Improving Estimates of Earth's Energy Imbalance

Gregory C. Johnson[1*], John M. Lyman[1,2], and Norman G. Loeb[3]

[1]NOAA/Pacific Marine Environmental Laboratory, Seattle Washington 98115 USA.

[2]Joint Institute for Marine and Atmospheric Research, University of Hawaii at Manoa,

Honolulu Hawaii 96822 USA.

[3]NASA Langley Research Center, Hampton Virginia 23681 USA.

[*]e-mail: gregory.c.johnson@noaa.gov

Revised 27 April 2016

Earth is gaining energy owing to the addition of greenhouse gasses and the large thermal inertia of the oceans[1]. This gain is difficult to measure directly because it is the small difference between two much larger components of Earth's energy budget—the amount of incoming solar radiation absorbed and the thermal infrared radiation emitted to space. With over 90% of Earth's energy imbalance (EEI) being stored in the ocean, the most accurate way to determine it is to measure increases in ocean temperatures (along with increases in land temperatures, decreases in ice mass, and increases in atmospheric temperature and moisture)[1]. While the observed net uptake of ocean heat energy is robust over decades, measurement biases and changes in sampling over time have made assessing year-to-year changes difficult[2].

We previously estimated[3] the EEI at 0.58±0.38 W m^{-2} (expressed here in terms of average heat uptake applied over Earth's surface area with 5–95% confidence intervals). This *in situ* estimate was made for 2005.5 (the year the Argo array of profiling floats achieved sparse near-global coverage) through 2010.5 by combing observed ocean heat uptake over 0–1800 m with published estimates of energy uptake by the deeper ocean, lithosphere, cryosphere, and atmosphere. It was used to anchor satellite-based EEI from the Clouds and the Earth's Radiant Energy System (CERES), which while stable over time, is not sufficiently accurate in absolute value to determine EEI at the required level. Year-to-year variations of 0–1800 m ocean heat uptake and CERES EEI were correlated at 0.46. Here, we update our calculations (Figure 1), and find a net heat uptake of 0.71±0.10 W m^{-2} from 2005.5–2015.5 (with 0.61±0.09 W m^{-2} taken up by the ocean from 0–1800 m; 0.07±0.04 W m^{-2} by the deeper ocean[4]; and 0.03±0.01 W m^{-2} by melting ice,

warming land, and a warming and moister atmosphere[1]). In addition to a remarkable quartering of uncertainty, owing to improved sampling by the Argo array over time (Figure 1), the correlation between year-to-year rates of 0–1800 m ocean heat uptake[5] and the latest release of CERES EEI is a much improved 0.78. This striking agreement between two completely independent measures of EEI variability bolsters confidence in both of these complementary climate observation systems, and provides valuable insights into climate variability.

Argo recognizes the imperative to improve its coverage of the global oceans, with a plan to sample the bottom half of the ocean volume[6], where significant changes in deep[7] and bottom[8] water circulation and properties have been observed in recent decades, in addition to expansions into marginal seas and the climatically vital seasonal ice-covered oceans, where ocean warming may melt sea ice, decreasing Earth's albedo[9] and undermine the marine terminations of ice sheets, raising sea level[10]. If supported, making Argo truly global, coupled with continued satellite observations, will also better allow us to monitor changes in EEI, and hence to refine and initialize global climate projections and predictions that are so vital to societal adaptation in a rapidly changing world.

REFERENCES

1   Rhein, M. *et al.* in *Climate Change 2013: The Physical Science Basis.* (eds
        Stocker, T. F. *et al.*) 255–315, (Cambridge University Press, 2013).

2   Lyman, J. M. *et al. Nature* **465**, 334–337 (2010).

3   Loeb, N. G. *et al. Nature Geosci.* **5**, 110–113 (2012).

4   Purkey, S. G. & Johnson, G. C. *J. Clim.* **23**, 6336–6351 (2010).

5   Lyman, J. M. & Johnson, G. C. *J. Clim.* **27**, 1945–1957 (2014).

6   Johnson, G. C., Lyman, J. M. & Purkey, S. G. *J. Atmos. Ocean. Technol.* **32**, 2187–2198 (2015).

7   Srokosz, M. A. & Bryden, H. L. *Science* **348**, 6 (2015).

8   Purkey, S. G. & Johnson, G. C. *J. Clim.* **26**, 6105–6122 (2013).

9   Polyakov, I. V., Walsh, J. E. & Kwok, R. *Bull. Am. Meteor. S.* **93**, 145–151 (2012).

10   Pritchard, H. D. *et al*. *Nature* **484**, 502–505 (2012).

Author contributions

All authors contributed equally to the formulation and revisions of this study. G.C.J. created the figure and drafted the text. J.M.L. calculated the 0–1800 m ocean heat content anomaly estimates. N.G.L. provided the CERES top-of-the atmosphere energy flux estimates.
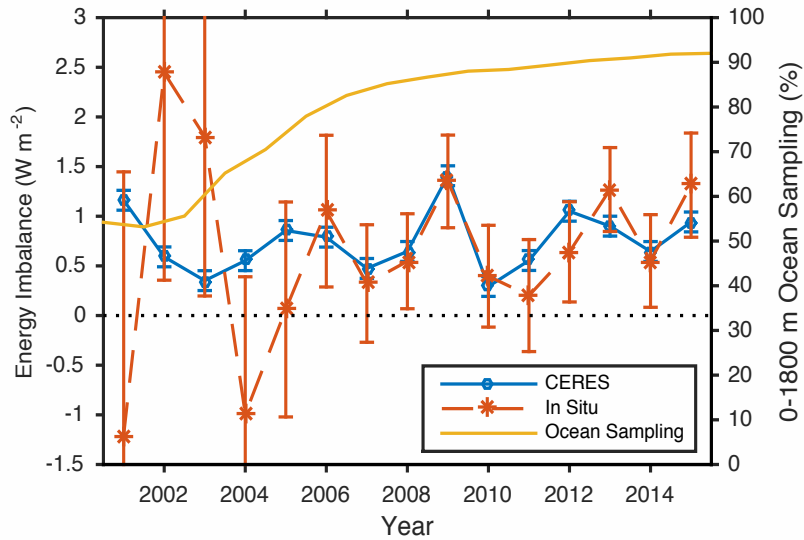
Figure 1. Comparison of year-to-year net top-of-the-atmosphere annual energy flux from the CERES Energy Balanced and Filled (EBAF) Ed2.8 product with an *in situ* observational estimate of uptake of energy by Earth's climate system. The *in situ* estimate (red asterisks joined by red dashed line) is composed of first differences of annual 0–1800 m ocean heat content anomalies estimated from Argo float profiles and other sources[5], adding a constant heating rate of 0.1 m^{-2} based on the sum of the multi-decadal rates of deep (> 2000 m) ocean warming[4], as well as land warming, ice melt, and atmospheric warming and moisture uptake[1]. *In situ* uncertainties (red error bars) are shown at one standard error of the mean[5]. CERES data (blue circles joined by solid blue line) are adjusted to agree with the 2005.5–2015.5 *in situ* heat uptake rate of 0.71±0.10 W m^{-2} (5–95% confidence intervals). CERES annual random errors (blue error bars) are shown at one standard deviation (0.1 W m^{-2}). The percentage volume of the 0–1800 m global ocean sampled for annual ocean heat uptake[5] (yellow line) shows substantial improvement over time with implementation of Argo.