

The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity

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7.1 Introduction, Conceptual Framework, and Advances Since the Fifth Assessment Report

This chapter assesses the major physical processes that affect the evolution of Earth's energy budget and the associated changes in surface temperature and the broader climate system, integrating elements that were dealt with separately in previous reports.

The top-of-atmosphere (TOA) energy budget determines the net amount of energy entering or leaving the climate system. Its time variations can be monitored in three ways, using: (i) satellite observations of the radiative fluxes at the TOA; (ii) observations of the accumulation of energy in the climate system; and (iii) observations of surface energy fluxes. When the TOA energy budget is changed by a human or natural cause (a 'radiative forcing'), the climate system responds by warming or cooling (i.e., the system gains or loses energy). Understanding of changes in the Earth's energy flows helps understanding of the main physical processes driving climate change. It also provides a fundamental test of climate models and their projections.

This chapter principally builds on the IPCC Fifth Assessment Report (AR5; Boucher, 2012; Church et al., 2013; M. Collins et al., 2013; Flato et al., 2013; Hartmann et al., 2013; Myhre et al., 2013b; Rhein et al., 2013). It also builds on the subsequent IPCC Special Report on Global Warming of 1.5°C (SR1.5; IPCC, 2018), the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; IPCC, 2019a) and the Special Report on climate change, desertification, land degradation, sustainable land management, food security,

and greenhouse gas fluxes in terrestrial ecosystems (SRCCL; IPCC, 2019b), as well as community-led assessments (e.g., Bellouin et al. (2020) covering aerosol radiative forcing and Sherwood et al. (2020) covering equilibrium climate sensitivity).

Throughout this chapter, global surface air temperature (GSAT) is used to quantify surface temperature change (Cross-Chapter Box 2.3 and Section 4.3.4). The total energy accumulation in the Earth system represents a metric of global change that is complementary to GSAT but shows considerably less variability on interannual-to-decadal time scales (Section 7.2.2). Research and new observations since AR5 have improved scientific confidence in the quantification of changes in the global energy inventory and corresponding estimates of Earth's energy imbalance (Section 7.2). Improved understanding of adjustments to radiative forcing and of aerosol–cloud interactions have led to revisions of forcing estimates (Section 7.3). New approaches to the quantification and treatment of feedbacks (Section 7.4) have improved the understanding of their nature and time-evolution, leading to a better understanding of how these feedbacks relate to equilibrium climate sensitivity (ECS). This has helped to reconcile disparate estimates of ECS from different lines of evidence (Section 7.5). Innovations in the use of emissions metrics have clarified the relationships between metric choice and temperature policy goals (Section 7.6), linking this chapter to WGIII which provides further information on metrics, their use, and policy goals beyond temperature. *Very likely* (5–95%) ranges are presented unless otherwise indicated. In particular, the addition of '(one standard deviation)' indicates that the range represents one standard deviation.

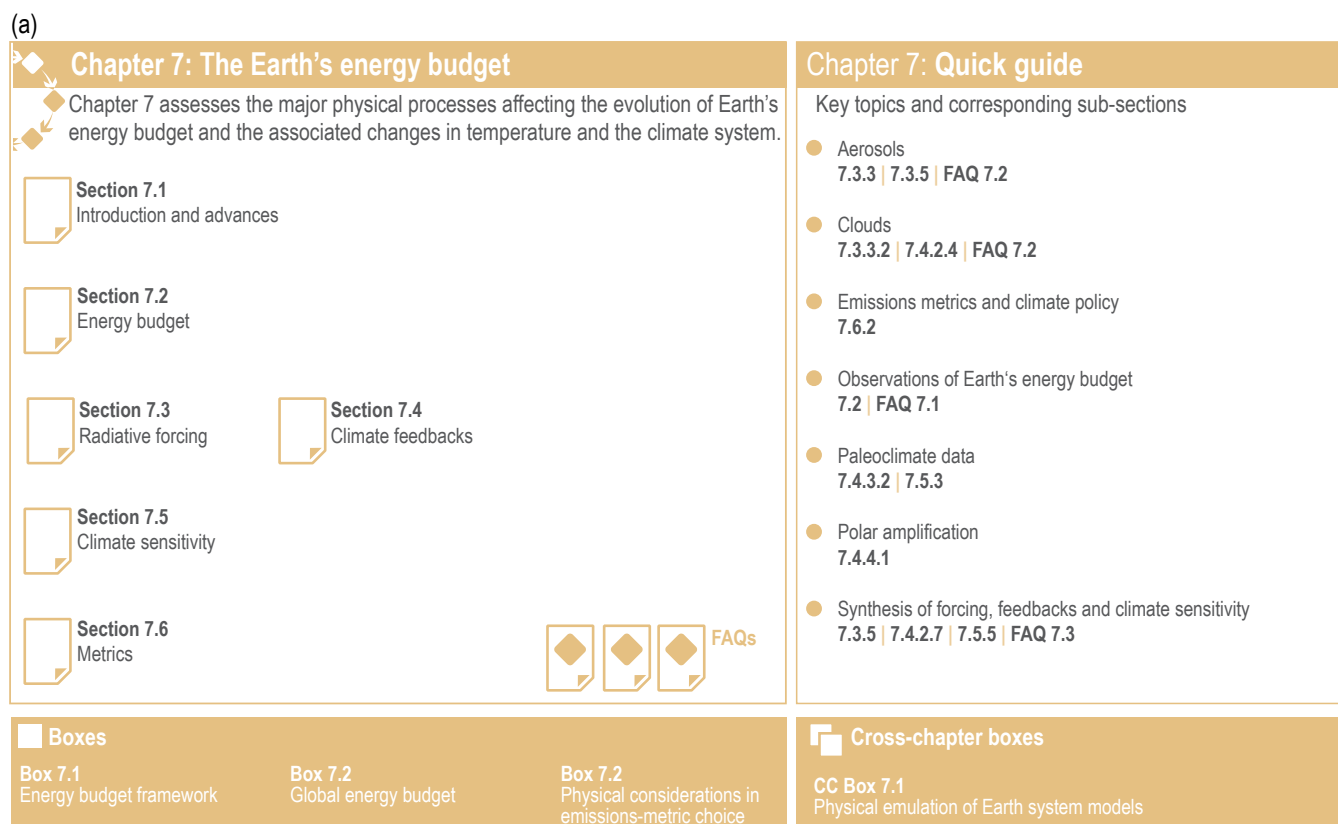


Figure 7.1 | Visual guide to Chapter 7. Panel (a) Overview of the chapter.

(b)

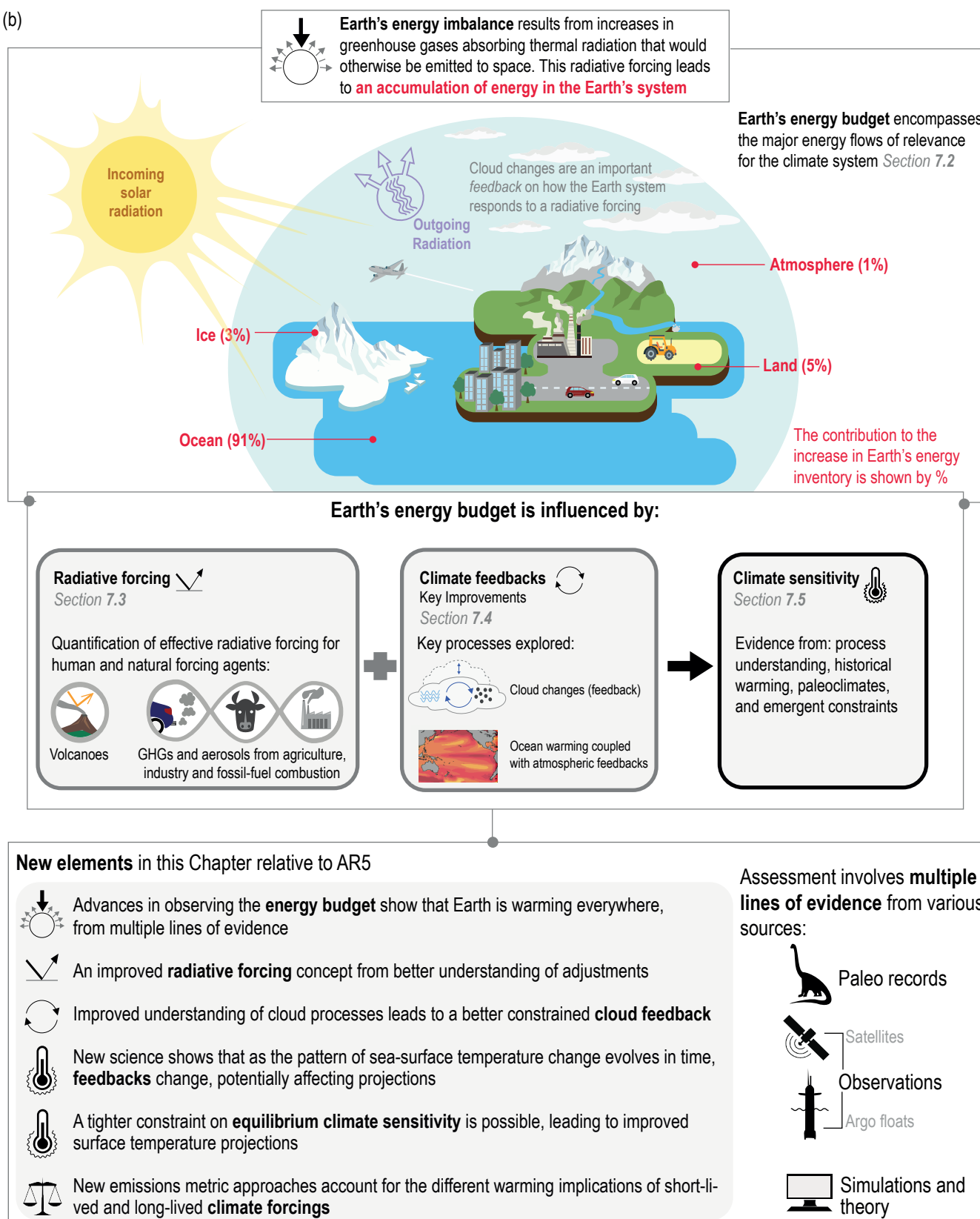


Figure 7.1 (continued): Panel (b) Visual abstract of the chapter, illustrating why the Earth's energy budget matters and how it relates to the underlying chapter assessment. The methods used to assess processes and key new findings relative to AR5 are highlighted. Upper schematic adapted from Von Schuckmann et al. (2020).

In Box 7.1 an energy budget framework is introduced, which forms the basis for the discussions and scientific assessment in the remainder of this chapter and across the Report. The framework reflects advances in the understanding of the Earth system response to climate forcing since the publication of AR5. A schematic of this framework and the key changes relative to the science reported in AR5 are provided in Figure 7.1.

A simple way to characterize the behaviour of multiple aspects of the climate system at once is to summarize them using global-scale metrics. This Report distinguishes between 'climate metrics' (e.g., ECS, TCR) and 'emissions metrics' (e.g., global warming potential, GWP, or global temperature-change potential, GTP), but this distinction is not definitive. Climate metrics are generally used to summarize aspects of the surface temperature response (Box 7.1). Emissions metrics are generally used to summarize the relative effects of emissions of different forcing agents, usually greenhouse gases (GHGs; Section 7.6). The climate metrics used in this report typically evaluate how the Earth system response varies with atmospheric gas concentration or change in radiative forcing. Emissions metrics evaluate how radiative forcing or a key climate variable (such as GSAT) is affected by the emissions of a certain amount of gas. Emissions-related metrics are sometimes used in mitigation policy decisions such as trading GHG reduction measures and life cycle analysis. Climate metrics are useful to gauge the range of future climate impacts for adaptation decisions under a given emissions pathway. Metrics such as the transient climate response to cumulative emissions of carbon dioxide (TCRE) are used in both adaptation and mitigation contexts: for gauging future global surface temperature change under specific emissions scenarios, and to estimate remaining carbon budgets that are used to inform mitigation policies (Section 5.5).

Given that TCR and ECS are metrics of GSAT response to a theoretical doubling of atmospheric CO₂ (Box 7.1), they do not directly correspond to the warming that would occur under realistic forcing scenarios that include time-varying CO₂ concentrations and non-CO₂ forcing agents (such as aerosols and land-use changes). It has been argued that TCR, as a metric of transient warming, is more policy-relevant than ECS (Frame et al., 2006; Schwartz, 2018). However, as detailed in Chapter 4, both established and recent results (Forster et al., 2013; Gregory et al., 2015; Marotzke and Forster, 2015; Grose et al., 2018; Marotzke, 2019) indicate that TCR and ECS help explain variation across climate models both over the historical period and across a range of concentration-driven future scenarios. In emission-driven scenarios the carbon cycle response is also important (Smith et al., 2019). The proportion of variation explained by ECS and TCR varies with scenario and the time period considered, but both past and future surface warming depend on these metrics (Section 7.5.7).

Regional changes in temperature, rainfall, and climate extremes have been found to correlate well with the forced changes in GSAT within Earth System Models (ESMs; Section 4.6.1; Giorgetta et al., 2013; Tebaldi and Arblaster, 2014; Seneviratne et al., 2016). While this so-called 'pattern scaling' has important limitations arising from, for instance, localized forcings, land-use changes, or internal climate variability (Deser et al., 2012; Luyssaert et al., 2014), changes in GSAT nonetheless explain a substantial fraction of inter-model differences in projections of regional climate changes over the 21st century (Tebaldi and Knutti, 2018). This Chapter's assessments of TCR and ECS thus provide constraints on future global and regional climate change (Chapters 4 and 11).

Box 7.1 | The Energy Budget Framework: Forcing and Response

The forcing and response energy budget framework provides a methodology to assess the effect of individual drivers of global surface temperature response, and to facilitate the understanding of the key phenomena that set the magnitude of this temperature response. The framework used here is developed from that adopted in previous IPCC reports (see Ramaswamy et al., 2019 for a discussion). **Effective Radiative Forcing (ERF)**, introduced in AR5 (Boucher et al., 2013; Myhre et al., 2013b) is more explicitly defined in this Report and is employed as the central definition of radiative forcing (Sherwood et al., 2015, Box 7.1, Figure 1a). The framework has also been extended to allow variations in feedbacks over different time scales and with changing climate state (Sections 7.4.3 and 7.4.4).

The global surface air temperature (GSAT) response to perturbations that give rise to an energy imbalance is traditionally approximated by the following linear energy budget equation, in which ΔN represents the change in the top-of-atmosphere (TOA) net energy flux, ΔF is an **effective radiative forcing** perturbation to the TOA net energy flux, α is the net **feedback parameter** and ΔT is the change in **GSAT**:

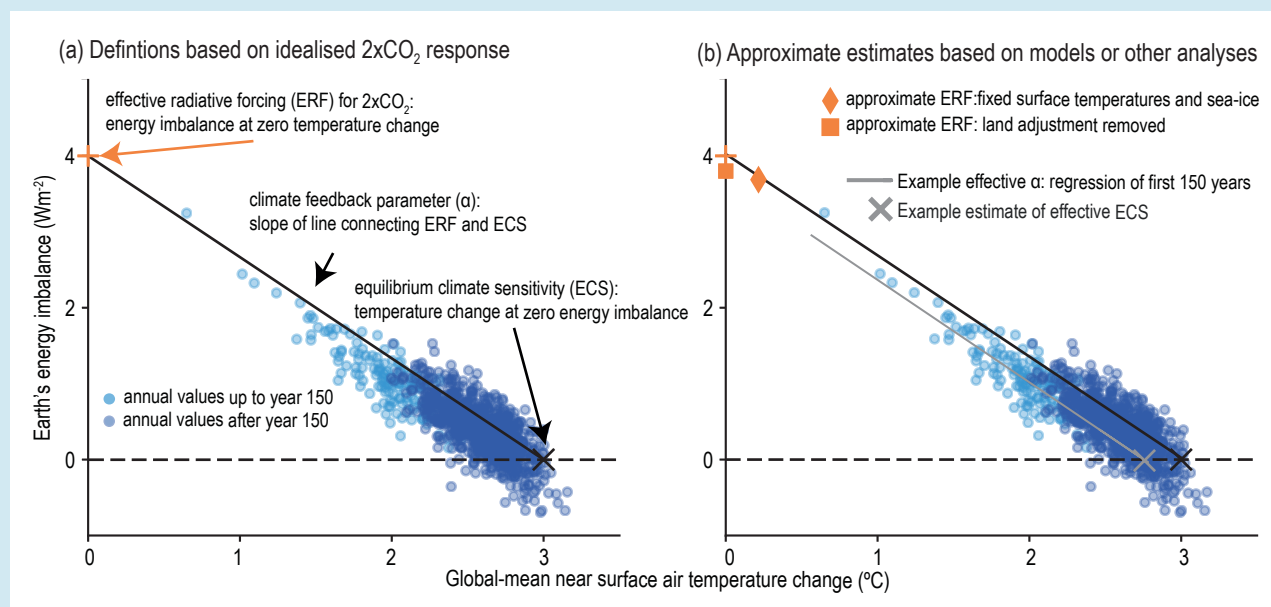
$$\Delta N = \Delta F + \alpha \Delta T \quad (\text{Box 7.1, Equation 7.1})$$

ERF is the TOA energy budget change resulting from the perturbation, excluding any radiative response related to a change in GSAT (i.e., $\Delta T = 0$). Climate feedbacks (α) represent those processes that change the TOA energy budget in response to a given ΔT .

The **effective radiative forcing, ERF** (ΔF ; units: W m⁻²) quantifies the change in the net TOA energy flux of the Earth system due to an imposed perturbation (e.g., changes in greenhouse gas or aerosol concentrations, in incoming solar radiation, or land-use change). ERF is expressed as a change in net downward radiative flux at the TOA following adjustments in both tropospheric and stratospheric temperatures, water vapour, clouds, and some surface properties, such as surface albedo from vegetation changes, that are uncoupled to

Box 7.1 (continued)

any GSAT change (Smith et al., 2018b). These adjustments affect the TOA energy balance and hence the ERF. They are generally assumed to be linear and additive (Section 7.3.1). Accounting for such processes gives an estimate of ERF that is more representative of the climate change response associated with forcing agents than stratospheric-temperature-adjusted radiative forcing (SARF) or the instantaneous radiative forcing (IRF; Section 7.3.1). Adjustments are processes that are independent of GSAT change, whereas feedbacks refer to processes caused by GSAT change. Although adjustments generally occur on time scales of hours to several months, and feedbacks respond to ocean surface temperature changes on time scales of a year or more, time scale is not used to separate the definitions. ERF has often been approximated as the TOA energy balance change due to an imposed perturbation in climate model simulations with sea surface temperature and sea-ice concentrations set to their pre-industrial climatological values (e.g., Forster et al., 2016). However, to match the adopted forcing–feedback framework, the small effects of any GSAT change from changes in land surface temperatures need to be removed from the TOA energy balance in such simulations to give an approximate measure of ERF (Box 7.1, Figure 1b and Section 7.3.1).



Box 7.1, Figure 1 | Schematics of the forcing–feedback framework adopted within the assessment, following Equation 7.1. The figure illustrates how the Earth's top-of-atmosphere (TOA) net energy flux might evolve for a hypothetical doubling of atmospheric CO₂ concentration above pre-industrial levels, where an initial positive energy imbalance (energy entering the Earth system, shown on the y-axis) is gradually restored towards equilibrium as the surface temperature warms (shown on the x-axis). **(a)** illustrates the definitions of effective radiative forcing (ERF) for the special case of a doubling of atmospheric CO₂ concentration, the feedback parameter and the equilibrium climate sensitivity (ECS). **(b)** illustrates how approximate estimates of these metrics are made within the chapter and how these approximations might relate to the exact definitions adopted in panel (a).

The **feedback parameter**, α (units: W m⁻² °C⁻¹) quantifies the change in net energy flux at the TOA for a given change in GSAT. Many climate variables affect the TOA energy budget, and the feedback parameter can be decomposed, to first order, into a sum of terms

$$\alpha = \sum_x \frac{\partial N}{\partial x} \frac{dx}{dT}$$

where x represents a variable of the Earth system that has a direct effect on the energy budget at the TOA. The sum of the feedback terms (i.e., α in Equation 7.1) governs Earth's equilibrium GSAT response to an imposed ERF. In previous assessments, α and the related ECS have been associated with a distinct set of physical processes (Planck response and changes in water vapour, lapse rate, surface albedo, and clouds; Charney et al., 1979). In this assessment, a more general definition of α and ECS is adopted such that they include additional Earth system processes that act across many time scales (e.g., changes in natural aerosol emissions or vegetation). Because, in our assessment, these additional processes sum to a near-zero value, including these additional processes does not change the assessed central value of ECS but does affect its assessed uncertainty range (Section 7.4.2). Note that there is no standardized notation or sign convention for the feedback parameter in the literature. Here the convention is used that the sum of all feedback terms (the net feedback parameter, α) is negative for a stable climate that radiates additional energy to space with a GSAT increase, with a more negative value of α corresponding to a stronger radiative response and thus a smaller GSAT change required to balance a change in ERF (Equation 7.1).

Box 7.1 (continued)

A change in process x amplifies the temperature response to a forcing when the associated feedback parameter α_x is positive (positive feedback) and dampens the temperature response when α_x is negative (negative feedback). New research since AR5 emphasizes how feedbacks can vary over different time scales (Section 7.4.4) and with climate state (Section 7.4.3), giving rise to the concept of an 'effective feedback parameter' that may be different from the equilibrium value of the feedback parameter governing ECS (Section 7.4.3).

The **equilibrium climate sensitivity, ECS** (units: °C), is defined as the equilibrium value of ΔT in response to a sustained doubling of atmospheric CO₂ concentration from a pre-industrial reference state. The value of ERF for this scenario is denoted by $\Delta F_{2\times\text{CO}_2}$, giving $\text{ECS} = -\Delta F_{2\times\text{CO}_2}/\alpha$ from Equation 7.1 applied at equilibrium (Box 7.1, Figure 1a and Section 7.5). 'Equilibrium' refers to a steady state where ΔN averages to zero over a multi-century period. ECS is representative of the multi-century to millennial ΔT response to $\Delta F_{2\times\text{CO}_2}$, and is based on a CO₂ concentration change so any feedbacks that affect the atmospheric concentration of CO₂ do not influence its value. As employed here, ECS also excludes the long-term response of the ice sheets (Section 7.4.2.6) which may take multiple millennia to reach equilibrium, but includes all other feedbacks. Due to a number of factors, studies rarely estimate ECS or α at equilibrium or under CO₂ forcing alone. Rather, they give an 'effective feedback parameter' (Section 7.4.1 and Box 7.1, Figure 1b) or an 'effective ECS' (Section 7.5.1 and Box 7.1, Figure 1b), which represent approximations to the true values of α or ECS. The 'effective ECS' represents the equilibrium value of ΔT in response to a sustained doubling of atmospheric CO₂ concentration that would occur assuming the 'effective feedback parameter' applied at that equilibrium state. For example, a feedback parameter can be estimated from the linear slope of ΔN against ΔT over a set number of years within ESM simulations of an abrupt doubling or quadrupling of atmospheric CO₂ ($2\times\text{CO}_2$ or $4\times\text{CO}_2$, respectively), and the ECS can be estimated from the intersect of this regression line with $\Delta N = 0$ (Box 7.1, Figure 1b). To infer ECS from a given estimate of effective ECS necessitates that assumptions are made for how ERF varies with CO₂ concentration (Section 7.3.2) and how the slope of ΔN against ΔT relates to the slope of the straight line from ERF to ECS (Section 7.5 and Box 7.1, Figure 1b). Care has to be taken when comparing results across different lines of evidence to translate their estimates of the effective ECS into the ECS definition used here (Section 7.5.5).

The **transient climate response, TCR** (units: °C), is defined as the ΔT for the hypothetical scenario in which CO₂ increases at 1% yr⁻¹ from a pre-industrial reference state to the time of a doubling of atmospheric CO₂ concentration (year 70; Section 7.5). TCR is based on a CO₂ concentration change, so any feedbacks that affect the atmospheric concentration of CO₂ do not influence its value. It is a measure of transient warming accounting for the strength of climate feedbacks and ocean heat uptake. The **transient climate response to cumulative emissions of carbon dioxide (TCRE)** is defined as the transient ΔT per 1000 Gt C of cumulative CO₂ emissions increase since the pre-industrial period. TCRE combines information on the airborne fraction of cumulative CO₂ emissions (the fraction of the total CO₂ emitted that remains in the atmosphere at the time of doubling, which is determined by carbon cycle processes) with information on the TCR. TCR is assessed in this chapter, whereas TCRE is assessed in Chapter 5 (Section 5.5).

7.2 Earth's Energy Budget and its Changes Through Time

Earth's energy budget encompasses the major energy flows of relevance for the climate system (Figure 7.2). Virtually all the energy that enters or leaves the climate system does so in the form of radiation at the TOA. The TOA energy budget is determined by the amount of incoming solar (shortwave) radiation and the outgoing radiation that is composed of reflected solar radiation and outgoing thermal (longwave) radiation emitted by the climate system. In a steady-state climate, the outgoing and incoming radiative components are essentially in balance in the long-term global mean, although there are still fluctuations around this balanced state that arise through internal climate variability (Brown et al., 2014; Palmer and McNeill, 2014). However, anthropogenic forcing has given rise to a persistent imbalance in the global mean TOA radiation budget that is often referred to as Earth's energy imbalance (e.g., Trenberth et al., 2014; von Schuckmann et al., 2016), which is a key element of the energy budget framework (N ; Box 7.1, Equation 7.1) and an important metric of the rate of global climate change (Hansen et al., 2005a; von Schuckmann et al., 2020). In addition

to the TOA energy fluxes, Earth's energy budget also includes the internal flows of energy within the climate system, which characterize the climate state. The surface energy budget consists of the net solar and thermal radiation as well as the non-radiative components such as sensible, latent and ground heat fluxes (Figure 7.2, upper panel). It is a key driver of the global water cycle, atmosphere and ocean dynamics, as well as a variety of surface processes.

7.2.1 Present-day Energy Budget

Figure 7.2 (upper panel) shows a schematic representation of Earth's energy budget for the early 21st century, including globally averaged estimates of the individual components (Wild et al., 2015). Clouds are important modulators of global energy fluxes. Thus, any perturbations in the cloud fields, such as forcing by aerosol–cloud interactions (Section 7.3) or through cloud feedbacks (Section 7.4) can have a strong influence on the energy distribution in the climate system. To illustrate the overall effects that clouds exert on energy fluxes, Figure 7.2 (lower panel) also shows the energy budget in the absence

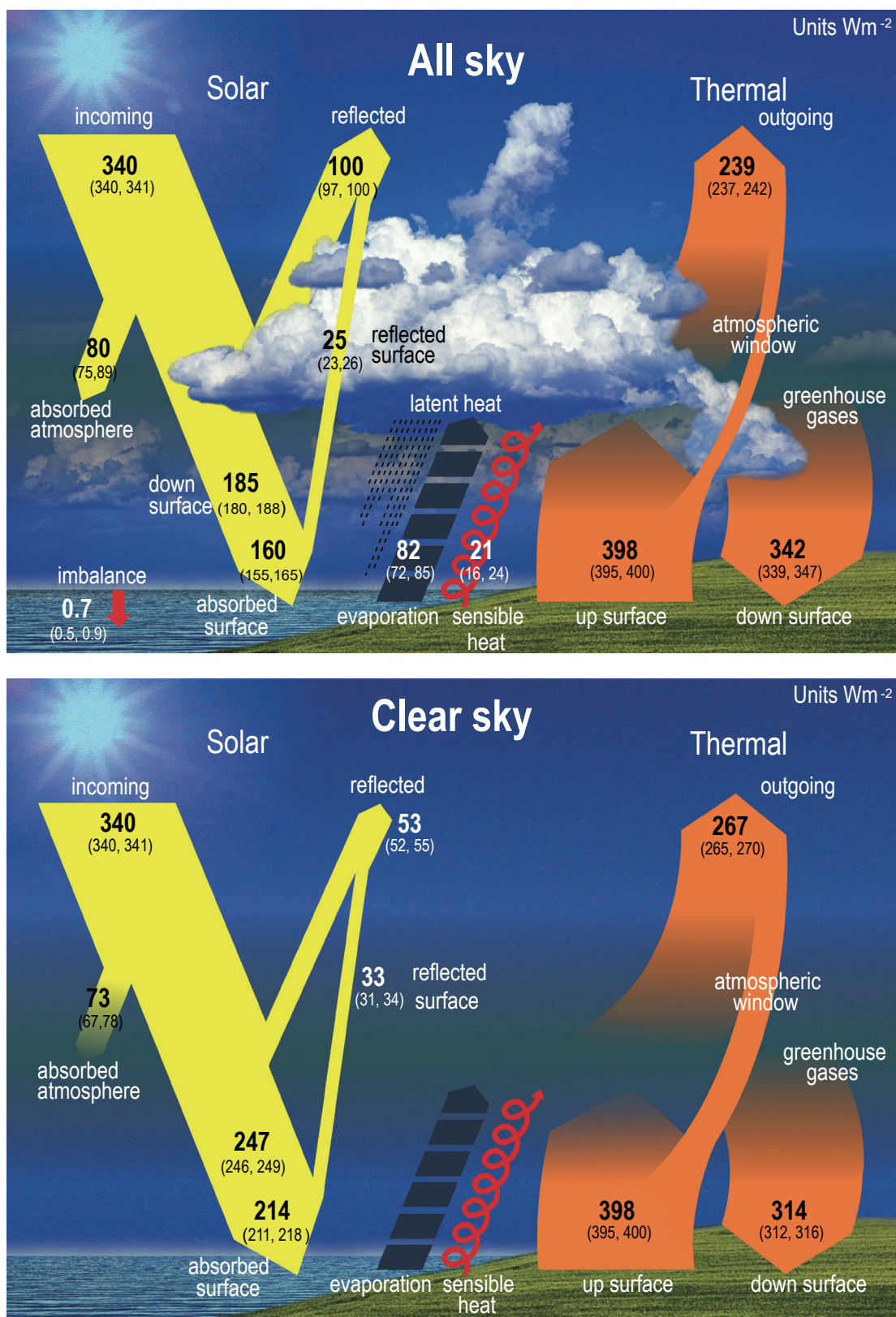


Figure 7.2 | Schematic representation of the global mean energy budget of the Earth (upper panel), and its equivalent without considerations of cloud effects (lower panel). Numbers indicate best estimates for the magnitudes of the globally averaged energy balance components in W m^{-2} together with their uncertainty ranges in parentheses (5–95% confidence range), representing climate conditions at the beginning of the 21st century. Note that the cloud-free energy budget shown in the lower panel is not the one that Earth would achieve in equilibrium when no clouds could form. It rather represents the global mean fluxes as determined solely by removing the clouds but otherwise retaining the entire atmospheric structure. This enables the quantification of the effects of clouds on the Earth energy budget and corresponds to the way clear-sky fluxes are calculated in climate models. Thus, the cloud-free energy budget is not closed and therefore the sensible and latent heat fluxes are not quantified in the lower panel. Figure adapted from Wild et al. (2015, 2019).

of clouds, with otherwise identical atmospheric and surface radiative properties. It has been derived by taking into account information contained in both in situ and satellite radiation measurements taken under cloud-free conditions (Wild et al., 2019). A comparison of the upper and lower panels in Figure 7.2 shows that without clouds, 47 W m^{-2} less solar radiation is reflected back to space globally ($53 \pm 2 \text{ W m}^{-2}$ instead of $100 \pm 2 \text{ W m}^{-2}$), while 28 W m^{-2} more thermal radiation is emitted to space ($267 \pm 3 \text{ W m}^{-2}$ instead of $239 \pm 3 \text{ W m}^{-2}$). As a result, there is a 20 W m^{-2} radiative imbalance at the TOA in the clear-sky energy budget (Figure 7.2, lower panel), suggesting that the Earth would warm substantially if there were no clouds.

The AR5 (Church et al., 2013; Hartmann et al., 2013; Myhre et al., 2013b) highlighted the progress that had been made in quantifying the TOA radiation budget following new satellite observations that became available in the early 21st century (Clouds and the Earth's Radiant Energy System, CERES; Solar Radiation and Climate Experiment, SORCE). Progress in the quantification of changes in incoming solar radiation at the TOA is discussed in Chapter 2 (Section 2.2). Since AR5, the CERES Energy Balance EBAF Ed4.0 product was released, which includes algorithm improvements and consistent input datasets throughout the record (Loeb et al., 2018b). However, the overall precision of these fluxes (uncertainty in global mean TOA flux of 1.7% (1.7 W m^{-2}) for reflected solar and 1.3% (3.0 W m^{-2}) for outgoing thermal radiation at the 90% confidence level) is not sufficient to quantify the Earth's energy imbalance in absolute terms. Therefore, the CERES EBAF reflected solar and emitted thermal TOA fluxes were adjusted, within the estimated uncertainties, to ensure that the net TOA flux for July 2005 to June 2015 was consistent with the estimated Earth's energy imbalance for the same period based on ocean heat content (OHC) measurements and energy uptake estimates for the land, cryosphere and atmosphere (Section 7.2.2.2; Johnson et al., 2016; Riser et al., 2016). ESMs typically show good agreement with global mean TOA fluxes from CERES-EBAF. However, as some ESMs are known to calibrate their TOA fluxes to CERES or similar data (Hourdin et al., 2017), this is not necessarily an indication of model accuracy, especially as ESMs show significant discrepancies on regional scales, often related to their representation of clouds (Trenberth and Fasullo, 2010; Donohoe and Battisti, 2012; Hwang and Frierson, 2013; J.-L.F. Li et al., 2013; Dolinar et al., 2015; Wild et al., 2015).

The radiation components of the surface energy budget are associated with substantially larger uncertainties than at the TOA, since they are less directly measured by passive satellite sensors and require retrieval algorithms and ancillary data for their estimation (Raschke et al., 2016; Kato et al., 2018; Huang et al., 2019). Confidence in the quantification of the global mean surface radiation components has increased recently, as independent estimates now converge to within a few W m^{-2} (Wild, 2017). Current best estimates for downward solar and thermal radiation at Earth's surface are approximately 185 W m^{-2} and 342 W m^{-2} , respectively (Figure 7.2). These estimates are based on complementary approaches that make use of satellite products from active and passive sensors (L'Ecuyer et al., 2015; Kato et al., 2018) and information from surface observations and Earth system models (ESMs; Wild et al., 2015). Inconsistencies in the quantification of the global mean energy and water budgets discussed in AR5 (Hartmann et al., 2013) have been reconciled within the (considerable) uncertainty

ranges of their individual components (Wild et al., 2013, 2015; L'Ecuyer et al., 2015). However, on regional scales, the closure of the surface energy budgets remains a challenge with satellite-derived datasets (Loeb et al., 2014; L'Ecuyer et al., 2015; Kato et al., 2016). Nevertheless, attempts have been made to derive surface energy budgets over land and ocean (Wild et al., 2015), over the Arctic (Christensen et al., 2016b), and over individual continents and ocean basins (L'Ecuyer et al., 2015; Thomas et al., 2020). Since AR5, the quantification of the uncertainties in surface energy flux datasets has improved. Uncertainties in global monthly mean downward solar and thermal fluxes in the CERES-EBAF surface dataset are, respectively, 10 W m^{-2} and 8 W m^{-2} (converted to 5–95% ranges; Kato et al., 2018). The uncertainty in the surface fluxes for polar regions is larger than in other regions (Kato et al., 2018) due to the limited number of surface sites and larger uncertainty in surface observations (Previdi et al., 2015). The uncertainties in ocean mean latent and sensible heat fluxes are approximately 11 W m^{-2} and 5 W m^{-2} (converted to 5–95% ranges), respectively (L'Ecuyer et al., 2015). A recent review of the latent and sensible heat flux accuracies over the period 2000–2007 highlights significant differences between several gridded products over ocean, where root-mean-squared differences between the multi-product ensemble and data at more than 200 moorings reached up to 25 W m^{-2} for latent heat and 5 W m^{-2} for sensible heat (Bentamy et al., 2017). This uncertainty stems from the retrieval of flux-relevant meteorological variables, as well as from differences in the flux parametrizations (Yu, 2019). Estimating the uncertainty in sensible and latent heat fluxes over land is difficult because of the large temporal and spatial variability. The flux values over land computed with three global datasets vary by 10–20% (L'Ecuyer et al., 2015).

ESMs also show larger discrepancies in their surface energy fluxes than at the TOA due to weaker observational constraints, with a spread of typically $10\text{--}20 \text{ W m}^{-2}$ in the global average, and an even greater spread at regional scales (J.-L.F. Li et al., 2013; Wild et al., 2013; Boeke and Taylor, 2016; Wild, 2017, 2020; C. Zhang et al., 2018). Differences in the land-averaged downward thermal and solar radiation in CMIP5 ESMs amount to more than 30 and 40 W m^{-2} , respectively (Wild et al., 2015). However, in the global multi-model mean, the magnitudes of the energy budget components of the CMIP6 ESMs generally show better agreement with reference estimates than previous model generations (Wild, 2020).

In summary, since AR5, the magnitudes of the global mean energy budget components have been quantified more accurately, not only at the TOA, but also at the Earth's surface, where independent estimates of the radiative components have converged (*high confidence*). Considerable uncertainties remain in regional surface energy budget estimates as well as their representation in climate models.

7.2.2 Changes in Earth's Energy Budget

7.2.2.1 Changes in Earth's Top-of-atmosphere Energy Budget

Since 2000, changes in top-of-atmosphere (TOA) energy fluxes can be tracked from space using CERES satellite observations (Figure 7.3). The variations in TOA energy fluxes reflect the influence of internal climate variability, particularly that of El Niño–Southern Oscillation

(ENSO), in addition to radiative forcing of the climate system and climate feedbacks (Allan et al., 2014; Loeb et al., 2018b). For example, globally, the reduction in both outgoing thermal and reflected solar radiation during La Niña conditions in 2008/2009 led to an energy gain for the climate system, whereas enhanced outgoing thermal and reflected solar radiation caused an energy loss during the El Niños of 2002/2003 and 2009/2010 (Figure 7.3; Loeb et al., 2018b). An ensemble of CMIP6 models is able to track the variability in global mean TOA

fluxes observed by CERES, when driven with prescribed sea surface temperatures (SSTs) and sea ice concentrations (Figure 7.3; Loeb et al., 2020). Under cloud-free conditions, the CERES record shows a near zero trend in outgoing thermal radiation (Loeb et al., 2018b), which – combined with an increasing surface upwelling thermal flux – implies an increasing clear-sky greenhouse effect (Raghuraman et al., 2019). Conversely, clear-sky solar reflected TOA radiation in the CERES record covering March 2000 to September 2017 shows a decrease due to

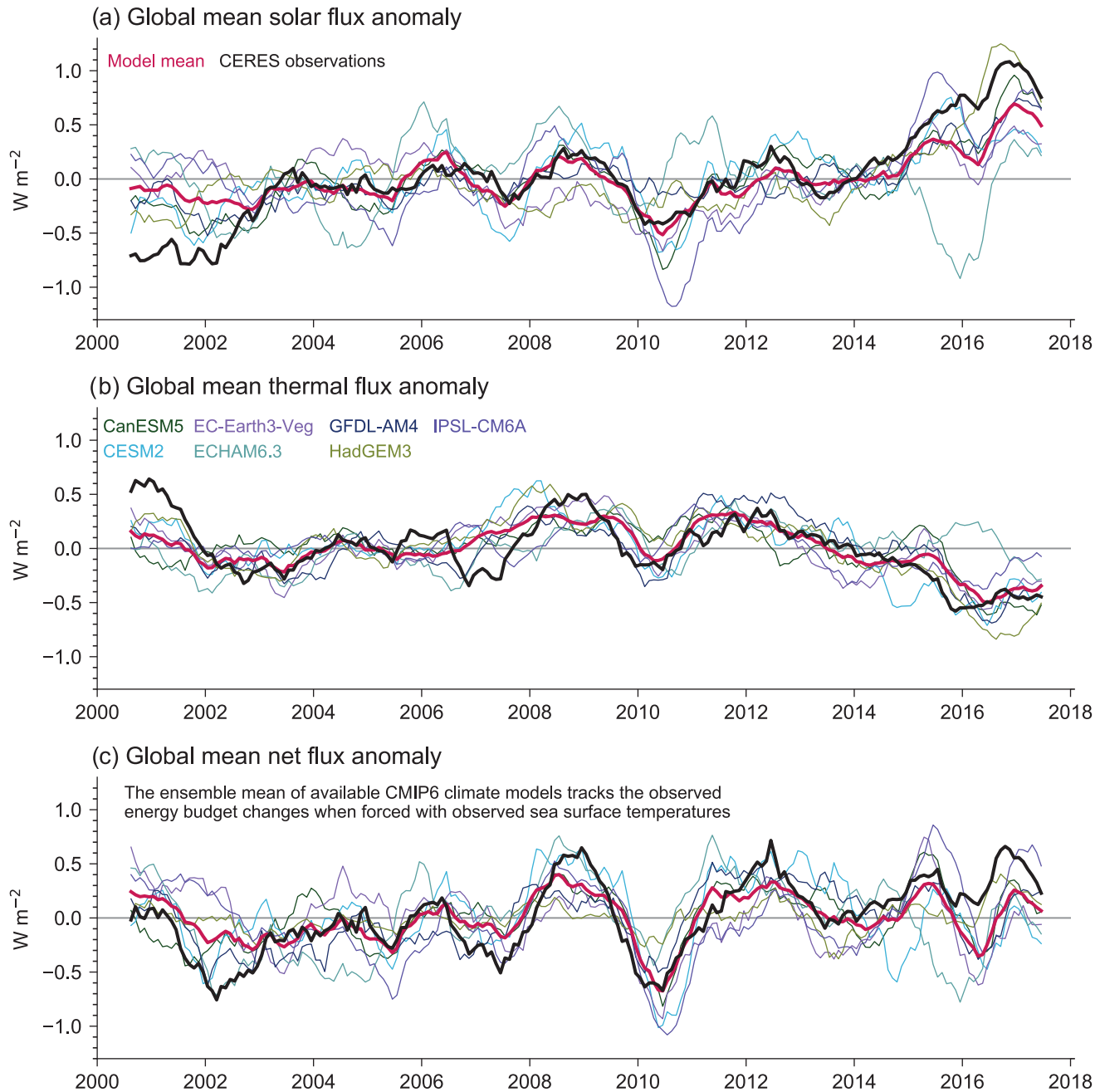


Figure 7.3 | Anomalies in global mean all-sky top-of-atmosphere (TOA) fluxes from CERES-EBAF Ed4.0 (solid black lines) and various CMIP6 climate models (coloured lines) in terms of (a) reflected solar, (b) emitted thermal and (c) net TOA fluxes. The multi-model means are additionally depicted as solid red lines. Model fluxes stem from simulations driven with prescribed sea surface temperatures (SSTs) and all known anthropogenic and natural forcings. Shown are anomalies of 12-month running means. All flux anomalies are defined as positive downwards, consistent with the sign convention used throughout this chapter. The correlations between the multi-model means (solid red lines) and the CERES records (solid black lines) for 12-month running means are: 0.85 for the global mean reflected solar; 0.73 for outgoing thermal radiation; and 0.81 for net TOA radiation. Figure adapted from Loeb et al. (2020). Further details on data sources and processing are available in the chapter data table (Table 7.SM.14).

reductions in aerosol optical depth in the Northern Hemisphere and sea ice fraction (Loeb et al., 2018a; Paulot et al., 2018).

An effort to reconstruct variations in net TOA fluxes back to 1985, based on a combination of satellite data, atmospheric reanalysis and high-resolution climate model simulations (Allan et al., 2014; Liu et al., 2020), exhibits strong interannual variability associated with the volcanic eruption of Mount Pinatubo in 1991 and the ENSO events before 2000. The same reconstruction suggests that Earth's energy imbalance increased by several tenths of a W m^{-2} between the periods 1985–1999 and 2000–2016, in agreement with the assessment of changes in the global energy inventory (Section 7.2.2.2, and Box 7.2, Figure 1). Comparisons of year-to-year variations in Earth's energy imbalance estimated from CERES and independent estimates based on ocean heat content change are significantly correlated with similar phase and magnitude (Johnson et al., 2016; Meyssignac et al., 2019), promoting confidence in both satellite and in situ-based estimates (Section 7.2.2.2).

In summary, variations in the energy exchange between Earth and space can be accurately tracked since the advent of improved observations since the year 2000 (*high confidence*), while reconstructions indicate that the Earth's energy imbalance was larger in the 2000s than in the 1985–1999 period (*high confidence*).

7.2.2.2 Changes in the Global Energy Inventory

The global energy inventory quantifies the integrated energy gain of the climate system associated with global ocean heat uptake, warming of the atmosphere, warming of the land, and melting of ice. Due to energy conservation, the rate of accumulation of energy in the Earth system (Section 7.1) is equivalent to the Earth energy imbalance (ΔN in Box 7.1, Equation 7.1). On annual and longer time scales, changes in the global energy inventory are dominated by changes in global ocean heat content (OHC; Rhein et al., 2013; Palmer and McNeall, 2014; Johnson et al., 2016). Thus, observational estimates and climate model simulations of OHC change are critical to the understanding of both past and future climate change (Sections 2.3.3.1, 3.5.1.3, 4.5.2.1 and 9.2.2.1).

Since AR5, both modelling and observation-based studies have established Earth's energy imbalance (characterized by OHC change) as a more robust metric of the rate of global climate change than GSAT on interannual-to-decadal time scales (Palmer and McNeall, 2014; von Schuckmann et al., 2016; Wijffels et al., 2016; Cheng et al., 2018; Allison et al., 2020). This is because GSAT is influenced by large unforced variations, for example linked to ENSO and Pacific Decadal Variability (Roberts et al., 2015; Yan et al., 2016; Cheng et al., 2018). Measuring OHC change more comprehensively over the full ocean depth results in a higher signal-to-noise ratio and a time series that increases steadily over time (Box 7.2, Figure 1; Allison et al., 2020). In addition, understanding of the potential effects of historical ocean sampling on estimated global ocean heating rates has improved (Durack et al., 2014; Good, 2017; Allison et al., 2019) and there are now more estimates of OHC change available that aim to mitigate the effect of limited observational sampling in the Southern Hemisphere (Lyman and Johnson, 2008; Cheng et al., 2017; Ishii et al., 2017).

The assessment of changes in the global energy inventory for the periods 1971–2018, 1993–2018 and 2006–2018 draws upon the latest observational time series and the assessments presented in other chapters of this report. The estimates of OHC change come directly from the assessment presented in Chapter 2 (Section 2.3.3.1). The assessment of land and atmospheric heating comes from von Schuckmann et al. (2020), based on the estimates of Cuesta-Valero et al. (2021) and Steiner et al. (2020), respectively. Heating of inland waters, including lakes, reservoirs and rivers, is estimated to account for <0.1% of the total energy change, and is therefore omitted from this assessment (Vanderkelen et al., 2020). The cryosphere contribution from the melting of grounded ice is based on the mass-loss assessments presented in Chapter 9, Section 9.4.1 (Greenland Ice Sheet), Section 9.4.2 (Antarctic Ice Sheet) and Section 9.5.1 (glaciers). Following AR5, the estimate of heating associated with loss of Arctic sea ice is based on a reanalysis (Schweiger et al., 2011), following the methods described by Slater et al. (2021). Chapter 9 (Section 9.3.2) finds no significant trend in Antarctic sea ice area over the observational record, so a zero contribution is assumed. Ice melt associated with the calving and thinning of floating ice shelves is based on the decadal rates presented in Slater et al. (2021). For all cryospheric components, mass loss is converted to heat input using a latent heat of fusion of $3.34 \times 10^5 \text{ J Kg}^{-1} \text{ }^\circ\text{C}^{-1}$ with the second-order contributions from variations associated with ice type and warming of ice from sub-freezing temperatures disregarded, as in AR5. The net change in energy, quantified in Zettajoules ($1 \text{ ZJ} = 10^{21} \text{ Joules}$), is computed for each component as the difference between the first and last year of each period (Table 7.1). The uncertainties in the depth-interval contributions to OHC are summed to get the uncertainty in global OHC change. All other uncertainties are assumed to be independent and added in quadrature.

For the period 1971–2010, AR5 (Rhein et al., 2013) found an increase in the global energy inventory of 274 [196 to 351] ZJ with a 93% contribution from total OHC change, approximately 3% for both ice melt and land heating, and approximately 1% for warming of the atmosphere. For the same period, this Report finds an upwards revision of OHC change for the upper (<700 m depth) and deep (>700 m depth) ocean of approximately 8% and 20%, respectively, compared to AR5 and a modest increase in the estimated uncertainties associated with the ensemble approach of Palmer et al. (2021). The other substantive change compared to AR5 is the updated assessment of land heating, with values approximately double those assessed previously, based on a more comprehensive analysis of the available observations (von Schuckmann et al., 2020; Cuesta-Valero et al., 2021). The result of these changes is an assessed energy gain of 329 [224 to 434] ZJ for the period 1971–2010, which is consistent with AR5 within the estimated uncertainties, despite the systematic increase.

The assessed changes in the global energy inventory (Box 7.2, Figure 1, and Table 7.1) yields an average value for Earth's energy imbalance (N in Box 7.1, Equation 7.1) of 0.57 [0.43 to 0.72] W m^{-2} for the period 1971–2018, expressed relative to Earth's surface area (*high confidence*). The estimates for the periods 1993–2018 and 2006–2018 yield substantially larger values of 0.72 [0.55 to 0.89] W m^{-2} and 0.79 [0.52 to 1.06] W m^{-2} , respectively, consistent with the increased radiative forcing from GHGs (*high confidence*). For the