CSQ-46 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How does the Earth energy imbalance and Earth heat inventory changes over time and why? And what can we learn from this for the interplay between effective radiative climate forcing, Earth's surface temperature response and climate sensitivity, as well as its implication on Earth system change?	A) Earth heat inventory evaluation to unravel how much and where surplus heat from climate change is going	• Ocean heat content (direct, indirect: ocean mass & sea level) • Land heat content (continental, permafrost and inland water bodies) • Atmospheric heat content • Heat available to melt ice (Ice shelf, sea ice, glaciers, snow cover)	• High-spatial resolution (e.g., ¼°, min. 1°) • High-temporal resolution to capture from extremes to long-term change (e.g., daily) • Multi-satellite approach • Multi-product approach (in situ, satellite, model)	Earth system models Atmospheric & oceanic & coupled assimilation systems	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models (validation, parametrization, detection & attribution)
	B) Global budget closure studies for the global energy budget relation linking planetary heating, effective radiative forcing, surface temperature response and climate sensitivity to take stock on the long-term change in the Earth energy imbalance, further tackle underlying uncertainties.	• Net flux at the top of the atmosphere (incoming & outgoing radiation) • Effective radiative forcing • Climate sensitivity (indirect observed) • Earth heat inventory (see above)			
	C) Study the impact and causality of impacts of a changing Earth energy imbalance over time on planetary warming and associated implications for Earth system variability and change.	• Both lists above (inventory & constraint approach) • Ocean change (sea level, hydrography, carbonate system, mass) • Atmosphere change (hydrography incl. water vapor, radiative & turbulent fluxes, circulation) • Land (hydrography, incl. soil water, radiative & turbulent			

		fluxes, subsidence & erosion monitoring) • Cryosphere (Ice sheets, Sea ice, glaciers, snow cover)			

CSQ 46 Narrative

The Earth climate system is out of energy balance manifested as a positive Earth energy imbalance (EEI) at the top of the atmosphere (IPCC, 2021; von Schuckmann et al., 2020). As a consequence, heat has accumulated continuously over the past decades, warming the ocean, the land, the cryosphere and the atmosphere. As the ocean, the land, the cryosphere and the atmosphere warms from this surplus heat, unprecedented and committed changes in the Earth system have evolved, with adverse impacts for ecosystems and human systems (IPCC, 2021, 2022). This Earth heat inventory (Fig. 2a) plays a central role for climate change monitoring as it provides information on the absolute value of the Earth energy imbalance, the total Earth system heat gain, and how much and where heat is stored in the different Earth system components. Quantifying the heat stored in the different Earth system components is then essential to further unravel impacts of increase in heat content across the entire Earth system (Fig. 2b). Moreover, a quantification of the Earth heat inventory is also relevant for climate model constraint approaches, validations, and unraveling sources of uncertainties in the calculations such as for example on effective climate sensitivity (Gregory et al., 2002; Mauritzen and Roegner, 2020; Rugenstein et al., 2020). The Earth heat inventory is estimated via the heat content of each Earth system component, using a combination of in situ measurements, satellite data, reanalysis and model outputs. Given the large gaps in the observing system for these quantifications, estimates still suffer large uncertainties, and partly rely on a hybrid data approach, which is particularly the case for the cryosphere and the land components (von Schuckmann et al., 2023).

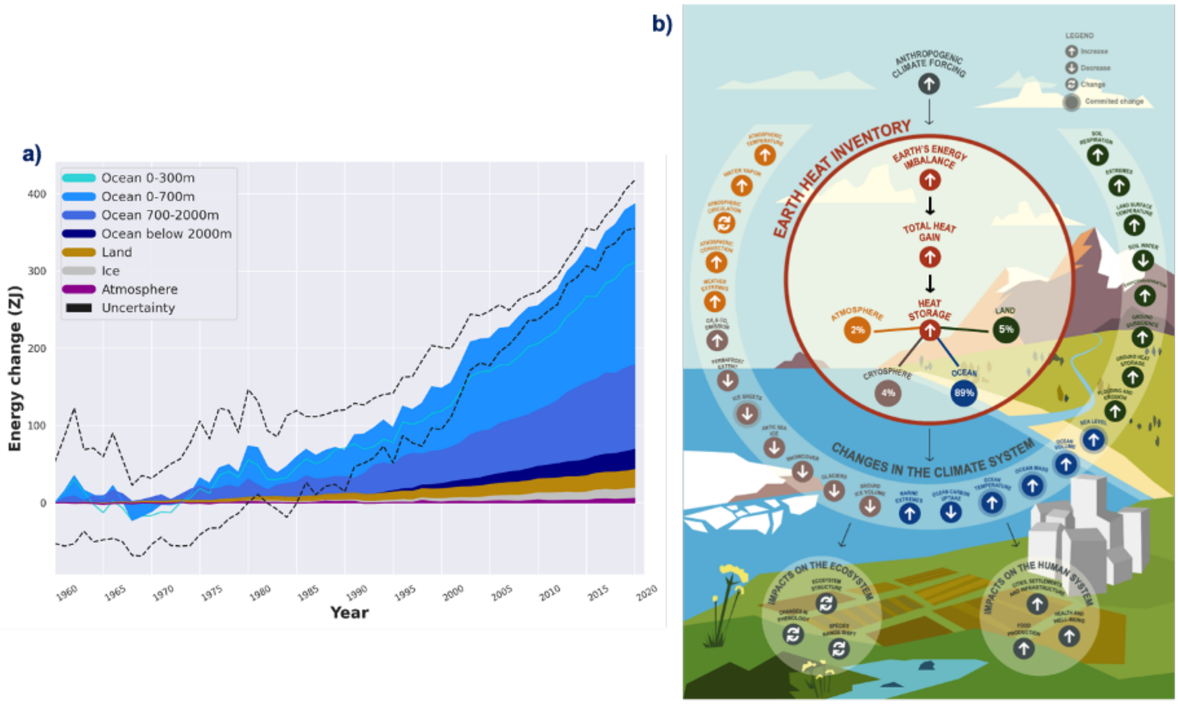

Figure 2: a) *Total Earth system heat gain in ZJ (1 ZJ =10^{21} J) relative to 1960 and from 1960 to 2020, with a total heat gain of 381±61 ZJ over the period 1971–2020, which is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2} applied continuously over the surface area of the Earth (5.10×10^{14} m^2).* ***b)*** *Schematic overview on the central role of the Earth heat inventory and its linkage to anthropogenic emissions, the Earth energy imbalance, change in the Earth system and implications for ecosystems and human systems. Examples of associated global-scale changes in the Earth system as assessed in (Gulev et al., 2021) are drawn, together with major implications for the ecosystem and human systems*

(IPCC, 2022). Upward arrows indicate increasing change, downward arrows indicate decreasing change, and turning arrows indicate change in both directions. After (von Schuckmann et al., 2023).

Most recent studies have shown that the EEI has increased during the most recent era as compared to the long-term (e.g., past century) estimate of EEI increase (Forster et al., 2022; Hakuba et al., 2021; Kramer et al., 2021; Loeb et al., 2021; Raghuraman et al., 2021; von Schuckmann et al., 2020). The drivers of a larger EEI in the 2000s than in the long-term period since 1971 are still unclear, and several mechanisms are discussed in literature. For example, Loeb et al. (2021) argue for a decreased reflection of energy back into space by clouds and sea-ice, and increases in well-mixed greenhouse gases (GHG) and water vapor to account for this increase in EEI. (Kramer et al., 2021) refers to a combination of rising concentrations of well-mixed GHG and recent reductions in aerosol emissions accounting for the increase, and (Liu et al., 2020) addresses changes in surface heat flux together with planetary heat re-distribution and changes in ocean heat storage. (Raghuraman et al., 2021) attribute the observed increase to anthropogenic forcing, manifesting the observed evidence of climate change from remote sensing. Sustained and continued measurements are needed to monitor the temporal evolution of the EEI (Cheng et al., 2022; Dewitte et al., 2019; Hakuba et al., 2019), and to further study drivers of EEI change, together with implications for changes in the Earth system.

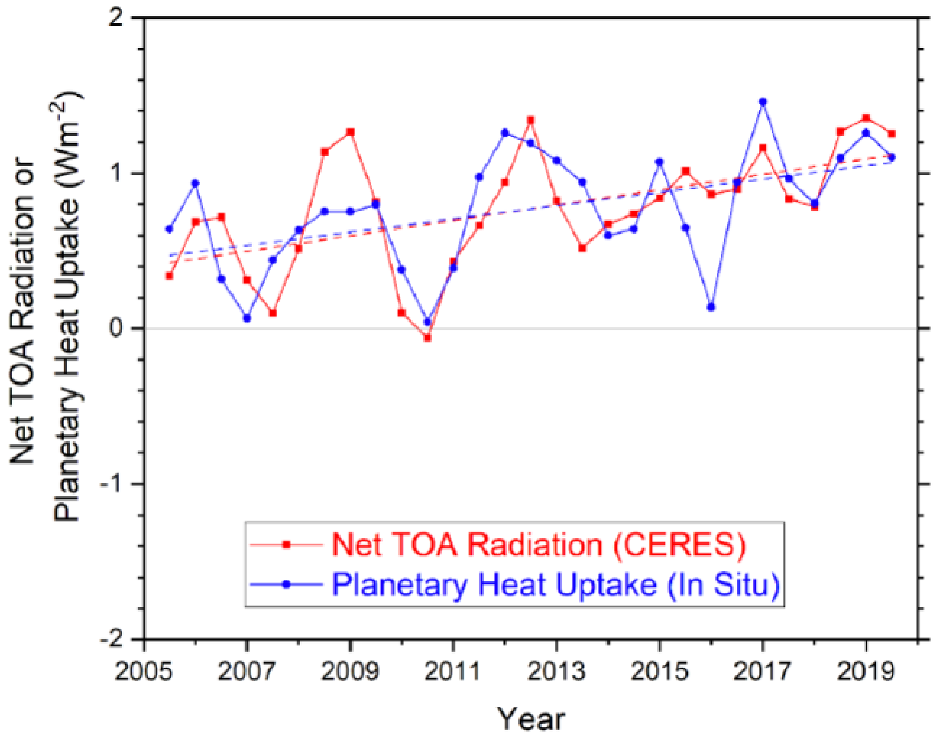

Figure 3: Comparison of overlapping one-year estimates at 6-month intervals of net top-of-the-atmosphere annual energy flux from CERES (red) and the uptake of energy by the Earth climate system. From Loeb et al., 2021.

As the ocean, the land, the cryosphere and the atmosphere warms from the anthropogenic surplus heat accumulated in the Earth system, unprecedented and committed changes in the Earth system have evolved, with adverse impacts for ecosystems and human systems (IPCC, 2021, 2022). This Earth heat inventory (Fig. 2a) plays a central role for climate change monitoring as it provides information on the absolute value of the Earth energy imbalance, the total Earth system heat gain, and how much and where heat is stored in the different Earth system components. Quantifying the heat stored in the different Earth system components is then essential to further unravel impacts of increase in heat content across the entire Earth system (Fig. 2b). Moreover, a quantification of the Earth heat inventory is also relevant for climate model constraint approaches, unraveling sources of uncertainties in the calculations such as for example on effective climate sensitivity (Gregory et al., 2002). The Earth heat inventory is estimated via the heat content of each Earth system component, using a combination of in situ measurements, satellite data, reanalysis and model outputs. Given the large gaps in the observing system for these quantifications, estimates still suffer large uncertainties, and partly rely on a hybrid data approach, which is particularly the case for the cryosphere and the land components (von Schuckmann et al., 2023). Estimates for continental heat storage suffer from lacking international data acquisition and curating efforts for subsurface temperature profile data (Cuesta-Valero et al., 2021). Both, heat storage estimates for permafrost and inland freshwater bodies suffer from a lack of relevant observations, and are hence dependent on model evaluations. However, data from the SWOT mission are promising for this purpose (Cuesta-Valero et al., 2022). For the estimate of atmospheric heat content, a sustained and enhanced operational long-term monitoring system for the provision of climate data records of relevant ECVs is recommended, including associated reference data (e.g., upper air network GRUAN, radio occultation). Moreover, there is an urgent need for satellite missions in high inclination orbits to provide full global and local time coverage. For the cryosphere, sustained remote-sensing with polar-focused orbits and multi-frequency altimeters (e.g., albedo, sea ice area & thickness) are recommended, together with an earlier launch of Sentinel-1c for monitoring ice-speed change at higher frequency. Moreover, reliable gravimetric, geodetic, ice velocity, ice thickness and extent, snow and firn thickness and density measurements are recommended. For the ocean, sustained in-situ measurements are recommended together with extensions into the deep, polar and shallow ocean areas. Recent efforts for full-depth ocean heat content estimates from remote sensing are under the way (Hakuba et al., 2021; Marti et al., 2022).