First Earth Energy Imbalance Assessment WCRP-ESA Workshop Summary and Recommendations Executive Brief

15–17 May 2023 | ESA–ESRIN | Frascati, Italy

Written, including contributions from the WCRP-ESA-EEIA workshop participants, by Benoit Meyssignac[1], Maria Hakuba[2], Seiji Kato[3], Tim Boyer[4] and Jérôme Benveniste[5]

[1] LEGOS-CNES, Toulouse, France
[2] JPL,CA, USA
[3] LaRC, VA, USA
[4] NOAA, VA, USA
[5] European Space Agency (ESA-ESRIN), Frascati, Italy.

17 October 2023

Published by:
Jérôme Benveniste, European Space Agency (ESA-ESRIN), Directorate of Earth Observation Programmes, Largo Galileo Galilei, 1, Frascati (Roma), I-00044, Italy, email: altimetry.info@esa.int

Cite as:
Benoit Meyssignac, Maria Hakuba, Seiji Kato, Tim Boyer and Jérôme Benveniste (2023) First Earth Energy Imbalance Assessment WCRP-ESA Workshop Summary and Recommendations Executive Brief, ESA Publication, http://doi.org/10.5270/wcrp-esa-eeia-2023.final_report_brief

Introduction

The first edition of the Earth Energy Imbalance Assessment Workshop series was organized by the European Space Agency (ESA) with the support from CNES and 4 others institutions, and took place on 15 to 17 May 2023 at ESA-ESRIN in Frascati (Italy). The workshop brought together 61 scientists from 14 countries. The workshop engaged a wide community with expertise in radiometric remote sensing, satellite altimetry, space gravimetry, ocean in situ measurements and ocean reanalysis to assess and intercompare estimates of Earth's energy imbalance and their time variability and uncertainties.

Key topics covered by the workshop

Key topics discussed at the workshop covered 6 themes: 1) Science questions associated with EEI, 2) Space techniques to measure the EEI, 3) In-situ techniques to measure the EEI, 4) Reanalyses techniques to measure the EEI, 5) Surface flux component approach and 6) Future concepts to measure EEI. New contributions on synergies among satellite observations, in-situ observations and models were also extensively reviewed. In addition, the progress of energy budget at regional scales was discussed.

Key results from the workshop

The workshop highlighted the critical importance of measuring accurately the Earth energy imbalance to improve our scientific understanding of climate change but also to help society mitigate and adapt to climate change. Indeed, measuring the absolute magnitude of EEI and its variability accurately is essential to constraining the global energy budget. It also provides an observational constraint on key characteristics of the climate change dynamics, such as the global climate feedback parameter and the climate sensitivity, allowing to better understand the causes for climate change and how climate change is unfolding. Furthermore, monitoring the EEI precisely is also crucial for society because it provides the most fundamental metric of the physical response of the climate system to current GHG emissions. As mitigation policies are put into force by more and more countries, the measurement/estimate of EEI, if precise enough, is a key metric/quantity to evaluate the efficacy of these policies on the physical climate system. The science community identified during the workshop different levels of accuracy and precision in EEI that are needed to answer different science questions and to respond to different societal needs.

During the workshop the science community assessed the different observational estimates of EEI magnitude, trend and variability and reviewed the recent progress in estimating the EEI and its uncertainty. To date, the approaches based on the measurement of the ocean heat uptake (OHU), namely the geodetic approach based on satellite altimetry and space gravimetry and the in-situ approach based on ocean temperature measurements from the Argo network, provide the most accurate estimate of EEI absolute magnitude. They indicate an EEI of 0.8±0.3 Wm^{-2} (90% CL) over the period 2005-2020. The radiometric measurement of the top of the atmosphere (TOA) radiation budget (by the CERES experiment) provides the most precise estimates of the EEI variability and trend. It indicates a trend in EEI of +0.4±0.2 Wm^{-2} (66% CL) per decade over the period 2005-2020. This is in agreement with the trend observed by the geodetic approach and the in-situ approach although the latter two approaches show larger uncertainties than CERES. On the interannual variability of EEI the CERES estimate shows a good agreement (correlation of 0.7) with the geodetic approach on 2-year and longer time scales. The agreement is equally good with the in-situ approach when satellite altimetry is used to interpolate the Argo measurements. Note that OHU accounts for ~90% of total planetary heat uptake, the indirect EEI estimate based on heat inventory assessment (von Schuckmann et al. 2023).

In terms of uncertainty, the geodetic approach provides a comprehensive uncertainty estimate on the global EEI with time correlation which enables to derive consistent estimates of the EEI uncertainty on different time scales from biannual to long-term trends. There are attempts to validate part of the uncertainty budget with the sea level budget closure and the energy budget closure. On regional scales, the uncertainty of the ocean heat content (OHC) estimate lacks information on spatial correlation of errors. Concerning the in-situ approach, there is progress in estimating uncertainty. A solution based on the interpolation of Argo measurements with satellite altimetry provides an uncertainty that accounts for the time autocorrelation in the measurements. There has been also promising progress on the characterization of the spatio-temporal statistical uncertainty of the mapped fields of ocean heat uptake. It paves the way for a more comprehensive representation of the uncertainties in the Argo estimates of the OHC and the EEI. Note that both the geodetic approach and the in-situ approach suffered from a drift in Argo salinity profiles since 2016, which increased the uncertainty from 2016 onwards, but this drift is now corrected in the up-to-date Argo measurements (delayed-mode).

EEI derived from ocean reanalysis has shown important progress in the recent years. The large time- and space-dependent biases in OHC are now every much reduced in the current generation of ocean/sea-ice reanalyses/state estimates despite their differing algorithms and forcings. The remaining differences in the global average OHU estimated from reanalysis are caused by slight differences in the patterns of regions of heat uptake and heat release. There are now attempts to characterize the EEI uncertainty in reanalyses estimates through an ensemble approach. Overall, EEI estimates from ocean reanalysis are becoming an interesting alternative that has the advantage to be consistent with the ocean dynamics. In addition, a reanalysis ensemble approach is a useful tool to provide a concrete estimate of uncertainties, including structural and parametric errors.

EEI derived by the approach based on the sum of all surface energy flux components has a larger bias of approximately 10 Wm^{-2}. There is progress in reducing this bias but it is slow. However, this approach is important to understand the changes in the global and regional energy fluxes associated with the current EEI change. A good example of the current progress in this field is the globally unbiased estimate of net surface energy flux inferred from the divergence and storage of atmospheric energy as diagnosed from reanalyses and combined with CERES estimate of the TOA fluxes. This method shows an increased degree of consistency between the estimate of the net surface energy flux and the ocean heat uptake derived from the geodetic approach or the in-situ approach, especially on monthly to 2-year time scales. It makes this surface budget approach a useful complementary dataset for investigating the regional energy budget.

Looking ahead, several new concepts were proposed during the workshop to measure EEI in the future. These new concepts include in-situ concepts based on the measurement of ocean conductivity content as well as space-based concepts that a) measure the TOA radiation budget with wide-field-of-view radiometers 2) improve absolute calibration of current radiometric observations with SI-traceable, narrow-field-of-view spectral radiance observations or 3) a constellation of geodetic satellites with accelerometers to measure the radiation pressure from Sun and Earth.

Key recommendations from the workshop

The EEI community present at the workshop came out with a number of requirements to improve the estimate of the EEI and its uncertainty at all time scales.

1) **Continue EEI assessment efforts (in support of society):** The EEI community encourages the organization of a community workshop to identify key science questions associated with the EEI and their requirements in terms of observed EEI mean, trend and variability accuracy and precision.
2) **Expand assessment efforts to the regional scale:** The EEI community recommends to follow-on the GEWEX EEI assessment effort and expand the analysis to comparing not only global mean EEI time series but also maps of ocean heat content.
3) **Assess consistency of EEI variability across methods:** The EEI community recommends to assess the consistency between ocean heat uptake estimates and TOA radiation budget estimates at interannual and longer time scales. The 2016 dip in ocean heat uptake observations that is not visible in TOA radiation budget data is particularly puzzling and poses a challenge to the EEI community. A small discrepancy between the geodetic and in-situ based steric sea level changes persists and requires continued investigation
4) **Extend geodetic OHC to the regional scale:** Concerning the geodetic approach, the EEI community encourages to update the estimate of the global OHU to the most recent years and to extend the regional estimate of OHC to the whole ocean including near the coast and at high latitudes. In addition, the EEI community recommends improving the global and regional uncertainty estimates by performing a synthetic data analysis to evaluate the exact role of sampling in the error budget and by including the spatial correlation in the error budget.
5) **Characterize uncertainty of in-situ OHC estimates:** Concerning the in-situ approach, the EEI community encourages to pursue the effort on the characterization of the uncertainties including the uncertainty due to time and space correlation in errors. The EEI community also supports the current ME4OH effort in characterizing the uncertainty due to mapping through a synthetic data approach and recommends this effort should be pursued in a concerted way with a similar effort that is ongoing in the geodetic community. The EEI community encourages also a wider effort in the in-situ community to characterize the uncertainty on ocean heat content in a comprehensive way that includes all sources of errors. It is proposed to pursue such an effort with an ensemble approach.
6) **Consider Hybrid OHC estimates to improve understanding of EEI variability:** The EEI community recommends pursuing also approaches that combine both ocean temperature measurement and geodetic measurement to estimate the ocean heat content and the ocean heat uptake as these approaches are promising to resolve the ocean heat uptake in a consistent way with TOA radiation budget and the atmospheric energy divergence at monthly and longer time scales. This should allow a better resolution of the heat redistribution in the ocean and help in improving regional surface energy budgets.
7) **Characterize uncertainty in reanalysis and ocean state modeling:** Concerning the reanalysis approach, the EEI community recommends a wider intercomparison exercise that includes more reanalysis estimates of the ocean heat content in order to get a broader view of the remaining differences among the reanalysis estimates. The EEI community encourages also a wider effort in the reanalysis community to characterize the uncertainty on ocean heat content in a comprehensive way that includes all sources of errors. It is proposed to pursue such an effort with an ensemble approach.
8) **Implement best practices:** On a general manner the EEI community encourages the different groups involved in each technique to agree on best practices in uncertainty estimates to improve and homogenize the uncertainty calculation among the community. That would allow for a consistent comparison of the uncertainty estimates and raise significantly the level of confidence in EEI uncertainty estimates.
9) **Ensure continuity and intercalibration capabilities**: The EEI community recommends a sustained effort to ensure the continuity and improvement of the measurement of the ocean heat content through the geodetic and in-situ approaches as well as the TOA radiation budget

through space radiometry. For this purpose, the EEI community strongly underlines that TOA radiation budget observations should continue and potential gaps in the TOA radiation measurements will increase uncertainties in EEI variability and trend. The longer the gap the larger the uncertainties will be. The EEI community also highlights the importance of reference missions that help improve the absolute calibration accuracy of broadband radiometric observations in space like CLARREO Pathfinder and TRUTHS. Having the reference missions is especially important in a potential future era of small-sat constellations. . For the ocean heat content measurements, the EEI community strongly supports the current deployment and its expansion of the deep-Argo system and the ongoing efforts in the geodetic community to decrease the uncertainty by better characterizing the errors.

10) **Improve regional surface energy budget**s: The EEI community recommends reducing the bias of regional surface energy budgets estimated from energy flux components. Better estimates of the uncertainty in regional energy flux components and the uncertainty in the trend of each component are required. For this purpose, the EEI community strongly encourages collaborations among different surface flux data providers and the reanalysis community.
11) **Investigate the potential of novel observing system concepts**: The EEI community recommends to continue investigating the feasibility and requirements of future observing systems that target the direct measurement of net radiative fluxes from space at sufficient absolute accuracy.
12) **Attribute, understand and predict EEI changes:** The EEI community recommends investigating and attributing the observed changes in EEI to improve process understanding. This will help to probe climate models more effectively, understand discrepancies and improve predictions, which ultimately supports society in informed decision making. (Knowing why EEI changes and how it might change in the future is equally as important as consistent monitoring)

Conclusion

The recommendations from this first edition of the Earth Energy Imbalance Assessment Workshop series are aimed at specifying the need for future research activities based on the wide community discussions that took place at the Workshop, based on the gathered expertise in radiometric remote sensing, satellite altimetry, space gravimetry, ocean in-situ measurements and ocean reanalysis. It was also recommended that the community meets again to repeatedly assess and inter-compare estimates of Earth's energy imbalance and their time variability and uncertainties as progress is achieved. A host institution would be welcome to organize the second edition of the Earth Energy Imbalance Assessment Workshop series, in 2024.

Acknowledgements

The authors would like to warmheartedly thank all the Members of the Organising Committee, the session co-chairs and the presenters of the WCRP-ESA-EEIA Workshop. The authors would like to also warmheartedly thank all the people involved in the logistic organisation at the ESA-ESRIN Conference Bureau, as well as Federica, Giorgia and Ornella from the ESA Earth Observation Graphic Bureau for the workshop graphics. ESA has funded the event, with substantial support from CNES/CNRS/WCRP and all the Organising Committee Member's institute for their effort invested in the shaping of the workshop.