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Earth's Energy Imbalance More Than Doubled in Recent Decades

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Highlight
Editor's Highlight—Earth's Energy Imbalance is Growing Faster Than Expected

Abstract

Global warming results from anthropogenic greenhouse gas emissions which upset the delicate balance between the incoming sunlight, and the reflected and emitted radiation from Earth. The imbalance leads to energy accumulation in the atmosphere, oceans and land, and melting of the cryosphere, resulting in increasing temperatures, rising sea levels, and more extreme weather around the globe. Despite the fundamental role of the energy imbalance in regulating the climate system, as known to humanity for more than two centuries, our capacity to observe it is rapidly deteriorating as satellites are being decommissioned.

Plain Language Summary

Global warming is caused by the imbalance between the incoming radiation from the Sun and the reflected and outgoing infrared radiation from the Earth. The imbalance leads to energy accumulation in the atmosphere, oceans and land, and melting of the cryosphere, resulting in increasing temperatures, rising sea levels, and more extreme weather around the globe according the the United Nations Intergovernmental Panel on Climate Change (IPCC). Observations from space of the energy imbalance shows that it is rising much faster than expected, and in 2023 it reached values two times higher than the best estimate from IPCC. We argue that we must strive to better understand this fundamental change in Earth's climate state, and ensure our capacity to monitor it in the future.

Key Points

- Earth's energy imbalance more than doubled in recent decades
- The large trend has taken us by surprise, and as a community we should strive to understand the underlying causes
- Our capability to observe the Earth's energy imbalance and budget terms is threatened as satellites are decommissioned

Global warming results from anthropogenic greenhouse gas emissions which upset the delicate balance between the incoming sunlight, and the reflected and emitted radiation from Earth. The imbalance leads to energy accumulation in the atmosphere, oceans and land, and melting of the cryosphere (von Schuckmann et al., 2023), resulting in increasing temperatures, rising sea levels, and more extreme weather around the globe (IPCC, 2021). Despite the fundamental role of the energy imbalance in regulating the climate system, as known to humanity for more than two centuries (Fourier, 1822), our capacity to observe it is rapidly deteriorating as satellites are being decommissioned (Loeb et al., 2024).

Worryingly, the observed energy imbalance is rising much faster than expected, reaching 1.8 Wm^{-2} in 2023—or twice that predicted by climate models—after having more than doubled within just two decades (Figure 1). This strong upward trend in the imbalance is difficult to reconcile with climate models: even if the increase in anthropogenic radiative forcing and associated climate response are accounted for, state-of-the-art global climate models can only barely reproduce the rate of change up to 2020 within the observational uncertainty (Raghuraman et al., 2021). The continued rise in the energy imbalance since 2020 leaves us with little doubt that the real world signal has left the envelope of model internal variability. The root cause of the discrepancy between models and observations is currently not well known, but it seems to be dominated by a decrease in Earth's solar reflectivity (Goessling et al., 2024; Stephens et al., 2022), and model experiments suggest it could be due to poorly modeled sea surface temperature patterns, the representation and emissions of polluting aerosol particles, or something else (Hodnebrog et al., 2024).

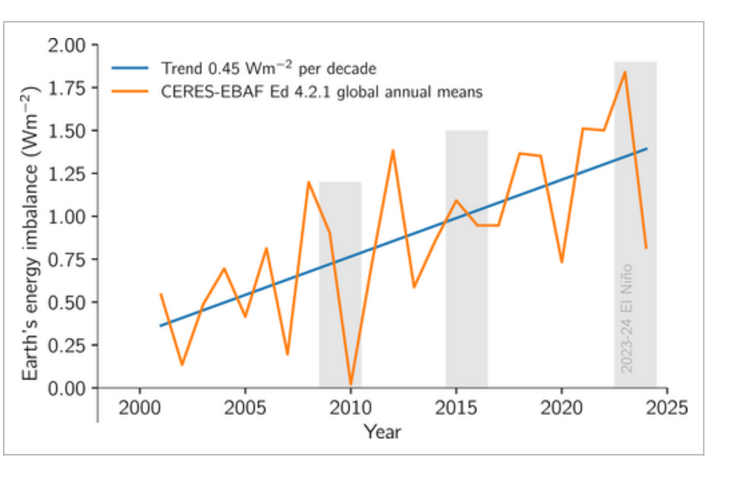

Figure 1 Open in figure viewer | PowerPoint

Annual global mean energy imbalance observed from space during 2001–2024. The imbalance is derived from the CERES-EBAF Edition 4.2.1 data set (Loeb et al., 2018). The blue line shows the linear trend over the 2001–2024 period when full annual means are available. Gray shading shows years affected by major El Niño events.

The energy imbalance is the result of multiple factors: forcing, feedback and internal variability. The main forcing is that of anthropogenic emissions that lead to accumulation of carbon dioxide and other greenhouse gases in the atmosphere, emitted infrared radiation to space is reduced, driving a gradually increasing imbalance. Part of the positive greenhouse gas forcing is offset by the presence of anthropogenic aerosols, which cool climate by reflecting sunlight back to space and influence cloud reflection. The forcing from aerosols, even in recent decades, is poorly known (Bellouin et al., 2020). But some evidence suggests the cooling effect is weakening as governments address air quality issues (e.g., Hodnebrog et al., 2024). However, the rising surface temperatures also lead to more infrared emission to space, which reduces the energy imbalance, constituting a negative feedback mechanism. The warming further activates other climate feedbacks from clouds, water vapor, the cryosphere, etc., which together act to amplify global warming. Overall, the negative feedbacks are believed to dominate so that over the last decades the enhanced outgoing radiation from feedback mechanisms should have countered a substantial part of the increase in radiative forcing. In addition, internal variability arising from weather and slower modes, such as El Niño, can cause year-to-year fluctuations in the energy imbalance. This shows that there are many, sometimes counteracting drivers of the energy imbalance, all of which can play a role in determining the observed accelerating rate of increase. With an observed global warming of about 0.6 K over the 2001–2024 period, the enhanced outgoing radiation from feedback mechanisms should have countered a substantial part of the increase in radiative forcing, but that is not clearly evident from the observational record.

Much attention has been given to the record breaking surface temperatures in 2023 and 2024, and this has a bearing on the energy imbalance since it too beat all records in 2023. A large accumulation of energy in a single year, however, does not necessarily cause the temperature anomaly in that year. Rather, the temperature in 1 year is perhaps better thought of as the result of the energy accumulated in earlier years, combined with any rapid change in forcing (e.g., aerosol emissions, volcanic eruptions or solar forcing), internal variability within the climate system, as well as climate feedback mechanisms. The energy imbalance started to decrease already in the second half of 2023, and continued to weaken in 2024 (Figure 1), suggesting that stabilizing feedback mechanisms are now active in the aftermath of the El Niño event. A similar pattern was seen after the 2009/10 El Niño, but not nearly as pronounced for the 2015/16 event. Notably, the drop in 2024 relative to 2010 follows the overall upward trend and coming years will tell if the energy imbalance remains at this more modest level, or bounces back up to the high levels observed in recent years.

Disentangling the underlying causes and effects of changes in the energy imbalance relies heavily on observing trends in both the emitted infrared and reflected sunlight, and how they vary spatially and over seasons. The components of the Earth's energy imbalance are currently observed using a combination of NASA's CERES onboard several polar-orbiting satellites, and the total solar irradiance (TSIS-1) instrument on the International Space Station. The mean of these observations for 07/2005-06/2015 is constrained by estimates of the increase in interior energy, predominantly from rising ocean temperatures monitored using thousands of autonomous Argo floats (Johnson et al., 2016). The resulting radiation budget record requires an overlap of different instruments in orbit to ensure there are no discontinuities between successive missions and to prevent loss of critical data. If there is a gap in the record with this system, then our ability to track and understand changes in the energy imbalance is severely compromised (Loeb et al., 2024). Currently, four sets of CERES instruments are in space, and the Libera follow-on mission (e.g., Hakuba et al., 2024) with similar or improved capabilities is planned to launch in 2027. It is likely that within a decade Libera will be the only instrument in space as the other satellites are decommissioned. It will by then be a single point of failure, and at present, there are no formal plans to continue this vital record after Libera's mission-end. For solar irradiance, the follow-on total solar irradiance instrument (TSIS-2) is scheduled to launch in 2025, but has only a 3-year planned mission lifetime.

In the longer perspective there are complementary initiatives that focus on measuring the energy imbalance itself, and less so on the individual incoming and outgoing budget components. One US initiative is based on nearly spherical black satellites with accelerometers that will measure the radiation pressure (Hakuba et al., 2019), and a European proposed mission uses a constellation of satellites each equipped with four evolved wide field of view radiometers, complemented with cameras for spatial information (e.g., Hocking et al., 2024). By focusing on accurately measuring the energy imbalance itself, these direct measurements from space can be made independently from other systems. Neither of these proposed missions are yet funded, and even with sufficient funding, they are unlikely to fly before the second half of the 2030s. However, successful implementation of these missions will provide independent measurements, complementary capabilities and crucial redundancy when combined with the CERES/Libera line of instruments.

It will indeed be crucial to closely monitor and quantitatively understand changes in the Earth's energy accumulation, particularly during the coming decades as the nations of the world take steps to keep global warming well below 2° (United Nations, 2015). Stabilizing global warming below 2° can still be achieved by swiftly phasing out fossil fuel burning. If successful, such mitigation efforts will first manifest in a peak, followed by a slowly declining trend in Earth's energy imbalance, essentially decades ahead of the temperature signal (Figure 2, Meyssignac et al., 2023). It is in the energy imbalance that we can follow up and assess the effectiveness of the mitigation efforts on the fly. And if surprises lie ahead, for example, from unexpectedly large aerosol forcing (Hansen et al., 2023), or an unexpected loss of climate stability, then the imbalance is the first place this can be detected.

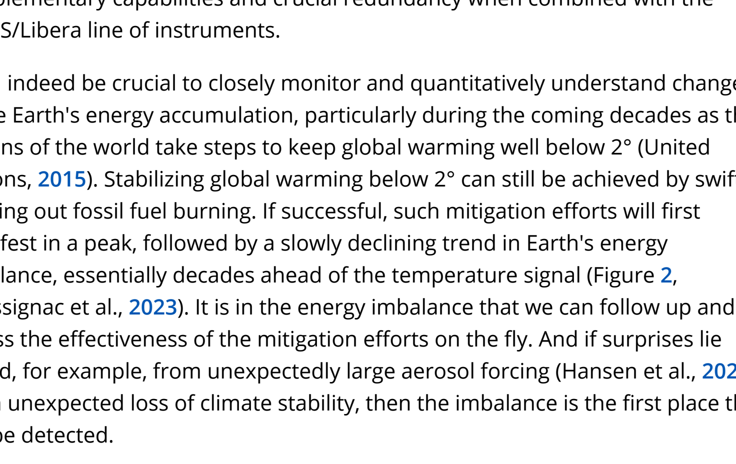

Figure 2 Open in figure viewer | PowerPoint

Climate model global mean temperature and energy imbalance under a strong mitigation scenario meeting the 2° target (SSP1-2.6). Time series are estimated from the IPCC AR6 Earth system emulator (IPCC, 2021, Chapter 7 supplementary material). Displayed data are from (Meyssignac et al., 2023). Uncertainty ranges indicate the 90 percent confidence interval of the spread caused by uncertainties in forcing, the climate response, and the carbon cycle. The displayed uncertainty range therefore excludes internal variability. The dots mark the peak year on each time series.

As a community we must work systematically to understand and quantify the underlying causes of the changes in the energy imbalance, not only far into the future, but also on a year to year basis, as questions mount with regards to the 2023 combined record imbalance and temperatures; an anomaly which has clearly caught us all off guard. And, together with funding agencies and policy makers, we must strive to secure a robust and reliable capability to observe the energy imbalance—the perhaps most fundamental quantity in the climate system—during this pivotal moment in history.

Acknowledgments

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

CERES-EBAF Edition 4.2.1 data (Loeb et al., 2018) displayed in Figure 1 was downloaded from https://ceres-tool.larc.nasa.gov/ as monthly global means. Model output displayed in Figure 2 is described in a supplement to the (IPCC, 2021) working Group 1 Chapter 7 (Smith et al., 2021), and Meyssignac et al. (2023). The underlying model code and parameters are available on https://github.com/IPCC-WG1/Chapter-7.

Supporting Information

References

Citing Literature

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