CSQ-45 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirements	Tools & Models	Policies / Benefits
How can we improve estimates of the internal flow of energy within the climate system with respect to major uncertainties for equilibrium climate sensitivity evaluations?	A) Regional budget closure studies to further unravel regional uncertainties of surface observations, retrieval of energy flux and their parametrisation, and to allow for improved observational constraints for climate models	• Incoming solar (shortwave) radiation • outgoing reflected solar radiation outgoing thermal (longwave) radiation • surface temperature atmospheric temperature (vertical structure) • Radiative fluxes • Turbulent fluxes (e.g., Latent & sensible heat flux, evaporation, precipitation) • Ocean heat content • Atmospheric and oceanic planetary heat transport	• High-spatial resolution (e.g., , ¼°) • High-temporal resolution (e.g., daily, min. monthly) • Sustainability to improve climate change monitoring	Atmospheric & oceanic assimilation systems; Earth system models	CC mitigation and adaptation policy CC monitoring and stocktake Improvements of CC prediction / climate models
	B) Study of cumulative regional cloud feedbacks, weighted by the global ratio of fractional coverage to evaluate the global cloud feedback	• Cloud properties (e.g., droplet concentrations, fractional coverage, vertical structure, type, height, Ice nucleating particles) • Water vapour, humitidy • Cloud liquid water path • Atmospheric temperature		Atmospheric assimilation systems Earths system models High-resolution cloud resolving models (CRMs) Large eddy simulations (LES) Aerosol reanalysis; multi-model ensembles (e.g., AEROCOM)	
	C) Study the causality in aerosol–cloud relationships, particularly for anthropogenic perturbations	• List above (cloud feedbacks) • Aerosols			

CSQ-45 Narrative

The surface energy budget is a key driver of the global water cycle, atmosphere and ocean dynamics, as well as a variety of surface processes (Forster et al., 2022). These internal flows of energy within the climate system are another critical part of the Earth's energy budget, and consist of the net solar and thermal radiation as well as the non-radiative components such as sensible, latent and ground heat fluxes (Wild, 2020) (Fig. 1). The radiation components of the surface energy budget are associated with large uncertainties since they are less directly measured by passive satellite sensors and require retrieval algorithms and ancillary data for their estimate (Kato et al., 2018) (Raschke et al., 2016; Huang et al., 2019). The use of 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) has resulted into recent converge of independent estimates within a few Wm^{-2} (Wild et al., 2017).

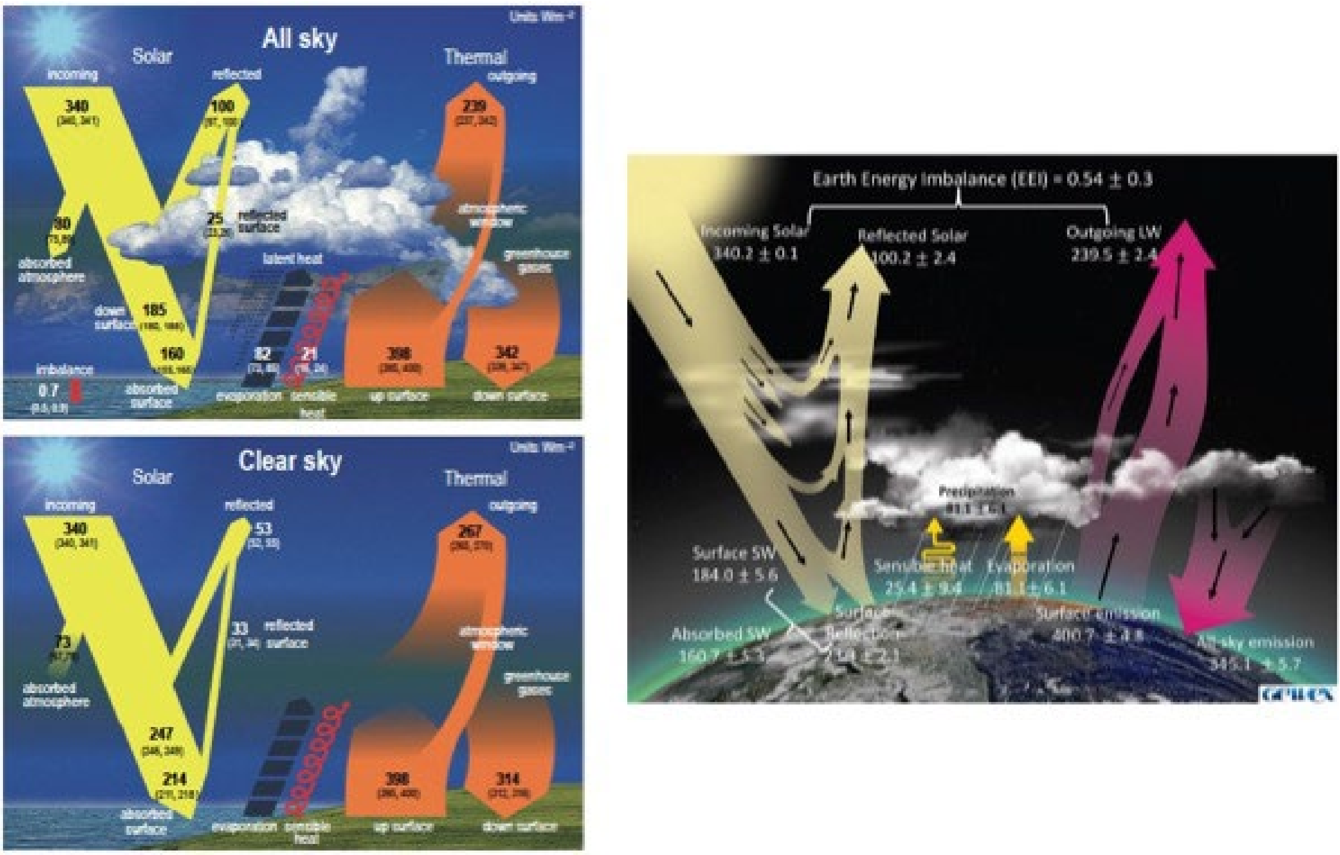

***Fig. 1:** Schematic representation of internal flow of energy within the climate system for all sky (upper) and clear sky (lower) conditions (left panels) after Wild et al., 2020. Their difference is used to obtain the cloud radiative effect on Earth's energy budget. Right panel: mean annual fluxes of the global energy budget after Stephens et al. (2023). All values are given in $W\,m^{-2}$.*

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), and associated uncertainties being area dependent with respect to the number of surface sites, regional uncertainty of surface observations (Kato et al., 2018; Previdi et al., 2015), the retrieval of flux-relevant meteorological variables, as well as from differences in the flux parametrizations (Yu, 2019). For example, uncertainties can reach up to 25 Wm^{-2} for latent heat and 5 Wm^{-2} for sensible heat over the ocean (Bentamy et al., 2017), and 10-20% over land (L'Ecuyer et al., 2015).

Albeit the magnitude of the energy budget components of the CMIP6 climate models generally show better agreement with reference estimates than previous model generations, considerable uncertainties remain in the representation of the internal flows of energy in climate models. Particularly, climate models show larger discrepancies in their surface energy fluxes than at the Top Of the Atmosphere (TOA) due to weaker observational constraints, with a spread of typically 10–20 W m^{-2} in the global average, and an even greater spread at regional scales (Li et al., 2013; Wild et al., 2013; Boeke and Taylor, 2016; Wild, 2017, 2020; Zhang et al., 2018), often related to their representation of clouds (Trenberth and Fasullo, 2010; Donohoe and Battisti, 2012; Hwang and Frierson, 2013; Li et al., 2013; Dolinar et al., 2015; Wild et al., 2015).

Clouds are important modulators of energy fluxes, and the cloud radiative effect on Earth's energy budget is measured by through the difference between clear and all skies radiation budgets (e.g., Wild et al., 2019, Fig. 1). Clouds affect shortwave (SW) radiation by reflecting sunlight due to their high albedo (cooling the climate system), and depends on the cloud optical properties. They also affect longwave (LW) radiation by absorbing the energy from the surface and emitting at a lower temperature to space, and this greenhouse effect of clouds strengthens with height.

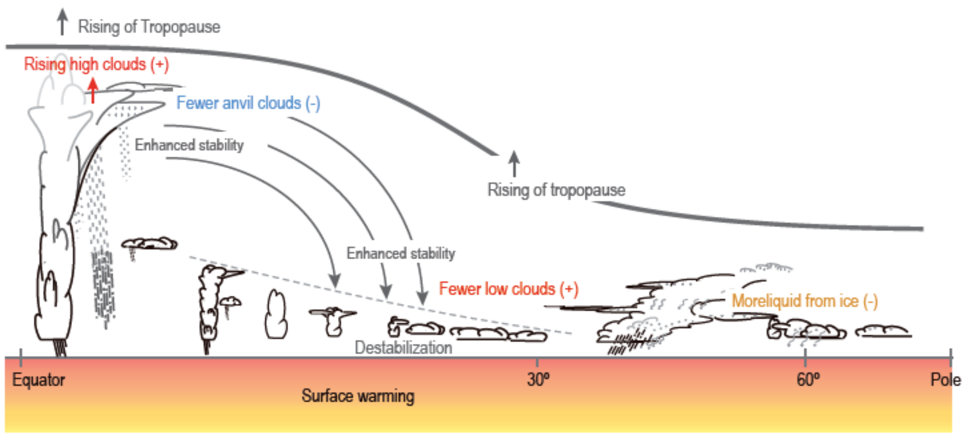

Fig. 2: *Schematic representation of cloud feedsbacks in different regimes from diverse cloud responses to surface warming. Adopted from Foster et al., 2021.*

Clouds consist of liquid water droplets and/or ice crystals, and these droplets and crystals can grow into larger particles of rain, snow or drizzle. These microphysical processes interact with aerosols, radiation and atmospheric circulation, resulting in a highly complex set of processes governing cloud formation and life cycles that operate across a wide range of spatial and temporal scales. Any perturbations of the cloud fields can hence have a strong influence on the energy distribution in the climate system, such as the positive net cloud feedback in different cloud regimes (Foster et al., 2021, Fig. 2), which is a dominant source of uncertainty to evaluate equilibrium climate sensitivity in climate models (e.g., Gettelman and Sherwood, 2016; Boucher et al., 2013; Zhao et am., 2015; Sherwood et al., 2020), and hence remains the largest contributor to uncertainty of net climate feedback evaluations (Forster et al., 2021).

Another perturbator of cloud fields includes forcing by aerosol–cloud interactions (or also called 'indirect aerosol effect') affecting cloud micro- and macro-physics and thus cloud radiative properties. Different cloud regimes show different sensitivities to aerosols (Stevens and Feingold, 2009). Multiple studies have found a positive relationship between cloud fraction and/or cloud liquid water pathway and aerosols (e.g., Nakajima et al., 2001; Kaufman and Koren, 2006; Quaas et al., 2009). There is high confidence that anthropogenic aerosols lead to an increase in cloud droplet concentrations (Foster et al., 2021). However, albeit considerable advances have been made to infer causality in aerosol–cloud relationships, a major challenge remains the identification of the anthropogenic perturbation of the aerosol to assess (Foster et al., 2021).