geoengineering in the form of direct air carbon capture and storage (DACCS) at the gigaton scale would require trillions of US dollars using current technology[2,3]. To render the problem tractable, costs would need to fall by a factor of a million or more. To observers not familiar with the accelerating nature of technological progress, it might seem reasonable to assume that DACCS will therefore not be feasible for thousands of years. But at least one technological pathway to a million-fold cost reduction for megaprojects of this scale (and much else besides) is already clear: intelligent machine labour, a technology that lies only decades away[4].

The prospect of technological progress does not at all diminish the severity of any form of environmental degradation or the urgency with which mitigation and adaptation action are called for. The carbon and climate problem is a crisis today, regardless of what tomorrow may bring. Moreover, the risk of 'mitigation obstruction' and complacency associated with the anticipation of geoengineering 'techno-fixes' remains a legitimate concern[5–8]. Likewise, the risks — both known and unknown — of all forms of geoengineering warrant rigorous evaluation (see for example, refs 9,10). Nevertheless, the question of whether CDR geoengineering will be feasible in the relatively near future must not be conflated with the question of whether it is desirable. And the fact that CDR geoengineering may indeed become feasible far sooner than many people imagine only underscores the importance of starting to evaluate its desirability now.

Scenarios such as those presented by Clark *et al.*[1] may, just like 'business as usual', provide instructive baselines for comparison. Nevertheless, any scenario that claims or implies itself to be a realistic forecast rather than a prospective counterfactual one must include an open-eyed accounting of the technological changes that current research across the engineering and computer science disciplines suggests we are very likely to see over the remainder of this century. ❒

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CORRESPONDENCE:

Improving estimates of Earth's energy imbalance

To the Editor — Earth is gaining energy owing to increasing concentrations of greenhouse gases 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 total 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]. Although 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 from 2005 (the year the Argo array of profiling floats achieved sparse near-global coverage) to 2010 by combining observed ocean heat uptake over 0–1,800 m with published estimates of energy uptake by the deeper ocean, lithosphere, cryosphere, and atmosphere. It was used to anchor satellite-observed EEI from the Clouds and the Earth's Radiant Energy System (CERES), which, although stable over time, is not sufficiently accurate in absolute value to determine EEI at the required level. Year-to-year variations of 0–1,800 m ocean heat uptake and CERES EEI were correlated at 0.46. Here, we update our calculations (Fig. 1), and find a net heat uptake of 0.71 ± 0.10 W m^{-2} from 2005 to 2015 (with 0.61 ± 0.09 W m^{-2} taken up by the ocean from 0–1,800 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 an increasingly warmer and moister atmosphere[1]). In addition to a remarkable quartering of uncertainty, owing to improved sampling by the Argo array over time (Fig. 1), the correlation between year-to-year rates of 0–1,800 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 the 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. ❒

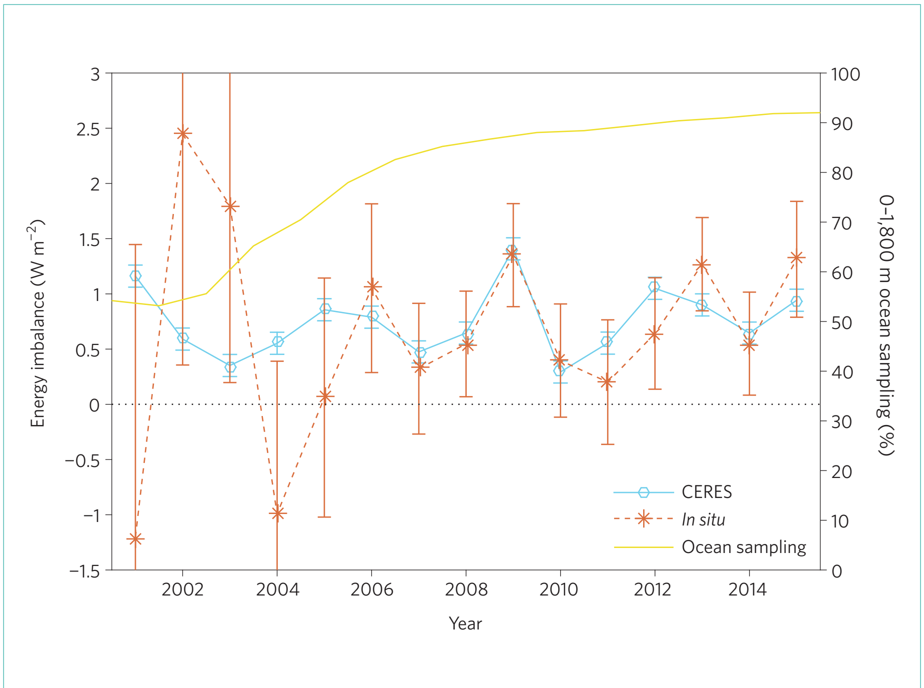

Figure 1 | Comparison of year-to-year net top-of-the-atmosphere annual energy flux from the CERES Energy Balanced and Filled (EBAF) Ed2.8 product with an *in situ* observational estimate of uptake of energy by Earth's climate system. The *in situ* estimate (orange asterisks joined by an orange dashed line) is composed of first differences of annual 0–1,800 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 (>2,000 m) ocean warming[4], as well as land warming, ice melt, and atmospheric warming and moisture uptake[1]. *In situ* uncertainties (orange 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 through 2015 *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 0–1,800 m global ocean sampled for annual ocean heat uptake[5] (yellow line) shows substantial improvement over time with implementation of Argo.

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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 0–1,800 m ocean heat content anomaly estimates. N.G.L. provided the CERES top-of-the-atmosphere energy flux estimates.

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COMMENTARY:

Preventing fires and haze in Southeast Asia

Luca Tacconi

Indonesian peatlands need to be protected and restored to prevent fires and the health, environmental and economic impact that they have on the wider region.

During September and October 2015, Southeast Asia was engulfed in a toxic haze emanating from forest and peatland fires in Indonesia. Every year fire is used for agricultural purposes, but droughts such as that of 2015 — associated with the El Niño–Southern Oscillation and Indian Ocean Dipole — create the conditions that allow extensive fires to burn in disturbed tropical forests and peatlands, which are normally highly resistant to fire in their undisturbed state[1–3]. The 2015 fires were the second worst of the past two decades (after the 1997–1998 event) in terms of greenhouse gas (GHG) emissions[4]. The Indonesian Government estimates that between June and October, fires affected about ~2.61 million hectares[5] (Table 1), of