Response to comments on "Modelling aModern-like-pCO2 Warm Period (MIS KM5c) with Two Versions of IPSL AOGCM" by Ning Tan et al.

Anonymous Referee #1

In the paper, the authors document their Pliocene experiments with IPSL-CM5A and CM5A2, which contribute to the PlioMIP2. They carry out the experiments following the PlioMIP2 guideline. The results are clearly presented. I suggest that the paper should be accepted after minor revisions. I have two suggestions that authors should consider in the revised version.

Response: Thanks a lot for these positive comments on this paper.

1. The energy balance at the top of atmosphere should be added in Table 3.

Response: We have added this in Table 3.

2. In this study, the authors use modern river routing, but modify the land-sea mask (closing the Bering Strait, the Canadian Archipelago and the Hudson Bay). In this way, rivers might not reach ocean, in particular in the Hudson Bay. It is likely that the simulated responses in AMOC are caused not only by the closing of these seaways, but also the salinity drift in the Pliocene simulations. To exclude this possibility, I suggest the authors check the mean salinity in ocean, and add them in Table 3.

Response: Thanks for this suggestion. The river routing is generally kept the same as the PI configuration. But if the estuaries change to land after the land-sea mask modification, the new estuaries are created towards the closest ocean. So, we confirm river water have flowed into the ocean and there is no salinity drift in our experiments.

As you suggested, we have added the mean ocean surface salinity in Table 3.

Other minor corrections

Page 3 line 5, “therefore” also appears in the previous sentence. Reword.

Response: Corrected.

Page 3 line 6, “but will not be use in this paper” change to “but not used in this study”.

Page 4 line 3, 20km or 2km?

Response: Corrected. It is 20 km. In LMDZ, there are 39 levels in vertical in total and above 20 km, there are 15 levels.

Page 4 line 19, please check if “litter” is rightly used in the sentence.

Response: We change to “litterfall” which is better.

Page 5 line 21, respectively should be deleted.

Response: Corrected.

Page 5 line 22, the second “and“ can be changed to as well as

Response: Changed as suggested.

Page 5 line 28, “only by closing Bering Strait and North Canada Archipelago region, and modifying the topography in Hudson Bay”, change to “only by closing the Bering Strait and the North Canadian Archipelago region, and modifying the topography in the Hudson Bay”

Response: Changed as suggested.

Page 7 line 21, add the before Bering Strait

Response: Corrected.

Page 7 line 32, add Canadian Page 9 line 11, “contribution” to “contributions”

Response: Corrected.

Anonymous Referee #2

I would like to begin by apologizing to the authors for the considerable delay in getting my review back to them. I was occupied throughout August on a personal matter and my expectation of still being able to review the paper on time proved over-optimistic. Nevertheless, I should have known better and I apologize for my failing once again. Overall I have found the paper to be scientifically sound. The only principle issue with the manuscript in the current form is the language which requires considerable editing. With this review I am attaching a copy of the paper that has been extensively annotated using Acrobat Reader for language and technical edits. The following document therefore only contains points not included on the annotated manuscript. The paper can be accepted with minor changes.

Response: Thanks a lot for the detailed language editing and constructive comments which largely improve the quality of this paper. Concerning the editing and comments in the PDF, we have corrected directly in the paper and these comments are not listed in the follow.

1. The abstract sentence spanning lines 23-25 is not very clear and also potentially confusing. Please consider re-writing this.

Response: We have re-written this sentence as "When considering the pCO_2 uncertainties (+/-50 ppmv) during the Pliocene, the responses of the modelled mean annual surface air temperature to changes to pCO2 (+/-50 ppmv) are not symmetric, which is likely due to the non-linear response of the cryosphere (snow cover and sea ice extent)." (Revised version Page 1, lines 24-25)

2. On Page 2 regarding the comment about the zonal SST gradient in line 10: I think there is still considerable discussion in the literature about this aspect of the Pliocene climate. So I don't think the sentence should only provide one point of view.

Response: Thanks for this suggestion. We have re-organized this sentence to include more point of view on the reduced zonal SST gradient: "The zonal SST gradient is much weaker than present day (Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2013). Different causes have been investigated for this weaker zonal SST gradient during the Pliocene. Brierly et al (2009) argue that the ocean warm pool expansion over most of the tropics can be responsible for the reduced zonal SST gradient (Brierley et al., 2009). Some researchers argue that a reduction in the meridional gradient of cloud albedo can sustain the reduced zonal and meridional SST gradient (Burls and Fedorov 2014)." (Revised version, Page 2, lines 10-14.)

3. On Page 5 after the end of paragraph on section 3, please add: Because we report on experiments performed with two versions of the IPSL model, we indicate the experiment
conducted using the updated version of the model by the suffix "_v2".

Response: We have added this sentence in the related place.

4. Page 5 line 16: what equilibrium conditions did the model start from?

Response: Here, the model starts from the conditions that the carbon pools are close to equilibrium in the coupled model. More details are provided in Dufresne et al., 2013, section 4.1. For your convenience, we copy the paragraph here: “The initial state of the IPSL-CM5A-LR model was obtained in four steps. First, a 2500-year long simulation of the oceanic model without carbon cycle where the atmospheric conditions are imposed and correspond to the version 2 of the Coordinated Ocean-ice Reference Experiments data sets (Large and Yeager 2009) was achieved. Second, the full carbon-cycle configuration of the IPSL- CM5A-LR model was integrated for a period of 600 years with the solar constant and the concentrations of GHGs and aerosols corresponding to their pre-industrial values. Third, because this last simulation is too short for the ocean and biosphere carbon pools to reach equilibrium, offline simulations a few thousand year-long with the ocean and land carbon cycle models (ORCHIDEE and PISCES) were conducted separately. These offline simulations were forced by the atmospheric and oceanic variables from the preceding 600-year simulation and by a constant preindustrial value for the atmospheric CO2. Fourth, and once the carbon pools are equilibrated, their values are included back into the complete IPSL-CM5A-LR model, which is again integrated for another 400 years. At this time, carbon pools are close to equilibrium in the coupled model as well. This long integration is used as initial state for the control pre-industrial simulations.”

5. Page 5: The statement “River routing and soil….” You mean unchanged from PI?

Response: Sorry, we need to clarify the details here. The soil types and river routing are generally kept the same configuration with PI, except the regions where the changes to the topography modify the river routing and the estuaries. We have added this clarification in the related place. (Revised version, Page 5, lines 32-34.)

6. Page 6, line 1: You mean Eoi400_v2 and not Eo400_v2 right?

Response: It was a typo. It is Eoi400_v2. We have corrected it.

7. Page 6, lines 2-3 I don't follow the meaning of the sentence on these lines up to the "800 years".

Response: We have re-written the sentence as "Eoi400 has run for 800 modelling years and the initial condition is from the equilibrium state of PlioMIP1 experiment (Contoux et al., 2012), which has 650-years integration length. Eoi400_v2 has run for 1500 modelling years." (Revised version, Page 6, lines 8-10.)

8. Page 7. Please break and re-write the long sentence spanning 23-26. There is too much there.

Response: We have re-written this sentence as "Consequently, the Arctic sea water gets much denser and thus the wind-driven Beaufort gyre and transpolar drift get weakened (Figure 3c). The associated East Greenland current and the Labrador current get weaker resulting in saltier conditions in these adjacent regions (Figure 4b). Thus, the deep convection and the formation of North Atlantic Deep Water (Figure 4c, Figure 5b) over these regions enhance." (Revised version, Page 7, lines 31-33 and Page 8, line 1)

9. Page 10: Foley and Dowsett 2019 reference is not present in the list of references. Whereas the list contains a Dowsett 2019 reference that seems incorrect.

Response: Corrected.

10. Page 13, Table 2: Please also put in details of the PI experiment to this table

Response: We have put the PI information in Table 2.

11. Page 14, Table 3 new suggested title: Diagnostics for each experiment. The anomalies are computed against the PI controls corresponding to the version of the numerical model employed"

Response: Changed as suggested.

12. Page 14, Fig 1 suggested title: Anomalies of the PlioMIP2 topography relative to PI control (upper) and PlioMIP 1 (lower).

Response: Changed as suggested.

13. Page 21, I suggest a different color scheme for sub-figures (b) and (c) and the inclusion of a 0 value contour line.

Response: Figure 10 is modified as suggested.

Modelling a Modern-like-pCO_2 Warm Period (MIS KM5c) with Two Versions of IPSL AOGCM

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Abstract. The mid-Piacenzian warm period (3.264 to 3.025 Ma) is the most recent geological period with a present-like atmospheric pCO_2 –as thereby it is expected to have exhibited a warm climate similar to or warmer than present day.exhibiting significant warming relative to present conditions. On the basis of understanding that has been gathered onWith the advanced Uunderstanding of the climate variability of this interval, a specific interglacial (marine isotope stage KM5c, MIS KM5c, 3.205 Ma) has been is selected for the Pliocene Model Intercomparison Project phase 2 (PlioMIP 2) and updated boundary conditions are provided. In this study., Wewe carried out a series of experiments according to the design of PlioMIP2 with two versions of the IPSL Atmosphere-Ocean Coupled General Circulation Model (AOGCM): (IPSL-CM5A and IPSL-CM5A2). Compared to By comparing with PlioMIP 1 experiment, run with IPSL-CM5A, our results show that the simulated MIS KM5c climate presents enhanced warming in mid-to-high latitudes, especially over oceanic in ocean regions. This warming can be largely attributed to the largely enhanced Atlantic Meridional Overturning Circulation caused by the high latitude seaway changes. The sensitivitytier experiments, conducted with IPSL-CM5A2 (with faster computation scheme), show that besides the increased pCO_2, both modified orography and reduced ice sheets contribute substantially toin mid-to-high latitudes warming inof MIS KM5c. When considering the pCO_2 uncertainties (+/-50 ppmv) during the Pliocene, the warming pattern changes, the responses of the modelled mean annual surface air temperature toour model response to changes to the variation of pCO_2 by +/-50ppmv (+/-50 ppmv) is not symmetric in the surface air temperature, which is likely

due to the non-linear response of the cryosphere (snow cover and sea ice extent). By analysing the Greenland Ice Sheet surface mass balance, we also demonstrate its vulnerability under both MIS KM5c and modern warm climate.

1 Introduction

The mid-Piacenzian warm period (MPWP; 3.264 to 3.025 Ma) is the most recent geological period with a present-like pCO_2 concentration and exhibited~~exhibiting~~ significant warming relative to today. This interval has been intensively studied during the past~~last~~ three decades as this time period~~it~~ is generally considered to be a potential analogue~~guide~~ for the future warmer climate~~ing~~. There is an abundance of marine and terrestrial data that allow us to reconstruct~~provided to represent~~ the ocean/land temperatures, soil and vegetation conditions for this period. The reconstructed pCO_2 for the~~data during~~ MPWP ranges from 350 to 450ppmv (Bartoli et al., 2011; Pagani et al., 2010; Martínez-Botí et al., 2015), which bracket the ~~are similar to~~ present~~-~~day level. The MPWP is thought to be globally warmer by 2-4°C than preindustrial climate (e.g., Dowsett et al., 2009). A large warming amplification of 7-15°C is estimated in arctic regions derived from terrestrial proxies from the lake El'gygytgyn in NE arctic Russia (Brigham-Grette et al., 2013) and Ellesmere Island in North Arctic circle (Rybczynski et al., 2013). The meridional SST gradient is reduced compared to the present day~~largely decreased~~ due to the amplified warming in the high latitudes. The zonal SST gradient is much weaker than present day (Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2013). Different causes have been investigated for this weaker zonal SST gradient during the Pliocene. Brierly et al (2009) argue that ~~as~~ the ocean warm pool expansion~~extends~~ over most of the tropics can be responsible for the reduced zonal SST gradient~~(Brierley et al., 2009)~~. Some researchers argue that a reduction in the meridional gradient of cloud albedo can sustain the reduced zonal and meridional SST gradient (Burls and Fedorov 2014). Reconstruction of ~~The distribution of~~ vegetation distribution indicates~~depicts~~ a northward shift of boreal forest at the expense of tundra regions due to the warmer~~ing~~ conditions (Salzmann et al., 2008). Associated with this strong warmth, the ~~reconstructed~~ eustatic sea level is estimated to have been~~be~~ 22(+/-10m) higher (between 2.7 and 3.2 Ma) than present (e.g., Miller et al., 2012) suggesting a complete disintegration ~~large melting~~ of Greenland ice sheet and a significant collapse of the West Antarctic Ice sheet as well as unstable regions of East Antarctic (Hill, 2009; Dolan et al., 2015; Koenig et al., 2015).

An early motivation for~~The initial purpose of~~ studying ~~on~~ this period was to apply the knowledge thus gained to the issue of the ongoing ~~is to learn its relevance for the future~~ climate change. However, considering the non-equilibrium state of the present and the future climate due to the continuously changing anthropogenic~~e~~ ~~of~~ forcing factors, the simulated quasi-equilibrium~~stabilized~~ MPWP may not be directly regarded as an analogue for future warming (Crowley, 1991). The importance of studying the MPWP nowadays~~studies now~~ is to investigate the abilities of climate models to produce warm climates and to study the relative impacts~~respective contribution~~ of forcings ~~factors~~ and feedbacks of internal climate components under warm conditions, and which can assist in developing ~~also serve~~ future climate projections. In Pliocene Model Intercomparison Project phase 1 (PlioMIP1), 11 models conducted the MPWP experiments. Among these modelsresults, there is agreement with regards to exists consistency in surface temperature change across models in the tropics but a and lack of agreement on temperature changes consistency identified in model responses at high latitudes as well as total precipitation rate in the tropics (Haywood et al., 2013). The modeled Atlantic Meridional Overturning Circulation and the associated ocean heat transport for this interval in different models are not very different comparedlikely unchanged relative to modern conditions (Zhang et al., 2013). However, when comparing to proxy data of sea surface and surface air temperature, climate models uniformly underestimate the warming in the high latitudes (Dowsett et al., 2012, 2013, Haywood et al., 2016b). Reasons for this discord between data and model are complex, but they can be attributed to three main aspects: boundary conditions uncertainty, modeling uncertainty (e.g., the model bias, annual variability in the produced climatology fields) and data uncertainty (Haywood et al., 2013). In PlioMIP1, the MPWP is regarded simply as a stable interval despite of the climate variability existing over a 300-kyrs time slab due to the climate sensitivity and orbital parameters' change, thus the boundary conditions are made as an averaged condition over this long interval, whereas proxy data are representative of some orbital conditions inside this time slab. This boundary conditions uncertainty is thus considered as the main contributor to this data-model discrepancy (Haywood et al., 2016a). Therefore, the ongoing PlioMIP phase 2 (PlioMIP2) switched tochanged strategy by choosing a representative interglacial during the MPWP interval: marine isotope stage KM5c (MIS KM5c; 3.205 Ma). Thustherefore, boundary conditions (known as PRISM4; Dowsett et al., 2016) have been updated for PlioMIP2, which include a new paleogeography reconstruction containing ocean bathymetry, and land/ice surface topography, which represent closure of Bering Strait and North Canadian Archipelago region and a reduced Greenland ice sheet by 50% in comparison to PlioMIP1. Besides, extra information of lake distribution and soil types (Pound et al., 2014) are also provided, but notwill not be used in this paper.

This study is conducted in the framework of PlioMIP2. Here we employ the new PRISM4 boundary conditions to conduct the MPWP experiments by using two versions of French AOGCM models: (IPSL-CM5A and the updated IPSL-CM5A2). The purpose of this study is to better understand the warm climate of the MPWP and to study the sensitivity of the IPSL AOGCM model to the changes of boundary conditions, such as changes of of land-sea mask and pCO_2. As IPSL AOGCM model has participated in PlioMIP1 (Contoux et al., 2012), we also compare the modelling results of PlioMIP2 with those of PlioMIP1 to quantify the impact of the high latitude seaways' changes on the climate system.

2 Model Descriptions

To accomplish the modelling work, we have employed the two versions of Institute Pierre-Simon Laplace (IPSL) coupled atmosphere-ocean general circulation model (AOGCM): IPSL-CM5A and IPSL-CM5A2. IPSL-CM5A is a low resolution coupled model which has been applied in CMIP5 for historical and future simulations (Dufresne et al., 2013) as well as for Quaternary and Pliocene paleoclimate studies (Kageyama et al., 2013; Contoux et al., 2012). IPSL-CM5A2 (Sepulchre et al., in prep) is an updated version of IPSL-CM5A. Critical changes from IPSL-CM5A include (i) technical developments to make IPSL-CM5A2 run faster (64yrs/day in CM5A2 instead of 8 years per day in CM5A), (ii) updates of the versions of components and (iii) a major re-tuning of~~on~~ the cloud radiative forcing to correct the ~~IPSL-CM5A~~ cold bias in the mid and high latitudes that is known to be present in CM5A. Thus, to compare with PlioMIP1 results (Contoux et al., 2012), we carried out PlioMIP2 core experiment with IPSL-CM5A~~, ~~ and the~~conducted~~ PlioMIP2 core experiment and tiered experiments with IPSL-CM5A2 to save the computational cost. ~~Components of these models are shortly presented as following. More details can be referred to Dufresne et al. (2013).~~ The various components of the model are briefly described in the following subsections and the reader is referred to Dufresne et al. 2013 for details.

2.1 Atmosphere

The atmosphere component is LMDZ ~~model~~ (Hourdin et al., 2013) developed at Laboratoire de Météorologie Dynamique in France. This is a complex model that incorporates several ~~many~~ processes decomposed into a dynamic part that calculates~~, calculating~~ the numerical solutions of the general equations of atmospheric dynamics, and a physical part, calculating the details of the climate in each grid point and containing parameterizations processes such as the effects of clouds, convection, orography (LMD_ Modelling _Team, 2014). Atmospheric~~e~~ dynamics are represented by a finite-difference discretization of the primitive equations of motion ~~meteorology~~ (e.g., Sadourny and Laval, 1984) on a longitude-latitude Arakawa C-grid (e.g., Kasahara, 1977). The ~~horiozontal~~horizontal~~chosen~~ resolution of the model is 96x95~~x39~~, corresponding to an interval of 3.75 degrees in longitude and 1.9 degrees in latitude. There are 39 vertical levels, with around 15 levels above 20 km. This model has the specificity to be zoomed (the Z of LMDZ) if necessary on a specific region and then may be used for regional studies (e.g., Contoux et al., 2013). In IPSL-CM5A2, re-tuning of the model has been done by altering the cloud radiative effect to decrease the cold bias of the model. More details can be found in Sepulchre et al (in prep).

2.2 Land

The land component in both~~IPSL-~~ CM5A and CM5A2 is ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems (Krinner et al., 2005) which is comprised of~~including~~ three modules: hydrology, vegetation dynamics and carbon cycle. The hydrological module (Ducoudré et al., 1993) describes the exchange of energy and water between the atmosphere as well as~~and~~ the biosphere, and the soil water budget (Krinner et al., 2005). Vegetation dynamics parameterization is derived from the dynamic global vegetation model LPJ (Sitch et al., 2003; Krinner et al., 2005). The carbon cycle model simulates plant phenology and carbon dynamics of the terrestrial biosphere. Vegetation distribution~~s~~ is~~are~~ described using 13 plant functional types (PFTs) including agricultural C3 and C4 plants, which are not present~~used~~ in the MPWP simulations~~, bringing down the number of PFTs to 11, including bare soil~~. In this case, hydrology and carbon modules are activated, but vegetation is prescribed as the PlioMIP1 study by Contoux et al. (2012), using 11 PFTs, derived from the PRISM3 vegetation dataset (Salzmann et al., 2008). Therefore, soil, litterfall, and vegetation carbon pools (including leaf mass and thus LAI) are calculated as a function of dynamic carbon allocation.

2.3 Ocean and sea ice

The ocean model included in IPSL-CM5A is NEMOv3.2 (Madec, 2008) which includes three principle modules: OPA (for the dynamics of the ocean), PISCES (for ocean biochemistry), and LIM (for sea ice dynamics and thermodynamics). The configuration of this model is ORCA2.3 (Madec and Imbard, 1996), which uses a tri-polar global grid and its associated physics. The average horizontal resolution is 2° by 2°, which increases to -refined at 0.5° in the tropics and there are 31 layers in vertical.; vertical layers are 31. Temperature and salinity advection areis calculated by a total variance dissipation scheme (Lévy et al., 2001; Cravatte et al., 2007). The mixed layer dynamics is parameterized using the Turbulent Kinetic Energy (TKE) closure scheme of Blanke and Delecluse (1993) improved by Madec (2008). The sea ice module LIM2 is a two-level thermodynamic-dynamic sea ice model (Fichefet and Morales Maqueda 1997). Sensible heat storage and vertical heat conduction within snow and ice are determined by a three-layer model. OASIS model plays as a coupler (Valcke, 2006) is used to interpolate and exchange the variables and to synchronize the models. This coupling and interpolation procedures ensure local energy and water conservation. New version NEMOv3.6 is included in IPSL_CM5A2 in which the river runoffs are now added through a non-zero depth , and have a specific temperature and salinity. The coupling system has been switched from OASIS3.3 to OASIS3-MCT (for Model Coupling Toolkit). More details are provided by Sepulchre et al (in prep).

3 Experiment Design

This section describes the boundary and the initial conditions imposed in our experiments. Here, the experiment names are generally consistent with the design of PlioMIP2 (Haywood et al., 2016a) and, they are referred to by thean abbreviated form E(x)(c), where c is the concentration of atmospheric CO_2 in ppmv and x represents boundary conditions that have been changed from the pre-industrial (PI) conditions, such that x can be absent for cases in which no boundary conditions have been modified or it can be "o" for a change in orography and/or "i" for a change in land ice configuration. Because we report on experiments performed with two versions of the IPSL model, we indicate the experiment conducted using the updated version of the model by the suffix "_v2".

3.1 Pre-industrial experiments

The pre-industrial control simulation in IPSL-CM5A was performed as required by CMIP5/PMIP3 by the LSCE modelling group. It is a 2800-years simulation, which already started from equilibrium conditions. The pre-industrial control simulation in IPSL-CM5A2 was conducted by Sepulchre et al., (in prep) forced by CMIP5 pre-industrial boundary conditions and has 3000-years integration length.

3.2 Pliocene experiments

We have conducted six AOGCM experiments for the PlioMIP2~~ study~~, they are ~~respectively~~the core experiment Eoi400 using the~~with~~ IPSL-CM5A model and the core experiment Eoi400_v2 ~~an~~as well as ~~d~~ four tiered experiments E400_v2, Eoi450_v2, Eoi350_v2, Eo400_v2 using the~~with~~ IPSL-CM5A2 model. The pCO_2 concentration in each experiment is indicated in the experiment name as mentioned above. ~~As defined by the abbreviated form, the atmospheric CO_2 concentration imposed in each simulation can be referred to the number of the experiment's name (e.g., in the experiment "E400", the number "400" indicates that pCO_2 is set to 400 ppmv).~~ Other greenhouse gases and orbital forcing are kept the same as in the IPSL PI control run (Table 1). Vegetation is kept the same as in the PlioMIP1 AOGCM simulation by Contoux et al. (2012). Soil patterns and river routing ~~River routing and soil patterns~~ are kept the same configurations with PI control, except the regions where the changes to the topography modify the river routing and the estuaries~~not changed in this study~~. Land sea mask in these experiments is modified from present, only by closing the Bering Strait and the North Canadian~~a~~ Archipelago region, and by modifying the topography in the Hudson Bay (Figure 1). Ice sheet mask is changed~~referred~~ to PRISM4 dataset (Dowsett et al., 2016) except in~~for~~ Eo400_v2 experiment, in which the modern ice sheet is imposed~~ with modern ice sheet~~. Topography in these five experiments is~~are~~ calculated based on modern topography used in the IPSL model, on which ~~by superimposing on the~~ the anomaly between the PRISM4 reconstructed topography and the modern topography provided by PlioMIP2 database (Haywood et al., 2016a) is superimposed. Wherever~~en~~ the resulting ~~new~~ topography was lower than zero, it was replaced by the~~,~~ absolute PRISM4 topography~~ was implemented~~. Figure 1 shows the resulting topography anomalies in our PlioMIP2 experiments respectively compared to PI and ~~topography anomaly between PlioMIP2 and~~ PlioMIP1 experiments. The initial sea surface temperature and sea ice in Eoi400 and Eoi400_v2 are derived from the IPSL PlioMIP1 AOGCM simulation (Contoux et al., 2012). Eoi400 has run for 800 modelling years and the initial condition is from ~~is conducted based on~~ the equilibrium state of PlioMIP1 experiment (Contoux et al., 2012), which has ~~with~~ 650~~-~~years ~~of~~ integration length. ~~and integrated for 800 years, while~~ Eoi400_v2 has run for 1500 modelling years~~ years integration length~~. Average climatologies for these two experiments are calculated over the last 50 years. Four tiered experiments: E400_v2, Eoi450_v2, Eoi350_v2, Eo400_v2 are conducted based on the equilibrium state of Eoi400_v2 core experiment and have 400 years of integration length. Average climatologies for these four experiments are calculated over the last 30 years. Table 2 summarizes the aforementioned information~~comments~~.~~provides a summary for the experiments settings.~~ Figure S1 shows time series of surface air temperature and deep ocean temperature at around 2.3km depth. For both core simulations, the trend in both the global mean surface air temperatures (< 0. 18°C century^{-1}) and the deep ocean temperature (< 0.05°C century^{-1}) over the final 50 years of integration are small. The tiered~~Other tier~~ experiments also show relatively stable trends over the last 30 years of integration

(< 0.2°C century^{-1} and < 0.08°C century^{-1} in surface air temperature and sub-surface ocean temperature respectively). Therefore, we conclude that~~consider~~ model runs have reached a quasi-equilibrium state.

Although a standard pCO_2 of 400ppmv is selected for the Pliocene core experiments, the pCO_2 records during this interval mostly range from 350 to 450ppmv. Thus, the tiered experiments Eoi450_v2 and Eoi350_v2 are conducted to investigate the impact of pCO_2 uncertainty on the modelled Pliocene climate. The tiered experiments E400_v2 and Eo400_v2 combined with the core experiment Eoi400_v2 and PI control are used to quantify the relative importance of pCO_2, land ice and orography in the PlioMIP2 warmth. Because of the limited ~~the limitation of~~ computational resources, we apply the linear decomposition for the forcing factors as: dT_{CO2} = E400_v2 – E280_v2 (1); $dT_{orography}$ = Eo400_v2 – E400_v2 (2); dT_{land_ice} = Eoi400_v2 – E400_v2 (3)$\Delta T = dT_{CO2} + dT_{orography} + dT_{land\_ice}$ (4).

4 Results and Discussion

4.1 Pliocene runs with IPSL-CM5A

4.1.1 Results in the Atmosphere

Figure 2 shows the anomalies of global mean annual near surface air temperature (SAT, i.e. temperature at 2 meters), precipitation rate and sea surface temperature (SST) between PlioMIP experiments and pre-industrial control with IPSL-CM5A. The global mean annual SAT in Eoi400 ~~experiment~~ is ~~about~~ 14.4°C which is 2.3°C warmer than that of pre-industrial. The warming in Northern Hemisphere (NH) high latitudes (>50°N) (4.2°C) is higher than that in the tropics (1.8°C). The magnitude of the warming for Eoi400 is slightly larger than that for PlioMIP1 experiment, which shows a global warming by 2.1°C. The major differences in SAT between Eoi400 and PlioMIP1 are found respectively in mid-latitude Eurasia and arctic regions due to the change of regional topography and high latitude seaways as well as the reduced Greenland ice sheet. Thus, Eoi400 shows a reduced meridional temperature gradient than that in PlioMIP1 experiment.

The global mean annual precipitation rate increases by 0.14 mm/d in Eoi400 due to the vapour varying capacity of the warmer atmosphere and the increase is mostly confined to~~warming, the major increase locates in~~ the global monsoon regions and tropical oceans. The increase in~~d~~ global mean precipitation rate as well as the monsoon area index (Figure S2, calculated based on the method of Wang et al (2008)) in Eoi400 compared to PI is similar to that in PlioMIP1. However, regional discrepancies still exist between these two experiments: the precipitation rates in Eoi400 in the tropics and NH high latitudes are higher than those in PlioMIP1 by 0.03 - 0.05 mm/d because of the increased warming in Eoi400 in these regions. Regional differences also exist over~~in~~ mountainous regions (e.g., the Andes, the Rockies, Tibetan Plateau, the Himalayas and the Ethiopian Highlands) since the elevation over these regions is~~are~~ modified largely in PlioMIP2 ~~Eoi400~~compared to ~~from the~~ PlioMIP1 (Figure 1). In East Africa, Eoi400 simulates an intensified precipitation than PlioMIP1, which is better consistent with proxy data from East Africa inferring a wet vegetation condition and hydrological systems during this period (Drapeau et al.,2014; Bonnefille 2010). Apart from the high latitude seaways' change, the regional difference in topography between PlioMIP2 and PlioMIP1 can also contribute to the rainfall change. Further sensitivity studies are needed to verify it.

4.1.2 Results in the Ocean

The~~Accordingly, the~~ global mean annual SST of Eoi400 is 1.7°C warmer compared to the pre-industrial. It is 0.3°C warmer than PlioMIP1 and the~~this~~ warming is largely confined to ~~majorly locates in~~ the mid to high latitude oceans of the Northern Hemisphere. The warming in Eoi400 relative to PlioMIP1 can be attributed to the closure of the Bering Strait and the Canadian Archipelago, which is the major difference in the boundary conditions between these two experiments. In the preindustrial control run (Figure 3a), the water flow~~flux~~ through the Bering Strait is about 1.0 Sv and through which ~~transporting~~ much fresher and warmer water from the North Pacific are transported to the Arctic Ocean. In Eoi400, as showed in Figure 3b, the water currents from the North Pacific to the Arctic through the Bering Strait and from the Arctic to the Baffin Bay are shut down. Consequently, the Arctic sea water gets much denser and thus~~, then~~ the wind-driven Beaufort gyre and transpolar drift get weakened (Figure 3c). ~~and further reduce~~ T~~t~~he associated East Greenland current and the Labrador current get weaker resulting ~~, hence lead to saltier~~in saltier conditions in these adjacent regions (Figure 4b). Thus, ~~resulting in the enhancement of the~~ the deep convection and ~~as well as~~ the formation of North Atlantic Deep Water (Figure 4c, Figure 5b) over these regions enhance. The sea surface condition changes (compared to the PI) in the North Atlantic region in Eoi400 (Figure 4) are in~~show~~ agreement with the CCSM4 model results of Otto-Bliesner et al. (2017). Accordingly, we observe a strengthened Gulf Stream and North Atlantic currents as well as enhanced sub-polar gyre (Figure 3c), which can transport more heat to high latitudes (Figure 6b) and may be linked ~~-~~to a stronger convection. Thus, a shoaled~~allowed~~ and enhanced AMOC (+4.9 Sv)~~by 4.9 Sv~~ is observed in Eoi400, whereas the~~while~~ AMOC in PlioMIP1 was~~is~~ not much different from the modelled pre-industrial level (Figure 5). The increased AMOC resulting from the closure of Bering Strait and Canadian Archipelagos is broadly~~likely~~ consistent with previous studies of Hu et al. (2015), Kamae et al. (2016) and Chandan and Peltier (2017). However, the change in~~of~~ the AMOC strength in our PlioMIP2 simulation is much larger than other models. Hu et al. (2015) using CCSM3 and CCSM2 with different climate backgrounds show that the AMOC responses to the closure of the Bering strait are about 2-3 Sv. Chandan and Peltier. (2016) show an increased AMOC strength by ~2 Sv after closing the Bering strait in the CCSM4 model. In the study of Kamae et al. (2016), with a different flux adjustment, they present a much stronger AMOC in their PlioMIP2 than their pre-industrial level. In fact, the simulated AMOC largely depends upon the vertical mixing schemes (Zhang et al., 2013)~~. It is expected to see variations of simulated AMOC across models~~. Although we observe an increase in the strength of ~~a largely increased~~ AMOC (15.7 Sv) in our PlioMIP2 simulation conducted with IPSL-CM5A, the AMOC~~ strength~~ is still weaker than the modern observations (17.2 Sv, McCarthy et al.,2015). This is because the simulated modern AMOC (11 Sv) with this model is much weaker than the observations. Moreover, the simulated AMOC in PlioMIP1 with our model is also weaker than other models (Zhang et al.,2013). As shown in Figure 6, the total heat transport in ~~among~~ PI control, Eoi400 and PlioMIP1 simulations is similar. The stronger AMOC in Eoi400 indeed strengthens the northward heat transport in the Atlantic Ocean, while the weakened Pacific meridional ocean circulation in Eoi400 (PMOC, Figure S3), which contrasts with the data-based findings by Burls et al (2017), decrease the northward heat transport, thus leading to very slight change in total ocean heat transport. –This compensation was also found by Chandan and Peltier (2017).~~.~~

The simulated warm conditions in high latitudes prevent sea ice from ~~largely~~ expanding during winter season and increase sea ice melt during summer season (Figure 7). When compared to the PI condition, sea ice extent in the Eoi400 decreases by 5.4 Mkm^2 and 3.8 Mkm^2 respectively for the winter and summer season in the NH. In the Southern Hemisphere (SH), sea ice extent reduces by 8.8 Mkm^2 for the winter season and is nearly extinct during the summer. In comparison with PlioMIP1, NH sea ice cover in Eoi400 reduces by 2.1 Mkm^2 and 0.8 Mkm^2 respectively for cold and warm season but there is no large difference in SH between these two experiments. The largely decreased sea ice extent can amplify the warming in the high latitudes, through its role as an insulation between the ocean and the atmosphere as well as positive albedo temperature feedback (Howell et al.,2014; Zheng et al., 2019). Reconstructed data in the Arctic Basin suggest the presence of seasonal rather than perennial sea ice in the Pliocene Arctic (Polyak et a., 2010; Moran et al.,2006), indicating a less or diminished summer sea ice cover. However, our IPSL model as well as half of participating models in PlioMIP1 cannot predict sea ice-free conditions during the summer season (Howell et al., 2016). Reasons for that are discussed in Howell et al (2016), which demonstrate the unreasonable sea ice albedo parameterization for the warmer condition.

4.2 Pliocene runs with IPSL-CM5A2

4.2.1 Results from ~~in~~ the core experiment Eoi400_v2

Figure 8 shows the anomalies of global mean annual near SAT (2-meter temperature), precipitation rate and SST between Eoi400_v2 and pre-industrial control with the CM5A2~~identical~~ model. The global mean SAT in Eoi400_v2 is ~~about~~ 15.3°C, which is 2.2°C warmer than pre-industrial conditions with greater~~and the~~ warming in high latitudes~~is much larger than in the tropics~~. It should be noted that the absolute SAT in Eoi400_v2 is greater~~warmer~~ than that obtained in Eoi400, while the SAT anomaly in Eoi400_v2 is lower~~weaker~~ than that in Eoi400. This is due to the cold bias correction in the new version of the IPSL model. ~~between these two models:~~ IPSL-CM5A2 simulates a ~~presents a warmer~~ pre-industrial that is warmer ~~condition by 1.1°C~~ (Sepulchre et al., in prep) than the~~hat with~~ IPSL-CM5A pre-industrial by 1.1°C. The global mean annual precipitation rate increases~~d~~ by 0.13 mm/d in Eoi400_v2 compared to PI, which is comparable to the results obtained~~of core experiments~~ with IPSL-CM5A. In Eoi400_v2, the changes in the ocean conditions relative to the~~its~~ pre-industrial control are similar to changes seen with ~~like~~ Eoi400. The global mean annual SST in~~of~~ Eoi400_v2 is 0.7°C warmer than Eoi400, the AMOC strength (Figure S4) in Eoi400_v2 is ~~about~~ 17.9 Sv which is 2.2 Sv larger than Eoi400, while AMOC anomaly is about 4.7 Sv relative to its pre-industrial level of 13.2 Sv.~~,~~ The magnitude of this anomaly is close to the result obtained with~~in~~ IPSL-CM5A, indicating a coherent response of the AMOC to the same changes of boundary conditions. The sea ice cover is also largely decreased due to the warming in high latitudes (Figure 7).

4.2.2 Relative importance of various boundary conditions in MIS KM5c warmth

Figure 9 shows the relative contribution of various boundary conditions (CO_2 (a), o~~O~~rography (b) and~~,~~ land ~~Land~~ ice (c)) to~~on~~ the warming during~~of~~ MIS KM5c as obtained using~~calculated by~~ the linear decomposition method. Among these forcings, the increase in~~d~~ pCO_2 by 120 ppmv (from 280 to 400 ppmv) plays the most important role in both the annual (+1.4°C) and seasonal SAT~~warming~~ (+1.38°C and +1.48°C respectively during ~~in~~ the summer and winter ~~season~~). The changes to~~of~~ orography in PlioMIP2 also exert~~take~~ an important influence~~control~~ on the annual mean warming (+0.51°C), especially in~~for~~ the north Atlantic and Barents Sea regions. However, ~~the~~ changes to~~in~~ the orography decrease the temperature in the NH mid-to-high latitude inland regions, which may result from ~~the~~ changes in~~of~~ North Pacific circulation. Seasonally, the orography changes contribute more ~~importantly~~ to the warming ~~(+0.65°C)~~ in summer (+0.65°C) than that in winter (+0.38°C). The impact of smaller ~~decreased~~ ice sheets ~~impact~~ is largely restricted to the high latitude regions and is less important than the other two forcing factors in North polar region but plays the key role in the warming of South polar region. The mean annual warming resulting from the smaller~~decreased~~ ice sheets is about 0.25°C which is close to contribution in both~~its~~ summer and ~~winter~~ winter seasons, indicating that the ice sheet contribution is seasonally invariant~~contributions~~. The residual impact besides the pCO_2, orography and land ice forcings is relatively small and negligible when making the linear decomposition of the forcing factors. These~~is~~ results are in ~~shows some~~ agreements with those~~the study~~ of Chandan and Peltier~~.~~ (2018) wherein~~in~~ ~~which~~ they ~~have~~ applied the non-linear decomposition of Lunt et al 2012 to diagnose the contributions of the forcing factors~~.~~

4.2.3 Greenland ice sheet instability under MIS KM5c warmth

To understand the extent to which~~how far could~~ the Greenland ice sheet (GrIS) could be sustained under the warmth of~~a~~ MPWP ~~warm climate~~, we impose the modern GrIS into the Pliocene simulation (Eo400_v2). In comparison with PI control (Figure 10a), the mean annual surface mass balance (SMB) in Greenland in Eo400_v2 (Figure 10b) is strongly negative around the coastal regions, indicating vulnerable conditions along~~for~~ costal ice sheet and ice shelves. This negative SMB condition largely~~majorly~~ results from the increased summer temperature which leads to enhanced ablation in~~around~~ these regions (Figure S5). The mean annual SMB condition in Eo400_v2 is similar to that in modern condition (E400_v2,

Figure10c). However, the warmer condition in Eo400_v2 bring more precipitation in the South and Northwest Greenland, leading to enhanced accumulation (Figure S5), thus we observe increased SMB in these areas as when compared to the PI control condition. In E400_v2, we also have increased SMB in these regions but much weaker than that in Eo400_v2, due to the different paleogeography settings as discussed earlierabove. Although these snapshot results cannot quantify the impact of the warm climate on the modern GrIS extent, which needs another series of climate model-ice sheet model experiment, without considering the climate-ice sheet interaction, the results we get here can also herald the vulnerability of GrIS under such warm climate condition.

4.2.4 pCO_2 uncertainties in MIS KM5c warmth

Figure 11 depicts the anomalies of global mean annual SAT, precipitation rate and SST inof Eoi450_v2 and Eoi350_v2 compared to thein comparison with core experiment of Eoi400_v2. By increasing pCO_2 of 50ppmv in Eoi450_v2, global climate getsis slightly warmered up (+0.48°C) and the warming in high latitudes is larger more important (+0.7°C). However, when lowering pCO_2 by 50ppmv in Eoi350_v2, the change of climate is more important than that in Eoi450_v2, since we observe a global cooling of 0.71°C and cooling of 1.29°C over NH high latitudes. This asymmetric pattern in temperature response to change of in increasing/decreasing temperatures when augmenting/lowering pCO2 largelymajorly results from the –changes toof surface albedo associated with snow cover (not shown here). In Eoi450_v2, the mean annual snowfall decreases by 6% between 40°N and 80°N when comparing to Eoi400_v2, while Eoi350_v2 shows an increase byrepresents an increased mean annual snow fall by 30% (not shown). The asymmetric pattern between Eoi450_v2 and Eoi350_v2 is also found in the changes of precipitation rates: gGlobal climate gets slightly moister with an increased global precipitation rate by 0.02mm/d (+15%) in Eoi450_v2, while in Eoi350_v2, the global precipitation rate reduces by 0.04mm/d (-31%) and this reduction is more important in the tropical regions. Thus, our results can also show that the response of IPSL coupled model to changing pCO_2 from 350 to 400 ppm is larger than from 400 to 450 ppm.

However, in the ocean, the increaseed or decrease ind SSTs resulting from increasingaugmenting or lowering pCO_2 byof 50ppmv is nearly the same magnitudeare likely symmetric. The AMOC strengths are also similar between Eoi450_v2 (17.4 Sv) and Eoi350_v2 (17.6 Sv) (Figure S4). Nevertheless, the changes of sea ice cover in these two experiments are unlike from each other (Figure 7). As in Eoi450_v2, the sea ice covers decrease slightly relative to Eoi400_v2 for both hemispheres (decreased by 0.2-0.5 Mkm^2 during cold season and decreased by 0.01-0.2 Mkm^2 during warm season). Whereas in Eoi350_v2, the sea ice cover expands for both hemispheres, especially during the warm season in the NH (+1.7 Mkm^2).

4.3 Model-Data Comparison

Figure 12 shows the simulated mean annual SST anomalies (relative to PI experiments) of both core experiments (Eoi400, Eoi400_v2), -together with the reconstructed SST (3.20 – 3.21Ma, Foley and Dowsett 2019) anomalies relative to near pre-industrial data (1870-1900, Rayner et al.,2003). The simulated SST anomalies in both core experiments are generally in phase with the reconstructed data. Some extremely warm sites are in disagreement with model results (e.g., Drilling sites in North Greenland seaGreenland Sea, in Mediterranean and Benguela current region). OverallIn summary, the simulated MIS KM5c SSTs generally underestimate the warming that is inferred from proxiesobserved in the data, especially for the sites showing warming higher than 4°C (Figure 12b). Amongst theese three experiments (PlioMIP1, Eoi400, Eoi400_v2), bBoth Eoi400 and Eoi400_v2 show increased warming in the mid-to-high latitudes aswhen compared to the PlioMIP1 result. However, despite the increased warming exhibited by our PlioMIP2 simulation, there is still a veryan obvious disagreementdiscord in the strong warming between model and data proxy, for which model performance is partly to blame. this may partly rely on the model performance. However,Moreover, the interpretation of the reconstructed data can also affect the data-model comparison results. —ConventionallyNormally, SSTs arewere reconstructed from $U_{37}^{k\prime}$ paleothermometry assuming they represent annual mean values, whereas it has been shown that they can represent seasonal temperatures, for example representing the warmest summer month in the North Atlantic (NATL) (Leduc et al., 2017) and in the Benguela (Leduc et al., 2014). If we compare the reconstructed SST anomaliesy with modelled SST anomalies for the warmest summer month rather than the mean annual anomaliesy from the model for the NATL and the Benguela region (Figure S6), the discrepancies between model and data is reducedwill largely decrease. However,Moreover, in some regions, this comparison leads to the modelling results overestimatinge the warming. To well understand the discord, more studies are further needed with regards toin the aspects of data interpretation as well as the multi-model comparison.

5 Conclusions

In this paper, we describe the results of modellingled the warm interglacial of MIS KM5c (3.205 Ma), located in MPWPthe interval of the MPWP (3.0-3.3 Ma), while driving the model with with imposing the new PRISM4 boundary conditions (Dowsett et al., 2016). Two versions of the core Pliocene experiments namelydenoted Eoi400 and Eoi400_v2 are conducted based on two versions of the IPSL coupled model: IPSL-CM5A and IPSL-CM5A2. Four tiered experiments (E400_v2, Eoi450_v2, Eoi350_v2, Eo400_v2) are also conducted with IPSL-CM5A2 to study the relative contribution of variouseach forcing factor towardsin the warming of climate. The new PRISM4 boundary conditions of PRISM4 adapted in our models produce an enhanced global warming in MIS KM5c, especially overfor the mid-to-high latitudes oceans when compared to the results from PlioMIP phase 1 results. The enhanced warming can be largelymajorly attributed to changes to the change of high latitude seaways which strengthens AMOC and transports more heat to high latitudes, and to the reduction in the spatial extent ofof ice sheets and sea ice whichcovers that largely decreases the outgoing shortwave radiation. The simulated warming conditions in MIS KM5c simulated with either of our models is weaker than those found in other studies (e.g.

Kamae et al., 2016; Chandan and Peltier, 2017). In both our two core experiments, AMOC strength~~s~~ increases remarkably (+4.7 Sv) in comparison to ~~with their related~~ PI controls due to the closure of the Bering Strait and the North Canadian Archipelago regions. This result agrees with other studies (Kamae et al., 2016; Hu et al., 2015), but the extent of the increase of the AMOC highly depends upon the processes included in the ocean models.

In addition to~~Apart from~~ the orography changes, changes to the concentration of ~~the~~ greenhouse gases ~~emissivity~~ and changes to the configuration of high latitude ice ~~sheet configuration~~ play ~~also~~ important roles to~~in~~ the polar ~~warm~~ amplification, e.g., the reduced ice sheets over~~in~~ Antarctica play a key role in the warming of the high-latitudes of the ~~the~~ Southern Hemisphere ~~warming~~. S~~The s~~urface mass balance analysis show that the modern GrIS is vulnerable around the coastal regions under the warm conditions of the MPWP as well as present~~modern~~ conditions. The model response to changes to~~the~~ pCO_2 ~~uncertainties~~ (+/-50ppmv~~-~~) was found to not be ~~based on the core simulation) is not~~ symmetric with respect to~~in~~ the surface air temperature and which is likely~~e ,~~ due to the non-linear response of ~~the~~ snow cover and sea ice extent. When ~~the~~ snow cover and~~as well as~~ sea ice extent are reduced ~~has been largely decreased~~ in area and duration, the sensitivity of climate model to the growing pCO_2 may have a weaker thermal impact, in contrast to the near-linear response~~manner~~ of global surface air temperature ~~responds~~ to the cumulative emissions of pCO_2 in both the present short-term observations and transient modelling scenarios for the future. ~~Finally~~Finally~~To conclude~~, further model inter-comparison work and data-model comparison work are needed to better understand the role of variable boundary conditions and the internal climatic processes in modelling the Pliocene warming climate.

Figures and Tables

Table 1: Configuration common to all experiments described in this paper.

CH_4	760 ppb
N_2O	270 ppb
O_3	Local modern
CFC_s	0
Solar constant	1365 W/m^2
Eccentricity	0.016715
Obliquity	23.441
Perihelion	102.7
Dynamic vegetation	Off
Soil types and lakes	Local modern

Table 2: Details of experimental settings.

Exp names	Models	Topography &Ice sheet	CO_2 (ppmv)	Integration length (yrs)	Climatologies
PI	IPSL-CM5A	Modern	280	2800	Last 100 yrs
PI_v2	IPSL-CM5A2	Modern	280	3000	Last 100 yrs
Eoi400	IPSL-CM5A	PRISM4	400	650+800	Last 50 yrs
Eoi400_v2	IPSL-CM5A2	PRISM4	400	1500	Last 50 yrs
Eoi450_v2	IPSL-CM5A2	PRISM4	450	1500+400	Last 30 yrs
Eoi350_v2	IPSL-CM5A2	PRISM4	350	1500+400	Last 30 yrs
Eo400_v2	IPSL-CM5A2	Modern Ice sheet, PRISM4 topo in other regions	400	1500+400	Last 30 yrs
E400_v2	IPSL-CM5A2	Modern	400	1500+400	Last 30 yrs

Table 3: Diagnostics for each experiment. **The anomalies are computed against the PI controls corresponding to the version of the numerical model employed.**~~**Anomalies are calculated by comparing the related PI controls.**~~

Exp names	MA SAT & PRECIP (Anomaly) (units:℃ & mm/d)			Radiation balance at the top of atmosphere (unit: W/m^2)	MASST (Anomaly) (unit: ℃)	MASSS (Anomaly) (unit: Psu)	AMOC index (unit: Sv)
	Global	Tropics	High Latitudes (NH)				
PlioMIP 1	2.1 & 0.13	1.7 & 0.17	3.9 & 0.21	0.68	1.4	-0.13	10.8
Eoi400	2.3 & 0.14	1.8 & 0.20	4.2 & 0.28	0.69	1.7	-0.26	15.7
Eoi400_v2	2.2 & 0.13	1.6 & 0.19	3.8 & 0.23	0.43	1.6	-0.16	17.9
Eoi450_v2	2.6 & 0.15	2.1 & 0.23	4.5 & 0.27	0.57	1.9	-0.20	17.4
Eoi350_v2	1.5 & 0.09	1.0 & 0.13	2.5 & 0.14	0.39	1.2	-0.20	17.6
Eo400_v2	1.92 & 0.12	1.56 & 0.18	3.56 & 0.23	0.35	1.5	-0.10	17.4

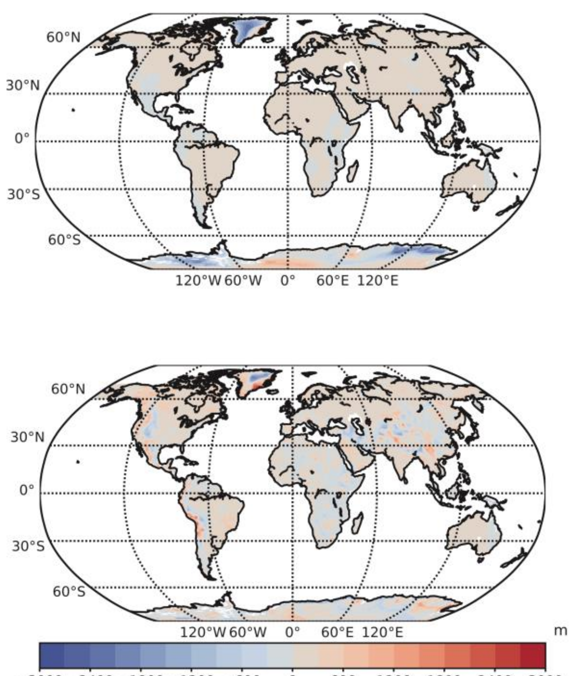

Figure 1: Anomalies of the PlioMIP2 topography relative to PI control (upper) and PlioMIP 1 (lower). ~~Anomalies prescribed in topography of PlioMIP2 respectively in relative to PI control (upper) and PlioMIP 1 (lower).~~

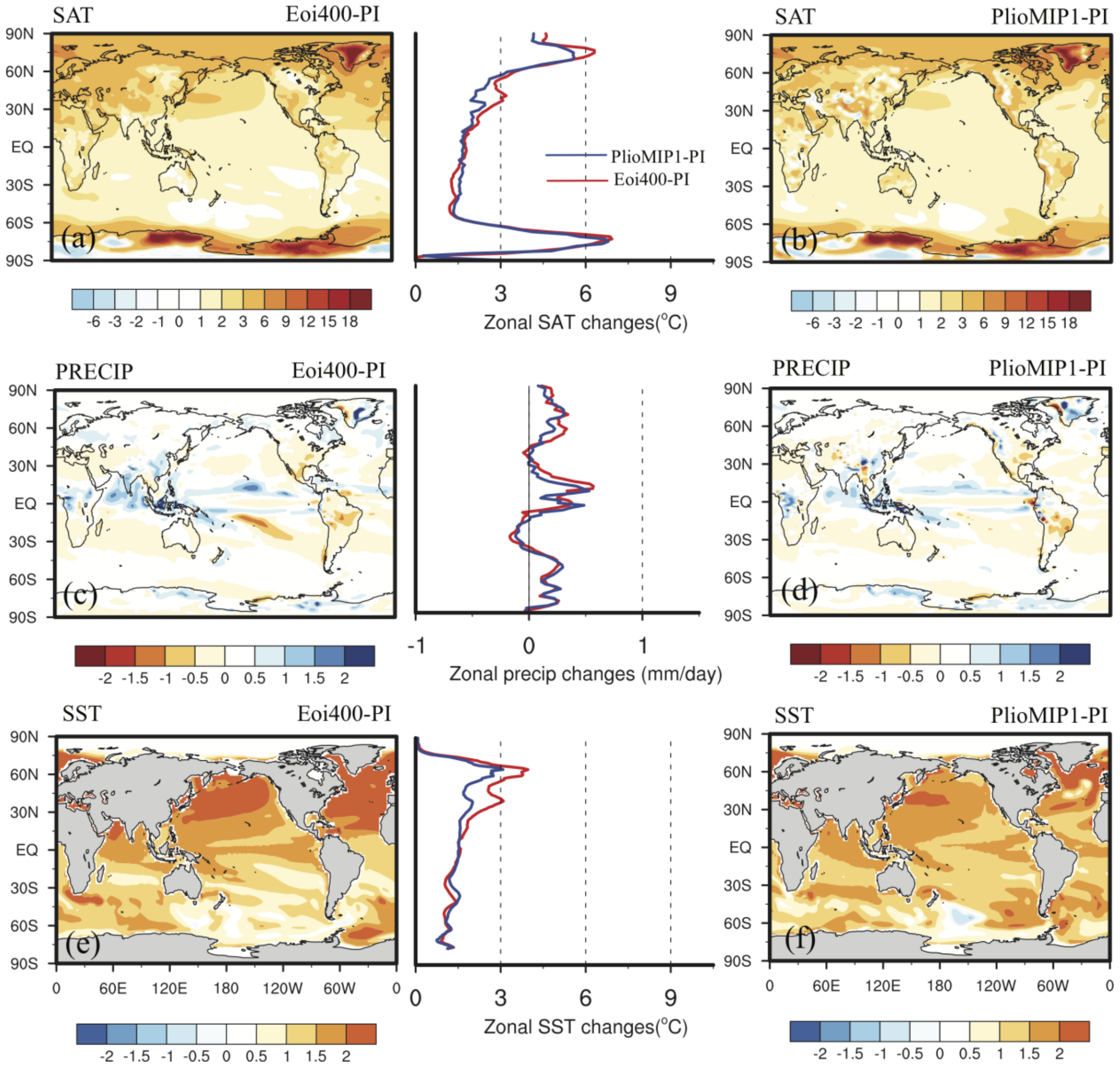

Figure 2: Anomalies of mean annual SAT (a, b), mean annual precipitation rates (c, d) and mean annual SST for PlioMIP 2 (Eoi400) and PlioMIP 1 conducted with IPSL-CM5A in comparison with associated pre-industrial control experiment. The middle panel represents the zonal mean of related anomalies (red lines for Eoi400, blue lines for PlioMIP 1).

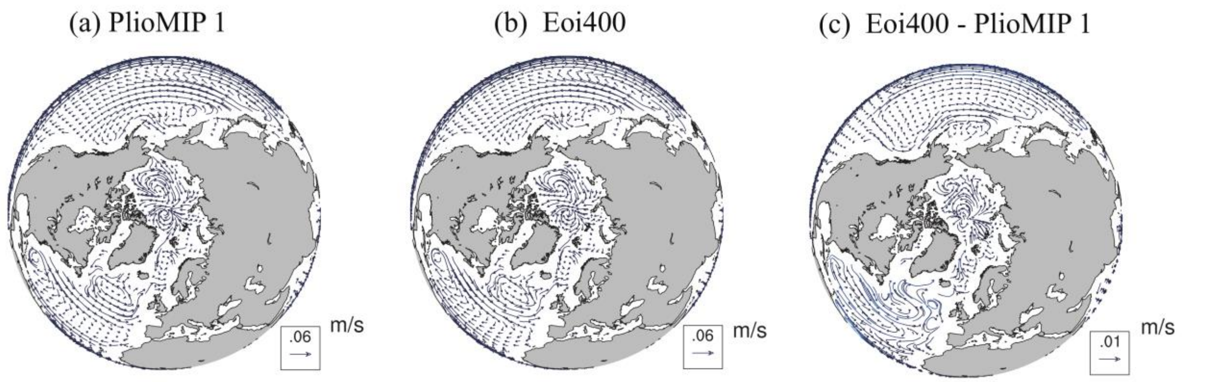

Figure 3: Mean annual Ocean current above 500 meters for PlioMIP 1 (a) and Eoi400 (b), (c) shows the difference in ocean current between Eoi400 and PlioMIP1.

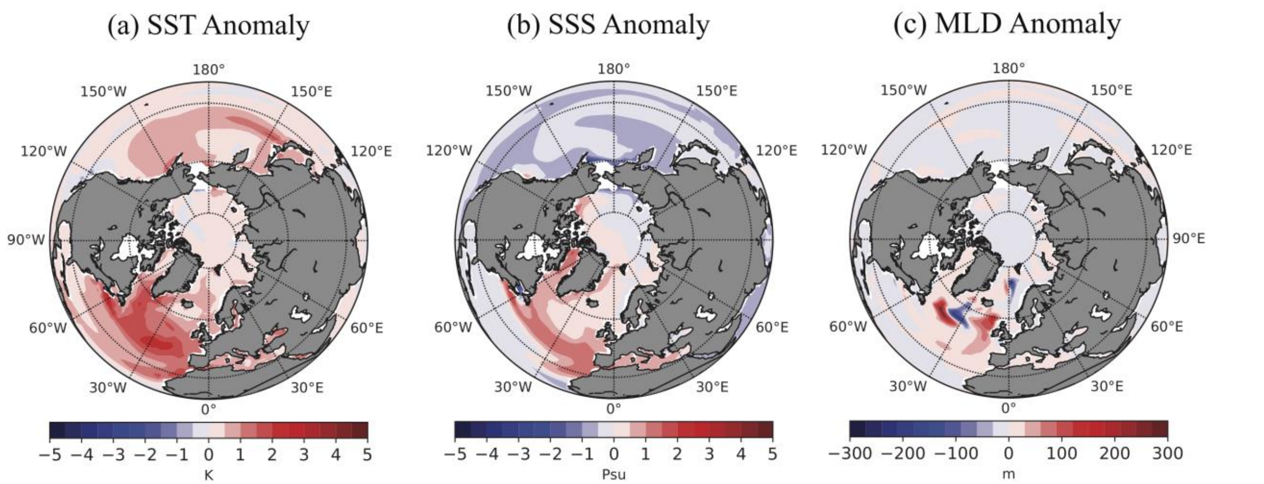

Figure 4: The differences in the mean annual sea surface temperature (a), sea surface salinity (b) and the mixed layer depth (c) between Eoi400 and PlioMIP 1 experiment.

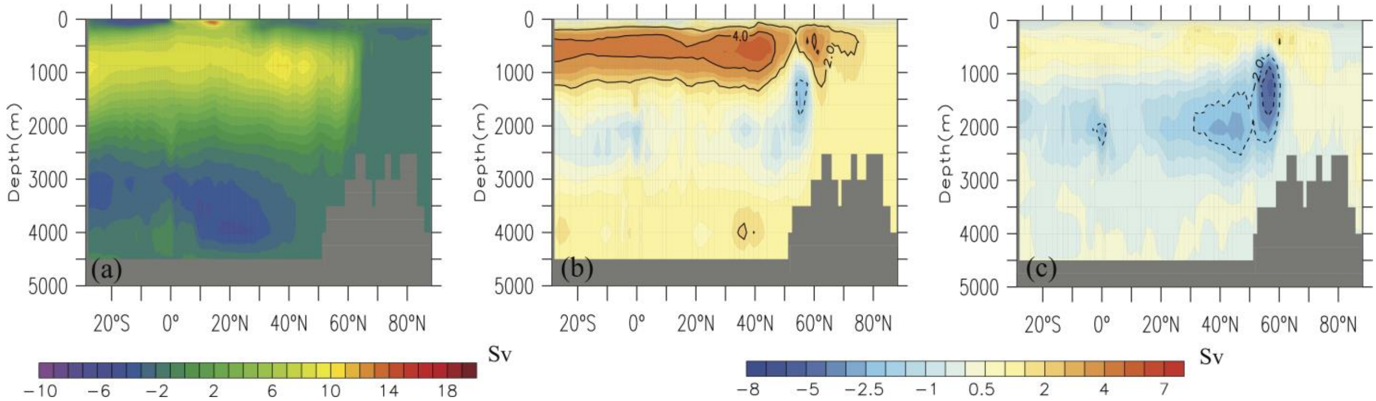

Figure 5: Mean annual AMOC of PI control (a) and AMOC anomalies of Eoi400 (b) and PlioMIP 1 (b) in comparison with PI condition.

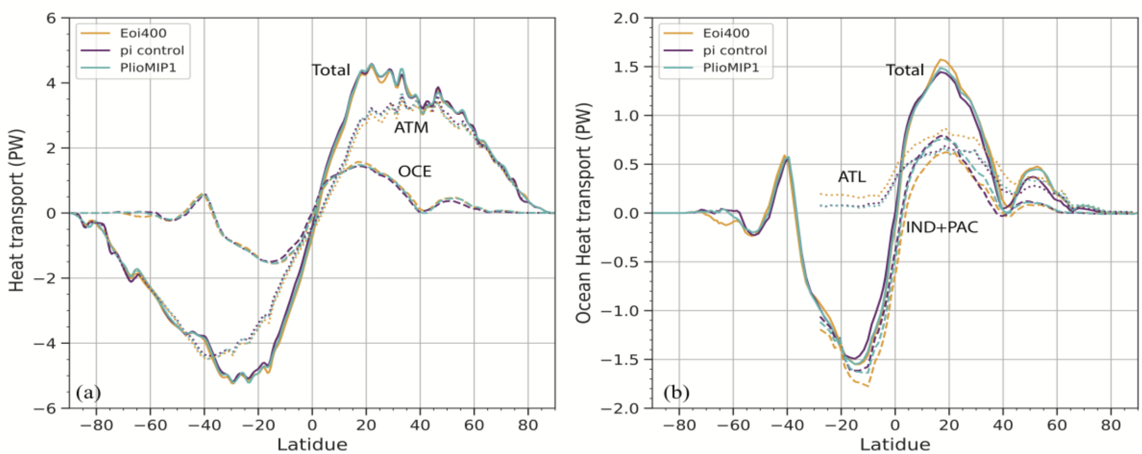

Figure 6: Meridional heat transport in both atmosphere and ocean (a), Meridional ocean heat transport in different regions (b). (Orange, purple and blue lines represent respectively for the results of Eoi400, PI control and PlioMIP 1)

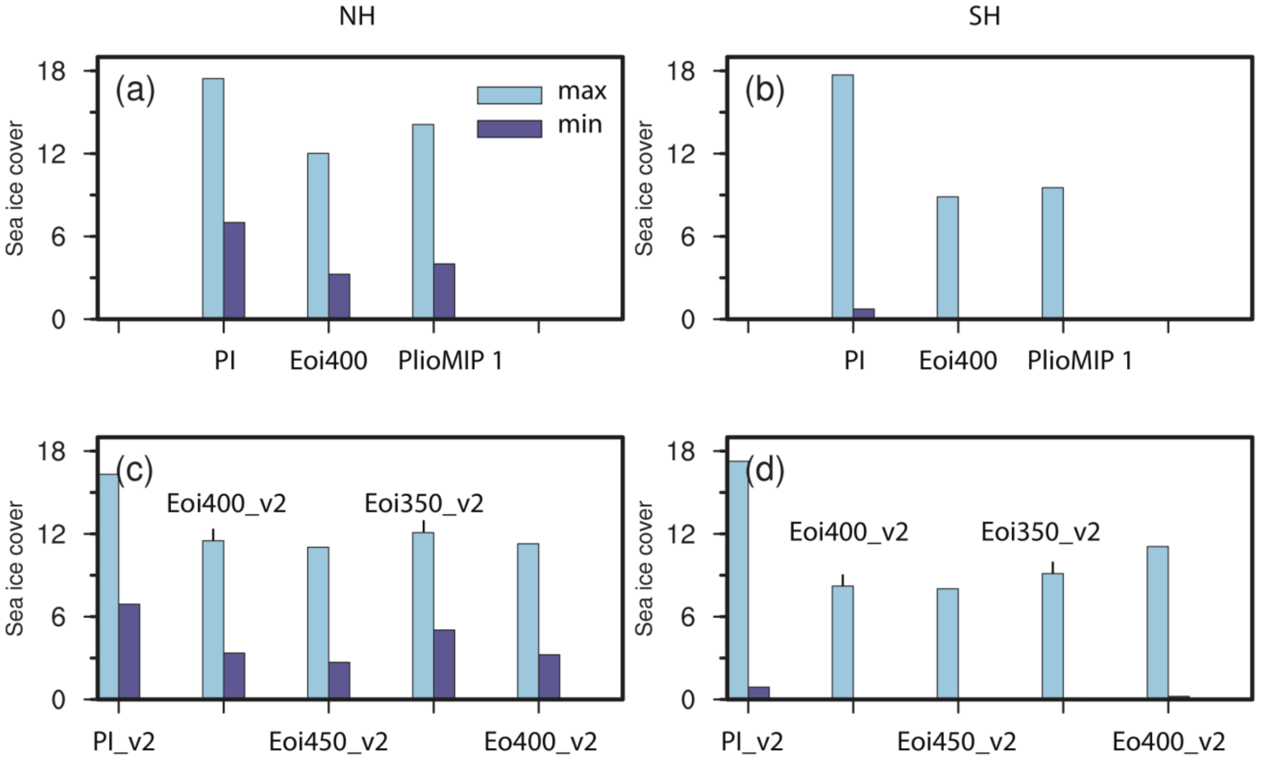

Figure 7: Maximum and Minimum sea ice covers for both hemispheres in each experiment (unit:1E+10^6 km^2).

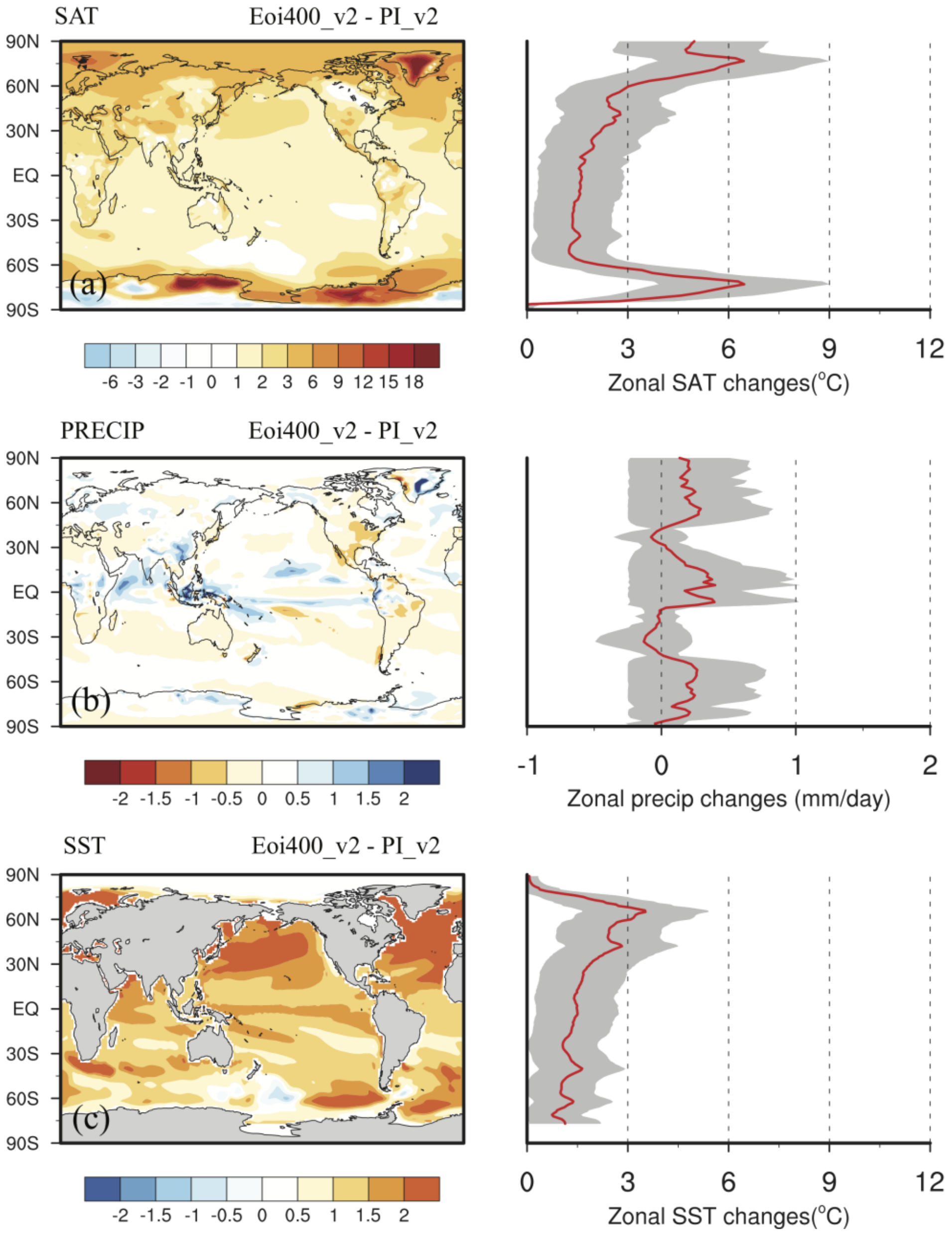

Figure 8: Anomalies of mean annual SAT(a), mean annual precipitation (b) and mean annual SST (c) of Eoi400_v2 in comparison with associated PI control experiment. The right panel represents the zonal mean of related anomalies; the shaded area shows the one sigma standard deviation.

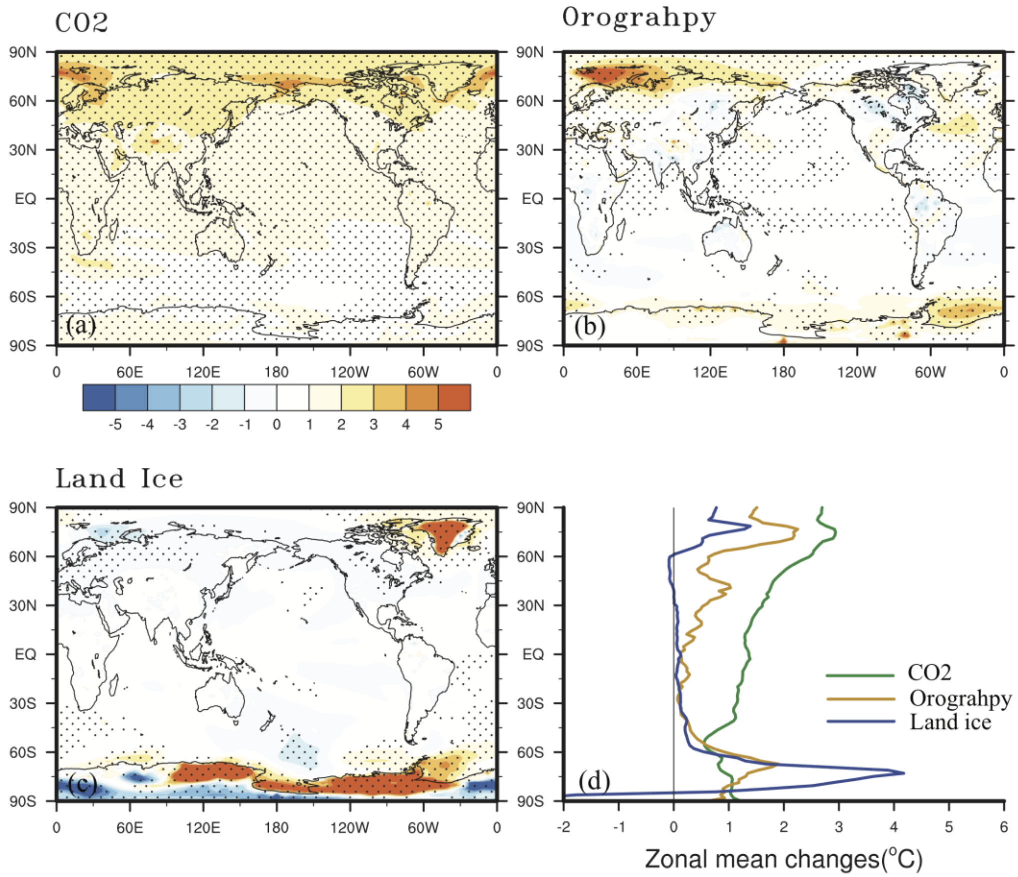

Figure 9: The relative contribution of various boundary conditions (CO2 (a), Orography (b), Land ice (c)) on the warmth of PlioMIP 2 and their zonal mean values (d). Stippling indicates regions where results are statistically significant at ~~a~~ 99% confidence criteria.

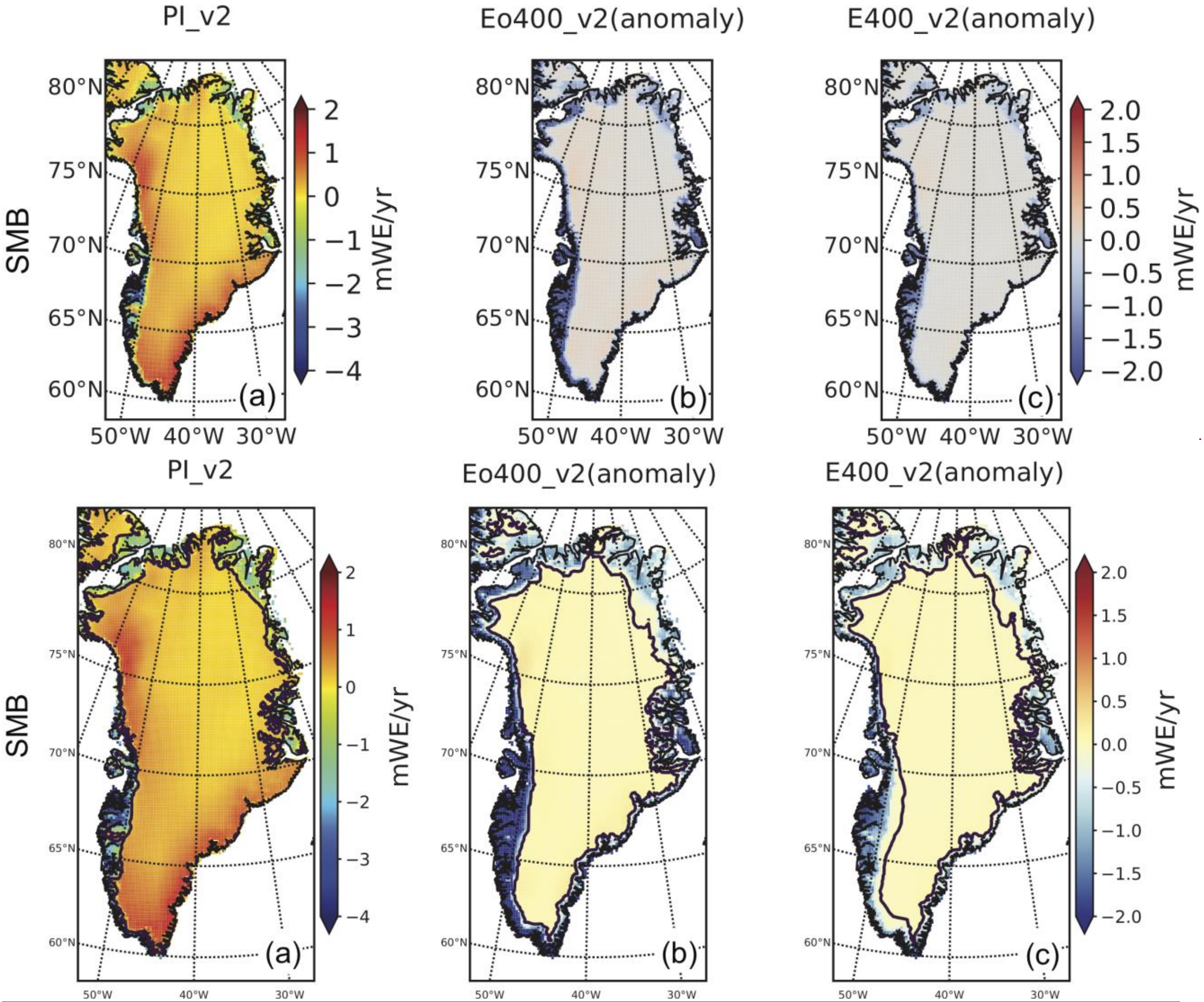

Figure 10: Mean annual surface mass balance (SMB) in Greenland in PI control experiment (a) and the anomalies of SMB in Eo400_v2 and E400_v2 experiments in comparison with PI control (unit: mWE(water equivalent)/yr). Contour line indicates the zero value.

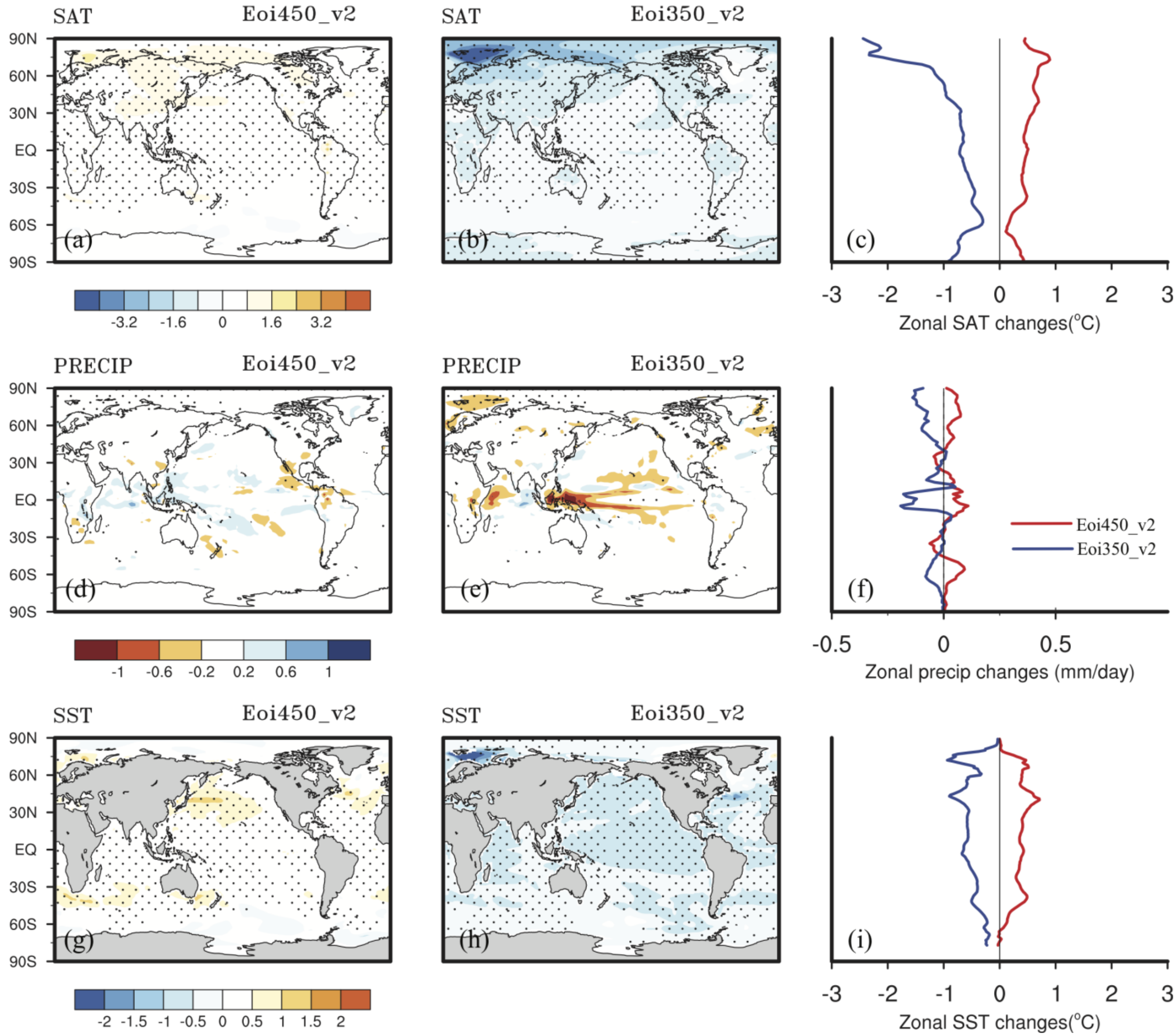

Figure 11: Anomalies of mean annual SAT, mean annual precipitation rate and mean annual SST for Eoi450_v2(a, de, ge), Eoi350_v2(b, ed, hf) in comparison with Eoi400_v2. The last column (c, f, ij) of this panel shows the zonal mean of related anomalies (red and blue lines represent respectively for the results of Eoi450_v2 and Eoi350_v2). Stippling indicates regions where results are statistically significant at a 99% confidence criteria.

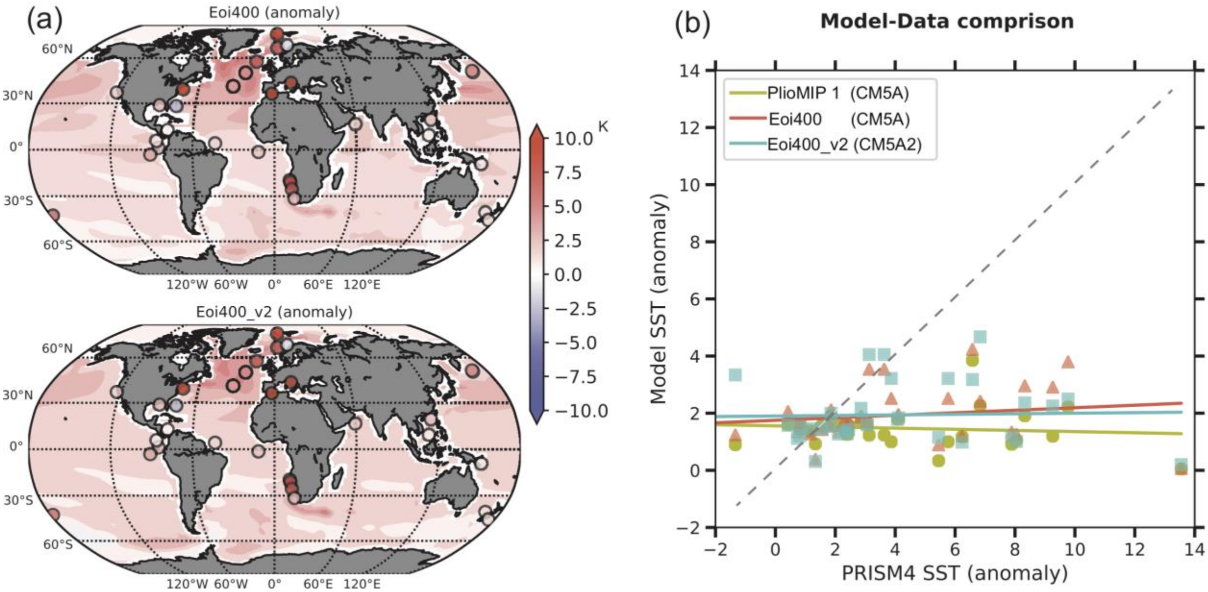

Figure 12: SST model data comparison. (a) Modelled mean annual SST anomalies of MIS KM5c (in relative to PI controls, shaded area) and reconstructed MIS KM5c SST anomalies (in relative to near pre-industrial data, circle markers). (b) The relationship between modelled SST anomalies and PRISM4 data anomalies.

Data availability: Climatological averages of each simulation in NetCDF format will be uploaded to the PlioMIP2 data repository soon (sftp://see-gw-01.leeds.ac.uk). Specific data requests should be sent to the lead author (ning.tan@mails.iggcas.ac.cn). All PlioMIP2 boundary conditions are available on the USGS PlioMIP2 web page (http : //geology.er.usgs.gov/egpsc/prism/7_pliomip2/).

Author Contributions: N. T., G. R. and C. C. designed the study. N. T. conducted the model set-up, spin-up and major data analysis and wrote the manuscript. Y. S., C. C., ~~and~~ C. D. and Z. G. contributed to discuss the data analysis and the structure of this work. P. S. provided the IPSL-CM5A2 information and its related control run simulation. All co-authors helped to improve this manuscript. Correspondence and requests for materials should be addressed to N. T.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements: We thank Oliver Marti and Jean-Baptiste Ladant for their helps on the model set-ups. This study was performed using HPC resources from GENCI-TGCC under the allocation 2019-A0050102212 and supported by three projects: the French State Program Investissements d’Avenir (managed by ANR), ANR HADOC project (ANR-17-CE31-0010), ~~, by the “Strategic Priority Research Program” of the Chinese Academy of Sciences (Grant No.XDB 26000000) and~~

the Basic Science Center Project of by the Major Program of National Science Foundation of China (Grant No. 4188810141690114) and the "Strategic Priority Research Program" of the Chinese Academy of Sciences (Grant No.XDB 26000000).

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