Point-to-point response to reviewers' comments

The comments are in black, and our answers are in blue.

Reviewer #4:

General Comments:

I recommend this work being accepted only after major revisions and rewriting for improved English composition. The late Pliocene is a unique warm period, representing a climate in equilibrium to modern levels of atmospheric greenhouse gas concentrations. This study makes a contribution to understanding the impact on sea ice response to Arctic amplification in a past warm climate state for which there is a large body of climate proxy data and other model studies. Most of the results shown here concerning the decomposition of the effects of sea-ice change on Arctic amplification are not new, as discussed in Serreze and Barry (2011), though the methodology, of using CFRAM may be new to this particular application. As this work pertains to a Pliocene simulation that compares well to the proxy-reconstruction, it would make a good contribution to the literature. More details of the CFRAM methodology used in this application would be beneficial to the readers.

We are grateful for the overall positive evaluation and detailed comments that follow. Below are our responses and we have revised the manuscript accordingly.

Specific comments:

This manuscript needs to be thoroughly edited by someone with more English proficiency in order to improve the grammar and many awkward sentence structures. The result would be greater clarity for understanding the methodology and results. As written, many sections are not written with the necessary clarity for communicating the authors' intent. I point out some examples in my detailed comments by line number, below.

A native English speaker has proofread the revised manuscript. Thanks a lot for your detailed comments! All these comments have been taken into account in the revised manuscript.

A TOA net energy imbalance of about -0.5Wm^{-2} (Fig. S1) is large and suggests the simulation is not at a near equilibrium. In addition, the weak negative trend in the TOA energy imbalance suggests the model is moving away from equilibrium. Is this not globally integrated? A net loss of energy at the top of the model is inconsistent with both a positive SST trend and a negative sea ice concentration trend, both of which suggest the model is warming, unless a negative TOA flux is directed downward. This figure needs more explanation.

Strictly speaking, the TOA net radiation should balance after reaching an equilibrium. However, a small imbalance generally remains associated with numerical errors, such as -1.5 Wm^{-2} displayed in ERA-Interim (Hazeleger et al., 2011) and 0.9 Wm^{-2} shown in Trenberth et al. (2009). From our last 200 years output in the Pliocene simulation, the mean TOA net radiation (globally integrated) is about -0.5 Wm^{-2} and its trend is near zero. The trend of mean SST is about 0.02 K/century, which fulfils the PMIP4 equilibrium criterion that the trend of mean SST should be less than 0.05 K/century (Kageyama et al., 2018). The negative TOA flux is directed upward, meaning a heat loss of the earth-atmosphere system, which seems inconsistent with a positive SST trend and a negative sea ice concentration trend. However, the positive net surface energy fluxes (also shown in Hazeleger et al., 2011) can explain the inconsistency. For clarity, the explanation about the direction of energy flux is added in the revised text and Figure S1.

Overall, there is a general lack of specific details of the analyses presented. For example, how are the anomalies computed, i.e. are trends first removed? A more physical explanation is needed for why you are using spatial correlations because as written, “limitation of data and computation” is quite vague. More detail is also needed to explain how CFRAM was applied to the surface energy balance in the Arctic. For example, what is the “first part of CFRAM” (line 143) used to obtain the surface radiative fluxes. Some equations would be useful, as would a citation to the same specific use of CFRAM as applied here.

More detail of the analyses presented is specified in the revised version. The last 100-year-mean of all variables in preindustrial control run and Pliocene sensitivity experiment are used for analysis, and the Pliocene anomalies are computed by subtracting the mean of the preindustrial simulation without trends removal. As the CFRAM calculation of high temporal resolution, such as 6-hourly or daily, is computationally expensive, monthly data are used in the analysis. However, the monthly resolution is too coarse to explain the relationship between heat fluxes and sea ice concentration by temporal correlations. Therefore spatial correlations are calculated. More detail including a partial radiative perturbation equation is added in the CFRAM introduction and the “first part of CFRAM” is specified in the revised version.

More detailed comments by line number: (Note: this is not a complete list of every grammatical issue in the text.)

11: “current warming climate” suggests transient climate change.

Replace “analogue” with “equilibrium state”.

14: Define PRISM and give a citation.
Done.

17: “Given the facts…”
Done.

19: Run-on sentence structure.
Done.

20: During winter months…
Done.

29: Either “…in the recent decade…” or “…in recent decades...” “Moreover, an ice-free Arctic…”
Done.

31: “As the sea ice retreats…” Isn’t it the average reflectivity of the surface that decreases due to a decrease in the fractional sea ice coverage and a decrease in the sea-ice albedo due to melting snow and ice. Are these two effects separated out here? For improved clarity it might be better to say “As sea ice retreats, the surface Arctic Ocean becomes less reflective and the enhanced open ocean region leads to greater air-sea heat exchange due to the reduction in the insulating effect of sea ice.” However, as sea ice melts, its reflectivity changes and as the sea ice concentration changes the surface albedo is impacted. Both of these changes affect the net shortwave radiation at the surface.
The sentence was rewritten as suggested. The decrease in the sea-ice albedo due to a decrease in the fractional sea ice coverage is the focus in this paper, and the decrease in the sea-ice albedo due to melting snow and ice is mentioned in section 4. These two effects are not separated out here, and it can be found in section 4 that the former is dominant when they affect the net shortwave radiation at the surface.

“This leads to changes in the surface heat budget and changes in…”
Done.

33: “…possibly results from…”
Done.

38: "…consequence…has been reviewed"
Done.

46: shown
Done.

57: First "attributions" should perhaps be "characteristics" or "properties". Second "attributions" in line 59 should perhaps be "effects" or "mechanisms" here.
Done.

59: Run on sentence. I suggest cutting into two separate sentences or using a semi-colon instead of the comma after "…atmosphere and ocean"
Done.

69: should be "effects"
Done.

78: "represents"
Done.

79: Should amend "future climate at equilibrium with modern ghg levels"
Done.

138: "temperature"
Done.

143: "first part of CFRAM" is vague. More details on how CFRAM is applied should be given here.
More details on how CFRAM is applied have been given here.

169: Replace "present" with "modern", omit "benthic,"
Done.

170-174: Make a stronger statement linking the Arctic amplification statement starting on line 174, because that is the focus in this paper. To do this, I suggest rewriting here. I also suggest that you omit describing the tropical anomalies mainly because it is irrelevant to this work. Also, see Scroxton et al., Paleoceanography (2011); Brierley, PAGES News, 21(2), (2013);

Watanabe et al., Nature, 471, 209-211, (2012); for recent papers discussing evidence for a robust Pliocene ENSO.
Rewrite the sentences and remove the description of the tropical anomalies as suggested.

176-177: "…even though they have comparable CO_2 concentration…" replace with "…despite comparable CO_2 concentrations…" I also suggest breaking this sentence into two after the Ballantyne citation. Then in the next sentence suggest possible reasons why there is enhanced Arctic warming or amplification compared to today. I would add these newer citations for the amplified response to closed gateways: Otto-Bliesner et al. GRL, 44, 2017 and Feng et al. EPSL 466, 2017.
The sentences have been rephrased as suggested and the newer citations are added.

187: Omit the brief, sentence starting in line 187 with, "Meanwhile…" because the paper's focus is on the Arctic response.
Done.

192: "region" should be "regions" and omit "but they are apparently" for improved conciseness.
Done.

194: "Noteworthily…" Awkward. A potential replacement is "Notably"
Replace "Noteworthily" with "Notably".

194-195: Suggest replacing "…SAT, and the maximum…" with "SAT; the maximum…" using a semi-colon to join the two clauses instead of the conjunction "and".
Done.

197: The first line of this paragraph contains little meaning.
Remove the first sentence of this paragraph.

204-208: An equation for the net air-sea heat flux with the components presented symbolically is written in equation (4), but then these symbols are never used again, and reference to (4) is never made. I suggest removing the equation and stating this decomposition elsewhere. Also, what about the ice-ocean heat flux? A surface heat budget for the Arctic ocean should include the ice-ocean heat fluxes associated with the freezing and melting of sea-ice.

The equation for the net air-sea heat flux has been removed as suggested. And the decomposition is stated before the illustration of four flux terms in Figure 3. The ocean-atmosphere and ice-atmosphere interface heat exchanges are concerned in this study to understand the impact of sea-ice on Arctic amplification. The ice-ocean heat flux can affect the freezing and melting of sea-ice and then affect Arctic amplification indirectly, which would be investigated in the further study.

209-218: This paragraph discusses the anomalies or differences in the heat flux components in the Pliocene simulation as compared to the Preindustrial simulation, not heat fluxes. Every mention of a flux in this paragraph should reflect the fact that what is discussed are differences in the flux.
The word “anomalies” is added for clarity.

210: “The radiative and turbulent heat fluxes…” These are differences or anomalies.
The word “anomalies” is added for clarity.

211: “…the positive shortwave radiation is dominant…” should be “…the positive change in the shortwave radiation is dominant…”
Done.

212: “On the contrary” should be “In contrast”
Done.

220: “accounted as the synergy…” Awkward phrase. Suggest a rewrite of the first paragraph of this section for better clarity and conciseness. The definition of albedo needs to be more precise, to distinguish from planetary albedo.
The first paragraph of this section including the definition of albedo has been rewritten.

224: relevant to net shortwave…
Done.

225: Be more specific: net shortwave flux at the surface… Also, is this due to changes in sea-ice and snow albedo (that is, changes in the albedo due to changes in the state of sea-ice or snow, or to the change in albedo over the ocean grid box due to both albedo change and change in sea-ice concentration?
The word “net” is added. The albedo effect here is due to the combination of various albedo changes, including melting snow or ice and change in sea-ice concentration.

226-227: "…most…shows…"
Done.

227: net shortwave
Done.

229: changes in sea ice extent
Done.

231: changes in snow cover … (and, I presume, any change affecting the actual sea-ice albedo which could be changes in the sea-ice or snow state, such as melting, because the albedo is a function of the sea-ice state as well as thickness according to earlier descriptions of LIM.)
Done. We agree and revise the possible causes in the manuscript.

233: net shortwave
Done.

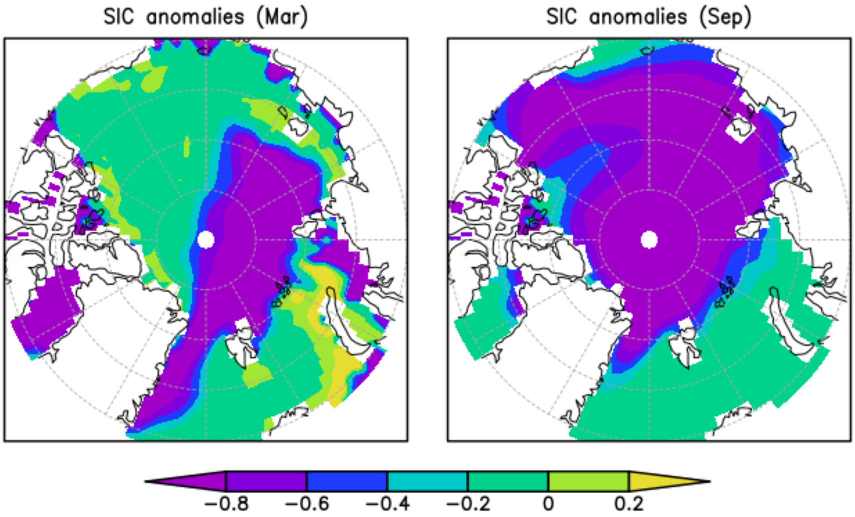
234: "Regarding the…" This opening sentence is awkwardly stated and vague.
The sentence is revised.

235: *net* shortwave radiation, i.e. shortwave radiation absorbed?
The word "net" is added. Shortwave radiation are defined positive downward, i.e. shortwave radiation absorbed.

238: "The prominent oceanic heating in May and June seems inconsistent with the maximum SST warming in August,…" Second clause of sentence seems to explain why the SST warming lags the SW heating response, thus it is not "inconsistent" but "consistent."
We agree and replace "inconsistent" with "consistent".

240: About the SIC anomalies: Shouldn't this be something "like the mean spatial variance over the Arctic of the Pliocene SIC anomalies is not strongly variable over the mean annual cycle." This is a curious result. A nice additional supplemental figure could show the Pliocene anomaly pattern at the minimum and maximum of the SIC annual cycle.
The SIC anomalies show different patterns at the maximum and minimum of the SIC annual cycle as the figure below. However, the relative rate of change of spatial variance over the Arctic of the Pliocene SIC anomalies has been checked and

demonstrated to be less as compared with that of net shortwave radiation anomalies due to albedo effect.



243: “our correlation analysis indicates that…

Done.

246: Needs to be more specific: …seasonal cycle of incident shortwave or net shortwave? …sea ice concentration variation, or some other sea ice property variation?

Here it’s “seasonal cycle of net shortwave”. It should be pointed out that the seasonal cycle of net shortwave depends not only on incident shortwave, but also on sea ice concentration variation and some other factors that can change surface albedo.

250: …insulation effect of sea-ice…

Done.

251: omit “In fact,”

Done.

251: “insulation effect”

Done.

250-255: This first paragraph should be rewritten. The insulating effect of sea-ice has an indirect effect on the net surface shortwave and longwave fluxes. By separating the overlying atmosphere from the ocean, sea-ice reduces evaporation from the ocean resulting in a decrease of water vapour and cloud cover. This reduction plays a non-negligible role in the amount of downward shortwave and longwave radiation

reaching the surface. However, remote moisture transport also affects water vapour and cloud amount. Thus, …
Thanks! The paragraph has been rewritten in the revised version as suggested.

256:262: It is not clear in this paragraph whether the discussion is about the SW and LW feedbacks after the remote effects on clouds and water vapour have been removed. This is suggested in the Figure 7 caption however.
The phrase "before removing the remote effects on clouds and water vapour" has been added in the manuscript and the Figure 7 caption for clarity.

258: …cloud characteristics…
Done.

263:274: Then this paragraph discusses just the local effect due to changes in sea ice concentration? I don't know what is meant by "counterpart of sea-ice insulation."
Yes. The phrase "counterpart of sea-ice insulation" is not clear, so it is changed to "the local insulation effect due to changes in sea ice concentration".

264: "Like the steps performed to isolate the albedo effect…"
Done.

266: "In the annual mean…"
Done.

270: "…shows a pronounced…"
Done.

271: "Compared to…" And this is being compared to the standard deviation of the shortwave anomalies due to clouds ? Also, should be "SIC anomalies" and
Done. Yes, "the standard deviation of" and "associated with local SIC anomalies" have been added for clarity.

272: Net shortwave radiation change and net longwave radiation change?
The word "net" is added.

274: …when there is a lack of…
Done.

279: ice-free conditions

Done.

280: the insulation effect
Done.

280: …and differentiate fluxes from ice-covered versus ice-free areas, not "ice-covered fluxes"
Done.

281: displays the Pliocene anomalies in …heat fluxes…as a function of SIC anomalies.
Done.

282: There is a larger spread in the turbulent heat flux anomalies over the ice-free area (grey symbols, corresponding to the diagonal hatched region in Figure 2c) than compared to anomalies from the ice-covered areas (light blue symbols, cross-hatched region in Fig. 2c) because the former is free from the constraint of sea-ice.
Done.

284: …and changes in SIC…
Done.

285: Are these estimates of variance explained from the regression lines shown in Figure 9? Is this and the response coefficient shown in the figure just for the ice-covered region? Be specific in both the Figure caption and the main text.
Yes, these estimates of variance explained are square of correlation coefficient shown in Figure 9. Yes, they are just for the ice-covered region, which has been specified in the figure caption and the text.

286:293: This paragraph jumps all over the place and is very unclear. First it discusses annual mean response coefficients vs. trends elsewhere, to the y-intercept of the regression line, then jumping to explaining seasonal variation.
This paragraph has been rewritten for clarity. The paragraph intends to explain the linear regressions of sensible and latent heat flux anomalies on SIC, including slope and intercept. Trends elsewhere are specified in the text, which refers to the different variability of turbulent heat fluxes over different latitude regions. Here "cold season" means the turbulent heat transport is the most pronounced in winter and can determine the overall value of annual turbulent heat fluxes, and we do not intend to explain the seasonal variation.

287: Noteworthily—a better choice would be “Notably” as mentioned previously.
Done.

288: “trend of sensible heat flux” this comes out of nowhere, to what does this refer? Is this “trend” referring to 20th century trends observed? Describe accurately.
The “trend” is specified in the revised version as the trend of turbulent heat flux over the low- and mid-latitude North Pacific and North Atlantic oceans from 1984–2004.

289: …turbulent flux anomaly axis?
Done.

290: “even without SIC change” for improved conciseness.
Done.

294: …to the sea-ice concentration? Or to sea-ice changes in general (thickness, albedo, concentration, etc.)? Also, replace “two” with “the”.
The phrase “to the sea-ice concentration” is fine here. Replaced “two” with “the”.

295: “…have a similar…” and “…showing a negative response…”
Done.

296: “…maximum warming of SAT occurs in November as a consequence…” It looks like changes in the net LW due to the response of clouds and water vapour is also a contributing factor to the warming in fall. As a complete budget for SAT is not presented, it would require adding heat transports and other fluxes, one can only suggest contributing factors.
The net longwave radiation change in response to cloud and water vapour is attributed to downwelling longwave radiation as upwelling longwave radiation depends solely on the surface temperature according to the Stefan–Boltzmann law. The more downwelling longwave radiation is in favour of the warming in SST rather than in SAT, therefore changes in the net LW due to the response of clouds and water vapour is not a contributing factor to the warming in fall, which is demonstrated by the opposite sign of the response coefficients in net LW radiation and turbulent heat fluxes. The phrase “contributing factor” is more appropriate than “as a consequence”, the sentence is rewritten in revision.

Section 6 Summary and Discussion;

This section is mostly a summary of results. Additional discussion could compare these results to previous results (see Serreze and Barry, 2011), could compare to the other Pliocene simulations which showed weaker Arctic amplification, highlight what is new here, etc.
A paragraph to compare these results to previous results and the other Pliocene simulations is added in Section 6.

304-309: Paragraph should be rewritten as it contains many awkward phrases. Also, I disagree that a model ever reveals a complete picture, but a model may be applied to investigate mechanisms and processes that help in understanding.
The paragraph has been rewritten. We agree that a model can not reveal a complete picture and revise it as suggested in the text.

312: "…the effects of changes in"
Done.

314: "…expected to partly interpret the variability of heat flux" Very unclear as to what this is supposed to mean.
The sentences are rewritten for clarity. Here we would like to highlight that albedo and insulate effects of sea ice can only partly explain the mechanism of Arctic amplification and a complete energy budget is required for a full understanding of Arctic amplification.

315-328: This paragraph appears to summarize the albedo and the insulation effects of sea ice on surface heat fluxes over the annual cycle, but doesn't seem to say anything about the Arctic amplification noted in the comparison of the Pliocene to preindustrial climate simulations. This section needs to be more specific.
More descriptions associated with Arctic amplification are added, and anomalies (in the Pliocene as compared to the preindustrial) are specified for clarity.

326: sea ice decline…Is this the decline of Pliocene sea ice as compared to the preindustrial, or over a seasonal cycle? It is not clear whether anomalies are being discussed. Also, "accelerates" should be "amplifies" as "accelerates" suggests time evolution, and here equilibrium runs are being discussed.
"sea ice decline" here refers to the decline of Pliocene sea ice as compared to the preindustrial, which is specified in the text. Replace "accelerates" with "amplifies".

Comments on Figures:

2) Please make the hatching in 2c more visible with another color or thickness. Be specific about describing the heat flux. “Net heat flux at the surface” Is this net heat flux at the surface (ice and ocean), or net heat flux at the surface of the ocean (air-sea and ice-ocean interfaces)?
The hatching is made more visible by changing its thickness.
The net heat flux is at the surface (ice and ocean) and is specified in the text and figure caption.

3) State when the flux is a “net” flux change, that is for the sw and lw fluxes.
The word “net” is specified.

4) Be more specific. Does the figure show the change in mean annual net shortwave flux at the surface?
Yes. The phrase “at the surface” is added.

5) and 6) net shortwave flux, also in 5) and 9) “All changes are” or “All change is”
Done.

7) More clarification is needed in the figure caption. Also, “caused by” should be “related to”, because causality is difficult to attribute in feedback processes.
The phrase “before removing the remote effects on clouds and water vapour” has been added in the figure caption for clarity.

8) Specify “net” again. Also, “caused by...” should be “related to…”.
Done.

9) Define ice-free vs ice-covered regions here referring to Fig. 2c. Also…“Pliocene changes shown are computed relative to the preindustrial simulation.” Describe the regression lines, i.e. which set of scatter points are being regressed. “caused by” should be “related to”.
Done.

S1) Are all of these quantities global averages?
Yes. The phrase "global annual mean” is used.

Contribution of sea -ice albedo and insulation effects to Arctic amplification in the EC-Earth Pliocene simulation

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Abstract. In the present work, we simulate the Pliocene climate with the EC-Earth climate model as an ~~analogue~~equilibrium state for current warming climate induced by rising CO_2 in the atmosphere. The simulated Pliocene climate shows a strong Arctic amplification ~~featured by~~featuring pronounced warming sea surface temperature (SST) over the North Atlantic, in particular over Greenland Sea and Baffin Bays, which is comparable with geological SST reconstructions from the Pliocene Research, Interpretation and Synoptic Mapping group (PRISM~~.~~, Dowsett et al., 2016). To understand the underlying physical processes, the air~~-~~-sea heat flux variation in response to Arctic sea -ice change is quantitatively assessed by a climate feedback and response analysis method (CFRAM) and an approach similar to equilibrium feedback assessment~~ (EFA) like approach. Giving~~. Given the ~~facts~~fact that the maximum SST warming ~~in SST~~ occurs in summer while the maximum ~~warming in~~ surface air temperature warming happens during winter, our analyses show that a dominant ice-albedo effect is the main reason for summer SST warming, and a 1% loss in sea -ice concentration could lead to an approximate ~~2~~1.8 Wm^{-2} increase in shortwave solar radiation into open sea surface. During winter ~~month~~months, the insulation effect induces enhanced turbulent heat flux out of the sea surface due to sea -ice melting in previous summer months. This leads to more heat ~~release~~released from the ocean to atmosphere, thus explaining ~~the stronger~~why surface air temperature warming amplification is stronger in winter than in summer.

1 Introduction

~~Through~~As shown in the monitoring at Mauna Loa Observatory in Hawaii (https://www.esrl.noaa.gov/gmd/obop/mlo/), the CO_2 concentration in the atmosphere ~~had steadily~~ passed the 400 ppm threshold by September 2016. Accordingly, global mean temperature in 2016 increased by about 1.1 °C compared to ~~that of~~the preindustrial period, as released by the World Meteorological Organization (https://public.wmo.int/en/media/press-release~~), one~~). One major consequence of this continuing and accelerating warming is the rapid melting of ice ~~in~~at high latitudes. ~~Ten~~The ten lowest minimum Arctic sea -ice extents since satellite records were made available in 1979 have ~~taken place in recent~~happened in every year of the last decade except for 2005, as documented by National Snow and Ice Data Centre. Moreover, an ice-free Arctic Ocean is estimated to emerge in around 2050 on the basis of climate model projections (Overland et al., 2011). As ~~the~~ sea -ice retreats, ~~its reflectivity~~the surface of the Arctic Ocean becomes less reflective and ~~insulation decrease.~~the enhanced open-ocean region leads to greater air–sea heat exchange due to the reduced insulating effect of sea ice. This leads to ~~the~~ changes in the surface heat budget~~,~~ and ~~the~~ changes in overlying cloud and water vapour, further ~~amplify the~~amplifying Arctic warming and sea -ice melting. Many studies have shown that the accelerated Arctic sea -ice retreat ~~is~~ possibly ~~resulted~~results from local ice-albedo positive feedback (Winton, 2008), meridional heat transport by atmospheric circulation and oceanic current (Alexeev et al., 2013), or sea -ice drift out of the Fram Strait (Nghiem et al., 2007; Krumpen et al., 2016). In turn, Arctic sea -ice decline can result in a variety of impacts on climate change, such as Arctic amplification (Serreze et al., 2009), change of cloud cover and precipitation (Liu et al., 2012; Bintanja and Selten, 2014), shift in atmospheric circulation pattern (Alexander et al., 2004), and slow-down of the Atlantic Meridional Overturning Circulation (Sévellec et al., 2017). A detailed consequence of Arctic sea -ice decline classified by local and remote effects ~~have~~has been reviewed by Vihma et al. (2014).

Such ongoing high CO_2 level and low ice concentration in the Arctic is not unique in Earth's history. Geological data show that during the Pliocene, the CO_2 concentration in the atmosphere ~~did reach~~reached 400 ppm or even more, and extreme warmth and Arctic amplification are recorded in multi-proxy evidence, including the longest and most complete record from Lake El'gygytgyn, an undisturbed Siberian lake in northeast Arctic Russia (Brigham-Grette et al., 2013). Seasonally ice-free conditions existed in some Arctic regions in the mid-Pliocene until ~~the~~ circulation through the Bering Strait reversed ~~and~~, at which point the excess freshwater supply might have facilitated sea -ice formation (Matthiessen et al., 2009). Several climate models have simulated the Pliocene but failed to reproduce the strong Arctic amplification ~~showed~~shown in geological proxy data (Dowsett et al., 2012). While most of the previous studies on ~~contribution~~the contributions of the sea -ice effect to Arctic amplification focus on contemporary ~~trend~~trends or future ~~projection~~projections, here the Pliocene simulation is selected ~~because of~~for three reasons: (1) The Pliocene epoch ~~(~~ (approximately 3 million years ago), the most recent warm period with ~~the~~ CO_2 concentrations similar ~~CO_2 concentration as~~to today, is not only an analogue of future climate change but also an appropriate past time-slice to examine regarding sea -ice effect (Haywood et al., 2016a). (2) The Pliocene simulation can be partly verified by proxy data reconstructed from deep-sea oxygen isotope analysis (Dowsett et al., 2012), while projecting the future ~~projection~~ from a climate model is of high uncertainty owing to the lack of any validation. (3) Whereas the historical or undergoing climate variability is transient, the Pliocene simulation is obtained after the model integration reaches ~~a~~ quasi-equilibrium ~~state~~. As inferred from Li et al. (2013), the equilibrium response is in principle reversible, while transient response is hysteretic, suggesting that the Pliocene simulation can better represent a steady climate response.

Two physical ~~attributions~~characteristics of sea -ice are considered to affect climate system. One is much higher surface reflectivity of ice than that of open water, and the other is that ice can inhibit or reduce the exchange of momentum, heat, and mass between the atmosphere and ocean~~, hereafter~~. Hereafter we refer these two ~~attributions~~effects as "albedo" and "insulation~~ effects,~~" respectively. Most previous studies on the two effects are mainly carried out by sensitivity experiments with the atmospheric general circulation model (AGCM). For instance, Gildor et al. (2014) examined the role of sea ~~-~~ice ~~on~~in the hydrological cycle using the Community Atmospheric General Circulation Model (CAM3). ~~Two~~The two effects are separated by modifying the sea ~~-~~ice albedo to that of open-water, or setting the sea ~~-~~ice thickness to zero ~~but its albedo~~ and keeping albedo unchanged. Their results show that the insulation effect on the hydrological cycle is larger than the albedo effect, and these two effects are not independent, i.e. their total effect is not the sum of their separate contribution. Lang et al. (2017) also pointed out that the sea ~~-~~ice thinning in recent years can lead to a 37% increase~~ 37%~~ of Arctic amplification through the enhanced insulation effect, as estimated by an AGCM. Note that sea surface temperature (SST) is prescribed in their AGCM simulation, while sea ~~-~~ice albedo or thickness is modified. In fact, the modification of sea ~~-~~ice does not closely match the fixed SST~~ closely~~, which may lead to a bias in the sea ~~-~~ice effect estimation from the AGCM simulation. The climate system, in turn, reinforces sea ~~-~~ice loss while influenced by albedo or insulation ~~effect~~effects, which ~~is~~are known as ice~~-~~albedo feedback or ice~~-~~insulation feedback. In addition, albedo ~~effect~~ and insulation ~~effect interacts~~interact in a nonlinear way (Gildor et al., 2014). These feedbacks and ~~interaction~~interactions add more challenges to ~~understand~~understanding the effect of sea ~~-~~ice on climate. Recently, Burt et al. (2016) and Kim et al. (2016) addressed the relationship between sea ~~-~~ice loss and air~~-~~sea interface heat budget using the Community Earth System Model (CESM) simulation and cyclo-stationary empirical orthogonal function (CSEOF) analysis, respectively. However, the studies contain large uncertainties due to the hysteresis of transient processes (Li et al., 2013). Although the surface heat budget is the most fundamental ~~to~~ aspect of air~~-~~sea interaction, it is still not clear to what ~~degree~~extent heat flux responds to the change of Arctic sea ~~-~~ice. Therefore the present study aims to quantitatively assess the variation of each individual component of air~~-~~sea heat flux caused by the decrease of Arctic sea ~~-~~ice albedo and insulation. The analysis is based on the EC-Earth simulation of the Pliocene climate, which ~~representing~~represents an analogue for a future climate at equilibrium ~~climate~~with modern greenhouse gas levels, and the reference state is preindustrial equilibrium climate state.

The remainder of the paper is organized as follows. Section 2 describes the EC-Earth model and experimental design, and introduces the climate feedback and response analysis method (CFRAM~~),~~) as well as the approach to extract the impact ~~contributed from~~of sea ~~-~~ice loss. In ~~section~~Section 3, we present several climate features simulated in the Pliocene experiment. The albedo and insulation effects of sea ~~-~~ice on air~~-~~sea interface heat flux are investigated in Sections 4 and 5, respectively~~ in sections 4 and 5, ,~~ followed by summary and discussion in ~~section~~Section 6.

2 Model and method

2.1 Model description and experimental design

The model applied in the study is the global coupled climate model EC-Earth (version 3.1, Hazeleger et al., 2012). Its atmospheric component is the Integrated Forecast System (IFS, version cycle 36r4) developed at the European Centre for Medium-Range Weather Forecast (ECMWF), including the land model H-TESSEL (Balsamo et al., 2009). This atmospheric spectral model is run at T159 resolution (roughly 1.125°, ~approximately 125 km) with 62 vertical levels and coupled to thean ocean component that is based on the Nucleus for European Modelling of the Ocean (NEMO, version 3.3, Madec, 2008) and the Louvain-la-Neuve sea -ice Model (LIM, version 3, Vancoppenolle et al. 2009). The NEMO iswas developed at the Institute Pierre Simon Laplace (IPSL) and has a resolution of about 1° and 46 vertical levels. In LIM3, surface albedo parameterization follows Shine and Henderson-Sellers (1985),) with the following values: thick dry snow 0.8, thick melting snow 0.65, thick frozen bare ice 0.72, thick melting bare ice 0.53, and thin melting ice 0.47. The tuning of bare ice and snow albedo would affect whether the equilibrium ice thickness is reasonable and whether the ice is from a multi-year or seasonal ice zone. The coupling between the atmosphere and ocean/sea -ice is through the Ocean Atmosphere Sea -ice Soil coupler (OASIS, version 3.0, Valcke, 2006). EC-Earth has been used to examine the Arctic climate for the historical period and future scenarios in CMIP5. An evaluation of EC-Earth for the Arctic shows that the model simulates the 20th century Arctic climate reasonably well. EC-Earth simulated cloud variables with slightly larger cloud fraction and less cloud condensate compared tothan ERA-Interim, which leadled to similar longwave cloud radiative forcing. Moreover, total cloud forcing in EC-Earth is in good agreement towith the APP-x satellite estimates (Koenigk et al., 2013). Koenigk et al. (2013) showed that the annual mean surface temperature in the Arctic increases by 12 K in the EC-Earth RCP8.5 scenario simulation, and the most pronounced warming is during autumn and winter in the lower atmosphere. A likely ice-free Arctic is indicated in September around 2040. The enhanced oceanic meridional heat flux into the Arctic (Koenigk et al., 2013) and the enhanced atmospheric northward latent energy transport (Graversen and Burtu, 2016) are suggested as major contributors to the future Arctic warming in the EC-Earth simulation. Recently theThe EC-Earth model ishas also been applied to understand the past climateclimates, such as changes in the change of Arctic climate (Muschitiello et al., 2015), African monsoonmonsoons (Pausata et al., 2016; Gaetani et al., 2017), tropical cyclonecyclones (Pausata et al., 2017a)), and ENSO activity (Pausata et al., 2017b) during the mid-Holocene. In this study we apply the model to the mid-Pliocene climate and focus on the effects of sea -ice on Arctic climate change.

Two numerical experiments are performed with EC-Earth to facilitate this study. One is the preindustrial control run with the 1850 CO_2 concentration of 284.725 ppm, and the other is the mid-Pliocene warm period (3.264–3.025 Ma) sensitivity experiment in which the atmospheric CO_2 concentration is set to 400 ppm. Following the protocol of the Pliocene Model Intercomparison Project, phase 2 (PlioMIP2, Haywood et al., 2016b), several configurations are modified in the Pliocene simulation: (1) in the Pliocene experiment, all other trace gases exceptother than CO_2, such as CH_4 and, N_2O, and aerosols in the Pliocene experiment, are specified to beas identical to the preindustrial run. to account for the absence of proxy data. (2) Orbit forcing, including eccentricity, obliquity, and precession, remains same within the preindustrial run. as in the mid-Pliocene warm period, which has a near-modern orbital forcing. (3) Enhanced boundary conditionconditions from the Pliocene Research, Interpretation and Synoptic Mapping group (PRISM, Dowsett et al., 2016)), including land–sea mask, topography, bathymetry, and ice-sheet, are applied in the Pliocene experiment where the land-sea mask, orography, bathymetry, vegetation. The global distributions of lake, soil, and ice-sheetbiome are modified accordingly.to match the new land–sea mask and ice reconstruction. The integrations of the preindustrial control run and the Pliocene experiment are carried out for 500 years, and it takes approximateapproximately 300 years for the model to reach equilibrium. From our last 200 years of output in the Pliocene simulation (see Figure S1 in the Supplement), the mean top of the atmosphere (TOA) net radiation is about –0.5 Wm^{-2} and its trend is near zero. The trend of mean SST is about 0.027 K/century, which fulfils the PMIP4 criterion that the trend of mean SST should be less than 0.05 K/century (Kageyama et al., 2018). In this study, the last 100-year-mean of all variables are used for analysis, and the Pliocene climate anomalies are calculated with respect toby subtracting the mean of the preindustrial control run. The Arctic insimulation without trends removal. In the following analysis, the Arctic is defined as the region poleward of 70 °N.

2.2 Climate feedback and response analysis method (CFRAM)

Radiative forcing varies as CO_2 concentration increasesClimate system warming in the Pliocene experiment is driven by variation in radiative forcing, which drives climate system warming.is in turn caused by increased CO_2 concentration. In response to temperature change, factors such as surface albedo, cloud, water vapour, and air temperature will adjust and feedback until the climate system reaches equilibrium. The contribution from each factor can be quantitatively evaluated by climate feedback analysis. The traditionalTraditional climate feedback analysis methodmethods, such as partial radiative perturbation (PRP) technique, is based on TOA radiative budget (Wetherald and Manabe, 1988), while the radiative kernel method can be extended to the surface and remain computationally efficient (Soden and Held, 2006; Pithan and Mauritsen, 2014). However, none of them takes individual physical processes into account, particularly non-radiative processes. The climate feedback and response analysis method (CFRAM), proposed by Lu and Cai (2009)), overcomes this limitation.

CFRAM contains two parts: one is decomposing radiative perturbation into individual contribution, including shortwave and longwave components, from CO_2, surface albedo, cloud, water vapour, and air temperature. It:

$$\Delta Q_{rad} = \Delta\left(S+R\right)_{co_2} + \Delta S_{albedo} + \Delta\left(S+R\right)_{cloud} + \Delta\left(S+R\right)_{WV} + \Delta R_T \quad , \quad (1)$$

where ΔQ_{rad} is performed by offline calculation usingtotal radiative transfer model (Fu and Liou, 1993) withflux perturbation at the output fromsurface (ice and ocean), ΔS and ΔR are the preindustrial control run and net shortwave and longwave radiative perturbations at the Pliocene sensitivity experiment.surface, respectively, and the subscripts CO_2, albedo, cloud, WV, and T represent the partial radiative perturbation due to changes in the CO_2 concentration, surface albedo, cloud properties, atmospheric water vapour, and air temperature, respectively. Note that here it is assumed that the interactions among the factors (CO_2, surface albedo, cloud, water vapour, and air temperature) are negligible and the higher order terms of each factors are omitted. The other part is calculating partial temperatetemperature perturbation due to individual radiative and non-radiative feedback processes, which is based on total energy balance and derived from the relationship between longwave radiation and temperature change. A more detailed description about CFRAM can be found in Lu and Cai (2009).

CFRAM is a practical diagnostic tool to analyzeanalyse the role of various forcing and feedback agents and has been used widely in climate change research (e.g. Taylor et al., 2013; Song and Zhang, 2014; Hu et al., 2017). In the present study, total radiative flux perturbation is first calculated from the surface radiative flux difference between the Pliocene sensitivity experiment and the preindustrial control run. Then we apply the first part of CFRAM to ~~obtain the surface radiative flux~~ compute each partial radiative perturbation, which is performed by offline calculation using a radiative transfer model (Fu and Liou, 1993). The linear approximation in Equation (1) should be verified with the output from the radiative transfer model. Finally, the partial radiative perturbation due to albedo, cloud, and water vapour~~, and link it~~ can be used to evaluate albedo or insulation ~~effect~~effects of sea ~~-~~ice.

2.3 Approach to extract sea ~~-~~ice effects

As sea ~~-~~ice declines in the Pliocene warming climate, air–sea heat flux ~~at air-sea interface~~ varies. However, the variation is not only due to the impact of sea ~~-~~ice but also determined by other factors, such as atmospheric circulation. Therefore an approach capable of quantifying the influence of a factor is indispensable ~~to extract~~for extracting the corresponding ~~part~~contribution of sea ~~-~~ice effect from the total heat flux change. To distinguish sea ~~-~~ice's contribution from the other processes, the linkage between sea ~~-~~ice and heat flux needs to be identified through either temporal correlation or spatial correlation, if the effect of sea ~~-~~ice is assumed to be linear. A canonical case of the former is ~~the~~ equilibrium feedback assessment (EFA~~) method,~~), which has been used to quantify the influence of sea ~~-~~ice on cloud cover (Liu et al., 2012) and the heat flux response to SST (Frankignoul and Kestenare, 2002).

Here we adopt a method similar to EFA, but built on spatial correlation due to the limitation of data and computation. As a high-temporal–resolution CFRAM calculation, such as 6-hourly or daily, is computationally expensive, monthly data are used in the analysis. However, the monthly resolution is too coarse to explain the relationship between heat fluxes and sea-ice concentration by temporal correlations. Therefore, spatial correlations are calculated. This method is used in Hu et al. (2017) to correct cloud feedback. The response of heat flux to ~~change~~changes in sea ~~-~~ice concentration (SIC) is represented as

$$F(s) = \lambda I(s) + N(s), \quad (~~1)~~2)$$

where $F(s)$ is the heat flux anomaly at location s, $I(s)$ is anomalous SIC, λ is the response coefficient of heat flux to SIC change, and $N(s)$ is the climate noise independent of SIC variability. The response coefficient can be calculated as

$$\lambda = \frac{cov[F(s), I(s)]}{cov[I(s), I(s)]}, \quad (~~2)~~3)$$

where $cov[F(s), I(s)]$ is the spatial covariance between heat flux and SIC, and $cov[I(s), I(s)]$ is the spatial variance of SIC.

The statistical significance of response coefficient is tested using a two-sided Student's t-test, where the effective degree of freedom is estimated from the auto-correlation function (Bretherton et al., 1999) as

$$n = N\frac{1 - r_1 r_2}{1 + r_1 r_2}, \quad (~~3~~4)$$

where n is the effective degree of freedom, N is the sample size, and r_1 is the lag-one auto-correlation of heat flux ~~and~~ (similarly r_2 for SIC~~.~~). Note that auto-correlation of heat flux and SIC is so strong that r_1 and r_2 can approach 1, leading to a ~~drastically~~drastic decrease of effective degree of freedom.

3 Mid-Pliocene climate features

Unlike the present earthmodern Earth observation system, the Pliocene climate proxy data are reconstructed mainly from the benthic oxygen isotope analysis of deep-sea samples, such as forminifera, diatom, and ostracod assemblages. Several climate features have been revealed with the multi-proxy data, one (Haywood et al., 2016a). One of the most concern is permanent El Niño-like condition during the mid-Pliocene warm period (Wara et al., 2005; Federov et al, 2006), which points out that the SST difference between the western and eastern equatorial Pacific was absent or less evident, similar to the contemporary El Niño SST pattern while not happening on interannual timescale. The other characteristicconcerning is Arctic amplification — the warming in surface air temperature (SAT) in the Arctic region tends to be more than twice as warm as that in the low- and mid-latitude regionregions (Serreze and Barry, 2011). However, theFurthermore, Arctic SAT and SST during Pliocene is significantly warmer than today even though they have, despite comparable CO_2 concentrationconcentrations (Ballantyne et al., 2013), which). This probably stems from the fact that the present transient process that has not yet reached a steady state, or is due to the change of the gateways that can affect the Atlantic meridional overturning circulation (AMOC) (Brierley and Fedorov, 2016; Otto-Bliesner et al., 2017; Feng et al., 2017).

In Figure 1, we show the changes inannual mean warming and seasonal warming averaged over the Arctic Ocean for SST and SAT between the Pliocene and preindustrial period and the Pliocene epoch.simulations. The shaded circles in the SST change distribution (Figure 1a) represent the mean annual SST anomalies at 95% confidence-assessed marine sites from the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP),, which are available in the supplementary table of Dowsett et al. (2012). The overlay of proxy data over the filled contour maps does not show the difference well, so the difference of annual mean SST anomaly between EC-Earth simulation and the proxy data is shown in Figure S2. In contrast to the large underestimation of multi-model ensembles toregarding the warming over the northern Atlantic sector of the Arctic Ocean (Dowsett et al., 2012), the warming amplitude and pattern in EC-Earth simulation is comparable with the high-confidence proxy data. This is consistent with the resultsresult of Koenigk et al. (2013), which pointed outsuggests that the sea ice change in EC-Earth is strong and that the EC-Earth simulations show a strong Arctic amplification compared to most CMIP3 models. Meanwhile, a warming can be seen along the coastal upwelling zones off the America, which implies a permanent El Niño-like feature. According to Figure 1b, the Pliocene SAT north of 70 °N is as much as 10-–18 °C higher than the preindustrial period, similar to the mid-Pliocene paleoclimate estimate by Robinson et al. (2008).

FigureFigures 1a and 1b also show that the SST and SAT anomaly patterns are somewhat similar over low- and mid-latitude region, but they are apparentlyregions, different from over high-latitude regionregions, particularly over the Arctic Ocean, which iswas previously illustrated by Hill et al. (2014). This disparity results from the intense air-–sea coupling over tropical and subtropical oceanoceans, while the air-–sea interaction is relatively weak over the Arctic Ocean owing to the albedo and insulation effects of sea -ice. Noteworthily, theNotably, SST warming of SST averaged over the Arctic Ocean shows a distinct seasonal evolution from that of SAT, and; the maximum warming in SST occurs in summer, while the maximum warming in SAT happens during winter (FigureFigures 1c and 1d).

The SIC is very sensitive during the different period as shown in Figure 2a-c. During the preindustrial period, the annual mean sea -ice appears to cover the whole Arctic Ocean except for the Greenland Sea, the Norwegian Sea, and the Barents Sea, and it retreats to the western Arctic Ocean in the Pliocene, leading to a significant decrease of sea -ice extent over the Fram Basin and Baffin Bay. (Figures 2a–c). Consequently, the net air-sea interface heat exchange at the surface of ice or ocean varies greatly (Figure 2d-f). The sea-ice –f). The net heat flux and other flux terms mentioned hereafter are defined as positive downward. A positive value means that the ocean gains heat from the atmosphere and a negative value means oceanic heat loss. The net heat flux over the sea ice–covered area seems to beclearly shows net heat loss during both the preindustrial period and the Pliocene. (Figures 2d and 2e). Thus, it can be expected that net heat gain will occur when the sea -ice declines. However, the Fram Basin and Baffin Bay displaysdisplay pronounced heat loss, which might be linked to the disappearance of sea -ice in the Pliocene (Figure 2b).

The net heat flux at the air-sea interfacesurface of ice or ocean can be writtenrepresented as

$Q_{net} = Q_{sw} + Q_{lw} + Q_{sh} + Q_{lh}$, (4)

Where Q_{sw} and Q_{lw} are the sum of four terms: the net solar shortwave and radiative flux, the net longwave radiative heat fluxes, Q_{sh} and Q_{lh} areflux, the turbulent sensible heat flux, and the turbulent latent heat fluxes. All terms are defined positive downward. Therefore, the positive value means that ocean gains heat from the atmosphere and the negative value means oceanic heat loss.

—flux. Figure 3 compares the annual mean of the four components of surface heat flux terms to further illustrate the possible relationship between sea -ice and net heat exchange (FigureFigures 2c and 2f). The radiative and turbulent heat fluxesflux anomalies both are positive over the Chukchi Sea, therebyindicating a marked net heat gain emerging there. Over the Beaufort Sea and East Siberian Sea, the positive change in the net shortwave radiation isanomalies are dominant over the other three negative components, yielding the net heat gain. On the contraryIn contrast, the positive net shortwave radiation anomalies over the Fram Basin, the Greenland Sea, and Baffin Bay is are less than the sum of net longwave radiation and turbulent heat fluxesflux anomalies, thus leading to net heat loss. The negative turbulent heat fluxesflux anomalies over Fram Basin, the Greenland Sea, and Baffin Bay are so prominent, indicating the sea -ice effect on turbulent heat fluxesflux anomalies in light of the transition to ice-covered or ice-free state states, respectively. As shown inNote that the partition threshold of ice-free and ice-covered conditions is 15% SIC, i.e., a grid point with an SIC of less than 15% is considered ice-free. In Figure 2c, the diagonal stripe represents the region with the transition from ice-covered to ice-free condition, and the diagonal crosshatch represents the region remainingthat retains its ice-covered status as the simulation shifts from the preindustrial period to the Pliocene. Only ice-covered regions are examined, as there appears to be large surface heat flux changes in regions that contain no sea ice in both periods, which could be contaminating the statistical relationships between sea ice and the associated surface flux changes.

4 Albedo effect of sea -ice

Arctic amplification has been demonstrated by significant SAT anomalies in the foregoing Pliocene simulation, and it can be accounted as the synergy of CO_2 external forcing and feedback effects associated with . Similar to the process-based decomposition of a climate difference in Hu et al. (2017), the SAT anomalies in the Pliocene simulation as compared to the preindustrial simulation can be thought of as the combination of partial temperature perturbations due to radiative feedbacks (surface albedo, cloud, water vapour, and air temperature.) and non-radiative feedbacks (surface sensible and latent heat fluxes, dynamical advection, ocean processes, etc.). That is to say, the albedo effect of sea -ice and snow can be quantified by climate feedback analysis such as CFRAM. The surface Surface albedo is defined as the ratioproportion of the reflected to the incomingincident solar shortwave radiation that is reflected by the surface, therefore indicating that albedo effect is relevant withto net shortwave radiation rather than net longwave radiation and turbulent heat fluxes.

The annual mean net shortwave radiation change due to sea -ice and snow albedo derived from CFRAM is presented in Figure 4. The largest net shortwave radiation change exceeding 50 Wm^{-2} takes place over the Fram Basin and Baffin Bay, and most of the Arctic Ocean, except for part of the North Atlantic and the Barents Sea show, shows net shortwave radiative heat gain. ComparingCompared with the SIC change (Figure 2c), the increase of annual mean net shortwave radiation absorbed by the ocean is in accordance with sea -ice retreat, which can be clearly depicted in a scatter plot (Figure 5). The highThe effective degree of freedom is calculated from Formula (4) for testing statistical significance, and the correlation coefficient (r= = 0.92)84) is significant at a 99% confidence level. This indicates that changes in sea -ice extent can explain the approximate 8471% (square of correlation coefficient) variance of total shortwave radiation change due to albedo, and the residual variance may be caused by changes in snow cover orand sea -ice/snow state as well as thickness. The statistically significant response coefficient calculated according to formula (23) is −46.5 −43.0 Wm^{-2} (exceeding 99% confidence level),, indicating that a 1% decrease in annual mean SIC leads to an approximate 0.543 Wm^{-2} increase in net shortwave radiative heat flux at the surface.

Regarding the seasonal variation ofAs SIC and the incoming solar radiation are distinct in the polar region vary with season, we examine the response of net shortwave radiation to sea -ice change for every month. As shown in Figure 6, the response coefficient of albedo to SIC displays a seasonal variation, peaking in which it peaks in MayJune with thea maximum absolute value 188.1of 178.3 Wm^{-2} (approximate 21.8 Wm^{-2} increase in net shortwave radiation due to 1% decrease in SIC). The prominent oceanic heating in May and June seems inconsistentconsistent with the maximum SST warming in August, as the response of seawater lags about 2 months behind due to the great heat inertia and heat capacity of seawater (Venegas et al., 1997; Zheng et al., 2014). Even though Arctic sea -ice itself has a great variability owing to melting and freezing processes, the SIC anomalies do not exhibit a large variability in different seasons, ranging from 0.3419 to 0.4426 as shown in the standard deviation of SIC (Table 1). However, the standard deviation of net shortwave radiation anomalies (with respect to monthly mean) associated with albedo effect varies from 88.4352.45 Wm^{-2} in May to 0 Wm^{-2} in December, when the polar night occurringoccurs without any sunlight. Moreover, it is found fromour correlation analysis indicates that sea -ice has a statistically significant impact on surface shortwave radiation, except in November, December, and January, when there is low incident solar shortwave radiation during the Arctic winter. Overall, the seasonality of sea ice's albedo effect ~~of sea ice~~ on surface shortwave radiation is attributed primarily to the seasonal cycle of net shortwave radiation, and the contribution of ~~sea ice~~SIC variation is substantially small.

5 Insulation effect of sea -ice

5.1 Insulation effect of sea -ice on surface radiation

The ~~insulation~~insulating effect of sea -ice~~,~~ has an indirect effect on the net surface shortwave and longwave fluxes. By separating the overlying atmosphere from the ocean, ~~does not affect surface shortwave or longwave radiation directly. In fact, the insulation~~sea ice reduces ~~the~~ evaporation from the ocean ~~to atmosphere~~, resulting in a decrease ~~of~~ in water vapour and cloud cover~~, and thus playing~~. This reduction plays a non-negligible role ~~on~~ in the amount of downward shortwave and longwave radiation reaching the surface ~~radiation~~. However, ~~the water vapour and cloud contain a mixture of local evaporation and~~ remote moisture transport~~. In~~ also affects water vapour and cloud amount. Thus, in order to address the insulation effect of sea -ice, two steps have to be performed. First, we obtain the total influence of water and cloud on surface radiation by CFRAM. Second, we need to extract the contribution from a local source associated with sea -ice.

Figure 7 shows the annual mean cloud feedback and water vapour feedback on net shortwave and longwave radiation, respectively~~.~~, before removing the remote effects on clouds and water vapour. Even though ~~the~~an increase in cloud cover is expected with the diminishing Arctic sea -ice (Liu et al., 2012), whether the increased cloud cover will heat or cool the surface depends on the cloud characteristics ~~of cloud~~. The cloud feedback on shortwave radiation is nearly out of phase with that on longwave radiation, except in the Beaufort Sea and the East Siberian Sea (Figure 7a, 7b). The significant decrease of low cloud cover in the North Atlantic (Figure S3a) may enhance incoming shortwave radiation and weaken downwelling longwave radiation, thus contributing to the positive anomaly in shortwave radiation and negative anomaly in longwave radiation in the North Atlantic. Similarly, the increase of high cloud cover east and north of Greenland (Figure S3b) is responsible for the positive anomaly in longwave radiation over the related areas. In contrast, ~~the~~ water vapour feedback tends to simultaneously cool and heat the surface by absorbing solar radiation and ~~heat the surface by~~ downwelling longwave radiation, ~~and~~respectively; the ~~latter~~ heating is one order of magnitude higher than the ~~former~~ cooling (Figure 7c, 7d).

The approach to extract the ~~counterpart of sea ice~~ local insulation effect due to changes in sea ice concentration is based on the premise that the insulation effect on surface radiation is linear with SIC. Like the steps performed ~~in~~to isolate the albedo effect, the response coefficient of shortwave and longwave radiation due to cloud and water vapour for annual mean and seasonal evolution can be calculated respectively, and the results are shown in Figure 8. ~~As to~~In the annual mean, the main contributor comes from cloud feedback on longwave radiation ~~(–12.6~~(–11.1 Wm^{-2}), and the cloud feedback on shortwave radiation and water vapour feedback on longwave radiation are similar in magnitude, but opposite in sign. In addition, the annual mean absorption of incoming solar radiation by water vapour is negligible, and this is true for the individual month as well. The absorption and reflection of shortwave radiation by cloud ~~represents~~shows a pronounced seasonal cycle, with a large effect in ~~July and~~ August. However, there is no statistically significant relationship between ~~SIC and~~ cloud feedback on shortwave radiation and SIC (Table 2). ~~Comparing~~Compared to the seasonal variation of ~~shortwave radiation change,~~ standard deviation of the net shortwave radiation anomalies, standard deviation of the net longwave radiation anomalies caused by cloud and water vapour associated with local SIC anomalies both show smaller seasonal variation, therefore leading to a relatively constant contribution of sea ~~-~~ice insulation to surface longwave radiation, except in summer months when there is a lack of ~~significant interaction~~linear relationship between SIC and longwave radiation (Table 2). Note that the longwave cloud forcing in September (–17.6 Wm^{-2}) is quite large relative to all the other months, which might result from the maximum cloud cover over the Arctic, as well as the fact that the linear relationship between sea ice concentration and longwave radiation changes due to cloud is strongest in September.

5.2 Insulation effect of sea ~~-~~ice on turbulent heat fluxes

~~The air~~ Air–sea turbulent heat fluxes, including sensible and latent heat fluxes, have been widely studied with the bulk aerodynamic formula, which specifies that the turbulent heat fluxes are dependent on surface wind speed, sea surface and air temperature difference, specific humidity difference, and the bulk heat transfer coefficient. However, due to the existence of sea ~~-~~ice, the Arctic turbulent heat fluxes show distinctive features from ice-free ~~condition~~conditions, which has been mentioned in Section 3. It is therefore essential to take the insulation effect of sea ~~-~~ice into account and differentiate ~~ice-covered flux~~fluxes from ice-covered versus ice-free ~~one.~~areas. This is demonstrated in Figure 9, which displays the Pliocene anomalies in annual mean sensible and latent heat ~~flux change~~fluxes as a function of SIC anomalies. There ~~are~~ is a larger ~~spreads of~~ spread in the turbulent heat flux ~~change~~anomalies over the ice-free ~~area~~areas (grey symbols, corresponding to the diagonal hatched region in Figure 2c) than ~~that of~~ in anomalies from the ice-covered~~,~~ areas (light blue symbols, cross-hatched region in Figure 2c) because the former is free from the constraint of sea ~~-~~ice. The constraint of sea ~~-~~ice can be apparently captured through the scatter plot of turbulent heat flux and changes in SIC ~~change (the~~ (light blue ~~plot in Figure 9, corresponding to the diagonal crosshatch~~symbols). For the ice-covered areas ~~in Figure 2c), and,~~ SIC can explain approximate 59% and 74% (square of correlation coefficient) of the variance in the sensible heat flux and latent heat flux, respectively.

The linear regressions of sensible and latent heat flux anomalies on SIC are similar but different. The response coefficient of sensible heat flux (35.3 Wm^{-2}) to SIC is larger than that of latent heat flux (27.7 Wm^{-2}~~),~~) for the ice-covered areas, which means that the sensible heat flux is more sensitive to SIC change than the latent heat flux. ~~Noteworthily~~Notably, this is different from the turbulent heat flux variability over low- and mid-latitude regions, where the ~~trend~~variability of sensible heat flux is significantly less than that of latent heat flux ~~(e.g.,~~ , such as the trend of turbulent heat flux over the low- and mid-latitude North Pacific and North Atlantic oceans from 1984–2004 (Li et al., 2011). The positive intercept on the turbulent flux anomaly axis implies more heat gain at the sea surface, even ~~if there is no~~without SIC change. Because the large specific heat capacity of seawater leads to less warming of the ocean than of the atmosphere, ~~therefore~~ the sea surface and air temperature difference ~~or~~ (the specific humidity difference) decreases ~~in~~during the cold season when the turbulent heat transport is the most pronounced, ~~and~~ consequently resulting in ~~the less~~a lower annual heat loss from the ocean to the atmosphere.

Figure 10 shows the seasonal response coefficient of the sensible and latent heat fluxes to the ~~sea-ice. Apparently two~~ SIC. It appears that the turbulent heat fluxes have ~~the~~a similar seasonal evolution, peaking in November and showing a negative response in July. Therefore~~ the maximum warming of SAT occurs in November as a consequence of~~ , the prompt atmospheric ~~prompt~~ response to turbulent heating~~.~~ is an important contributing factor to the maximum SAT warming that occurs in November. The melting of sea~~-ice~~ ice due to warming by high levels of CO_2 can attenuate the insulation effect and result in more heat transfer through the processes of conduction or evaporation from the ocean to the atmosphere when SST is higher than SAT~~,~~; therefore, the turbulent heat fluxes correlate positively with SIC in all seasons except summer (Table 3). If SAT is higher than SST~~,~~ (for instance, in July~~ the~~), sea ~~-~~ice will inhibit the heat transfer from the atmosphere to ocean~~,~~; thus, the negative correlation emerges. However, the correlations between the turbulent heat fluxes and SIC in summer are not statistically significant (Table 3), indicating other factors ~~might be dominant~~ rather than sea ~~-~~ice might be dominant.

6 Summary and discussion

~~In the present work we attempt to understand the albedo and insulation effects of sea-ice, on a warm Arctic climate during Pliocene simulated by EC-Earth coupled model. In contrast to~~Arctic amplification in the Pliocene has previously been addressed from reconstructed data (e.g. Robinson et al., 2008; Brigham-Grette et al., 2013); however these data tell only part of the story because of a scarcity of data sites. A model may be applied to investigate mechanisms and processes that help understanding. In contrast to the underestimation of multi-model ensembles documented in Dowsett et al. (2012), the EC-Earth Pliocene simulation can better display some ~~main features manifested in the~~ characteristics that have been revealed by the paleoclimate proxy data from deep-sea oxygen isotope analysis. Thus the EC-Earth coupled model is used in the present work to simulate the Pliocene climate and study the contribution of sea ice albedo and insulation to Arctic amplification~~ in Pliocene had been confirmed by reconstructed data (e.g. Robinson et al., 2008; Brigham-Grette et al., 2013). Proxy data, however, tell only part of the story. Thus a model is applied and it can reveal the complete picture with reasonable explanation~~.

~~As a key to reveal the important features of Arctic amplification, the air~~ Air–sea heat flux variation in response to Arctic sea ~~-~~ice change is quantitatively assessed by CFRAM and an EFA-like method~~.~~ in order to reveal important features of Arctic amplification. Table 4 summarizes the results presented in ~~section~~Sections 4 and 5, which separately ~~illustrated~~illustrate the effects of changes in albedo and insulation of sea ~~-~~ice on surface heat exchange. Annual mean and seasonal evolution of effects are both considered~~, and~~ . These allow us to partly interpret the mechanisms of Arctic amplification because the results are merely the contribution from sea ~~-~~ice change. A complete energy budget, including dynamical and thermodynamical processes, is required to understand Arctic amplification comprehensively.
The Pliocene Arctic amplification compared to the preindustrial simulation represents a maximum SST warming in August and ~~expected to partly interpret the variability of heat flux.~~

~~The albedo~~a maximum SAT warming in November, which might be associated with the albedo and insulation effects of sea ice. Albedo only regulates the shortwave radiation, and its effect is primarily determined by annual cycle of insolation. As sea -ice melts ~~from~~starting in early spring, the enhanced insolation through open sea surface makes the ocean warmer, with the most pronounced heating anomalies in May and June. Because of the great heat inertia and heat capacity of seawater, the SST ~~warming~~anomaly peaks in August. As a result of the albedo effect of sea -ice, ocean heat content increases and more heat is stored in the upper ocean, which is the potential for the later enhanced heat release from ocean to atmosphere. The insulation effect of sea -ice can indirectly modulate ~~not only~~ shortwave and longwave radiation anomalies indirectly through cloud and water vapour~~, but also~~ as well as directly modulate sensible and latent heat ~~fluxes directly~~ flux anomalies, since sea -ice serves as a barrier. Averaged over the year, the absorption of longwave radiation due to insulation effect is about 4 times stronger than the reflected shortwave radiation by cloud, while the contribution of water vapour to shortwave radiation is almost negligible. The longwave radiation ~~change~~anomalies in response to cloud and water vapour is attributed to downwelling longwave radiation, as upwelling longwave radiation depends solely on the surface temperature according to the Stefan–Boltzmann law, and its seasonal variation is relatively small compared to the significant seasonality ~~showing~~ in shortwave radiation. The Pliocene sea -ice decline ~~accelerates~~, as compared to the preindustrial period, amplifies the turbulent exchange between the ocean and atmosphere, and the annual sum of sensible and latent heat ~~fluxes exceed~~flux anomalies exceeds radiation ~~fluxes.~~flux anomalies. In particular, heat is released to the atmosphere by the prominent enhanced turbulent heat ~~fluxes~~flux anomalies in ~~winter, amplifying the atmospheric warming~~November, contributing to the formation of the maximum SAT anomaly in November.

A synthesis of Arctic amplification given by Serreze and Barry (2011) has introduced some of the physical processes mentioned above, including sea ice loss, albedo feedback, cloud cover, and water vapour. Unlike Serreze and Barry (2011), in this work we apply CFRAM and an EFA-like method to untangle these physical processes and obtain a quantitative understanding of sea-ice effects, which would help to directly evaluate the impact on heat exchange once the sea-ice concentration variation within Arctic is given. The EC-Earth simulation shows a stronger Arctic amplification than multi-model ensembles (Dowsett et al., 2012). However, an underestimation of Arctic warming as compared to proxy data remains in the EC-Earth simulation, implying less warmth produced by the EC-Earth model from oceanic heat transport, which yields a clue for improving the simulation. Furthermore, caution should be exercised when discussing sea-ice effects on heat flux, as underestimating Arctic warming might affect the interface heat exchange.

Though significant albedo and insulation effects of sea -ice have been studied, the possible nonlinear response of heat flux to sea -ice can not be captured in this work. In addition, ~~the~~ this approach to ~~extract~~extracting sea -ice effects is based on ~~the~~ spatial correlation~~,~~; whether the corresponding conclusion is consistent with that from EFA ~~method~~ remains uncertain. The consistency check is computationally expensive for CFRAM calculation, as ~~the~~ EFA requires high temporal resolution. The present study is based on the Pliocene simulation with the EC-Earth, and the results may be model-dependent. Further work is needed to compare our results with other PlioMIP models.

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References

Alexander, M.A., Bhatt, U.S., Walsh, J.E., Timlin, M.S., Miller, J.S. and Scott, J.D.: The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter, J. Climate, 17, 890-905, doi:10.1175/1520-0442(2004)017<0890:TARTRA>2.0.CO;2, 2004.

Alexeev, V.A., Ivanov, V.V., Kwok, R. and Smedsrud, L.H.: North Atlantic warming and declining volume of arctic sea ice, The Cryosphere Discussions, 7, 245-265, doi:10.5194/tcd-7-245-2013, 2013.

Ballantyne, A.P., Axford, Y., Miller, G.H., Otto-Bliesner, B.L., Rosenbloom, N. and White, J.W.: The amplification of Arctic terrestrial surface temperatures by reduced sea-ice extent during the Pliocene, Palaeogeogr. Palaeoclimatol. Palaeoecol., 386, 59-67, doi:10.1016/j.palaeo.2013.05.002, 2013.

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., van den Hurk, B., Hirschi, M. and Betts, A.K.: A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System, J. Hydrometeorol., 10, 623-643, doi:10.1175/2008JHM1068.1, 2009.

Bintanja, R. and Selten, F.M.: Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat, Nature, 509, 479-482, doi:10.1038/nature13259, 2014.

Bretherton, C.S., Widmann, M., Dymnikov, V.P., Wallace, J.M. and Bladé, I.: The effective number of spatial degrees of freedom of a time-varying field, J. Climate, 12, 1990-2009, doi:10.1175/1520-0442(1999)012<1990:TENOSD>2.0.CO;2, 1999.

Brierley, C. M. and Fedorov, A. V.: Comparing the impacts of Miocene–Pliocene changes in inter-ocean gateways on climate: Central American Seaway, Bering Strait, and Indonesia, Earth Planet. Sci. Lett., 444, 116-130, doi:10.1016/j.epsl.2016.03.010, 2016.

Brigham-Grette, J., Melles, M., Minyuk, P., Andreev, A., Tarasov, P., DeConto, R. and Haltia, E.: Pliocene warmth, polar amplification, and stepped Pleistocene cooling recorded in NE Arctic Russia. Science, 340, 1421, doi:10.1126/science.1233137, 2013.

Burt, M.A., Randall, D.A. and Branson, M.D.: Dark warming, J. Climate, 29, 705-719, doi:10.1175/JCLI-D-15-0147.1, 2016.

Dowsett, H.J., Robinson, M.M., Haywood, A.M., Hill, D.J., Dolan, A.M., Stoll, D.K., Abe-Ouchi, A., Chandler, M.A., Rosenbloom, N.A., Otto-Bliesner, B.L. and Bragg, F.J.: Assessing confidence in Pliocene sea surface temperatures to evaluate predictive models, Nat. Clim. Change, 2, 365-371, doi:10.1038/nclimate1455, 2012.

Dowsett, H., Dolan, A., Rowley, D., Moucha, R., Forte, A. M., Mitrovica, J. X., Pound, M., Salzmann, U., Robinson, M., Chandler, M., Foley, K., and Haywood, A.: The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction, Clim. Past, 12, 1519-1538, doi:10.5194/cp-12-1519-2016, 2016.

Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., Barreiro, M., Pacanowski, R.C. and Philander, S.G.: The Pliocene paradox (mechanisms for a permanent El Niño), Science, 312, 1485-1489, doi:10.1126/science.1122666, 2006.

Feng, R., Otto-Bliesner, B. L., Fletcher, T. L., Tabor, C. R., Ballantyne, A. P., & Brady, E. C.: Amplified Late Pliocene terrestrial warmth in northern high latitudes from greater radiative forcing and closed Arctic Ocean gateways, Earth Planet. Sci. Lett., 466, 129-138, doi:10.1016/j.epsl.2017.03.006, 2017.

Frankignoul, C. and Kestenare, E.: The surface heat flux feedback. Part I: estimates from observations in the Atlantic and the North Pacific, Clim. Dynam., 19, 633-647, doi:10.1007/s00382-002-0252-x, 2002.

Fu, Q. and Liou, K.N.: Parameterization of the radiative properties of cirrus clouds, J. Atmos. Sci., 50, 2008–2025, doi:10.1175/1520-0469(1993)050<2008:POTRPO>2.0.CO;2, 1993.

Gaetani, M., Messori G., Zhang Q., Flamant C., and Pausata F.S.: Understanding the mechanisms behind the northward extension of the West African Monsoon during the Mid-Holocene. J. Climate, doi:10.1175/JCLI-D-16-0299.1, 2017.

Gildor, H., Ashkenazy, Y., Tziperman, E. and Lev, I.: The role of sea ice in the temperature-precipitation feedback of glacial cycles, Clim. Dynam., 43, 1001-1010, doi:10.1007/s00382-013-1990-7, 2014.

Graversen, R.G. and Burtu, M.: Arctic amplification enhanced by latent energy transport of atmospheric planetary waves, Q. J. Roy. Meteor. Soc., 142, 2046-2054, doi:10.1002/qj.2802, 2016.

Haywood, A.M., Dowsett, H.J. and Dolan, A.M.: Integrating geological archives and climate models for the mid-Pliocene warm period, Nat. Commun., 7, 1-14, doi:10.1038/ncomms10646, 2016a.

Haywood, A.M., Dowsett, H.J., Dolan, A.M., Chandler, M.A., Hunter, S.J. and Lunt, D.J.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design, Clim. Past, 12, 663-675, doi:10.5194/cp-12-663-2016, 2016b.

Hazeleger, W., Wang, X., Severijns, C., Ştefănescu, S., Bintanja, R., Sterl, A., Wyser, K., Semmler, T., Yang, S., Van den Hurk, B. and Van Noije, T.: EC-Earth V2. 2: description and validation of a new seamless earth system prediction model, Clim. Dynam., 39, 2611-2629, doi:10.1007/s00382-011-1228-5, 2012.

Hill, D.J., Haywood, A.M., Lunt, D.J., Hunter, S.J., Bragg, F.J., Contoux, C., Stepanek, C., Sohl, L., Rosenbloom, N.A., Chan, W.L. and Kamae, Y.: Evaluating the dominant components of warming in Pliocene climate simulations, Clim. Past, 10, 79-90, doi:10.5194/cp-10-79-2014, 2014.

Hu, X., Li, Y., Yang, S., Deng, Y. and Cai, M.: Process-based Decomposition of the Decadal Climate Difference between 2002-13 and 1984-95, J. Climate, 30, 4373-4393, doi:10.1175/JCLI-D-15-0742.1, 2017.

Kageyama, M., Braconnot, P., Harrison, S. P., Haywood, A. M., Jungclaus, J. H., Otto-Bliesner, B. L., Peterschmitt, J.-Y., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Brierley, C., Crucifix, M., Dolan, A., Fernandez-Donado, L., Fischer, H., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Lunt, D. J., Mahowald, N. M., Peltier, W. R., Phipps, S. J., Roche, D. M., Schmidt, G. A., Tarasov, L., Valdes, P. J., Zhang, Q., and Zhou, T.: The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan, Geosci. Model Dev., 11(3), 1033-1057, doi:10.5194/gmd-11-1033-2018, 2018.

Kim, K.Y., Hamlington, B.D., Na, H. and Kim, J.: Mechanism of seasonal Arctic sea ice evolution and Arctic amplification, The Cryosphere, 10(5), 2191-2202, doi:10.5194/tc-10-2191-2016, 2016.

Koenigk, T., Brodeau, L., Graversen, R. G., Karlsson, J., Svensson, G., Tjernström, M. and Wyser, K.: Arctic climate change in 21st century CMIP5 simulations with EC-Earth, Climate dynamics, 40(11-12), 2719-2743, doi: 10.1007/s00382-012-1505-y, 2013.

Krumpen, T., Gerdes, R., Haas, C., Hendricks, S., Herber, A., Selyuzhenok, V., Smedsrud, L. and Spreen, G.: Recent summer sea ice thickness surveys in Fram Strait and associated ice volume fluxes, The Cryosphere, 10, 523-534, doi:10.5194/tc-10-523-2016, 2016.

Lang, A., Yang, S. and Kaas, E.: Sea-ice thickness and recent Arctic warming, Geophys. Res. Lett., 44, 409-418, doi:10.1002/2016GL071274, 2017.

Li, C., Notz, D., Tietsche, S. and Marotzke, J.: The transient versus the equilibrium response of sea ice to global warming, J.Climate, 26, 5624-5636, doi:10.1175/JCLI-D-12-00492.1, 2013.

Li, G., Ren, B., Zheng, J. and Yang, C.: Net air–sea surface heat flux during 1984–2004 over the North Pacific and North Atlantic oceans (10N–50N): annual mean climatology and trend, Theor. Appl. Climatol., 104, 387-401, doi: 10.1007/s00704-010-0351-2, 2011.

Liu, Y., Key, J.R., Liu, Z., Wang, X. and Vavrus, S.J.: A cloudier Arctic expected with diminishing sea ice, Geophys. Res. Lett., 39, L05705, doi:10.1029/2012GL051251, 2012.

Lu, J. and Cai, M.: A new framework for isolating individual feedback processes in coupled general circulation climate models. Part I: Formulation, Clim. Dynam., 32, 873–885, doi:10.1007/s00382-008-0425-3, 2009.

Madec, G.: ‘‘NEMO ocean engine’’. Note du Pole de mode ́lisation, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN no 1288-1619, 2008.

Matthiessen, J., Knies, J., Vogt, C. and Stein, R.: Pliocene palaeoceanography of the Arctic Ocean and subarctic seas, Philos. Trans. R. Soc. A., 367, 21–48, doi: 10.1098/rsta.2008.0203, 2009.

Muschitiello, F., Zhang, Q., Sundqvist, H.S., Davies, F.J. and Renssen, H.: Arctic climate response to the termination of the African Humid Period, Quat. Sci. Rev., 125, 91-97, doi:10.1016/j.quascirev.2015.08.012, 2015.

Nghiem, S.V., Rigor, I.G., Perovich, D.K., Clemente‐Colón, P., Weatherly, J.W. and Neumann, G.: Rapid reduction of Arctic perennial sea ice, Geophys. Res. Lett., 34, L19504, doi:10.1029/2007GL031138, 2007.

Otto-Bliesner, B. L., Jahn, A., Feng, R., Brady, E. C., Hu, A., and Löfverström, M.: Amplified North Atlantic warming in the late Pliocene by changes in Arctic gateways, Geophys. Res. Lett., *44*(2), 957-964, doi:10.1002/2016GL071805, 2017.

Overland J.E., Wang M., Walsh J.E., Christensen J.H., Kattsov V.M., Champan W.L.: Climate model projections for the Arctic. In: AMAP (2011) Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. Xii, 538 pp , 2011.

Pausata, F.S., Messori, G. and Zhang, Q.: Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period, Earth Planet. Sci. Lett., 434, 298-307, doi:10.1016/j.epsl.2015.11.049, 2016.

Pausata, F.S., Emanuel, K.A., Chiacchio, M., Diro, G.T., Zhang, Q., Sushama, L., Stager, J.C. and Donnelly, J.P.: Tropical cyclone activity enhanced by Sahara greening and reduced dust emissions during the African Humid Period, Proc. Natl. Acad. Sci., 114, 6221-6226, doi:10.1073/pnas.1619111114, 2017a.

Pausata, F.S., Zhang, Q., Muschitiello, F., Lu, Z., Chafik, L., Niedermeyer, E.M., Stager, J.C., Cobb, K.M. and Liu, Z.: Greening of the Sahara suppressed ENSO activity during the mid-Holocene, Nat. Commun., *8*, 1-12, doi:10.1038/ncomms16020, 2017b.

Pithan, F. and Mauritsen, T.: Arctic amplification dominated by temperature feedbacks in contemporary climate models, Nat. Geosci., 7, 181-184, doi:10.1038/ngeo2071, 2014.

Robinson, M.M., Dowsett, H.J. and Chandler, M.A.: Pliocene role in assessing future climate impacts, EOS, Trans. Am. Geophys. Union, 89, 501-502, doi:10.1029/2008EO490001, 2008.

Serreze, M.C., Barrett, A.P., Stroeve, J.C., Kindig, D.N. and Holland, M.M.: The emergence of surface-based Arctic amplification, The Cryosphere, 3, 11-19, doi:10.5194/tc-3-11-2009, 2009.

Serreze, M.C. and Barry, R.G.: Processes and impacts of Arctic amplification: A research synthesis, Glob. Planet. Chang., 77, 85-96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Sévellec, F., Fedorov, A.V. and Liu, W.: Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation, Nat. Clim. Change, 7, 604-610, doi:10.1038/nclimate3353, 2017.

Shine, K.P. and Henderson-Sellers, A.: The sensitivity of a thermodynamic sea ice model to changes in surface albedo parameterization. Journal of Geophysical Research, 90, 2243–2250, 1985.

Soden, B. J. and Held, I. M.: An assessment of climate feedbacks in coupled ocean–atmosphere models, J. Climate, 19, 3354–3360, doi:10.1175/JCLI3799.1., 2006.

Song, X. and Zhang, G.J.: Role of climate feedback in El Niño–like SST response to global warming, J. Climate, *27*, 7301-7318, doi:10.1175/JCLI-D-14-00072.1, 2014.

Taylor, P.C., Cai, M., Hu, A., Meehl, J., Washington, W. and Zhang, G.J.: A decomposition of feedback contributions to polar warming amplification. J. Climate, 26, 7023-7043, doi:10.1175/JCLI-D-12-00696.1, 2013.

Valcke, S.: OASIS3 user guide (prism_2-5), PRISM report series, no 2, 6th edn., 2006.

Vancoppenolle, M., Fichefet T., Goosse H., Bouillon S., Madec G. and Maqueda M. A.: Simulating the mass balance and salinity of Arctic and Antarctic sea ice. 1. Model description and validation, Ocean Modelling, 27, 33-53, doi:10.1016/j.oceamod.2008.10.005., 2009.

Venegas, S. A., Mysak, L. A. and Straub, D. N.: Atmosphere–ocean coupled variability in the South Atlantic. J. Climate, 10(11), 2904-2920, doi:10.1175/1520-0442(1997)010<2904:AOCVIT>2.0.CO;2, 1997.

Vihma, T.: Effects of Arctic sea ice decline on weather and climate: a review. Surv. Geophys., 35, 1175-1214, doi:10.1007/s10712-014-9284-0, 2014.

Wara, M.W., Ravelo, A.C. and Delaney, M.L.: Permanent El Niño-like conditions during the Pliocene warm period. Science, 309, 758-761, doi:10.1126/science.1112596, 2005.

Wetherald, R. T. and Manabe S.: Cloud feedback processes in a general circulation model. J. Atmos. Sci., 45, 1397–1416, doi:10.1175/1520-0469(1988)045,1397:CFPIAG.2.0.CO;2., 1988.

Winton, M.: Sea ice–albedo feedback and nonlinear Arctic climate change. Arctic sea ice decline: Observations, projections, mechanisms, and implications, 111-131, doi:10.1029/180GM09, 2008.

Zheng, J., Ren, B., Li, G. and Yang, C.: Seasonal dependence of local air-sea interaction over the tropical Western Pacific warm pool. J. Trop. Meteorol., 20(4), 360-367, doi:10.16555/j.1006-8775.2014.04.009, 2014.

Table 1. The spatial standard deviation of SIC anomalies σ_{SIC} and net shortwave radiation anomalies due to albedo effect $\sigma_{SW\text{-}albedo}$ (Wm^{-2}) over the Arctic Ocean. $r_{SW\text{-}albedo}$ is the correlation coefficient between SIC and shortwave radiation anomalies. Those significant at a 99% confidence level are bolded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
σ_{SIC}	0.~~44~~25	0.~~44~~26	0.~~44~~26	0.~~43~~26	0.~~43~~25	0.~~39~~23	0.~~34~~23	0.~~36~~20	0.~~39~~19	0.~~38~~25	0.~~40~~25	0.~~43~~25
$\sigma_{SW\text{-}albedo}$	0.~~03~~01	~~1.55~~0.75	~~11.09~~5.81	~~42.79~~25.34	~~88.43~~52.45	~~80.37~~48.79	~~41.88~~26.28	~~29.85~~12.39	~~15.06~~6.85	~~3.59~~2.16	0.~~20~~21	0
$r_{SW\text{-}albedo}$	~~-~~–0.~~25~~22	~~-~~–0.~~43~~37	**~~-~~–0.~~75~~63**	**~~-~~–0.~~88~~77**	**~~-~~–0.~~90~~80**	**~~-~~–0.~~91~~85**	**~~-~~–0.~~90~~85**	**~~-~~–0.~~93~~83**	**~~-~~–0.~~88~~57**	**~~-~~–0.~~50~~53**	~~-~~–0.~~25~~11	/

Table 2. The spatial standard deviation of shortwave and longwave radiation anomalies due to cloud change ($\sigma_{SW\text{-}cloud}$, $\sigma_{LW\text{-}cloud}$) (Wm^{-2}) and water vapour change ($\sigma_{SW\text{-}WV}$, $\sigma_{LW\text{-}WV}$) (Wm^{-2}) over the Arctic Ocean. $r_{SW\text{-}cloud}$, $r_{LW\text{-}cloud}$, $r_{SW\text{-}WV}$, and $r_{LW\text{-}WV}$ are correlation coefficients between SIC and shortwave and longwave radiation anomalies due to cloud and water change, respectively. Those significant at a 99% confidence level are bolded. Here, the cloud and water vapour change is specified as the part caused by sea -ice decrease.

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\sigma_{SW\text{-}cloud}$	4.76	0.01	0.16	1.11	3.86	5.97	11.71	19.61	13.86	3.21	0.50	0.04	0
$r_{SW\text{-}cloud}$	0.18	0.14	0.22	0.36	0.36	0.16	0.01	0.05	0.24	0.26	0.25	0.32	/
$\sigma_{LW\text{-}cloud}$	8.02	9.13	9.29	8.25	7.64	10.20	11.91	15.11	13.56	11.96	10.01	10.18	9.86
$r_{LW\text{-}cloud}$	**–0.46**	**–0.59**	**–0.56**	**–0.56**	**–0.51**	–0.36	0.06	0.04	–0.23	**–0.54**	**–0.41**	**–0.60**	**–0.56**
$\sigma_{SW\text{-}WV}$	0.29	0.001	0.03	0.14	0.40	0.59	0.85	0.85	0.63	0.33	0.09	0.01	0
$r_{SW\text{-}WV}$	–0.02	–0.05	0.02	0.06	0.05	0.02	0.11	–0.07	**–0.57**	**–0.62**	**–0.43**	–0.22	/
$\sigma_{LW\text{-}WV}$	2.27	3.45	3.53	3.11	2.84	2.57	2.72	2.15	1.73	1.77	2.31	2.89	3.54
$r_{LW\text{-}WV}$	**–0.56**	**–0.45**	**–0.43**	**–0.50**	**–0.58**	**–0.57**	**–0.46**	–0.13	0.38	0.13	–0.36	**–0.58**	**–0.49**

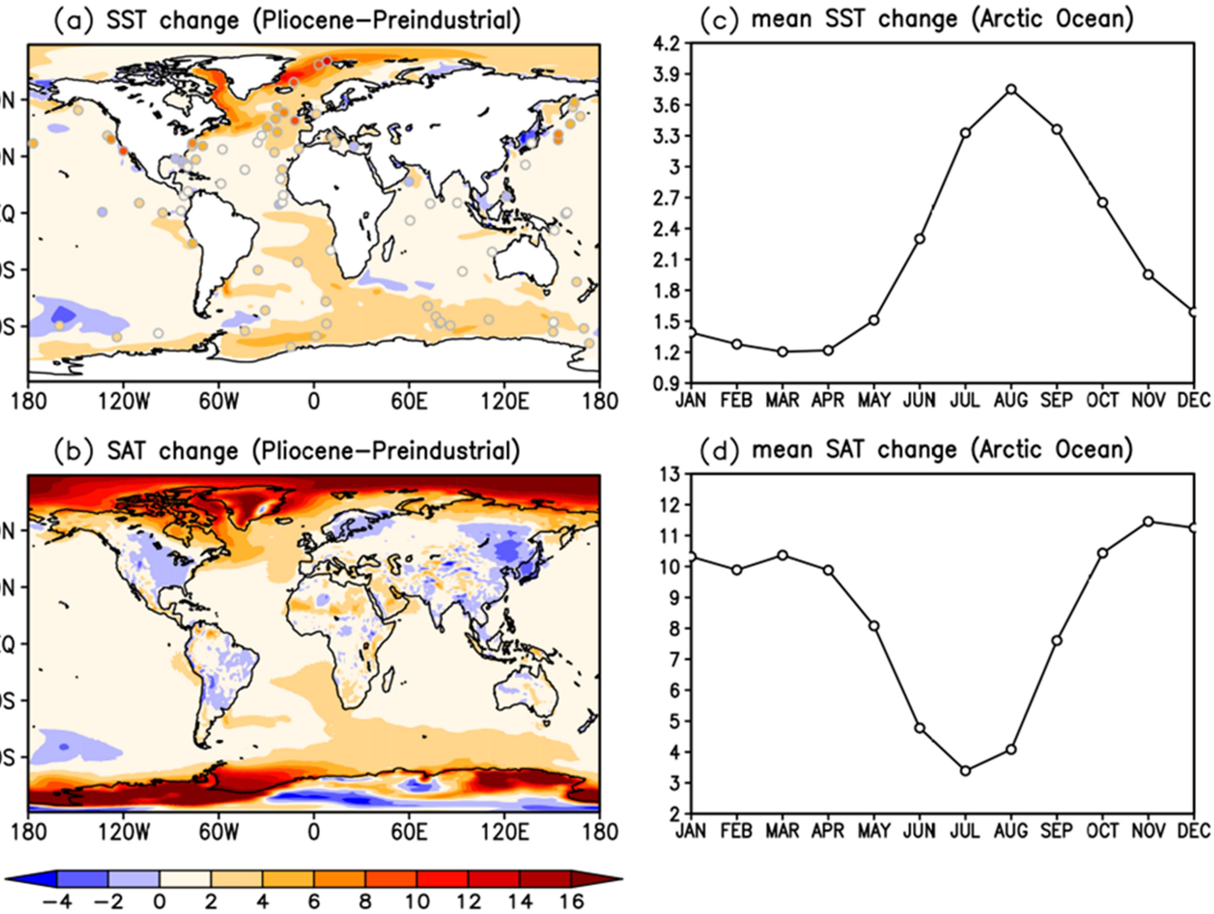
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\sigma_{SW\text{-}cloud}$	4.8676	0.01	0.16	1.2011	4.563.86	6.845.97	12.5311.71	19.1461	14.4513.86	4.163.21	0.6550	0.04	0
$r_{SW\text{-}cloud}$	0.3118	0.1514	0.2722	0.4136	0.4236	0.2916	0.1901	0.2105	0.3524	0.4026	0.3725	0.32	/
$\sigma_{LW\text{-}cloud}$	8.2502	8.899.13	9.1929	8.1325	7.9664	10.7320	11.8191	14.0615.11	13.5556	13.6411.96	11.3110.01	10.3118	9.8386
$r_{LW\text{-}cloud}$	—0.5246	—0.5859	—0.5956	—0.5856	—0.5551	—0.4536	-0.0906	-0.0704	-—0.3323	-—0.6254	-—0.5241	—0.6460	—0.5856
$\sigma_{SW\text{-}WV}$	0.2729	0.001	0.03	0.14	0.3840	0.5759	0.7985	0.7785	0.5663	0.2833	0.0809	0.01	0
$r_{SW\text{-}WV}$	—0.0702	—0.0805	-0.0302	0.0106	-0.0105	-0.0602	0.0611	-—0.0807	-—0.4957	-—0.5662	-—0.4443	—0.2422	/
$\sigma_{LW\text{-}WV}$	2.2327	3.4045	3.4653	3.0711	2.8084	2.5157	2.5372	1.922.15	1.5573	1.5877	2.2131	2.9689	3.6154
$r_{LW\text{-}WV}$	—0.6256	—0.5045	—0.4843	—0.5650	—0.6258	—0.6057	-—0.4846	-—0.1213	0.3338	-0.0613	-—0.5236	—0.6758	—0.5749

Table 3. The spatial standard deviation of sensible and latent heat flux anomalies σ_{SH}, σ_{LH} (Wm^{-2}) over the Arctic Ocean. r_{SH} and r_{LH} are correlation coefficients between SIC and sensible and latent heat flux anomalies, respectively. Those significant at a 99% confidence level are bolded.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
σ_{SH}	28.53	29.44	21.64	12.87	7.94	9.46	9.55	2.63	2.11	7.02	31.11	26.80
r_{SH}	**0.57**	**0.64**	**0.67**	**0.66**	**0.76**	0.26	−0.36	0.03	**0.65**	**0.80**	**0.71**	**0.56**
σ_{LH}	18.70	19.00	14.75	9.46	5.64	5.84	8.75	1.93	1.69	5.77	19.87	17.44
r_{LH}	**0.74**	**0.77**	**0.78**	**0.76**	**0.71**	0.14	**−0.42**	−0.37	**0.69**	**0.90**	**0.79**	**0.72**

Table 4. The response coefficients (Wm^{-2}) of radiation and turbulent heat fluxes to the albedo and insulation effects of sea-ice. Those significant at a 99% confidence level are bolded.

λ (Wm^{-2})	flux		Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
albedo	SW		**~~−46.5~~ −43.0**	0.0	−1.~~7~~1	**~~−18.9~~ −13.8**	**~~−87.2~~ −75.0**	**~~−188.1~~ −169.2**	**~~−186.0~~ −178.3**	**~~−109.7~~ −97.0**	**~~−77.5~~ −52.0**	**~~−34.4~~ −20.2**	**−4.~~7~~5**	−0.1	0
	SW	cloud	~~4.3~~2.6	0.0	0.1	~~1.1~~0.9	~~4.4~~3.1	~~4.6~~2.3	~~6.1~~0.4	~~11.~~3.1	~~13.7~~9.6	~~4.~~2.3	0.~~6~~4	0.0	0
	SW	WV	−0.~~1~~0	0.0	0.0	0.0	0.0	-0.~~1~~0	0.~~1~~2	−0.2	**−1.0~~.7~~**	**−0.45**	−0.1	0.0	0
insulation	LW	cloud	**~~−12.6~~ −11.1**	**~~−11.9~~ −12.1**	**~~−12.2~~ −11.7**	**−10.~~8~~4**	**~~−10.0~~ −8.9**	~~−11.4~~ −8.6	−~~2~~1.7	−~~2.8~~1.9	~~−12.2~~ −9.0	**~~−21.3~~ −17.6**	**~~−15.2~~ −11.6**	**~~−16.4~~ −15.8**	**−13.~~6~~0**
	LW	WV	**~~−4.0~~ −3.9**	**−3.~~9~~5**	**−3.~~8~~4**	**−3.~~9~~5**	**~~−4.0~~ −3.7**	**−3.~~6~~4**	**−3.~~1~~2**	−0.~~7~~9	1.~~4~~9	-0.~~3~~6	−2.3~~.0~~	**~~−5.0~~ −4.4**	**−4.~~8~~1**
	SH		**35.3**	**53.4**	**59.0**	**46.4**	**29.6**	**24.2**	10.4	−13.8	0.4	**7.1**	**22.3**	**79.2**	**54.0**
	LH		**27.7**	**45.3**	**46.0**	**36.6**	**25.0**	**16.1**	3.5	**−15.0**	−3.6	**6.0**	**20.5**	**56.7**	**45.7**


(a) SST change (Pliocene−Preindustrial)
(b) SAT change (Pliocene−Preindustrial)
(c) mean SST change (Arctic Ocean)
(d) mean SAT change (Arctic Ocean)
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
−4 −2 0 2 4 6 8 10 12 14 16
4.2 3.9 3.6 3.3 3 2.7 2.4 2.1 1.8 1.5 1.2 0.9
13 12 11 10 9 8 7 6 5 4 3 2
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

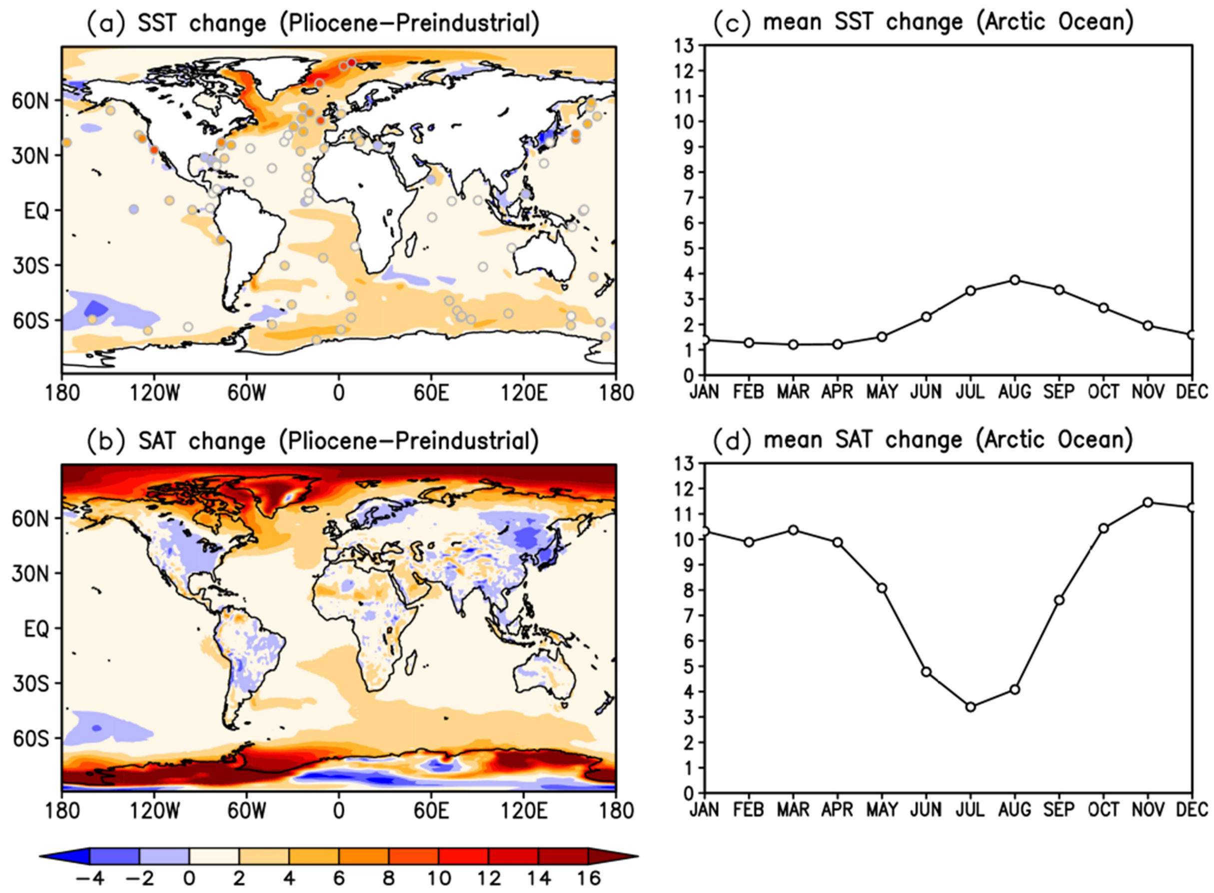
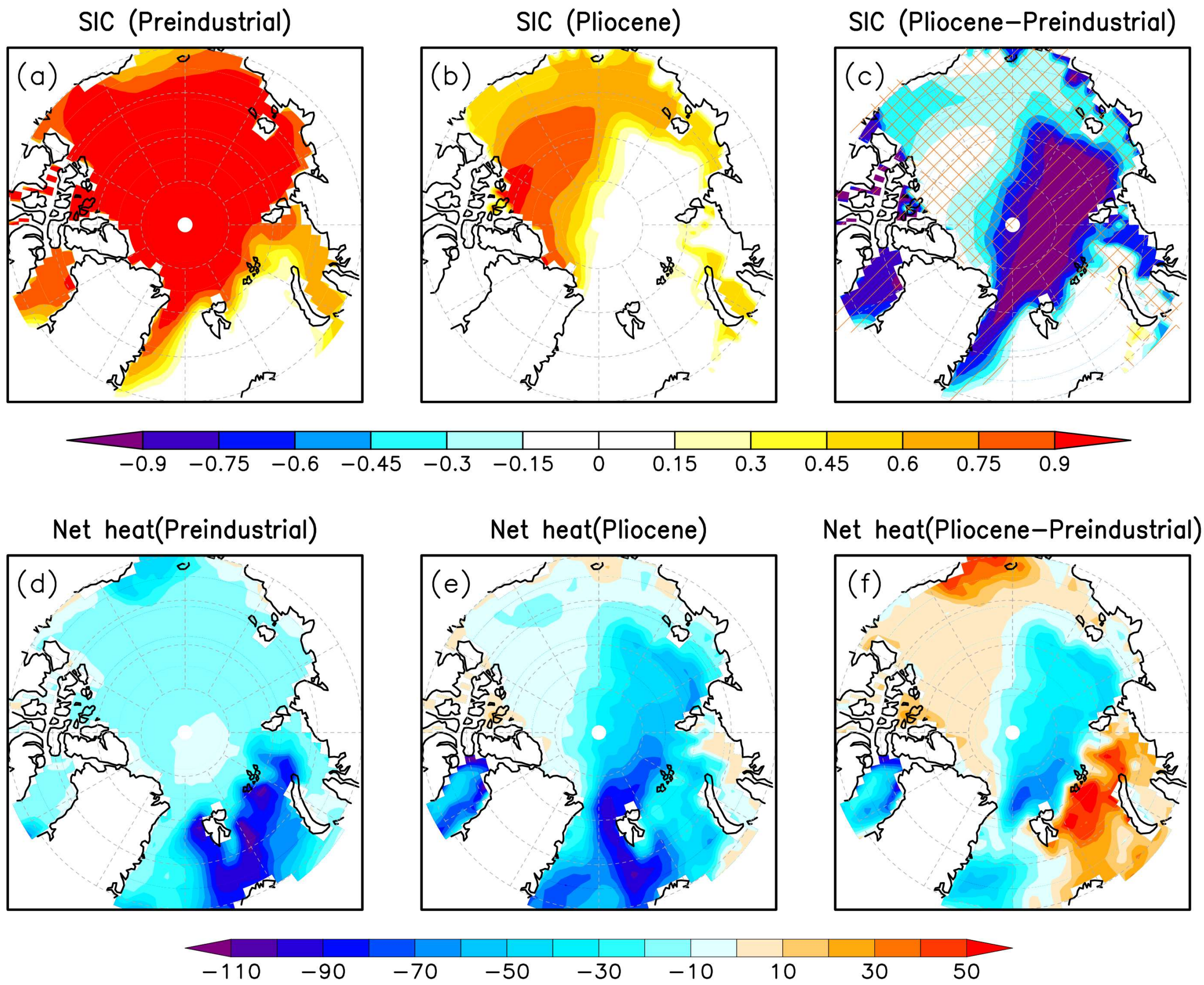


Figure 1. The annual mean warming (K) for (a) sea surface temperature (SST),) and (b) surface air temperature (SAT)), and seasonal warming (K) averaged over the Arctic Ocean for (c) SST, and (d) SAT between the Pliocene and preindustrial simulations. The shaded circles in (a) represent the annual mean SST anomalies at 95% confidence-assessed marine sites from the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP).


SIC (Preindustrial)
SIC (Pliocene)
SIC (Pliocene−Preindustrial)
(a)
(b)
(c)
−0.9 −0.75 −0.6 −0.45 −0.3 −0.15 0 0.15 0.3 0.45 0.6 0.75 0.9
Net heat(Preindustrial)
Net heat(Pliocene)
Net heat(Pliocene−Preindustrial)
(d)
(e)
(f)
−110 −90 −70 −50 −30 −10 10 30 50

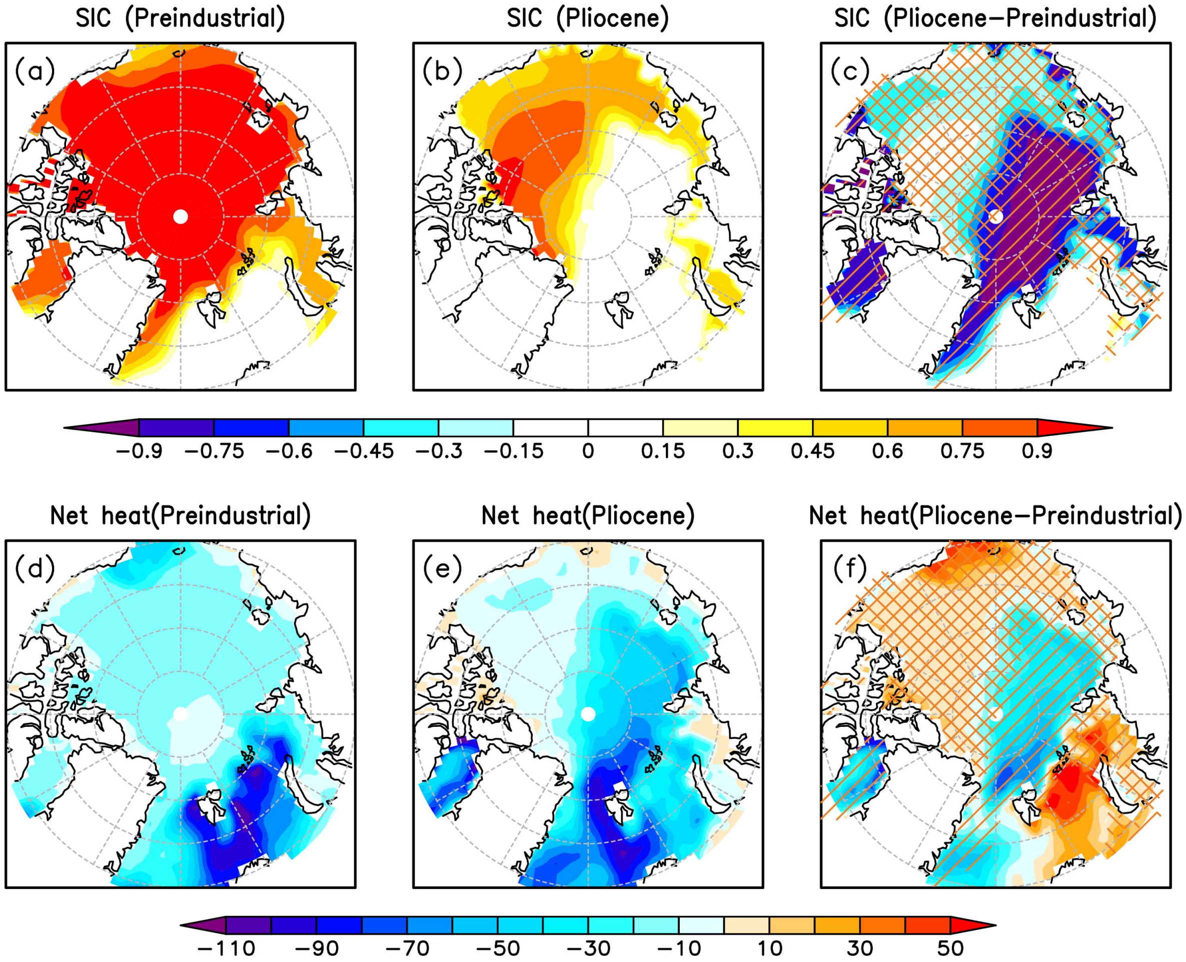


Figure 2. Spatial distributions of the annual mean sea -ice concentration (SIC) and ~~air-sea interface~~ net heat flux at the surface of ice and ocean (Wm^{-2}, positive downward) over the Arctic Ocean. (a) SIC in the preindustrial period, (b) SIC in the Pliocene, (c) the Pliocene SIC change with respect to the preindustrial period, (d) net heat flux in the preindustrial period, (e) net heat flux in the Pliocene, and (f) the Pliocene net heat flux change with respect to the preindustrial period. The diagonal stripe in (c) represents the regions from ice-covered to ice-free, and the diagonal crosshatch represents the regions from ice-covered to ice-covered.

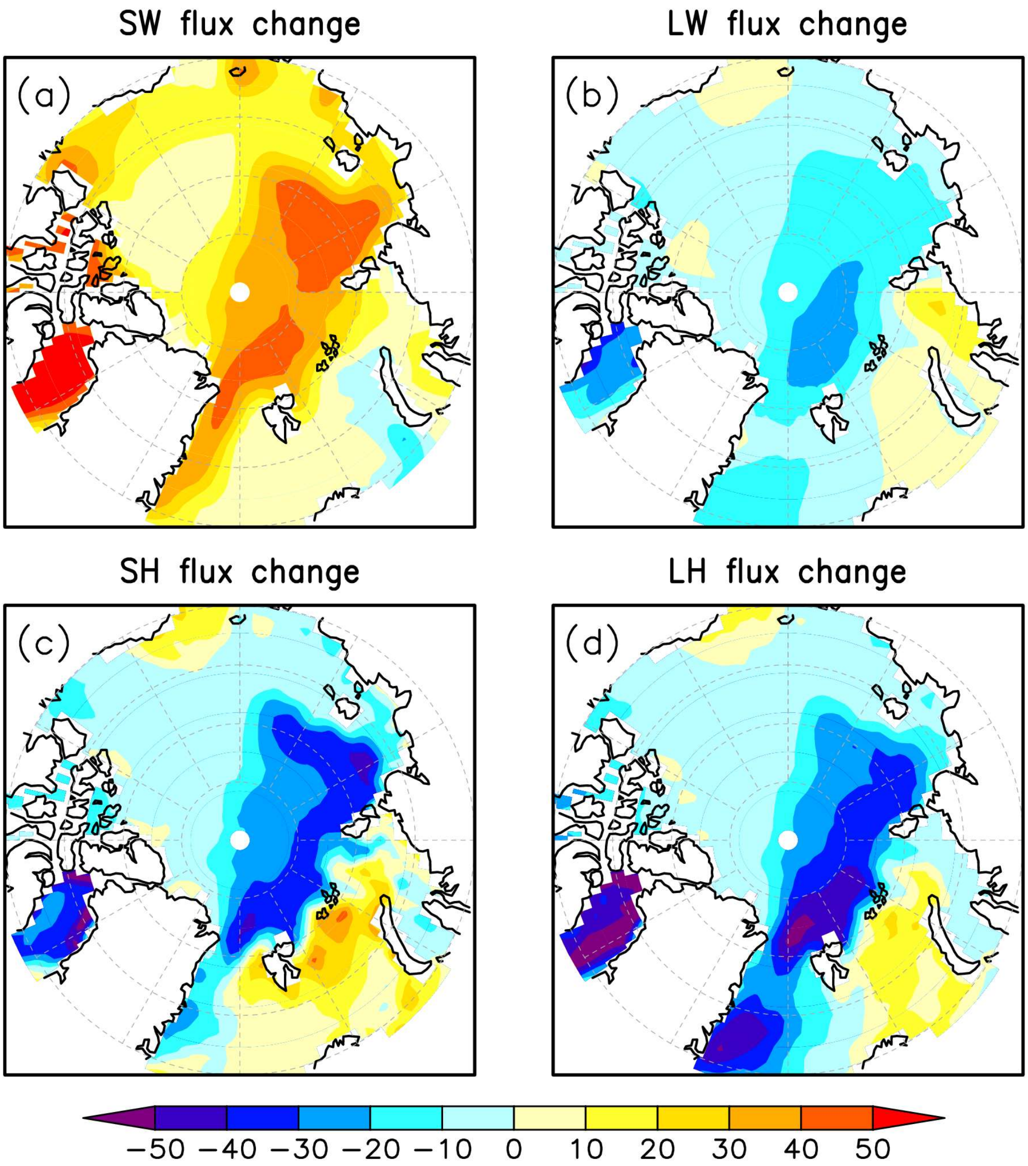


Figure 3. Spatial distributions of the Pliocene annual mean heat flux change (Wm^{-2}, positive downward) with respect to the preindustrial period over the Arctic Ocean. (a) net shortwave ~~radiation~~ flux, (b) net longwave radiation flux, (c) sensible heat flux, and (d) latent heat flux.

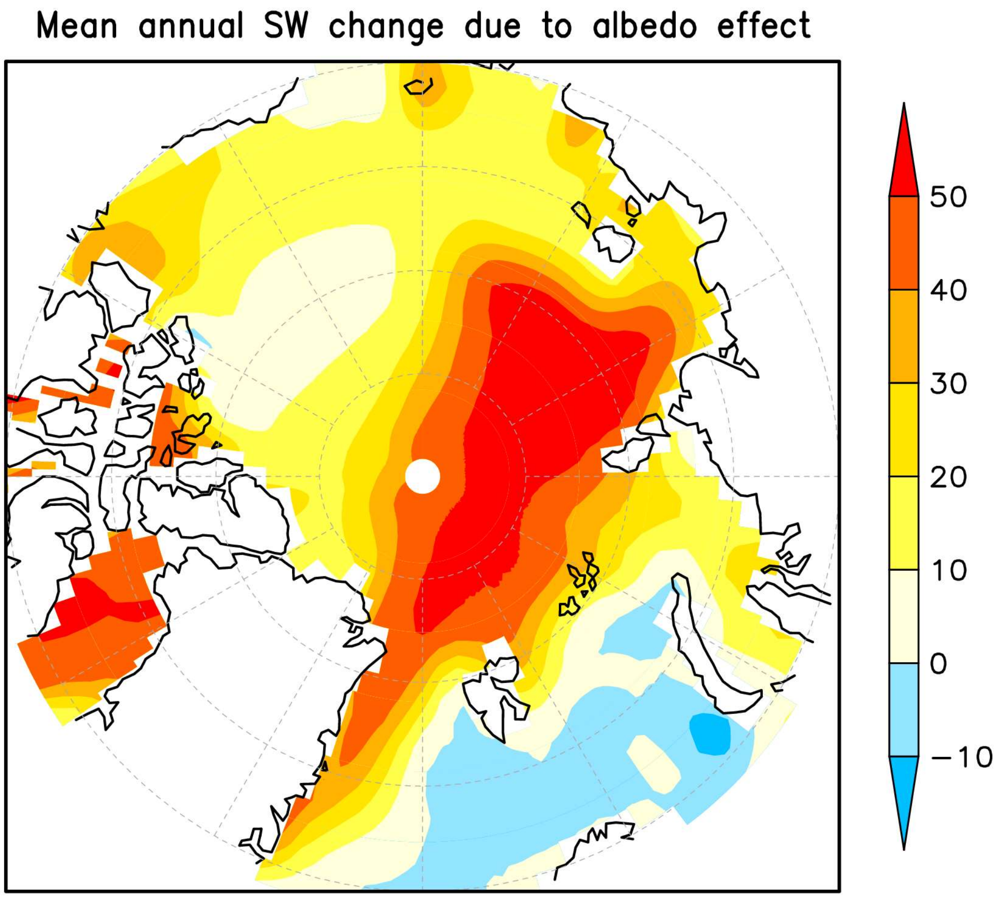
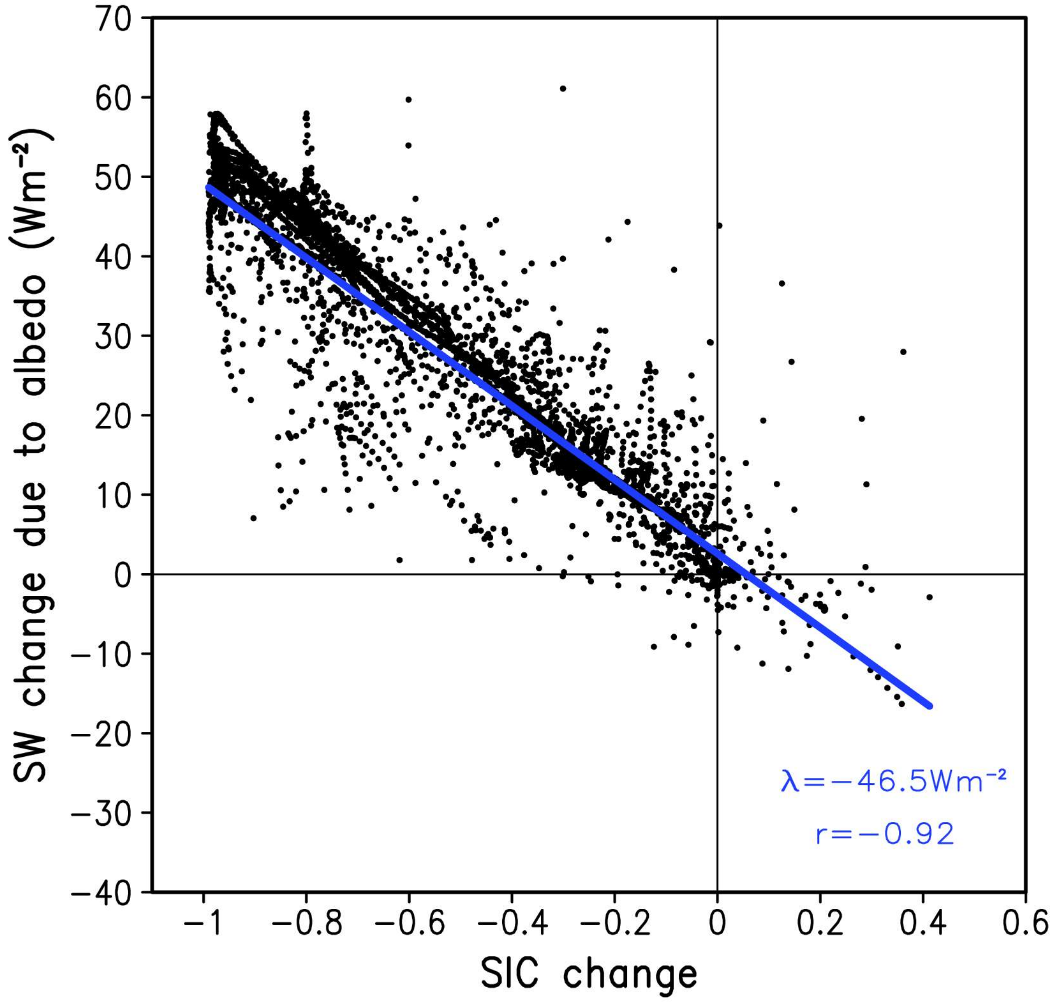


Figure 4. Spatial distributions of the Pliocene annual mean net shortwave ~~radiation~~ flux change (Wm^{-2}, positive downward) at the surface over the Arctic Ocean caused by albedo effect of sea -ice change with respect to the preindustrial period.


SW change due to albedo (Wm⁻²)
SIC change
λ=−46.5Wm⁻²
r=−0.92
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6

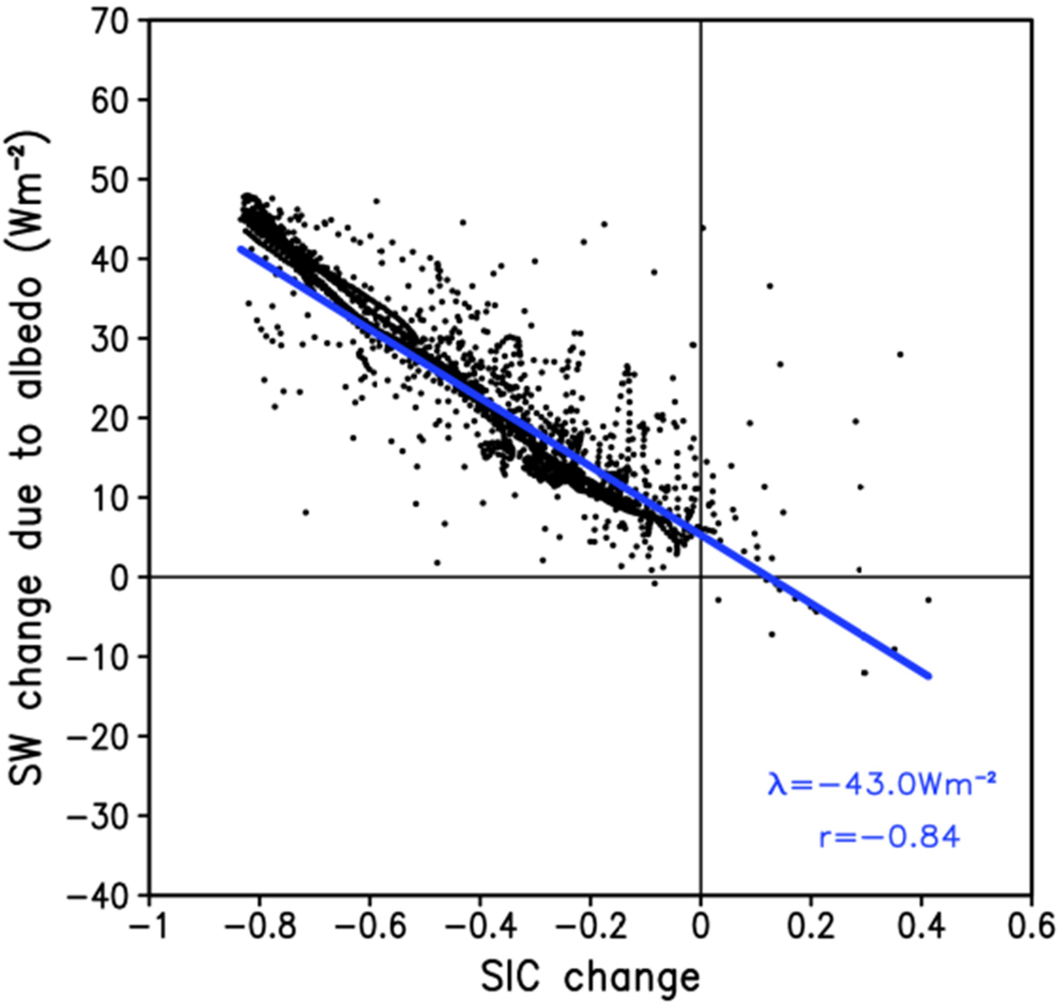
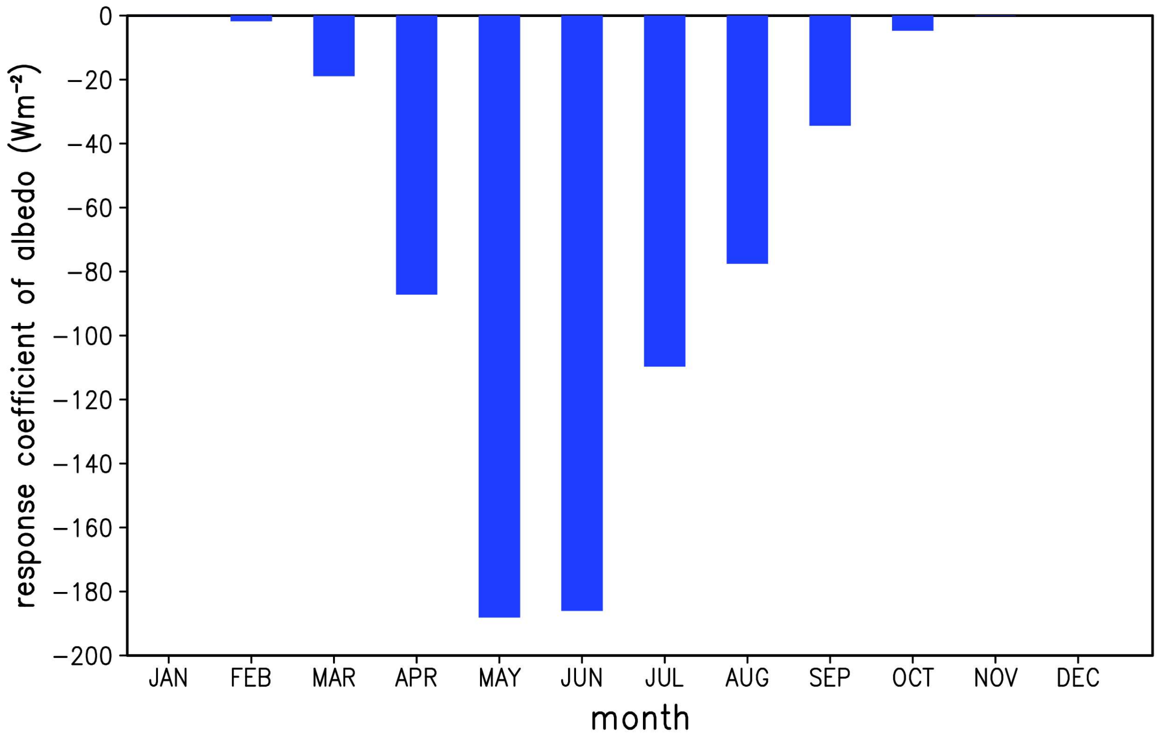


Figure 5. The annual mean net shortwave ~~radiation~~ flux change (Wm^{-2}, positive downward) caused by the albedo effect of sea -ice change averaged over the Arctic Ocean as a function of SIC change. All the change ~~are~~is with respect to the preindustrial period, and each dot represents one grid point value over the Arctic Ocean.



response coefficient of albedo (Wm⁻²)
0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
month

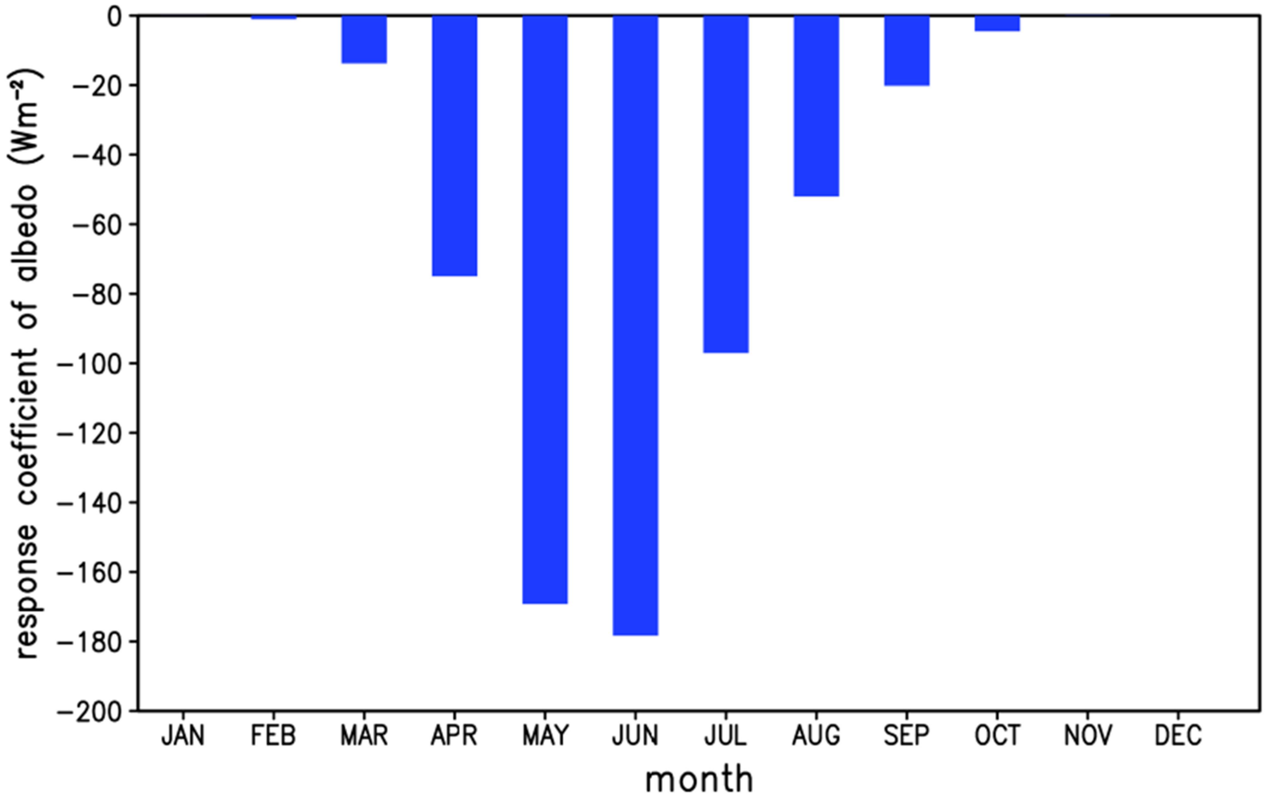


Figure 6. The monthly response coefficients (Wm^{-2}) of net shortwave ~~radiation~~ flux to the albedo effect of sea -ice.

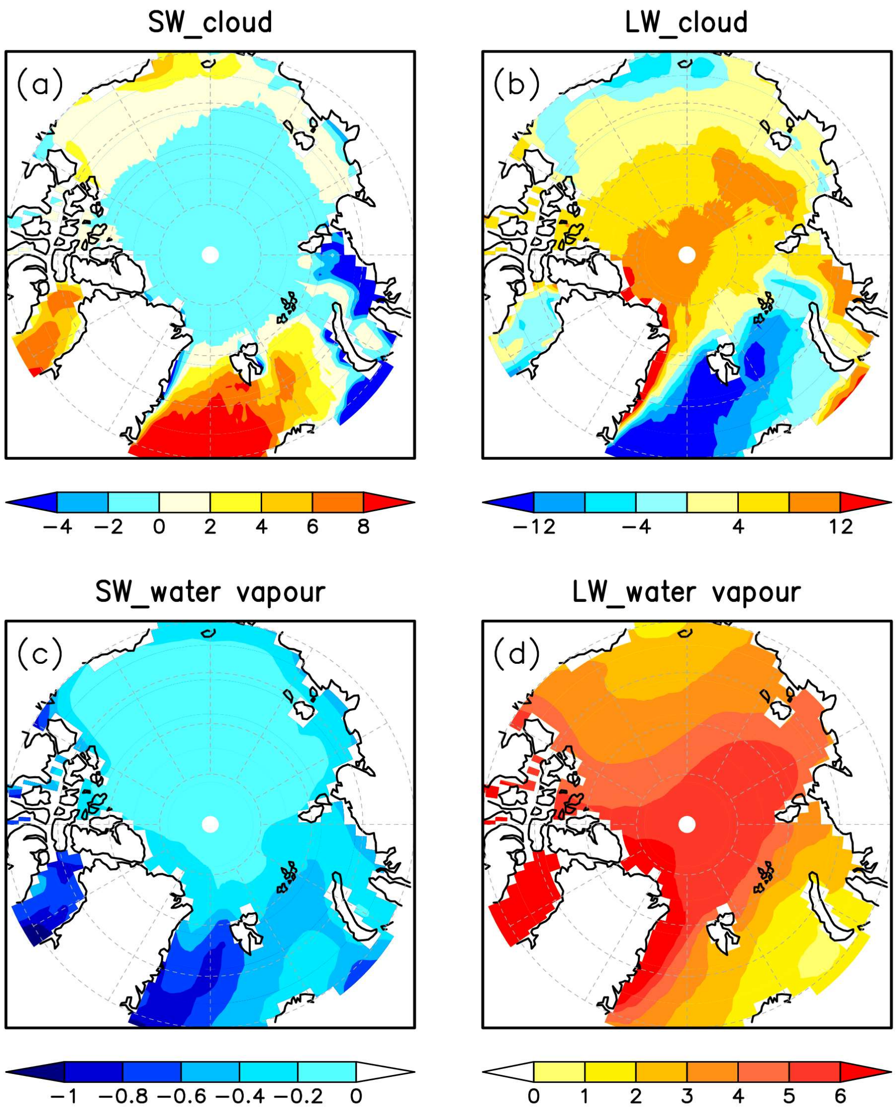
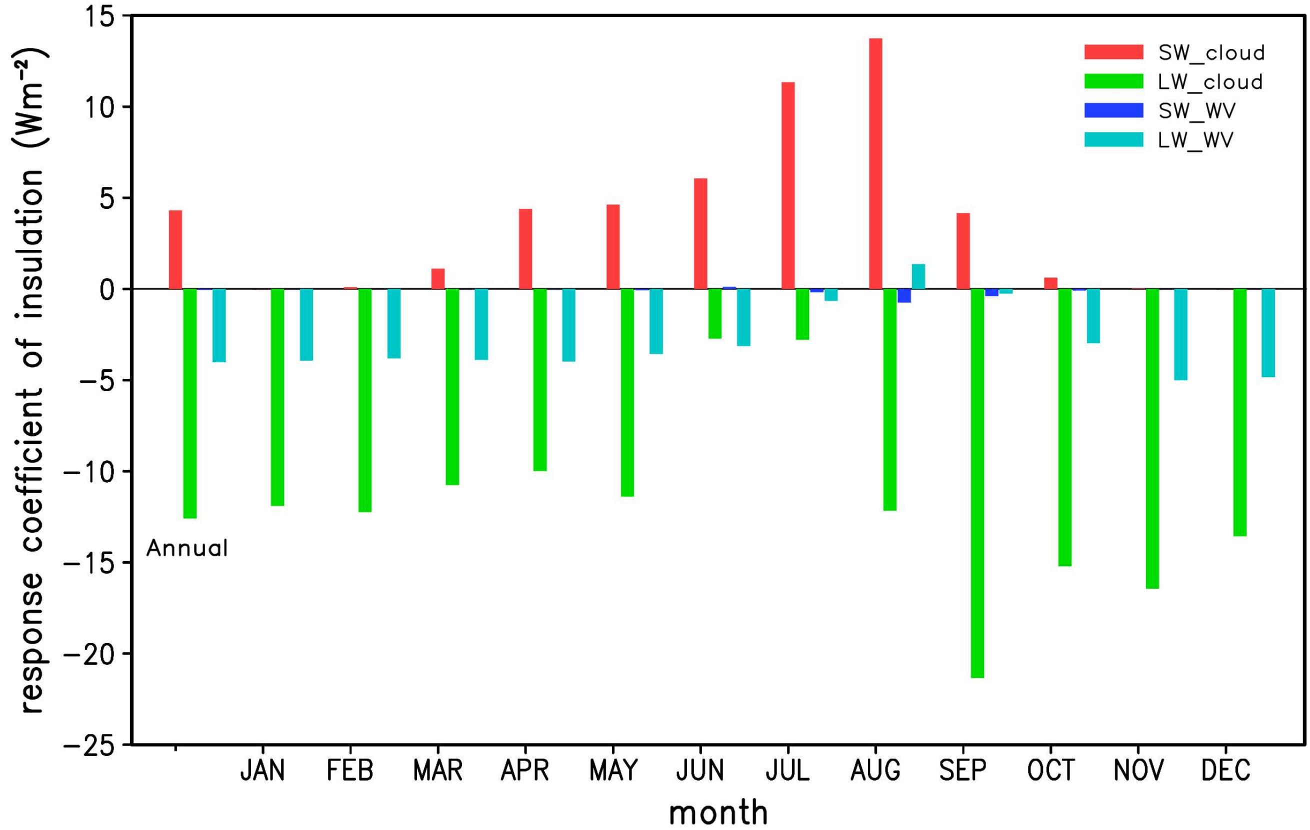


Figure 7. Spatial distributions of the Pliocene annual mean radiation fluxes change (Wm^{-2}, positive downward) with respect to the preindustrial period over the Arctic Ocean. (a) shortwave radiation due to cloud change, (b) longwave radiation due to cloud change, (c) shortwave radiation due to water vapour change, (d) longwave radiation due to water vapour change. Here ~~the~~ , cloud and water vapour change is ~~specified as~~the value before removing the ~~part caused by sea-ice decrease~~remote effects of clouds and water vapour.


SW_cloud
LW_cloud
SW_WV
LW_WV
Annual
response coefficient of insulation (Wm⁻²)
15
10
5
0
−5
−10
−15
−20
−25
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
month

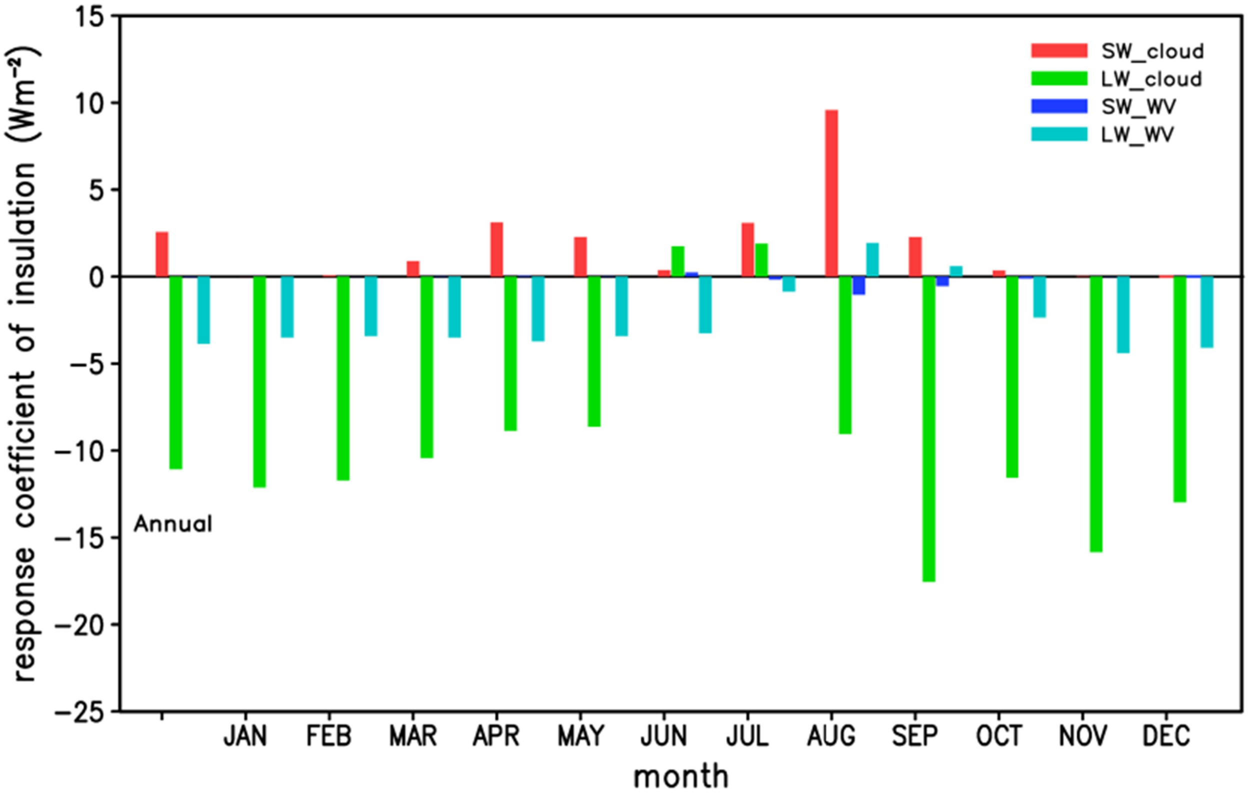


Figure 8. The annual and monthly response coefficients (Wm^{-2}) of net shortwave and longwave radiation flux ~~caused by~~related to cloud and water vapour change to the insulation effect of sea -ice. Here, the cloud and water vapour change is specified as the part ~~caused by~~related to sea -ice decrease.

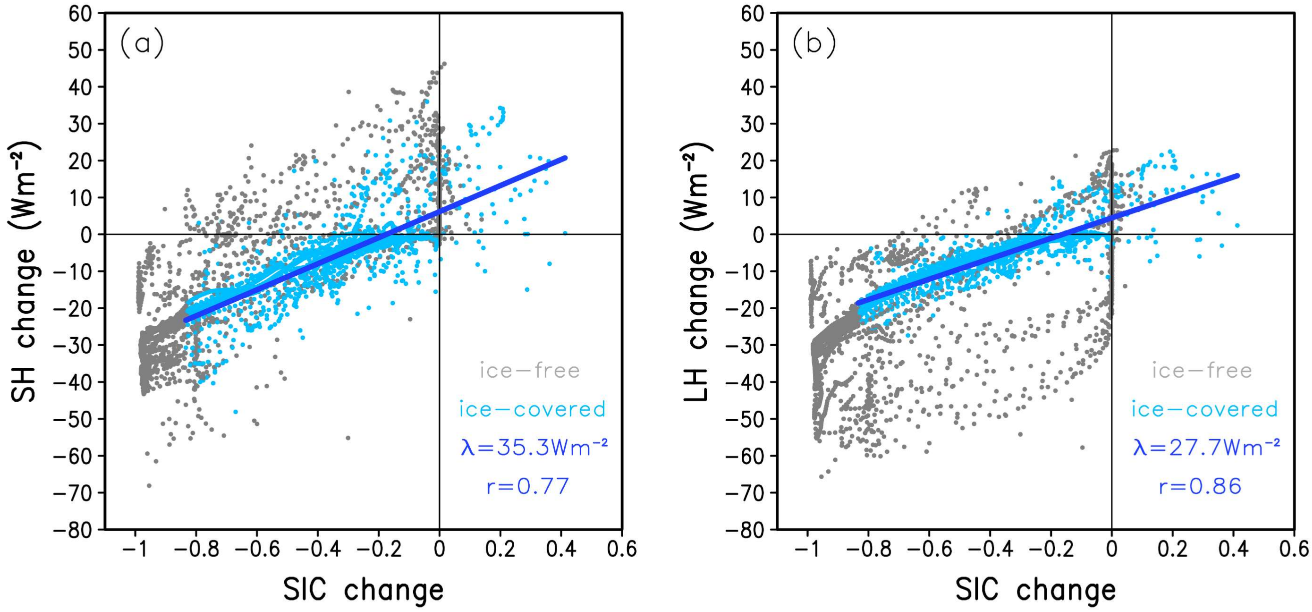
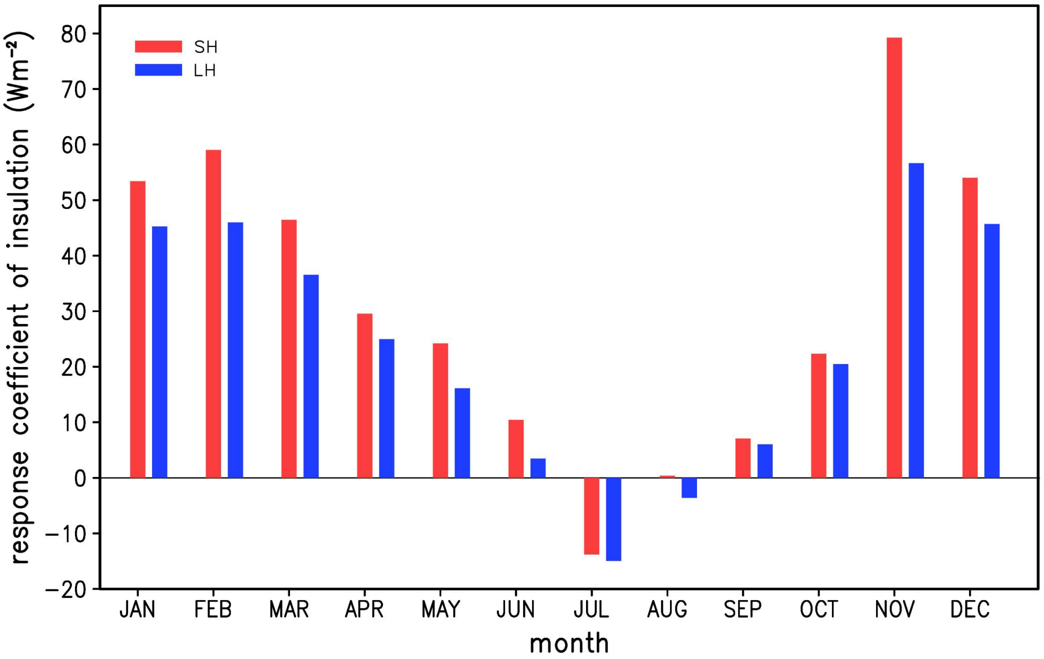


Figure 9. The annual mean sensible and latent heat flux change (Wm^{-2}, positive downward) caused byrelated to insulation effect of sea - ice change averaged over the Arctic Ocean as a function of SIC change. All the changePliocene changes shown are with respectcomputed relative to the preindustrial simulation. The ice-free and ice-covered regions here refer to the diagonal hatched and cross-hatched regions in Figure 2c, respectively. The blue line is the linear regression on the ice-covered scatter points, and the response coefficient (λ) and correlation coefficient (r) are just for the ice-covered areas.



725 **Figure 10.** The monthly response coefficients (Wm^{-2}) of sensible and latent heat fluxes to the insulation effect of sea -ice.

Supplementary Information

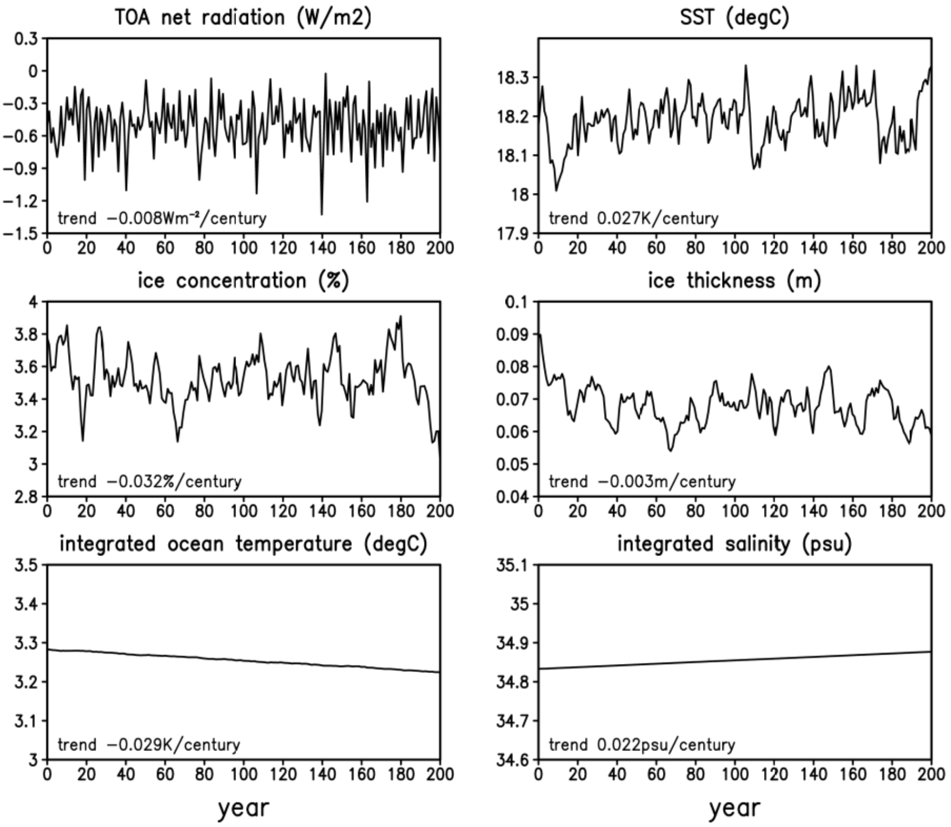


Figure S1. The global annual mean of last 200 model years output in the Pliocene simulation (The negative TOA net radiation represents a heat loss of the earth-atmosphere system.)

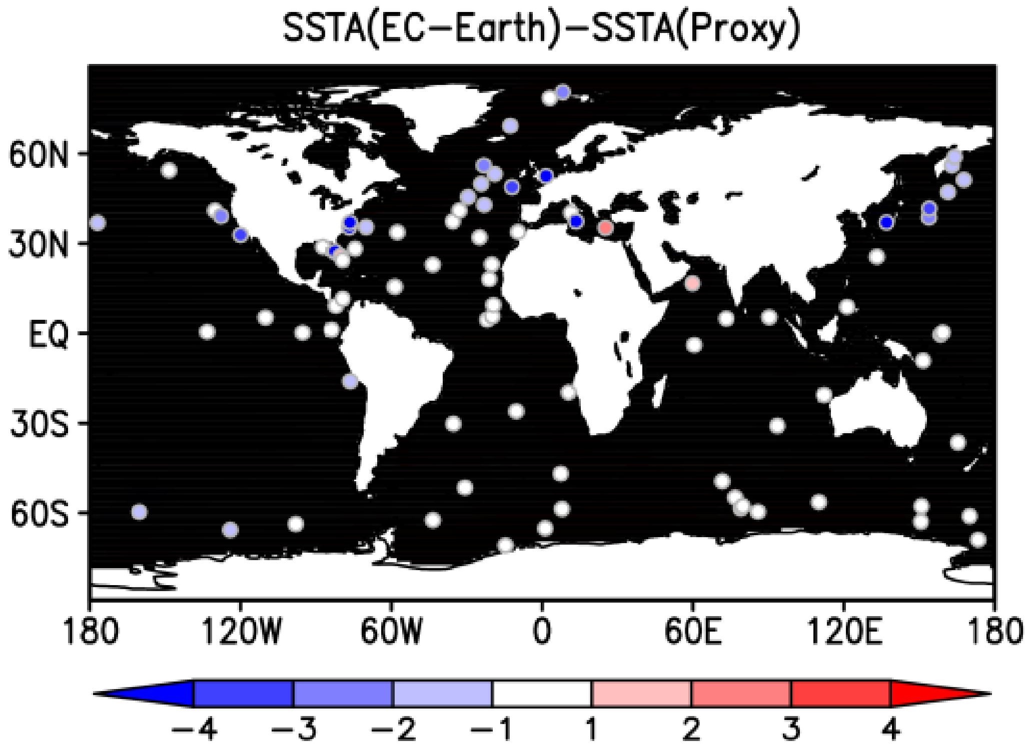


Figure S2. The difference of annual mean SST anomaly (Pliocene minus preindustrial, K) between EC-Earth simulation and the proxy data at 95% confidence-assessed marine sites from Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP).

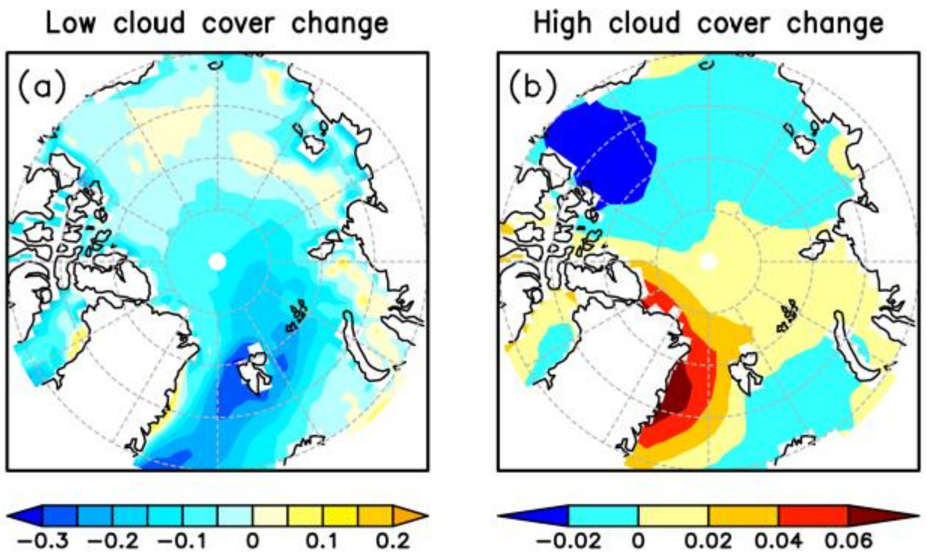


Figure S3. The difference of annual mean low cloud cover (a) and high cloud cover (b) anomaly in Pliocene with respect to the preindustrial.