How have issues in cloud and aerosol simulation affected predictions of climate sensitivity ranges in CMIP6.

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1 abstract

This report serves as an examination of the increased climate sensitivity from CMIP5-6. I discuss how global climate models are built and why uncertainties in cloud and aerosol forcing are the key cause of the uncertainty in CMIP6. I examine how the IPCC interpreted these models and arrived at their current estimate of climate sensitivity and the critiques that have been levelled.

2 Introduction

Climate sensitivity, as defined by the Intergovernmental Panel on Climate Change (IPCC), is a measure of how much Earth's average temperature would change in response to a doubling of atmospheric carbon dioxide (CO2) concentrations once the planet has reached a new equilibrium. It represents the eventual global temperature response to sustained radiative forcing. Radiative forcing is when the planets intake of solar energy is greater than the infrared radiation given off, which causes a warming effect.

The IPCC defines ECS to have a best estimate of 3°C and a likely range of 2.5°C to 4°C, with a very likely range to be 2°C to 5°C[**Forster2021**]. This range is calculated by using Paleo-climate and historical climate records as well as future climate models. The Coupled Model Inter-comparison Project (CMIP)[4] is formed of an ensemble of cutting-edge global climate models, which pools the results to inform future decisions. The calculated ECS values hold significant weight, shaping our understanding of the potential magnitude and pace of future climate change. ECS estimations from CMIP have historically been consistent. However, CMIP6, the most recent project found an alarming 16 out of 52 models1 had ECS values greater than 4.5. For context CMIP5 had 2 of its 29 models above this value. CMIP6 does not align with the IPCC's prediction of Earth warming, whereas its predecessors do.

Uncertainty is inherent in future climate predictions, as warming hinges on a wide variety of feedback loops. To fully prepare for future changes, the magnitude and speed of these changes needs to be accurately accessed. Reducing uncertainties is an import part of ensuring this accuracy.

These uncertainties primarily stem from the influence of forcing features. Forcing features are external factors that influence the energy balance of Earth due to radiative forcing. The 2 largest drivers of uncertainty in CMIP6 is forcing due to changing cloud cover and aerosol interactions[1]. I will explore how these forcing features have changed intergenerationally from CMIP5-6. The IPCC has not reflected this uncertainty in the AR6 report. I will discuss and address why this sudden divergence in uncertainty between the IPCC and the CMIP6 has occurred, specifically looking at how the IPCC arrived at their current uncertainty range and the critiques that have been levelled against their treatment/dismissal of higher ECS simulations. Owing to the emerging and highly technical nature of the problem I will not be able to come to a concrete conclusion on whether the ECS range is overly constrained on the upper end. The aim of this essay is instead an attempt to highlight why this uncertainty has emerged in CMIP6 and why the IPCC has not adjusted their aim.

CMIP	Mean ECS	STD	Number of Models
5	3.304	0.728	29
6	3.777	1.061	53

Table 1: Table showing mean and standard deviation of ECS for CMIP5&6 as well as number of models, made from data[22]

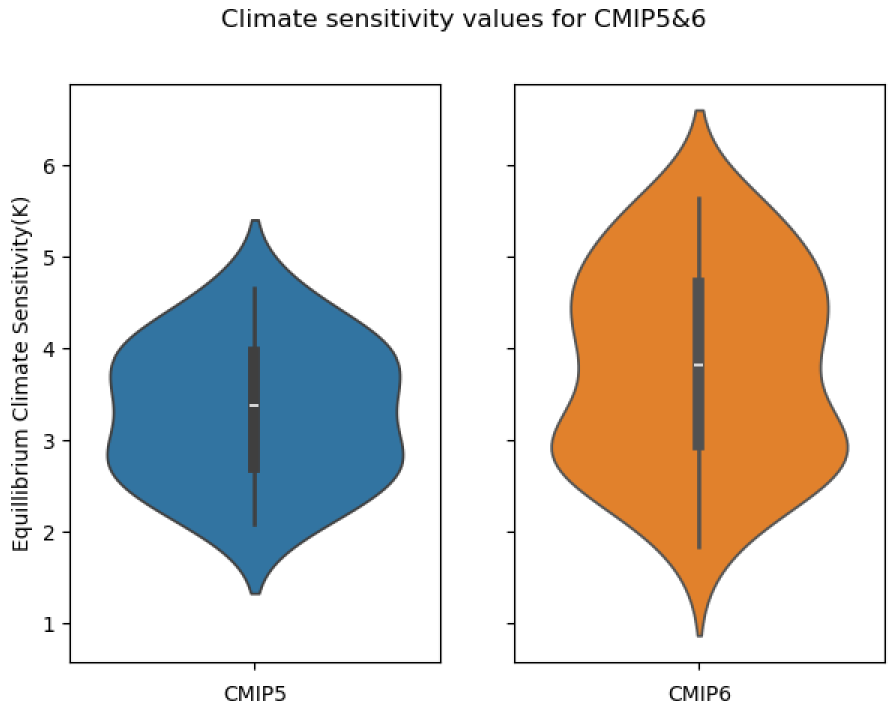

Figure 1: Violin plot for ECS values in CMIP5 & CMIP6, CMIP6 shows a greater range and mean value

3 Preliminary CMIP6 data analysis

CMIP6 has been a huge undertaking for the climate modelling community, with the operation falling significantly behind schedule in comparison to previous iterations. CMIP allows models to be compared directly by running a standard set of future scenarios or experiments. These are known as Shared Socioeconomic pathways(SSP), and vary in trajectory based on predictions of future greenhouse gas emissions. SSP1 represents immediate deescalation and moderate damage to the planet, and higher values depicting business as usual situations and far higher temperatures.

There are millions of climate models run around the world, all of which are assessed and then collected into many different 'MIPS' all looking at different features of Earth climate or specific locations. CMIP is the key global comparison project and is used to calculate future warming.

CMIP ECS predictions have been historically stable returning ECS values within the IPCC high confidence range. But the CMIP6 mean fell far outside this range- exhibiting both a higher mean and range of results. This is shown in table1 and Fig 1.

It is unusual that these models should be returning a broader range of results than previous collections. To understand the size and sudden increase of higher uncertainty present in CMIP6 it is essential to understand how climate models work. I will first explain the methodologies behind global climate models and how they simulate and simplify natural processes, resulting in uncertainty.

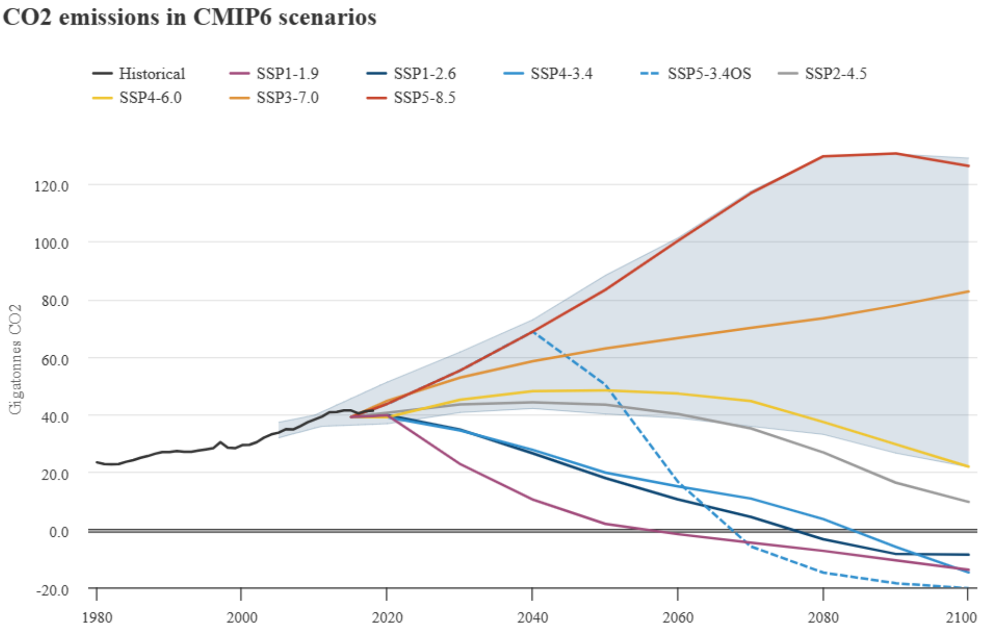

Figure 2: The collection of SSP's that were run for CMIP6, Imediate deescelatiion (SSP1), eventual Co2 reductions (SSP2-4), business as usual (SSP5). The grey area shows no-policy scenarios.[8]

4 Creating Climate Models

A climate model is an immensely intricate computer program designed to replicate Earth's complex systems. It enables scientists to simulate the dynamics of our planet's climate system, facilitating predictions about future changes in our planet's climate. Unlike weather models, which focus on short-term atmospheric conditions over a relatively limited time span, climate models provide a broader perspective by encompassing the long-term average of weather patterns which span for decades, centuries, or even millennia.

Models are created by constructing an analogue to Earth which is then dissected into a 3D grid structure, that spans from the atmosphere to the depths of the ocean. Within this grid, micro-climates are represented, each containing approximations of Earth's biosphere, atmosphere, hydrosphere, and troposphere specific to their location. Key atmospheric parameters like pressure, precipitation, humidity, and temperature are calculated individually for each grid cell.

Global models are then run on a number of SSP's for the near and far future. A representation of these different pathways can be seen in 2. Averages temperature rises are calculated for these models which are then used to inform policy decisions. CMIP is used to calculate the projected future temperature increases for each experiment.

The accuracy and biases of a climate model are determined by the interplay of forcing features and the resolution of the grid. Higher resolution allows for finer detail but also increases computational demands. Consequently, there's a limit to the resolution attainable due to computational constraints. Climate grid cells typically span tens to hundreds of kilometres, however, many meteorological processes, notably processes in clouds occur at fractions of this scale. To address this challenge, these processes are parameterized. Instead of explicitly modelling each individual sub-grid process, parameterization schemes represent the approximate effects of environmental process within the model[13].

Whilst parameterization drastically increases the scalability and efficiency of climate models, it also introduces uncertainties: these manifest both within the gap between real-world observations[19] and model results; and within various alternative future projections[15]. Currently, global climate models rely on parameterization, as neglecting these processes would provide an incomplete picture of the world.

4.1 Introducing Forcing Features

Clouds are particularly difficult to model owing to their myriad of processes at the sub-grid scale (condensation, evaporation, coalescence, etc). As well as changes of formation, dissipation, and vertical motion, that occur over thousands of Kilometres. These intricate dynamics make parameterization essential. However, inaccuracies are introduced as the model is unable to represent the processes entirely accurately[5].

Clouds form when water vapor rises from the Earth's surface in convection currents, cooling adiabatically as it ascends due to decreasing atmospheric pressure. When the vapor reaches its saturation point, condensation occurs, forming cloud droplets or ice crystals. Tiny particulates(2 nm to 10 μm) called aerosols, act as cloud condensation nuclei (CCD)[10], facilitating droplet formation. Without CCDs, water vapor can remain supersaturated, hindering droplet formation. These particulates also increase the planet's albedo, reflecting more incident radiation into space[9].

Many of these aerosols are naturally present in the atmosphere but there are many anthropogenic sources from fossil fuel activities, such as soot. These man-made aerosols serve the opposite purpose, being dark in colour they absorb solar radiation warming the atmosphere [20]

Different types of clouds have varying effects on Earth's energy budget, primarily through their interactions with visible and infrared (IR) light. When sunlight reaches a cloud, it can either be absorbed or scattered. Absorption of sunlight by the cloud leads to the emission of IR radiation, contributing to warming. Alternatively, sunlight can induce an electrical dipole on water droplets within the cloud, causing visible light to scatter. This scattering occurs when the radius of the droplet is comparable to the wavelength of the light, with larger droplets resulting in greater scattering. Dark clouds, which absorb more light, typically have larger droplets, while brighter clouds have smaller droplets.

Whether clouds cool or warm the Earth depends on their altitude and optical thickness. High-altitude(10Km) cirrus clouds are optically thin and are formed in air of a colder temperature than the ground. This causes the droplets to be larger and exhibit a strong IR effect, which leads to warming. They exhibit low scattering due to their low optical thickness, resulting in a minimal increase in albedo. By contrast, mid altitude cumulus(5km) and stratus(2Km) clouds display greater optical thickness, playing a crucial role in cooling the Earth's surface. These low clouds scatter incoming solar radiation more effectively due to their denser structure and higher water content. Additionally, their bright tops reflect sunlight back into space, contributing to a cooling effect on the Earth's surface.

5 Uncertainties in Models

The extent to which these forcing features warm or cool the climate is still a point of great uncertainty[14]. As the physical processes are uncertain this means that they cannot correctly be parameterized or coded into climate models, this results in large variance between models.

5.1 Cloud cover

As previously mentioned, many clouds have an impact on the Earth's energy balance but Stratocumulus clouds, particularly over the oceans, pose a considerable challenge in modelling. This is due to their very thin structures, posing challenges in accurately capturing their spatial distribution and micro physical properties within grid-based modelling systems. They also have very widespread coverage, accounting for approximately a fifth of the Earth's surface[16]. Meaning they present huge uncertainty in models.

Compared to the findings of AR5, significant progress in understanding cloud processes has led to a reduction in the uncertainty range of cloud feedback by approximately 50%[**Forster2021**]. Particularly the work done on marine stratocumulus cloud feedback, achieved using satellite data and cloud-specific

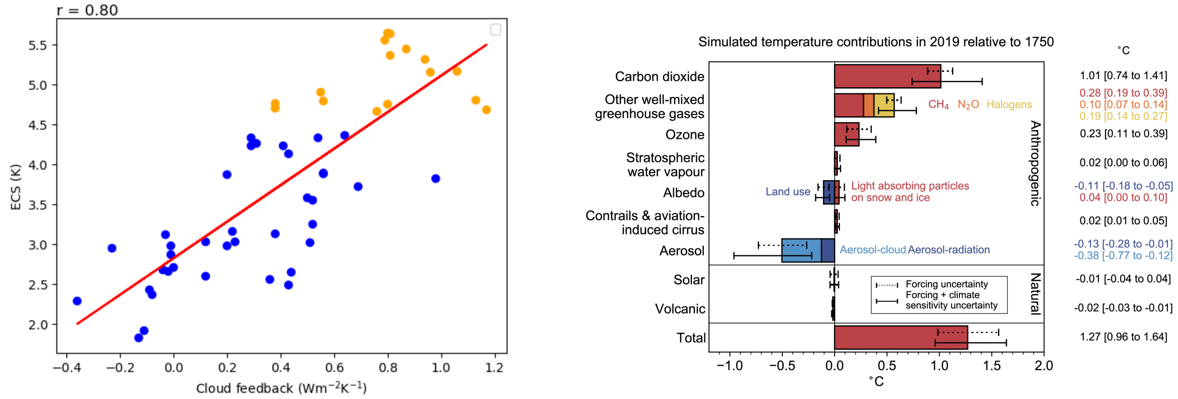

Figure 3: a) Shows the cloud feedback from models in $Wm^{-2}K^{-1}$ and how this correlates with climate sensitivity of these models. Models with ECS less than 4.5 are shown in orange. b) shows changes in effective radiative forcing from 1750 to 2019 by forcing agents [**Forster2021**].

simulations into global models. It was found that these clouds, though low and typically reflecting and scattering of incoming radiation, break up in the presence of high CO2 concentrations[17] allowing for sunlight to penetrate them. This results in positive feedback for the planet's climate.

This finding is corroborated by CMIP6, as strongly supported in Fig:3, where models with higher ECS also exhibit the most significant cloud feedback.

It is estimated that these changes in extra-tropical cloud feedback are set to become more greatly amplifying[3] as more CO2 enters the atmosphere, further damaging these clouds. It is clear that ECS in CMIP6 models has increased primarily due to strengthened cloud feedbacks[12].

5.2 Aerosols

Aerosols introduce significant uncertainty into climate forcing models, primarily stemming from their distribution across the atmosphere, composition, and interactions with clouds. These uncertainties greatly influence our understanding of how aerosols absorb and scatter sunlight, ultimately impacting Earth's energy balance and climate dynamics.

In Fig 3, the varying forcing effects of different agents on Earth are depicted. Notably, aerosols exert a negative forcing effect that has intensified over the industrial period, with considerable uncertainty surrounding these effects.

While aerosols contribute to cooling, counteracting some of the warming effects of greenhouse gases like carbon dioxide (CO2), their short atmospheric lifespan contrasts with the long-term persistence of greenhouse gases. This transient nature implies that reducing aerosol emissions could rapidly increase global temperatures. Speculations suggest that such a trend has been observed since the implementation of clean air laws in 2020, aimed at curbing pollution from shipping, with projections indicating a potential 0.5°C increase in global temperatures by 2050[6].

The uncertainty surrounding aerosols encompasses a 30% range in direct forcing (scattering and absorption) and a huge 100% uncertainty in indirect forcing related to Cloud-Climate Feedback interactions[11]. This uncertainty largely stems from challenges in accurately measuring anthropogenic and natural aerosol absorption, as well as understanding the intricacies of CCD operations[11].

5.3 Causes for increased uncertainty in CMIP6

The uncertainty in these new models is coming primarily from the insufficient resolution of cloud micro physics. This leads to greatly increased cloud feedback and aerosol cloud interactions.

To overcome these uncertainties more progress needs to be made in parameterization schemes and marrying them to the real world processes.

6 IPCC Evaluation

Since Jule Churney's establishment of ECS in 1979, the consensus regarding its 'likely' range, typically falling between 1.5°C to 4.5°C, has remained steadfast[2]. Initially derived from Paleoclimate data, this estimate gained validation through subsequent years via global climate models, notably including CMIP5. However, the emergence of CMIP6 introduced a significant departure from this established average, with the introduction of numerous 'hot models'[7] exhibiting considerably higher ECS values. This divergence posed a challenge for the IPCC in integrating these models into their new SSP predictions. The IPCC chose to weight models, favouring those that aligned more closely with historical data[21], thereby reducing the influence of models with high ECS values.

Awareness of this issue has prompted alternative methodologies of ECS estimation. Rather than dismissal of hot models, statistical methods such as Bayesian statistics can be used to weigh the models more accurately. These methods project temperature increases ranging from 2°C to 5°C for low and high emissions scenarios, respectively (SSP1-2.6 and SSP5-8.5).

Another key method of model evaluation is hindcasting and forecasting. Hindcasting is a technique used in model development that allows model makers to see how well their model predicts past weather, whereas forecasting involves using a climate model to create future predictions of climate and comparing the results to observations. This cannot be done for most climate models as they predict over long time periods. However, the MET office unified model HadGEM3, can be easily changed into a weather model, which happens to be one of the dubbed 'hot models'. This model was compared to its previous iteration which had a far lower ECS. The more recent hotter model produced the more accurate forecast[18]. The key difference between these two models was an increased resolution of cloud dynamics.

While the higher accuracy in forecasting achieved by the hotter model is notable, it's essential to consider the broader context. The focus on improved resolution of cloud dynamics in the hotter model highlights a specific aspect of climate modelling, which may lead to better short-term weather forecasts. However, the effectiveness of a climate model extends beyond short-term predictions to encompass long-term climate projections and capturing complex climate feedback mechanisms accurately. Therefore, while the hotter model may excel in certain aspects, comprehensive evaluation across multiple climate variables and timescales is necessary to determine its overall performance as a climate model. It is noteworthy that many of the models excluded from the 'very likely' range of IPCC's ECS assessment have demonstrated improved short term accuracy and refinement compared to their CMIP5 counterparts.

The issue of excluding models due to discrepancies with Churney's and subsequent studies on Paleoclimate data, particularly those suggesting ECS values below 4.5°C, continues to be a point of contention.

In assessing models, it's essential to consider basic numerical comparisons, revealing distinct differences in climate sensitivities between CMIP5 and CMIP6, emphasising the need for careful interpretation and weighting of model outputs. If other organisations were not to do this in a similar way to the IPCC then misinformation could become rampant.

Recently further evidence for higher ECS was published by James Hansen's paper 'Global warming in the pipeline' which predicted a ECS of 4.8°C $\pm$ 1.2°C, based on temperature analysis over the Cezonoic era and ice sheets. This is nearly 2°C higher than the IPCC best estimate of ECS. This paper gained lots of attention and spurred critiques of the IPCC dismissals of 'hot models'. If this data were to be correct then the 1.5 target is dead.

This work has been highly critiqued for its doom-saying and being a worst case scenario. It was called "quite subjective and not justified by observations, model studies or literature", by Piers Forster, one of the coauthors of AR5.

7 Conclusion

There are still so many uncertainties about the kinds of feedback factors affecting ECS. There is no way to predict with certainty how these will impact global warming and what temperature the planet will reach. Continued refinement of models is essential to reduce uncertainty. However, the presence of the 'hot models' in CMIP should be accounted for, irrespective of the historical estimations of ECS.

The IPCC has a role in advising government, and it may hinder policy decisions, for them to present the 'true' level of uncertainty in possible temperature rises. Instead, they must choose a narrative so that policy makers can see a future scenario with fewer variables. On the other hand, CIMP solely produces a set of models which attempt to be closer to reality, discrepancies between the models are not their direct concern.

It is paramount that climate scientists are not blinded by biases and look at all data, even if it does not agree with previous estimations. If Hansen is correct in his estimation of ECS then many of our best tools for predicting future change are currently being disregarded and downplayed.

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