observational evidence since AR4, the mean state as well as multi-decadal changes of the surface and TOA radiation budgets are assessed in the following.

2.3.1 Global Mean Radiation Budget

Since AR4, knowledge on the magnitude of the radiative energy fluxes in the climate system has improved, requiring an update of the global annual mean energy balance diagram (Figure 2.11). Energy exchanges between Sun, Earth and Space are observed from space-borne platforms such as the Clouds and the Earth's Radiant Energy System (CERES, Wielicki et al., 1996) and the Solar Radiation and Climate Experiment (SORCE, Kopp and Lawrence, 2005) which began data collection in 2000 and 2003, respectively. The total solar irradiance (TSI) incident at the TOA is now much better known, with the SORCE Total Irradiance Monitor (TIM) instrument reporting uncertainties as low as 0.035%, compared to 0.1% for other TSI instruments (Kopp et al., 2005). During the 2008 solar minimum, SORCE/TIM observed a solar irradiance of 1360.8 ± 0.5 W m^{-2} compared to 1365.5 ± 1.3 W m^{-2} for instruments launched prior to SORCE and still operating in 2008 (Section 8.4.1.1). Kopp and Lean (2011) conclude that the SORCE/TIM value of TSI is the most credible value because it is validated by a National Institute of Standards and Technology calibrated cryogenic radiometer. This revised TSI estimate corresponds to a solar irradiance close to 340 W m^{-2} globally averaged over the Earth's sphere (Figure 2.11).

The estimate for the reflected solar radiation at the TOA in Figure 2.11, 100 W m^{-2}, is a rounded value based on the CERES Energy Balanced and Filled (EBAF) satellite data product (Loeb et al., 2009, 2012b) for the period 2001–2010. This data set adjusts the solar and thermal TOA fluxes within their range of uncertainty to be consistent with independent estimates of the global heating rate based on *in situ* ocean observations (Loeb et al., 2012b). This leaves 240 W m^{-2} of solar radiation absorbed by the Earth, which is nearly balanced by thermal emission to space of about 239 W m^{-2} (based on CERES EBAF), considering a global heat storage of 0.6 W m^{-2} (imbalance term in Figure 2.11) based on Argo data from 2005 to 2010 (Hansen et al., 2011; Loeb et al., 2012b; Box 3.1). The stated uncertainty in the solar reflected TOA fluxes from CERES due to uncertainty in absolute calibration alone is about 2% (2-sigma), or equivalently 2 W m^{-2} (Loeb et al., 2009). The uncertainty of the outgoing thermal flux at the TOA as measured by CERES due to calibration is ~3.7 W m^{-2} (2σ). In addition to this, there is uncertainty in removing the influence of instrument spectral response on measured radiance, in radiance-to-flux conversion, and in time–space averaging, which adds up to another 1 W m^{-2} (Loeb et al., 2009).

The components of the radiation budget at the surface are generally more uncertain than their counterparts at the TOA because they cannot be directly measured by passive satellite sensors and surface measurements are not always regionally or globally representative. Since AR4, new estimates for the downward thermal infrared (IR) radiation at

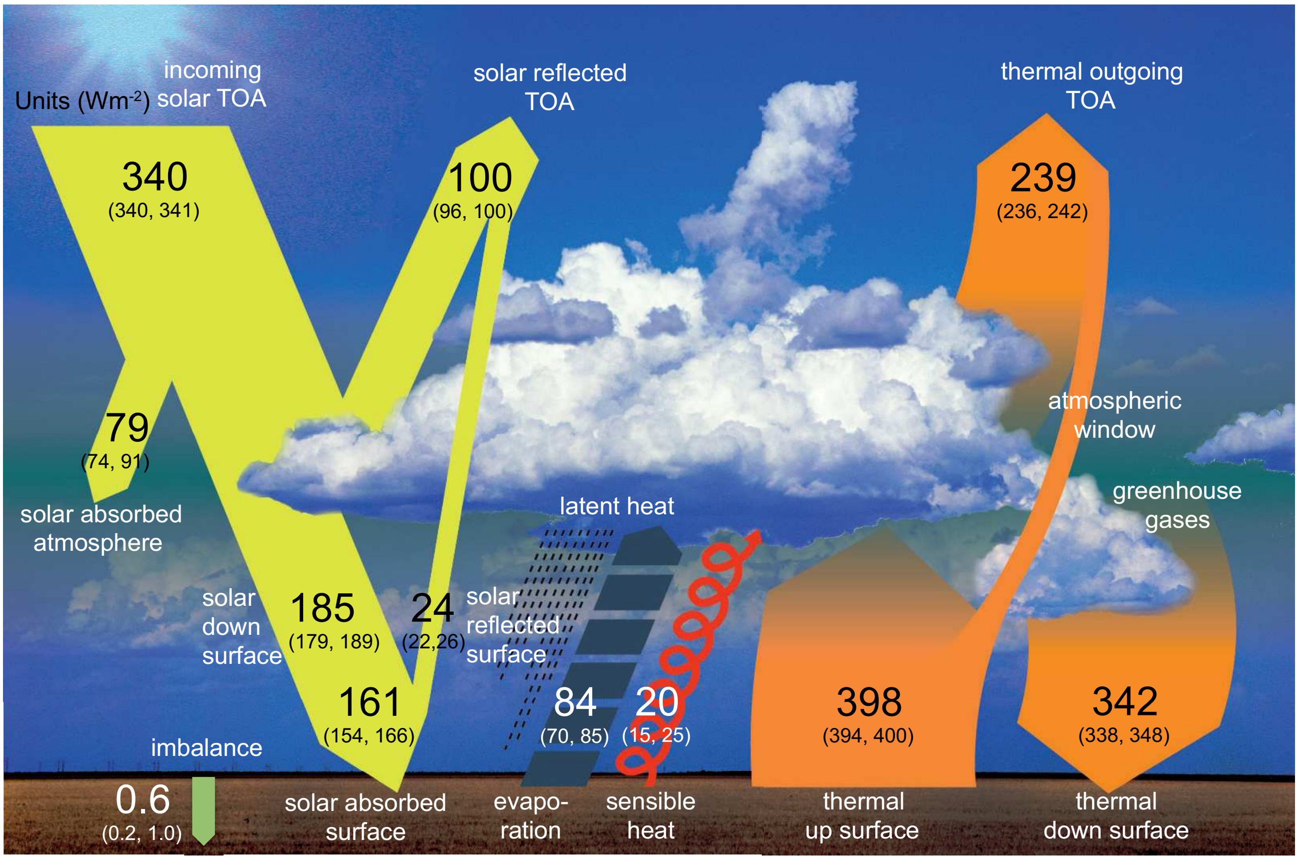

Figure 2.11: | Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes in W m^{-2}, adjusted within their uncertainty ranges to close the energy budgets. Numbers in parentheses attached to the energy fluxes cover the range of values in line with observational constraints. (Adapted from Wild et al., 2013.)

the surface have been established that incorporate critical information on cloud base heights from space-borne radar and lidar instruments (L'Ecuyer et al., 2008; Stephens et al., 2012a; Kato et al., 2013). In line with studies based on direct surface radiation measurements (Wild et al., 1998, 2013) these studies propose higher values of global mean downward thermal radiation than presented in previous IPCC assessments and typically found in climate models, exceeding 340 W m^{-2} (Figure 2.11). This aligns with the downward thermal radiation in the ERA-Interim and ERA-40 reanalyses (Box 2.3), of 341 and 344 W m^{-2}, respectively (Berrisford et al., 2011). Estimates of global mean downward thermal radiation computed as a residual of the other terms of the surface energy budget (Kiehl and Trenberth, 1997; Trenberth et al., 2009) are lower (324 to 333 W m^{-2}), highlighting remaining uncertainties in estimates of both radiative and non-radiative components of the surface energy budget.

Estimates of absorbed solar radiation at the Earth's surface include considerable uncertainty. Published global mean values inferred from satellite retrievals, reanalyses and climate models range from below 160 W m^{-2} to above 170 W m^{-2}. Recent studies taking into account surface observations as well as updated spectroscopic parameters and continuum absorption for water vapor favour values towards the lower bound of this range, near 160 W m^{-2}, and an atmospheric solar absorption around 80 W m^{-2} (Figure 2.11) (Kim and Ramanathan, 2008; Trenberth et al., 2009; Kim and Ramanathan, 2012; Trenberth and Fasullo, 2012b; Wild et al., 2013). The ERA-Interim and ERA-40 reanalyses further support an atmospheric solar absorption of this magnitude (Berrisford et al., 2011). Latest satellite-derived estimates constrained by CERES now also come close to these values (Kato et al., in press). Recent independently derived surface radiation estimates favour therefore a global mean surface absorbed solar flux near 160 W m^{-2} and a downward thermal flux slightly above 340 W m^{-2}, respectively (Figure 2.11).

The global mean latent heat flux is required to exceed 80 W m^{-2} to close the surface energy balance in Figure 2.11, and comes close to the 85 W m^{-2} considered as upper limit by Trenberth and Fasullo (2012b) in view of current uncertainties in precipitation retrieval in the Global Precipitation Climatology Project (GPCP, Adler et al., 2012) (the latent heat flux corresponds to the energy equivalent of evaporation, which globally equals precipitation; thus its magnitude may be constrained by global precipitation estimates). This upper limit has recently been challenged by Stephens et al. (2012b). The emerging debate reflects potential remaining deficiencies in the quantification of the radiative and non-radiative energy balance components and associated uncertainty ranges, as well as in the consistent representation of the global mean energy and water budgets (Stephens et al., 2012b; Trenberth and Fasullo, 2012b; Wild et al., 2013). Relative uncertainty in the globally averaged sensible heat flux estimate remains high owing to the very limited direct observational constraints (Trenberth et al., 2009; Stephens et al., 2012b).

In summary, newly available observations from both space-borne and surface-based platforms allow a better quantification of the Global Energy Budget, even though notable uncertainties remain, particularly in the estimation of the non-radiative surface energy balance components.

2.3.2 Changes in Top of the Atmosphere Radiation Budget

While the previous section emphasized the temporally-averaged state of the radiation budget, the focus in the following is on the temporal (multi-decadal) changes of its components. Variations in TSI are discussed in Section 8.4.1. AR4 reported large changes in tropical TOA radiation between the 1980s and 1990s based on observations from the Earth Radiation Budget Satellite (ERBS) (Wielicki et al., 2002; Wong et al., 2006). Although the robust nature of the large decadal changes in tropical radiation remains to be established, several studies have suggested links to changes in atmospheric circulation (Allan and Slingo, 2002; Chen et al., 2002; Clement and Soden, 2005; Merrifield, 2011) (Section 2.7).

Since AR4, CERES enabled the extension of satellite records of TOA fluxes into the 2000s (Loeb et al., 2012b). The extended records from CERES suggest no noticeable trends in either the tropical or global radiation budget during the first decade of the 21st century (e.g., Andronova et al., 2009; Harries and Belotti, 2010; Loeb et al., 2012a, 2012b). Comparisons between ERBS/CERES thermal radiation and that derived from the NOAA High Resolution Infrared Radiation Sounder (HIRS) (Lee et al., 2007) show good agreement until approximately 1998, corroborating the rise of 0.7 W m^{-2} between the 1980s and 1990s reported in AR4. Thereafter the HIRS thermal fluxes show much higher values, likely due to changes in the channels used for HIRS/3 instruments launched after October 1998 compared to earlier HIRS instruments (Lee et al., 2007).

On a global scale, interannual variations in net TOA radiation and ocean heating rate (OHR) should correspond, as oceans have a much larger effective heat capacity than land and atmosphere, and therefore serve as the main reservoir for heat added to the Earth–atmosphere system (Box 3.1). Wong et al. (2006) showed that interannual variations in these two data sources are in good agreement for 1992–2003. In the ensuing 5 years, however, Trenberth and Fasullo (2010) note that the two diverge with ocean *in situ* measurements (Levitus et al., 2009), indicating a decline in OHR, in contrast to expectations from the observed net TOA radiation. The divergence after 2004 is referred to as "missing energy" by Trenberth and Fasullo (2012b), who further argue that the main sink of the missing energy likely occurs at ocean depths below 275 m. Loeb et al. (2012b) compared interannual variations in CERES net radiation with OHRs derived from three independent ocean heat content anomaly analyses and included an error analysis of both CERES and the OHRs. They conclude that the apparent decline in OHR is not statistically robust and that differences between interannual variations in OHR and satellite net TOA flux are within the uncertainty of the measurements (Figure 2.12). They further note that between January 2001 and December 2012, the Earth has been steadily accumulating energy at a rate of 0.50 ± 0.43 W m^{-2} (90% CI). Hansen et al. (2011) obtained a similar value for 2005–2010 using an independent analysis of the ocean heat content anomaly data (von Schuckmann and Le Traon, 2011). The variability in the Earth's energy imbalance is strongly influenced by ocean circulation changes relating to the ENSO (Box 2.5); during cooler La Niña years (e.g., 2009) less thermal radiation is emitted and the climate system gains heat while the reverse is true for warmer El Niño years (e.g., 2010) (Figure 2.12).