Validation of the observed increase in the ocean heat content with the law of conservation of energy

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Key Points

- Energy conservation yields an equality between the energy imbalance at the top of the atmosphere and the chemical energy exchanged
- The energy imbalance at the top of the atmosphere is about equal to the increase in the ocean heat content (OHC)
- The observed increase in OHC is considerably greater than that permitted by energy conservation and should be verified

Abstract

The Ocean Heat Content (OHC) anomaly has become an increasingly important climate parameter for the Intergovernmental Panel on Climate Change (IPCC) assessment and evaluation of climate change. One good reason is that the OHC appears to be less prone to climate variability, typically experienced with surface temperature and other climate parameters. Therefore, a reasonable estimate of OHC increase is important for research and climate related policies. Levitus et al. (2012) (https://doi.org/10.1029/2012GL051106) is a relevant ocean heat content related paper, and their analysis and estimate of OHC increase between 1955 and 2010 is high, about four to seven times greater than what the law of conservation of energy may allow. The source of discrepancy is analyzed in this commentary and it appears to be a result of using corrected ocean data sources. Therefore, verification of the observed increase in OHC using alternative ocean data sources is recommended.

Keywords: Ocean Heat Content; Radiative Forcing; Energy Imbalance; Thermodynamics

Plain Language Summary

Climate change is an energy exchange phenomenon subject to the law of conservation of energy. Variation in the energy budget at the top of the atmosphere must be equal to the net change in the heat content of the earth's subsystems, mostly the ocean. This, however, does not appear to be the case in relevant ocean heat related literature such as Levitus et al. (2012). This paper shows considerably more heat accumulation in the ocean than what the energy balance may permit. The inconsistency appears to be attributed to corrections made to ocean temperature data sources. Consequently, verification of the observed increase in the ocean heat content is recommended.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) relies on published scientific papers for their assessment of climate change and climate change mitigation policy recommendations. The increase in the Ocean Heat Content (OHC) is a parameter used by IPCC in assessing and projecting Global Surface Air Temperature (GSAT), (Forster et al., 2021). The Executive Summary of chapter 7 of the IPCC's Sixth Assessment Report (AR6), Forster et al. (2021), reveals that the conclusions of this chapter capitalize on the IPCC's Fifth Assessment Report (AR5), Chapter 5 of the Special Report on the Ocean and Cryosphere in a Changing Climate, Bindoff et al. (2019), and Chapter 2 of the IPCC's Sixth Assessment Report (AR6), Gulev et al. (2021). The publication (Levitus et al., 2012) is cited in all of these IPCC products. Levitus et al. (2012) is a highly cited publication having societal impacts. Therefore, commentary on this paper merits consideration, notwithstanding the lapse time of 11 years since it was first published.

The intent of this commentary is to investigate why there appears to be an inconsistency in the energy balance of climate literature of which Levitus et al. (2012) is a relevant source of OHC. This endeavor was circumvented in the past for lack of suitable published literature necessary for comparison and validation. Lately, the IPCC's Sixth Assessment Report (AR6) has become available and the author of this commentary published Swedan (2023). This publication is an application of the first law of thermodynamics for climate change. The publication is in essence an application of the laws of conservation of mass and energy of the climate system, and, therefore, qualifies for comparison and validation. It is thus used in the investigation and conclusions of this commentary.

Theory and application

This section demonstrates that the law of conservation of energy for the climate dictates that the energy imbalance at the top of the atmosphere must be equal to the net variation in the chemical energy of fossil fuels, deforestation, and living green matter. Also, the energy imbalance at the top of the atmosphere is closely equal to the variation in the heat content of the ocean.

The earth's internal heat does not vary with climate change, it may thus be neglected. Also, the global surface evaporation may be neglected as well, because the total heat exchanged with the earth, Q_E, is a constant as demonstrated below by Eq. (5) of this section. The energy imbalance at the top of the atmosphere may be determined from the overall energy balance of the atmosphere with changes in climate as follows:

$$dE_A/dt=E_{in}-E_{out} \tag{1}$$

Where

dE_A/dt =Energy exchanged with the atmosphere, J yr^{-1}.

E_{in}=Incoming energy flux, J yr^{-1}.

E_{out}=Outgoing energy flux, J yr^{-1}.

The term $-(E_{in}-E_{out})$ is equal to the energy imbalance at the top of the atmosphere, it is equal to the forcing of greenhouse gases. Unlike the atmosphere, the earth as a whole exchanges heat with various heat sources during climate change, and the related energy balance or conservation of energy may be written as follows:

$$dQ_E/dt=E_{in}-E_{out}+Q_F+Q_D-Q_G \tag{2}$$

Where
dQ_E/dt=Heat exchanged with the earth, J yr^{-1}.
Q_F=Chemical energy production of fossil fuels, J yr^{-1}.
Q_D=Chemical energy of deforestation, J yr^{-1}.
Q_G=Chemical energy of living green matter or surface greening, J yr^{-1}.

Climate change occurs infinitesimally with time, 0.02 °C annually or less, it is thus a reversible thermodynamic transformation based on the state of thermodynamic understanding (Lin et al., 1984), which is observed in past climates (Petite et al., 1999). Variation in the sum of the entropy of the earth and its surrounding outer space is thus equal to zero. Because the outer space is at a temperature close to zero Kelvin, variation of the entropy of the outer space may be neglected based on the third law of thermodynamics. Therefore, variation in the entropy of the earth is nearly equal to zero and

$$dS_E=0 \tag{3}$$
$$dQ_E/T_E=dS_E= 0 \tag{4}$$
$$dQ_E/dt=0 \tag{5}$$

Where
S_E=Entropy of the earth, J °C^{-1}.
T_E=Average temperature of the earth, °K.

Equation (5) indicates that the heat exchanged with the earth, Q_E, remains unchanged. Based this equation, Eq. (2) may be simplified

$$-(E_{in}-E_{out})=Q_F+Q_D-Q_G \tag{6}$$

The chemical energy produced in the climate system, $Q_F+Q_D-Q_G$, on the other hand is equal to the increase in the heat content of the earth's subsystems (Swedan 2023, Eq. 13). Most of this heat ultimately accumulates in the ocean. Equation (6) shows that the energy imbalance at the top of the atmosphere is equal to the net chemical energy produced in the climate system, which is closely equal to the increase in the ocean heat content. This theoretical conclusion may be validated based on published literature available: The Executive Summary of chapter 7 of the IPCC's Sixth Assessment Report (AR6), Forster et al. (2021), concluded that the anthropogenic radiative forcing between 1750 and 2019 was 2.72 [1.96 to 3.48] W m^{-2}. This forcing at the top of the atmosphere is cumulative for the entire period of time between 1750 and 2019. Neglecting the heat to land for being small, (Forster et al., 2021), the equivalent total heat added to the ocean in ZJ may be determined by multiplying the radiative forcings by $A\tau$ and dividing the multiplication result by 1.0×10^{21}, which gives 43.70 [31.50 to 55.90] ZJ (1 ZJ=1.0×10^{21}J).

Where A is the total surface area of the earth, 5.1 x 10^{14} m^2, and τ is number of seconds in one year, 3.15 x 10^7 s. Therefore, the energy imbalance at the top of the atmosphere $-(E_{in}-E_{out})$ is equal to 43.70 [31.50 to 55.90] ZJ. Line 10 of Table 1 of Swedan (2023) indicates that the total net heat to the surface, $(Q_F+Q_D-Q_G)$, through 2019 is 67.3 ZJ. They are of the same order of magnitude. The theoretical Eq. (6) is thus correct based on the literature and observations available.

Discussion and conclusions

The derived Eq. (6) sets the limits of heat accumulation in the ocean based on the law of conservation of energy. The anthropogenic forcing expressed as an imbalance of the energy budget at the top of atmosphere is closely equal to the heat transferred to the surface, most of which (91%) accumulates in the ocean (Forster et al., 2021). The energy imbalance between 1750 and 2019 was 43.70 [31.50 to 55.90] ZJ, and the calculated and observed corresponding increase in the Global Surface Air Temperature was 1.29 [0.99 to 1.65] °C (Forster et al., 2021; Gulev et al., 2021). They are in agreement with those obtained by applying the first law of thermodynamics for climate change (Swedan, 2023). This paper concluded that the observed chemical energy transferred to the surface of the earth as heat was nearly 67.3 ZJ between 1750 and 2019, and the calculated corresponding increase in the average land surface air temperature was nearly 1.38 °C. The radiative forcing methodology thus adheres reasonably to the law of conservation of energy based on theory and observations.

Conversely, the observed increase in the ocean heat content by Levitus et al. (2012) exceeds the limits set by the energy balance. This paper estimated that nearly 236.5 ZJ of heat was added to the ocean between 1955 and 2010. The estimated heat is well above the energy budget imbalance at the top of the atmosphere by a factor of four to seven. The observed increase in the ocean heat content by Levitus et al. (2012) thus violates the law of conservation of energy. It creates a considerable amount of heat in the ocean. A possible explanation is that Levitus et al. (2012) used widespread corrected ocean temperature data, as explained in the abstract and data and method sections of Levitus et al. (2012). Sea water has a high thermal capacity, nearly 2.98 x 10^{24} J $°C^{-1}$ for the top 2 000 m of ocean. This value is calculated based on sea water density of 1 048 kg m^{-3} and sea water specific heat of 3 980 J $kg^{-1}°C^{-1}$ (Safarov et al., 2009), and using sea water area ratio of 0.7 with respect to the total earth's surface area of 5.1 x 10^{14} m^2. A correction by only 0.01 °C in the ocean temperature data may produce an error of ±2.98 x 10^{22} J in the ocean heat content, equivalent to ±29.80 ZJ or ±1.86 W m^{-2}. This is a large error for such a small and negligible temperature correction, nearly equal to ±68.2% of the total average heat accumulated in the ocean. Therefore, any correction of ocean temperature data is potentially an incorrect methodology. Given that corrections were made, Levitus et al. (2012) may have reported an increase in the ocean heat content that is higher than actual. Verification of the observed increase in the ocean heat content using alternative ocean temperature data is thus recommended.

Competing interests

The author declares no conflicts or competing interests with respect to the research, authorship,

and publication of this commentary on a published paper.

Data Availability

No new data has been added in the submitted manuscript. Data is available online through (Bindoff, et al., 2019, https://doi.org/10.1017/9781009157964.007; Forster et al., 2021, doi:10.1017/9781009157896.009; Gulev et al., 2021, doi:10.1017/9781009157896.004; Levitus, et al., 2012, https://doi.org/10.1029/2012GL051106; Rhein et al., 2013, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter03_FINAL.pdf).

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