LETTERS
PUBLISHED ONLINE: 22 JANUARY 2012 | DOI: 10.1038/NGEO1375

nature geoscience

Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty

Norman G. Loeb[1]*, John M. Lyman[2,3], Gregory C. Johnson[3], Richard P. Allan[4], David R. Doelling[1], Takmeng Wong[1], Brian J. Soden[5] and Graeme L. Stephens[6]

Global climate change results from a small yet persistent imbalance between the amount of sunlight absorbed by Earth and the thermal radiation emitted back to space[1]. An apparent inconsistency has been diagnosed between interannual variations in the net radiation imbalance inferred from satellite measurements and upper-ocean heating rate from *in situ* measurements, and this inconsistency has been interpreted as 'missing energy' in the system[2]. Here we present a revised analysis of net radiation at the top of the atmosphere from satellite data, and we estimate ocean heat content, based on three independent sources. We find that the difference between the heat balance at the top of the atmosphere and upper-ocean heat content change is not statistically significant when accounting for observational uncertainties in ocean measurements[3], given transitions in instrumentation and sampling. Furthermore, variability in Earth's energy imbalance relating to El Niño-Southern Oscillation is found to be consistent within observational uncertainties among the satellite measurements, a reanalysis model simulation and one of the ocean heat content records. We combine satellite data with ocean measurements to depths of 1,800 m, and show that between January 2001 and December 2010, Earth has been steadily accumulating energy at a rate of 0.50 ± 0.43 W m^{-2} (uncertainties at the 90% confidence level). We conclude that energy storage is continuing to increase in the sub-surface ocean.

Over 90% of the excess energy from anthropogenic forcing is stored in the ocean. The remainder heats the atmosphere and land, and melts snow and ice[4]. Large fluctuations in Earth's top-of-atmosphere (TOA) net energy imbalance and the ocean heating rate should therefore be in phase with one another[5]. At interannual timescales, El Niño-Southern Oscillation (ENSO)-related changes in atmospheric and oceanic circulations alter clouds and atmospheric temperature and humidity, leading to potentially large perturbations in net TOA radiation. Major volcanic eruptions reduce net TOA radiation temporarily, tending to cool Earth[6]. At longer timescales, Earth's energy imbalance exhibits appreciable variability[5], and is influenced by anthropogenic forcing due to greenhouse gases and aerosols, natural forcing by aerosols and solar radiation, and Earth's temperature response to climate forcing and feedbacks involving water vapour, temperature, clouds and the surface[7]. Earth's temperature response depends on the vertical distribution of heat in the ocean, with its large heat capacity and long equilibrium timescales.

Apparent inconsistencies after 2004 between short-term variations in upper-ocean heating rate from *in situ* ocean heat content data and net TOA flux from satellite radiation measurements cast doubt on our ability to account for the flows of energy in the climate system, and the lack of closure has given rise to the idea of 'missing energy' in the climate system[2]. Subsequent modelling investigations[8–11] seek to explain an apparent decline in upper-ocean heating rate during the past decade, which is central to the 'missing energy' argument. However, a critical component missing from the original study[2] is an assessment of the uncertainty in the observations. This issue is revisited here, taking into account uncertainties in the ocean and satellite data, and using more recent analyses of the observations.

Ship-based *in situ* expendable bathythermograph (XBT) measurements were the largest source of *in situ* upper-ocean temperature data in the historical archives from 1990 to 2002 (ref. 12). Following the commencement of the Argo Program[13] in 2000, profiling floats became the largest data source starting in 2003. Argo has been providing near-global coverage and year-round sampling of upper-ocean temperature since 2004, approaching full implementation by late 2007. Mapping irregularly spaced temperature data requires careful quality control, bias corrections to XBT data, mapping strategies to deal with unsampled and undersampled regions, and the choice of a suitable baseline mean climatology[3]. The ocean heating rate is determined from the time derivative of globally integrated annual average upper-ocean heat content anomaly (OHCA). The combined XBT and Argo data show a warming of 0.64 ± 0.11 W m^{-2} in the upper ocean between 1993 and 2008 (ref. 3). Starting around 2002–2003, during the transition from XBT to Argo, a period of large observational uncertainty in OHCA, the rate of upper (0–700 m) global annual average ocean heating in three different analyses[14] seems to decline (Fig. 1a). Uncertainties in upper-ocean heating rates take into account all the error sources mentioned above for the OHCA curves[3]. Although the different estimates of OHCA produce seemingly different estimates of interannual ocean heating rate variability, these differences are all within the range of observational uncertainty. The same conclusion is reached when ocean heating rates for 1993–2003 and 2004–2008

[1]NASA Langley Research Center, 21 Langley Boulevard, Hampton, Virginia 23681, USA, [2]Joint Institute for Marine and Atmospheric Research, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA, [3]NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington 98115, USA, [4]Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading, RG6 6BB, UK, [5]Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA, [6]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, USA. *e-mail: norman.g.loeb@nasa.gov.

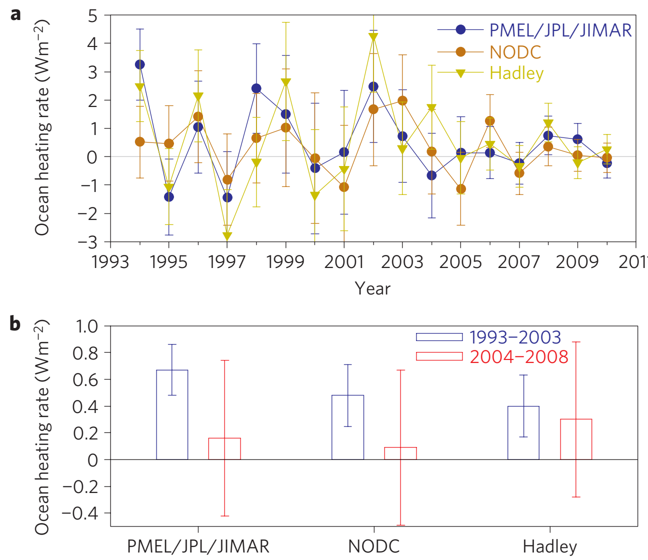

Figure 1 | 0–700 m upper-ocean warming rates. a, Annual global averaged upper-ocean warming rates computed from first differences of the Pacific Marine Environmental Laboratory/Jet Propulsion Laboratory/Joint Institute for Marine and Atmospheric Research (PMEL/JPL/JIMAR) 0–700 m OHCA curve[26] using data from Argo and the World Ocean Database 2009 (ref. 28), the National Oceanic Data Center (NODC) 0–700 m OHCA curve[29], and the Hadley Centre 0–700 m OHCA curve[30]. Uncertainties for all annual upper-ocean heating rates are given at one standard error and are derived from OHCA uncertainties[3]. **b**, Means and uncertainties at the 90% confidence level for 1993–2003 and 2004–2008.

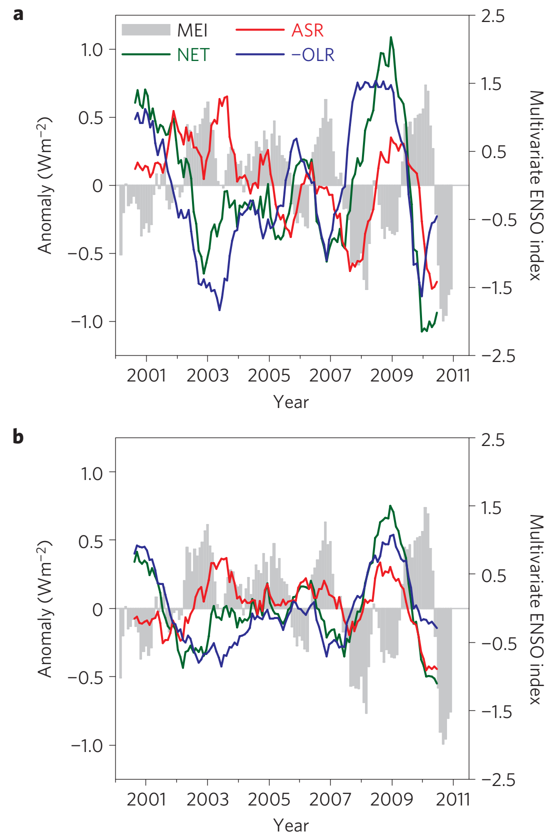

Figure 2 | Variations in TOA radiation and ENSO during the past decade. a,**b**, Anomalies in net radiation (NET), absorbed solar radiation (ASR), the negative of outgoing longwave radiation (-OLR), and two-month averages of the Multivariate ENSO Index (MEI) for 30° S–30° N (**a**) and globally (**b**). Positive/negative anomalies correspond to a gain/loss of Earth energy. Positive and negative values of MEI correspond to El Niño and La Niña conditions, respectively. TOA radiation anomalies are determined from monthly averages by removing the seasonal cycle then smoothing with a twelve-month running mean.

are compared (Fig. 1b). The decline after 2004 is therefore not statistically significant[3], nor does it show up in a previous analysis of the Argo data[15].

An alternative approach for tracking changes in the Earth's heating rate is to monitor changes in TOA net energy imbalance from satellite observations. Reflected solar and emitted thermal radiation observed from the Clouds and the Earth's Radiant Energy System (CERES; ref. 16) and observations of incoming solar radiation from the Total Irradiance Monitor (TIM) instrument aboard the Solar Radiation and Climate Experiment (SORCE; ref. 17) can be used to monitor changes in absorbed solar, emitted thermal, and hence net radiation at the TOA with a high degree of precision[18]. Furthermore, because CERES provides global coverage daily, these quantities are available at spatial scales from regional to global, and temporal scales from daily to annual.

Tropical and global anomalies in net TOA radiation, absorbed solar radiation (ASR) and outgoing longwave radiation (OLR) are closely related to ENSO (Fig. 2). During La Niña conditions (negative Multivariate ENSO Index, or MEI), the Earth tends to gain more energy. This gain is mainly associated with reductions in OLR, which closely track the MEI, particularly in the tropics. The two-year period following mid-2007 is characterized by strong La Niña conditions that result in a maximum in net radiation gain into the climate system in late 2008, followed by a sharp decline (of up to 2 Wm^{-2} in the tropics) when a transition to El Niño conditions occurs in mid-2009.

A limitation of the satellite data is their inability to provide an absolute measure of the net TOA radiation imbalance to the required accuracy level. The net TOA radiation imbalance is the difference between incoming and outgoing radiation, quantities that are well over two orders of magnitude larger than the net TOA imbalance. It is thus necessary to anchor the satellite data to an absolute scale using other data[19]. In refs 2 and 8 the CERES observations are anchored to a net radiation imbalance of 0.9 Wm^{-2} in the early part of the decade, based on a climate model simulation rather than actual observations. The change in net radiation between satellite and ocean *in situ* observations differs by as much as 1 Wm^{-2} over the five years 2004–2008. This deviation exceeds the CERES uncertainty of 0.3 Wm^{-2} per decade[18,20] by more than a factor of six.

To provide a more observation-based representation of changes in net TOA flux during the past decade, the CERES net TOA radiation record is anchored to an estimated Earth heat uptake for July 2005–June 2010 of 0.58 ± 0.38 Wm^{-2}, by combining the Pacific Marine Environmental Laboratory/Jet Propulsion Laboratory/Joint Institute for Marine and Atmospheric Research (PMEL/JPL/JIMAR; ref. 14; see Methods) Argo-only estimate from 0 to 1,800 m with estimates of smaller heat uptake terms from warming of the deep ocean, land and atmosphere, as well as melting ice. Argo alone samples consistently, persistently, globally, and to a greater depth than previous upper-ocean measurement programs. A comparison of year-to-year changes in CERES net TOA flux during the past decade with the PMEL/JPL/JIMAR estimates of 0–700 m and 0–1,800 m year-to-year ocean heating rates (Fig. 3a) reveals that although the satellite and ocean *in situ* interannual variability agree to within observational uncertainty, the error bars and year-to-year variations for upper-ocean heating rates are large earlier in the decade, when much of the ocean *in situ* data were from XBT measurements, which have poorer sampling than Argo and require large uncertain bias corrections that Argo does not. Consistency between satellite

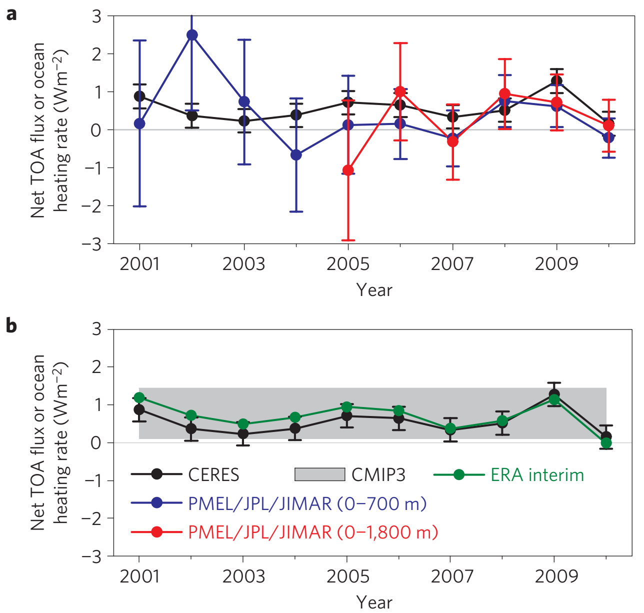

Figure 3 | Comparison of net TOA flux and upper-ocean heating rates. **a**, Global annual average (July to June) net TOA flux from CERES observations (based on the EBAF-TOA_Ed2.6 product) and 0–700 and 0–1,800 m ocean heating rates from PMEL/JPL/JIMAR (Ref. 26). Uncertainties for upper-ocean heating rates are given at one standard errorderived from OHCA uncertainties[3]. See Methods for a description of CERES uncertainties. **b**, Net TOA flux from CERES, ERA-Interim reanalysis[24] and the one standard deviation about the 2001–2010 average of 15 CMIP3 models (grey bar) are anchored to an estimate of Earth's heating rate for July 2005–June 2010 (see Methods).

net TOA flux and upper-ocean heating rate variability improves after 2004, when the Argo network provides near-global coverage. Importantly, the CERES net TOA flux observations do not show a sharp decline during the XBT to Argo transition around 2002–2005. For 2004–2010, the year-to-year changes in net TOA flux and the PMEL/JPL/JIMAR ocean heating rate track one another with a correlation coefficient of 0.46. During the same period, the correlation coefficients between CERES net TOA flux and 0–700 m ocean heating rates from both National Oceanic Data Center (NODC) and Hadley is 0.05. Although we cannot confidently claim that one ocean heat content estimate is preferable to another, the better agreement between the CERES and PMEL/JPL/JIMAR year-to-year changes after 2004 is encouraging. Combining the stable, decadal-length record of changes in net radiation from CERES with the 0–1,800 m Argo OHCA record and other minor storage terms, we compute Earth's energy imbalance for the period from January 2001–December 2010 to be $0.50\pm0.43\,\mathrm{Wm^{-2}}$ (see Methods).

Although the large observational uncertainty in year-to-year upper-ocean heating can be reduced by estimating warming rates over longer periods of time[21] (Fig. 1b), the sparse spatial and temporal sampling of the deep ocean means that a large portion of the total ocean volume is not included in the upper-ocean heating rates. An apparently bottom-intensified contribution can be estimated with some uncertainty over decadal timescales from sparse ship-based observations[22], but the deep ocean's contribution to the TOA net energy imbalance on shorter timescales will remain unknown until it is regularly sampled, as Argo does not sample oceans to depths greater than 2,000 m. Recent model results suggest that sampling the deep ocean would provide substantial improvement in our ability to constrain the Earth's radiative imbalance at decadal scales[23].

Changes in CERES net TOA flux also show remarkable consistency with simulations from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim)[24] (Fig. 3b, green line), which are completely independent of CERES. Coupled Model Intercomparison Project 3 (CMIP3)[25] simulations for the A1B scenario from 15 coupled atmosphere–ocean models exhibit a large spread in annual mean net TOA flux during the past decade, ranging from 0.09 to $1.5\,\mathrm{Wm^{-2}}$ (Fig. 3b, grey bar). Interannual variability of net TOA flux in the models is surprisingly large: the standard deviation in model net TOA flux between 2001 and 2010 exceeds that from the observations in 11 of the 15 models considered. The larger model variability is probably partly due to differences in model internal variability as well as differences in how the forcing is specified (for example, aerosol direct and indirect effects), how the various models were tuned, and model drift error (for more details about the model comparisons, see Supplementary Information).

The rise and fall in CERES and ERA-Interim net radiation and upper-ocean heating rates after 2007 (Figs 1 and 3) is entirely consistent with variability linked to ENSO (Fig. 2) and shows no evidence of a discrepancy between TOA net radiation and energy accumulating in Earth's climate system[2].

Our results demonstrate how synergistic use of satellite TOA radiation observations and recently improved ocean heat content measurements, with appropriate error estimates, provide critical data for quantifying short-term and longer-term changes in the Earth's net TOA radiation imbalance. The apparent decline in ocean heating rate after 2004 noted in other studies[2,8] is not statistically significant, nor is it observed by CERES. Differences in variations in ocean heating rate and satellite net TOA flux are well within the uncertainty of the measurements and, therefore, cast doubt on the argument for 'missing energy' in the climate system. Our results indicate that energy is continuing to accumulate in Earth's oceans. However, the large inconsistencies between independent observations of Earth's energy flows points to the need for improved understanding of the error sources and of the strengths and weaknesses of the different analysis methods, as well as further development and maintenance of measurement systems to track more accurately Earth's energy imbalance on annual timescales.

Methods

CERES_EBAF – TOA_Ed2.6r (see Supplementary Information for further details) was obtained from the CERES ordering page at http://ceres.larc.nasa.gov/order_data.php. Solar irradiance measurements are from the SORCE Level 3 Total Solar Irradiance Version 10, available from: http://lasp.colorado.edu/sorce/data/tsi_data.htm. Global annual mean net TOA fluxes for each calendar year from 2001 through 2010 are computed from CERES monthly regional mean values. In CERES_EBAF – TOA_Ed2.6r, the global annual mean values are adjusted such that the July 2005–June 2010 mean net TOA flux is $0.58\pm0.38\,\mathrm{Wm^{-2}}$ (uncertainties at the 90% confidence level). The uptake of heat by the Earth for this period is estimated from the sum of: (1) $0.47\pm0.38\,\mathrm{Wm^{-2}}$ from the slope of weighted linear least square fit to OHCA to a depth of 1,800 m analysed following ref. 26; (2) $0.07\pm0.05\,\mathrm{Wm^{-2}}$ from ocean heat storage at depths below 2,000 m using data from 1981 to 2010 (ref. 22), and (3) $0.04\pm0.02\,\mathrm{Wm^{-2}}$ from ice warming and melt, and atmospheric and lithospheric warming[1,27]. After applying this adjustment, Earth's energy imbalance for the period from January 2001 to December 2010 is $0.50\pm0.43\,\mathrm{Wm^{-2}}$. The $\pm0.43\,\mathrm{Wm^{-2}}$ uncertainty is determined by adding in quadrature each of the uncertainties listed above and a $\pm0.2\,\mathrm{Wm^{-2}}$ contribution corresponding to the standard error (at the 90% confidence level) in the mean CERES net TOA flux for January 2001–December 2010. The one standard deviation uncertainty in CERES net TOA flux for individual years (Fig. 3) is $0.31\,\mathrm{Wm^{-2}}$, determined by adding in quadrature the mean net TOA flux uncertainty and a random component from the root-mean-square difference between CERES Terra and CERES Aqua global annual mean net TOA flux values.

Received 11 August 2011; accepted 16 December 2011; published online 22 January 2012

References

1. Hansen, J. *et al*. Earth's energy imbalance: Confirmation and implications. *Science* **308,** 1431–1435 (2005).
2. Trenberth, K. E. & Fasullo, J. T. Tracking earth's energy. *Science* **328,** 316–317 (2010).

3. Lyman, J. M. *et al.* Robust warming of the global upper ocean. *Nature* **465,** 334–337 (2010).
4. Bindoff, N. L. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
5. Wong, T. *et al.* Reexamination of the observed decadal variability of the Earth radiation budget using altitude-corrected ERBE/ERBS nonscanner WFOV data. *J. Clim.* **19,** 4028–4040 (2006).
6. Minnis, P. *et al.* Radiative climate forcing by the Mount Pinatubo eruption. *Science* **259,** 1411–1415 (1993).
7. Soden, B. J. *et al.* Quantifying climate feedbacks using radiative kernels. *J. Clim.* **21,** 3504–3520 (2008).
8. Trenberth, K. E. & Fasullo, J. T. Tracking Earth's energy: From El Niño to global warming. *Surv. Geophys.* http://dx.doi.org/10.1007/s10712-011-9150-2 (2011).
9. Katsman, C. A. & van Oldenborgh, G. J. Tracing the upper ocean's "missing heat". *Geophys. Res. Lett.* **38,** L14610 (2011).
10. Meehl, G. A., Arbalster, J. M., Fasullo, J. T., Hu, A. & Trenberth, K. E. Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature Climate Change* **1229,** 360–364 (2011).
11. Hansen, J., Sato, M., Kharecha, P. & von Schuckmann, K. Earth's energy imbalance and implications. *Atmos. Chem. Phys.* **11,** 13421–13449 (2011).
12. Boyer, T. P. *et al.* in *NOAA Atlas NESDIS 66* (ed. Levitus, S.) (U.S. Gov. Printing Office, 2009) DVDs.
13. Roemmich, D. *et al.* Argo: The challenge of continuing 10 years of progress. *Oceanography* **22,** 46–55 (2009).
14. Johnson, G. C. *et al.* Ocean heat content. *Bull. Am. Meteorol. Soc.* **92,** S81–S84 (2011).
15. von Schuckmann, K., Gaillard, F. & Le Traon, P.-Y. Global hydrographic variability patterns during 2003–2008. *J. Geophys. Res.* **114,** C09007 (2009).
16. Wielicki, B. *et al.* Clouds and the Earth's Radiant Energy System (CERES): An earth observing system experiment. *Bull. Am. Meteorol. Soc.* **77,** 853–868 (1996).
17. Kopp, G., Lawrence, G. & Rottman, G. The Total Irradiance Monitor (TIM): Science results. *Sol. Phys.* **230,** 129–139 (2005).
18. Loeb, N. G. *et al.* Multi-instrument comparison of top-of-atmosphere reflected solar radiation. *J. Clim.* **20,** 575–591 (2007).
19. Loeb, N. G. *et al.* Toward optimal closure of the earth's top-of-atmosphere radiation budget. *J. Clim.* **22,** 748–766 (2009).
20. Loeb, N. G. *et al.* Advances in understanding top-of-atmosphere radiation variability from satellite observations. *Surv. Geophys.* (in the press, 2011).
21. Lyman, J. M. Estimating Global Energy Flow from the Global Upper Ocean. *Surv. Geophys.* http://dx.doi.org/10.1007/s10712-011-9167-6 (2011).
22. Purkey, S. G. & Johnson, G. C. Warming of global abyssal and deep southern ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *J. Clim.* **23,** 6336–6351 (2010).
23. Palmer, M. D., McNeall, D. J. & Dunstone, N. J. Importance of the deep ocean for estimating decadal changes in Earth's radiation balance. *Geophys. Res. Lett.* **38,** L13707 (2011).
24. Dee, D. P., Uppala, S. M., Simmons, A. J. & Berrisford, P. *et al.* The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* **137,** 553–597 (2011).
25. Meehl, G. A. *et al.* THE WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Am. Meteorol. Soc.* **88,** 1383–1394 (2007).
26. Lyman, J. M. & Johnson, G. C. Estimating annual global upper-ocean heat content anomalies despite irregular *in situ* ocean sampling. *J. Clim.* **21,** 5629–5641 (2008).
27. Trenberth, K. E. An imperative for climate change planning: Tracking Earth's global energy. *Curr. Opin. Environ. Sustainability* **1,** 19–27 (2009).
28. Johnson, D. R. *et al.* in *NODC Internal Report 20* (ed. Levitus, S.) (NOAA Printing Office, Available at http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html (2009).
29. Levitus, S. *et al.* Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* **36,** L07608 (2009).
30. Palmer, M. D., Haines, K., Tett, S. F. B. & Ansell, T. J. Isolating the signal of ocean global warming. *Geophys. Res. Lett.* **34,** L23610 (2007).

Acknowledgements

We thank the CERES science, algorithm, and data management teams and the NASA Science Mission Directorate for supporting this research. J.M.L. and G.C.J. were funded by the US National Oceanic and Atmospheric Administration (NOAA) Climate Program Office and NOAA Research. We thank S. Good at the UK Met Office for providing OHCA data from the Hadley Centre.

Author contributions

N.G.L. led the writing and analysis, with writing and analysis contributions from J.M.L., R.P.A., T.W. and B.J.S. and writing contributions from G.C.J.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to N.G.L.