

**Responses to Anonymous Referee #1 on “The effect of high dust amount on the surface temperature during the Last Glacial Maximum: A modelling study using MIROC-ESM” by Cp-2018-2 Ohgaito et al.**

5 We wish to express our appreciation to the referee for the constructive and insightful comments and suggestions, which have helped us improve our manuscript considerably. In the following, the referee’s comments are written in black and our replies are written in blue.

**General comments**

10 Overall, I didn’t find this work is placed very well in the context of past studies. How does the dust-cloud scheme used differ from Takemura et al 2009, and Sagoo et al 2017? How comparable is the snow-ageing scheme to Krinner et al 2006, or Ganopolski et al, 2010? Please re-write the introduction to better place the current work in the context of past studies. What is different (or the same) as past work? What do you hope to find? What are main uncertainties etc?

15 Our aerosol scheme is identical to that of Takemura et al. (2009). Both Takemura et al. (2009) and Sagoo and Strelvmo (2017) implemented parameterizations of interaction between aerosols and ice crystals based on empirically derived formulations following laboratory experiments and observations (i.e., Lohman and Diehl (2006) and DeMott et al. (2015), respectively). The formulations are different but the schemes of Takemura and Sagoo do similar things; both formulate ice nucleation dependent on temperature and aerosol concentration. It should also be noted that the representations of the cloud water phase of climate models are uncertain and all failed to reproduce the amount and distribution of global observations (Komurcu et al. 2014).

20 Concerning the ageing scheme, Krinner et al. (2006) used an ageing scheme based on Warren and Wiscombe (1980) and Wiscombe and Warren (1980) and the MIROC-ESM used that of Yang et al. (1997) based on Warren and Wiscombe (1982). Ganopolski et al. (2010) used simple scaling of albedo reduction with dust flux relationship. This information has been added in the introduction and model description sections.

25 Our main research objective was to elucidate how glaciogenic dust might influence the global climate, especially surface temperature. This has been added in the introduction.

The manuscript has insufficient detail on the methods used, especially on how glaciogenic dust was included. Did you tune the fluxes to the LGM dust observations somehow?

5 **In this work, as a first step, we forced additional dust emission constantly following the estimate of Mahowald et al. (2006). The source areas of glaciogenic dust in the MIROC-ESM are shown in Supplementary Fig. A. The source strengths for these areas are shown in Table 3 for the non-glaciogenic dust (LGM.a) and the non-glaciogenic and glaciogenic dust (LGMglac.a), following Mahowald et al. (2006a).**

How well does your snow ageing model agree with other schemes (e.g Warren Wiscombe, 1980).

10 **The snow ageing scheme of the MIROC-ESM is that of Warren and Wiscombe (1982). A suitable description has been added in the revised manuscript.**

Are your LGM results comparable with e.g. Krinner et al 2006?

15 **Krinner et al. (2006) suggest that the ageing effect of snow prevents formation of permanent snow over eastern Siberia, consistent with our results. An appropriate statement has been added in the revised text.**

You do not include any discussion of potential uncertainties, which would seem to be quite large, especially for dust-cloud interactions. Perhaps summarise the approach in SPRINTARS compared to other models (e.g. Komurcu et al., 2014).

20

**Yes, we agree the uncertainty of the aerosol–cloud interaction cannot be overlooked. Komurcu et al. (2014) provided an overview of the uncertainty among the major models and they reported wide ranges of uncertainty in both magnitude and spatial distribution; therefore, our results might differ from other schemes. Acknowledgement of this possibility has been added in the discussion section.**

25 Are your dust cloud effects in agreement with those presented for e.g. 'high dust' by Sagoo et al 2017? If not, could you speculate as to why.

**In terms of the global mean, the negative radiative effect of dust is consistent with Sagoo and Strelvmo (2017) and other studies. In the mid- to low latitudes, our results are also consistent with those previous works with regard to cooling. However, in the high latitudes, our**

5 results of warming via high dust deposition contrasted with their findings. Because Sagoo and Strelmvo (2017) did not conduct a standard LGM experiment (they changed only CO<sub>2</sub> and dust from their control experiment), it is not possible to specify a reason for this. However, their “idealized high dust” means that their emission factor is about 3.4 times that of the control experiment, globally, whereas our glaciogenic dust sources are located in the high latitudes. Therefore, it is likely that the influence of regions of glaciogenic dust emission  
10 such as the Pampas of South America on surface temperature around Antarctica is more pronounced in our simulation results. This analysis has been added in the discussion section.

Please also could you explain why the dust-cloud effects are so important in the southern hemisphere, but not in the northern hemisphere, and also why the reverse is true for the snow-ageing. Could you expand figure 9 to compare the radiative perturbations from the 3 separate effects of dust  
10 that you have studied. Hence, I would recommend major revisions to the text before publication.

Snow ageing in the MIROC-ESM is tuned to fit the observations in Aoki et al. (2006). According to Aoki et al. (2006), it can be considered (approximately) that albedo starts to reduce with snow impurity of  $\geq 10$  ppmw. Dust deposition over the northern high latitudes is of the order of  $100 \text{ g m}^{-2} \text{ y}^{-1}$ , which corresponds to the order of 1000 ppmw. Conversely, dust deposition near Antarctica is about  $0.01 \text{ g m}^{-2} \text{ y}^{-1}$ ,  
15 which corresponds to the order of 0.1 ppmw

Glaciogenic dust travels higher into the troposphere in the Southern Hemisphere and it promotes ice nucleation. Additionally, the dust deposition flux of the standard LGM.a is higher than PI.a in the Northern Hemisphere but lower in the Southern Hemisphere. Therefore, the impact of glaciogenic dust might be more efficient in the Southern Hemisphere. This has been explained in Sect. 3.3.  
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### Specific comments

Page 3, lines 3 to page 4 line 2. This whole section could be summarised more succinctly for the reader. What is the main message from all previous work? What were the main steps? I would say, most studies simulate a cooling effect, but it is variable and that the introduction of (i) vegetation feedback (Mahowald et al 1999), and (ii) glacio genic sources (Mahowald et al 2006) and (iii) dust-cloud interactions (Takemura et al 2009, Sagoo  
25 et al 2017) are the main developments.

The introduction has been rewritten more succinctly following your suggestions.

Page 4: Lines 3-11. I find it incomplete here to only list the inclusion of the ocean. You should also mention the dust-cloud interactions and the dust on snow effects and the inclusion of glaciogenic sources in this study.

**The sentence has been modified according to your suggestions.**

5

Page 5: lines 3-4: Did you reduce the imaginary part of the dust refractive index as done by Takemura et al 2009 (their page 3063)?

**Our aerosol module (SPRINTARS) is identical to that of Takemura et al. (2009). The refractive index of dust aerosols was taken from Deepak and Gerber (1983), but its imaginary part was reduced for consistency with recent measurements of weaker shortwave absorption.**

10

Page 6: Lines 5-6. More detail of the glaciogenic model setup is required. Did you optimise the fluxes from the emissions using the ice-core data, or marine data or both? What simulations did you use to calculate this? Or did you simply scale emissions in these regions to match the emissions simulated by Mahowald et al 2006?

15 **Our method is simple. As a first step, to develop a more sophisticated method for obtaining a best fit to the proxy data archive, we specified the area of glaciogenic dust emission (Supplementary Fig. A) and allowed the emission of a constant dust flux following the estimate of Mahowald et al. (2006). The next step will be to introduce a more realistic method for the emission of glaciogenic dust. We intend to investigate this in subsequent research using an updated version of the MIROC model, which is now under preparation for the submission of experiments to PMIP4. Here, we acknowledge that we adopted a simple method but it was shown successful in obtaining better dust**  
20 **deposition distribution in comparison with the proxy data. Improvement of the scheme is certainly required; however, we think even if a difference in amplitude is derived, the main conclusion will still hold.**

Page 9: lines 13-16: Isn't it more likely that this small 1 degree shift, is showing that the effect is small over North America? Your argument seems to be that a much higher resolution model would be more sensitive, but I can't see why this should necessarily be the case? Perhaps I have  
25 misunderstood.

**We agree that the sentences were confusing and we have rewritten them.**

Figure 8: Can I suggest you separate this plot out into several panels for clarity?

**For clarity, the shading has been changed to be semi-transparent.**

5 Figure 9: It would be nice to compare the dust-radiation, dust-cloud and dustcryosphere effects somehow?

**We have created Supplementary Fig. C. It shows the LGMglac.a–LGM.a anomaly of aerosol–radiation and aerosol–cloud interactions for the TOA and the surface. Furthermore, it also shows the same format without the snow ageing effect. The panels clarify that the snow ageing effect on the radiative perturbation is minor. The figure also clarifies that the anomaly of aerosol–radiation interaction tends to be significant at the level of  $0.1 \text{ W m}^{-2}$ , whereas the significance of the aerosol–cloud interaction is difficult to determine. Nevertheless, the positive anomaly around Antarctica at the surface is significant.**

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Table 2: Takemura et al 2009 quote  $-0.9 \text{ Wm}^{-2}$  for the net dust-cloud effect at the LGM relative to the PI, but your LGM.a -PI.a difference is only  $-0.36 \text{ Wm}^{-2}$ . Could you comment on the differences with that older study?

15

**The model of Takemura et al. (2009) and ours both use the SPRINTARS aerosol module. However, there are differences between the experimental setups for PI and LGM experiments and the model version.**

**The difference of the global mean value is derived mainly from the different boundary conditions for PI. The SST used by Takemura et al. (2009) (Ohgaito et al. 2009; Fig. 1) over the warm pool is about  $1^\circ$  warmer than the SST used in this study (Sueyoshi et al. 2013; Fig. 4). It suggests different convective activity, resulting in different amounts of cloud ice and cloud water. This tropical difference influences the global mean value, suggesting that the SST bias of the control experiment could affect both regional and global mean values. This discussion has been added in Sect. 4.**

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## 25 **Technical comments**

Abstract Line 23: "for a first trial": I think you are referring to coupling with the ocean? It might make more sense to say "for testing the dust feedbacks in a fully coupled GCM for the first time" or similar?

**Thank you for this observation. It has been changed accordingly.**

Abstract Line 25: Perhaps change "interaction" to "coupling"?

5 **This has been changed as suggested.**

Page 2 line 17: "Although mineral dust aerosol is not the most significant cause of warming, its effect is not negligible because it is the most abundant aerosol." This makes it sound like mineral dust might have contributed to recent warming. Suggest to rephrase as "Mineral dust is the most abundant natural aerosol today."

10

**This has been changed.**

Page 3 Line 13: "where supposed to generate substantial amount of moraine debris during glacial periods" Change "where" to "were". Perhaps include some of the primary references on this topic.

15

**The sentence has been changed.**

Page 4: Line 4: "The feedback of the aerosol to the ocean and sea ice and back to the atmosphere was not taken into account". Technically, in a slab ocean model the sea-ice can respond, only the oceanic circulation is fixed.

20

**The sentence has been rewritten.**

Page 4: Line 19: So the vegetation is not fully dynamic?

25 **The dynamic vegetation module simulates global vegetation dynamics and terrestrial carbon cycling (Sato et al., 2007) using the output of the physical module, but it returns only the LAI and amount of carbon back to the land and atmosphere, respectively. Thus, the dynamic vegetation model is loosely coupled with the MIROC-ESM.**

Page 5 Line 6: "that control" not "correlated to the" Also, do these variables also control the glaciogenic dust flux?

**This has been changed and explanation added regarding glaciogenic dust.**

5 Page 6 line 10: "The emission area is also consistent between the experiments, with little deviation following the land-sea mask of MIROC-ESM"  
Sorry, I don't follow this.

**Supplementary Fig. A has been added to clarify the source areas of glaciogenic dust used in our experiments and the sentence has been reworded.**

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Page 7, line1: Is it really drier over the Sahara? I would be less surprised if it was stronger winds?

**Yes, you are correct. Stronger wind is the reason for more dust from desert areas. The sentence has been modified appropriately in the revised text.**

15

Page 7: line 3: "is probably because of the increased soil moisture, resulting in an enhancement of precipitation" Shouldn't this be "resulting from"?

**This has been changed accordingly.**

20 Page 7 line 21: change "location" to "source".

**This has been changed accordingly.**

Page 8 line 10: "It represents the total effect of the glaciogenic dust on radiation towards the earth surface" Do you mean dust-radiation plus dust-  
25 cloud plus dust-cryosphere interactions?

**We mean the total effect of the glaciogenic dust load in the atmosphere toward the surface of the earth. The sentence has been rewritten to clarify this point.**

Page 8 line 19: Repeated sentence.

**Thank you. The duplicated text has been deleted.**

5

Page 9 line 7: Refer to figure 6 here.

**We have done as you suggested.**

10 Page 9: 18-19: Please can you briefly summarise what these are?

**An appropriate explanation has been added.**

Page 10 line 16: i.e. it contributes to atmospheric heating.

15

**The global mean radiative perturbation by glaciogenic dust is cooling ( $-0.19 \text{ W m}^{-2}$ )**

**However, glaciogenic dust behaves differently over the polar regions and it contributes to atmospheric heating. An appropriate explanation has been added in the revised manuscript.**

20 Page 13 line 12: "draught" should be "drought".

**Thank you for identifying this error; it has been changed accordingly.**

Page 15 line 15-16: How strong is this snow bias in MIROC-ESM? Might be worth shoing

25

**Supplementary Fig. H has been added to show that snow cover tends to remain in boreal spring over southern Siberia.**



Figure 8: This caption doesn't completely make sense to me: "Green line denotes LGMglac.naging.a-LGM.naging.a, which means the change arose from non-aging effect of snow albedo." Does this mean that the snow albedo is affected by dust but not by ageing? Also change "Shades" to "Shading".

- 5 **We wanted to say that the “LGMglac.naging.a–LGM.naging.a” shows “the change is not attributable to the ageing effect of snow”. The caption for the figure has been rewritten in the revised text.**
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**Response for the Anonymous Referee #2 on “The effect of high dust amount on the surface temperature during the Last Glacial Maximum: A modelling study using MIROC-ESM” by Rumi Ohgaito et al.**

5 The manuscript by Ohgaito and colleagues presents results of a study on the impacts of dust on the Last Glacial Maximum climate, conducted with different configurations of the MIROC-ESM global model. Attention is given to the role of glaciogenic source of dust. Dust feedbacks on climate include direct effects, cloud effects, and snow darkening. Dust effects are discussed, in terms of perturbation to the atmospheric radiation budgets and surface temperatures. The study is an interesting contribution to both the dust community and the paleoclimate community. In my opinion the manuscript still need some improvement before publication.

10 **We wish to express our appreciation to the referee for the positive and constructive comments and suggestions, which have helped us improve our manuscript considerably. In the following, the referee’s comments are written in black and our replies are written in blue.**

General comments

15 The abstract seems all focused on glaciogenic dust, whereas the title and the manuscript deal with both glaciogenic and non-glaciogenic dust. I suggest to make more clear in the abstract that both aspects are analyzed, and what are the relative contributions to the net dust effects.

**The abstract has been modified to include mention of both non-glaciogenic and glaciogenic dust.**

20 A more detailed description of what glaciogenic sources represent, and how glaciogenic sources are embedded in the model setup are strongly encouraged, given the relevant role they play in this manuscript.

**An appropriate description has been added in Sect. 2.2 and the source areas of glaciogenic dust are shown in Supplementary Fig. A.**

25 The discussion should be improved by comparing more extensively with existing results from the literature, and by enhancing the last section which is an original contribution.

**We have improved the discussion section following your suggestion.**

The final section of the manuscript is not simply an analysis of the original contribution but it also provides an evaluation of the effect of glaciogenic dust on surface temperature. We intended to leave detailed analysis of the oceanic response for subsequent study using ongoing PMIP4 model experiments. However, your suggestion made us realize the interest concerning the oceanic element. Therefore, the oceanic response to different dust fluxes under the conditions of the LGM is more discussed in Sect 3.4.

5

Specific comments

1/14: “the impact of glaciogenic dust”. Do you mean “glacial climate dust”? In fact your study explores the effect of both glaciogenic and non-glaciogenic dust.

10 **Our focus was on glaciogenic dust. Thus, the differences between scenarios with and without glaciogenic dust were analysed as a priority. However, analyses were also performed regarding scenarios with glaciogenic dust and non-glaciogenic dust. The sentence has been modified accordingly in the revised text.**

1/18: “sources” rather than “provenances”

15

**This has been changed as suggested.**

1/21: one gets curious here: is the enhanced cloud cover caused by semi-direct or indirect effects?

20 **According to the definition of the IPCC AR5 Chapter 7, the aerosol–cloud interaction does not include semi-direct effects. If semi-direct effects dominate, enhancement of cloud prevents shortwave radiation reaching the earth’s surface, whereas the change in longwave radiation causes surface warming in this case.**

1/22-23: It’s not clear what you mean by “a first trial of glacial dust modelling” in the specific context of fully-coupled simulations, rather than the  
25 atmosphere-only ones.

**This has been changed to “an initial examination of the effect of glaciogenic dust on an oceanic general circulation model”**

2/7-8: Rather than “capturing past climate sensitivity”, I would say “estimating climate sensitivity by looking at past climates”, or perhaps more appropriate for the scope of this manuscript, “capture past climate conditions”.

**This has been changed appropriately.**

5

2/21-3/2: Repetition that higher dust fluxes are more pronounced at higher latitudes

**Thank you. The repetition has been avoided in the revised text.**

10 Pages 3-4: In this historical review section some recent, relevant papers are not cited, e.g. Albani et al. (2014), Sagoo and Storevmo (2017). I would recommend to consider them along with other also studies in the discussion section, in terms of global dust budget and impacts.

15 **Both in the historical review and the discussion sections, the works by Albani et al. (2014) and Sagoo and Storevmo (2017) are now included. The global dust budget of previous studies is summarized in Table 1 of Hopcroft et al. (2015). They highlighted that the dust amount is highly dependent on the model, not only for LGM experiments but also for PI experiments. Our emissions and loadings are listed in Table 3. Our values fall in the middle of the ranges determined by previous studies. However, they are close to those of Takemura et al. (2009) for PI and LGM, probably because the models adopted are from the same model family and use the same aerosol module. The emission of LGMglac is close to that of Mahowald et al. (2006a), most likely because we adopted their glaciogenic dust.**

20 3/11-13: This sentence is not grammatically correct, please rephrase. Also, moraine debris does not appear to be itself a potential dust source type, but rather fine grained material would be. Please try to be more specific in your definition of glaciogenic sources (e.g. see Bullard et al. 2016).

**The sentence has been rewritten and the term “moraine debris” has been changed to “glacial flour” (Bullard et al. 2016).**

25 4/9-10: it’s not very clear what is the difference between Sections 3.2. and 3.3 in this brief description.

**Section 3.2 describes the effect of glaciogenic dust on surface temperature. The question of how glaciogenic dust might modulate the surface temperature, especially surrounding Antarctica, is discussed in Sect. 3.3. The text has been rewritten accordingly in the revised manuscript.**

5/11-13: I do not understand this sentence, i.e. how this weighting occurs

5 **The ageing of snow is implemented following Yang et al. (1997) and tuned to fit the observations by Aoki et al. (2003, 2006). The weighting parameters are defined according to the absorbing property of the material. However, this part has now been removed because soot is no longer discussed in this paper.**

5/14-15: Are you using this kind of off-line model in this study? If not, it seems irrelevant to mention this fact here.

10 **Because we discuss this in Sect. 4, the sentence you have identified has now been deleted.**

5/20: Maybe “specific” rather than “particular” would be more appropriate here?

**This has been changed as suggested.**

15

6/9-10: How is this implemented in the model? At the level of grid cells (do you have the same horizontal grid?)? Or rather you are redistributing total emissions on your own grid cells matching the spatial coverage of the same geographical area? Are the emission fluxes prescribed as a repeated monthly varying quantity, or some other way? Please provide more details on this central part of your methodology, and list the geographical location of these glaciogenic sources.

20

**The glaciogenic source areas are defined by following Mahowald et al. (2006). Supplementary Fig. A has been added to clarify the source areas of glaciogenic dust. For each source area, we set a constant dust emission to match the flux in Mahowald et al. (2006). As a first trial, glaciogenic dust is emitted constantly. Once it is emitted, the treatment of the dust is the same as any other dust, i.e., its transportation, advection, and deposition processes. Although constant emission cannot happen in nature, this attempt was simply intended to emit the identical flux as in Mahowald et al. (2006) as a first step. Introducing temporal variation in emission and obtaining original glaciogenic dust flux that fits the updated proxy archive is the next research ambition. This has been outlined in Sect. 4.**

25

Table 1: Does the integration length refer to the length of your simulations only, or does it also correspond to the period averaged to derive the diagnostic quantities discussed and compared in the manuscript? Please specify how long was our spin-up and how many years you averaged for analysis.

5 **The listed integration lengths include the analyses periods. Now the ranges of the analyses are shown in Fig. 1.**

6/18-19: Indeed Australia is the major missing dust source, but also South Africa and the SW North America would fall into this category. Can you comment on how the present day simulations with the same model perform in this respect?

10 **Our PI.a (PI.e) has wet bias and relevant high LAI over South Africa and SW North America. The manuscript has been rewritten to include mention of these areas.**

7/3-4: “enhancement” is repeated twice

15 **Thank you for noticing this error; it has been corrected.**

7/5-6: expressing these quantities in Tg/year would help the reader relating to the existing literature. Actually it would be very useful to report global budgets of dust emissions, load, and deposition in a table.

20 **The unit has been changed and the additional information requested is now presented in Table 3.**

7/11: What do you mean exactly by “higher uplift”? Transport to higher levels in the troposphere? Please clarify this aspect, as it may be confused with larger emissions (which should not be case, since glaciogenic sources appear to be prescribed to a fix emissions flux).

25 **We apologize for the confusion. We meant to indicate greater dust concentration at higher levels of the troposphere. The wording has been changed appropriately in the revised manuscript.**

Figure 4: please specify if the data reported from Albani et al. (2014) refer to the bulk or to the fine fraction in terms of particle size range. In the caption, please change to “Crosses represent terrestrial sediments, circles marine sediment cores, and diamonds ice core data” - terrestrial sediments are typically loess sections.

5 **We used the bulk values of Albani et al. (2014); the caption has been changed accordingly.**

7/21: Do you mean “the main source of dust deposited in this region”?

**Yes, you are correct. We have clarified this in the revised text.**

10

8/6: What do you mean by “glacial dust”? Glaciogenic dust or glacial climate dust? IF you mean the second one, it would be useful to explicitly clarify the distinction, better in earlier sections of the manuscript. If not, you should consistently use “glaciogenic” rather than “glacial” to avoid confusion, I think.

15 **This was an error. The word has now been changed to “glaciogenic” and the entire manuscript has been checked to avoid other such occurrences.**

8/11: Do you mean “Figure 7 shows a reduction in the shortwave radiation anomaly . . .”? Similarly, in the following lines, I would suggest referring to “-wave radiation anomaly”.

20

**This has been changed appropriately.**

8/15-16: What do you mean by “radiative perturbation by the dust”? And how is that different from the analysis just carried out in the previous lines?

25

**In this section, we discuss the surface radiation anomaly. In the following section, we discuss the causes of this anomaly. It is clear that the anomaly is caused by glaciogenic dust based on the experimental setting; however, we have separated the effects of aerosol–radiation, aerosol–cloud interactions. A suitable explanation has been added in the text.**

8/6-16: A comparison with Mahowald et al. (2006) seems in order here, being the only other study discussing directly the impacts of glaciogenic sources.

5 **Comparison with Mahowald et al. (2006b) and further discussions have been added.**

8/17-19: This paragraph is repeated twice.

**Thank you for identifying this error. The duplicate text has been deleted.**

10

9/6: Please indicate where we can see this effect, i.e. “the cooling effect of the dust loading in the atmosphere” - it is not self-evident.

**The likely cooling effect of dust on the earth’s surface is suggested in the IPCC AR5 Sec. 7 and references therein. However, the uncertainty ranges from negative to positive. Each of our experiments also resulted in a cooling effect of dust in the global mean (PI.a:  $-0.99 \text{ W m}^{-2}$ , LGM.a:  $-1.50 \text{ W m}^{-2}$ , and LGMglac.a  $-1.71 \text{ W m}^{-2}$ ) at the surface.**

15

9/6-9: Again, where can the reader see these features?

**Supplementary Fig. B has been added to show the albedo difference between LGMglac.a and LGM.a. A description of Supplementary Fig. B has also been added in the revised text.**

20

9/6-16: It would seem appropriate to compare you results for this process at least with the study by Krinner et al. (2006).

**Thank you for your suggestion. The result of Krinner et al. (2006) is consistent with ours and a sentence explaining this has been added in the manuscript.**

25

9/20: A net cooling of . . . how much?



Quantification of the cooling has been added in the revised text, i.e., PI.a:  $-0.99 \text{ W m}^{-2}$ , LGM.a:  $-1.50 \text{ W m}^{-2}$ , and LGMglac.a:  $-1.71 \text{ W m}^{-2}$ .

5 Table 2: Could you further split aerosol-radiation interactions between snow darkening and atmospheric impacts? Also, can you indicate the total dust radiative perturbation (from all types of feedback)?

10 We have created Supplementary Fig. C. It shows the LGMglac.a–LGM.a anomaly of aerosol–radiation and aerosol–cloud interactions for the TOA and the surface. Furthermore, it also shows the same format without the snow ageing effect. The panels clarify that the snow ageing effect on the radiative perturbation is minor. The figure also clarifies that the anomaly of aerosol–radiation interaction tends to be significant at the level of  $0.1 \text{ W m}^{-2}$ , whereas the significance of the aerosol–cloud interaction is difficult to determine. Nevertheless, the positive anomaly around Antarctica at the surface is significant.

15 10/1-18: There is ample space here to compare the results in terms of aerosol-radiation interactions with additional existing work, e.g. see Albani et al. (2014) and Hopcroft et al. (2015).

Comparison with the works of Albani and Hopcroft has now been included and appropriate discussion has been added.

10/16-18: Please rephrase, this sentence is not very clear to me.

20 The sentence has been rephrased appropriately.

10/19-20: The link between this statement and Figure 10 is not clear to me. Please review this passage.

The sentence explains the content of Fig. 10. It has been rephrased accordingly.

25

11/2-6: A comparison with Sagoo and Storelvmo (2017) would be appropriate here.

Comparison with Sagoo and Salmiento (2017) and appropriate discussions have been added at the end of paragraph.

11/7: A more precise title for this section could be “Influence of glaciogenic sources on the ocean SST”?

**Because consideration of the effect of dust on oceans has been added, the section title has been left unchanged.**

5

11/7-21: This section is potentially very interesting. Unfortunately in its present form the discussion is quite superficial in my opinion. I would recommend to expand the section and perhaps enhance

10 **We intended to elucidate the oceanic response in our next study using LGM experiments for PMIP4. However, additional analyses have been performed and the findings are explained in the revised text.**

Figure 12 with a scatterplot or some other representation that would allow the readers to appreciate the effects on SST and land temperature anomalies.

15 **The temperature anomaly of the zonal mean over land and scatter plots of the anomaly of the proxy data and of the anomaly of the corresponding model grids are shown in Supplementary Fig. E. It illustrates the level of agreement between the model and the proxy archives. Pronounced discrepancy is evident in the northern high latitudes with some proxy data suggesting warmer temperatures than PI, whereas the model shows a negative anomaly. Compared with LGM.e, LGMglac.e generally exhibits slightly closer agreement with the proxy data.**

20

13/1-3: As discussed in the manuscript, the mismatch is to be attributed to the lack of dust emissions in regions such as Australia in the model used for this study. I fail to see what's the link with the prescribed glaciogenic sources.

25 **We meant that Mahowald et al. (2006a) used the DIRTMAP dust deposition archive (Kohfeld and Harrison 2001) to fit the model deposition flux, which had no proxy points over the southern Pacific Ocean. This could also be one of the reasons for the underestimation. The manuscript has been rewritten to clarify this point.**

14/6: see also Mahowald et al. (2014) or Albani et al. (2014)

**Thank you for your suggestion. These studies have now been cited because discussion of their findings is appropriate in this section of our manuscript.**

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\*Manuscript showing all the changes from CPD

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## Effect of high dust amount on surface temperature during the Last Glacial Maximum: A modelling study using MIROC-ESM

Rumi Ohgaito<sup>1</sup>, Ayako Abe-Ouchi<sup>2,1</sup>, Ryouta O'ishi<sup>2</sup>, Toshihiko Takemura<sup>3</sup>, Akinori Ito<sup>1</sup>, Tomohiro Hajima<sup>1</sup>, Shingo Watanabe<sup>1</sup>, Michio Kawamiya<sup>1</sup>

10 <sup>1</sup>Japan Agency for Marine-Earth Science and Technology, Yokohama, 236-0001, Japan

<sup>2</sup>Atmosphere Ocean Research Institute, University of Tokyo, Kashiwa, Chiba 277-8564, Japan

<sup>3</sup>Research Institute for Applied Mechanics, Kyushu University, Fukuoka, 816-8580 Japan

Correspondence to: Rumi Ohgaito (ohgaito@jamstec.go.jp)

**Abstract.** The effect of aerosols is one of many uncertain factors in projections of future climate. However, the behaviour of mineral dust aerosols (dust) can be investigated within the context of past climate change. The Last Glacial Maximum (LGM) is known to have had enhanced dust deposition in comparison with the present, especially over polar regions. Using the Model for Interdisciplinary Research on Climate Earth System Model (MIROC-ESM), we conducted a standard LGM experiment following the protocol of the Paleoclimate Modelling Intercomparison Project phase 3 and sensitivity experiments. We imposed glaciogenic dust on the standard LGM experiment and we investigated the impacts of glaciogenic dust and of non-glaciogenic dust on the LGM climate. Global mean radiative perturbations by glaciogenic and non-glaciogenic dust were both found negative, consistent with previous studies. However, glaciogenic dust behaved differently in specific regions, e.g., it resulted in less cooling over the polar regions. One of the major reasons for reduced cooling is the ageing of snow or ice, which results in albedo reduction via high dust deposition, especially near sources of high glaciogenic dust emission. Although the net radiative perturbations in the lee of high glaciogenic dust provenances are negative, warming by ageing of snow overcomes this radiative perturbation in the Northern Hemisphere. In contrast, the radiative perturbation

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due to high dust loading in the troposphere acts to warm the surface in areas surrounding Antarctica, primarily via the longwave aerosol–cloud interaction of dust and it is likely the result of the greenhouse effect attributable to the enhanced cloud fraction in the upper troposphere. Although our analysis focused mainly on the results of experiments using the atmospheric part of the MIROC-ESM, we also conducted full MIROC-ESM experiments for an initial examination of the effect of glaciogenic dust on the oceanic general circulation module. A long-term trend of enhanced warming was observed in the Northern Hemisphere with increased glaciogenic dust; however, the level of warming around Antarctica remained almost unchanged, even after extended coupling with the ocean.

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## 1 Introduction

The Last Glacial Maximum (c.a. 21,000 years before present; LGM), which is the most recent period featuring maximum expansion of the land ice sheets in the Northern Hemisphere, has been investigated thoroughly using various paleo-proxy records and via modelling studies (Braconnot et al., 2007a,b, Kageyama et al., 2006, 2017). Global warming is considered an important driver in investigations seeking to clarify the mechanisms of climate change, as stated repeatedly by the Intergovernmental Panel on Climate Change (IPCC) in their assessment reports (IPCC, 2013). Therefore, it is especially important to evaluate the capability of numerical models to capture past climatic conditions.

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Paleo-proxy data and modelling studies are both required for proper understanding of past climates; however, the focus of this study was on modelling. General circulation models (GCMs) are one of the tools used most widely for investigation of the mechanisms of both climate and climate change. The improvement of computational resources has allowed the development of models with high complexity, that permit interactive coupling of various climatic components. In comparison with proxy data, previous modelling experiments targeting the LGM have tended to underestimate the magnitude of cooling, especially over high latitudes (Masson-

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Delmotte et al., 2006, 2010). The importance of feedback related to dust and vegetation has been identified in Chapter 5 of the IPCC's Fifth Assessment Report (IPCC, 2013).

It is recognized that uncertainty over the effect of aerosols is one of the most important factors regarding the radiative perturbation in estimates of global warming. Mineral dust is the most abundant atmospheric aerosol, even in the present climate. For example,

5 Mahowald et al. (2010) investigated the trend of the amount of atmospheric dust in the 20<sup>th</sup> century based on observations and modelling. They reported correlation between an increase of desert dust and a net negative radiative perturbation. Examination of proxy data has suggested clear enhancement of dust during the LGM, which was especially pronounced at high latitudes, i.e., reaching levels more than 20 times greater than the present day over Antarctica (Lambert et al., 2008, Lamy et al., 2014, Dome Fuji Ice Core Project members, 2017). Although the enhancement of dust deposition was found less over lower latitudes, it was still several times higher in comparison with the present day (Winckler et al., 2008).

Although earlier studies (Mahowald et al., 1999, Lunt and Valdes, 2002, Claquin et al., 2003) have estimated higher dust amounts during the LGM in comparison with the pre-industrial (PI) period, dust amounts over Antarctica have tended to be underestimated.

Claquin et al. (2003) estimated the radiative perturbation at the top of the atmosphere (TOA). They reported a cooling effect attributable to dust, but they also found a warming effect due to dust deposition on snow. Later, Mahowald et al. (2006a,b) estimated

15 the glaciogenic dust flux and the aerosol-radiation interaction. Their standard LGM experiment simulated underestimation of dust deposition flux, especially over high latitudes, in comparison with the DIRTMAP proxy data archive, (Kohfeld and Harrison 2001).

Then, they considered the effect of sources of glaciogenic dust surrounding the ice sheets and glaciers. Such areas are supposed to generate substantial amounts of glacial flour during glacial periods, (Bullard et al. 2016). The study considered the emission of various fluxes of dust from these glaciogenic source areas and a best fit to the DIRTMAP deposition distribution, was obtained. Although this

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estimate could conceal other possible and non-introduced processes of dust sources, it constitutes an important step forward in the determination of a reasonable representation of both the atmospheric loading and the depositional distribution of dust during the LGM. However, they did not estimate the effects of aerosol–cloud interaction. Takemura et al. (2009) used the Model for Interdisciplinary Research on Climate (MIROC) Atmospheric GCM (AGCM) with an online aerosol module to determine both the aerosol–radiation and the aerosol–cloud interactions for LGM and PI periods at both the surface and the tropopause. However, they underestimated the amount of dust deposition over Antarctica, probably because they did not consider glaciogenic dust. Yue et al. (2011) used an AGCM to estimate the aerosol–radiation interaction for dust and they reported an evident cooling effect. Albani et al. (2014) supposed high erodibility areas to obtain better representation of LGM dust. They also highlighted the importance of the optical properties and size distribution of dust aerosols. In comparison with the control setting, Sagoo and Strelvmo (2017) applied an emission factor of 3.4 to the dust emissions in an LGM level CO<sub>2</sub> experiment (i.e., the land sea mask and ice sheets were unchanged from the control) to mimic the high dust situation during the LGM and they estimated the aerosol–cloud interaction. Hopcroft et al. (2015) investigated the aerosol–radiation interaction at the TOA using an AGCM and the land module of an earth system model (ESM), based on which they suggested the necessity of further analyses of aerosol–cloud interaction as future work. They also summarized the global mean dust emissions and loadings of the PI and LGM periods reported in previous studies. It was suggested that the amount of dust is highly dependent on the model used, not only during the LGM but also in the PI period.

Another aspect of dust is related to ageing of the snow surface, which possibly modulates the surface temperature via albedo reduction. Krinner et al. (2006) discussed the importance of the ageing effect of snow, particularly over eastern Siberia. Their ageing scheme was based on that of Warren and Wiscombe (1981) and Wiscombe and Warren (1981). Moreover, Ganopolski et al. (2010) simulated the glacial–interglacial cycle using an intermediate complexity model, in which the ageing effect was implemented via simple scaling.

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Previous studies that have investigated the effect of glaciogenic dust have not taken into account the feedback of the dust to the atmosphere via the oceanic thermohaline circulation. Moreover, Lambert et al. (2013) identified the possibility of polar amplification attributable to dust.

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In summary, we claim that the evaluation of the total effect of dust on the LGM surface temperature is incomplete. Therefore, this study addressed the problem by incorporating the effects of aerosol–radiation interaction, aerosol–cloud interaction, snow ageing, and dust–ocean interaction. We undertook AGCM simulations and full ESM simulations of the LGM with sensitivity experiments targeting the effects of dust on climate.

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The following section explains the modelling and experimental set-ups. The resulting estimations of dust amount and dust depositional distribution are presented in Sect. 3.1, and the influence of dust on surface temperature is described in Sect. 3.2. To investigate how dust might modulate the atmospheric state, the radiative perturbation attributable to dust is described in Sect. 3.3, and the effect of glaciogenic dust on the ocean is discussed in Sect. 3.4. The results of the simulations are summarized and discussed in Sect. 4.

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## 2 Model and experimental design

### 2.1 Description of the MIROC-ESM

The MIROC-ESM (Watanabe et al., 2011) used in this study was the version submitted to both the Coupled Model Intercomparison Project phase 5 (CMIP5) and the Paleoclimate Modelling Intercomparison Project phase 3 (PMIP3). The resolution of the atmosphere in the model is T42 with 80 vertical levels, while that of the ocean is about  $1^\circ$  ( $256 \times 192$ ). Although the model is capable of prognosis of the amount of  $\text{CO}_2$  in the atmosphere, we prescribed the level of atmospheric  $\text{CO}_2$  in our experimental set-up. The spatially explicit individual-based Dynamic Global Vegetation Model (SEIB-DGVM) (Sato et al., 2007) was implemented to simulate global vegetation



dynamics and terrestrial carbon cycling in the system, but it returns only the leaf area index (LAI) to the Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) land module. (Takata et al., 2003). In this model, the SEIB-DGVM received several variables from the AGCM, but it returned only the carbon flux to the atmosphere. Also implemented was the Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) on-line aerosol module (Takemura et al., 2000, 2002, 2005, and 2009), which explicitly treats organic, black carbon, and mineral dust, sea-salt aerosols, and sulfate and its precursor gases. This module was coupled with the radiation and cloud microphysical schemes to calculate the aerosol-radiation and aerosol-cloud interactions. In the calculation of the former, refractive indices depending on wavelengths, size distributions, and hygroscopic growth were considered. The refractive index of dust aerosols was taken from Deepak and Gerber (1983) but its imaginary part was reduced for consistency with recent measurements of weaker shortwave absorption. Number concentrations of both cloud droplets and ice crystals are prognostic variables as are their mass mixing ratios, and the changes in their radii and precipitation rates were calculated. Thus, the aerosol-cloud interaction was taken into account. The processes controlling dust generation are the surface wind, vegetation type, soil moisture, LAI, and snow cover. Once dust is generated, it is transported via the atmospheric circulation, and deposited via the processes of wet/dry deposition, and gravitational settling. In this study, glaciogenic dust was imposed for the sensitivity experiments. The generation of glaciogenic dust flux followed the estimate of Mahowald et al. 2006a and it was emitted constantly independent of the other conditions.

In the MATSIRO module, the effect of dirt in snow (i.e., snow ageing) was considered based on the work of both Yang et al. (1997) and Warren and Wiscombe (1981). The magnitude of dirt concentration at the snow surface was varied to fit an observed relation between snow albedo and dirt concentration (Aoki et al., 2006). The dirt concentration in snow was calculated from the deposition fluxes of dust and soot calculated in the SPRINTARS module. The relative strength of the absorption coefficients for dust and soot were weighted to the deposition fluxes to obtain radiatively effective amounts of dirt in the snow.

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## 2.2 Experimental design

We performed eight experiments: five using the AGCM part of the MIROC-ESM and three using the full MIROC-ESM. The specific experiments labelled PI.a and PI.e represent the 1850 A.D. control climate of the PI era, with PI.e having been submitted to CMIP5.

- 5 The previous 100-year climatology of sea surface temperature (SST) and of sea ice of the period submitted to CMIP5 was used as boundary conditions for PI.a. The experiments labelled LGM.e and LGM.a represent the LGM climate following the PMIP3 protocol (Abe-Ouchi et al., 2015). The LGM.e experiment was submitted to CMIP5/PMIP3 (Sueyoshi et al., 2013). The LGM.a experiment was the AGCM experiment using the SST and sea ice taken from the PMIP3 LGM experiment (LGM.e). The LGM.e experiment was extended for a further 800 years beyond the PMIP3 period (Fig. 1). The LGMglac.a experiment was a new experiment based on the
- 10 same conditions as LGM.a, but with an additional glaciogenic dust flux following Mahowald et al. (2006a). The LGMglac.naging.a and LGM.naging.a experiments had the same settings as LGMglac.a and LGM.a, but without the effect of snow ageing. The LGMglac.e experiment was the full ESM version of LGMglac.a, which branched from the LGM.e experiment 40 years prior to the period submitted to CMIP5/PMIP3 (Fig. 1). The glaciogenic dust flux from each area was set identical to the estimates of Mahowald et al. (2006a) and the emission areas were defined to follow their work as closely as possible (see supplementary Fig. A), i.e., the three
- 15 areas of strongest emission were the Pampas of South America, central North America, and eastern Siberia. In contrast to non-glaciogenic dust, the emission of glaciogenic dust was independent of dust emission conditions and it was emitted constantly for consistency with the dust flux in Mahowald et al. (2006a) (Table 3(b)). Once emitted into the atmosphere, the treatment of glaciogenic

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dust was identical to non-glaciogenic dust. The integration of LGMglac.e was performed for 940 years. Table 1 lists the details of all the experiments.

### 3 Results

#### 3.1 Dust amount and comparison with data archives

5 The emission flux of dust ( $\text{g m}^{-2} \text{y}^{-1}$ ) is shown in Fig. 2 for the PI.a, LGM.a, and LGMglac.a experiments. For the PI.a experiment, the major dust sources are the Saharan, Arabian, Gobi, and Taklamakan deserts. A minor source is also found in the mid-latitude region of South America. While these dust sources look reasonable based on the present-day situation, there is too little dust emission from the other plausible dust sources such as Australia, southern Africa, and southwestern North America. The wet bias over these areas in the PI.a experiment leads to excess vegetation, which prevents dust emission, and persists in the LGM.a and LGMglac.a experiments. In the LGM.a and LGMglac.a experiments, the dust emission flux in the Saharan, Gobi, and Taklamakan deserts is significantly enhanced, which is the result of a windier and drier climate during the LGM, with additional emission flux evident from northern Siberia. In contrast, the emission flux from South America is reduced, which is probably because of increased soil moisture, resulting from enhanced precipitation in this region. For the LGMglac.a experiment, glaciogenic dust emission is evident surrounding the extended ice sheets during the LGM. The total emission amount is 2540 ( $\text{Tg y}^{-1}$ ) for the PI.a experiment, 7250 ( $\text{Tg y}^{-1}$ ) for the LGM.a experiment, and 13,400 ( $\text{Tg y}^{-1}$ ) for the LGMglac.a experiment. The total simulated emissions and atmospheric loads are listed in Table 3.

The global dust budget can be compared with the findings of previous studies. Hopcroft et al. (2015) summarized it in their Table 1.

They clarified that the dust amount is highly dependent on the model, not only for the LGM experiments but also for the PI experiments.

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Our emission and load values fall in the middle of the ranges determined by previous studies. However, they are close to those of Takemura et al. (2009) for PI.a and LGM.a, probably because the models adopted are from the same model family and use the same aerosol module. The emission of LGMglac.a is close to that of Mahowald et al. (2006a), most likely because we adopted their glaciogenic dust, but the load (39 Tg) is significantly smaller (62 Tg), which suggests overestimation of immediate dust deposition rates near the source areas (Fig. 4) attributable to our assumption of the independence of dust emission from wind speed. The change in the zonal mean dust loading in the atmosphere for the ratios LGM.a/PI.a and LGMglac.a/PI.a is shown in Fig. 3(a) and 3(b), respectively. In the LGM.a experiment, the dust mass concentration in the Northern Hemisphere is enhanced, but decreased in the Southern Hemisphere compared with the PI.a experiment. In contrast, the mass concentration is enhanced significantly in both the northern and the southern high latitudes in the LGMglac.a experiment. The glaciogenic dust reached higher levels of the troposphere in the Southern Hemisphere compared with the Northern Hemisphere. This can be attributed to the different conditions of the strong dust sources. In the Southern Hemisphere, they are exposed to stronger winds because of the lack of continental land, whereas in the Northern Hemisphere, the strong sources of glaciogenic dust are located over continents that are subject to lower wind speeds. The distribution of dust deposition for each experiment is shown in Fig. 4(a)–(c) and the ratio to PI.a is shown in Fig. 5 for comparison with the archives of ice and sediment core data, as indicated by the coloured circles (Kohfeld et al., 2013, Albani et al., 2014). The scatter plots shown in Fig. 4(d)–(f) compare the data with the modelled deposition rate at the grids corresponding to the data locations. The colours and mark types are used for categorization according to the area and the type of core data. Reasonable correlation is seen for the PI.a experiment, except in the grids over the Southern Ocean, which are mostly located in the southern Pacific Ocean region. The main source of the dust deposited in this region is expected to be Australia (Li et al., 2010, Albani et al., 2012), where our model underestimates the emission. In the LGM.a experiment, the dust deposition flux is underestimated in North America, Eurasia, the

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South Pacific, the Southern Ocean, and Antarctica. In contrast, in the LGMglac.a experiment, the underestimation is generally improved. The model-data linear correlation coefficients in the logarithmic scale are 0.79, 0.62, and 0.80 for the PI.a, LGM.a, and LGMglac.a experiments, respectively. The differences in the deposition flux between the PI.a and PI.e experiments, LGM.a and LGM.e experiments, and LGMglac.a and LGMglac.e experiments are almost negligible.

### 5 3.2 Effect of glaciogenic dust on surface temperature

The surface temperature at the height of 2 m is influenced by glaciogenic dust and the difference of LGMglac.a relative to LGM.a is presented in Fig. 6. The warming (i.e., less cooling compared with the PI.a results) is pronounced in the high latitudes in contrast to the expectation of the likely cooling effect of the dust (IPCC, 2013).

The changes in the LGMglac.a results relative to the LGM.a results for the net, longwave, and shortwave downward radiation at the surface are presented in Fig. 7. It represents the total effect of the atmospheric loading of glaciogenic dust on radiation toward the earth surface. Figure 7(c) shows a negative anomaly in shortwave radiation near the strong sources of glaciogenic dust, as well as in the northern high latitudes and the edge of Antarctica. In contrast, a positive anomaly of longwave radiation in the LGMglac.a experiment is pronounced around Antarctica and in the northern high latitudes. While the negative anomaly in shortwave radiation dominates the net change near the areas of glaciogenic dust emission, the positive longwave anomaly dominates the region surrounding Antarctica. The radiative perturbation attributable to the glaciogenic dust is detailed in the next section.

Figure 8 shows that warming of LGMglac.a–LGM.a south of 55° S is evident without the inclusion of the effects of the ageing of snow (LGMglac.naging.a–LGM.naging.a). This suggests the warming around Antarctica is not the result of snow ageing but that it follows from the change in the radiation balance in the atmosphere. Moreover, the magnitude of the warming is not significantly

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affected by ocean coupling (LGMglac.e–LGM.e). In contrast, more than 80 % of the warming in the Northern Hemisphere is the result of ageing of the snow surface, as is evident by inspection of the LGMglac.naging.a–LGM.naging.a results (Fig. 8). The high dust deposition rate reduces the surface albedo (Supplementary Fig. B) and leads to reduction of reflected shortwave radiation, which overcomes the cooling effect of the dust loading in the atmosphere, resulting in warming (Fig. 6). The warming in the Northern Hemisphere is most pronounced over eastern Siberia and central North America, where large amounts of glaciogenic dust are deposited, and therefore where the albedo of the LGMglac.a experiment is reduced significantly. The snow in the LGMglac.a experiment thaws earlier in the year than in the LGM.a experiment over eastern Siberia. Substantial snowmelt over a large area within this region accelerates warming via albedo reduction. This is consistent with the results of Krinner on the point of snow ageing preventing the accumulation of snow in this region. In contrast, in central North America, the snow is reduced compared with the LGM.a experiment, but it is still significantly higher than the PI.a experiment. The position of the –2 °C isopleth averaged over June–August, which is the threshold of ice sheet retreat–extension (Ohmura et al. 1996), shifted northward by about 1° latitude, which is significantly less than the model resolution. Therefore, the effect of our dust flux on climate is lesser melting of the Laurentide Ice Sheet. However, we question whether the model is able to represent the appropriate ageing of snow under such a high dust deposition flux. As this is beyond the scope of this study, further evaluation of the effects of snow ageing are required.

### 3.3 Aerosol–radiation and aerosol–cloud interactions by dust

The aerosol–radiation and aerosol–cloud interactions were estimated using the same method as Takemura et al. (2009). The aerosol–radiation interaction was estimated based on the difference between a standard experiment and another experiment under the same

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conditions but without the dust affecting radiation. The aerosol–cloud interaction was estimated based on the difference between a standard experiment and another experiment under the same condition but without dust.

The net global mean radiative perturbation (aerosol–radiation and aerosol–cloud) of dust is one of cooling at the earth’s surface for all the experiments, i.e., PI.a:  $-0.99 \text{ W m}^{-2}$ , LGM.a:  $-1.50 \text{ W m}^{-2}$ , and LGMglac.a:  $-1.71 \text{ W m}^{-2}$ . The breakdown of the LGM experiments relative to the PI experiment for the change in the global mean radiative perturbation is listed in Table 2. The net change of the global mean aerosol–radiation interaction at the TOA is slightly positive for the LGM.a–PI.a results and it amounts to  $0.12 \text{ W m}^{-2}$  for the LGMglac.a–PI.a results. However, the change at the surface is negative both with ( $-0.21 \text{ W m}^{-2}$ ) and without ( $-0.30 \text{ W m}^{-2}$ ) glaciogenic dust. The change is of similar magnitude to the findings of previous studies (e.g.,  $-0.25$  and  $-0.56 \text{ W m}^{-2}$  with and without glaciogenic dust in Mahowald et al. (2006b),  $-0.23 \text{ W m}^{-2}$  in Takemura et al. (2009), and  $-0.26 \text{ W m}^{-2}$  in Albani et al. 2014)), and it is caused primarily by changes in shortwave radiation. The net change of the global mean aerosol–cloud interaction at the TOA for the LGM.a–PI.a result is  $-0.36 \text{ W m}^{-2}$ . Both the shortwave and the longwave radiation increased with glaciogenic dust, resulting in a net change of  $-0.39 \text{ W m}^{-2}$ . At the surface, without glaciogenic dust, there is net negative reduction in comparison with the TOA. With the inclusion of glaciogenic dust, however, the change at the surface is slightly more negative than the change at the TOA. Considering the total effect of dust, but without glaciogenic dust, the radiative perturbation change at the TOA relative to the surface is small, whereas the inclusion of glaciogenic dust results in surface cooling via aerosol–radiation interaction.

Figure 9 shows the spatial distribution of radiative perturbation by dust at the TOA, which has a smaller difference between the LGMglac.a and LGM.a results compared with the surface (Fig. 10(a)). At the TOA, although the influence of glaciogenic dust from the Pampas region is distributed over the Southern Ocean, the positive longwave and negative shortwave radiation almost cancel each other out. There are local negative effects over the strong sources of glaciogenic dust but the amplitudes are much smaller than at the

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surface (Figs. 9(a) and 10(a)). Supplementary Fig. C shows the LGMglac.a–LGM.a anomaly of aerosol–radiation and aerosol–cloud interactions for the TOA and the surface; it also presents the same information but without the snow ageing effect. The panels clarify that the effect of snow ageing on the radiative perturbation is minor. The figure also clarifies that the anomaly of the aerosol–radiation interaction tends to be significant at the level of  $0.1 \text{ W m}^{-2}$ , whereas the significance of the anomaly of the aerosol–cloud interaction is difficult to determine. Nevertheless, the positive anomaly around Antarctica at the surface is significant. Therefore, although glaciogenic dust changes the TOA radiation budget only marginally, it heats/cool the atmosphere and causes a greater change in the radiation budget at the surface. The global mean change resulting from the addition of glaciogenic dust is cooling ( $-0.19 \text{ W m}^{-2}$ ), but with local atmospheric heating over the high latitudes. Hereafter, we investigate the changes in the spatial distribution and strength of radiation at the surface under different climatic conditions.

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Figure 10 shows the change of the net radiative perturbation at the surface for the LGMglac.a–LGM.a, LGMglac.a–PI.a, and LGM.a–PI.a experiments. The aerosol–radiation interaction dominates near the massive dust sources, e.g., the Sahara Desert. Except for such regions, the aerosol–cloud interaction dominates the radiative perturbation. The addition of glaciogenic dust acts to reduce shortwave radiation. The negative radiative perturbation is distinct near the emission areas. In contrast, for longwave radiation, a general positive radiative perturbation resulting from glaciogenic dust is obvious, especially near the strong sources of dust and at the edge of Antarctica. The negative shortwave radiation forcing overcomes the positive longwave radiation forcing near the sources of glaciogenic dust. However, the positive longwave radiative perturbation plays a role in the regions surrounding Antarctica. The higher dust loading in the higher troposphere in the Southern Hemisphere promotes the generation of cloud ice nucleation and high-level clouds, especially in the regions surrounding Antarctica, likely resulting in an enhanced greenhouse effect, which warms the lower troposphere (Figs. 3(c) and 11). Because the dust deposition flux of the standard LGM.a experiment is higher than the PI.a experiment

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in the Northern Hemisphere but lower in the Southern Hemisphere, the impact of glaciogenic dust might be more efficient in the Southern Hemisphere. Sagoo and Strelvmo (2017) reported global mean cooling in a “high” dust experiment, consistent with our results (Table 2). The discrepancies could arise because of different cloud ice nuclei schemes, of their experimental setting (no change of land from their control) and because their sources of high dust emission were located mainly in desert areas, whereas our glaciogenic dust sources are located in the high latitudes.

### 3.4 Influence of glaciogenic dust on the ocean

We extended the LGM.e experiment by 800 years beyond the original PMIP3 period (Fig. 1) and the LGMglac.e experiment was conducted for 940 years. Because the temperatures become quasi-stable after year 600 in Fig. 1, the average of the final 300 years is used for the analyses. The strength of the Atlantic Meridional Overturning Circulation (AMOC) of LGM.e reduced by about 10 Sv in the analysis period compared with the spin-up period and LGMglac.e. The different behaviour of the AMOC might be attributable to higher dust deposition resulting in enhanced snow ageing in LGMglac.e. The strength of the abyssal cells (Supplementary Fig. D) is more stable but with differences of a few Sverdrup between LGM.e and LGMglac.e reflecting the AMOC state. The surface air temperature and SST changes according to the LGMglac.e–LGM.e results are presented in Fig. 12. The zonal mean anomaly of air temperature over land and scatter plots of the anomaly of the proxy data (Bartlein et al., 2011) and of the anomaly of the corresponding model grids are shown in Supplementary Fig. E. It illustrates the level of agreement between the model and the proxy archives. Pronounced discrepancy is evident in the northern high latitudes with some proxy data suggesting warmer temperatures than PI, whereas the model shows a negative anomaly. Although the differences between LGM.e and LGMglac.e appear minor in comparison with the pollen proxy archive, LGMglac.e generally exhibits slightly closer agreement with the proxy data.

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Warming of the SST by the increased air temperature is obvious in the northern high latitudes, but the magnitude of the SST change is mostly below 0.5 °C. Locally strong warming along the Gulf Stream can be attributed to differences in the strength of the thermohaline circulation. Although investigation of the effect of dust on the thermohaline circulation is left for future work, we note there might be a possibility of an effect of strong snow ageing in the Northern Hemisphere. In contrast, almost no change is calculated in the SST around Antarctica (Fig. 12(f)), which confirms that warming around Antarctica is not attributable to a change in the temperature of the ocean surface. Even after the extended integration times of our simulations, the high plateau over the Antarctica, which is often the location of ice core sites, does not warm further (e.g., see circled letters in Fig. 12(a)–(c)). The LGMglac.e cooling from the PI.e results for this area is largely within the range of observational estimates (–7 to –10 °C) (Stenni et al., 2010, Uemura et al., 2012).

10 The SST anomaly in both the LGM.e-PI.e and the LGMglac.e-PI.e experiments appear reasonable in comparison with the LGM SST reconstruction shown by coloured circles (MARGO project members, 2009) (Fig. 12(d) and (e)). Local cooling of the ocean temperature is seen in the lee of the source of glaciogenic dust in Argentina, which would be caused by the negative radiative perturbation (Figs. 7 and 10(a)).

15 The zonal mean potential temperature and salinity anomalies in the Atlantic and Pacific oceans for the LGM.e-PI.e and LGMglac.e-PI.e experiments are presented in Supplementary Figs. F and G. The positive anomalies in the Northern Hemisphere in Supplementary Figs. F(c) and G(c) are attributable to the difference in the strength of the AMOC between LGM.e and LGMglac.e. The minor negative anomaly in the upper 100 m around 30° S in the Atlantic basin can be attributed to the effect of glaciogenic dust from the Pampas area.

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#### 4 Conclusions and discussion

This study used the MIROC-ESM to investigate the effect of mineral dust aerosols on the glacial climate. The representations of climatology by the PI.a and PI.e simulations are considered reasonable for a state-of-the-art ESM (Watanabe et al. 2011). The cooling evident in the LGM.e experiment in comparison with the PI.e results is also generally comparable with paleo-proxy archives (Fig. 12).

5 The net effect of global mean dust during the LGM is negative, which is the same trend as reported in previous studies (Mahowald et al. 2006b, Albani et al. 2014, Hopcroft 2015, Sagoo and Strelvmo 2017). The global mean value is dominated by high emission of dust from subtropical deserts. Takemura et al. (2009) suggested an LGM-PI anomaly of  $-0.9 \text{ W m}^{-2}$  for the global mean aerosol-cloud interaction, whereas our anomaly is  $-0.36 \text{ W m}^{-2}$  (Table 2), even though the results are based on models from the same model family. This difference in the global mean value is derived mainly from the different boundary conditions used for the PI experiment.

10 The SST used by Takemura et al. (2009) (Ohgaito et al. 2009; Fig. 1) over the warm pool was about  $1^\circ$  warmer than the SST used in this study (Sueyoshi et al. 2013; Fig. 4), suggesting different convective activity and consequently, different amounts of cloud ice and cloud water. This tropical difference influences the global mean value, suggesting that the SST bias of the control experiment could affect both regional and global mean radiative perturbations.

The focus of this study was on the high latitudes, with investigation of the effect of glaciogenic dust based on new LGMglac.a and LGM.a experiments using the AGCM part of the MIROC-ESM. The effect of the addition of glaciogenic dust on climate is evident mainly as warming in the high latitudes. Our results are different from likely cooling aerosol effect (IPCC, 2013) and that demonstrated by Mahowald et al. (2006b) in the zonal mean. Especially for the northern high latitudes, areas are warmed via albedo reduction because of snow ageing and because of prolonged disappearance of snow at certain periods, which is especially pronounced in eastern Siberia. Although the longwave radiative perturbation is negative near the strong sources of glaciogenic dust flux, the snow ageing

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effect overcomes this cooling, resulting in a net increase in temperature. The possibility of overestimation of ageing of snow effect or our simple emission method may influence the result. The findings of the cooling effect of dust and the warming effect of snow ageing are consistent with the results of Claquin et al. (2003).

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5 The warming effect resulting from the addition of glaciogenic dust is also seen in areas surrounding Antarctica; however, it is not attributable to snow ageing but to longwave aerosol–cloud interactions. Accounting for this effect would alter the distribution of the scatter evident in Fig. 5.5(d) in the IPCC’s Fifth Assessment Report, which shows the correlation of eastern Antarctic cooling during the LGM with the future projection.

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10 We adopted additional dust sources from Mahowald et al. (2006a, b) as a first step, where their glaciogenic dust flux was identified as a best fit to the DIRTMAP data archive. Nevertheless, as noted, their deposition flux does not correspond well to new proxy data at locations in the Southern Ocean. However, in our case, this mismatch can also be attributed to a feature of our model, i.e., insufficient dust emission from Australia and South Africa, which is caused mainly by overestimation of soil moisture and the resulting excess of vegetation. Our study draws attention to the high dust loading over the Southern Ocean that affects the increase in surface temperature in areas surrounding Antarctica, implying the necessity of investigation of climate sensitivity to the amount of dust emission in future work. However, over the Southern Ocean, SST is affected minimally (Fig. 8) by the surface radiation change (Figs. 7(a) and 10(a)),  
15 probably because of the large heat capacity of the ocean.

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Glaciogenic dust was imposed constantly in this study, which is not realistic. In reality, temporal variability of glaciogenic dust should be dependent on changes both in wind speed and in the threshold wind friction velocity at which dust emission is initiated. Thus, the independence of dust emission from wind speed might cause overestimation of dust deposition rates at the grids close to emission areas and under low atmospheric loading, but result in good agreement with the measurements of deposition flux in general. We note

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that matching the simulated Fe depositions might cause low bias in atmospheric concentrations (Albani et al., 2014). Thus, we suggest the possibility that the anomaly surrounding Antarctica is underestimated. It will be necessary to implement a better scheme for glaciogenic dust in subsequent research. Sagoo and Strevmo (2017) prescribed a globally “idealized high” dust emission factor for their LGM-like experiment. Because our glaciogenic dust sources are located in the high latitudes, the influence of glaciogenic dust emission on the surface temperature around Antarctica is likely more pronounced in our simulation results.

In the tropics, the effect of enhanced dust input on the surface temperature is similar to what Mahowald et al. (2010) reported in their study of the mid- to late 20<sup>th</sup> century, but with contrasting effects at high latitudes. The major difference is that dust is enhanced at low latitudes, i.e., the Sahara-Sahel drought in the 20<sup>th</sup> century perturbation compared with the additional high dust inputs at high latitudes in our study, where the background albedo is high because of the extended areas of snow and ice cover.

10 In the MIROC-ESM, snow cover in the PI.e (PI.a) experiment tends to persist in boreal spring over Siberia in comparison with reanalysis data (Supplementary Fig. H). This positive bias might influence the change we see in the LGM.e (LGM.a) and LGMglac.e (LGMglac.a) experiments.

The strong effect of snow ageing is especially significant in the Northern Hemisphere. Because snow ageing has been tuned to fit modern observations in Hokkaido, Japan (Aoki et al., 2003, 2006) in the MIROC-ESM, a strong dust provenance near snow-covered areas is lacking, e.g., as in the glaciogenic dust situation seen in eastern Siberia. Therefore, evaluation of the quantitative influence of snow ageing using various observational sites is needed. The albedo impurity relationship provided by Aoki et al. (2003, 2006), in which ageing starts to work when the impurity is  $\geq 10$  ppmw, explains the reason for the considerable snow ageing in the Northern Hemisphere but lack of snow ageing over Antarctica. The deposition flux over Antarctica is 3–4 orders of magnitude smaller than the

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regions of high dust emission in the Northern Hemisphere. The threshold of activation of snow ageing is in between the high dust deposition in the Northern Hemisphere and the low deposition flux around Antarctica.

Although we were unable to treat the effect of Fe supply to the ocean in this model, activating the Fe-fertilization effect and enhancing the amount of plankton would influence CO<sub>2</sub> uptake, especially over the Southern Ocean (Martin, 1990). Improved representation of the distribution of dust deposition is possible as a boundary condition for off-line biogeochemical models to investigate CO<sub>2</sub> uptake, e.g., in a more realistic version of the experiments by Oka et al. (2011). Further investigation of the non-negligible effect of the change in the size distribution of dust as identified by Albani et al. (2014), Mahowald et al. (2014), and Hopcroft et al. (2015) might also be necessary.

Plant functional types are considered in the dynamic vegetation module but not returned to the land module in the MIROC-ESM; i.e., the climate–vegetation interaction is limited. The importance of full vegetation coupling was highlighted by O’ishi and Abe-Ouchi (2013), who suggested the necessity for future models to evaluate the changes of plant functional types and especially, their effect on dust cycles.

Under global warming, the amount of dust emission remains uncertain (Woodward et al., 2005, Tegen et al., 2004, Jacobson and Streets, 2009, Liao et al., 2009, Mahowald et al., 2006a, Ito and Kok, 2017). Therefore, improving the understanding of dust processes in models of the past climate would be a practical way to reduce the uncertainty of projections into the future.

**Author Contributions:** ROH, AA and ROI discussed the paleoclimate motivations on LGM dust and experimental design. ROH designed, conducted, analysed experiments and documented the manuscript. TT and AI advised the analyses on the aerosol module. SW, TH, and MK developed MIROC-ESM. All authors contributed discussions.

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**Conflicts of Interest: The authors declare that they have no conflict of interest.**

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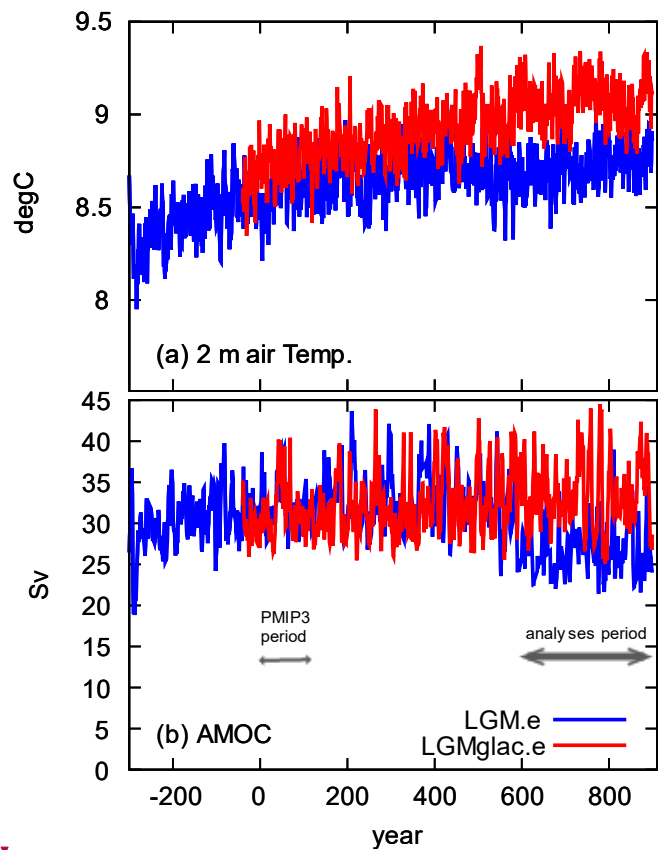


Figure 1: Time series of (a) global mean annual mean temperature at 2 m height ( $^{\circ}\text{C}$ ) and (b) peak strength of the Atlantic meridional overturning circulation (AMOC; Sv) for LGM.e and LGMglac.e. The year zero was set to the beginning of the period submitted to CMIP5.

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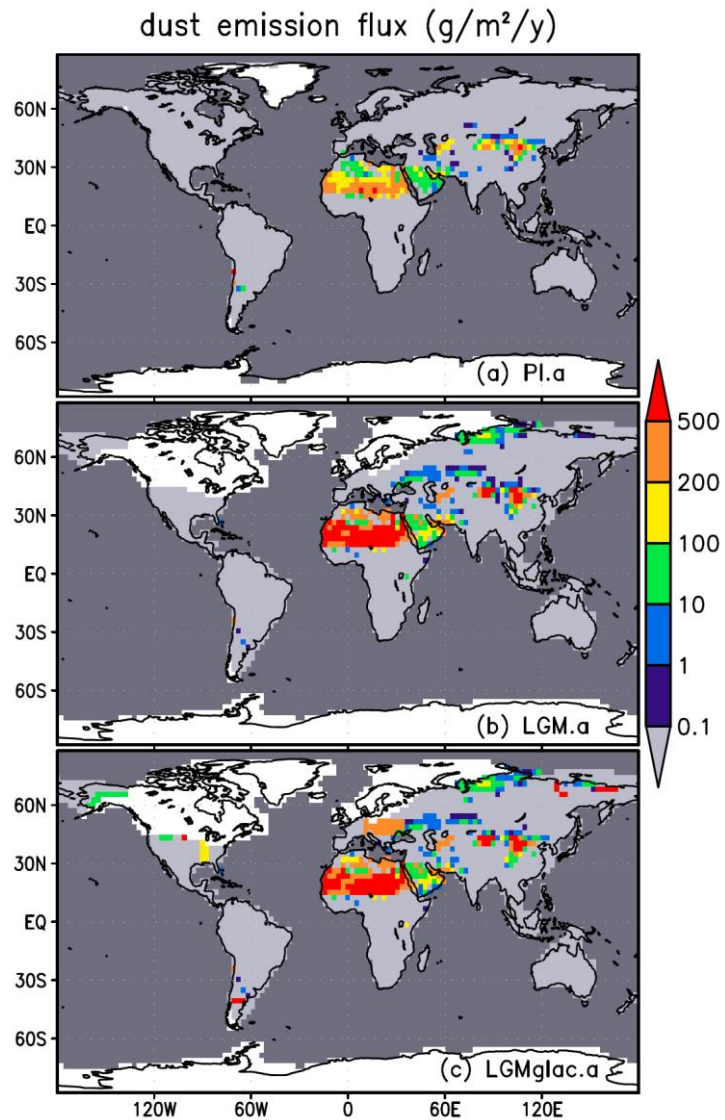


Figure 2: Dust emission flux ( $\text{g m}^{-2} \text{y}^{-1}$ ) for (a) PLa, (b) LGM.a, and (c) LGMglac.a. Ocean areas are dark grey and ice sheets are white.

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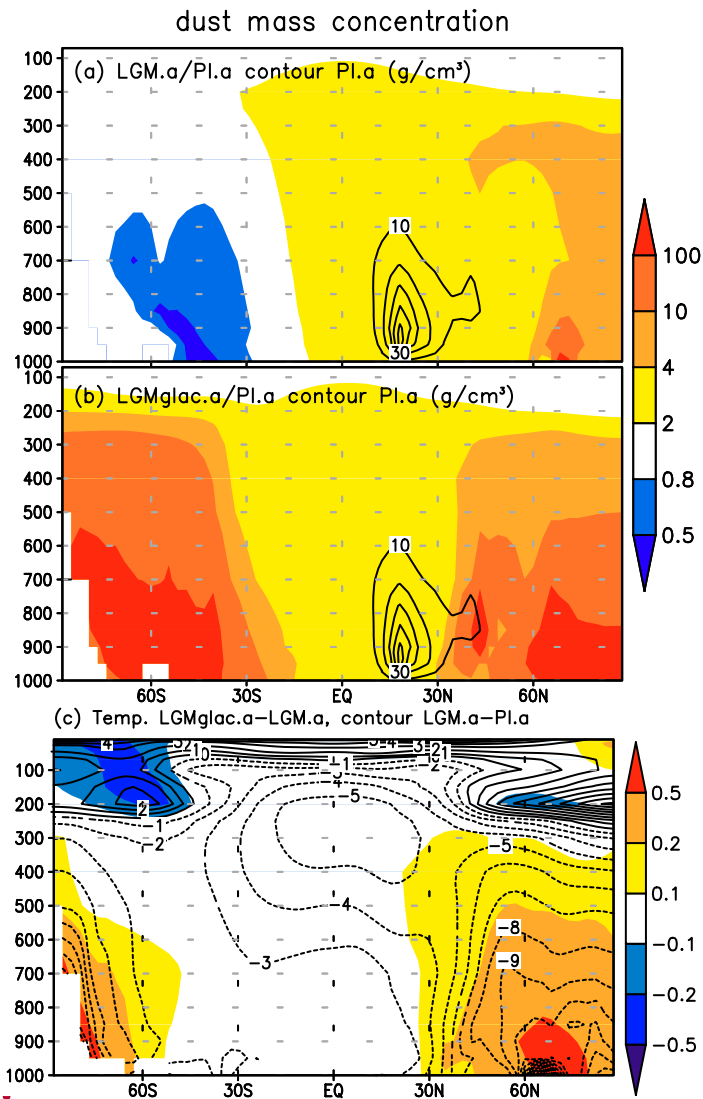


Figure 3: All panels are zonal mean height plots. Ratio of the dust mass concentration for (a) LGM.a/PI.a, (b) LGMglac.a/PI.a, and (c) temperature change for LGMglac.a-LGM.a. Contour lines in (a) and (b) show the dust mass concentration for PI.a ( $\text{g cm}^{-3}$ ) and in (c) the temperature change for LGM.a-PI.a (°C).

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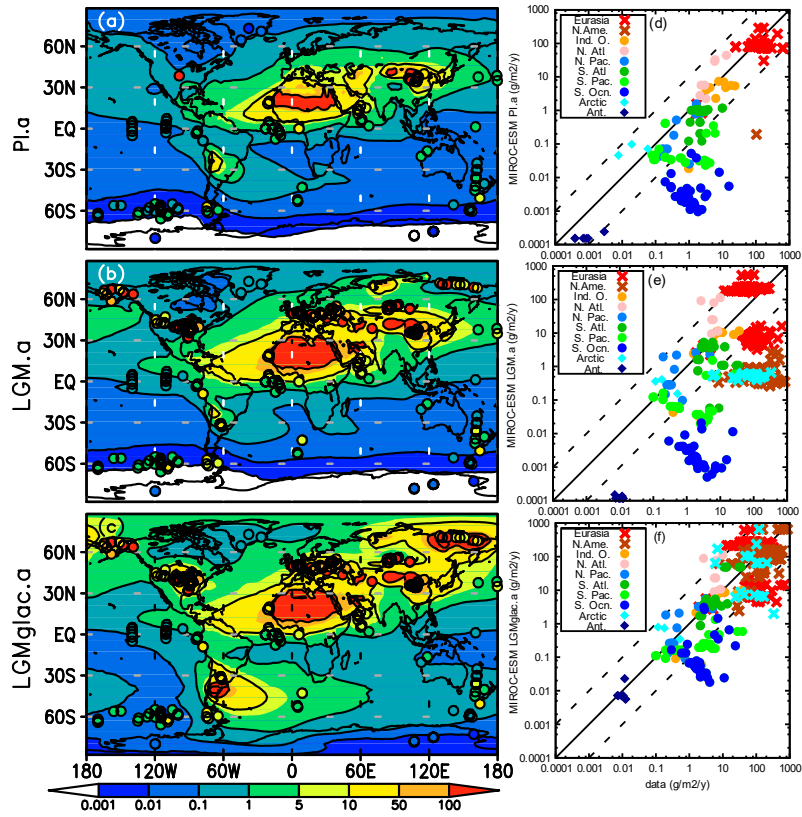
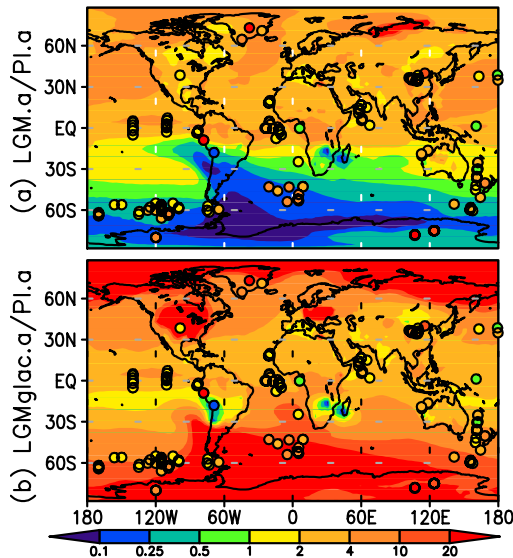


Figure 4: **Model**-data comparison of dust deposition flux ( $\text{g m}^{-2} \text{y}^{-1}$ ) estimated from the ice and sediment core data archives obtained from Kohfeld et al. (2013) and **bulk data from** Albani et al. (2014): (a) PI.a, (b) LGM.a, and (c) LGMglac.a. **Model**-data scatter plots for (d) PI.a, (e) LGM.a, and (f) LGMglac.a. Colours and marks represent **areas** and core types, i.e., red: Eurasia, brown: North America, orange: Indian Ocean, pink and light blue: Atlantic and Pacific oceans in the Northern Hemisphere, respectively, green and light green: Atlantic and Pacific oceans in the Southern Hemisphere, respectively, blue: Southern Ocean, turquoise blue: Arctic, and dark blue: Antarctica. Crosses, circles, and diamonds represent **terrestrial, marine core, and ice core sediments, respectively.**



10 Figure 5: **Model**-data comparison of ratio of dust deposition flux estimated from the ice and sediment core data archives obtained from Kohfeld et al. (2013) and Albani et al. (2014): (a) LGM.a/PI.a and (b) LGMglac.a/PI.a.

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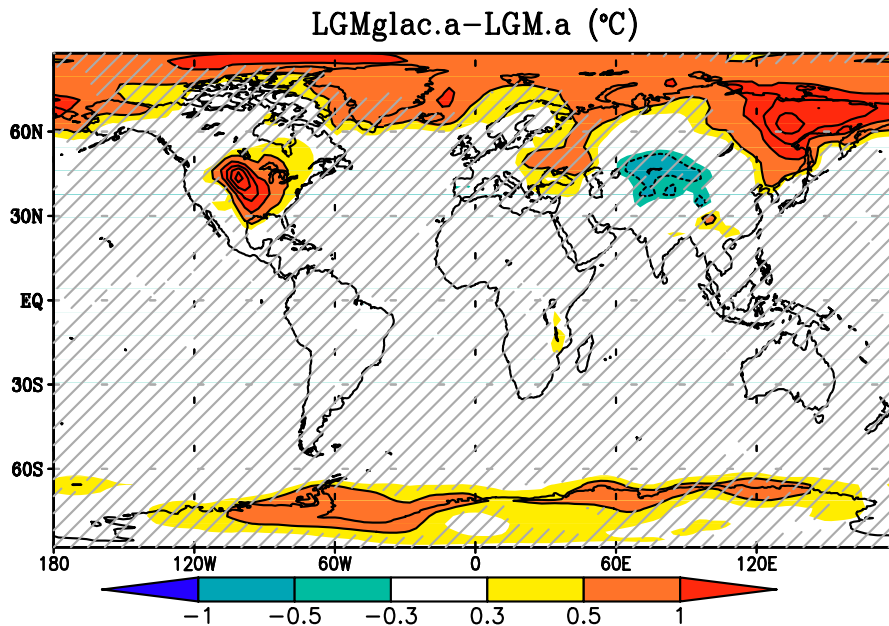


Figure 6: Difference of surface temperature at 2 m height for LGMglac.a-LGM.a. Change is **considered** not significant at the **95 % confidence level in the hatched area based on a t-test**.

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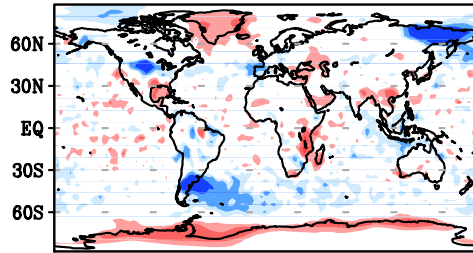
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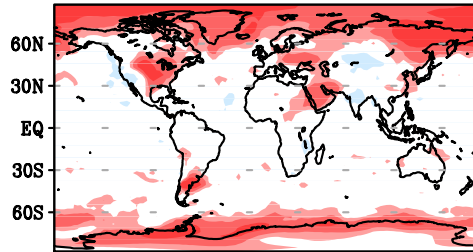
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downward surface radiation  
 LGMglac.a-LGM.a ( $\text{W m}^{-2}$ )  
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(c) shortwave

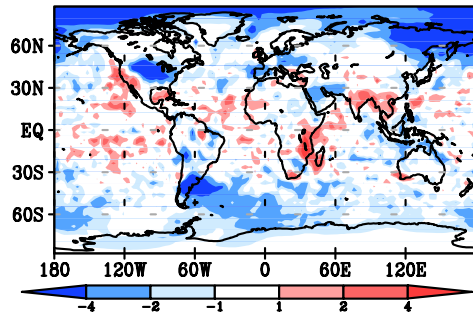


Figure 7: Change in (a) net, (b) longwave, and (c) shortwave downward radiation at the surface LGMglac.a-LGM.a ( $\text{W m}^{-2}$ ) (downward, positive).

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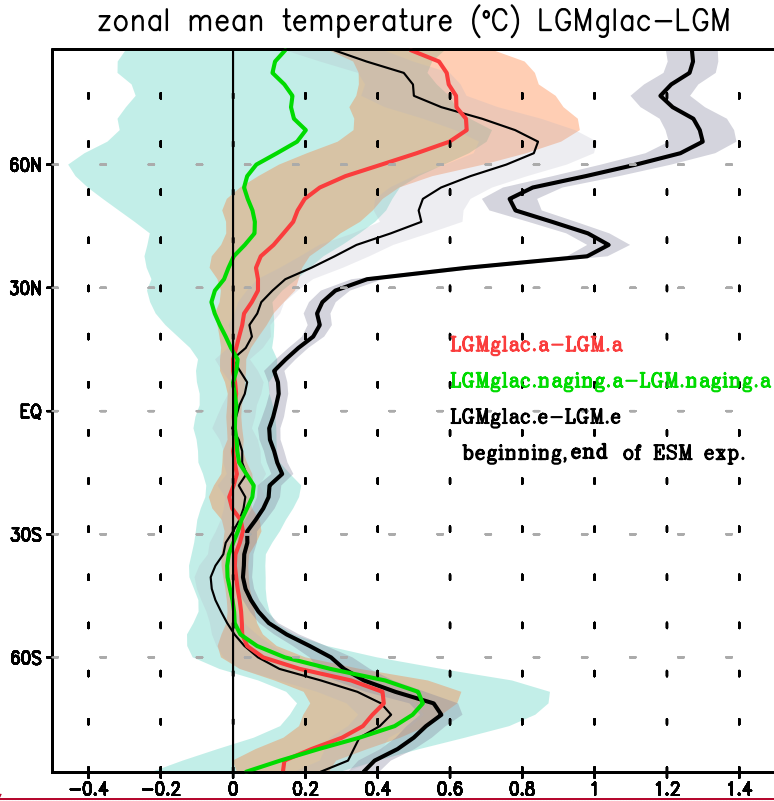


Figure 8: Difference in 2 m air temperature between LGMglac and LGM. Red line denotes LGMglac.a-LGM.a. Green line denotes LGMglac.naging.a-LGM.naging.a, which means the change is not attributable to the ageing effect of snow. Thin and thick black lines denote LGMglac.e-LGM.e at the beginning (average of year 1 to 100 in Fig. 1) and the end (average of year 701 to 900) of the experiments, respectively. Shading represents the year-to-year standard deviation.

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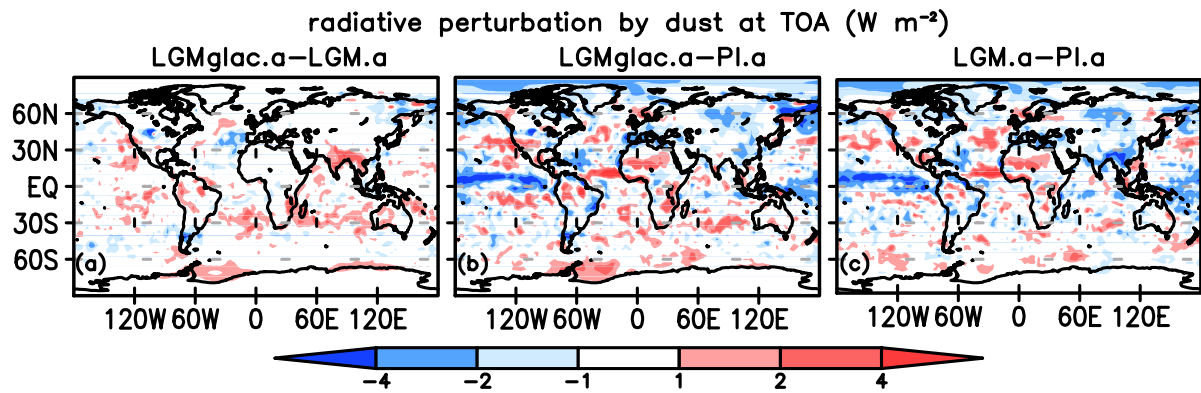
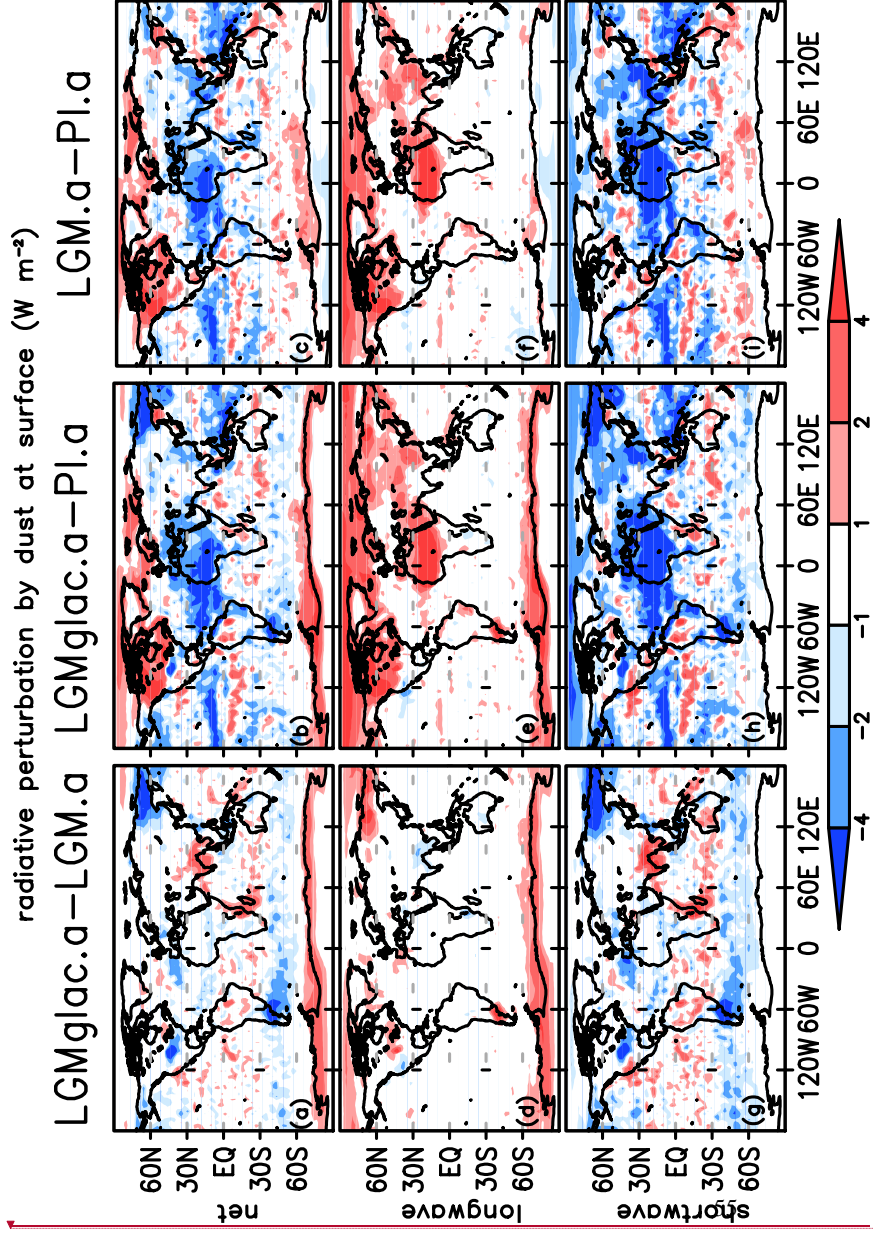


Fig. 9: Change of net radiative perturbation by dust at the top of the atmosphere (TOA): (a) LGMglac.a-LGM.a, (b) LGMglac.a-PI.a, and (c) LGM.a-PI.a.

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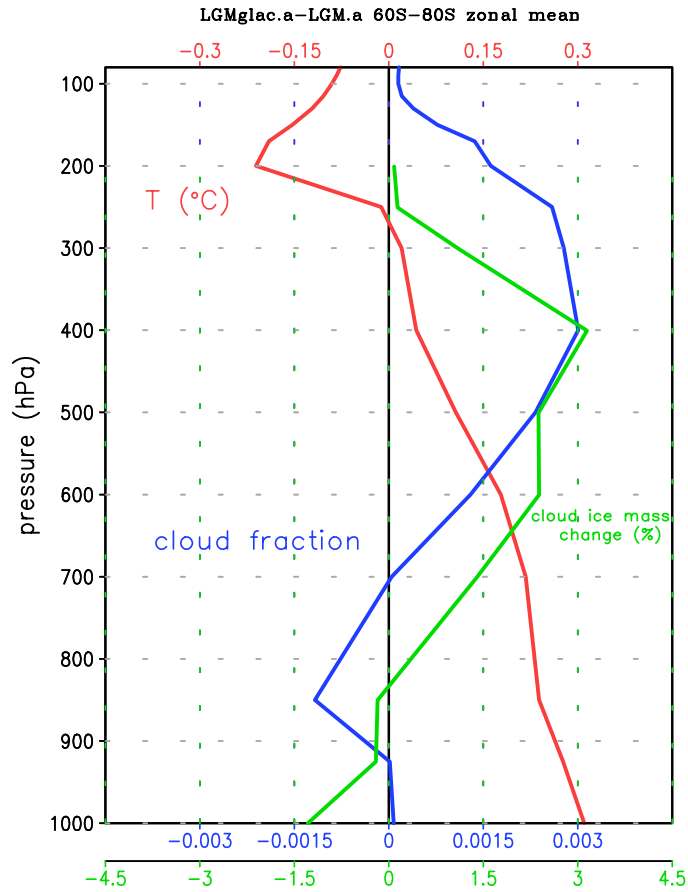
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Figure 10: Change of net radiative perturbation by dust at the surface: (a) LGMglac.a-LGM.a, (b) LGMglac.a-PI.a, and (c) LGM.a-PI.a. Decomposition of net change for the longwave: (d) LGMglac.a-LGM.a, (e) LGMglac.a-PI.a, and (f) LGM.a-PI.a and for the shortwave: (g) LGMglac.a-LGM.a, (h) LGMglac.a-PI.a, and (i) LGM.a-PI.a.

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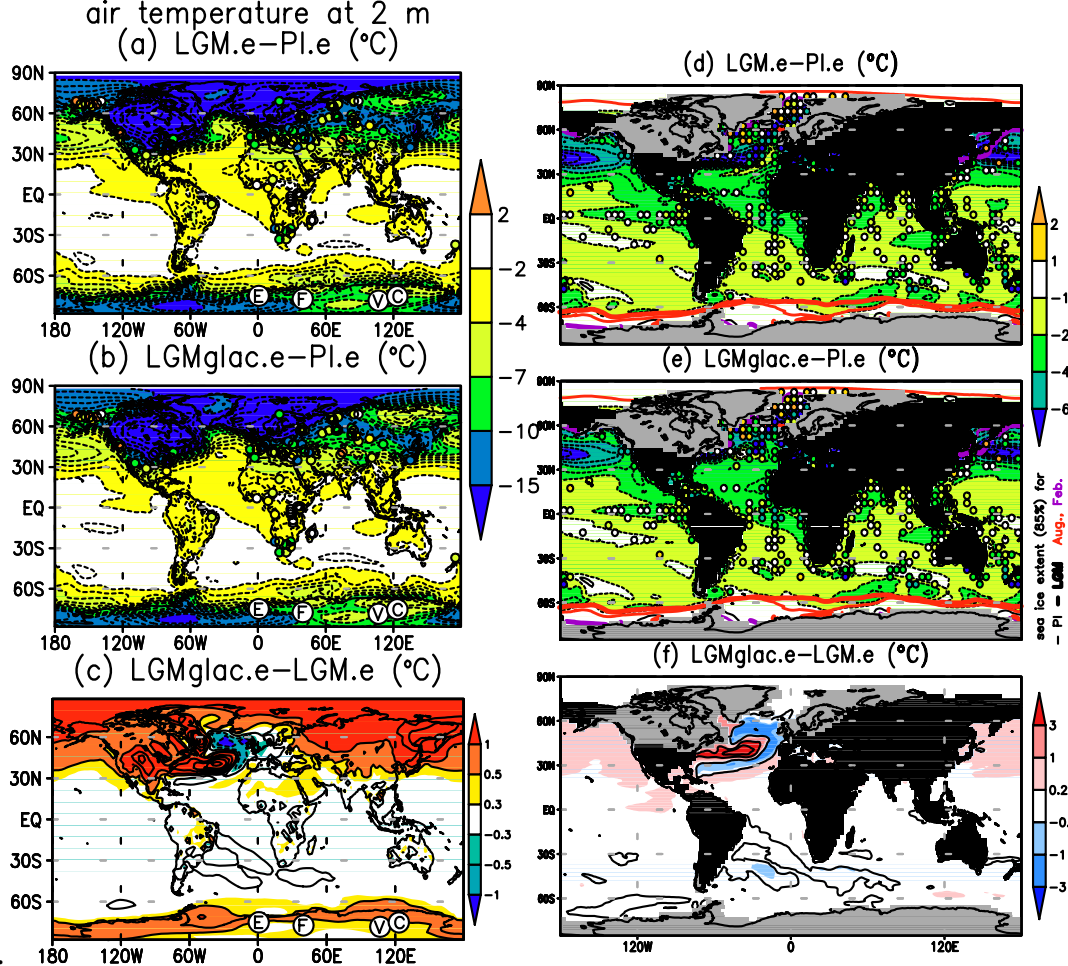
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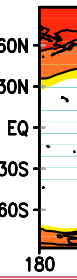
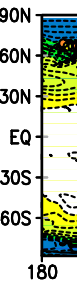
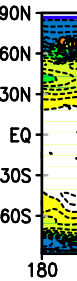


Figure 11: Averaged value height plot (60°–80° S) for change in LGMglac.a–LGM.a for temperature (red), cloud fraction (blue), and cloud ice mass concentration (green). Note the cloud ice mass concentration is plotted only at values exceeding  $1e-8 \text{ kg kg}^{-1}$  in LGM.a.



5 Figure 12: Difference of surface temperature at 2 m height: (a) LGM.e-PI.e, (b) LGMglac.e-PI.e, and (c) LGMglac.e-LGM.e. Coloured circles represent reconstructed temperature change by pollen proxy archives (Bartlein et al., 2011). Circled letters in Antarctica represent four ice core locations: E for EDML, F for Dome Fuji, V for Vostok, and C for Dome C. Sea surface temperature (SST) changes: (d) LGM.e-PI.e, (e) LGMglac.e-PI.e, and (f) LGMglac.e-LGM.e. Purple and red lines in (d) and (e) are 85 % sea ice concentration in February and August for PI (thin) and LGM (thick), respectively. Coloured circles represent MARGO SST

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reconstruction (MARGO project members, 2009). Light grey represents ice sheet areas.

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**Table 1: List of experiments**

5 **(a) Experiment using MIROC-ESM**

Experiment names	Explanation	Integration length (years)
PI.e	The piControl experiment submitted to CMIP5	530
LGM.e	The lgm experiment submitted to CMIP5/PMIP3. The integration is extended further 800 years <u>from the end of PMIP3 period</u>	1200
LGMglac.e	LGM.e + adding glaciogenic dust flux following Mahowald et al. (2006a)	940

**(b) Experiments using AGCM part of MIROC-ESM**

Experiment names	Explanation
PI.a	Pre-industrial control, SST, sea ice and LAI are taken from the climatology of
LGM.a	The lgm experiment submitted to CMIP5/PMIP3. The integration is extended further 800 years
LGMglac.a	LGM.e + adding glaciogenic dust flux following Mahowald et al. (2006a)
LGM.naging.a	LGM.a + no ageing of snow albedo
LGMglac.naging.a	LGMglac.a + no ageing of snow albedo

10 **Table 2: LGMglac.a-PI.a and LGM.a-PI.a changes in global mean radiative perturbation by dust: (a) at the surface and (b) at the top of the atmosphere (TOA) ( $W m^{-2}$ )**

(a) surface	LGMglac.a-PI.a Aerosol-radiation	LGM.a-PI.a Aerosol-radiation	LGMglac.a-PI.a Aerosol-cloud	LGM.a-PI.a Aerosol-cloud
net	-0.30	-0.21	-0.42	-0.28
Long wave	0.37	0.28	0.50	0.34
Short wave	-0.67	-0.50	-0.92	-0.62

(b) TOA	LGMglac.a-PI.a Aerosol-radiation	LGM.a-PI.a Aerosol-radiation	LGMglac.a-PI.a Aerosol-cloud	LGM.a-PI.a Aerosol-cloud
net	0.12	0.07	-0.39	-0.36
Long wave	0.17	0.14	0.62	0.26
Short wave	-0.05	-0.07	-1.01	-0.63

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**Table 3: (a) Simulated total dust emissions ( $Tg\ y^{-1}$ ) and atmospheric burden ( $Tg$ ) for PI.a, LGM.a, and LGMglac.a**

<b>Experiment</b>	<b>PI.a</b>	<b>LGM.a</b>	<b>LGMglac.a</b>
<b>Emission</b>	<u>2540</u>	<u>7250</u>	<u>13400</u>
<b>Burden</b>	<u>11.09</u>	<u>30.65</u>	<u>39.20</u>

**(b) Glaciogenic dust flux ( $Tg\ y^{-1}$ ) (Mahowald et al. 2006a) from the areas shown in Supplementary Fig. A in longitudinal order**

<b>area</b>	<b>Glaciogenic dust flux (<math>Tg\ y^{-1}</math>)</b>
<b>Europe</b>	<u>288</u>
<b>Eastern Siberia</b>	<u>3320</u>
<b>Alaska</b>	<u>39</u>
<b>Western North America</b>	<u>17</u>
<b>Central North America</b>	<u>841</u>
<b>Mississippi river basin</b>	<u>92</u>
<b>Pampas</b>	<u>1935</u>