Thematic Focus Elements

TFE.6 | Climate Sensitivity and Feedbacks

The description of climate change as a response to a forcing that is amplified by feedbacks goes back many decades. The concepts of radiative forcing (RF) and climate feedbacks continue to be refined, and limitations are now better understood; for instance, feedbacks may be much faster than the surface warming, feedbacks depend on the type of forcing agent (e.g., greenhouse gas (GHG) vs. solar forcing), or may have intrinsic time scales (associated mainly with vegetation change and ice sheets) of several centuries to millennia. The analysis of physical feedbacks in models and from observations remains a powerful framework that provides constraints on transient future warming for different scenarios, on climate sensitivity and, combined with estimates of carbon cycle feedbacks (see TFE.5), determines the GHG emissions that are compatible with climate stabilization or targets (see TFE.8). {7.1, 9.7.2, 12.5.3; Box 12.2}

The water vapour/lapse rate, albedo and cloud feedbacks are the principal determinants of equilibrium climate sensitivity. All of these feedbacks are assessed to be positive, but with different levels of likelihood assigned ranging from *likely* to *extremely likely*. Therefore, there is *high confidence* that the net feedback is positive and the black body response of the climate to a forcing will therefore be amplified. Cloud feedbacks continue to be the largest uncertainty. The net feedback from water vapour and lapse rate changes together is *extremely likely* positive and approximately doubles the black body response. The mean value and spread of these two processes in climate models are essentially unchanged from the IPCC Fourth Assessment Report (AR4), but are now supported by stronger observational evidence and better process understanding of what determines relative humidity distributions. Clouds respond to climate forcing mechanisms in multiple ways and individual cloud feedbacks can be positive or negative. Key issues include the representation of both deep and shallow cumulus convection, microphysical processes in ice clouds and partial cloudiness that results from small-scale variations of cloud-producing and cloud-dissipating processes. New approaches to diagnosing cloud feedback in General Circulation Models (GCMs) have clarified robust cloud responses, while continuing to implicate low cloud cover as the most important source of intermodel spread in simulated cloud feedbacks. The net radiative feedback due to all cloud types is *likely* positive. This conclusion is reached by considering a plausible range for unknown contributions by processes yet to be accounted for, in addition to those occurring in current climate models. Observations alone do not currently provide a robust, direct constraint, but multiple lines of evidence now indicate positive feedback contributions from changes in both the height of high clouds and the horizontal distribution of clouds. The additional feedback from low cloud amount is also positive in most climate models, but that result is not well understood, nor effectively constrained by observations, so *confidence* in it is *low*. {7.2.4–7.2.6, 9.7.2}

The representation of aerosol–cloud processes in climate models continues to be a challenge. Aerosol and cloud variability at scales significantly smaller than those resolved in climate models, and the subtle responses of clouds to aerosol at those scales, mean that, for the foreseeable future, climate models will continue to rely on parameterizations of aerosol–cloud interactions or other methods that represent subgrid variability. This implies large uncertainties for estimates of the forcings associated with aerosol–cloud interactions. {7.4, 7.5.3, 7.5.4}

Equilibrium climate sensitivity (ECS) and transient climate response (TCR) are useful metrics summarising the global climate system's temperature response to an externally imposed RF. ECS is defined as the equilibrium change in annual mean global mean surface temperature (GMST) following a doubling of the atmospheric carbon dioxide (CO_2) concentration, while TCR is defined as the annual mean GMST change at the time of CO_2 doubling following a linear increase in CO_2 forcing over a period of 70 years (see Glossary). Both metrics have a broader application than these definitions imply: ECS determines the eventual warming in response to stabilisation of atmospheric composition on multi-century time scales, while TCR determines the warming expected at a given time following any steady increase in forcing over a 50- to 100-year time scale. {Box 12.2; 12.5.3}

ECS and TCR can be estimated from various lines of evidence (TFE.6, Figures 1 and 2). The estimates can be based on the values of ECS and TCR diagnosed from climate models, or they can be constrained by analysis of feedbacks in climate models, patterns of mean climate and variability in models compared to observations, temperature fluctuations as reconstructed from paleoclimate archives, observed and modelled short term perturbations of the energy balance like those caused by volcanic eruptions, and the observed surface and ocean temperature trends since preindustrial. For many applications, the limitations of the forcing-feedback analysis framework and the dependence of feedbacks on time scales and the climate state must be kept in mind. {5.3.1, 5.3.3, 9.7.1–9.7.3, 10.8.1, 10.8.2, 12.5.3; Box 5.2; Table 9.5} *(continued on next page)*

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Newer studies of constraints on ECS are based on the observed warming since pre-industrial, analysed using simple and intermediate complexity models, improved statistical methods and several different and newer data sets. Together with paleoclimate constraints but without considering the CMIP based evidence these studies show ECS is *likely* between 1.5°C to 4.5°C (*medium confidence*) and *extremely unlikely* less than 1.0°C. {5.3.1, 5.3.3, 10.8.2; Boxes 5.2, 12.2}

Estimates based on Atmosphere–Ocean General Circulation Models (AOGCMs) and feedback analysis indicate a range of 2°C to 4.5°C, with the Coupled Model Intercomparison Project Phase 5 (CMIP5) model mean at 3.2°C, similar to CMIP3. High climate sensitivities are found in some perturbed parameter ensembles models, but recent comparisons of perturbed-physics ensembles against the observed climate find that models with ECS values in the range 3°C to 4°C show the smallest errors for many fields. Relationships between climatological quantities and climate sensitivity are often found within a specific perturbed parameter ensemble model but in many cases the relationship is not robust across perturbed parameter ensembles models from different models or in CMIP3 and CMIP5. The assessed literature suggests that the range of climate sensitivities and transient responses covered by CMIP3 and CMIP5 cannot be narrowed significantly by constraining the models with observations of the mean climate and variability. Studies based on perturbed parameter ensembles models and CMIP3 support the conclusion that a credible representation of the mean climate and variability is very difficult to achieve with ECSs below 2°C. {9.2.2, 9.7.3; Box 12.2}

New estimates of ECS based on reconstructions and simulations of the Last Glacial Maximum (21 ka to 19 ka) show that values below 1°C as well as above 6°C are *very unlikely*. In some models climate sensitivity differs between warm and cold climates because of differences in the representation of cloud feedbacks. Estimates of an Earth system sensitivity including slow feedbacks (e.g., ice sheets or vegetation) are even more difficult to relate to climate sensitivity of the current climate state. The main limitations of ECS estimates from paleoclimate states are uncertainties in proxy data, spatial coverage of the data, uncertainties in some forcings, and structural limitations in models used in model–data comparisons. {5.3, 10.8.2, 12.5.3}

Bayesian methods to constrain ECS or TCR are sensitive to the assumed prior distributions. They can in principle yield narrower estimates by combining constraints from the observed warming trend, volcanic eruptions, model climatology and paleoclimate, and that has been done in some studies, but there is no consensus on how this should be done robustly. This approach is sensitive to the assumptions regarding the independence of the various lines of evidence, the possibility of shared biases in models or feedback estimates and the assumption that each individual line of evidence is unbiased. The combination of different estimates in this assessment is based on expert judgement. {10.8.2; Box 12.2}

Based on the combined evidence from observed climate change including the observed 20th century warming, climate models, feedback analysis and paleoclimate, as discussed above, ECS is *likely* in the range 1.5°C to 4.5°C with *high confidence*. ECS is positive, *extremely unlikely*

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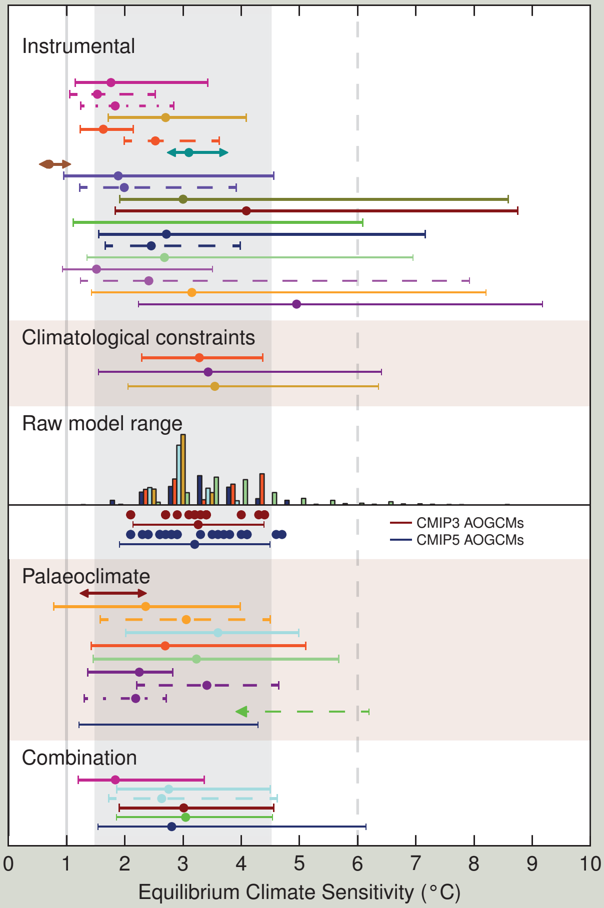

TFE.6, Figure 1 | Probability density functions, distributions and ranges for equilibrium climate sensitivity, based on Figure 10.20b plus climatological constraints shown in IPCC AR4 (Box AR4 10.2 Figure 1), and results from CMIP5 (Table 9.5). The grey shaded range marks the *likely* 1.5°C to 4.5°C range, grey solid line the *extremely unlikely* less than 1°C, the grey dashed line the *very unlikely* greater than 6°C. See Figure 10.20b and Chapter 10 Supplementary Material for full caption and details. {Box 12.2, Figure 1}

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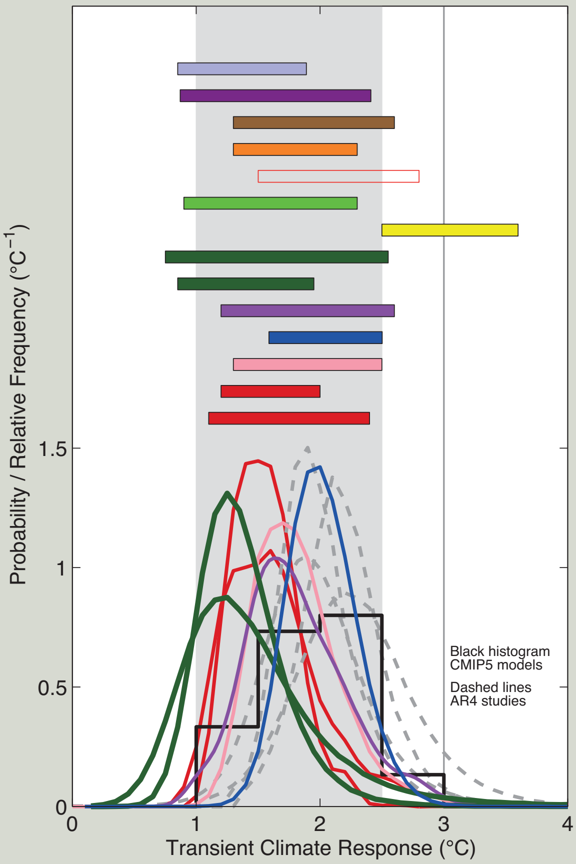
less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*). The tails of the ECS distribution are now better understood. Multiple lines of evidence provide *high confidence* that an ECS value less than 1°C is *extremely unlikely*. The upper limit of the *likely* range is unchanged compared to AR4. The lower limit of the *likely* range of 1.5°C is less than the lower limit of 2°C in AR4. This change reflects the evidence from new studies of observed temperature change, using the extended records in atmosphere and ocean. These studies suggest a best fit to the observed surface and ocean warming for ECS values in the lower part of the *likely* range. Note that these studies are not purely observational, because they require an estimate of the response to RF from models. In addition, the uncertainty in ocean heat uptake remains substantial. Accounting for short-term variability in simple models remains challenging, and it is important not to give undue weight to any short time period which might be strongly affected by internal variability. On the other hand, AOGCMs with observed climatology with ECS values in the upper part of the 1.5 to 4.5°C range show very good agreement with observed climatology, but the simulation of key feedbacks like clouds remains challenging in those models. The estimates from the observed warming, paleoclimate, and from climate models are consistent within their uncertainties, each is supported by many studies and multiple data sets, and in combination they provide *high confidence* for the assessed *likely* range. Even though this assessed range is similar to previous reports, confidence today is much higher as a result of high quality and longer observational records with a clearer anthropogenic signal, better process understanding, more and better understood evidence from paleoclimate reconstructions, and better climate models with higher resolution that capture many more processes more realistically. All these lines of evidence individually support the assessed *likely* range of 1.5°C to 4.5°C. {3.2, 9.7.3, 10.8; Boxes 9.2, 13.1}



TFE.6, Figure 2 | Probability density functions, distributions and ranges (5 to 95%) for the transient climate response from different studies, based on Figure 10.20a, and results from CMIP5 (black histogram, Table 9.5). The grey shaded range marks the *likely* 1°C to 2.5°C range, the grey solid line marks the *extremely unlikely* greater than 3°C. See Figure 10.20a and Chapter 10 Supplementary Material for full caption and details. {Box 12.2, Figure 2}

On time scales of many centuries and longer, additional feedbacks with their own intrinsic time scales (e.g., vegetation, ice sheets) may become important but are not usually modelled in AOGCMs. The resulting equilibrium temperature response to a doubling of CO_2 on millennial time scales or Earth system sensitivity is less well constrained but *likely* to be larger than ECS, implying that lower atmospheric CO_2 concentrations are compatible with limiting warming to below a given temperature level. These slow feedbacks are less likely to be proportional to global mean temperature change, implying that Earth system sensitivity changes over time. Estimates of Earth system sensitivity are also difficult to relate to climate sensitivity of the current climate state. {5.3.3, 10.8.2, 12.5.3}

For scenarios of increasing RF, TCR is a more informative indicator of future climate change than ECS. This assessment concludes with *high confidence* that the TCR is *likely* in the range 1°C to 2.5°C, close to the estimated 5 to 95% range of CMIP5 (1.2°C to 2.4°C), is positive and *extremely unlikely* greater than 3°C. As with the ECS, this is an expert-assessed range, supported by several different and partly independent lines of evidence, each based on multiple studies, models and data sets. TCR is estimated from the observed global changes in surface temperature, ocean heat uptake and RF including detection/attribution studies identifying the response patterns to increasing GHG concentrations, and the results of CMIP3 and CMIP5. Estimating TCR suffers from fewer difficulties in terms of state- or time-dependent feedbacks, and is less affected by uncertainty as to how much energy is taken up by the

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ocean. Unlike ECS, the ranges of TCR estimated from the observed warming and from AOGCMs agree well, increasing our confidence in the assessment of uncertainties in projections over the 21st century.

The assessed ranges of ECS and TCR are largely consistent with the observed warming, the estimated forcing and the projected future warming. In contrast to AR4, no best estimate for ECS is given because of a lack of agreement on the best estimate across lines of evidence and studies and an improved understanding of the uncertainties in estimates based on the observed warming. Climate models with ECS values in the upper part of the *likely* range show very good agreement with observed climatology, whereas estimates derived from observed climate change tend to best fit the observed surface and ocean warming for ECS values in the lower part of the *likely* range. In estimates based on the observed warming the most likely value is sensitive to observational and model uncertainties, internal climate variability and to assumptions about the prior distribution of ECS. In addition, "best estimate" and "most likely value" are defined in various ways in different studies. {9.7.1, 10.8.1, 12.5.3; Table 9.5}

~~TS.5.4 Near-term Climate Change~~

~~Near-term decadal climate prediction provides information not available from existing seasonal to interannual (months to a year or two) predictions or from long-term (mid 21st century and beyond) climate change projections. Prediction efforts on seasonal to interannual time scales require accurate estimates of the initial climate state with less focus extended to changes in external forcing[12], whereas long-term climate projections rely more heavily on estimations of external forcing with little reliance on the initial state of internal variability. Estimates of near-term climate depend on the committed warming (caused by the inertia of the oceans as they respond to historical external forcing) the time evolution of internally generated climate variability, and the future path of external forcing. Near-term predictions out to about a decade (Figure TS.13) depend more heavily on an accurate depiction of the internally generated climate variability. {11.1, 12, 14}~~

~~Further near-term warming from past emissions is unavoidable owing to thermal inertia of the oceans. This warming will be increased by ongoing emissions of GHGs over the near term, and the climate observed in the near term will also be strongly influenced by the internally generated variability of the climate system. Previous IPCC Assessments only described climate-change projections wherein the externally forced component of future climate was included but no attempt was made to initialize the internally generated climate variability. Decadal climate predictions, on the other hand, are intended to predict both the externally forced component of future climate change, and the internally generated component. Near-term predictions do not provide detailed information of the evolution of weather. Instead they can provide estimated changes in the time evolution of the statistics of near-term climate. {11.1, 11.2.2; Box 11.1; FAQ 11.1}~~

~~Retrospective prediction experiments have been used to assess forecast quality. There is *high confidence* that the retrospective prediction experiments for forecast periods of up to 10 years exhibit positive skill when verified against observations over large regions of the planet and of the global mean. Observation-based initialization of the forecasts contributes to the skill of predictions of annual mean temperature for the first couple of years and to the skill of predictions of the GMST and the temperature over the North Atlantic, regions of the South Pacific and the tropical Indian Ocean up to 10 years (*high confidence*) partly due to a correction of the forced response. Probabilistic temperature predictions are statistically reliable (see Section 11.2.3 for definition of reliability) owing to the correct representation of global trends, but still unreliable at the regional scale when probabilities are computed from the multi-model ensemble. Predictions initialized over 2000–2005 improve estimates of the recent global mean temperature hiatus. Predictions of precipitation over continental areas with large forced trends also exhibit positive skill. {11.2.2, 11.2.3; Box 9.2}~~

~~TS.5.4.1 Projected Near-term Changes in Climate~~

~~Projections of near-term climate show small sensitivity to GHG scenarios compared to model spread, but substantial sensitivity to uncertainties in aerosol emissions, especially on regional scales and for hydrological cycle variables. In some regions, the local and regional responses in precipitation and in mean and extreme temperature to land use change will be larger than those due to large-scale GHGs and aerosol forcing. These scenarios presume that there are no major volcanic eruptions and that anthropogenic aerosol emissions are rapidly reduced during the near term. {11.3.1, 11.3.2, 11.3.6}~~

~~TS.5.4.2 Projected Near-term Changes in Temperature~~

~~In the absence of major volcanic eruptions—which would cause significant but temporary cooling—and, assuming no significant future long-term changes in solar irradiance, it is *likely* that the GMST anomaly for the period 2016–2035, relative to the reference period of 1986–2005 will be in the range 0.3°C to 0.7°C (*medium confidence*). This is based on multiple lines of evidence. This range is consistent~~

[12] ~~Seasonal-to-interannual predictions typically include the impact of external forcing.~~