Requirements for tracing energy flow variability in atmosphere, ocean and cryosphere

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1. Introduction

The vertically integrated energy budget equations for atmosphere, sea ice and ocean read as:

$$DIVFA = Rad_{TOA} - F_s - AET$$
$$DIVFO = (1-f_i)F_s + f_i F_{IB} - OHCT$$
$$DIVFI = f_i(F_s - F_{IB}) - IHCT$$

f_i is ice fraction, F_S is net surface energy flux F_{IB} is flux through sea ice bottom, *AET, OHCT, IHCT* are atmospheric/oceanic/ice energy tendencies, *DIVFA, DIVFO, DIVFI* are divergences of horizontal atmospheric/oceanic/sea ice energy transports, *Rad_{TOA}* is net radiation at TOA

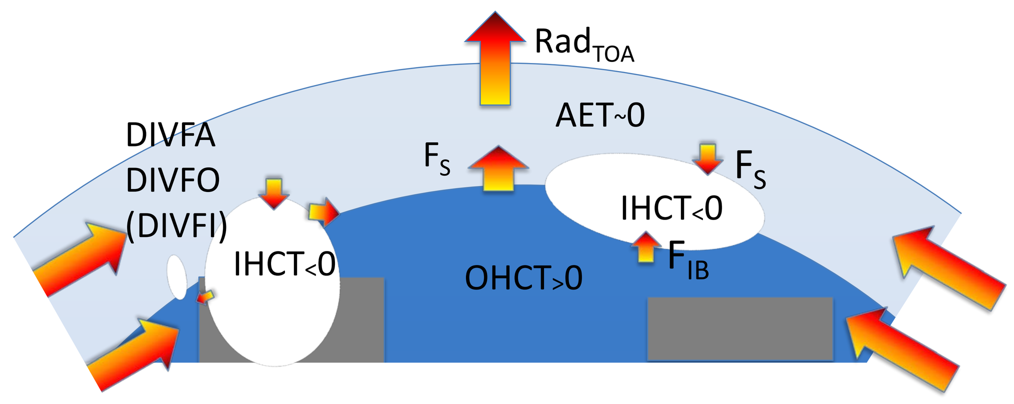

Fig. 1: Schematic of energy budget components of arctic ocean.

- *DIVFA* can be calculated directly (from reanalysed *u,v,T,q*) and is saved in most reanalysis archives. Mass flux adjustment is needed, however (Mayer and Haimberger, 2012). Highly useful e.g. for estimating surface energy flux F_s (Fig. 2), DIVFI is small.
- *DIVFO* is **NOT** available in current ocean reanalysis archives. Indirect estimate error-prone. Exceptions: e.g. arctic gateway array (Tsubouchi et al. 2012), selected global belt integrals

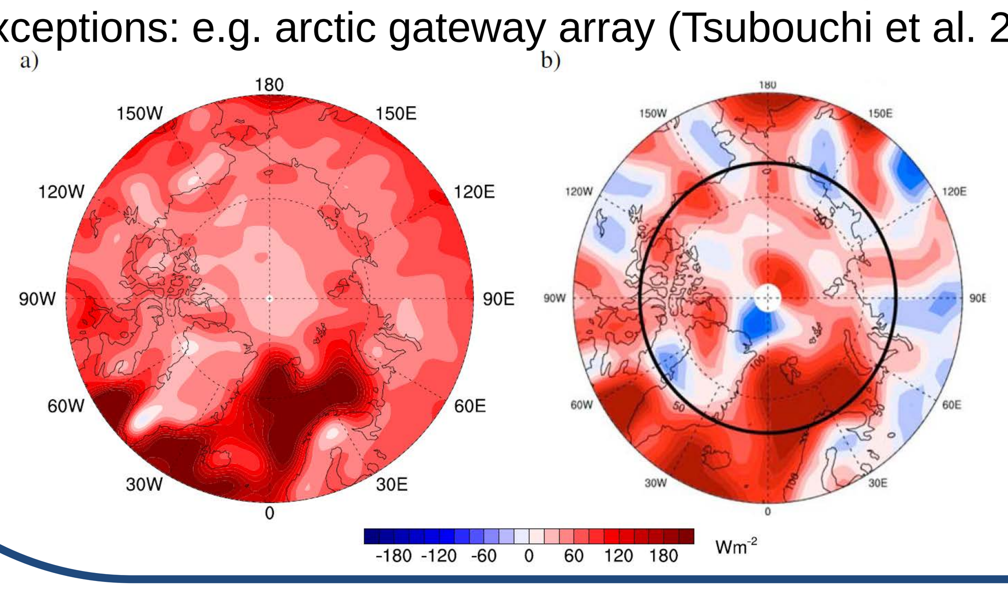

Fig. 2: Arctic F_s for January (2001-2005) indirectly estimated as residual a) from CERES Rad_{TOA} (Allan et al. 2014) and ERA-Interim *DIVFA* according to Mayer and Haimberger (2012), b) from Porter et al. (2010) without adequate mass adjustment

2. CMIP6 design (Griffies et al, 2015):

- It is .. the **convergence of a flux vector** into a region that causes the change in heat or salt in that region
- **we are compelled for CMIP6 to recommend saving** budget terms comprised of the **convergence of fluxes** associated with various physical processes.
- **From flux convergences one can garner mechanistic insight** into the impacts from various physical processes in that region, without having to make direct use of flux components

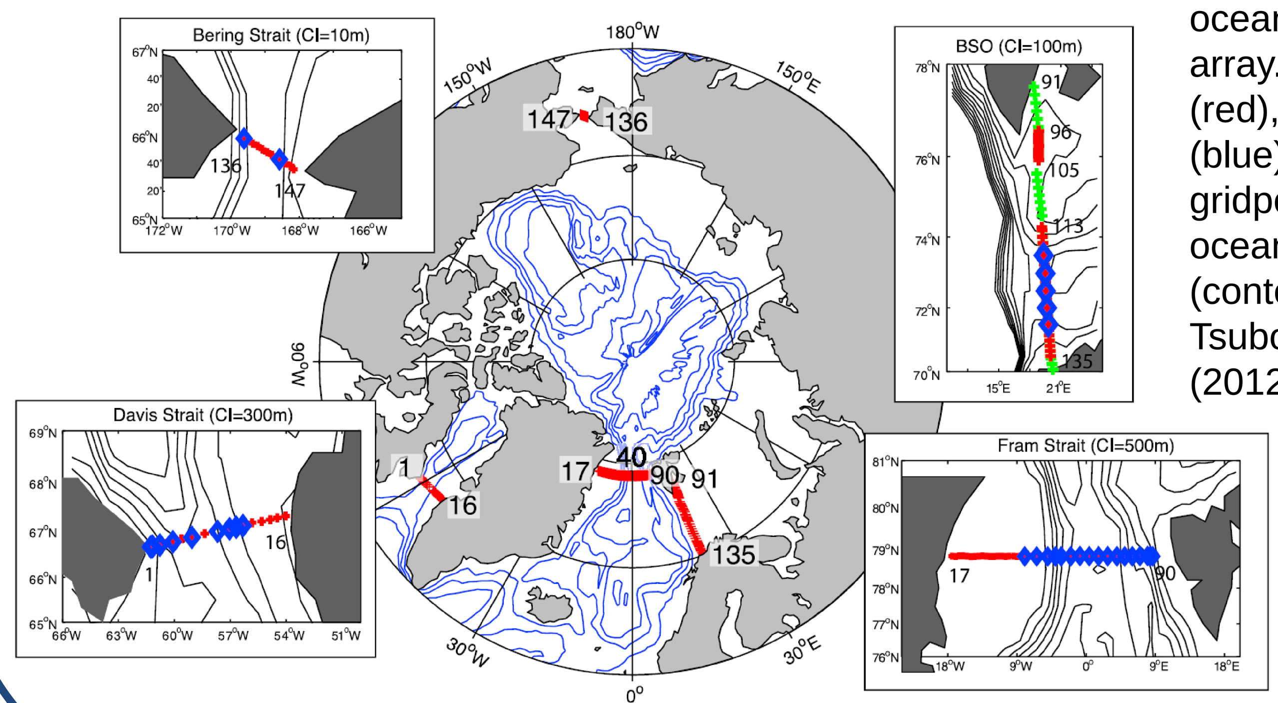

Fig. 3: Arctic ocean gateway array. CTD stations (red), moorings (blue), OGCM gridpoints (green), ocean depth (contours). From Tsubouchi et al. (2012)

3. Direct estimates of DIVFO from ocean state:

$$DIVFO = \frac{\rho_w c_w}{e_{1t} e_{2t}} \sum_k \left(\delta_i [e_{2u}\, e_{3u}\, uT] + \delta_j [e_{1v}\, e_{3v}\, vT] \right)$$

- This vertically integrated term (from NEMO (Madec, 2015) manual, eq. 5.1) could easily be calculated during model integration but is to our knowledge **NOT** saved in ORAS or any other ocean reanalysis archive
- Difference between forecast and observed sea surface height (η) tendency can be used to adjust column mean mass flux divergence

$$\frac{\partial \eta}{\partial t} = \frac{1}{e_{1t} e_{2t}} \sum_k \left(\delta_i [e_{2u}\, e_{3u}\, u] + \delta_j [e_{1v}\, e_{3v}\, v] \right) - \frac{emp}{\rho_w}$$

emp is Evaporation – Precipitation – Runoff at ocean surface.

- Fields of column integrated fluxes (*Tu,Tv, Su,Sv*) would also be highly desirable, e.g. for comparison with arctic ocean gateway array fluxes.
- We strongly propose energy (and salinity) flux divergence as standard diagnostic output fields for ocean reanalyses. This is in line with CMIP6 and will allow overspecification of column integrated budgets.

4. Tropical Pacific energy budget analysis

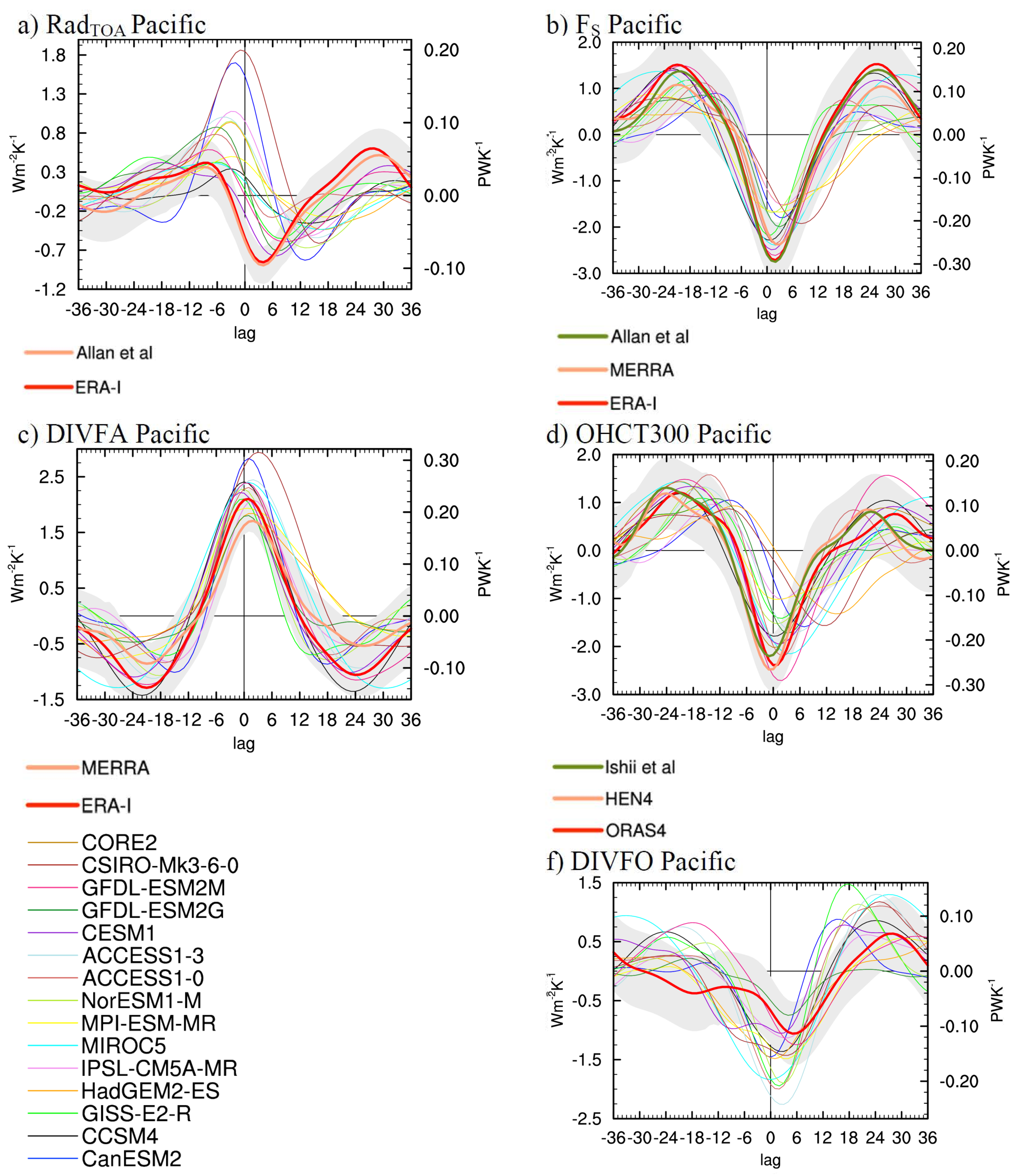

Fig. 4: Tropical Pacific (30S-30N) lagged regressions of complete set of energy budget quantities against Nino 3.4 index (units K) from atmospheric and oceanic reanalyses (Dee et al. 2011, Rienecker et al. 2011, Balmaseda et al. 2013, Good et al. 2013) and CMIP5 (Taylor et al. 2012) model runs. Left axes in flux density units, right axes in flux units. DIVFO (panel f) from ORAS4 is estimated from lateral fluxes (nonstandard output provided by M.A. Balmaseda). See Mayer et al. 2015.

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5. Homogeneity of early reanalysis input data

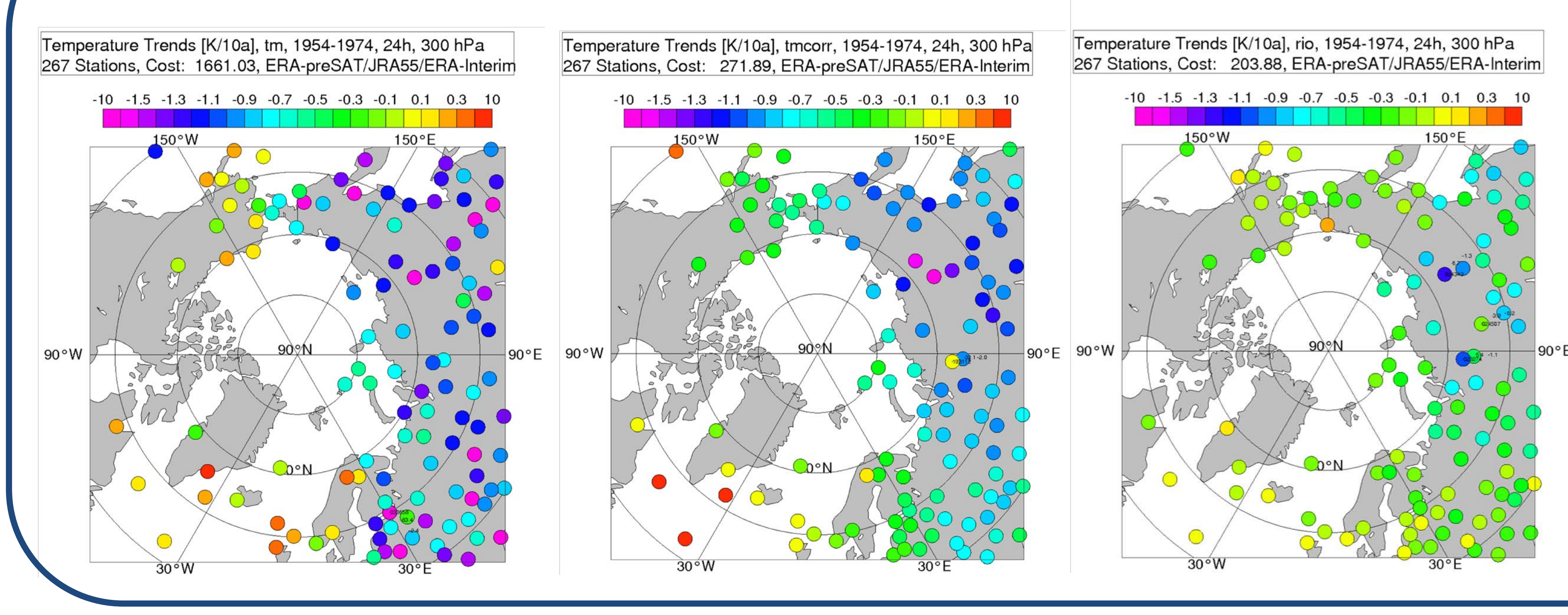

Fig. 5: Temperature trends 1954-1974, <3 years missing) at 300 hPa from a) unadjusted, b) RAOBCORE adjusted, c) RICH adjusted radiosonde records (Haimberger et al. 2012).
Reference series for homogenization: ERA-preSAT (-1967), JRA55 (1968-1979), ERA-Interim (1979-)

6. Conclusions

- CMIP6 diagnostic output will include (vertically integrated) energy, moisture, trace substance flux divergences
- Diagnostic output from ocean reanalyses should be expanded such to permit direct mass-consistent evaluation of flux divergences and overspecified budgets.
- Indirect estimates possible already now, albeit with large error accumulations.
- For atmospheric budgets backwards extension to the early 1950s may be feasible.
- Upper air data set for the Arctic relatively dense but with serious inhomogeneities.