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Uncertainties on Projecting Future Cloud Feedback and Possible Ways to Address Them

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Abstract: The issue of climate change is hotly debated in today's world. More attention is paid to climate-related issues, including global warming. It is accepted that clouds are responsible for the rise of global surface temperature. People have spent decades trying to develop climate models that are capable of more accurate cloud projections without getting the ultimate solution since clouds are complicated compounds. This review article focuses on clouds' role in global warming, the mechanisms of cloud warming the Earth's surface, uncertainties of cloud parameterizations, and some researches aiming at mitigating the uncertainties . This paper concluded that although advancements are made in adding new constraints and taking new observable variables, uncertainty remains. The majority of new methods and constraints reviewed in this paper are still limited to different extents. Therefore, more complete climate models that can be applied to more conditions and regions could be the direction for future studies in the field.

Keywords: Climate change, global warming, mixed-phase clouds, cloud microphysics.

1. Introduction

In 2023, the world has experienced unprecedented extreme weather and a larger amount of broken climate records, with several regions already surpassing the 1.5°C temperature limit. This is a warning to humans that we are getting closer to the red line of controlling global temperature increase within 1.5°C above the pre-industrial level to sustain a livable planet and avoid the worst impacts of climate change [1]. Although there have been advancements in computer power and higher resolution climate models, there are still obstacles in accurate cloud projections due to complicated interplay between various physical processes such as turbulent fluxes. Also, the effects of cloud feedback on atmospheric changes and the time dependence of cloud feedback are currently unclear [2]. Since clouds are crucial in predicting future climate change and also precipitations, which are directly responsible for droughts and floods, there is a need for humans to learn more about clouds' role in climate change to be better prepared and even find ways to reverse future challenges. This article is primarily based on paper reading, in an attempt to explain the mechanisms of how clouds affect the surface temperature, identify the obstacles to getting desirable future cloud projections, and find possible ways that are proven to have the potential to mitigate these errors. This paper is expected to serve as a source of information when making cloud projections in the future.

2. Clouds' role in climate warming

Clouds' warming effects differ from their different particles and densities. Generally, an object can transmit, reflect, and absorb radio waves. Since one of the main components of a cloud--water barely absorbs radio waves, the cloud mostly reflects and transmits radiowaves that come from the sun. On one hand, clouds reflect short waves from outer space, cooling down the surface of the Earth; on the other hand, they radiate some short-wave radiation back to the ground, causing a rise in the surface temperature. The warming effect of clouds is qualified as long-wave cloud radiative effects, which are primarily based on the height of the cloud. Cloud's phase changes according to their different latitudes because the temperature and pressure are different. Low clouds are comparably inefficient in blocking long-wave radiation (LW) that comes from the surface. High clouds, in contrast, are more significant in their greenhouse effects since they primarily consist of ice particles ,which are larger than water particles in low clouds. This means the density of ice particles in high clouds is lower than that of water particles in low clouds, making them ineffective in scattering the sunlight. However, the ice particles have strong LW radiation absorbency, making high clouds one of the most effective greenhouse components [3]. Understanding different phases of clouds would be informative in making future climate projections since it is highly possible that cloud phase could significantly influence the climate [4]. Previous studies have shown that the ice nucleation of clouds is critical in determining the water phases of clouds, which is fundamental to assessing clouds' greenhouse effect since ice particles in the clouds are one of the major sources of the warming effects of clouds. The study conducted by Lohmann replaced all particles in mixed-phase clouds with ice particles and found visible decreases in global annual mean changes of LW radiation and clouds' net radiation at the top of the atmosphere (TOA) [5]. Under warmer conditions, clouds contain more liquid water. Uncertainties in the cloud phase contribute to challenges in predicting future equilibrium climate sensitivity (ECS), which is used to determine the change of global surface temperature when the global CO_2 concentration doubles and reaches a new equilibrium climate state. Therefore, refining models and methods for monitoring clouds-especially mixed-phase clouds could help humans understand and predict future climate change more accurately.

3. Sources of uncertainties

Although numerous climate models have been proposed for representing climatic elements including clouds, the outcomes are still undesirable because there are many uncertainties in the composition of clouds and the interrelationship between air parcels and their surrounding atmosphere, etc. Mathematically, there are multiple variables in the functions of clouds that are non-linearly related. The Theory of Chaos proposed by Launrenz indicates the possibility of getting multiple answers when solving the equations of clouds. Moreover, round-off errors are unavoidable in computer calculations, causing distortions in obtained quantitative information [6]. This section will present two sources of uncertainties related to clouds.

3.1. Complicated microphysics

The cloud condensation nuclei and ice nuclei accelerate the formation of cloud droplets and ice particles, respectively. Once they are formed, these droplets and particles start to aggregate and take different forms depending on different temperatures. It is not hard to find that water could exist in a variety of forms in the cloud. The development of these forms is influenced by 7 basic types of microphysics processes, including nucleation of particles, vapor diffusion, collection, breakup of particles, etc. [7]. The problem arises because this series of processes has to be parameterized in ways that contain insoluble errors. Though people's ability to represent cloud phase has been advancing with more complex cloud microphysics parameterizations aided by stronger computational abilities

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[8], the preferred bin schemes with a higher level of complexion do not necessarily lead to consistency of results from repetitive simulations, as shown in the study by VanZanten et al. [9]. The problem is more severe when there are ice particles forming in clouds, as their formation and growth have more uncertainties than water droplets [8].

The uncertainty further increases because of the radiative effects of aerosols. Aerosols can scatter or absorb sunlight and are also able to alter the level of supersaturation as well as the number and size distributions of formed cloud droplets and ice particles, affecting the the clouds' radiative effects [3]. What is problematic is that people are having a hard time with simplifications of aerosols because almost every particle is disparate in its physical properties, sizes, and chemical characteristics [10].

Besides, as mentioned above, the aerosols could reflect the sunlight. They also radiate LW radiation back to the surface. Therefore, the aerosols have cooling effects and warming effects on surface temperature simultaneously, increasing the difficulty of measuring future climate sensitivity. Anthropogenic aerosols are especially hard to quantify on a global scale because the aerosols are inhomogeneously distributed (e.g. the concentration of Anthropogenic aerosols is higher in industry and city centers than in rural areas)[3].

3.2. Difficulties in identifying and analyzing mixed-phase clouds

Clouds can contain water, ice, or both ice and water. In mixed-phase clouds (MPCs), water and ice coexist and the interactions of liquid water, water vapor, and ice inside them increase the difficulty of accurate parameterizations of their structure and phase. MPCs have been observed in Europe, North America, Asia, Australia, and Antarctica. This means people need to understand the properties and particle distribution of the cloud to get more accurate results on future climate projections. Representing MPCs is a problem studied by many scientists, yet, the results differ greatly according to different methods and models [11]. Some of the uncertainties come from people's insufficient understanding of the clouds' microphysics, as mentioned in the previous part. Korolev, A. et al. studied the cloud phase composition by applying a set of instruments and identified the significance of turbulence in forming clouds with different phases. MPCs are generated when the turbulence of different phases forms a mixture [12]. The problem is, that there is no known function that could accurately represent the turbulence and the actual distribution of the clouds.

More problems were discovered when the study by Zhang, M. et al. [13] revealed the heterogeneity between ice and water particles. In addition, theoretical analysis by Korolev, A. and Mazin suggests that the cloud phase varies from a few seconds to tens of minutes[14], indicating satellites with higher temporal resolution are needed for more accurate monitoring and future prediction. Korolev, A. et al. noted that the heterogeneous distribution of MPCs is not considered even in high-resolution models [12], thus the parameterization of mixed-phase clouds is still undesirable.

4. Possible ways to reduce uncertainties

Microphysical mechanisms of clouds significantly affect clouds' radiative effects, and thus their greenhouse effects. The main goal of this field of study should be, as proposed by Gettelman and Sherwood in their review, to seek a new approach to constrain the process of cloud feedback and validate emergent constraints[15]. Immense studies have been conducted in an attempt to reduce model and computer analysis errors, including applying high-density observations [16], developing better prognosis cloud schemes [17], and using integrated computational software tools to evaluate the various climate models [18] etc.

4.1. Evaluate clouds phase projections using the simulator approach

Previous studies have confirmed the viability of reducing the model error by comparing the simulated data with observations [19]. Recently, a study by Cesana et al. evaluated cloud phase projections by applying a similar approach and found surprising negative feedback between the cloud's liquid phase ratio (LPR) and cloud feedback and further evidence for the facticity of super-cooled cloud feedback. Also, they confirmed that refining constraints on model LPR helps increase the accuracy of climate projections [20].

4.2. Constraining the top phase of clouds

Hofer et al. took the advantage of novel active satellites, Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) satellites, to detect both the interior and the top of the cloud, providing data sources for improving the ability to constrain MPCs (Figure 1). The research team found that the consistency between the results of the climate model (here they used the Norwegian Earth System Model—NorESM2) and the observational data are strongly influenced by the way they constrain the cloud phase (whether constrain only the cloud interior or constrain both the top and the interior of the cloud at the same time). The team also discovered that new constraints on the model lead to a more sensitive climate (i.e. a larger amount of increase in surface temperature after the concentration of anthropogenic greenhouse gases increased) compared to previous models [21].

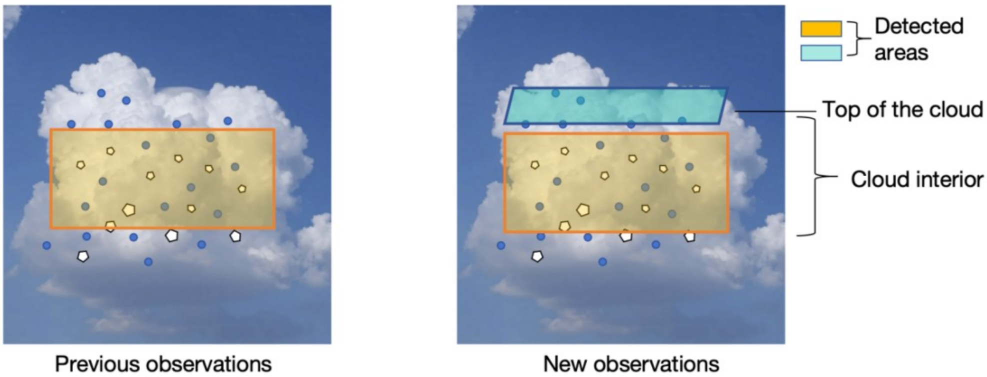

Figure 1: A diagrammatic figure of the comparison between previous satellite observations and new observations made by active satellites.

Areas shaded with orange and cyan stands for areas detected by satellites. Novel observations detect both the top (cyan) and the interior (orange) of the cloud.

4.3. Considering the effect of temperature rise on the Ocean surface

Bjorbal et al. suggest that the correlation between ocean surface warming and the weakening of cloud feedback deserves more attention [22]. The team discovered cloud feedbacks are positively correlated with the optical depth of the cloud. With that conclusion, the 150-year simulator shows a general positive zonal mean optical depth feedback at low latitudes and negative feedback especially visible in the mid-to-high latitudes in the Southern Ocean (Figure 2). However, near the end of the simulation, the negative feedback almost disappeared. The team explains that when the temperature increases, the LPR of the cloud also increases, leading to a thicker cloud. Consequently, the cloud feedback becomes negative and reduces warming. Ultimately, the LPR of clouds in the Southern Ocean region will reach 1 if the temperature continues to rise, resulting in reduced negative cloud feedback in the region and thus an overall increase in global cloud feedback. The role of sea surface warming in

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clouds' warming effects needs more attention because a 40-year observation of Southern Ocean sea ice reveals the temperature rise in the area is accelerating [23].

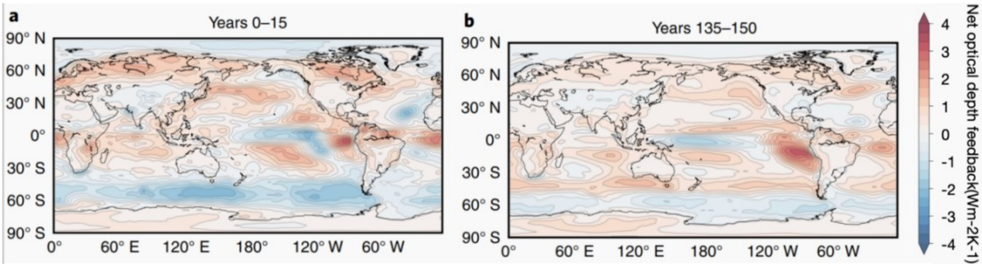

Figure 2: Maps of the net optical depth feedback at the beginning and end of the simulation [22].

Figure 2 (a) and (b) show the net optional cloud feedback distribution for the first and last 15 years of the simulation of 150 years (1870-2020) under quadrupled carbon dioxide concentration using the Community Earth System Model, Version 2 (CESM2).

5. Conclusion

This paper introduces the mechanism of how clouds warm the surface of the Earth and identifies two significant factors of the complexity of cloud monitoring and projection. Clouds' warming effects are innegligible in global warming and various uncertainties in could projection also contribute to challenges in predicting future climate change. Previous studies acknowledged the inconsistency between different climate models and identified the importance of deeper study on MPCs [11]. Since the integration of liquid phase and ice particles is very complicated, MPCs are hard to constrain in climate models. Although multiple studies have been conducted to mitigate the clouds' climate uncertainties by applying new satellite observations, higher observation frequencies, etc. None of the research cited in this paper can present a solution that could be applied to all conditions due to various limitations. (e.g. limitations of the climate model, which would require updates on new observations from satellites [17]). But people are getting closer to more accurate cloud projections. New studies keep correcting previous predictions on global climate sensitivity and noting more detectable variables that could affect the cloud phase. Combining current models with more powerful computer algorithms for more accurate representation of the cloud’s microphysics can be one of the directions for future works. Climate models still need further refinement and higher temporal resolution, as the cloud phase is altering according to the temperature in a relatively small timescale. There are other uncertainties on cloud formation and, the cloud's chemistry components. Due to the word limit, studies focused on stratiform clouds and the influence of cloud microphysical properties on precipitations are not discussed in this paper.

References

[1] United Nation environment programme. Emissions Gap Report 2023 [R/OL]. [2024.5.18]. https://www.un.org/en/climatechange/net-zero-coalition

[2] Ceppi, Paulo, et al. "Cloud feedback mechanisms and their representation in global climate models." Wiley Interdisciplinary Reviews: Climate Change 8.4 (2017): e465.

[3] Tziperman, E. (2022). Global warming science: A quantitative introduction to climate change andits consequences. Princeton University Press.

[4] Komurcu, M., Storelvmo, T., Tan, I., Lohmann, U., Yun, Y., Penner, J. E., ... & Takemura, T. (2014). Intercomparison of the cloud water phase among global climate models. Journal of Geophysical Research: Atmospheres, 119(6), 3372-3400.

[5] Lohmann, U. (2002). A glaciation indirect aerosol effect caused by soot aerosols. Geophysical Research Letters, 29(4), 11-1.

[6] *Schwartz, L. M. (1980). Round-off error. Analytical Chemistry, 52(7), 1141-1147.*
[7] *Houze, R. A. (2014). Cloud microphysics. International geophysics, 104, 47-76.*
[8] *Grabowski, W. W., Morrison, H., Shima, S. I., Abade, G. C., Dziekan, P., & Pawlowska, H. (2019). Modeling of cloud microphysics: Can we do better? Bulletin of the American Meteorological Society, 100(4), 655-672.*
[9] *VanZanten, M. C., Stevens, B., Nuijens, L., Siebesma, A. P., Ackerman, A. S., Burnet, F., ... & Wyszogrodzki, A. (2011). Controls on precipitation and cloudiness in simulations of trade ‐ wind cumulus as observed during RICO. Journal of Advances in Modeling Earth Systems, 3(2).*
[10] *Prather, K. A., Hatch, C. D., & Grassian, V. H. (2008). Analysis of atmospheric aerosols. Annu. Rev. Anal. Chem., 1(1), 485-514.*
[11] *Shupe, M. D., Daniel, J. S., De Boer, G., Eloranta, E. W., Kollias, P., Long, C. N., ... & Verlinde, J. (2008). A focus on mixed-phase clouds: The status of ground-based observational methods. Bulletin of the American Meteorological Society, 89(10), 1549-1562.*
[12] *Korolev, A., & Milbrandt, J. (2022). How are mixed ‐ phase clouds mixed?. Geophysical Research Letters, 49(18), e2022GL099578.*
[13] *Zhang, M., Liu, X., Diao, M., D'Alessandro, J. J., Wang, Y., et al. (2019). Impacts of representing heterogeneous distribution of cloud liquid and ice on phase partitioning of Arctic mixed ‐ phase clouds with NCAR CAM5. Journal of Geophysical Research: Atmospheres, 124(23), 13071-13090.*
[14] *Korolev, A. , & Mazin, I. (2003). Supersaturation of water vapor in clouds. Journal of the atmospheric sciences, 60(24): 2957-2974.*
[15] *Gettelman, A., & Sherwood, S. C. (2016). Processes responsible for cloud feedback. Current climate change reports, 2, 179-189*
[16] *Pan, Linlin, et al. "Impact of four ‐ dimensional data assimilation (FDDA) on urban climate analysis." Journal of Advances in Modeling Earth Systems 7.4 (2015): 1997-2011.*
[17] *Forbes, Richard M., and Maike Ahlgrimm. "On the representation of high-latitude boundary layer mixed-phase cloud in the ECMWF global model." Monthly Weather Review 142.9 (2014): 3425-3445.*
[18] *Bodas-Salcedo, Alejandro, et al. "COSP: Satellite simulation software for model assessment." Bulletin of the American Meteorological Society 92.8 (2011): 1023-1043.*
[19] *Zhang, Y., Lin, W., Klein, S. A., Zelinka, M., et al. (2019). Evaluation of clouds in version 1 of the E3SM atmosphere model with satellite simulators. Journal of Advances in Modeling Earth Systems, 11(5), 1253-1268.*
[20] *Cesana, G. V., Ackerman, A. S., Fridlind, A. M., Silber, I., et al. (2024). Observational constraint on a feedback from supercooled clouds reduces projected warming uncertainty. Communications Earth & Environment, 5(1), 181.*
[21] *Hofer, S., Hahn, L.C., Shaw, J.K. et al. Realistic representation of mixed-phase clouds increases projected climate warming. Commun Earth Environ 5, 390 (2024). https://doi.org/10.1038/s43247-024-01524-2*
[22] *Bjordal, J., Storelvmo, T., Alterskjær, K., & Carlsen, T. (2020). Equilibrium climate sensitivity above 5 C plausible due to state-dependent cloud feedback. Nature Geoscience, 13(11), 718-721.*
[23] *Parkinson, C. L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proceedings of the National Academy of Sciences, 116(29), 14414-14423.*