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Observed energy flow in the Earth system

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Abstract: The energy budget imbalance and flow in the Earth system play an essential role in the climate change over the global and regional scales. Under the constraint of observations, the radiative fluxes at the top of atmosphere have been reconstructed prior to CERES between 1985 and 2000, and the total atmosphere energy divergence is mass corrected. The net surface energy flux (F_s) is derived from the residual method based on the energy conservation. The F_s is then verified directly and indirectly with observations, and results shows that our estimated F_s is superior to those from model simulations. This paper gives a brief review of the observed energy flow in the Earth system and provides some suggestions for the improvements of the aforementioned data set.

Keywords: TOA radiative flux; mass corrected atmospheric energy divergence; net surface flux; energy transport

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1. Introduction

The net global radiative flux F_T at the top of atmosphere (TOA) is the difference between the absorbed shortwave radiation and the outgoing longwave radiation of the Earth system, representing a nexus between changes in radiative forcings and climate responses, as well as the influence by unforced variability internal to the climate system [1]. A positive F_T indicates the accumulation of energy in the Erath system and a warming up climate.

CERES (Clouds and the Earth's Radiant Energy System) provides high quality TOA radiative flux data since March 2000 [2] and the data since 1985 prior to CERES have been reconstructed by Allan et al. [1] using the satellite observations of ERBE WFOV (Earth Radiation Budget Experiment Satellite wide field of view, 72 day mean) and ECMWF ERA-Interim reanalysis. Discontinuities in the reconstruction were dealt with using the 5th Atmospheric Model Intercomparison Project (AMIP5) simulations and other high resolution atmospheric model simulation results. The reconstruction was updated using ERA5 reanalysis and the AMIP6 simulations [3]. The net surface fluxes have also been estimated by the residual method [4-7] in which mass corrected horizontal transport of atmospheric energy and atmospheric energy accumulation from atmospheric reanalyses are combined with net TOA fluxes. The reconstructed TOA fluxes are regarded as "high confidence" in the IPCC AR6 report [8] (see page 17 of Chapter 7 of the report), and both the TOA fluxes and estimated net surface energy fluxes have been widely used in various studies. The data set is normally referenced as DEEPC (or DEEP-C: Diagnosing Earth's Energy Pathways in the Climate system) and can be available at https://researchdata.reading.ac.uk/347/.

This paper will review briefly the development of the DEEPC data set and the inferred energy flow. Comparisons with RAPID observations will be described and the future work needed for the improvement of this data set will be discussed.

2. Net TOA radiative flux

The radiative fluxes at TOA over 1985-1999 are reconstructed using CERES climatology and ERA5 anomalies constrained by the observed ERBE WFOV anomalies. The discontinuities in 1993 and 1999 are adjusted based on the AMIP6 ensemble mean differences at both sides of the discontinuity points [2-3, 6]. The deseasonalized global mean monthly anomaly (reference period is 2001–2005) time series of net TOA fluxes (NET) are shown in Figure 1, including data from DEEPC v5.0, CERES Ed4.1, AMIP6 ensemble mean (gray shading denotes the ± 1 standard deviation of the ten AMIP6 simulations), ERA5 and ERBE WFOV v3.0. All lines are three month running means, while the ERBE WFOV data are 72 days means and are deseasonalized with respect to the 1985–1999 period. The whole ERBE WFOV anomaly line is shifted vertically for clarity. The multiannual mean NET fluxes are 0.10±0.61 Wm^{-2} over 1985–1999 and 0.62 ± 0.10 Wm^{-2} over 2000–2016, which is qualitatively consistent with the results of Cheng et al. [9]. Both the reconstructed and CERES data are regarded as "high confidence" by the IPCC AR6 report. It is noticed that the uncertatity range of 0.61 Wm^{-2} over 1985–1999 is still large and it is mainly from the spread of the AMIP6 simulations at the discontinuity points around 1999.

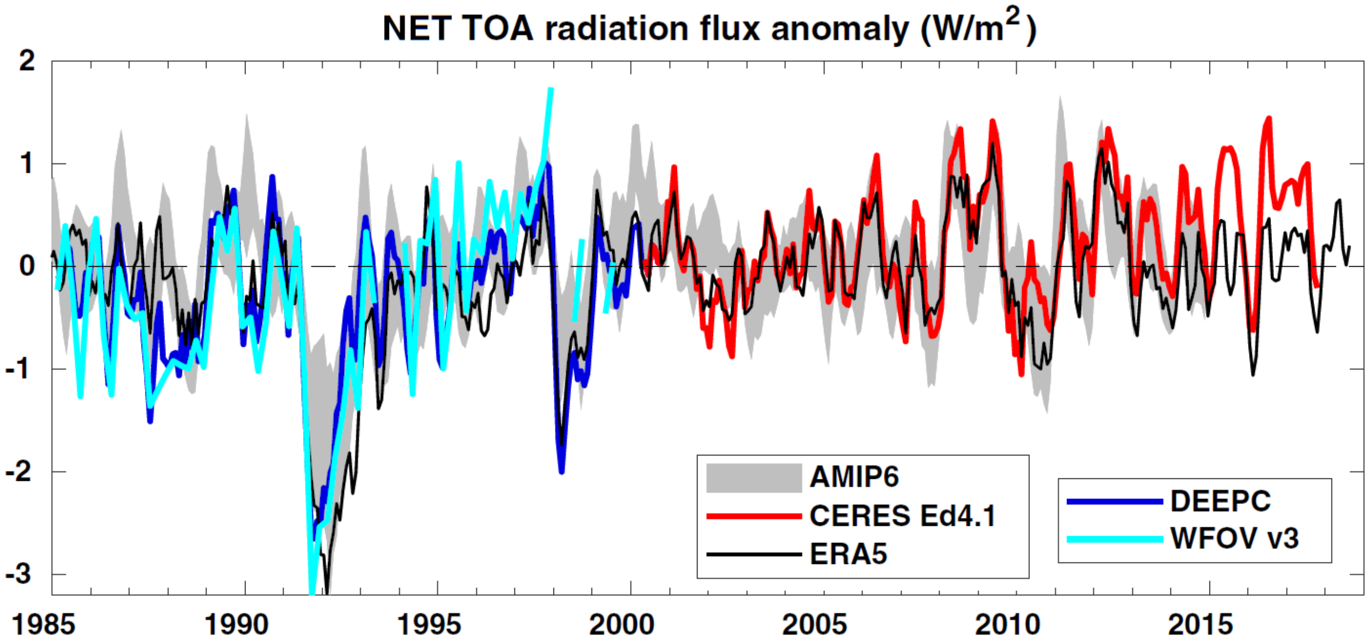

Figure 1. Deseasonalized monthly mean net TOA radiation fluxes (NET) in Wm^{-2} (with reference period 2001–2005). All lines are three month running means. The WFOV data are 72 day mean and are deseasonalized with respect to the 1985–1999 period, the corresponding lines are shifted vertically for clarity. Gray shading denotes the ± one standard deviation from ten AMIP6 simulations.

3. Energy flow in the Earth system

Figure 2 is the schematic diagram showing the energy flow terms used in the estimation of net surface energy fluxes. The left and right columns show the energy flow over land and ocean, respectively, and there is a net energy transport from the ocean to land. The surface energy flux F_s can be calculated by $F_T - \partial TE/\partial t - <\nabla \cdot F_A>_{mass}$, where F_T is the net TOA ratiative flux, TE is the total energy of the atmosphere [6]. $<\nabla \cdot F_A>_{mass}$ is the mass corrected atmospheric energy divergence. Because both observed three dimentional winds and surface pressure have been assimilated to the atmospheric model, the mass balance is not guaranteed. The mass corrected atospheric energy divergence is from Mayer et al. [10]. It has been noticed that the estimated F_s over land is unrealistic, so the global land mean F_s over 2004–2014 is anchored to a new estimate of 0.2 Wm^{-2}, and the excess/deficit energy fluxes are then redistributed over oceans (see [7] for details).

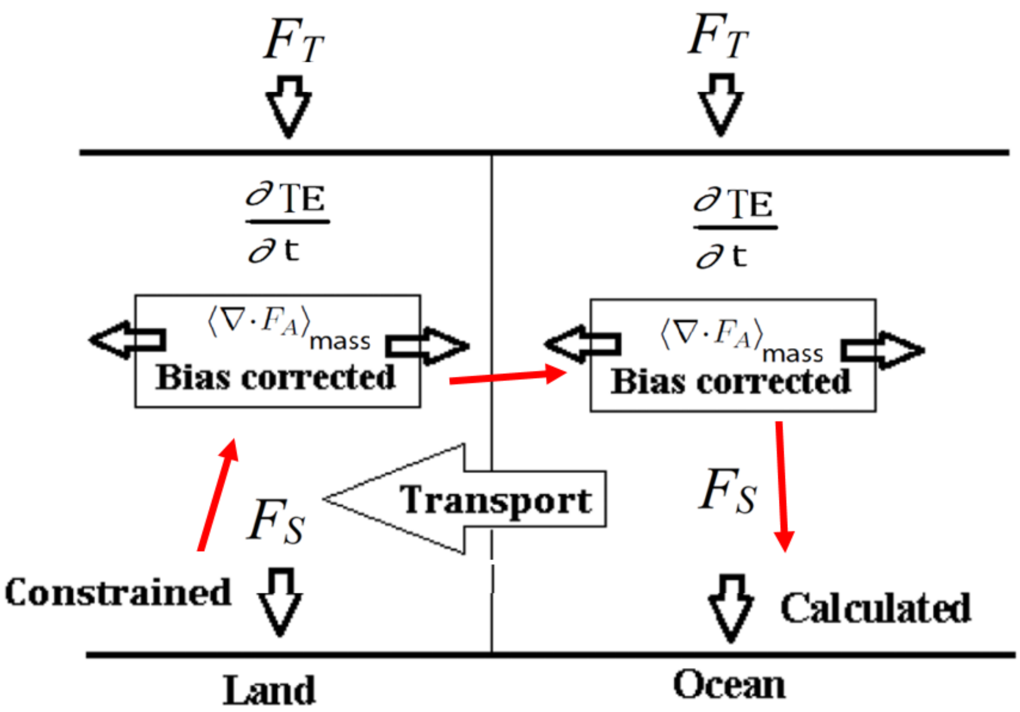

Figure 2. Schematic diagram showing the energy flow terms in the estimation of surface energy fluxes over land and ocean. Red arrows indicate the readjustment sequence after the land surface flux is constrained.

The DEEPC data set includes the TOA radiative fluxes, the atmospheric energy divergences and the net surface energy fluxes, so it can be used to estimate the energy flow in the atmosphere. By combining with the ocean heat content tendency from ORAS5, the ocean heat transport can also be estimated, then the energy flow in the Earth system (including atmosphere and ocean) can be esimated.

The latest estimation [3] from DEEPC data shows that the multiannual mean (2006-2013) net downward radiation flux at TOA is 0.36±0.04 PW in the southern hemisphere and −0.01±0.04 PW in the northern hemisphere, so the southern hemisphere is gaining energy while the northern hemisphere is close to balance at TOA. At the surface, the net downward energy flux is 0.79±0.16 PW in the southern hemisphere and a net upward energy flux of 0.44±0.16 PW in the northern hemisphere. The ocean heating is 0.29±0.02 PW in the southern hemisphere and a small amount accumulation of 0.06±0.01 PW in the northern hemisphere. The hemispheric imbalance leads to a northward heat transport of 0.50±0.16 PW by the ocean and the southward energy transport of 0.44±0.16 PW by the atmosphere. The absolute values of the energy transports can be sensitive to the time period selected.

One indirect check of the F_S is to compare the inferred oceanic heat transport at 26°N in the Atlantic with the RAPID (Rapid Climate Change-Meridional Overturning Circulation and Heat flux array) observations. The time series of the transport from RAPID and that inferred from DEEPC surface fluxes and ocean heat content tendency are plotted in Figure 3. The inferred heat transport from DEEPC shows good agreement with the RAPID observation in both quantity and variability. The correlation coefficient over the period from April 2004 to February 2017 is 0.32, and the mean heat transports are 1.22 PW from RAPID and 1.23 PW from DEEPC, respectively. The earlier trend of RAPID data from 2006–2008 is subject to greater uncertainty in observations. The variability agreement is much better after 2008, and the correlation coefficient is 0.73 over 2008–2016.

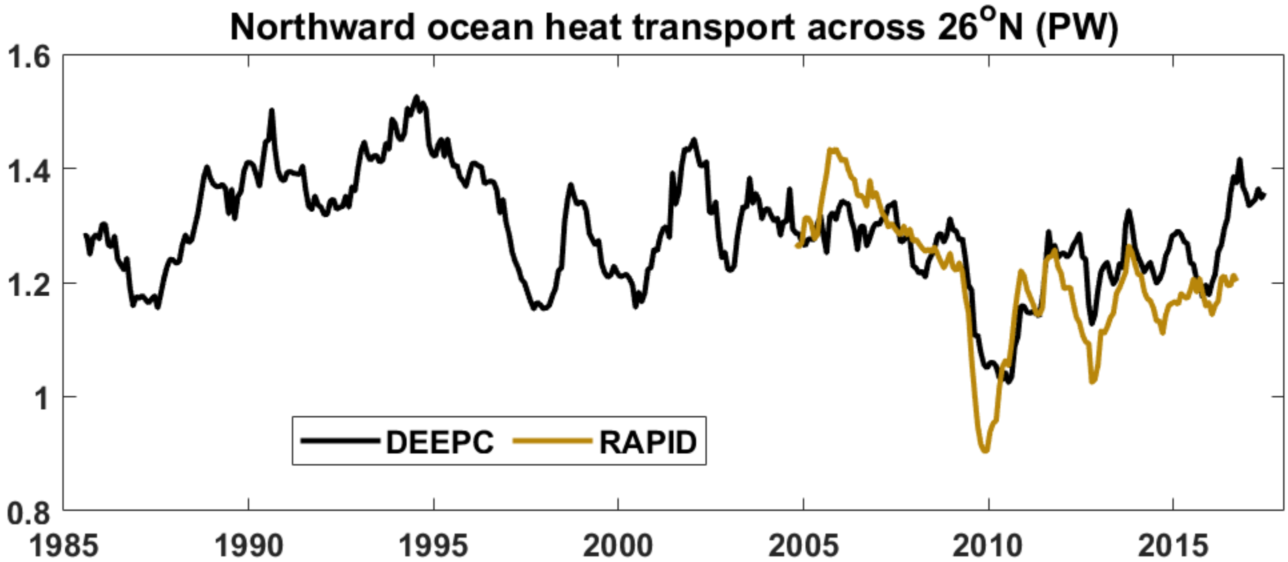

Figure 3. Northward meridional ocean heat transports at 26°N in the Atlantic from RAPID observations and DEEPC net surface fluxes combined with the sea ice melting and ocean heat content tendency of ORAS5 over 0–2000 m.

4. Discussion and conclusions

The DEEPC data set has been widely used in the climate research community. The reconstructed TOA radiative fluxes are regarded as "high confidence" by the IPCC AR6 report [8]. However, the large uncertatity of 0.61 Wm^{-2} over the reconstructed period from 1985–1999 should be further improved. This large uncertatity is mainly from the spread of the AMIP6 simulations at the discontinuity points around 1999 and it will significantly affect the uncertainty range of the ocean heat content derived from the net TOA flux F_T. This can be improved by using ensemble runs from a high quality AMIP model, such as the UK Met Office HadGEM model. This work is onging.

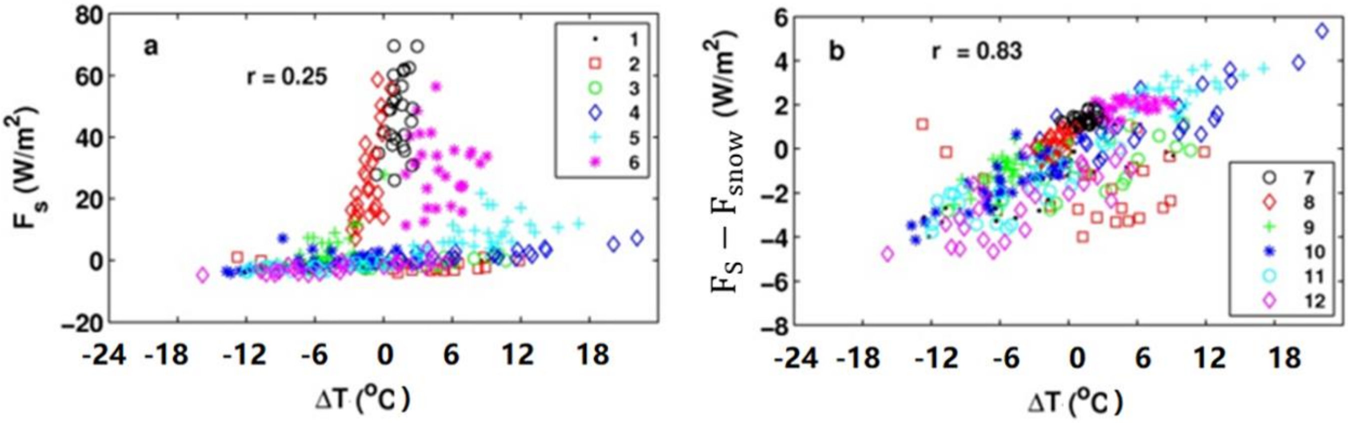

Figure 4. (a) Scatter plot between the net surface energy flux F_s and surface temperature change ΔT for each month (1-12 means JAN-DEC). (b) Scatter plot between F_s- F_{snow} and surface temperature change ΔT.

The verification of the DEEPC data is mainly over ocean areas [11-12], the F_s over land area is still not well validated. Figure 4 shows the snowmelt effect on the relationship between the net surface energy flux and the surface temperature change ΔT at a location (22°W, 64°N) in Iceland. ΔT is the temperature difference between two adjacent months (e.g., The April F_s verses the temperature change between April and March). It can be seen that before the energy needed for snowmelt (F_{snow}) is considered, the correlation coefficient is only 0.25 for data in all months, and it improves significantly to 0.83 after F_{snow} is considered. Similarly, the vegetation type and soil moisture, as well as other surface condition changes, also influence this relationship. Therefore, a more complicated energy budget model should be build for this study, in order to improve the accuracy of the land surface energy flux F_s.

Data Availability Statement: The DEEPC data can be downloaded from https://researchdata.reading.ac.uk/347/. The RAPID data can be downloaded from https://rapid.ac.uk/rapidmoc/rapid_data/datadl.php, the ORAS5 data can be accessed from https://www.cen.uni-hamburg.de/icdc/data/ocean/easy-init-ocean/ecmwforas5.html, and the AMIP6 data are available from https://esgfnode.llnl.gov/projects/cmip6/. We acknowledge all teams and climate modeling groups for making their data available.

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Conflicts of Interest: The authors declare no conflict of interest.

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