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Bachelor Thesis

Is staying under 1.5 degrees still possible? New estimate of committed warming using observational data.

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Zusammenfassung

Als *Committed Warming* bezeichnet man den unvermeidbaren zukünftigen Anstieg der globalen Temperatur, der eintreten würde, wenn die anthropogenen Emissionen sofort eingestellt würden. Dies ist auf die Trägheit des Klimasystems zurückzuführen, weshalb sich das heutige Klima nicht im Gleichgewicht mit dem anthropogenen Forcing befindet. Auch wenn es eine unrealistische Annahme ist, ein Ende der anthropogenen Emissionen in naher Zukunft zu erwarten, gibt uns dies die Möglichkeit, besser zu verstehen, wie ein vollständiges Ende der Emissionen die zukünftige globale Erwärmung beeinflussen würde. Außerdem kann das Ausmaß der noch zu erwartenden Erwärmung abgeschätzt werden. Damit lässt sich die Wahrscheinlichkeit berechnen, dass bestimmte Temperaturschwellwerte, wie das 1,5-Grad-Ziel oder das 2-Grad-Ziel des Pariser Klimaabkommens (2015), aufgrund der bisherigen Emissionen bereits überschritten werden. Dies ist wichtig, da die globale Temperatur bereits mehr als 1,1 Grad über dem vorindustriellen Niveau liegt. Darauf folgte eine große Debatte über die Erreichbarkeit der vorgeschlagenen Ziele. Das Hauptziel dieser Arbeit besteht darin, das Committed Warming anhand aktueller Beobachtungsdaten genauer zu charakterisieren. Zu diesem Zweck werden ein aktualisierter Energy balance framework und ein vereinfachtes Klimamodell, das Finite Amplitude Impulse Response (FaIR) Model, verwendet.

Damit erhält man ein Committed Warming von 2,13 K im Gleichgewicht (mehrere Jahrtausende) im Vergleich zur vorindustriellen Zeit, wenn man den Wegfall des Forcings von Aerosolen und kurzlebigen Treibhausgasen berücksichtigt. In diesem Jahrhundert beträgt das Committed Warming dann 1,86 K. Wenn die Kohlenstoffaufnahme durch die Biosphäre und den Ozean einbezogen wird, verringert sich das Committed Warming auf 1,5 K. Das Risiko, dass das 1,5-Grad-Ziel überschritten wird, liegt dann trotzdem bei 50,3%. Legt man die Unsicherheitssprache des IPCC zugrunde, ist es *wahrscheinlicher als nicht wahrscheinlich*, dass die bisherigen Emissionen bereits zu einer Erwärmung von mehr als 1,5 Grad führen. Vergleicht man die Ergebnisse mit einem FaIR-Modell-Lauf, so ergibt sich ein ähnliches Committed

Warming.

Die unmittelbare Folge dieser neuen Ergebnisse ist, dass es fast unmöglich sein wird, die Erwärmung durchgehend unter 1,5 Grad zu halten. Dies liegt daran, dass anthropogene Emissionen höchstwahrscheinlich noch längerfristig anhalten werden. Das würde dann zu einer globalen Durchschnittstemperatur führen, wie sie auf der Erde seit mindestens 120.000 Jahren nicht mehr gemessen wurde. Dies wird mit großer Sicherheit zu negativen globalen Auswirkungen wie häufigeren Wetterextremen und dem Verlust von Lebensräumen und biologischer Vielfalt führen. Negativemissionstechnologien könnten daher entscheidend sein, um wieder auf den richtigen Kurs zu kommen.

Abstract

Committed warming is defined as the unavoidable future increase in global temperature that would arise from an immediate cessation of anthropogenic emissions. This is due to the inertia of the climate system, therefore today's climate is not in equilibrium with anthropogenic forcing. Although it is unrealistic to expect an abrupt cessation of anthropogenic emissions in the near future, this assumption provides an opportunity to gain insight into the potential impact of a complete cessation of emissions on future global warming. This, in turn, can help to determine the amount of warming that is yet to come. Thus, it is possible to calculate the probability that certain temperature thresholds, such as the 1.5 degree target or the 2 degree target from Paris Agreement (2015), will already be exceeded due to past emissions. This is important, given that the global temperature is already more than 1.1 degrees above pre-industrial levels, followed by much debate about the achievability of the proposed targets. The main objective of this thesis is to characterize the committed warming more precisely using current observational data. An updated energy balance framework and a reduced-complexity climate model, the Finite Amplitude Impulse Response (FaIR) model, are used for this purpose.

At equilibrium (multi-millennial), a committed warming of 2.13 K relative to pre-industrial values is found when the forcing from aerosols and short-lived climate forcers is removed. Within this century, there is a committed warming of 1.86 K. When carbon uptake by the biosphere and ocean is taken into account, committed warming is reduced to 1.5 K. However, the risk of exceeding the 1.5 degree target is 50.3%. Using the IPCC's uncertainty language, it is *more likely than not* that past emissions will already lead us to a warming of more than 1.5 degrees. Comparing the results with a FaIR model run, a similar committed warming is found.

The immediate implication of these new results is that it will be almost impossible to stay below 1.5 degrees of warming overall, as anthropogenic emissions are very likely to continue for years. This would then lead to a global mean temperature

that has not been seen on Earth for at least 120,000 years. Thus, this is certain to be accompanied by negative global impacts such as more frequent weather extremes and the loss of habitats and biodiversity. Negative emission technologies could therefore play a crucial role in getting us back on track.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
ECS	Equilibrium Climate Sensitivity
EEI	Earth's Energy Imbalance
ERF	Effective Radiative Forcing
ESMs	Earth System Models
FaIR	Finite amplitude Impulse Response
IPCC	Intergovernmental Panel on Climate Change
RCMIP	Reduced Complexity Model Intercomparison Project
SCMs	Simplified Climate Models
SLCFs	Short-Lived Climate Forcers
SSP	Shared Socioeconomic Pathway
TCR	Transient Climate Response
TOA	Top Of Atmosphere
ZEC	Zero Emissions Commitment

Variable Names

Symbol	Variable name	Unit
F	Effective radiative forcing	$[\mathrm{W\,m^{-2}}]$
T	Temperature	$[\mathrm{K}]$
λ	Feedback parameter	$[\mathrm{W\,m^{-2}\,K^{-1}}]$
Q	Energy imbalance	$[\mathrm{W\,m^{-2}}]$
ECS	Equilibrium climate sensitivity	$[\mathrm{K}]$
TCR	Transient climate response	$[\mathrm{K}]$
$F_{2\mathrm{x}}$	Forcing from a doubling of CO_2	$[\mathrm{W\,m^{-2}}]$
δF	Forcing correction	$[\mathrm{W\,m^{-2}}]$

1

Introduction

Committed warming, also known as Zero Emissions Commitment (ZEC), is a measure of the future increase in global temperature that would occur if anthropogenic emissions were to cease immediately. Because the climate system is inert, it will not be in equilibrium at the moment we stop emissions. Therefore, there will still be some warming as thermal sinks such as the deep ocean reach a new equilibrium. Future warming will also be influenced by changes in the forcing from anthropogenic aerosols and short-lived climate forcers (SLCFs) and the associated impacts on the climate system. If emissions were stopped immediately, aerosols would disappear within weeks due to chemical processes and atmospheric deposition. Since most of the aerosols currently cool the Earth's temperature by reflecting incoming solar radiation, their vanishing will lead to further global warming. However, SLCFs are removed by chemical processes within a few years after emissions cease, resulting in less global warming. The main aim of this thesis is to provide new estimates of committed warming using current observational data.

There are many different definitions of committed warming or ZEC used, often referring only to the impact of CO_2 emissions. In this respect, it is important to note that this thesis considers the commitment of all greenhouse gas emissions, including aerosols. Furthermore, the committed warming as defined here quantifies the total warming relative to pre-industrial levels. Some studies define ZEC as the change in global temperature from the moment emissions cease to the peak warming, as done in the Zero Emissions Commitment Model Intercomparison Project.

As climate policy currently aims to stay below a certain level of global warming by reaching net-zero emissions, committed warming is important when it comes to the calculation of the globally remaining carbon budgets. These represent the total amount of CO_2 that can still be emitted in order to stay below certain temperatures compared to pre-industrial levels (MacDougall et al., 2020). Nevertheless, Rogelj et al. (2019) mention that committed warming is often neglected in carbon budget studies or alternatively assumed to be zero or negative. Thus, gaining new insights into committed warming could alter estimated carbon budgets and reduce the uncertainty of exceeding certain temperature thresholds, such as the 1.5 and 2 degree targets from Paris Agreement (2015).

There are a number of ways to determine committed warming. I will focus on two methods here: the calculation with an energy balance framework and the run of a reduced-complexity climate model. This type of model is often referred to as a simplified climate model (SCMs).

Mauritsen and Pincus (2017) used an energy balance framework based on the assumption of a constant forcing from now on. This does not pertain to the forcing from aerosols and SLCFs, as these change significantly after emissions cease. Thus, committed warming is mainly due to changes in temperature, aerosol forcing and SLCFs forcing, as well as changes in the Earth's energy imbalance (EEI) relative to the pre-industrial period, scaled by the appropriate climate sensitivity. The framework is updated using current observational data of these quantities for the period 2012 - 2022, which provides new estimates of committed warming. The results are compared with the estimates of Mauritsen and Pincus (2017), who used the years 2005 - 2015 as present-day period, and in addition to a run of a reduced-complexity climate model, the Finite Amplitude Impulse Response (FaIR). The FaIR model is run with emissions data from different sources. Emissions are set to zero after 2023. Aerosol forcing is also set to zero to account for their vanishing in weeks after emissions cease. However, natural forcing is maintained in the model run to allow for natural background forcing. As there are gas cycles integrated into the model such as the carbon cycle, carbon uptake is included here. Committed warming is then defined as the maximum annual temperature anomaly after the cessation of emissions relative to pre-industrial values. Thus, the determined committed warming from this model can only be compared with estimates of the energy balance framework considering carbon uptake as well.

The term *forcing* in this thesis always refers to effective radiative forcing, which is widely used in the Intergovernmental Panel on Climate Change (IPCC). For the sake of simplicity, this will always be referred to as forcing. The brackets [ ] indicate the 5th to 95th percentile. Both the FaIR model and the energy balance framework are run in Python.

At the beginning, I describe the main methods by explaining the energy balance framework used by Mauritsen and Pincus (2017) and then the basic structure of the FaIR model. Besides, I introduce two measures of the climate response to a doubling of CO_2 concentrations. The updates regarding the energy balance framework as well as the performance of the FaIR model run are discussed in the modelling chapter. Following that, the new estimates of committed warming are presented and compared with the results of Mauritsen and Pincus (2017) and the FaIR model run. In order to gain further insight into the behaviour of the energy balance framework, it is examined for a particular scenario and time period to identify the main drivers of changes in committed warming.

2

Methods

2.1. Methodology developed by Mauritsen and Pincus

One way to determine the committed warming is to use an energy balance framework. The main assumption for employing this is that the change in the energy balance of the system is the sum of the forcing F and the response R of the system:

$$N = F + R \ . \tag{2.1}$$

N is the anomaly of the global mean net radiative flux at the top of the atmosphere (TOA). The unit of all these quantities is $\mathrm{W\,m^{-2}}$. The response of the climate system depends on Earth's surface temperature:

$$\Delta R = \lambda \, \Delta T \ . \tag{2.2}$$

The feedback parameter λ defines the magnitude of the Earth's radiative response to a given change in its global mean surface temperature. Gregory et al. (2002) and Gregory et al. (2004) introduced this energy balance framework. In the following, two measures of the climate response to doubled CO_2 concentrations relative to pre-industrial levels can be derived from observational data: the transient climate response (TCR) and the equilibrium climate sensitivity (ECS). While the TCR refers to centennial scales, the ECS refers to multi-millennial scales. These are generally known as climate sensitivities, as they measure the change in global mean surface temperature in response to a forcing.

The equations below are derived from a linearized two-layer model with an upper-ocean layer with a temperature T_u and a deep-ocean layer with a temperature T_d. T_u

describes the temperature of the upper ocean as well as the troposphere and land. The two-layer model consists of three equations describing the energy balance of the whole system as well as the energy balance of the upper and deep layer. The deep-ocean heat uptake coefficient γ and the deep-ocean heat uptake efficacy ϵ are introduced. As the deep-ocean heat uptake depends on the state of the upper- and deep-ocean layers and thus on how the temperature difference $T_\mathrm{u} - T_\mathrm{d}$ changes, γ describes the rate of the heat uptake in $\mathrm{W\,m^{-2}\,K^{-1}}$. The efficiency of deep-ocean heat uptake in different regions is represented by ϵ. This is related to the pattern effect, as it is seen that different regions of the world warm differently.
However, the equations of this model are not trivially solvable. Therefore, a simplification, the diagnostic zero-layer approximation, is applied in order to obtain the equations below. This is described by Jiménez de la Cuesta and Mauritsen (2019) as an energy-balance-inference method. The zero-layer approximation is valid for cases where a gradual forcing is acting on relatively long time scales, so that the upper layer is approximately in equilibrium, but the deep ocean has not yet changed significantly and is therefore an infinite sink of energy (Jiménez de la Cuesta and Mauritsen, 2019). This assumption eliminates λ and γ, which reduces complexity. Besides, ϵ is set to 1, so the pattern effect is not taken into account here.

From this, the ECS and TCR can be estimated by taking into account the changes in observational data between two time periods. ECS is defined as the temperature change due to a doubling of CO_2 after a new equilibrium has been reached. Therefore, the new equilibrium state of the system must fulfil the condition $\Delta N = 0$:

$$\Delta F + \lambda\,\Delta T = 0\ . \tag{2.3}$$

The ECS follows from solving equation (2.3) for ΔT using $\Delta F = F_{2\mathrm{x}}$:

$$\mathrm{ECS} = -\frac{F_{2\mathrm{x}}}{\lambda}\ . \tag{2.4}$$

$F_{2\mathrm{x}}$ describes the effective radiative forcing (ERF) from a doubling of CO_2, which is set to 3.71 $\mathrm{W\,m^{-2}}$. Then λ is rearranged using equations (2.1) and (2.2) and inserted into equation (2.4). Thereby energy imbalance Q is used equivalent to N. It is taken into account by using the Earth's energy imbalance (EEI) anomaly at TOA. The result is the following equation, already used by Mauritsen and Pincus (2017):

$$\mathrm{ECS} = F_{2\mathrm{x}} \frac{\Delta T}{\Delta F - \Delta Q} \ . \tag{2.5}$$

This equation can be used to calculate the ECS from observational data. The terms ΔT, ΔF and ΔQ refer to changes in these quantities between two time periods.

The TCR is defined as the temperature change at the time of a doubling of CO_2 from a linear increase of CO_2 of 1% per year. The TCR is obtained by taking into account changes in ΔT and ΔF. As this is a centennial quantity, ΔQ is assumed to be zero:

$$\mathrm{TCR} = F_{2\mathrm{x}} \frac{\Delta T}{\Delta F} \ . \tag{2.6}$$

Furthermore, five different scenarios (a) - (e) are developed in order to infer new estimates of the committed warming (Mauritsen and Pincus, 2017). This is done by holding the forcing constant at present-day values and scaling the EEI and forcing increment by the appropriate climate sensitivity and adding this to the current temperature anomaly T. δF serves as a correction for the forcing, as forcing from years after the used present-day period cannot be taken into account by other means. This provides a contemporary estimate of the forcing. Besides, it is assumed that the warming that balances the present EEI is consistent with the response to the past forcing. Scenarios (a) - (c) are multi-millennial scenarios based on a scaling with ECS. However, scenarios (d) and (e) are centennial scenarios, as scaled with TCR. The different $T_{\mathrm{a-e}}$ indicate different committed warmings calculated by the equations below (Mauritsen and Pincus, 2017).

Thereby scenario (a) corresponds to the standard condition, where the forcing is held constant at present-day values and everything else is left unchanged:

$$T_{\mathrm{a}} \approx T + [Q + \delta F] \frac{\mathrm{ECS}}{F_{2\mathrm{x}}} \ . \tag{2.7}$$

Scenarios (b) and (c) are also based on the calculation with ECS, but slightly modified from (a). A few weeks after a complete cessation of fossil fuel emissions, anthropogenic aerosols such as sulphur compounds would have been completely removed by washout, chemical reactions or deposition. The global cooling effect of aerosols therefore disappears. This is accounted for in scenario (b) by subtracting the aerosol forcing F_{aerosol} from the increment:

$$T_{\mathrm{b}} \approx T + [Q + \delta F - F_{\mathrm{aerosol}}]\frac{\mathrm{ECS}}{F_{2\mathrm{x}}} \ . \tag{2.8}$$

Natural aerosols, such as sea salt from the ocean, pollen or pollutants from biomass burning and their forcing are not included here.

Humans emit not only CO_2, but also short-lived climate forcers (SLCFs). As their name suggests, they have a shorter lifetime than CO_2 due to chemical reactions, but generally a much higher global warming potential. The main short-lived climate forcers are methane (CH_4), nitric and nitrogen oxides (NO_x) and carbon monoxide (CO). The magnitude of the forcing induced by SLCFs is quantified by summing up the forcing of each quantity, as this equation indicates:

$$F_{\mathrm{slcf}} = f_{\mathrm{ff}} \cdot F_{\mathrm{CH_4}} + F_{\mathrm{NO_x}} + F_{\mathrm{CO}} \ . \tag{2.9}$$

As anthropogenic methane emissions arise from many different sources, such as land use change associated with rice cultivation or gas combustion, only the fraction f_{ff} of these methane emissions that comes from fossil fuels is considered here. This is done in order to be consistent with the fundamental assumption of an immediate cessation of anthropogenic emissions.

Scenario (c) accounts for the loss of warming due to the disappearance of short-lived climate forcers by subtracting their forcing F_{slcf} from the increment:

$$T_{\mathrm{c}} \approx T + [Q + \delta F - F_{\mathrm{aerosol}} - F_{\mathrm{slcf}}]\frac{\mathrm{ECS}}{F_{2\mathrm{x}}} \ . \tag{2.10}$$

Besides, the vanishing of the aerosols is still being considered. Even taking into account the effect of SLCFs, which counteracts the lost cooling from aerosols, both scenarios are still expected to lead to a higher warming than scenario (a).

Scenario (d) is calculated with the TCR by using the same assumptions as for scenario (c):

$$T_{\mathrm{d}} \approx T + [Q + \delta F - F_{\mathrm{aerosol}} - F_{\mathrm{slcf}}]\frac{\mathrm{TCR}}{F_{2\mathrm{x}}} \ . \tag{2.11}$$

Scenario (e) is developed using the same assumptions as for scenario (d), but also taking into account the uptake of carbon by the climate system through land sinks and ocean:

$$T_{\mathrm{e}} \approx T + [\delta F - F_{\mathrm{aerosol}} - F_{\mathrm{slcf}}]\frac{\mathrm{TCR}}{F_{2\mathrm{x}}} \, . \tag{2.12}$$

This is done by a crude approximation, since there is no carbon cycle implemented in this simplified model framework. It is accounted for by excluding future warming from EEI, which was proved to be approximately true by studying the behaviour of Earth system models (ESMs) after emissions were stopped (Mauritsen and Pincus, 2017). I will further investigate the validity of this approximation regarding SCMs by performing the FaIR model run later.

2.2. The FaIR model

The FaIR model is a simplified climate model (SCMs) for the use in probabilistic future climate and scenario exploration. For modelling committed warming, version 2.0.0 of the FaIR model is used which was developed by Leach et al. (2021). It consists of a set of six equations, five of which are standard impulse equations taken from the Fifth Assessment Report (AR5) of the IPCC. The sixth equation represents state-dependencies of greenhouse gas cycles, which reproduce non-linearities in these cycles as seen in ESMs (Leach et al. (2021)). Gas cycles are mainly described by fixing a pre-industrial gas concentration and adding an atmospheric load. All this is constructed by a number of reservoirs with different uptake fractions and decay timescales.

The model operates on globally averaged scales and determines the temperature response through the following pathway: globally averaged emissions result in concentrations, which are translated into effective radiative forcing (ERF), leading to the temperature response. It is run with emissions data from 81 sources. Emissions data in gigatons is used from the Reduced Complexity Model Intercomparison Project (RCMIP). The translation from emission concentration data to ERF is done by a simple equation motivated by the concentration–forcing relationships. There are individual coefficients for each greenhouse gas. Aerosol emissions are converted directly to ERF because of their short atmospheric lifetime. The temperature response is derived from the sum of the ERF using an energy balance model, in particular a three-box model. This is explained in more detail in Leach et al. (2021).

3
Modelling

3.1. Update of Mauritsen and Pincus

In order to obtain new estimates of committed warming, the previously mentioned methodology requires revisions regarding input data and time periods to account for recent changes. The years 1850 - 1899 are used as the baseline period for determining the total committed warming. This is adopted from Mauritsen and Pincus (2017).
Firstly, new input data needs to be employed. Therefore, new annual global mean temperature data is extracted from the current HadCrut temperature dataset (HadCrut5.0.1.0)[1]. Moreover, Table AIII.3 of Annex III from the Sixth Assessment Report (AR6) of the IPCC (IPCC, 2021b), serves as the new forcing dataset. Chapter 7 of the AR6 (Forster et al., 2021) provides a new estimate of forcing uncertainties. The supplementary material from chapter 6 of the AR6[2] provides the values and uncertainties of the forcing from SLCFs (Szopa et al., 2021). Estimates of the EEI are derived from NASA CERES EBAF-TOA[3] Edition 4.2 data.
Secondly, two time periods have to be defined as reference periods, so that it is possible to account for changes in the above mentioned quantities. I therefore choose a pre-industrial period as well as a present-day period. The aim here is to meet the boundary conditions as closely as possible, so that neither large natural variability in one of these periods, such as volcanic eruptions, nor anthropogenic forcing in the pre-industrial period, is taken into account. Otherwise it would not be possible to calculate the change in quantities correctly. Hence, I would not be able to compare

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[1] https://www.metoffice.gov.uk/hadobs/hadcrut5/data/current/download.html

[2] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter06_SM.pdf

[3] https://ceres.larc.nasa.gov/data/

the new estimates with those from Mauritsen and Pincus (2017).

I choose the years 1859 - 1882 as the pre-industrial period. This period was already used by Mauritsen and Pincus (2017) and is a good compromise between low volcanic activity as well as comparatively low anthropogenic influence on the climate system. Periods just after 1750, with presumably even less anthropogenic influence, show some lack of data or higher volcanic activity. Mauritsen and Pincus (2017) mention that anthropogenic forcing certainly had already an impact in the baseline period 1850 - 1899 compared to 1750. As observations do not date back that long, the early anthropogenic forcing is obtained from estimated forcings for this period. They attribute a forcing of 0.15 $\mathrm{W\,m^{-2}}$ to this.

To consider volcanic activity for choosing the two reference periods is crucial. Therefore, a long-term mean volcanic forcing is required to be present in these periods. This is assumed to be close to zero. If there had been a major volcanic eruption with stratospheric impact in one of the reference periods, this would lead to a systematic under- or overestimate of ΔF due to aerosol injection (Pitari et al., 2016). Figure 3.1 shows significant changes in the estimated past volcanic forcing between AR5 and AR6. This is due to a better understanding of the climate response to volcanic eruptions from improved modelling, as well as more comprehensive observational and paleo data since AR5 (Lee et al., 2021). Nevertheless, the forcing data of the chosen pre-industrial and present-day period shows similar conditions and only small changes from slightly negative to slightly positive forcing. The volcanic forcing in AR6 is estimated to be marginally higher in the present-day period than in the pre-industrial period. Thus, comparing the mean forcing of the two time periods leads to a difference in forcing of -0.02 $\mathrm{W\,m^{-2}}$ for AR5 and 0.04 $\mathrm{W\,m^{-2}}$ for AR6. Mauritsen and Pincus (2017) pointed out, that the slight overestimation of the volcanic forcing in AR5 would be roughly offset by the above stated anthropogenic forcing of 0.15 $\mathrm{W\,m^{-2}}$ in the baseline period (1850 - 1899). Using the AR6 forcing data, I find an anthropogenic forcing of 0.26 $\mathrm{W\,m^{-2}}$ in the baseline period compared to 1750. The increase is due to changes of forcing estimates between AR5 and AR6. With these new forcing estimates from AR6, an offset of volcanic and early anthropogenic forcing is unlikely. However, the quantities and therefore the impacts are small, so I am not going to consider them any further.

Now the mean temperature T and the mean forcing are calculated for this period. The EEI for this period is estimated to be 0.15 ± 0.075 $\mathrm{W\,m^{-2}}$ by Lewis and Curry (2015), which was already used by Mauritsen and Pincus (2017).

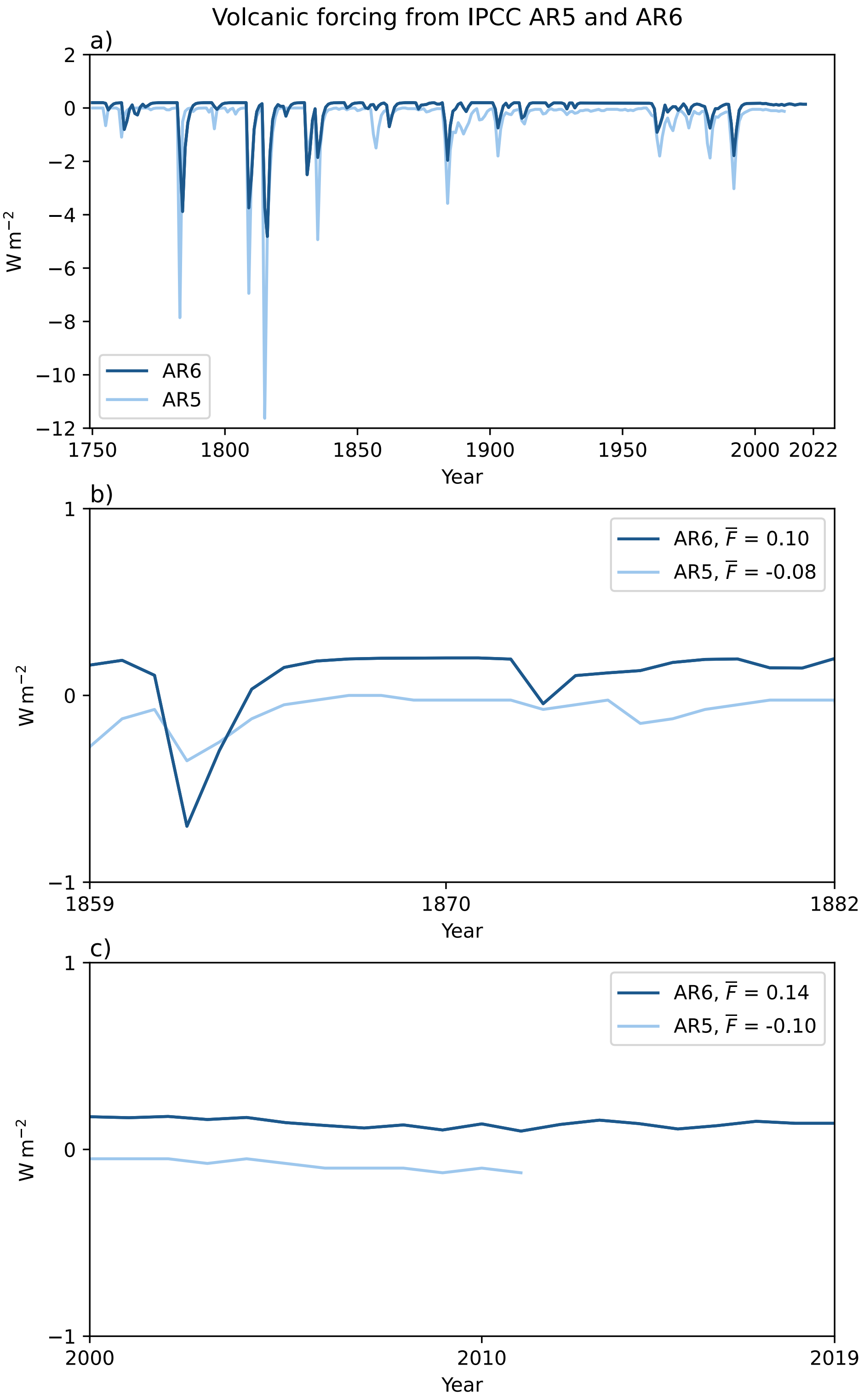

Figure 3.1: Volcanic forcing from AR5 and AR6 for different time periods. a) shows the period 1850 - 2019. b) and c) show the pre-industrial reference period 1859 - 1882 and the recent years 2000 - 2019, respectively. Mean forcing in b) is calculated for the years 1859 - 1882. In c) it is calculated for 2012 - 2019 (AR6) and for 2005 and 2011 (AR5), taking into account the previously defined periods and some lack of data at the end of each period.

My choice of time period for the present is 2012 - 2022 in order to obtain the most recent estimates of committed warming possible. Mean temperature T is calculated for this period. The present-day forcing F is calculated for the year 2017. I have chosen 2017 because it is in the center of this period and the forcing data from AR6 ends already in 2019. To be consistent, I have used the same forcing agents as Mauritsen and Pincus (2017). This covers forcing data from CO_2, CH_4, nitrous oxide (N_2O), other well-mixed greenhouse gases, ozone (O_3), aerosol–radiation interactions (ERFari), aerosol–cloud interactions (ERFaci), land use change, stratospheric water vapour, black carbon on snow, contrails, solar variations and volcanoes. The term other well-mixed greenhouse gases refers mainly to halogenated compounds. Estimates of forcings and their uncertainty from chapter 8 of AR5 (Myhre et al., 2013a) and chapter 7 of AR6 (Forster et al., 2021) are shown in Table 3.1. No estimate is made for volcanic forcing, as volcanic eruptions occur in episodes. Estimated values and uncertainties of SLCFs from AR5 and AR6 are given in Table 3.2. These are taken from the supplementary material of chapter 8 (Myhre et al., 2013b) for AR5 and from the supplementary material of chapter 6 (Szopa et al., 2021)[2] for AR6. The fractions of anthropogenic methane emissions from fossil fuel combustion are estimated from table 6.8 in chapter 6 (Ciais et al., 2013) for AR5 and from table 5.2 in chapter 5 (Canadell et al., 2021) for AR6 by calculating the ratio of CH_4 fossil fuel emissions to total anthropogenic CH_4 emissions.

Table 3.1: Estimated forcings and uncertainties [5th to 95th percentiles] of different forcing agents in $W\,m^{-2}$ from AR5 and AR6. Well-mixed greenhouse gases include CO_2, CH_4, N_2O and halogenated compounds.

Forcing agent	AR5	AR6
Well-mixed greenhouse gases	2.83 [2.54 - 3.12]	3.32 [3.03 - 3.61]
Ozone	0.35 [0.15 - 0.55]	0.47 [0.24 - 0.71]
Aerosol-radiation interactions	−0.45 [−0.95 - 0.05]	−0.22 [−0.47 - 0.04]
Aerosol-cloud interactions	−0.45 [−1.2 - 0.0]	−0.84 [−1.45 - −0.25]
Land use change	−0.15 [−0.25 - −0.05]	−0.20 [−0.30 - −0.10]
Stratospheric water vapour	0.07 [0.02 - 0.12]	0.05 [0.0 - 0.1]
Black carbon on snow	0.04 [0.02 - 0.09]	0.08 [0.0 - 0.18]
Contrails	0.01 [0.005 - 0.03]	0.06 [0.02 - 0.10]
Solar variations	0.05 [0.0 - 0.10]	0.01 [−0.06 - 0.08]
Total anthropogenic	2.3 [1.1 - 3.3]	2.72 [1.96 - 3.48]

Table 3.2: Estimated forcing values and uncertainties [5th to 95th percentiles] by emitted components of short-lived climate forcers (SLCFs) in W m^{-2} and the fraction of the anthropogenic CH_4 emissions that is due to fossil fuel combustion from AR5 and AR6.

Quantity	AR5	AR6
CH_4	0.97 [0.805 - 1.135]	1.195 [0.805 - 1.584]
NO_x	−0.151 [−0.338 - 0.024]	−0.267 [−0.546 - 0.013]
CO	0.234 [0.178 - 0.29]	0.340 [0.166 - 0.514]
CH_4 fraction	0.29	0.32

Present-day EEI is derived from monthly TOA net flux values from CERES[3] data for the years 2012 - 2022. This results in an estimate of mean EEI of 1.11 W m^{-2}. The uncertainty ± 0.1 W m^{-2} is taken from Johnson et al. (2016) as they also used CERES data in their study.

Thus ΔT characterizes the change in global mean temperature between the periods 1859 - 1882 and 2012 - 2022. ΔQ quantifies the change in EEI between the same periods. Changes in forcing ΔF are calculated between 1859 - 1882 and 2017. This is corrected with δf as the forcing of the recent years 2018 - 2022 cannot be accounted for by other means. F_{aerosol} and F_{slcf} are also calculated with the forcing data of the years 2012 - 2022.

The total uncertainty is determined by considering the uncertainty of each component: Temperature anomaly, EEI and all forcing agents as well as SLCFs forcing quantities. For this purpose, the uncertainty of each quantity is determined by applying Gaussian normal distributions with their means and standard deviations with a sample size of 5 million. Estimates of medians and percentiles can be derived from these distributions. The standard deviation of a temperature change of HadCrut data due to uncertainty and variability is given by Lewis and Curry (2015) as 0.08 K. Forcing uncertainties are taken from Table 3.1. These refer to the 5th - 95th percentiles of the forcing estimates. The uncertainties of the forcing from SLCFs are taken from Table 3.2 and the uncertainty ± 0.1 W m^{-2} of the EEI is obtained from Johnson et al. (2016).

By taking all this into account, values of ECS and TCR can be calculated with equations (2.5) and (2.6). For this purpose, 5 million replications are used to quantify uncertainty by obtaining distributions of the quantities. In addition, this large number of replications improves the estimates of medians and percentiles. Following that, the committed warming of scenarios (a) - (e) can be calculated from equations (2.7), (2.8), (2.10), (2.11) and (2.12). From this, the probabilities of exceeding given temperature thresholds can be determined.

3.2. FaIR model run

As a validation, an emission-based run of the FaIR model with the version FaIRv2.0.0 is conducted. The FaIR model runs on 81 emission variables assigned to the main categories carbon dioxide, methane, nitrous oxide, other well-mixed greenhouse gases, ozone, stratospheric water vapour, black carbon on snow, contrails and aerosols, the latter separated into atmosphere-radiation interactions and atmosphere-cloud interactions. These originate from emissions data from RCMIP, which are later translated to ERF. Subsequently, emissions are set to zero after 2023 to obtain estimates of committed warming. The forcings are therefore not set to constant, but are still actively changing, e.g. due to carbon cycle activity. However, the aerosol forcing is an exception, as it is set to zero to account for natural vanishing of aerosols through processes such as wash-out, deposition and chemical reactions within weeks after a complete cessation of emissions. Forcing data from land use change, solar variations and volcanoes is left unchanged to allow natural background forcing to continue. Additionally, there is no reason for assuming a sudden or even human-induced change of these forcings. The emissions scenario used is the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5), which is a middle path scenario. However, the choice of the emissions path does not lead to large differences as the main changes in emissions will affect the future years and emissions are assumed to cease after 2023. For past years the estimates are quite similar for the different emissions paths.

The model run includes 5000 ensemble members to quantify uncertainty. This also improves the estimates of median and percentiles. The calculated temperature is subtracted from the global mean temperature of the baseline period 1850 - 1899 to obtain the committed warming relative to that period. The uncertainty is given by the 5th to 95th percentile of the calculated temperature of the 5000 ensemble members. By considering the number of members above a certain temperature threshold for a given year, I can calculate the likelihood of exceeding that threshold. As the FaIR model integrates various gas cycles, particularly the carbon cycle, its results can be compared primarily with scenario (e) of the energy balance framework mentioned in Sections 2.1 and 3.1.

4

Results

4.1. Updating climate sensitivities

Using the energy balance framework, I can calculate values and ranges for both climate sensitivities, TCR and ECS, where TCR again refers to centennial timescales and ECS to multi-millennial timescales. To estimate their uncertainty, the changes in temperature, forcing and energy imbalance are calculated using Gaussian normal distributions with a sample size of 5 million and their respective means and standard deviations. These quantities are assumed to be uncorrelated. By making use of equations (2.5) and (2.6), 5 million estimates of TCR and ECS are obtained. Then the median and the 5th and 95th percentiles of each distribution can be derived. The probability distributions of the TCR and ECS are shown in Figure 4.1. The new estimated median of the TCR is 1.66 K with a range of 1.24 K to 2.42 K, given by the 5th to 95th percentiles of the distribution. The ECS is estimated to have a median of 2.70 K and a range of 1.76 K to 5.65 K. Mauritsen and Pincus (2017) found for the TCR an estimated median of 1.32 K with a range of 0.88 K to 2.36 K and for the ECS an estimated median of 1.79 K with a range of 1.08 to 4.44 K. As expected, the uncertainty in the calculated TCR between 2017 and 2023 decreases as we get closer to a doubling of CO_2 over time and gain a better understanding of the framework's limitations.

The estimated range of the ECS is visibly higher than in 2017. This is mainly due to the uncertainty induced by a higher EEI in the present-day period. Thus ΔQ is increased by the larger difference in the EEI between the two periods. Since in equation (2.5) $\Delta F - \Delta Q$ stands in the denominator, the ECS is increased. This leads to a shift in the distribution of the 5 million replications towards higher values. Table 4.1 gives

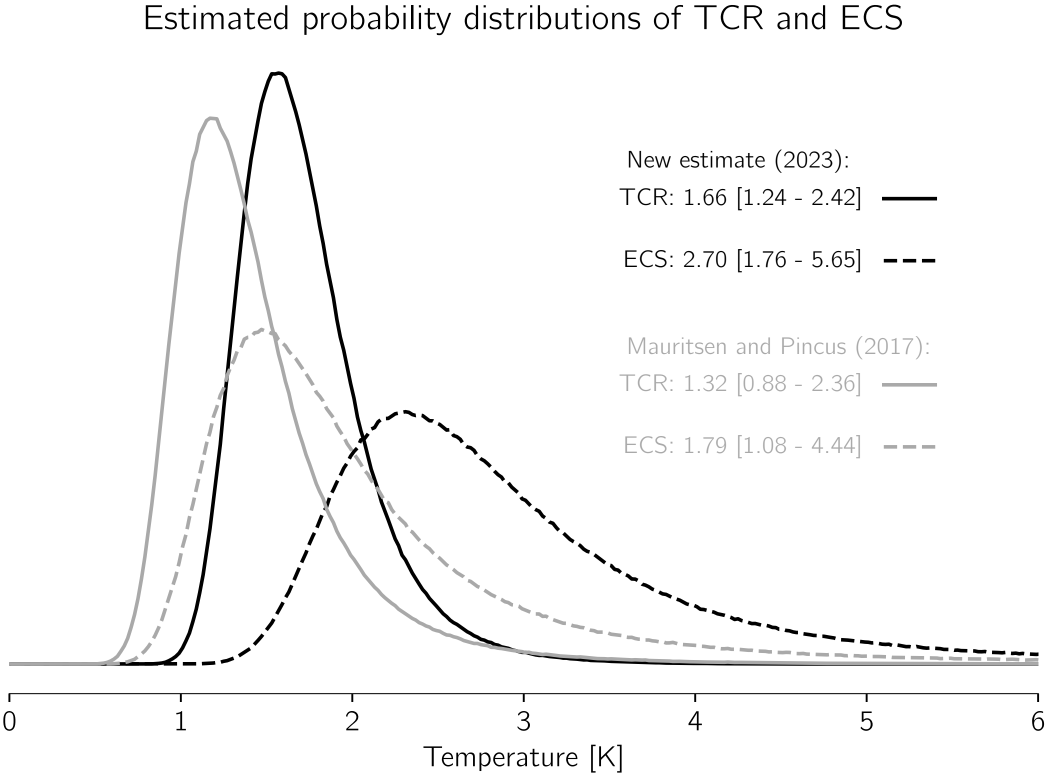

Figure 4.1: Estimated probability distributions of transient climate response (TCR) and equilibrium climate sensitivity (ECS) for the years 2023 (black) and 2017 (grey). Probabilities of TCR are shown as solid lines, probabilities of ECS as dashed lines. The ranges consist of the estimated medians together with the 5th to 95th percentiles of each distribution.

an overview of the different estimates of TCR and ECS from various studies using different approaches. Using the energy balance framework following the methods of Otto et al. (2013), the AR6 comes up with quite similar estimates of TCR and ECS. The TCR is given as 1.9 K [1.3 - 2.7 K], the ECS is estimated to be 2.5 K [1.6 - 4.8 K]. All estimates in AR6 are higher than those in AR5. In AR5, the likely range for ECS was estimated to be between 1.5 K and 4.5 K, and for TCR the range was given between 1 K and 2.5 K (Collins et al., 2013). AR6 mentions four possible reasons for this increase, based on four different revisions that have been made in the new report and that could be responsible for this increase: Forster et al. (2021) point to (i) an upward revision of historical global surface temperature trends based on newly published trend estimates, and (ii) a more negative estimate of the aerosol forcing overall, which reduces the estimates of historical forcing trends. Additionally, they mention (iii) an 8% increase in the forcing for F_{2x} and (iv) the inclusion of the pattern effect in the ECS estimates. I address (i) and (ii) by using new HadCrut temperature data and AR6 forcing data, respectively. Both (iii) and (iv) are not included in my calculations. I used 3.71 $\mathrm{W\,m^{-2}}$ as the forcing for F_{2x}, which is a commonly used estimate (IPCC, 2021a). In addition, it is not possible to account for the pattern effect within this framework. As a general estimate, Forster et al. (2021) give a value of 1.8 K [1.2 - 2.4 K] for the TCR and 3 K [2 - 5 K] for the ECS. Their estimates are slightly higher than mine. This is probably because their estimates include the pattern effect and the dependence of feedbacks on the climate state. Overall, my new estimates of climate sensitivities from observational data show good agreement.

Table 4.1: Estimates of TCR and ECS using different approaches. Ranges refer to the 5th to 95th percentiles of the estimated medians. All values in Kelvin (K).

Study	TCR (K)	ECS (K)
This thesis	1.66 [1.24 - 2.42]	2.70 [1.76 - 5.65]
AR6 observational data	1.90 [1.30 - 2.70]	2.50 [1.60 - 4.80]
AR6 general estimate	1.80 [1.20 - 2.40]	3.00 [2.00 - 5.00]
Jiménez and Mauritsen (2019)[4]	1.67 [1.17 - 2.16]	2.83 [1.72 - 4.12]
Mauritsen and Pincus (2017)	1.32 [0.88 - 2.36]	1.79 [1.08 - 4.44]

4.2. Committed warming reaches 1.5 K

By using the new updates of climate sensitivities along the method from Section 2.1, I have calculated new estimates of committed warming relative to the pre-industrial baseline period (1850-1899). The results for the different scenarios (a) - (e) are shown in Figure 4.2. Assuming a standard scenario (a), there is a committed warming of 2.11 K [1.68 - 3.26 K] at equilibrium. Standard scenario means that the forcing is assumed to be constant after the present-day period (2012 - 2022) and δF is used as a correction for the forcing of the recent years 2018 - 2022 that could not be accounted for by other means, but nothing else is changed. Further considering the removal of aerosols (scenario (b)), which results in the loss of their cooling effect, a committed warming of 2.87 K [1.91 - 5.86 K] is obtained. The high uncertainty in the committed warming of this scenario is mainly due to the high uncertainty in the aerosol forcing. In addition, as shown in Section 4.1, the estimate of the ECS is increased compared

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[4] Jiménez de la Cuesta and Mauritsen (2019)

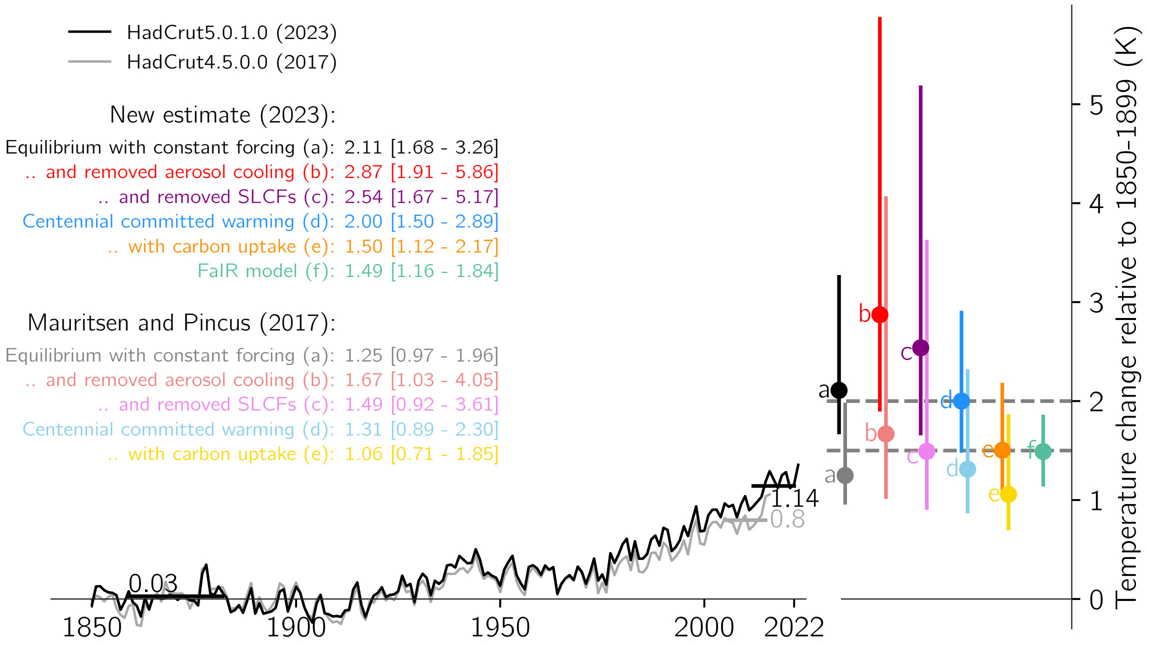

Figure 4.2: Estimated committed warming for 5 different scenarios obtained from the energy balance framework in Kelvin. Darker coloured scenarios show the new estimate, lighter colours the results from Mauritsen and Pincus (2017). Scenarios (a) - (c) refer to multi-millennial (equilibrium) states using ECS. Scenario (a) is a standard scenario, (b) takes into account the loss of aerosol cooling. Scenario (c) also includes the effect of removed short-lived climate forcers (SLCFs). Scenarios (d) and (e) show centennial (transient) states using TCR. Scenario (d) uses the same assumptions as scenario (c). Scenario (e) also includes carbon uptake. Scenario (f) refers to the FaIR model run. Dashed grey lines indicate 1.5 and 2 degrees of warming. HadCrut temperature data from the years 2023 (HadCrut5, black) and 2017 (HadCrut4, grey).

to 2017. This leads to increased estimates of committed warming for all multi-millennial (equilibrium) scenarios. When also considering the impact of removed SLCFs (scenario (c)), the committed warming is calculated to be 2.54 K [1.67 - 5.17 K]. This shows that even the removal of SLCFs will not offset the warming that emerges from the vanishing of aerosols. Thus, aerosols are the dominant driver of further change in committed warming.

Within this century, there is a committed warming of 2.00 K [1.50 - 2.89 K] (scenario (d)). The assumptions from scenario (c) remain unchanged. If carbon uptake by the biosphere and ocean is also taken into account, the committed warming is reduced to 1.50 K [1.12 - 2.17 K] (scenario (e)). However, there is still a 50.3% risk of exceeding the 1.5 degree target for this scenario (Table 4.2). The likelihood of exceeding 2 degrees is 9.2%. This means that staying below 1.5 degrees is unachievable with a chance of 50%.

The IPCC uncertainty language uses the following terms for different likelihoods: *very likely* refers to 90 – 100%, *likely* to 66 – 100%, *more likely than not* to > 50 – 100%, *about as likely as not* to 33 – 66%, *unlikely* to 0 – 33% and *very unlikely* to 0 – 10% (IPCC, 2021c). Using this language, it is *more likely than not* that past emissions are already taking us towards a warming of more than 1.5 degrees. For the other scenarios, the likelihoods of exceedance are much higher.

Table 4.2: New estimated likelihoods (in %) that committed warming already exceeds 1.5 K and 2 K for the different scenarios (a) - (e).

Scenario	Likelihood of exceeding 1.5 K	Likelihood of exceeding 2 K
(a)	99.6%	62.9%
(b)	99.8%	92.4%
(c)	98.5%	80.7%
(d)	94.9%	49.9%
(e)	50.3%	9.2%

Thus, for the multi-millennial scenarios (a) - (c) it is very likely or likely that both the 1.5 degree target and the 2 degree target will already be exceeded. However, the scenarios do not specify whether the committed warming refers to the warming at the end of the respective time scale or to some time in the middle. Assessing overshooting, where the temperature surpasses a threshold for a few years before falling back below it, is also challenging within this framework. So, I suggest focusing more on the likelihoods on centennial scales. Nevertheless, for scenario (d) it is very likely that 1.5 degrees will be exceeded, and it is about as likely as not that 2 degrees will be also exceeded.

Looking further at the Paris Agreement[5], it reads as follows:

Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.

The resolution does not specify the likelihood of these targets being met, nor does it set a target year. Overall, the wording is rather vague. However, the statement that the temperature should be kept well below 2 °C can be understood to mean that it should not be exceeded at any time.

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[5] https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

All estimates of committed warming by Mauritsen and Pincus (2017) are substantially lower than my new estimates. They found a committed warming of 1.25 K [0.97 - 1.96 K] for the standard scenario (a). Considering the loss of aerosol cooling (scenario (b)), the committed warming increased to 1.67 K [1.03 - 4.05 K]. By also taking removed SLCFs into account, the committed warming was slightly reduced to 1.49 K [0.92 - 3.61 K] at equilibrium and was 1.31 K [0.89 - 2.30 K] within this century (scenarios (c) and (d)). When carbon uptake was considered (scenario (e)), the committed warming was reduced to 1.06 K [0.71 - 1.85 K]. The likelihoods of exceeding the temperature thresholds mentioned above were also much lower. For scenario (e) the risk of exceeding 1.5 degrees was 13% and for exceeding 2 degrees warming it was even lower at 3.4%.

As discussed in Section 4.1, one explanation for the increased estimates of committed warming is the higher estimates of TCR and ECS resulting from changes in temperature ΔT and forcing ΔF. The ECS also depends on the change of the energy imbalance ΔQ accounted for by the use of EEI.

Overall, this is due to further emissions from fossil fuel combustion. The temperature anomaly is also included separately in the calculation of the committed warming. Thus, parts of the calculated warming are caused by the change of the mean temperature anomaly from 0.8 K to 1.14 K between the periods (2005 - 2015) and (2012 - 2022) alone. Forster et al. (2021) provide an explanation for this large change: The estimates of global mean sea surface temperature from HadCrut4, used as temperature dataset by Mauritsen and Pincus (2017), were based on blended observational data. They did not interpolate over regions with incomplete observational data coverage. This mainly concerns the Arctic and Antarctic regions. As these regions show large amplifications of warming, this led to an underestimation of real warming. Forster et al. (2021) further mention that estimates of ECS and TCR derived from these datasets have smaller ECS and TCR values than those derived from model-inferred estimates. As plenty of previous studies have relied on this HadCrut4 data, this is generally a more widespread problem leading to an underestimation of temperature increase in these studies.

In addition to the change in temperature, the forcing has also changed in the meantime. The changes can be seen in Figure 4.3, which shows the total forcing data from AR5 and AR6. The total forcing for AR6 is estimated to be 2.84 $\mathrm{W\,m^{-2}}$ compared to 2.43 $\mathrm{W\,m^{-2}}$ in AR5. This includes data from both anthropogenic and natural sources. Natural sources are the sun and volcanoes. As natural forcing remained constant at

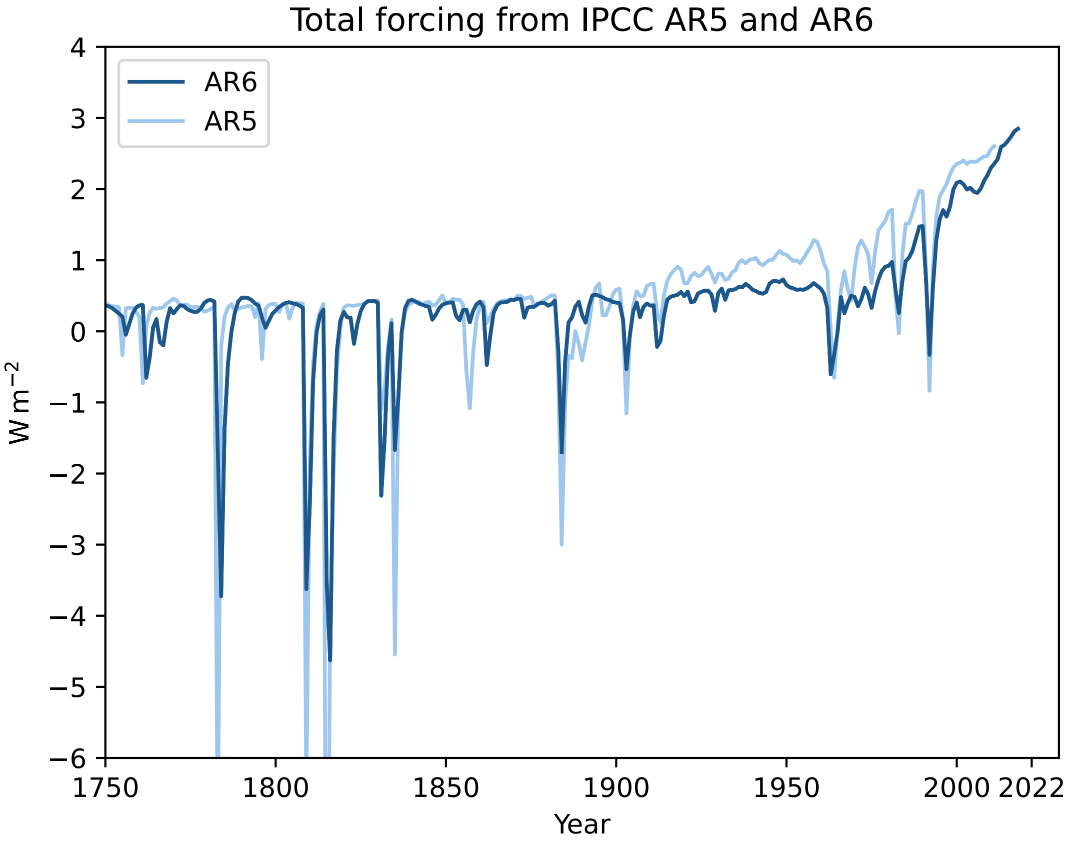

Figure 4.3: Total forcing from AR5 and AR6. AR5 data covers the period from 1750 to 2011, while AR6 covers the period from 1750 to 2019.

about 0.12 W m^{-2} in AR5 and AR6, Forster et al. (2021) focus mainly on the changes in anthropogenic forcing. The changes in estimated forcing values and uncertainties are shown in Table 3.1. They give a new estimate of the total anthropogenic forcing for 1750 – 2019 of 2.72 W m^{-2} [1.96 - 3.48 W m^{-2}]. This is an increase of 0.42 W m^{-2} compared to the AR5 estimate for the period 1750 - 2011 of 2.3 W m^{-2} [1.1 - 3.3 W m^{-2}]. Forster et al. (2021) emphasise that this increase is the result of compensating effects. As greenhouse gas concentrations have increased since 2011 due to combustion of fossil fuels and their forcing estimates have been revised upwards, this has led to an increase in their forcing of 0.59 W m^{-2}. As a result, there is an increased estimate of the forcing of SLCFs F_{slcf} of 0.46 W m^{-2} compared to 0.36 W m^{-2} from Mauritsen and Pincus (2017) (Table 4.3). This is included in equations (2.10), (2.11) and (2.12) to calculate the committed warming. Otherwise, the total aerosol forcing is expected to be more negative than in AR5, mainly due to revised estimates rather than trends. Changes in the aerosol forcing are shown in Figure 4.4. In particular, since 1900 the forcing has been strongly underestimated in AR5 with a peak of underestimation roughly between the 1980s and 2010s. Overall, AR6 comes up with an estimated aerosol forcing of $-1.06\,\mathrm{W\,m^{-2}}$ [-1.81 - $-0.31\,\mathrm{W\,m^{-2}}$] for the period 1750 - 2019 (Forster et al., 2021). Values of aerosol forcing are a combination of estimates from ERFari and ERFaci. The exact values of ERFari and ERFaci can be found in Table 3.1. This is a large difference compared to $-0.9\,\mathrm{W\,m^{-2}}$ [-1.9 - $0.1\,\mathrm{W\,m^{-2}}$] for 1750 - 2011 from AR5. While the magnitude of ERFari was reduced by about 50% compared to AR5 due to the agreement between observational and model-based evidence, the magnitude of ERFaci is increased by 85% for the same reason. The overall result is an increased estimate of the aerosol forcing. The F_{aerosol} for the present-day period, which is also

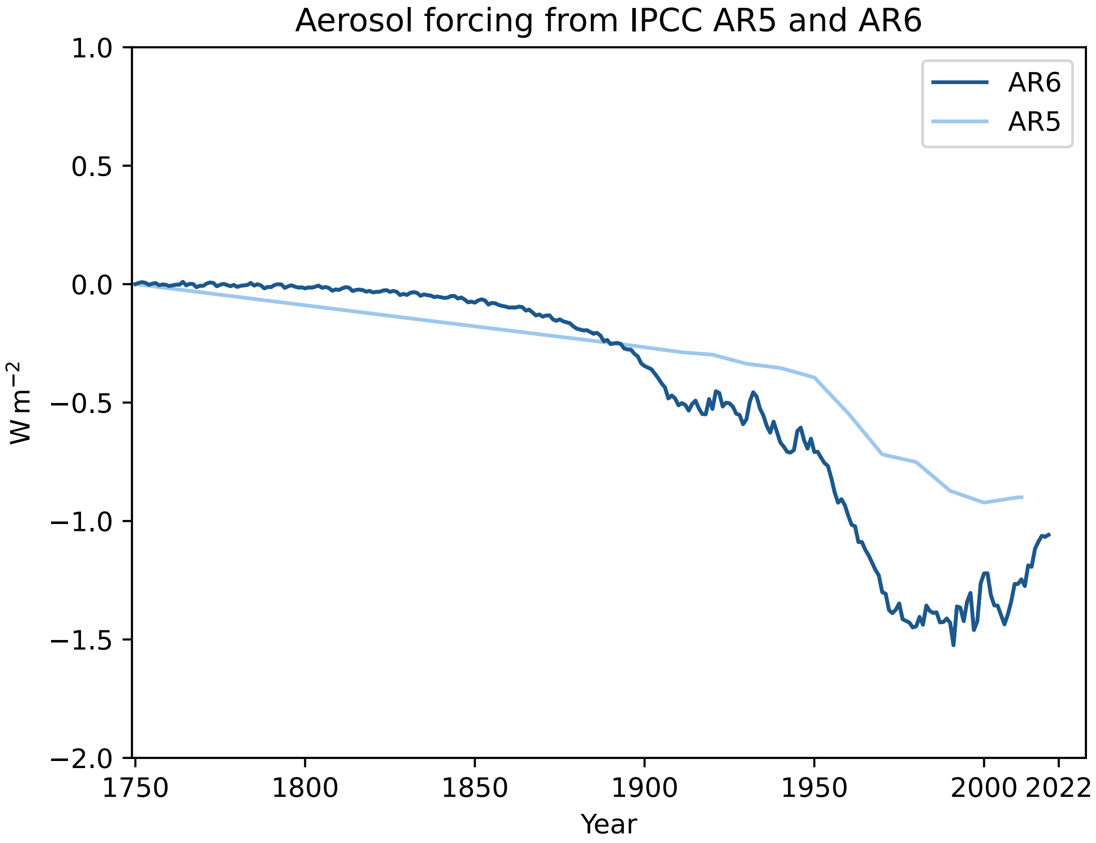

Figure 4.4: Aerosol forcing from AR5 and AR6. AR5 data covers the period from 1750 to 2011, while AR6 covers the period from 1750 to 2019.

used in the equations to calculate the committed warming, therefore has a value of $-1.06\ \mathrm{W\,m^{-2}}$ (Table 4.3). Mauritsen and Pincus (2017) found $-0.90\ \mathrm{W\,m^{-2}}$. This increase in forcing further increases the warming when the vanishing of aerosols due to the complete cessation of emissions is considered. Furthermore, this increase in the warming is only slightly reduced by considering removed SLCFs.

Table 4.3: Estimated forcing values and uncertainties [5th to 95th percentiles] of the periods 2005 - 2015 (Mauritsen and Pincus) and 2012 - 2022 (new estimate) in $\mathrm{W\,m^{-2}}$ used in the energy balance framework.

Forcing	Mauritsen & Pincus	New estimate
F_{aerosol}	−0.90 [−1.80 - 0.00]	−1.06 [−1.76 - −0.36]
F_{slcf}	0.36 [0.17 - 0.56]	0.46 [0.12 - 0.80]

Overall, in this model framework the change in forcing ΔF is evaluated between the period 1859 - 1882 and the year 2017. This results in an estimated change in forcing of $2.49\ \mathrm{W\,m^{-2}}$ [1.68 - $3.30\ \mathrm{W\,m^{-2}}$]. Mauritsen and Pincus (2017) came up with a ΔF of $2.16\ \mathrm{W\,m^{-2}}$ [1.18 - $3.13\ \mathrm{W\,m^{-2}}$] by using the period 1859 - 1882 and the year 2010.

The large changes in the negative peaks of the forcing estimate in Figure 4.3 between 1790 and 1900 are due to an overestimation of the volcanic forcing. As mentioned in the Section 2.1, a better database and modelling leads to the new assessment that the volcanic forcing is less negative. Since the volcanic forcing is assumed to be about zero on average, this does not lead to significant changes in the committed warming.

In addition, the forcing correction δF used for the years 2018 - 2022 is slightly higher at $0.22\ \mathrm{W\,m^{-2}}$ compared to $0.2\ \mathrm{W\,m^{-2}}$ estimated by Mauritsen and Pincus (2017) for the years 2012 - 2016. The change arises because the annual increase in forcing rises from about $0.033\ \mathrm{W\,m^{-2}\,yr^{-1}}$ to $0.044\ \mathrm{W\,m^{-2}\,yr^{-1}}$.

4.3. What are the main drivers of the change in committed warming?

To answer this question, the energy balance framework is rerun using the years 2005 - 2015 as present-day period for the calculations. The forcing is calculated as the change between the pre-industrial period and 2010, as 2010 is in the middle of the period. This allows me to get an updated estimate of the committed warming using new datasets for this period and compare it with the result of Mauritsen and Pincus (2017). New datasets refer to data derived from HadCrut5 and AR6 and previous datasets refer to HadCrut4 and AR5. The mean temperature of the present-day period increased from 0.8 K (HadCrut4) to 0.97 K (HadCrut5). The forcing decreased from 2.16 $\mathrm{W\,m^{-2}}$ (AR5) to 1.97 $\mathrm{W\,m^{-2}}$ (AR6). Scenario (e) is used for this purpose, as it appears to be the most suitable in terms of timescale and realism. As shown in Fig. 4.5, this leads to a new estimate of committed warming of 1.47 K compared

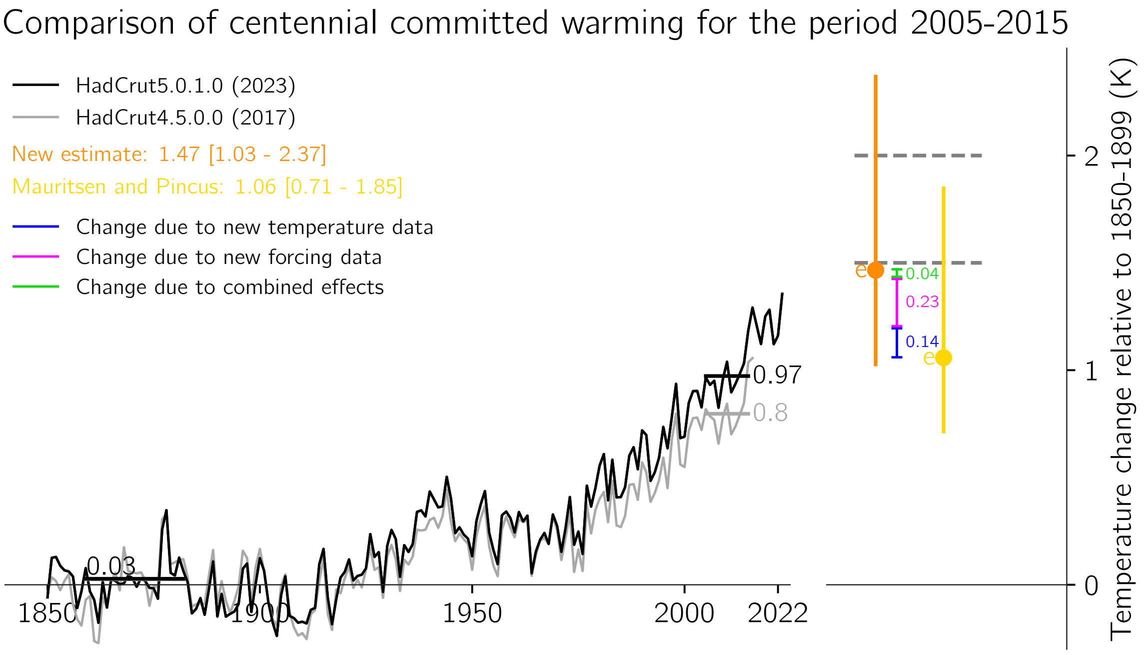

Figure 4.5: Estimated committed warming for the scenario with carbon uptake (e) obtained from the energy balance framework using 2005 - 2015 as present-day period. Orange indicates the new estimate using current datasets, yellow shows the result from Mauritsen and Pincus (2017). Blue indicates a change in committed warming due to a change in temperature data, pink indicates a change in committed warming due to a change in forcing data and green accounts for combined effects.

to 1.06 K in 2017. This is surprisingly high, as it suggests that the revision of the datasets contributes an additional warming of 0.41 K within the same time period. By considering only the change in one dataset and leaving the other one unchanged, it is possible to further determine what drives the change in committed warming. The result is that 0.23 K (56%) of the change in committed warming is induced by new forcing data. The change due to the use of new temperature data is 0.14 K (34%) and combined effects lead to a change of 0.04 K (10%). Combined effects refer to a change in committed warming that only occurs when both current datasets are used simultaneously. These combined effects arise from the definition of the TCR in equation (2.6), as it is mainly given by the ratio $\frac{\Delta T}{\Delta F}$. As both ΔF and ΔT change, the calculated TCR is increased or decreased and this will either intensify or lessen the warming within the scenarios. ΔQ is not relevant here, as it does not appear in equation (2.12) of scenario (e).

One might now think that with the new estimate of committed warming for the period 2005 - 2015, the additional emissions since 2016 have led to an additional warming of only 0.03 K. This refers to the difference between the new estimates of committed warming for this scenario in Figures 4.2 and 4.5. As Figure 4.6 shows, this interpretation leads in the wrong direction. In fact, the main issue is the different estimates of the TCR from the different time periods due to the ratio $\frac{\Delta T}{\Delta F}$. The TCR calculated with the current period (2012 - 2022) is 1.66 K [1.24 - 2.42 K] and thus smaller than the 1.78 K [1.24 - 2.93 K] estimated from an update of the 2005 - 2015 period by Mauritsen and Pincus (2017) with today's data for that period. They again found a significantly lower estimate of 1.32 K [0.88 - 2.36 K] in 2017.

Thus, the similar estimates of committed warming are mainly due to the compensation of the currently lower estimate of the TCR and the increases in temperature and forcing since then. The TCR estimate changes due to the changes in forcing and temperature as mentioned above. Temperature changes could also result from a decadal oscillation of the climate system.

In general, a different estimate of the TCR for a time period can lead to a different estimate of committed warming due to a (non-)compensation of forcing and temperature changes. This could be further explored by using different time periods and examining the changes in TCR estimates due to changes in forcing and temperature. Looking only at the changes in mean forcing and mean temperature due to fossil fuel emissions from 2016 to the present, would result in more committed warming than the 0.03 K difference between the new estimates.

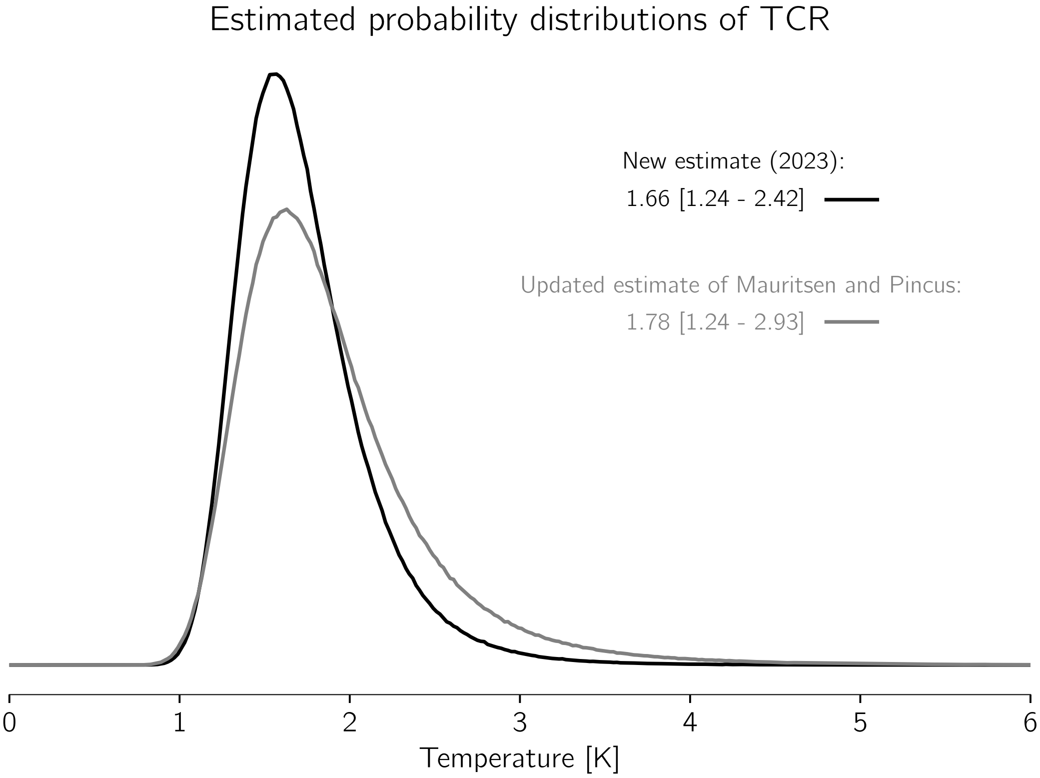

Figure 4.6: Estimated probability distributions of transient climate response (TCR). The probability of TCR using the present-day period is shown in black, the probability using the 2005 - 2015 period and new data is shown in grey. The ranges consist of the estimated medians together with the 5th to 95th percentiles of each distribution.

4.4. Results from FaIR model

Conducting an emission-based FaIR model run with a cessation of anthropogenic emissions after 2023 leads to a result with an overshoot, as shown in Fig. 4.7. This is due to further changes in forcing after emissions stop. I find the highest committed warming for the year 2027 with 1.48 K [1.16 - 1.84 K]. The risk of exceeding the 1.5 degree target is then 48.1%. The reason why the uncertainty of the committed warming is quite low is that 2027 is not far away and also only one single year. If one were to choose a year further in the future, up to 2100, the uncertainty would be higher. This is indicated by the 5th to 95th percentile range shown in Figure 4.7.
Dvorak et al. (2022) also used the FaIR model to estimate the committed warming after a complete cessation of anthropogenic emissions in 2021 and every year thereafter until 2080. For this purpose, they assumed that the emissions follow different SSP

scenarios. By using the medium SSP2-4.5 scenario, they found out that we are already committed to a peak warming of more than 1.5 K with a likelihood of 42%, assuming that emissions cease in 2021. The likelihood increased to 66%, if emission were to cease in 2029. Overall, this is in line with my findings. Smith et al. (2019) also used the FaIR model to estimate committed warming. Back in 2018, they found a 64% chance that the peak global mean temperature increase would remain below 1.5 K. Uncertainties from the energy balance framework are substantially higher because it considers long time scales rather than specific years. As there is a carbon cycle implemented in FaIR, the model output is mainly comparable with scenario (e) mentioned above in order to consider similar assumptions. The results of scenario (e) and the FaIR model output show good agreement. Based on this, the assumption from

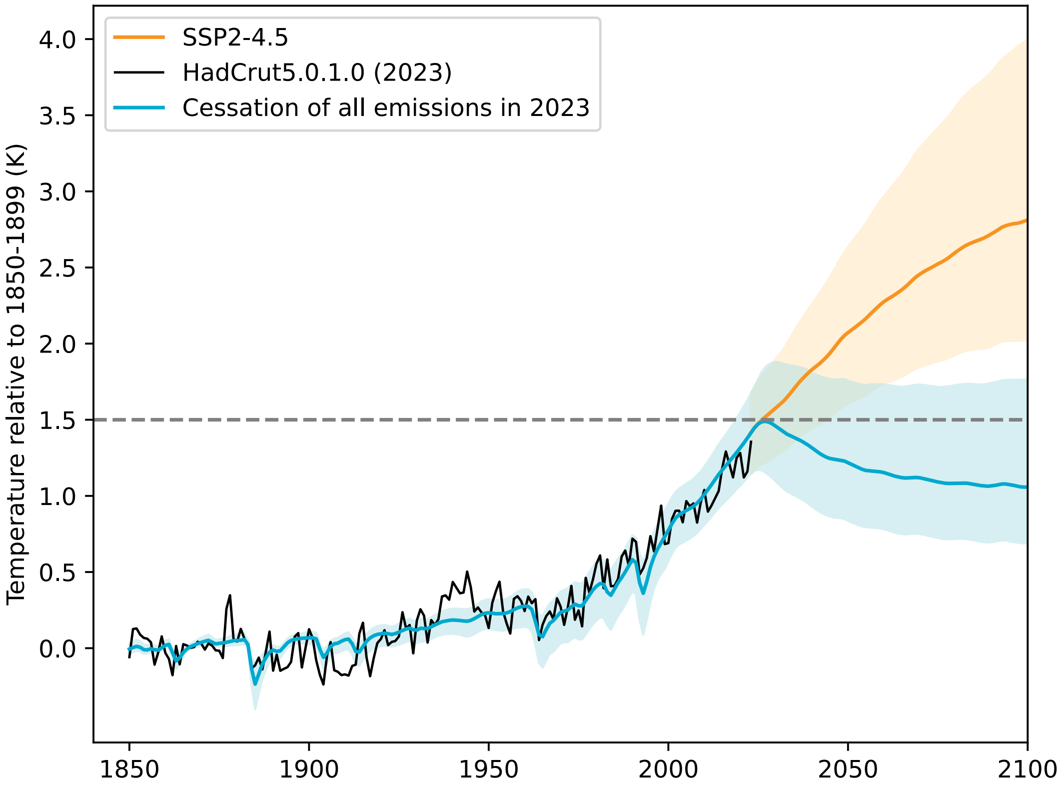

Figure 4.7: Results of committed warming from the 5000 ensemble member FaIR model run. The blue curve shows the global mean temperature anomaly relative to the pre-industrial period 1850 - 1899 in the case of complete cessation of all emissions in 2023. Lighter blue indicates uncertainty (5th - 95th percentile). The risk of exceeding the 1.5 degree target is 48.1% (2027). The black curve in relation shows the recent global mean temperature anomaly from HadCrut compared to 1850 - 1899. The orange curve shows a very likely scenario based on current efforts (SSP2-4.5).

the energy balance framework that carbon uptake can be considered by excluding future warming from EEI therefore also appears to be valid for today. The reason why scenarios (a) - (d) show such high committed warming for scenarios (a) - (d) and no overshoot as seen in the FaIR model is the inaccurate assumption of keeping the forcing constant.

5

Conclusion

This thesis provides new insights into global warming to which we are committed as a result of past emissions. By using an updated form of the energy balance framework, introduced by Mauritsen and Pincus (2017), I provide new estimates of the committed warming until the end of the century (centennial scale) and at equilibrium (multi-millennial scale). This is done by defining two reference periods to account for changes in temperature, forcing and the Earth's energy imbalance (EEI): The years 2012 - 2022 are used as the present-day period and the years 1859 - 1882 define the pre-industrial period. These two periods were not characterized by unusually high volcanic activity. This is important to not include major natural variability. The period 1850 - 1899 serves as the baseline period for determining the total committed warming. Future forcing is assumed to be constant. However, this does not pertain to the forcing of aerosols and SLCFs, as these undergo significant changes after emissions cease.

Committed warming is calculated by taking into account the temperature anomaly relative to pre-industrial values and linearly adding an increment which is scaled by the appropriate climate sensitivity. The increment contains a forcing correction, and depending on the scenario, also the forcing from aerosols and short-lived climate forcers as well as the energy imbalance. The committed warming for the equilibrium scenarios is generally higher than for the centennial scenarios, as thermal sinks such as the deep ocean reach a new equilibrium. This is associated with heat release and hence additional global warming.

According to my calculations, there is a committed warming of 2.54 K relative to pre-industrial values at equilibrium when the forcing from aerosols and short-lived climate forcers is removed. By calculating scenarios (a) - (c), I find that the effect of vanishing aerosols is the dominant driver of further global warming after emissions cease. The disappearance of SLCFs within a few years can offset less than half of the additional warming from the loss of aerosol cooling. For all equilibrium scenarios, the likelihoods that the committed warming will already exceed 1.5° and 2° global warming are mostly above 90%. According to the IPCC uncertainty language, an exceedance is very likely.

Calculating the committed warming on centennial scales including carbon uptake by terrestrial biosphere and ocean, results in a warming of 1.5 K. Therefore, the likelihood that committed warming will exceed 1.5 degrees in this respect amounts to 50.3%, for 2 degrees it is 9.2%. Applying the IPCC's uncertainty language, it is *more likely than not that committed warming will exceed 1.5 K*. This means that the 1.5 degree target from Paris Agreement cannot be achieved with a likelihood of at least 50%. As recently as 2018, the IPCC Special Report on Global Warming of 1.5°C (Allen et al., 2018) concluded that it is unlikely (less than 33% probability) that past emissions alone will increase global temperatures by more than 1.5 degrees compared to 1850 - 1900.

In Mauritsen and Pincus (2017), the estimates of the committed warming and hence the exceedance likelihoods were much lower. For the centennial committed warming including carbon uptake they found 1.06 K. The likelihoods that committed warming will already exceed 1.5° and 2° were back then 13% and 3.4% respectively. This discrepancy is mainly caused by changes in forcing, temperature and EEI data since 2017. These changes are mainly due to anthropogenic emissions since then, but there are also changes in these quantities because of a different data evaluation in the new datasets. Temperature data is estimated to be higher in HadCrut5 than in HadCrut4 as a result of a different integration of temperature in regions with a lack of data. Changes in the total forcing between AR5 and AR6 arise from an upward revision of the greenhouse gas forcing and a more negative aerosol forcing. Thus F_{aerosol} is more negative and F_{slcf} is slightly increased for the present-day period.

This also changes the estimates of TCR and ECS, resulting in a shift towards higher values. While the uncertainty of the TCR is reduced, the uncertainty of the ECS is largely increased due to a higher EEI value. Thus, the estimated ECS is much closer to the general AR6 estimate than found in previous studies based on observational data.

I also show that the change in centennial committed warming for a given period (2005 - 2015) is mainly due to changes in temperature and forcing data. As both quantities change, this induces non-linearities arising from the definition of the TCR. Using the new data for this period, the compensation of the currently lower estimate of the TCR and increases in forcing and temperature result in similar values of committed warming for the two periods.

Performing a FaIR model run with emissions stopped at the end of 2023 gives a committed warming of 1.48 K in 2027. This result is similar to the committed warming in the centennial scenario with carbon uptake from the energy balance framework. This proves the sufficiency of the assumption that carbon uptake can be considered by not accounting for further warming from the EEI. This was previously observed by the behaviour of ESMs to ceased emissions.

This makes the results more reliable overall, although it should be stressed that the FaIR model is also run with observational data.

In summary, we are not on track to stay below 1.5 degrees of global warming relative to pre-industrial levels. This is due to our inability to stop emitting fossil fuels. To limit global warming to below 2 degrees, we must significantly intensify our efforts on reaching net-zero emissions.

6

Outlook

This thesis clearly shows that we are not on track to reach the 1.5 degree target. However, there is some positive news: Looking only at the warming to which we are inevitably committed to due to past emissions and the inertia of the climate system, achieving the 1.5 degree target (which is almost 50% likely to be reached) is not as unattainable as is commonly believed in society.

The reason why humanity is currently far from reaching the 1.5 degree target is that we are unable to stop emissions from fossil fuel combustion, which is due to the inertia of socio-economic system drivers. This leads to slow progress in the change processes. This was the main finding of the last Hamburg Climate Future Outlook (Engels et al., 2023).

A next step could be to calculate remaining carbon budgets with both methods including the committed warming, as Dvorak et al. (2022) have done with the FaIR model. This would help to ensure that global warming targets are met in the future. If negative emission technologies are to contribute to remaining carbon budgets, as is often considered, significant technical progress will be needed in this area.

Nevertheless, there are processes that are not included in the calculations with the energy balance framework and the FaIR model that could lead to different estimates of committed warming. One such process is the pattern effect which refers to the fact that the Earth's energy balance is sensitive to spatial changes in land and sea surface temperatures. Zhou et al. (2021) suggest that, including the pattern effect, committed warming rises above 2 K at constant present-day forcing and is still above 1.5 K for the year 2100. However, the strength of the pattern effect and therefore its impact on committed warming remains uncertain. Neither model framework takes into account potential future destabilising climate feedbacks, such as reduced ice sheet cover, thawing permafrost or drying out of the Amazon rainforest. As a result, the calculated committed warming could be reached earlier or exceeded. One could also ask for a multi-millennial scenario within the energy balance framework that considers carbon uptake. This is not done because it is difficult to make simplistic assumptions within this model framework regarding biogeochemical feedbacks and other future destabilising climate feedbacks that would need to be taken into account. Including these processes in the future could reduce uncertainty. Furthermore, calculations of climate sensitivities and committed warming for different time periods could improve our understanding of the impacts and could help to constrain the estimates of the climate sensitivities. Additionally, updating committed warming with future data will provide new insights.

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