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A Thermodynamic Analysis of Earth's Energy Imbalance

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Abstract

Earth's energy imbalance (EEI) is defined as the difference between the globally averaged incoming solar radiation absorbed by the climate system and the outgoing longwave and reflected shortwave radiation at the top of the atmosphere (TOA). Thermodynamically, EEI is a measure of the rate at which free energy is being stored in the Earth system and converted into increased internal energy, predominantly ocean heat content, as the system adjusts toward a new radiative equilibrium under anthropogenic forcing. Using recent observational estimates from satellite radiation measurements and global energy inventory data, this paper analyzes EEI over recent decades, interprets the imbalance within a thermodynamic framework, and assesses its implications for climate sensitivity and future warming. Results indicate that the global mean EEI has increased from about $0.5 \pm 0.2 \text{ W m}^{-2}$ in the early 2000s to about $1.0 \pm 0.2 \text{ W m}^{-2}$ over the last decade, implying a more than doubling of the rate of heat uptake by the Earth system (Loeb, N. G. et al. 2024, von Schuckmann, K. et al. 2023). Over 2005–2019, the average EEI is estimated to be about $0.90 \pm 0.15 \text{ W m}^{-2}$, consistent with independent constraints from ocean heat content observations and energy budget analyses (von Schuckmann, K. et al. 2023). Thermodynamic relations connecting radiative forcing, climate feedbacks, temperature change and entropy production clarify how this imbalance drives both persistent warming and an intensification of the climate system's irreversible processes (Kleidon A., 2024., Swedan NH. 2023). The analysis underscores that EEI is a fundamental metric for diagnosing the state of global climate and constraining remaining warming “in the pipeline.”

Keywords: Solar, Thermodynamics, Greenhouse gas, Turbulent, Hydrology, Earth's energy, etc.

Introduction

The Earth's climate system can be viewed thermodynamically as an open, non-equilibrium system maintained by differential solar heating and longwave radiative cooling to space (Kleidon A., 2024., Swedan NH. 2023). In radiative equilibrium, global mean absorbed solar radiation (ASR) equals outgoing longwave radiation (OLR) plus reflected shortwave radiation, and global mean temperature remains statistically stable over long time scales. Anthropogenic perturbations—primarily increased

greenhouse gas concentrations and changes in aerosols and surface albedo—have altered the balance at the TOA, creating a positive EEI that causes net heat uptake by the Earth system (Hansen, J. et al. 2011). EEI is therefore both a diagnostic of ongoing climate forcing and a predictor of committed future warming, since the climate will continue to warm as long as this imbalance remains positive. (von Schuckmann, K. et al. 2023., Hansen, J. et al. 2011).

Thermodynamic framework

From a global energy balance perspective, the net radiative flux at the TOA can be written as

$$EEI=ASR-(OLR+RSR)$$

where ASR is absorbed shortwave radiation, OLR is outgoing longwave radiation, and RSR is reflected shortwave radiation [2]. A positive EEI indicates that the climate system is gaining energy, which is manifested as increases in internal energy (primarily heat content) of the oceans, atmosphere, land, and cryosphere, and as the latent heat used in phase changes such as ice melt (von Schuckmann, K. et al. 2023).

In a linearized climate feedback framework, the global mean surface temperature change ΔT satisfies

$$\Delta T=\lambda RF$$

where RF is the effective radiative forcing and λ is an effective climate sensitivity parameter [5]. The instantaneous imbalance can be related to the forcing and the feedback response as

$$EEI=RF-\alpha\Delta T$$

where α is the net climate feedback parameter ($\text{Wm}^{-2} \text{K}^{-1}$), which governs how strongly outgoing radiation increases with temperature (Swedan N.H., 2023). As the system warms, $\alpha\Delta T$ grows until it cancels most of the forcing and the imbalance approaches zero, at which point a new quasi-equilibrium is reached at a higher temperature (IPCC AR6 WGI, 2021).

From a thermodynamic disequilibrium standpoint, differential heating and cooling maintain a finite temperature gradient between the equator and poles and between the surface and space, enabling the generation of available potential energy that sustains atmospheric and oceanic circulations. The heat fluxes associated with EEI and internal transports contribute to entropy production, which quantifies the irreversibility of climate processes such as turbulent mixing, phase changes, and radiative transfer (Swedan N.H., 2023).

Research Methods:

This paper uses a synthesis approach rather than an original observational dataset. Representative values for EEI and its components are drawn from:

Satellite radiation budget measurements (e.g., CERES EBAF products) that provide TOA net radiation and its shortwave and longwave components (Loeb, N. G. et al. 2024).

Global energy inventory assessments that combine ocean heat content, land heat storage, ice melt, and atmospheric heat content to infer EEI over multi-decadal periods (von Schuckmann, K. et al. 2023).

Recent reviews and analyses of Earth's energy budget and EEI, including those that explicitly interpret EEI in thermodynamic terms.

Key quantitative inputs include:

Observational estimates of EEI for different recent periods (e.g., 2001–2010, 2010–2020, 2005–2019). Partitioning of heat storage among the ocean, land, ice, and atmosphere. Trends in ASR and OLR associated with cloud changes, greenhouse gases, and aerosols (Myhre, G. et al. 2025). The thermodynamic analysis interprets these values within the linear energy balance model and links them to entropy production and irreversible processes by considering the effective temperature differences

between the Earth's surface, atmosphere, and space, following non-equilibrium thermodynamics of the climate system.

Results:

Magnitude and trend of EEI

Multiple recent assessments converge on an EEI of order $0.7\text{--}1.0\text{ W m}^{-2}$ averaged over the early 21st century, with an increase over time:

Satellite-based analysis indicates Earth's energy imbalance increased from about $0.5 \pm 0.2\text{ W m}^{-2}$ during 2001–2010 to about $1.0 \pm 0.2\text{ W m}^{-2}$ in 2010–2019, implying a doubling of the net radiative surplus. A synthesis of global heat storage (oceans, land, ice, atmosphere) for 2006–2020 yields an average EEI of $0.76 \pm 0.2\text{ W m}^{-2}$, consistent with independent constraints from TOA radiation measurements.[3], Over 2005–2019, another assessment reports an EEI of approximately $0.90 \pm 0.15\text{ W m}^{-2}$.

Newer analyses extended into the early 2020s indicate that EEI has continued to rise and, in some years, reached values roughly twice the long-term average, consistent with the recent surge in global mean temperatures. This growth in EEI reflects combined effects of increasing greenhouse gas forcing, reductions in aerosol cooling, and cloud and surface-albedo changes that enhance net solar absorption.

Partitioning of heat uptake

The excess energy associated with EEI is primarily stored in the oceans, with smaller but important contributions from other reservoirs:

Over 1960–2020, about 89–90% of the accumulated heat is stored in the ocean, mainly in the upper 2000 m, with the remainder distributed among land, ice melt, and atmospheric warming. For the recent period 2006–2020, ocean heat uptake remains dominant, with land storing roughly 5–6%, the cryosphere (ice melt) about 3–4%, and the atmosphere about 1–2% of the total heat gain. This distribution reflects the high heat capacity and vertical mixing of the ocean, which acts as the main buffer for EEI and delays the full manifestation of radiative forcing in surface temperature change.

Shortwave and longwave contributions

Changes in EEI can be decomposed into shortwave (SW) and longwave (LW) components:

Increasing ASR, largely due to reductions in reflective low and mid-level clouds and regional albedo changes (e.g., Arctic Sea-ice loss), has contributed substantially to the positive trend in EEI, particularly in the Northern Hemisphere. Enhanced greenhouse gas concentrations reduce OLR to space for a given surface temperature; as the climate warms, OLR gradually increases, partially offsetting the forcing but leaving a residual positive imbalance until a new equilibrium is reached (IPCC AR6 WGI, 2021).

Recent satellite analyses show that the strengthening of EEI since the early 2000s is associated with both increased SW absorption and changes in LW radiation, with models that have low climate sensitivity failing to reproduce the observed trend, implying that the climate system may be more sensitive than some models indicate (Myhre, G. et al. 2025).

Temporal evolution and intensification

Longer-term reconstructions of EEI back to the latter half of the 20th century suggest a relatively modest imbalance for much of the period, followed by intensification in the mid-1990s and into the 21st century, coincident with accelerated global warming and cryospheric changes. Recent work estimates globally averaged EEI over 1977–2024 at about 0.68 W m^{-2} , increasing to nearly 1 W m^{-2} over 2012–2024, indicating a clear upward trend.

Discussion:

Thermodynamic interpretation

Within the linear energy balance framework, the relation

$$EEI = RF - \alpha \Delta T$$

shows that EEI represents the portion of radiative forcing not yet balanced by temperature-dependent increases in outgoing radiation. A persistently positive EEI therefore signifies that the climate system has not yet fully equilibrated to the applied forcing and that additional warming is “in the pipeline” even if greenhouse gas concentrations were stabilized.

From a thermodynamic disequilibrium standpoint, the positive EEI increases the internal energy of the Earth system while also maintaining or enhancing temperature gradients that drive atmospheric and oceanic circulations. The irreversible processes that smooth these gradients—turbulent mixing, phase changes, and radiative transfer—produce entropy, and the magnitude of EEI is directly linked to the rate of entropy production and the intensity of the climate system’s dynamics (Kleidon A., 2024).

Implications for climate sensitivity and committed warming

The observed doubling of EEI over the early 21st century implies that the net effective forcing has grown faster than the system’s ability to restore balance through increased OLR. Climate models with low effective climate sensitivity tend to underestimate the observed increase in EEI and its SW and LW components, suggesting that higher-sensitivity models may better capture the real system’s response (Myhre, G. et al. 2025).

Because EEI is directly proportional to the rate of heat uptake, integrated EEI over time provides an estimate of additional warming yet to occur as the ocean mixed layer equilibrates with deeper layers and the cryosphere continues to respond. For a given cumulative forcing, a larger present-day EEI indicates more unrealized warming and a longer timescale for the system to approach a new steady state.

Ocean heat uptake and lagged response

The dominance of ocean heat uptake in the global energy inventory explains the multi-decadal lag between forcing and surface temperature response (von Schuckmann, K. et al. 2023). The upper ocean warms relatively quickly, but heat penetration into the deep ocean occurs on timescales of decades to centuries, delaying full equilibrium and causing future warming even under stabilized radiative forcing.

This lag has critical implications:

It means that observed surface warming underestimates the full response to historical emissions, as part of the forcing is still being equilibrated.

It commits the climate system to continued sea-level rise through ongoing thermal expansion and ice melt, both of which depend on cumulative heat uptake rather than instantaneous EEI alone (von Schuckmann, K. et al. 2023).

Entropy production and climate dynamics

Non-equilibrium thermodynamics links EEI not only to energy storage but also to the intensity of entropy production, which is associated with irreversible processes such as:

- Meridional heat transport by the atmosphere and oceans.
- Turbulent mixing in the boundary layer and ocean interior.

Phase changes of water (evaporation, condensation, freezing, melting).

Increases in EEI imply that more energy is available to be converted into these irreversible processes, potentially modifying circulation patterns, hydrological extremes, and the frequency and intensity of weather events. While the detailed dynamical consequences depend on regional feedbacks and modes

of variability, the thermodynamic constraint is that a higher EEI generally corresponds to a more strongly forced, more vigorously dissipative climate system (Kleidon A., 2024).

Observational and methodological considerations

Estimating EEI with high accuracy is challenging because the imbalance is small compared to the absolute fluxes, which are on the order of hundreds of W m^{-2} . Current best estimates rely on:

- Calibration and stability of satellite radiation instruments.
- Comprehensive, quality-controlled ocean heat content measurements, including the Argo float network and deep-ocean observations.
- Consistent methods for combining different heat storage components and closing the global energy budget.

Uncertainties in cloud radiative effects, aerosol forcing, and deep-ocean heat uptake remain significant sources of error and continue to motivate efforts to improve observation systems and energy-budget closure (IPCC AR6 WGI 2021).

Conclusions

Thermodynamic analysis reveals that Earth's energy imbalance is a central, physically grounded indicator of the state of the climate system, directly linking radiative forcing, heat uptake, entropy production, and future warming. Recent observational evidence indicates that EEI currently lies near $0.7\text{--}1.0 \text{ W m}^{-2}$ and has more than doubled since the early 2000s, with most of the excess energy being stored in the oceans. As long as this positive imbalance persists, further global warming, sea-level rise, and intensification of climate-related processes are inevitable, even under ambitious mitigation scenarios.

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