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Geophysical Research Letters

RESEARCH LETTER

10.1029/2022GL100034

A Quantitative Analysis of the Source of Inter-Model Spread in Arctic Surface Warming Response to Increased CO_2 Concentration

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Key Points:

- The surface warming in the Arctic is strongest in the cold months and so is its uncertainty, especially in the months of January-February-March
- Contributions to the inter-model spread of seasonal pattern of Arctic warming are quantified via a linearized radiative transfer model
- The inter-model spread in sea ice melting in early summer is relayed to and gets amplified in cold months by oceanic heat storage/release

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Hu, X., Liu, Y., Kong, Y., & Yang, Q. (2022). A quantitative analysis of the source of inter-model spread in Arctic surface warming response to increased CO_2 concentration. *Geophysical Research Letters*, *49*, e2022GL100034. https://doi.org/10.1029/2022GL100034

Received 15 JUN 2022
Accepted 12 SEP 2022

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Abstract This study exams the main sources of inter-model spread in Arctic amplification of surface warming simulated in the abrupt-4 × CO_2 experiments of 18 CMIP6 models. It is found that the same seasonal energy transfer mechanism, namely that the part of extra solar energy absorbed by Arctic Ocean in summer due to sea-ice melting is temporally stored in ocean in summer and is released in cold months, is responsible for the Arctic amplification in each of the 18 simulations. The models with more (less) ice melting and heat storing in the ocean in summer have the stronger (weaker) ocean heat release in cold season. Associated with more (less) heat release in cold months are more (less) clouds, stronger (weaker) poleward heat transport, and stronger (weaker) upward surface sensible and latent heat fluxes. This explains why the Arctic surface warming is strongest in the cold months and so is its inter-model spread.

Plain Language Summary The seasonal energy transfer mechanism, namely that the part of extra solar energy absorbed by Arctic Ocean during sea-ice melting season is temporally stored in ocean, which in turn is released in cold months, is recognized as the primary mechanism accounting for the Arctic amplification of surface warming. The same seasonal energy transfer mechanism is responsible for the Arctic amplification in each of the 18 CIMP6 abrupt CO_2 quadrupling climate simulations. The models that have more (less) ice melting and heat storing in the ocean during the early melting season (April-May-June) would have the stronger (weaker) ocean heat release in January-February-March, contributing directly to stronger (weaker) surface warming in cold months. Associated with more (less) heat release from Arctic Ocean in cold months are more (less) clouds, stronger (weaker) poleward heat transport, and stronger (weaker) upward surface turbulent sensible and latent heat fluxes, which further increases the inter-model spread of the winter warming, and thereby the annual mean warming as well. Therefore, the inter-model spread of the sea-ice melting in April-May-June accounts for the major portion (more than 80%) of the inter-model spread in both the winter warming and the annual mean warming.

1. Introduction

Arctic Amplification (AA) is referred to a fundamental phenomenon of recent observations showing surface warming in the Arctic region about twice as large as the global average warming (Previdi et al., 2021; Taylor et al., 2022). AA exhibits a pronounced seasonal pattern with maximum warming in boreal winter and minimum warming in boreal summer. The consensus in the literature regards AA as a collective response to anthropogenic greenhouse forcing involving various local climate feedback and remote processes (Henderson et al., 2021). The direct climate response to the increase in CO_2 concentration causes sea ice retreat and more open water in summer over Arctic Ocean (Post et al., 2019). Because most of the extra solar radiation absorbed by open water resulting from the sea-ice melting (or the ice-albedo feedback) is temporally stored in ocean, the net effect of the ice-albedo feedback only result in a weaker warming in summer months. The winter release of heat stored in summer, or the seasonal energy transfer (SET), is the primary mechanism responsible for the pronounced winter warming amplification in Arctic (Boeke & Taylor, 2018; Chung et al., 2021; Lu & Cai, 2009; Sejas et al., 2014).

Numerous studies identify the sea-ice thermal inertial feedback as the determing factor responsible for the SET mechanism that acts to suppress climate sensitivity in summer and amplify it in cold season (e.g., Dwyer et al., 2012; Hahn et al., 2022; Robock, 1983; Sejas & Taylor, 2020). As elucidated vividly using an idealized single-column sea ice model in addition to numerical experiments made with an updated CESM model (Community Earth

System Model) in Hahn et al. (2022), the transition from a lower thermal inertia of sea ice to significantly higher thermal inertia of sea water slows the surface warming during the melting season. Under the CO_2 forcing, the enhanced increase of the thermal inertial from sea ice surface to open water surface would amplify such seasonal asymmetry by suppressing the summer warming and amplifying the winter warming.

Moreover, the vertical inversion of air temperature restricts warming in a shallow near-surface layer instead of creating convection (Pithan & Mauritsen, 2014). Model simulations with fixed sea-ice cover prove that the AA still exists without ice-albedo feedback (Graversen & Wang, 2009), suggestive of that the enhanced remote poleward energy transport via atmospheric motions (Baggett & Lee, 2015; M. Cai, 2005; Mahlstein & Knutti, 2011) and oceanic circulations (Eyring et al., 2016; Singh et al., 2022) play important roles in AA. Other processes including water vapor, cloud, and lapse-rate feedbacks simultaneously contribute to surface warming in the Arctic (Colman & Soden, 2021; Previdi et al., 2021). All of these aforementioned processes make AA robust even when one or two of them are absent.

The AA phenomenon is not only the dominant signal in future climate projections by climate models but also the primary contributor to the uncertainty of global warming projections (Cai, Hsu et al., 2021; Cai, You, et al., 2021; Hu et al., 2020). Significant efforts have been devoted to improve understanding of the sources of the uncertainty in AA (Cai, Hsu et al., 2021; Cai, You, et al., 2021; Hahn et al., 2021; Mahlstein & Knutti, 2011), which is critically important for reducing the uncertainty of global warming projections (Hu et al., 2021; Thackeray & Hall, 2019). The AA signal is stronger in the most recent Coupled Model Intercomparison Project 6 (CMIP6) than CMIP5 and so its uncertainty (Davy & Outten, 2020; Zelinka et al., 2020). It is found that the albedo feedback contributes greatly to the inter-model spread in AA among CMIP5 models, followed by the lapse-rate feedback (Pithan & Mauritsen, 2014). Additionally, the moist poleward atmospheric heat transport (AHT) acts to further enhance the AA uncertainty, while the dry AHT tends to weaken it (Hahn et al., 2021). Interactions among different feedback processes also contribute to the large uncertainty of AA in climate models. For example, cloud process contributes to AA uncertainty via model discrepancies in the projected cloud properties as well as in the ways of clouds' modifying the strength of other feedbacks (Alkama et al., 2020; Zelinka et al., 2017). According to Boeke and Taylor (2018), the coupling between albedo feedback and ocean heat storage/release result in model differences in SET over sea-ice retreat regions in summer, playing an important role in driving the inter-model spread in AA. However, the SET mechanism cannot be directly identified in the top-of-atmosphere (TOA)-based climate feedback analysis framework. Quantifying the contribution of SET mechanism to the inter-model spread in AA has not been achieved.

The climate feedback-response analysis method (CFRAM; M. Cai & Lu, 2009), a surface-atmosphere energy budget framework, provides a quantitative insight into the relative contributions to AA from the individual radiative and non-radiative processes. By applying CFRAM to seasonal warming forced by a 1%/yr increase in the CO_2 from CCSM4 (Sejas et al., 2014; Taylor et al., 2013), the SET mechanism can be clearly and directly identified: the surface cooling due to ocean heat storage that opposes the warming due to ice-albedo feedback in summer is accompanied with the warming in winter due to ocean heat release. Hu et al. (2020) extends the CFRAM analysis to inter-model spread in annual mean surface warming under RCP8.5 scenario from CMIP5. They find that the ice-albedo, ocean heat storage, and surface heat fluxes collectively play the key role in shaping the inter-model spread in AA. Obviously, the annual mean approach would not directly reveal the SET mechanism. In this study, we apply CFRAM to the seasonal cycle of Arctic surface warming in abrupt-4×CO_2 simulations from 18 models in CMIP6, to quantify the contribution of model difference in SET to AA uncertainty. In addition, the couplings between local ocean heat storage/release and remote effect associated with atmospheric and ocean heat transport are also discussed to improve the understanding of local and remote processes contributions to AA and its uncertainty.

2. Data and Method

All data analyzed are monthly mean fields derived from the abrupt-4 × CO_2 experiments of CMIP6 climate models (Eyring et al., 2016). The differences between the 20-year means in 121–140 years of the abrupt-4 × CO_2 experiments and their counterparts of the last 50 years of the pre-industrial (PI) experiments are defined as the climate responses to the CO_2 quadrupling. AA is represented by areal mean of changes in surface temperature over the Arctic region (60°–90°N). Table S1 in Supporting Information S1 lists the 18 CMIP6 climate models whose climate simulations for Arctic warming are considered in this study. The inter-model spread is defined as the deviations of individual models' simulations from the multiple model ensemble (MME) mean. The amplitude of the inter-model spread is defined as the standard deviation of the deviations of individual models' simulations from the MME.

We examine the main sources of inter-model spread in climate projections of AA using the CFRAM analysis. Specifically, we decompose surface warmings in the Arctic into partial surface temperature changes (PTCs) due to external forcing and individual climate feedback processes from a surface perspective. By applying CFRAM to AA from 18 models, the total surface warming is decomposed into PTCs due to changes in CO_2 (CO2), albedo (AL), water vapor (WV), cloud (CLD, including longwave and shortwave effects), atmospheric heat transport (ATM), oceanic transport and heat storage (OCH), surface heat fluxes (HF), namely,

$$\begin{aligned}\Delta T_{\mathrm{MODEL}} &= \Delta T^{\mathrm{CO2}} + \Delta T^{\mathrm{AL}} + \Delta T^{\mathrm{WV}} + \Delta T^{\mathrm{CLD}} + \Delta T^{\mathrm{ATM}} + \Delta T^{\mathrm{OCH}} + \Delta T^{\mathrm{HF}} + \Delta T^{\mathrm{ERR}} \\ &= \Delta T^{\mathrm{SUM}} + \Delta T^{\mathrm{ERR}} \end{aligned} \quad (1)$$

Errors are introduced due to linearization and offline radiative transfer model calculations. We have validated the sum of the terms on the right-hand side of Equation 1 is very close to the total temperature change for each of the 18 model simulations, as indicated by the nearly overlaps between shadings (the sum) and contours (the total) in Figures S1i (for MME) and S3i (for amplitude of inter-model spread) in Supporting Information S1. Such additive feature allows us to quantify individual process contributions to the inter-model spread of the Arctic warming, including inter-model spreads of both the annual mean and seasonal pattern.

To link the partial temperature change due to oceanic transport and heat storage to the sea-ice thermal inertial feedback, in terms of both the MME and inter-model spread, we calculate the seasonal cycle response of the effective thermal inertial (ETI) over Arctic Ocean to the quadrupling CO_2 forcing according to

$$\Delta(\mathrm{ETI}) \approx -\frac{\partial < T_s >}{\partial t}\Delta\left(< C_{\mathrm{eff}} >\right) + \Delta\left(-\frac{\partial < T_s >}{\partial t}\right) < C_{\mathrm{eff}} > \quad (2)$$

where < > represents the areal mean operator over all ocean and sea-ice grid points north of 60°N; T_s is the surface air temperature, corresponding approximately with the SIC (sea ice concentration) weighted surface temperature at each ocean/sea ice grid point; and C_{eff} corresponds to the effective heat capacity of each ocean/sea ice grid point (see Supporting Text in Supporting Information S1 for details).

Empirical orthogonal function (EOF) is applied to extract the SET patterns that are dominant for the inter-model spread in AA. Since sea ice melting is the key process responsible for SET mechanism and AA (Feldl & Merlis, 2021; Jenkins & Dai, 2021), we apply EOF analysis to the inter-model spread in the PTC due to albedo feedback (ΔT^{AL}) and project the total Arctic surface warming and other PTCs to the dominant EOF modes derived from the PTC due to albedo feedback.

3. Results

3.1. Multi-Model Ensemble Mean

The salient features in Figures 1a–1c are that the phenomenon of the Arctic warming amplification mainly takes place in cold months and is more pronounced over Arctic marine region instead of land region. Shown in Figure S1 in Supporting Information S1 are seasonal cycles of MME of the zonal mean of PTCs over ocean grids due to individual processes obtained from the CFRAM analysis. Among these partial temperature changes, partial temperature changes due to oceanic heat storage and dynamic terms (ΔT^{OCH}, Figure S1g in Supporting Information S1), atmospheric dynamic feedback (Figure S1f in Supporting Information S1), and cloud longwave feedback (ΔT^{CLDL}, Figure S1e in Supporting Information S1) are the leading three positive contributors to the Arctic warming amplification in cold months. Partial temperature changes due to the enhancement of upward surface turbulent sensible and latent heat fluxes act to reduce the strength of the Arctic warming amplification in cold months (ΔT^{HF}, Figure S1h in Supporting Information S1). In summer months, the three leading contributors to summer warmings over Arctic Ocean are ice-albedo feedback (Figure S1a in Supporting Information S1), water vapor feedback (Figure S1b in Supporting Information S1), and the reduction of upward surface turbulent sensible and latent heat fluxes (Figure S1h in Supporting Information S1), whereas the oceanic heat storage term

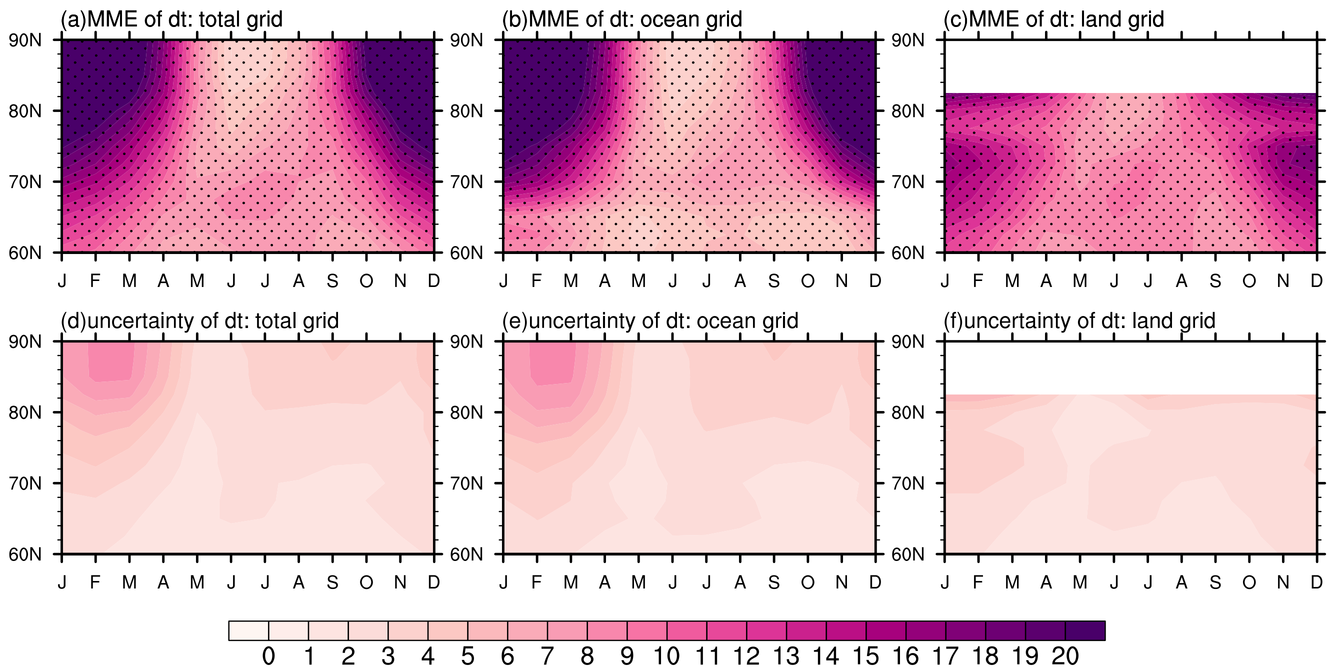

Figure 1. Seasonal cycles of multi-model ensemble mean (top row) and the standard deviation of their inter-model spreads (bottom row) of the zonal mean of surface warmings (K) simulated by CMIP6 abrupt-4 × CO_2 experiments of the 18 models listed in Table S1 in Supporting Information S1 as a function of latitude (ordinate) and time (month, abscissa). The left, middle, and right columns are for all grid points, ocean-only grid points, and land-only grid points, respectively. Black dots in (a–c) indicate the 99% confidence level of statistical significance.

(Figure S1g in Supporting Information S1) acts to suppress summer warmings over Arctic ocean regions. The analysis presented in the Supporting Text confirms the finding of Sejas and Taylor (2020) and Hahn et al. (2022, and the reference therein) that the enhanced increase of the thermal inertial from sea ice surface to open water surface in response to the CO_2 forcing act to amplify the seasonal asymmetry of Arctic warming by suppressing the summer warming and amplifying the winter warming.

These results confirm the findings of SET mechanism by Sejas et al. (2014) and Chung et al. (2021). Specifically, the largest Arctic summer warming is caused by melting of sea ice. This ice-albedo feedback induced summer warming is enhanced by water vapor feedback, but partially canceled out by the dominance of shortwave cloud feedback over longwave cloud feedback, and by the temporal withholding of the warming due to the oceanic heat storage/dynamics feedback, resulting in a warming minimum. In polar winter, surface albedo and shortwave cloud feedbacks are nearly absent due to a lack of insolation. However, the oceanic heat storage feedback relays the withheld polar warming from summer to winter, and the longwave cloud feedback adds additional warming to the polar surface. Furthermore, the strengthening of atmospheric poleward energy transport also contributes positively to the Arctic warming amplification in cold months. The collective effect of these processes overwhelms the surface cooling due to the strengthening of upward surface turbulent sensible and latent heat fluxes, responsible for the maximum polar warming in fall and winter.

3.2. Inter-Model Spread

Coincidently or not, the inter-model spread of the CMIP6's Arctic surface warming forced by abrupt-4 × CO_2 is also mainly in cold months (Figure 1d), especially over Arctic Ocean in the months of January, February, and March (JFM, Figures 1e and 1f). This indicates that a significant portion of inter-model spread of global warming project originates from inter-model spread of physical processes over marine region. The Arctic warmings in the months of April, May, and June (AMJ) of individual models are strongly correlated positively with their warmings in JFM (Figure S2a in Supporting Information S1) and their annual mean warmings (Figure S2b in Supporting Information S1). These results, together with the results shown in Figures 1a–1c and Figure S1 in Supporting Information S1, suggest that the large inter-model spread of Arctic warming in cold months originate in the inter-model spread of the oceanic withholding of the warming due to ice-albedo feedback in late spring/early summer (i.e., AMJ).

Seasonal patterns of the amplitude of inter-model spreads of PTCs due to individual processes support the conjecture above (Figure S3 in Supporting Information S1). Specifically, partial temperature changes due to the ice-albedo feedback have the largest inter-model spreads mainly in late spring and early summer. The amplitude of the seasonal cycle of the inter-model spread of PTCs due to oceanic heat storage terms is pronounced during the months from January to June. The large inter-model spread of partial temperature changes due to shortwave cloud feedback occurs in summer months, overlapping with the sea-ice melting season. This together with the inter-model spread of oceanic heat storage acts to damp the spread of ice-albedo feedback, resulting in the weaker spread of Arctic Ocean warming in warm months. The large inter-model spread of partial temperature changes due to atmospheric dynamic (surface turbulent flux) feedbacks is expected to contribute positively (negatively) to the stronger inter-model spread of Arctic Ocean warming in cold months.

Next, we wish to further quantify individual process contributions to the inter-model spread of summer warming over Arctic Ocean and to relate Arctic warming amplification in cold months to the source(s) of the inter-model spread of Arctic summer warming. Given the key role of sea ice retreat in Arctic warming and in initiating SET mechanism, we apply the cross-model EOF analysis for extracting the dominant seasonal patterns of the inter-model spread of PTCs due to ice-albedo feedback. The EOF analysis reveals that the first two modes account for, respectively, 80.3% and 10.7% (total of 91%) of the inter-model spread of PTCs due to ice-albedo feedback (Figures 2a–2d). The seasonal pattern associated with EOF1 is dominated by a large inter-model spread of ice melting in late spring/early summer (AMJ) whereas that of EOF2 represents a large inter-model spread of ice melting in late summer (JAS, July-August-September). This is consistent with the findings of Bonan et al. (2021) that uncertainty in projections of Arctic sea ice change in March is dominated by differences among different models, while uncertainty in September is dominated by scenario uncertainty. According to Figure 2e, models that have more (less) ice melting in spring and early summer would have a stronger (weaker) annual mean Arctic warming, which explains nearly 83% of the inter-model spread of the annual mean Arctic warming. The contribution of inter-model spread in ice melting in late summer to the uncertainty of annual mean Arctic warming is negligible (Figure 2f).

How do the various feedback processes collectively contribute to the inter-model spread in the annual mean Arctic warming? Shown in Figure 3 are the regressed seasonal patterns of individual PTCs against the principal component of EOF1 (Figure 2c). It vividly indicates that the only main process that substantially damp the large inter-model spread of PTCs due to ice-albedo feedback in late spring/early summer is the oceanic heat storage term (Figure 3g), which temporally store more (less) heat into the ocean in models that have more (less) ice melting in melting in spring and early summer. Associated with more (less) ocean heat storage in spring and early summer is more (less) heat release from Arctic Ocean in the remaining months, which particularly strong in JFM. We have confirmed that the inter-model spread of the sea-ice thermal inertial feedback is the key factor responsible the inter-model spread of SET mechanism (see Supporting Text for details). Associated with more (less) heat release from Arctic Ocean in fall and winter months are more (less) clouds dominated by cloud longwave effect, stronger (weaker) poleward heat transport, and stronger (weaker) upward surface turbulent sensible and latent heat fluxes. Therefore, the inter-model spread of Arctic winter warming amplification is further enhanced by cloud longwave effect (Figure 3e) and atmospheric dynamic feedbacks (Figure 3f), but is partially reduced by surface turbulent sensible and latent heat flux feedbacks (Figure 3h). Beyond that, contributions of CO_2 forcing, water vapor feedback, and the shortwave effect of cloud feedback are small to the uncertainty of annual mean Arctic warming and even negligible to the large uncertainty in cold season.

4. Concluding Remarks

In this study, we exam the main sources of inter-model spread in climate projections of Arctic amplification of surface warming simulated in the abrupt-4 $\times$ CO_2 experiments of CMIP6 climate models using the CFRAM (climate feedback-response analysis method) analysis, a surface-atmosphere energy budget based climate feedback analysis framework.

We use Figure 4 to summarize the main findings of this study, revealing the role of seasonal energy transfer (SET) mechanism in both the multi-model ensemble mean (Figures 4a and 4b) and the inter-model spread (Figures 4c

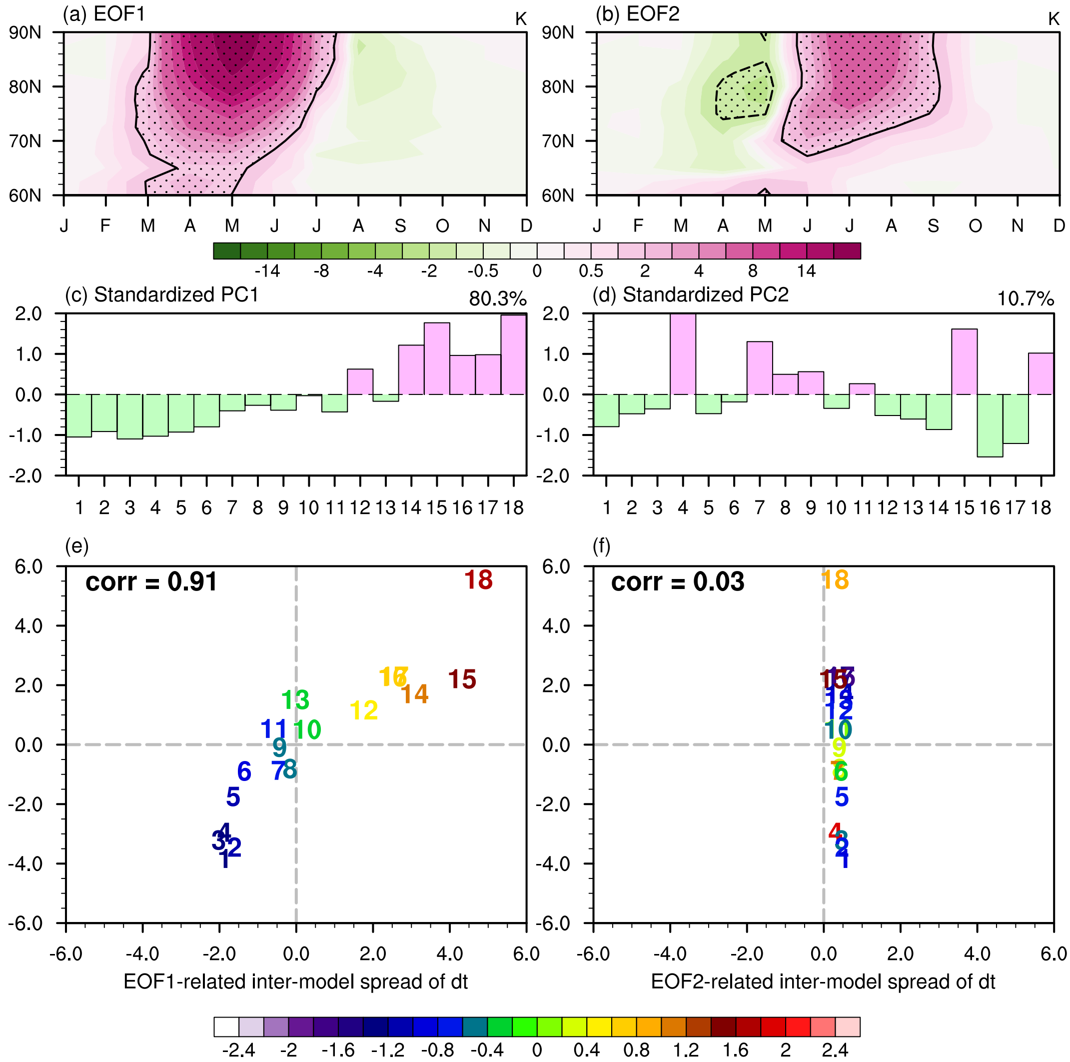

Figure 2. Empirical orthogonal function (EOF) Analysis of inter-model spreads of seasonal cycles of partial temperature changes (PTCs) due to ice-albedo feedback. (a) and (b) are the latitude-time pattern (K) of the first and second EOF modes; (c) and (d) are the principal components (dimensionless) of first and second EOF modes with values in the abscissa indicating the model number; (e) and (f) are scatter plots of the inter-model spread of Arctic annual mean warming (ordinate) versus the inter-model spread of Arctic annual mean surface temperature changes captured by the first and second EOF modes with the numbered points for the model number.

and 4d) of Arctic amplification of surface warming. The positive/negative abscissa values of the magenta/blue dots in Figures 4a and 4b indicate that the Arctic warming during AMJ the inter-model spread of is excited by ice melting but suppressed simultaneously by the oceanic heat storage. The other processes contribute little to the AMJ Arctic warming with the abscissa values of the other dots close to zero. However, all processes contribute positively to the JFM warming, as well as to the annual mean Arctic warming, except the surface turbulent flux feedbacks.

The dominant seasonal pattern of the inter-model spread of partial temperature changes (PTCs) due to ice-albedo feedback is characterized by a large inter-model spread of ice melting in spring and early summer (AMJ), explaining nearly 80.3% of the inter-model spread of partial temperature changes due to ice-albedo feedback and 83% of the inter-model spread of the annual mean (total) Arctic warming. The inter-model spreads of the PTCs associated with this dominant mode of the inter-model spread of ice-albedo feedback (Figures 4c and 4d) exhibit a similar pattern as their MME counterparts (Figures 4a and 4b). This together with the similarity between Figures S4a and S4b in Supporting Information S1 strongly suggests that the same SET mechanism through the sea-ice

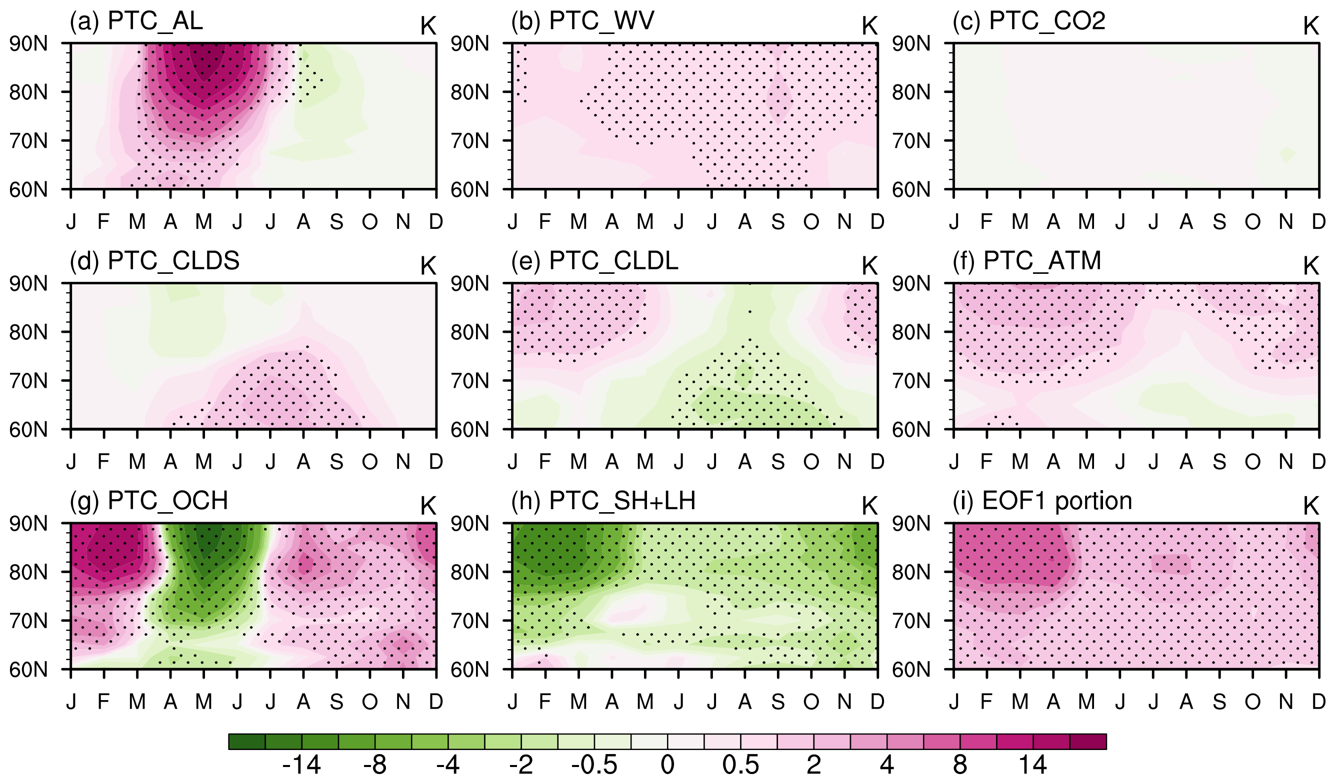

Figure 3. Regressed seasonal cycles of the inter-model spread in the zonal mean of partial surface temperature changes (K) due to individual processes against PC1 shown in Figure 2c, namely to changes in (a) ice albedo, (b) atmospheric water vapor, (c) the concentration of CO_2, (d) shortwave effect of clouds, (e) longwave effect of clouds, (f) atmospheric heat transport induced downward longwave radiative fluxes at the surface, (g) oceanic circulation and oceanic heat storage terms, (h) surface turbulence sensible and latent heat fluxes, and (i) the sum of (a–h). Black dots indicate the 99% confidence level of statistical significance.

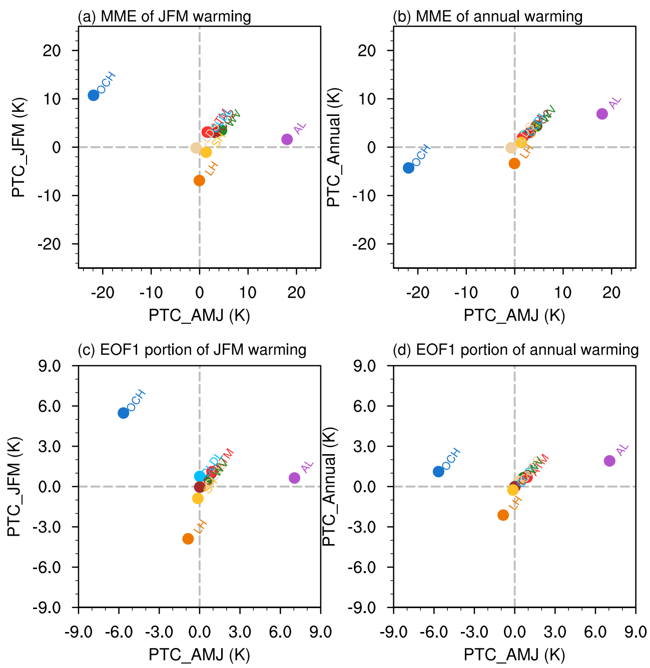

Figure 4. Contributions to the Arctic surface warming centered at the year-130 of the CMIP6 abrupt-4 × CO_2 experiments. Panels (a, b) are for the MME and (c, d) for the EOF1 portion of the inter-model spread. The abscissa is for mean partial temperature changes (PTCs) in the months of April, May, and June and ordinate in (a) and (c) is for mean PTCs in the months of January, February, and March and in (b) and (d) for their annual means.

thermal inertial feedback operates in all CMIP6 climate simulations, responsible for the strong seasonal asymmetry of Arctic warming albeit the differences in the strength of the sea-ice thermal inertial feedback. Specifically, the positive/negative abscissa values of the magenta/blue dots in Figure 4c indicate that, during AMJ, the inter-model spread of Arctic warming is excited by ice melting but suppressed simultaneously by the oceanic heat storage. The other processes contribute little to the uncertainty of AMJ Arctic warming with the abscissa values of the other dots close to zero. Correspondingly, the more ice melting and heat storing in the ocean in AMJ are, the stronger the ocean heat release in JFM (positive ordinate value of the blue dot). The reversed can be said to the models that have less ice melting in late spring/early summer. This clearly indicates that the SET mechanism is the key mechanism for the inter-model spreads of the Arctic warming not only in cold months but also in the annual mean (Figure 4d). Associated with more (less) heat release from Arctic Ocean in cold months are more (less) clouds, stronger (weaker) poleward heat transport, and stronger (weaker) upward surface turbulent sensible and latent heat fluxes.

Our findings suggest that the large inter-model spread of Arctic surface warmings is mainly caused by the inter-model spreads in sea-ice melting in AMJ. Although the uncertainty in projection of albedo feedback over the May to August can be the emergent constraint using the observed strength of albedo feedback in current climate state (Thackeray & Hall, 2019), our findings call for a future study to examine to what extent the inter-model spread of Arctic surface warmings is related to the inter-model spreads in the climatological seasonal cycles of sea ice coverage and/or surface temperature. In addition, the SET mechanism responsible for the inter-model spread in Arctic warming primarily involves local energy transfer between the ocean and the atmosphere. The relative roles of local energy transfer and remote energy transport especially for the oceanic heat transport should be addressed by further investigation. Previous studies pointed out that the response of oceanic heat transport to increase in CO_2 concentration could be regulated by the background oceanic circulation (Armour et al., 2016; Marshall et al., 2014, 2015). The control climate perspective of these aforementioned factors would allow us to further probe the question of what drives the uncertainty in climate simulations.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study are derived from model simulations produced by the Coupled Model Intercomparison Project Version 6 (CMIP6), which are archived and freely accessible at https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6. The CMIP6 model simulations used in this study are listed in Table S1 in Supporting Information S1.

Acknowledgments
The authors are grateful for the insightful comments from the editor and two anonymous reviewers that help improve the paper greatly. This study was supported by the National Key Research and Development Program of China (2019YFA0607004), the National Natural Science Foundation of China (Grants 42075028 and 41911540470), and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (Grant SML2021SP302).

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