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Ways to Estimate Climate Sensitivity

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Abstract. This paper mainly explores the specific significance of climate sensitivity and the various methods to assess it. In this paper, three major methods to calculate climate sensitivity are evaluated, including direct observation, climate models, and paleoclimate dataset. Direct observation utilizes instrument records to obtain environment data since the mid-19thcentury. Climate models simulate physical processes in the environment to analyse the increase in temperature resulted from the doubling of atmospheric CO_2 concentration. Paleoclimate dataset reconstructs past climate based on some natural resources, such as ocean sediments. Paleoclimate dataset and climate models often work together to calculate climate sensitivity.

Keywords: Climate Sensitivity, Direct Observation, Paleoclimate Dataset, Climate Model.

1. Introduction

Climate sensitivity is utilized by the Intergovernmental Panel on Climate Change (IPCC) to portray the degree to which rising greenhouse gases influence the Earth's temperature. To be more detailed, it depicts the increase in global temperature when CO_2 concentration in the atmosphere doubles. The term climate sensitivity is very important to the measurement of our climate condition. For the long-term improvement of human-being and the sustainability of Earth, the scientists have to evaluate the ultimate result of anthropogenic global warming. Nowadays, the contemporary climate change considers that the global warming and its impact on Earth's weather patterns. Until now, scientists observed that the human activities like the burning fossil fuels produced the greenhouse gases. There are some dominant factors, the production of carbon dioxide and methane. We wanted to protect the health of planet, and this article is going to help us to comprehend climate sensitivity, in order to correct the problems on Earth in climate way.

There are three types of climate sensitivity. Firstly, the transient climate response (TCR) refers to the change in temperature at the time of CO_2 doubling. Secondly, the equilibrium climate sensitivity (ECS) alludes to the change in temperature when a new equilibrium has been established in the system after CO_2 doubles. Moreover, the Earth system sensitivity (ESS) contains various kinds of long-term Earth framework feedback [1].

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Many factors, such as clouds and sea ice, can vary the speed of the rise in air temperature, so climate sensitivity has a wide range. Tese factors are called "feedback effects," and they can complicate anticipating Earth's future climate. Scientists have reached an agreement that the climate sensitivity would be only 1°C if there is no feedback effect. Much of the controversy in climate science hinges on the quality of different feedback and if researchers explain all of them. For illustration, clouds can warm or cool the planet, relying on the stature of the cloud and the measure of the water beads. In general, most scientists anticipate cloud changes to fundamentally warm the planet, but a few of them say it's difficult to know.

Even though the climate sensitivity is useful to comprehend climate risks people face nowadays, there is no need to stick to the precise number. The definition of climate sensitivity centers on the multiplying of carbon dioxide within the climate. In the event that greenhouse gases increase more than twofold over the long term, the feedback effects could alter and the sensitivity of Earth's temperature to the additional carbon emissions will change, leading to different speed of global warming. It is widely believed that some time is essential for the worldwide climate to stabilize after carbon emanations reach a certain level. So within the brief term, even though people no longer release any greenhouse gases now, several years are required for global warming to catch up with our sensitivity to climate.

2. Methods

2.1. Direct observation

From the definition of Met Office, direct observation refers to the instrumental records of warming since the mid-19thcentury, combined with gauges of nursery gas and vaporized emanations can be utilized to survey the worldwide temperature reaction to emanation of CO_2 by human activities to date [2].

Using direct observations of temperatures and greenhouse gas levels during the industrial era, climate sensitivity can be evaluated from observed temperature increments, observed ocean warm take-up.

The average temperature of a section of the ocean is usually measured because the rise in sea surface temperature does not represent the total amount of heat absorbed, and the temperature varies with depth. There's a kind of robotic floater (Figure 1), and they spend most of their time below the surface. They measure temperature and salinity, and when they surface, they transmit the data they collect to a satellite. After that, they sink again and drift for another 10 days. The profiles collected by these buoys provide better data for understanding and quantifying climate change than satellite observations of surface temperatures [3]. In this way, people can measure the average temperature change by the ocean heat uptake.

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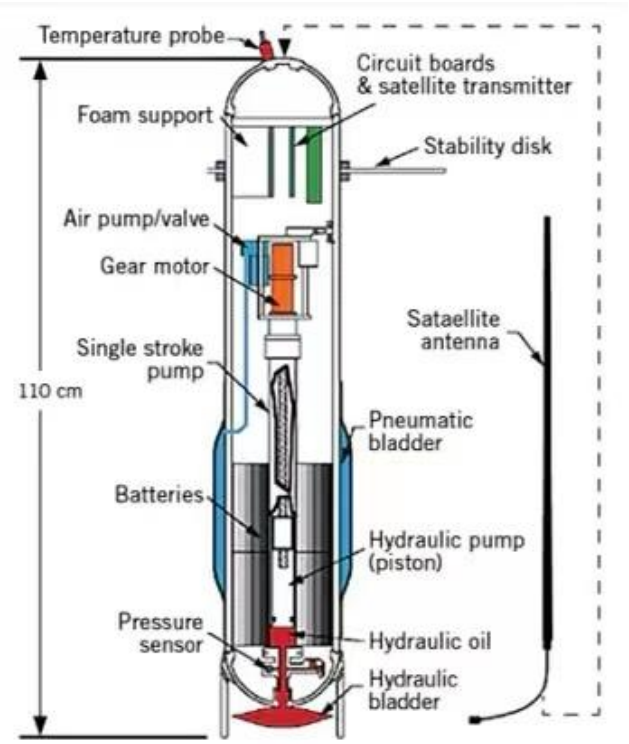

Figure 1. A hydraulic bladder at the tip of the float and a pneumatic bladder on the side can change the density of the float. The float will sink as the density increases and rise when the density decreases.

The direct observation method is to compare data from the industrial era with data from today. So, predicting equilibrium climate sensitivity is better than predicting other sensitivities.

However, there are some drawbacks of direct observation. First, the time period that the climate record covers is too short to take some very slow processes into consideration. In addition, the observations cannot cover the entire planet, so scientists cannot obtain the warming trend from them [3]. Climate sensitivity is also measured with uncertainty. As the planet warms, changes in water vapor, clouds, surface reflectance and other factors can lead to inaccuracies [1].

2.2. Climate models

According to National Oceanic and Atmospheric Administration (NOAA), climate models are controlled by computer programs that turn physical processes into codes [4]. In this way, the flow of energy and materials through the climate system can be simulated. The actual quantity of energy and materials engaging in activities in the environment can be calculated by mathematical equations.

Due to the tremendous number of interactions in weather modelling, computers are not capable of modelling the complication of the Earth. Therefore, scientists use simplifications to make the whole process manageable. Typically, there are seven physical principles that regulate the dynamics of the climate system: conservation of air mass, conservation of water mass, conservation of energy, conservation of momentum of air in three directions, the ideal gas law applied to air [5].

Climate models divide the whole planet into three-dimensional cells and calculate multiple variables in each cell based on codes (figure 2). To represent the transfer of matter and energy, the calculations are exchanged among nearby cells.

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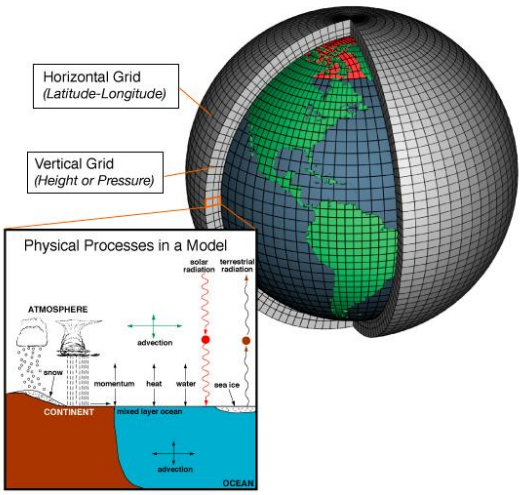

Figure 2. Basic principles of climate models. In climate models, each cell is a set of mathematical equations calculating materials in it [4].

The accuracy of a climate model is the major consideration of people. As NOAA states, "hind-casting" is a popular process to test climate models. It starts from the current conditions and runs backwards to obtain the modelling results of the past [4]. Then scientists will compare the outcome to the observed data to evaluate the accuracy of the models.

Climate models can be global or regional. Global models have resolutions of hundreds of kilometers to cover the entire planet. In contrast, regional climate models have much finer resolutions, usually a few tens of kilometres [5]. Since climate is a complex system related to the conditions of every place, global climate models are chosen to estimate climate sensitivity.

Scientists run climate models to simulate the climate processes to estimate climate sensitivity.

Early in the 1960s, scientists used general circulation models (GCMs) to quantify some important parameters, such as sea surface temperature, forcings and feedbacks [6]. Then the climate sensitivity can be calculated based on these values. Most of the results fell in the range of 1.5–4.5 °C. In the 2000s, IPCC's Fourth Assessment Report (AR4) showed that climate models at that time gave the range of 2–4.5 °C with the best estimate of 3 °C [7]. However, some experiments with GCMs argued that the value might be higher [8]. When the Coupled Model Intercomparison Project (CMIP) evolved over five phases into a major international multi-model research activity, it became the major model being used to estimate climate sensitivity. Recently, IPCC's Sixth Assessment Report demonstrated that the very likely range of equilibrium climate sensitivity was 2-5 °C based on CMIP6 [9]. Nowadays, scientists are still running models and compare model results to observations (figure 3).

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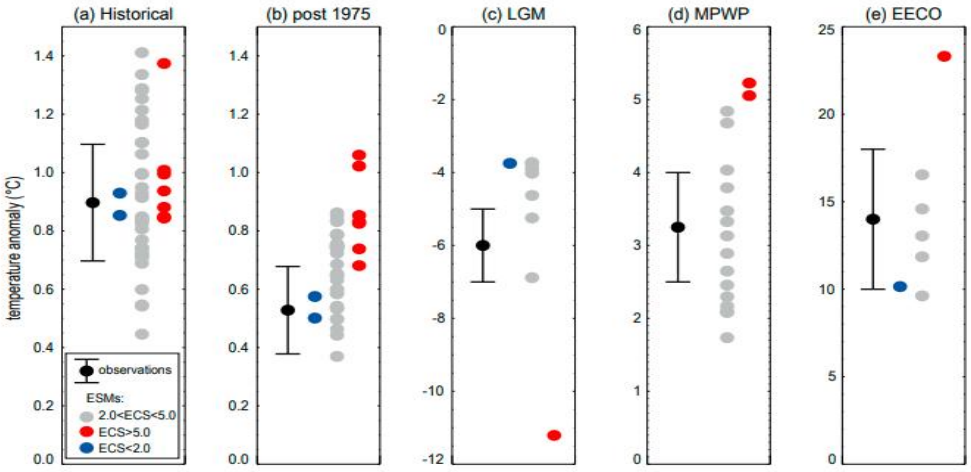

Figure 3. Global mean temperature anomaly obtained from observation and models in (a) history; (b) post-1975; (c) Last Glacial Maximum; (d) mid-Pliocene Warm Period; (e) Early Eocene Climatic Optimum [9].

The biggest problem about climate model is that it has a lot of uncertainty related to cloud processes and some other factors [10]. Clouds, the major cause of uncertainty, affect climate sensitivity estimation in two ways, including cloud optical properties and cloud formation parameterizations [11]. For optical properties, clouds can either absorb or reflect sunlight, leading to warming or cooling of the climate. Therefore, the effect of carbon dioxide on temperature change will be influenced. For cloud formation parameterizations, climate models use Bulk microphysical parameterization schemes to simulate clouds and precipitation. However, the size of hydraulic particles and their number distribution functions are different in distinct schemes. The assumptions about the physical properties of the frozen hydraulic particles vary in different schemes as well. Moreover, the physical process parameterization of hydrometeor production and transformation has also been formulated differently. As the result, climate models produce various outcomes in estimating climate sensitivity [12].

2.3. Palaeoclimate dataset

Some natural resources such as tree rings and ocean sediments can indicate past climate. For example, planktonic foraminifera can be utilized to reconstruct sea-surface temperature. The climate information archive can now cover millions of years based on these proxy climate data. Therefore, scientists can calculate climate sensitivity based on paleoclimate dataset. This method is often combined with climate models to investigate CO_2 concentration and temperature over millions of years through three main approaches.

Approach 1: logarithmic relation simulation

Some important factors, such as solar evolution, paleohydrology, and global degassing, ought to be considered in order to find the connection between the change in temperature and CO_2 level. In this method, the calculation of the CO_2-doubling response ($\Delta T(2\times)$) varies from most existing methods. It does not require free estimations of temperature, incorporated data from warm periods, and reflections of ECS that coordinatees over millions of a long time [13].

The GEOCARBSULF model is adjusted in this research to incorporate a well-defined temperature coefficient for the weathering of calcium and magnesium silicates and make the CO_2-doubling response serve as the only variable. The comparison between model results and proxy data sets for atmospheric CO_2 over the Phanerozoic reveals that the most proper result for $\Delta T(2X)$ is 2.8°C. For $\Delta T(2X) < 1.5$°C, unreasonably high levels of atmospheric CO_2 are required to sustain the essential feedback effect. For $\Delta T(2X) > 6$°C, atmospheric CO_2 levels cannot be as high as past values shown by proxy data because of the silicate weathering feedback.

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The GEOCARBSULF calculations used standard parameters from GEOCARB and GEOCARBSULF without activation energy for Ca and Mg silicate weathering of 42 kJ mol-1 (Figure 4). The dashed white line represents the proxy record gathered from 47 published studies. Five different approached were utilized9. Each curve is shown in a 10-myr time-step. Each time-step's±1 standard deviation is represented by the proxy error envelope (black). The combined sensitivity analysis (10% and 90% percentile levels) of the four components employed in the model formed the basis of the GEOCARBSULF error envelope (yellow).

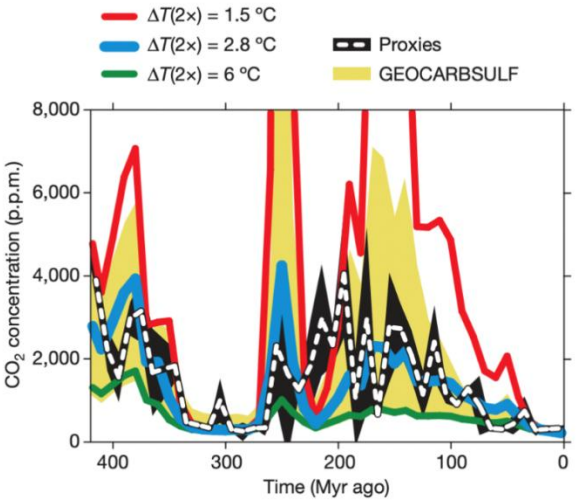

Figure 4. Comparison of a separate CO_2 record derived from proxies with CO_2 estimated using GEOCARBSULF for increasing T(2x).

The periodical rising in CO_2 concentration is obvious from the curve in red line ($\Delta T(2\times)$ = 1.5 ℃). After each time of increase, an approximately same period in length of decrease follows. Such pattern repeats several times. The blue line ($\Delta T(2\times)$ = 2.8 ℃) also shows similar change. The CO_2 concentration remained stable for certain millions of years without much change. The graph also reveals that the current CO_2 concentration has remained at a valley value for more than ten million years. The time scale for data is almost 420 million years, large enough to reach reliable conclusion. According to this model, CO_2 concentration will rise dramatically.

As a result, the paleoclimate dataset shows that the earth's climate has changed continuously and periodically, proving that changes in CO_2 concentration and temperature are sensitive to future climate change.

Approach 2: model integration

In the study, an ensemble of 19 pairs of fully coupled atmosphere-ocean-vegetation climate models are run with varying paleogeography and solar luminosity that are appropriate for each geological stage from the earliest Cretaceous (Berriasian stage, ~143 Ma) to the most recent Eocene (Priabonian stage, ~36 Ma), at ×2 and ×4 preindustrial atmospheric CO_2 concentrations (i.e., 560 and 1,120 ppmv) [5].

In figure 5, several models are combined into one. As seen in graph a, the rise in surface temperature required to double the concentration of CO_2 (from 560ppmv to 1120ppmv) was less than 3℃ (from 19 to 21.5) 34 million years ago. The difference in temperature 65 million years ago was 5.5℃ (from 18.5 to 24). The trend in graph b is formed from the integrated model, showing that current sensitivity is relatively low [14].

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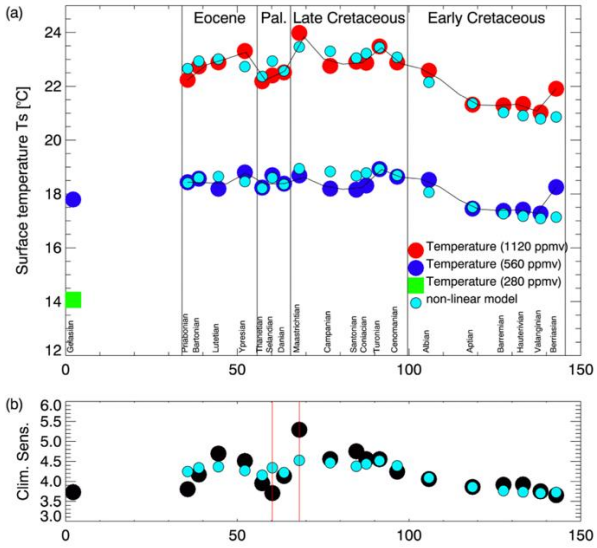

Figure 5. (a) Global annual mean near-surface air temperature in different simulations. (b) Climate sensitivities.

In graph a, global annual mean near-surface air temperature in the ×2, ×4 CO_2 simulations, and the Gelasian ×1 simulation are represented by dark blue circles, red circles, and green squares respectively. The curved black line is a spline fit to the data with a resolution of approximately 5 million years for each set of simulations. With light blue circles, the nonlinear model fitted to the 2, 4 simulations is displayed.

Graph b shows the global mean climate sensitivity over time (black circles), nonlinear model sensitivity (light blue circles), and time periods when the ocean circulation alternates between the ×2 and ×4 simulations (red vertical lines).

Approach 3: Palaeoclimate Modelling Intercomparison Project

This approach systematically applies palaeoevaluation techniques to models that simulate the past climate to predict the future (figure 6).

It is valuable and efficient in shrinking model-related uncertainty and making more reliable estimates of twenty-first century climate [3].

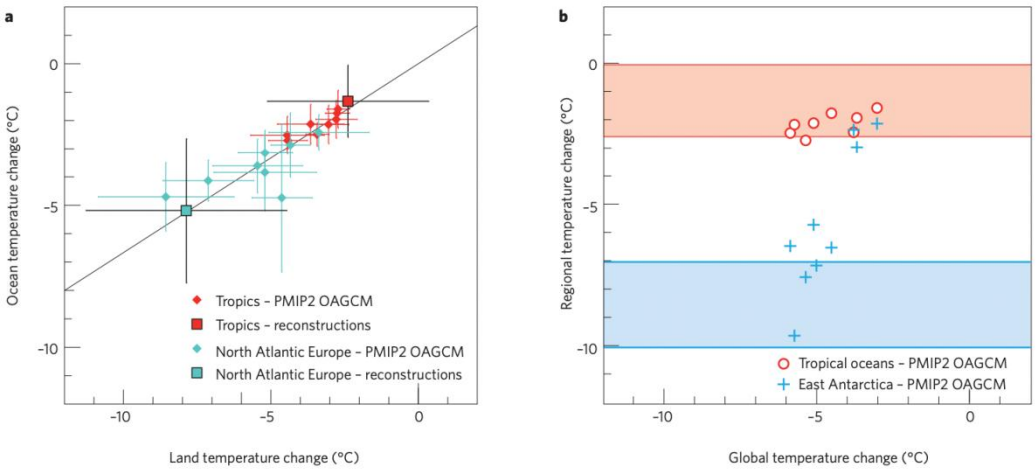

Figure 6. Figure a and b reveal connections between key temperature indices at the Last Glacial Maximum from observations and model simulations [15].

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a. The chart shows the fluctuation in cruel yearly temperature over sea and line of tropics (red curve) as well as over the North Atlantic and Europe (blue curve). The squares speak to the cruel esteem of the reconstructions, and the extend is shown in dark. The diamonds represent the output of individual coupled ocean–atmosphere general circulation models from the second phase of PMIP (PMIP2 OAGCM). The bars represent simulated values' range from PMIP2 OAGCM [15].

b. The red circles appear tropical temperatures as reenacted by individual coupled ocean–atmosphere general circulation models from the second stage of PMIP (PMIP2 OAGCM). The blue crosses appear reenacted temperatures over East Antarctica from the same reenactments. The simulated relationship between global cooling and regional cooling of the tropical oceans and over East Antarctica [15].

3. Conclusion

This paper introduced the concept of climate sensitivity and analyzed three major methods to estimate climate sensitivity, including direct observation, paleoclimate dataset, and climate models. Direct observation utilizes instruments such as satellites to obtain surface air temperature and carbon dioxide concentration. The data collected are accurate but only cover a short period of time. Climate models simulate physical processes through equations represented by computer codes to calculate climate sensitivity. Environmental factors, especially cloud processes, can cause significant uncertainty in models' results. Paleoclimate dataset studies ancient environment to find surface air temperature and carbon dioxide concentration in the past, even millions of years ago. It is often bonded with climate models such as the GEOCARBSULF model to estimate climate sensitivity.

This research provided insights for better estimation methods. With more accurate results, people can design more proper plans to deal with future climate problems.

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