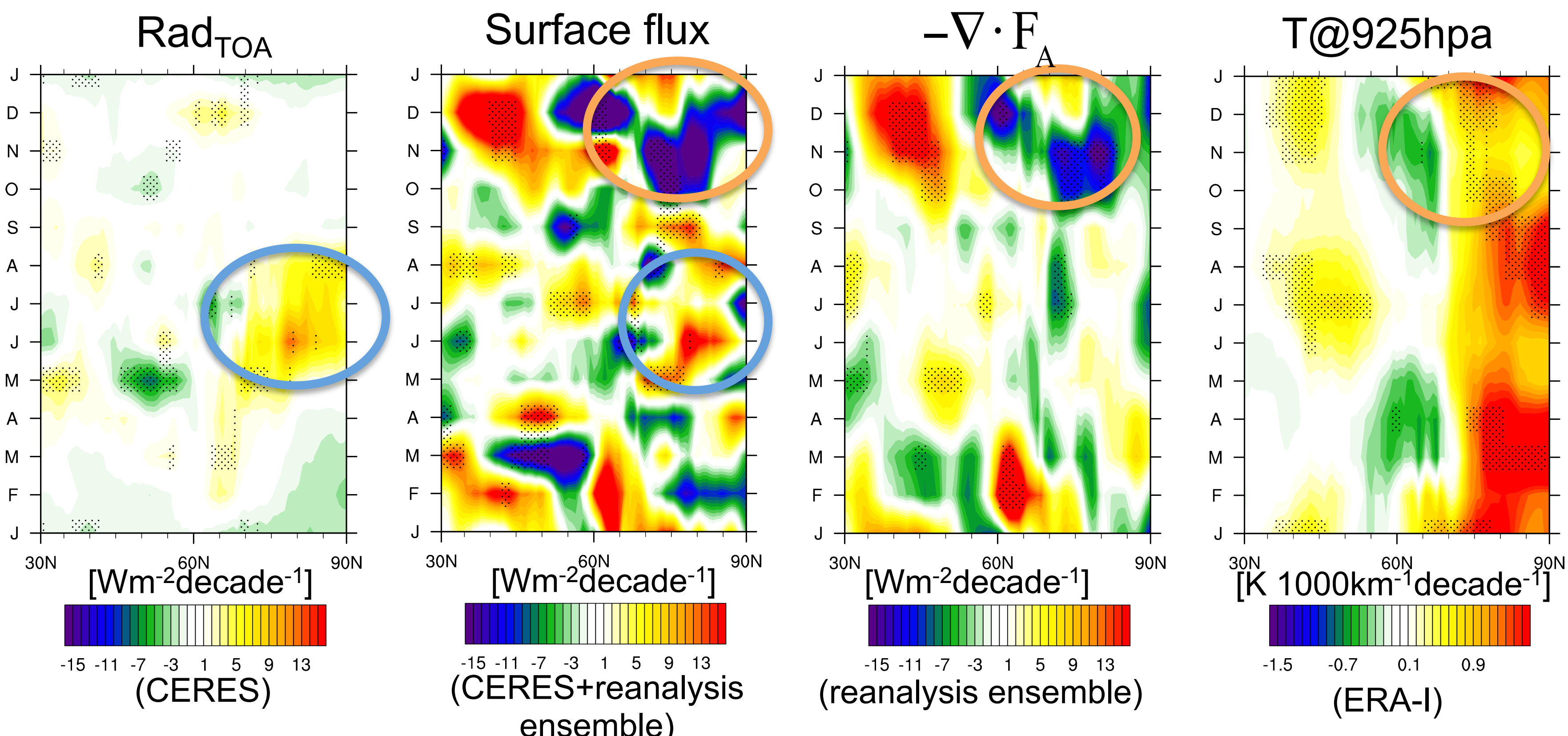
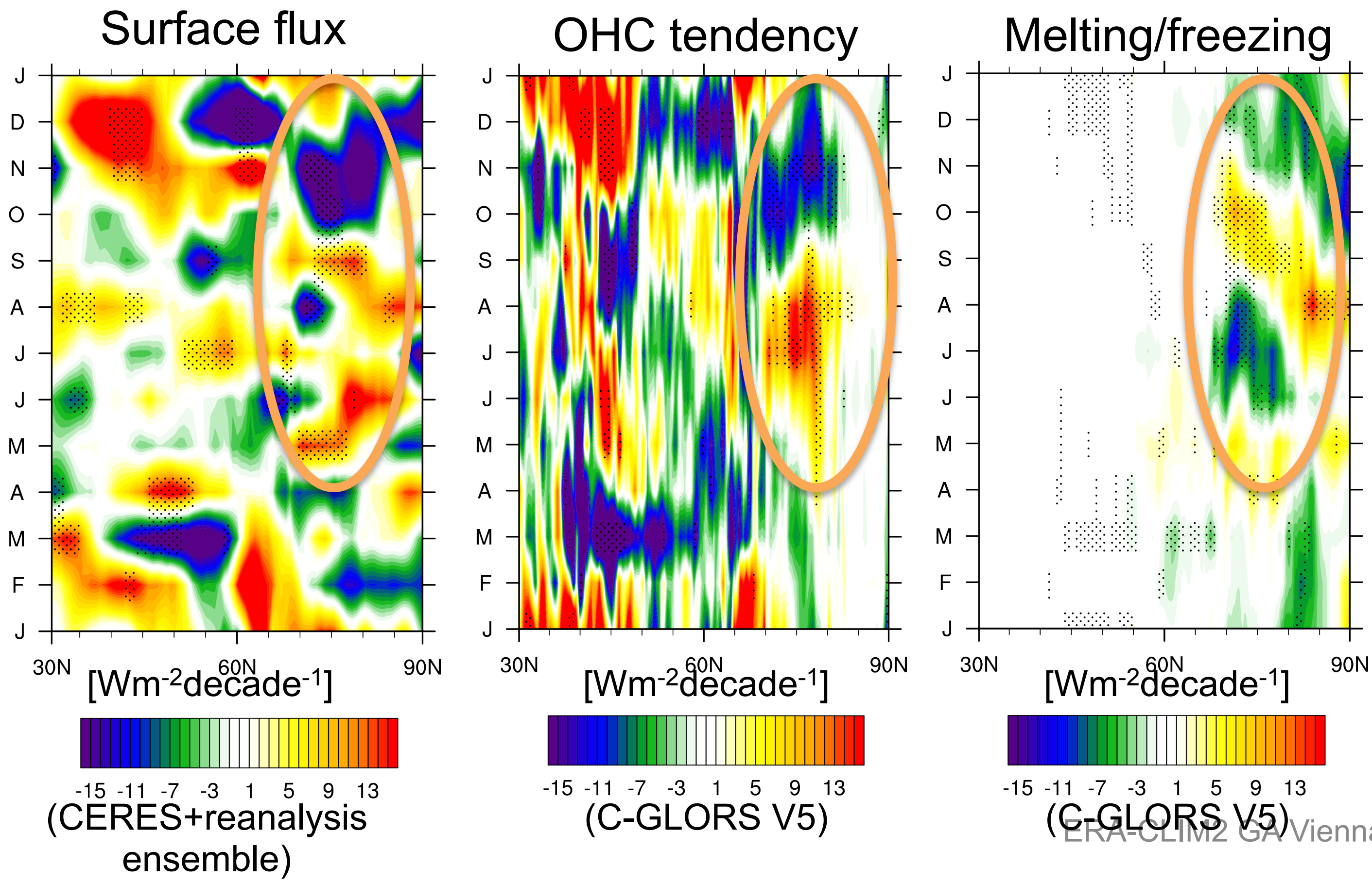


Seasonal trends: ocean and ice

- Changes in energy used for melting/freezing consistent with F_S changes – interesting temporal structure in ice melt trends
- Very noisy OHCT trend picture



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